

**THE EFFECT OF LOCAL CONFINEMENT ON THE IGNITION OF  
FLAMMABLE VAPOUR/ AIR MIXTURE AT A HOT SURFACE**

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To my mother and father - Helenice and Vanildo Duarte -

for the life and love they have given to me

To my sister and brother - Katya and Marcos Duarte - for their love

## ABSTRACT

Although ignition by hot surfaces has received some attention in the past, most of the data refer to flat surfaces and hot wires. The effect of "local confinement" around the ignition source on the ignition process has not been extensively studied. The investigations of two well known accidents, the Tunnel Summit fire and the Piper Alpha disaster, showed that more data and knowledge about the ignition mechanism by heated surfaces are needed. In both cases, ignition at hot surfaces of complex geometry was identified as a possible cause of the fire, but the temperature was much lower than 900°C, the temperature considered necessary for ignition of a vapour/air mixture at a hot surface. There have been a number of studies of ignition by hot surfaces, in which the ignition sources were hot spheres, wires and strips. In all these studies the ignition sources were unconfined. However, it is important to understand the influence of the "local confinement" around the ignition source on the ignition mechanism.

The work described in this thesis is confined to the ignition of a flammable vapour/air mixture at a hot surface. The objective of the experimental work was to generate new data which could be used to help understand the effect of "local confinement" on the ignition of flammable mixture at a hot surface. Electrically heated nichrome strips were used as the ignition source, and measurements were made of the effect of "local confinement" on the minimum temperature required to cause ignition of a 3% propane/air mixture. It was found that the ignition temperature decreased as the depth of the confinement was increased. The results obtained were analysed using the thermal theory of Frank-Kamenetskii.

The ignition temperature for the case of the open ignition source is predicted by the equations included in Chapter 4. The equations seem to give a close correlation with the experimental results obtained in the present study as well as with the data obtained by Cutler and Laurendeau.

## DECLARATION

This thesis is the result of the research work undertaken in the Department of Civil Engineering and Building Science at the University of Edinburgh, for the degree of Doctor of Philosophy.

I declare that all the work in this thesis has been carried out by myself unless otherwise stated, and the thesis has been composed by myself under the supervision of Dr. D. D. Drysdale.

Edinburgh, March 1994.

Dayse Cavalcanti de Lemos Duarte

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# Chapter 1

## 1. Introduction

### 1.1 Background

The electrical age in mining began at the end of the last century (1895). The increase in the use of electricity in mining operations established a trend which was followed closely in other forms of industry. The gases liberated from coal are flammable and the hazards associated with operating electrical equipment in a flammable atmosphere were soon recognised. The development of the coal mining industry as well as other forms of industry became dependent on improvements in the safe use of electricity. At that time there was a vague idea about the risks of ignition from electric sources. Three great colliery disasters occurred over a short period; West Stanley (Durham) in 1909, Hulton (Lancashire) in 1910, Senghenydd (South Wales) in 1913, and the accident inquiries took seriously the possibility of the subsequent ignition source being related to electrical effects. Some potential sources of ignition were carefully considered, such as ignition due to: electrostatic discharge and friction, lamps and hot wires, electrical sparks and shot-firing generators. These are noted in the paper 'Safe use of electricity in coal mines' published in 1924 [1] by the Institution of Electrical Engineers.

Prior to the First World War ammonia was manufactured for the first time. It may be argued that this process was the first to use both a high temperature and a high pressure. This marked the beginning of the importance of chemical industries and also the risks associated with these processes.

During the period between the First and Second World Wars there was much interest in obtaining an optimum design of combustion chamber for use in aircraft and missiles travelling at high speed and at high altitude. There was much innovative research work being conducted on the development of jet engines. The problem of ignition by a heated surface surrounded by a high velocity fuel-air mixture was particularly important in this technology.

The period after the Second World War was characterised by the extremely rapid development of the petrochemical industry and especially of the techniques of handling liquefied gases. The beginning of the 1960s saw the start of developments which resulted in great changes in the chemical, petrochemical and petroleum industries. A number of factors are involved in these changes, in particular the process-operating conditions such as temperature and pressure have become more severe, representing a greater hazard.

The rapid growth of the process industry which occurred in a number of phases has given rise to several hazards. The major hazards are fire and explosion. It is essential to understand how these events can start and develop, in order that measures can be taken to avoid their occurrence. The strict control of ignition sources is one such measure.

The earliest research into the problem of the ignition of gases and vapours began around the end of the 19th century when several studies of ignition by hot wires were reported. Ignition of a flammable vapour/air mixture by a hot wire ( or more generally at a hot surface) is a manifestation of autoignition (see section 1.2 autoignition) in which the mixture in the boundary layer is heated sufficiently for spontaneous ignition to take place. Autoignition

temperatures are quoted in the literature, but these refer to a standard procedure in which a stoichiometric mixture is heated uniformly in a test apparatus [2]. However in the standard test, the gases are confined and uniformly heated within a reaction vessel, while in practical situations an exposed hot surface can be open to the surrounding atmosphere. In BS 5345 [3] it is stated that for ignition to occur at a hot surface, its temperature has to be greater than the 'ignition temperature', taken to be the autoignition or spontaneous ignition temperature. According to this standard, to avoid ignition of a flammable vapour/air mixture at the hot surface of an item of electrical equipment, the temperature of all parts of the surface should not exceed the ignition temperature. Flammable gases are classified in BS 5345 according to their susceptibility to ignition. This standard identifies 'ignition temperature', some values of which are given in Table 1, along with the apparatus group, as defined in BS4683 [4]: these are clearly based on the standard autoignition temperatures.

In a detailed review of ignition at hot surfaces, Powell [5] showed that in practice much higher temperatures are generally required for ignition to occur than is suggested from these 'ignition temperature' values. The relevant data considered in his review were derived from studies in which static vapour/air mixtures were brought into contact with heated surfaces at various temperatures. Movement of the mixture was by natural convection. His review includes data on ignition by hot wires, tapes and small spheres, which were obtained during different periods in the development of the process industry. Each study included in his review addressed a specific objective. Powell concluded that the minimum temperature of an open surface for ignition of Group IIA vapours was in excess of 1,200°C for surface areas of a few square millimetres, but fell 'quasi-asymptotically' towards a value of *ca* 900°C for

characteristic surface dimensions of 10-15mm. Laurendeau [6] reported similar results for methane/air mixtures, although the required surface temperatures were higher, typically above 1,000°C for ignition at a surface of characteristic dimension *ca* 10mm. This conclusion is in accordance with the American Petroleum Safety Data [7]. Thus, strict adherence to the recommendation in BS 5345 (see Table 1) introduces a very conservative safety factor and it would seem that much higher surface temperatures are considered acceptable in practice. For example, in the report of the Piper Alpha Inquiry [8], it is stated that the normal operating temperature of the gas turbine centrifugal compressors in Module C was 700°C.

**Table 1.** Ignition temperatures of selected gases and vapours [3]

	<b>Ignition Temperature °C</b>	<b>Apparatus Group</b>
Firedamp(CH <sub>4</sub> )	595	I
Propane	470	IIA
Ethylene	425	IIB
Hydrogen	560	IIC

Although it can be argued that strict adherence to the quoted 'autoignition temperature' is both too conservative and too restrictive, it would appear that there are no well-defined criteria on which judgements of 'safe' surface temperature can be made. There is therefore a need to gain further data on the ability of a hot surface to cause ignition in order that more reliable guidelines can be developed. This is important not only for the purposes of design and hazard analysis, but also in the context of accident investigation in which it is necessary to establish the likely ignition source. In these circumstances, an incorrect conclusion could lead to 'improper or ineffectual remedial action' [7].

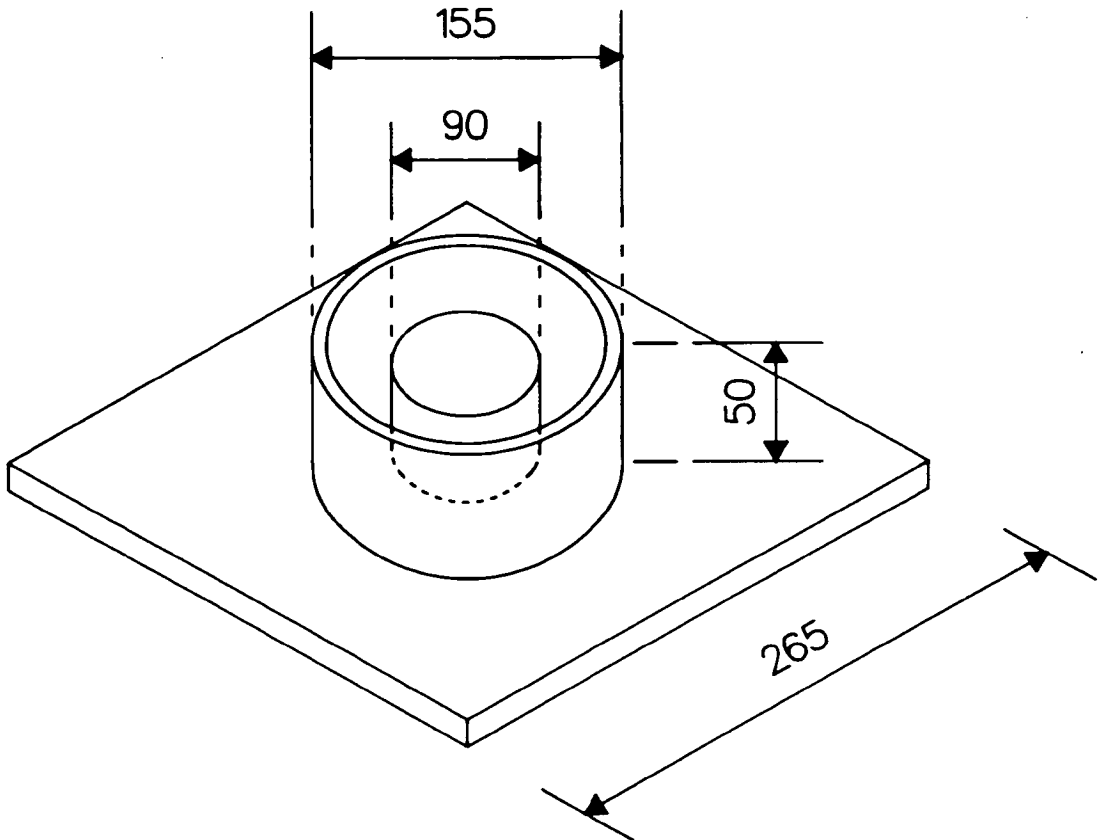
However the available data on ignition at hot surfaces [5,6] are insufficient to develop guidelines on acceptable temperatures for open surfaces. There is now evidence that the geometry and configuration of a hot surface can influence the temperature at which ignition of the flammable vapour/air mixture can occur. This can be illustrated by reference to Summit Tunnel Fire and Piper Alpha disaster.

### **Summit Tunnel Fire [9]**

On 20 December 1984 a south-bound goods train transporting over 800 tonnes of petrol was derailed in the Summit Tunnel between the towns of Tormorden and Littleborough, to the north of Manchester. The derailment occurred over 1km into the tunnel and was attributed to the failure of an axle box bearing on the fourth tank wagon. The axle broke, causing disintegration of the track and derailment of the other wagons. There was a major leakage of petroleum spirit, although ignition did not occur immediately. Subsequent investigation by the Health and Safety Executive revealed that the possible causes of ignition were a hot axle on Wagon Number 4 and a hot journal end and axlebox unit which lay near Wagon Number 10.

Ignition was reported to have occurred 'within minutes' of the derailment. The subsequent investigation concentrated on the possibility of ignition at a hot surface rather than by mechanical sparks which were of short duration. Examination revealed that the temperature of the fracture surface of the axle had reached 1,200°C, and some of the metal housing had been at over 1,000°C [10]. This led to a series of three experiments in which it was shown that petrol vapour could be ignited at a surface designed to simulate the

fracture face of the journal end and axle box unit (Figure 1) if it was at 650-700°C, much lower than the 900°C quoted by Powell. By contrast, a flat plate (300mm x 200mm) at 700°C failed to cause ignition.



**Figure 1.** Surface designed to simulate the fracture face of the journal end and axle box unit.

### **The Piper Alpha Explosion and Fire [8]**

The Piper Alpha disaster occurred on 6th July 1988, claiming the lives of 165 men. It remains the highest death toll in the history of the off-shore oil industry. It is believed that the initial event was an explosion following a high pressure leak of condensate [8] in 'C' Module, the gas compression module which contained three centrifugal compressors, each in a separate enclosure

with its turbine, and two reciprocating compressors. The casing of the gas turbines were reported to 'glow red' while running, i.e., at a temperature of 550 - 700°C, but this was considered to be 'no cause for concern'. It is well above the 'autoignition temperature' of the light hydrocarbons released from the condensate line, but well below 900°C ( see Figure 13). The source of ignition in C Module was not established by the Inquiry, but the possibility of ignition at the profiled hot surface of the gas turbine units cannot be ruled out.

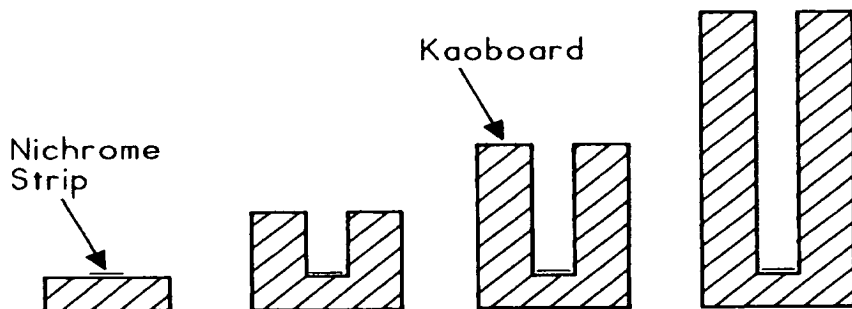
The investigation into the Summit Tunnel Fire by the HSE suggested that ignition took place readily at a hot surface which was highly profiled and presented some kind of local confinement.

The Piper Alpha Inquiry led to the conclusion that the recommendation included in BS 5345, about the 'ignition temperature' is too conservative and it is not used for design purposes. The American Petroleum Institute stated that for ignition due to a hot surface to occur, a much higher temperature than the ones included in BS 5345 are required. However, it failed to answer the question 'How many degrees above the autoignition temperature can be considered to be safe ?' In design of equipment for the process industry and in the context of fire investigation, the surface temperature accepted seems to be the one suggested by Powell; it appears to be internationally accepted that 900°C is the minimum surface temperature for ignition of a flammable vapour/air mixture at an open surface.

Silver [11] reported the enhancement of ignition by lengths of heated copper wire 0.11 to 0.16 mm in diameter, when the wires were wound in the form of a spiral rather than being presented to a flammable mixture as straight lengths. This type of 'local confinement' has a significant effect on the ability of a

heated surface to act as an ignition source. Surprisingly, there appears to have been no systematic investigation into the effect of the surface profiling on the temperature at which ignition occurs. Accordingly, the present study was undertaken to investigate this effect and to generate new data which could be used to help resolve the issue.

Before proceeding to the next sections, some definitions are necessary to avoid confusion in the terminology. Autoignition temperatures are determined in enclosed vessels (a closed configuration). 'Open configuration' refers to the situation in which the 'ignition source' (in the form of a heated surface, or wire) is placed in an open location in contact with a flammable vapour/air mixture [5, 6, 14, 15, 28]. The term 'local confinement' is used in this thesis to describe the situation in which there is some confinement around the hot surface, or the hot surface itself is highly profiled. The configuration used to investigate the effect of 'local confinement' in the present investigation is shown in Figure 2.



**Figure 2.** Shape of the 'open configuration' and 'local confinement' used in the present work.

## **1.2 Flammability limits and ignition**

Hazards always exist when flammable mixtures are generated in the course of regular operations in a plant process. If an ignition source is present an explosion or fire could be initiated. The consequences for the plant and operating personnel can be devastating. Therefore, the prevention of unwanted fires and gas explosions requires a knowledge of the flammability characteristics of the pertinent flammable gases and vapours likely to be encountered. Information on the probable ignition sources and ignition temperatures are also important.

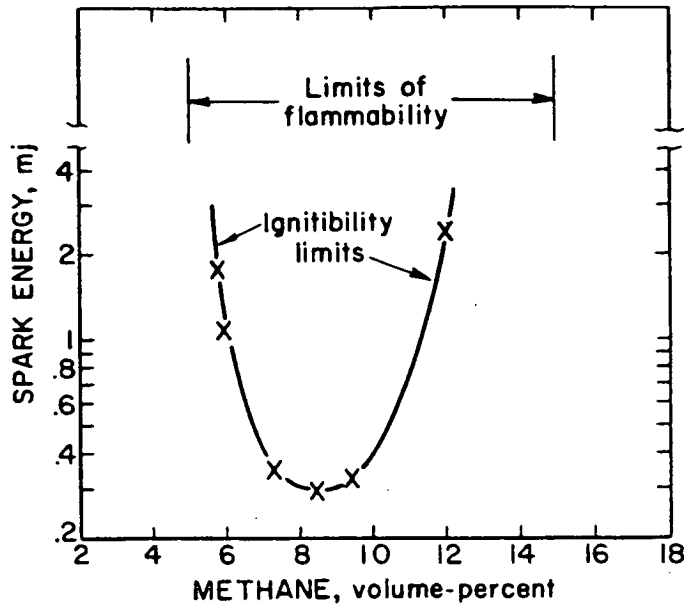
This section presents a discussion of ignitability limits and flammability limits, autoignition temperatures and sources of ignition. An understanding of these factors is of importance in other aspects of the present work.

### **Ignitability and Flammability Limits**

The earliest reference relating to the investigation of ignitability limits was contained in a report by Sir Humphrey Davy who worked on the problem of explosions in coal mines between 1815 and 1819. He discovered that cooling the gas-air mixture by either a diluent or the wall of a narrow tube prevented the passage of a flame through a flammable mixture.

A flammable gas burns in air only over a limited range of composition. Figure 3 shows how this range of composition is affected by ignition source strength. In general this graph is U-shaped. The conditions lying inside the U result in ignition whereas those lying outside do not. Several inferences can be drawn from this graph. The first observation is that there exists both a lower and an

upper concentration limit for ignition; if the mixture is either fuel-lean or fuel-rich, ignition is not possible, regardless of the ignition source strength. Secondly, it can be seen that as the ignition source strength is lowered, these two limits approach one another, thus narrowing the range of ignition. Finally, if the ignition source strength is too low, ignition is impossible for any composition.



**Figure 3.** Ignitability curve and limits of flammability for methane-air mixture at atmospheric pressure and ambient temperature [12].

It is evident that the limits which define the critical mixture compositions depend on the strength of the ignition source. The range of mixture compositions that depend on the ignition source strength are defined as the limits of ignitability or simply the ignitability limits. The range of mixture compositions which are independent of the ignition source strength is known as the flammability limits, thus considerably greater energies are required to establish limits of flammability than are required for limits of ignitability [12].

In the standard technique [12,13] which identified the flammability limits, the ignition source adopted was an electrical spark (Figure 3). The work done by Shepherd and Wheeler [14] illustrated the effect of methane-air mixtures on the minimum current required for ignition by a hot wire (Figure 4). Their ignition sources were tungsten wires 0.1 mm and 0.065 mm in diameter. The ignitability curve which they obtained was similar to the one presented by Zabetakis [12]. The most reactive mixture for the case of spark ignition lies just on the fuel-rich side of stoichiometry. However, for the case of hot wire ignition, the most easily ignited mixture seems to be on the fuel-lean side of stoichiometry. Shepherd and Wheeler found that the most easily ignitable concentration was 8% of methane/air. Cutler [15] also reported that 7% of methane-air mixture was the most reactive mixture when the ignition source was tungsten wires.

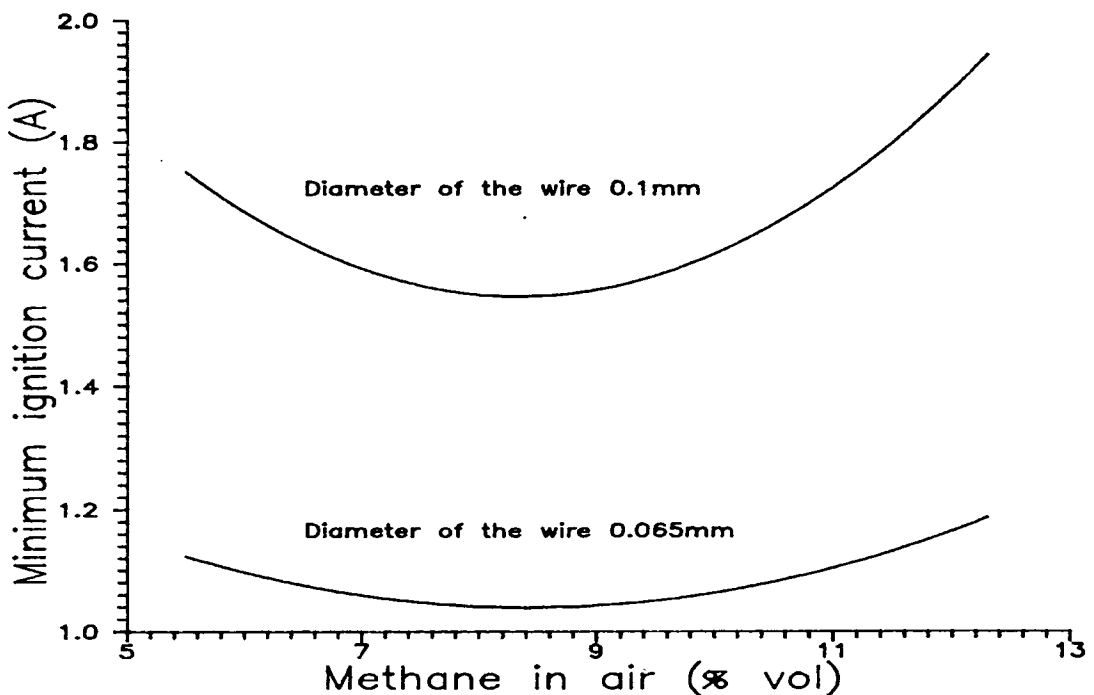


Figure 4. Ignitability curves for methane-air mixtures by tungsten wires [14].

For every flammable gas or vapour there is a range of concentration in air within which ignition can occur. The flammability limits define this range, which is determined by using standardised apparatus and conditions to eliminate variations due to temperature, dimensions of the apparatus and spark strength.

Pressure has an effect on flammability limits, the rich limits become much wider with increased pressure; on the other hand, the lean limits are not appreciably affected by the pressure. This is especially true for hydrocarbon-air mixtures.

In view of the effect of temperature on the rate of chemical reactions, it is reasonable to expect that limits of flammability should be broadened if the initial temperature is increased. Thus a mixture lying outside the normal flammability limits will become flammable if the temperature is raised high enough.

In summing up the factors that affect the limits of flammability, Lovachev and others [16] point out that convection plays a significant role in determining the limits. The observations of how convection affects the limits were important, in order to define the diameter of the tube in the standardised apparatus for determining the flammability limits. The various and complex interactions which take place between convection currents and flames is illustrated by the following excerpt from Coward and Jones [13]: "When a spark was passed near the lower confines of methane-air mixture standing over water in a vessel 6ft high and 12 inches square section, the following observations were made: 5.1% methane; a vortex ring of flame travelled upward about 12 inches, broke and died out as a tongue of flame about 12

inches higher. 5.3% methane; in one experiment the ring of flame resolved itself into a flame that travelled steadily to the top of the vessel; in another experiment the flame became extinguished during a violent uprush on one side. 5.6% methane; steady flame with a convex front passed throughout the mixture."

The addition of a chemical inhibitor to a flammable mixture narrows the flammability limits, i.e., above some particular concentration of inhibitor no fuel/air/inhibitor mixture will propagate flame. Some inhibitor such as CO<sub>2</sub>, N<sub>2</sub> merely replace part of the O<sub>2</sub> in the mixture, but they do not all have the same extinction power. It is found that the order of efficiency is the same as the order of the heat capacities of these gases. It has been observed that rich limits are more sensitive to the presence of inert diluents than lean limits. There are more effective inhibitors, such as the halogenated hydrocarbons. The halogenated hydrocarbons act chemically to suppress combustion by decreasing the rate of the chemical reaction at the flame front and resulting in a narrowing of the flammability range [17].

All mixtures of gases and vapours with air within the flammable range may be ignited, particularly if the mixture is partly or wholly confined. The flammability limits are obtained using standardised apparatus which will be discussed in section 1.3. In practice flammable mixtures may form either by accident or design, and they are encountered in the production of many chemicals, therefore precautions must be taken to avoid their formation or ensure that a non-flammable mixture is rapidly formed by the addition of some inhibitor, for example.

## **Autoignition**

Apart from the ignition processes introduced by external sources such as sparks, pilot flames, and hot surfaces, there is a process called autoignition which is sometimes referred to as spontaneous ignition, self-ignition or homogeneous ignition, without source of pilot ignition . The definition of autoignition given by Spalding [18] is as follows "when a reactive mixture is formed, raised to a definite temperature and pressure, and then left alone, it may burst into flame after a certain time,".

In a spark ignition engine, a fuel-air mixture is introduced into a cylinder closed at one end, which contains a movable piston. The mixture is compressed by the motion of the piston and then it is ignited by a spark. The hot burnt gases at high pressure provide the energy which drives the piston back down the cylinder, the linear motion being converted to a rotary action by a crankshaft and flywheel. The operation of a diesel engine is similar in principle to the spark-ignition engine, i.e., gasoline engine; however, instead of a fuel air mixture being introduced into the cylinder, air is taken into the cylinder and compressed adiabatically. At the top of the compression, liquid fuel is sprayed into the cylinder where it ignites spontaneously as it mixes with the hot air.

Strictly speaking the process of the diesel engine is not autoignition, since there is no sharp distinction between the mixture preparation and the ignition phase; however, it is an example of the application of the autoignition theory to a practical system in which the ignition is deliberate.

On the other hand, the phenomenon of 'knock' in gasoline engines is an autoignition process. It is the autoignition of the fuel-air mixture as it is compressed in the combustion chamber prior to the firing of the spark. It is a problem as it reduces the power and makes the engine noisy and is counteracted by the addition of antiknock compounds to the fuel.

Intended as a model for explosion in reacting gases, the autoignition theory opened up the application of the model to the problem of self-ignition of a solid body. Self-ignition is a problem in the processing, storage and transport of material. Examples are material handled in process equipment such as, driers, storage in piles in warehouses or transported in large containers as in ships. In some cases the hazard is intensified by the fact that the material enters storage relatively hot. This can occur, for example, with material which has just been passed through a drier.

In general, when the time required for the formation of a certain gaseous mixture at high temperature is short in comparison with the chemical reaction time and also the gaseous mixture is not exposed to a piloted ignition source, one can apply the autoignition analysis to the ignition of the mixture. Some aspects of the autoignition theory will be presented in Chapter 2.

## **Sources of Ignition**

The energy required to initiate a fire needs to be supplied by an ignition source until the combustion process is self-sustaining. Sources of ignition capable of igniting gases and vapours can arise in a number of ways. In the

process industries as a whole, 90% of all fires may be caused by 11 sources of ignition, which are listed below in order of frequency (fires due to arson are not included) [19],

Although ignition sources cannot be eliminated altogether in an industrial installation, their identification combined with proper management procedures can reduce the probability of ignition. In this section some ignition sources will be discussed: spark ignition, ignition by frictional heating, ignition by hot surface, ignition of a high velocity stream by a solid body and two-stage ignition.

**Table 2.** The statistics of ignition in Process Industry [19]

Electrical sources	19%
Friction	14%
Mechanical sparks	12%
Smoking and matches	8%
Spontaneous ignition	8%
Hot surfaces	7%
Combustion sparks	6%
Open flame	5%
Cutting and welding	4%
Overheating	3%
Static discharges	2%

## Spark Ignition

Ignition of a combustible mixture can be accomplished by producing an electrical spark of short duration between two electrodes. The spark instantly establishes a small volume of gas within which the temperature is very high, known as flame kernel. It has been found experimentally that for capacitance spark ignition up to 95% of the stored energy appears in the flame kernel of gas in less than  $10^{-5}$  seconds. The temperature in the flame kernel decreases rapidly due to the flow of heat to the ambient unburned gas. In the adjacent layer of ambient gas the temperature rises and induces chemical reaction, so that a combustion wave is formed which propagates outward the burned gases in the flame kernel with approximately spherical symmetry. In order to continue to propagate, the flame should at that time have grown to a critical size so that the temperature gradient between the burned gases in the flame kernel and the outer unburned gases has approximately the same slope as the temperature gradient in the steady-state flame. Otherwise the rate of heat loss to the unburned gas ahead of the flame will be too great to allow sustained burning.

Ignition of a flammable gas-air mixture by an electrical spark occurs only if the latter delivers a certain amount of energy into the mixture. This minimum ignition energy is defined as the smallest quantity of spark energy that must be added to the system to start flame propagation. This minimum usually occurs close to the stoichiometric mixture. Following BS 5345 [3], flammable gases and vapours are divided into four groups I, IIA, IIB and IIC, according to their ease of ignition by electrical sparks [20]. Methane a member of Group I, has a minimum ignition energy of 0.29 mJ. Most flammable gases and vapours belong to Group IIA having a value around 0.25 mJ. The apparatus used for

these measurements comprised a glass tube containing two electrodes, and it was found that when non-conducting flanges were placed on the electrodes there was a minimum gap through which a flame could propagate from the flame kernel to the mixture. This minimum gap is called the quenching distance and it is also the diameter of the sphere which contains the minimum volume from which flame can propagate. The minimum quenching distance for most hydrocarbons/air mixtures is about 2mm.

One method of protection against ignition by electrical means uses the principle of 'intrinsic safety', i.e., that the energy of any spark produced under normal and fault conditions should be less than the minimum ignition energy of any flammable gas or vapour which is most likely to be present.

### **Ignition by Frictional Heating**

Whenever two materials slide over each other, mechanical energy is expended in doing work against friction, and the energy dissipated is transformed into heat. Frictional impact and rubbing can produce hot surfaces or eject hot particles into the surrounding atmosphere; such hot surfaces produced in the vicinity of flammable gases or vapours can lead to fire or explosion. Friction heating capable of igniting gases/vapours may be produced in various ways, such as collision between two vessels. In industry, friction is responsible for approximately 14% of fires and explosions [19].

Nearly all work on ignition by frictional heating is qualitative and device specific. One of the fundamental studies of methane ignition by frictional

heating was carried out by Blickensderfer [21]. Rock-metal impact was simulated by pushing a metal rod into a sandstone flywheel. Impact energies in a 7% methane/air mixture were measured by determining the angular velocity of the flywheel just before and after impact. The impact zone was analyzed using high speed photography and a two-colour optical pyrometer. The temperature, lifetime and area of the hot surface were investigated using a non-steady conductive heat transfer analysis.

The experiments were plagued by reproducibility problems; since rubbing predominates at surface asperities, fluctuations in surface temperatures are expected. However, several consistent patterns emerged from the many tests performed. Ignition was always accompanied by a bright yellow flash in the impact region and the formation of a molten metal smear on the rock surface. High speed photography suggested association of ignition with the hot surface rather than a yellow flash. This conclusion was corroborated by two-colour pyrometer of a  $1 \text{ cm}^2$  area behind the impact zone which showed an average surface temperature of approximately  $1420^\circ\text{C}$ , roughly equivalent to the melting point of mild steel.

The experimental work done by Bowden and Tabor [22], showed that sliding friction produces a number of small hot spots whose temperature does not exceed that of the lower of the melting points of the two materials. If the load is increased further, the number of points of contact and the heated area increase. Then, for loads and velocities sufficient to achieve melting of the metal, the biggest effect of velocity is the development of enough area for ignition. The probability of ignition will then depend on the exact area and lifetime of the smear. For steel or sandstone, Blickensderfer found a hot streak with a length of 2-8 mm ( $250\text{-}800\text{mm}^2$ ) at velocities of 1.5-4.6 m/sec and

lifetime of 2 msec, as determined by both theory and experiment. In conclusion, at 1500°C such an area and lifetime are sufficient for methane/air mixture ignition. Similar areas and even longer lifetimes could be available during a tanker collision [23].

The work done by Powell [24] showed that ignition of flammable gases and vapours by friction between footwear and flooring materials is possible. He also reported that where steel on footwear is in contact with quartzite material, such as sandstone, granite, or clay tiles, brick and concrete or asphalt, the risk of ignition is small with methane, but ignition is possible with propane and very likely in ethylene and air.

### **Ignition by Hot Surface**

In ignition by a hot surface, the heat transfer to the gas layers immediately adjacent to the heated surface is due to conduction and it increases the temperature in these layers. A convective flow is set up, and a higher temperature in this region will induce a chemical reaction. The mechanism involves the chemical reaction and the convective flow can be interpreted in terms of the convection time and the chemical time. The convection time, sometimes referred to as the residence time, is the length of time that the mixture remains in the reaction zone (i.e., at elevated temperature). The chemical time is the chemical reaction time. The first Damkohler number physically represents the ratio of convective-diffusion time to the kinetic time, i.e.  $Da_1 = \frac{\text{convective time}}{\text{chemical time}}$ . If the convective time is much shorter than the chemical time, the mixture does not have time to react. On the other hand, if the chemical time is much shorter than the convection time then

reaction is possible. Ignition will occur if the heat generated by the chemical reaction compensates for the heat losses due to conduction and the diffusion of chemical species between the interface of hot gas layers near the surface and the 'free stream' mixture (Figure 5, see page 24).

**Table 3.** Comparison of methods of igniting a flammable mixture.

	Minimum Spark Energy <sup>1</sup>	Minimum Ignition Temperature <sup>2</sup>	Autoignition Temperature <sup>3</sup>
Methane	0.29mJ	> 1,200°C	545°C
Propane	0.25mJ	>1,000°C	470°C
Ethylene	-	>785°C	425°C
Hydrogen	-	>735°C	560°C

1- NFPA 68 [25].

2- Powell review [5].

3- BS 4056 [2].

The results of ignition of different combustible gases by different sources are difficult to correlate (see Table 3). Hot surfaces and sparks differ in time scale, in method of energy release and in quantity of released energy. For a spark ignition the energy is released within  $10^{-5}$  seconds from a high-voltage capacitor. When the ignition source, such as wire, is brought up to a very high temperature by a capacitor discharge or by passing a high current through the wire [5], the experiments which have been done in the past have involved time scales of around 0.5msec to 40sec in which the energy is delivered. On

the other hand, the ignition temperature usually listed in the literature is the autoignition temperature, and it is determined by allowing a gas or vapour to remain in contact with the walls of an almost completely closed chamber for 5 minutes. The methods of energy release are different, a hot surface transfers energy to the gas by conduction, whereas spark energy creates a plasma, rich in atoms and free radicals. The quantity of energy transferred by a hot surface depends on the time that the vapour/air mixture is in contact with the surface and is dissipated by convective flows [15], whereas the energy of a spark is released virtually instantaneously and remains localised.

The conditions of ignition associated with the standard autoignition test are different from those in which the ignition source is placed in an open configuration. In the standard autoignition test, conditions for ignition are highly favourable because the gases are confined and uniformly heated within the reaction vessel, unlike the open configuration in which the energy can be lost to the surrounding atmosphere. A buoyancy-induced flow will be established which will not only limit the temperature to which the mixture will be raised in the vicinity of the surface, but it will also ensure that the time of contact between the mixture and the surface will be of short duration. According to Powell [5] the temperature that a hot surface requires for ignition is higher than the one obtained in the autoignition tests.

As already pointed out by Shepherd and Wheeler [14] and Cutler [15] there is a difference between ignition by an electrical spark and by a hot surface. Their work showed that in the case of wire ignition the most readily ignitable mixture was in the fuel-lean side of the stoichiometry, while for spark ignition the most ignitable mixture tends to lie on the fuel-rich side.

If the heated surface is catalytic, chemical reaction develops rapidly in the gas layer close to the body, but heat of reaction is drained into the solid material and the body becomes insulated from the explosive medium by a relatively cool layer of inert burned gas [26, 27]. If the surface is noncatalytic, chemical reaction develops more slowly and to a greater depth around the body, and since the more remote layers suffer less loss of heat to the body, a combustion wave develops more readily in this case than in the case of a catalytic surface [26]

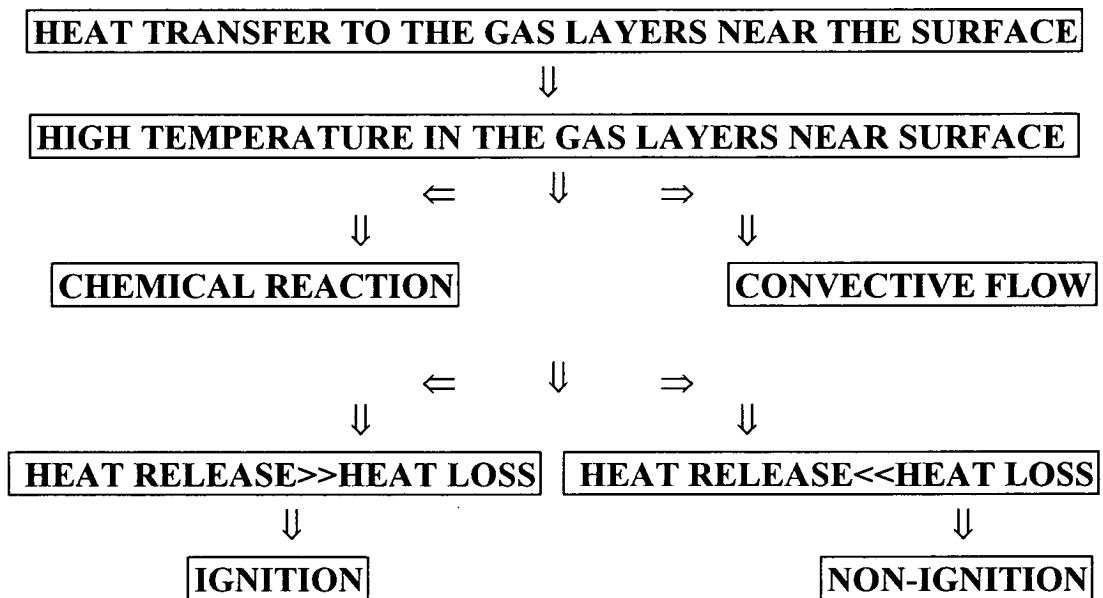
### **Ignition of a High Velocity Stream by a Solid Body**

Mullen and others [28] in a systematic series of experiments studied the problem of ignition of fuel-air mixtures of higher velocities. As an ignition source a stainless steel rod fitted tightly over two solid copper electrodes about 6.35 mm apart was used. The rod was brought up to a very high temperature by means of a current supplied by a powerful welding generator. The surface temperature was observed by means of an optical pyrometer, and the stream velocity was obtained from Pitot tube measurement upstream from the rods.

They observed that the stagnant gas near the downstream face of the rod was made up in part of well heated gas that had been in close contact with the surface, and in part of much cooler gas that swirled back towards the cylinder from considerable distances downstream; thus lobes of hot gas were formed. The high speed photographs taken during the tests showed that ignition develops in the stagnant volume of gas near the downstream face of the heated cylinder where a relatively low velocity exists. In this region ignition would

occur if the heat liberated by the chemical reaction plus the heat supplied from the rod overbalances heat dissipated to ambient.

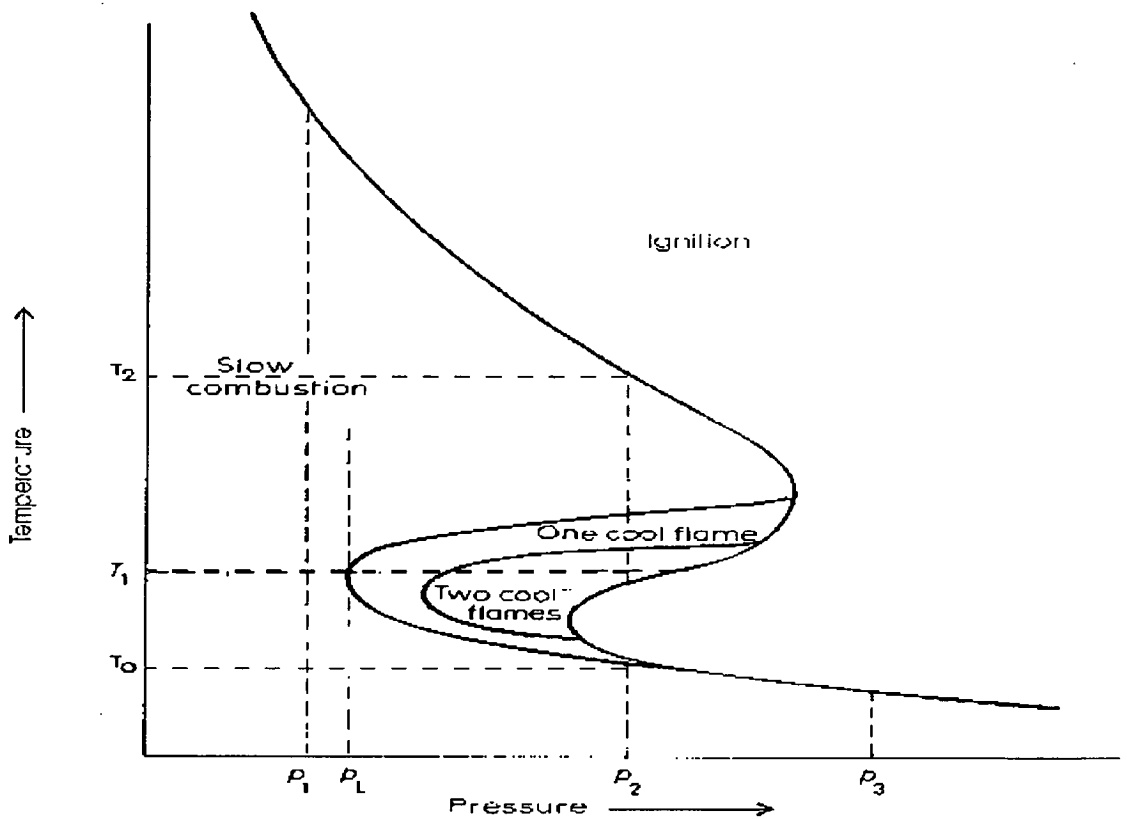
The effect of flow on the ignition process is in principle the same, whether a gas stream is passing around a heated body or a heated body is moving through a combustible mixture. The experiment on the latter type was reported by Silver [29] and Paterson [30].



**Figure 5.** Schematic diagram of the ignition process by hot surface.

## Two-Stage Ignition

It is important to describe the two-stage ignition mechanism to distinguish it from the ignition process studied in this work. Explosive limits are dependent on both pressure and temperature, and the boundaries for a specific mixture ratio of fuel and oxidizer can be displayed on a pressure-temperature diagram. This shows regions of slow and fast combustion. A general representation of the explosion limits of propane is shown in Figure 7 (see page 27).



**Figure 6.** Schematic representation of a typical two-stage ignition diagram [31].

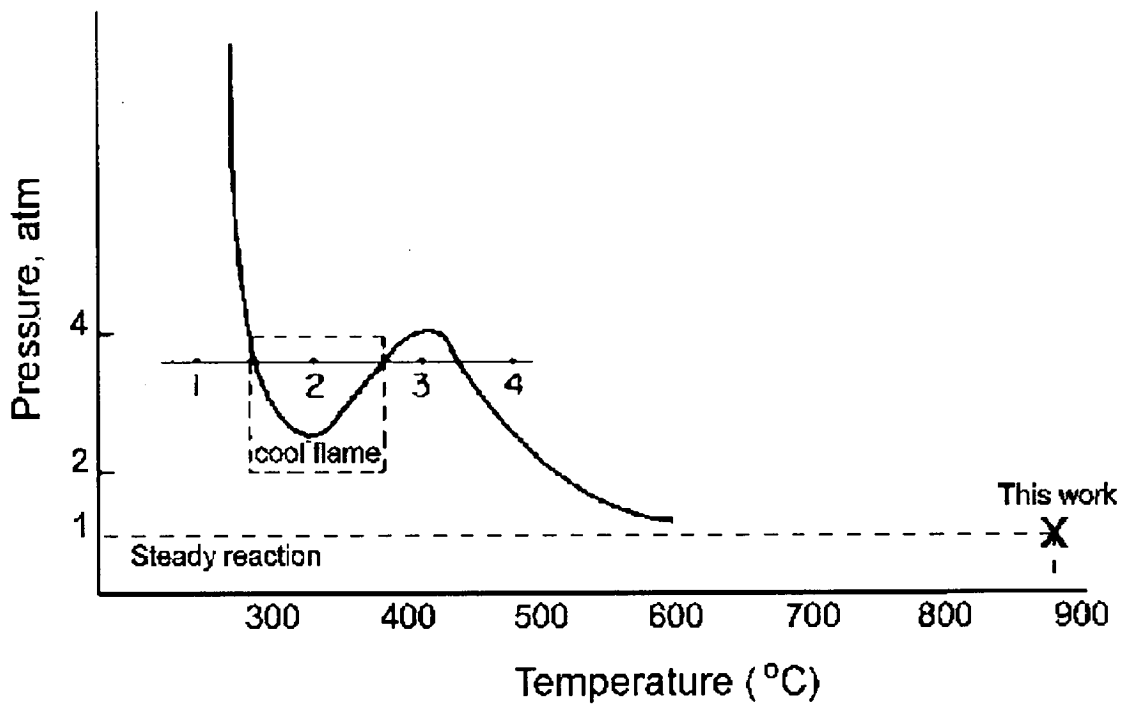
Figure 6 [31] can be derived from a simple static system in which the reaction vessel is kept at a constant temperature. Several regions with different reaction behaviour that depend on temperature and pressure are observed. In one region combustion is slow and may be unmeasurable, while in another explosive reaction occurs. At  $T_1$  and pressure below  $p_L$ , slow reaction takes place.

This is the region of low temperature and slow combustion. As the pressure is increased above  $p_L$ , a pale blue flame is seen to traverse the vessel during the reaction process. This is accompanied by a momentary pressure pulse during which the temperature may increase by about 150K before returning to  $T_1$ , and the low temperature slow combustion. This phenomenon is known as a 'cool flame'. As the pressure is increased, several cool flames may be observed, and if the pressure is high enough, true ignition takes place. This is preceded by a cool flame and the process is known as two-stage ignition.

At a pressure of  $p_2$ , if the temperature is increased from  $T_0$  a cool flame is followed by ignition. However, at a higher temperature still, only slow combustion occurs, and at  $T_2$  ignition again occurs. This is due to the existence of a negative temperature coefficient. At low ( $p_1$ ) and high ( $p_3$ ) pressures there is no cool flame before explosion as the temperature is raised. In the present investigation, ignition occurred without a cool flame since it was confined to the case in which the initial pressure was relatively low and the temperature was high (in excess of 900°C).

At temperatures below 500°C the ignition of most hydrocarbons and other organic vapours occurs in a two-stage ignition process in which autoignition is preceded by a self-quenching temperature pulse, i.e., cool flame [32,33]. Most experiments in which cool flame was observed have been carried out in static system in a closed heated vessel. The work carried out at Shell Research Ltd.

[33-37] dealt with the hot surface autoignition temperature of acetaldehyde and the two-stage ignition process was observed. This work is not concerned with it, therefore the work carried out at Shell will be not included in the review presented in Chapter 2.



**Figure 7.** General explosion limit characteristics of a stoichiometric propane-air mixture. Inset box denotes cool flame region [32].

## 1.3 Tests Available

### Flammability Limits Tests

For every flammable gas or vapour there is a range of concentrations in air in which ignition can occur. The evaluation of hazards requires a knowledge of the concentrations of these mixtures. The limits of flammability which are obtained experimentally represent the extreme concentration limits of the flammable mixtures in which ignition is possible.

The United States Bureau of Mines in Pittsburgh, Pennsylvania has developed one particular technique for determining flammability limits as a standard method [12,13]. The choice of this technique is dependent on a considerable amount of research that has gone on in the past.

In this technique, a 51mm internal diameter tube 1.5 metres long is mounted vertically and closed at the upper end while the lower end is open to the atmosphere. The spark ignition is located at the lower end. As the flammability limit test is concerned with the capability of a mixture to propagate flame, and not with the capacity of the spark to initiate flame, a spark of high energy is used so that the limits are not determined by the strength of the spark ignition. If flame propagates at least 50% of the length of the tube (75 cm) towards the upper end, the mixture is said to be flammable. The apparatus is illustrated in Figure 8.

The flame propagation depends on the transfer of heat and mass from the burned gas in the flame kernel to the neighbouring unburned gas. The flame travels from the open end of the tube to the closed end at uniform speed [13]. Therefore anything that tended to reduce the probability of the flame

propagating through the tube was carefully considered. Experience has shown that if the observations are made in a tube 51 mm in diameter and 1.5 metres in height, the results are nearly the same as those obtained in apparatus with a larger diameter. It was observed that in an apparatus with tube of a narrower diameter, usually 25 mm or less, the limits were significantly narrower. In addition, the results obtained with these narrow tubes were very misleading. Hence, the diameter of the tube was standardized to 51mm since an increase of the diameter above 50mm rarely had an effect on the limits.

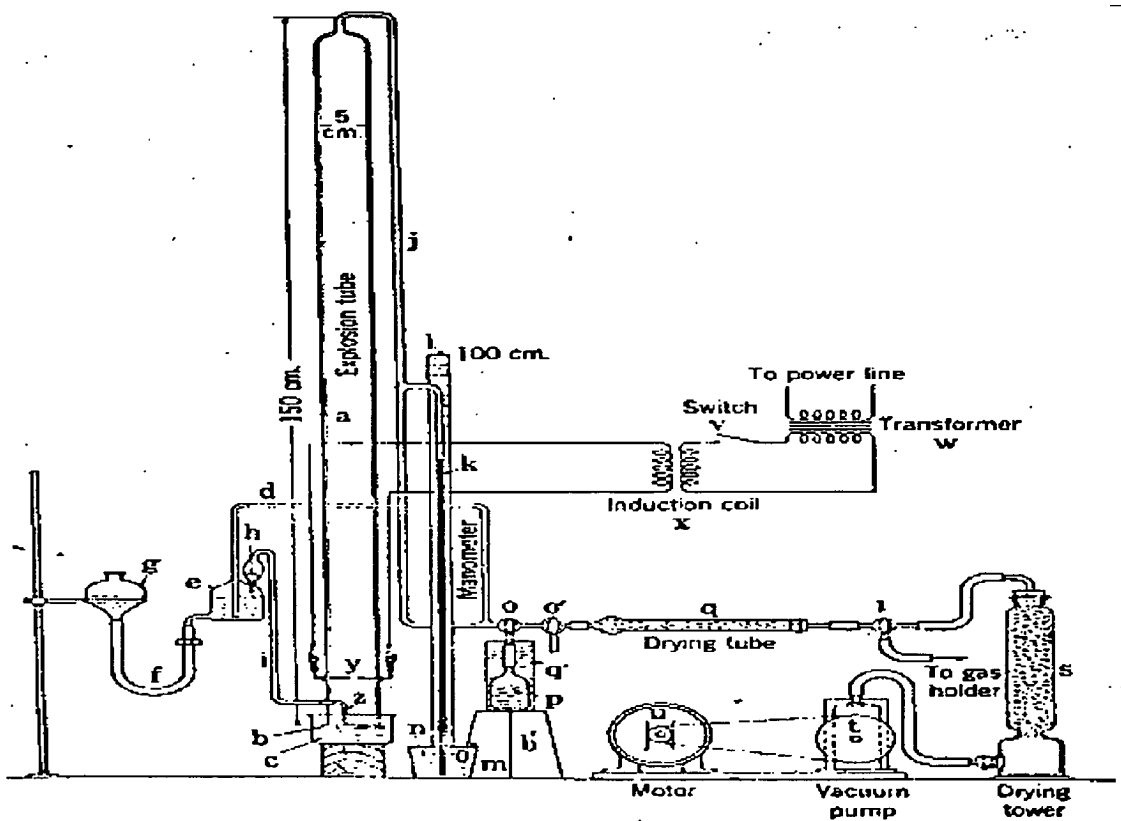


Figure 8. Apparatus for determining limits of flammability of gases and vapours [13].

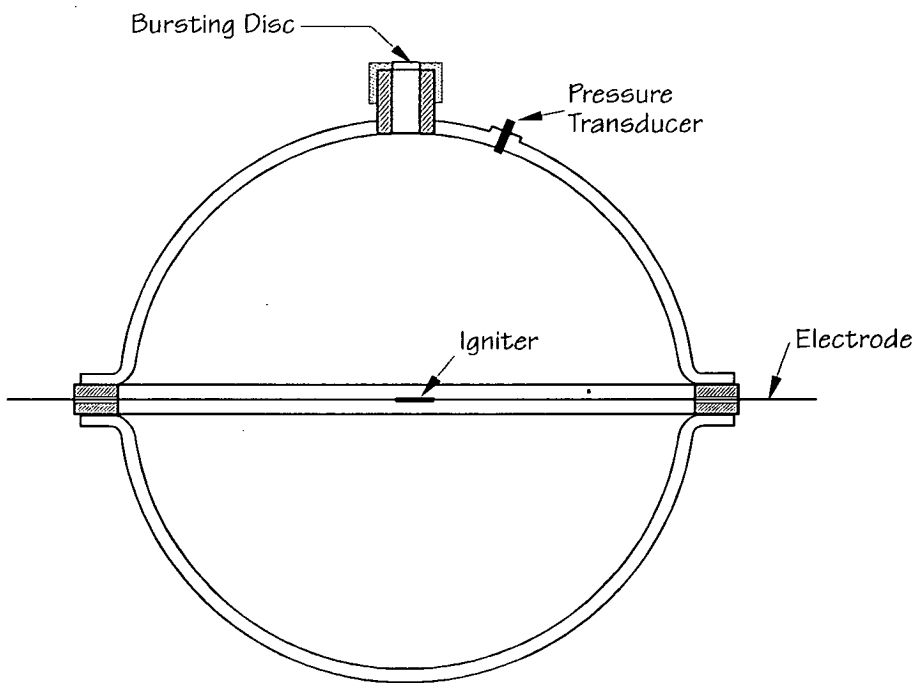
For safety in industrial operations it is wise to consider the limits to upward propagation as a measure of the hazard, since these limits are wider than those for horizontal or downward propagation. The difference arises because the buoyant movement of the burnt gases acts in opposition to the downward propagating flame.

In the light of the previous paragraphs, in Figure 8, *a* is the glass tube in which the mixture is tested. Its lower end is closed by a lightly lubricated ground-glass plate *b*, sealed with mercury *c*. It is evacuated by a pump through the tube *j*. The vapour under test drawn from its liquid in the container *p*, in amount measured by the manometer *k*. Air or other 'atmosphere' is then admitted through the drying tube *q* until atmospheric pressure is reached. The air and vapour are then thoroughly mixed by circulation, by suitably raising and lowering the mercury vessel *q* repeatedly for 10 to 30 minutes, depending on the density of the added combustible vapour. The mercury seal is then removed, the glass plate *b* is slid off the tube and the flammability is tested almost at the same moment by sparking across the open end of the tube, *y*.

However, this procedure may allow extraneous air to enter the tube if the mixture is denser than air, and this may affect the mixture concentration at the ignition source. This problem can be solved by using a spherical vessel similar to that used for studying inerting concentration of the halons. The flammability criterion in this case is based on the propagation of a flame for a relatively short distance from the ignition source. The detection of ignition is by the resulting pressure increase. A sketch of the pressure vessel is shown in Figure 9. The lower limits obtained by the spherical vessel method are found to be in good agreement with the ones obtained by tube method (Table 4) [17].

The flammable limits of any particular fuel are of considerable importance to industrial safety. For example, a good rule of thumb relative to ventilation systems is that they should ingest sufficient air so that any flammable mixture that is ingested will be diluted to a fuel concentration of less than one-fourth of the flammable limit concentration for that particular fuel.

A large body of experience exists on this subject and the experimentally determined limits have proved to be reliable for safety and other uses, even though the methods of determining limits are somewhat arbitrarily standardized.



**Figure 9.** 6l steel vessel used to determine the flammability limits [17].

**Table 4.** Flammability limits in air

Compound	Flammability Limits in air (Vol %)			
	Hirst [17]		Zabetakis [12]	
	lower	upper	lower	upper
Methane	4.9	15.4	5	15
Propane	2.23	11	2.1	9.5
Ethylene	-	-	2.7	36
Hydrogen	-	-	4	75

### Autoignition Temperature Tests

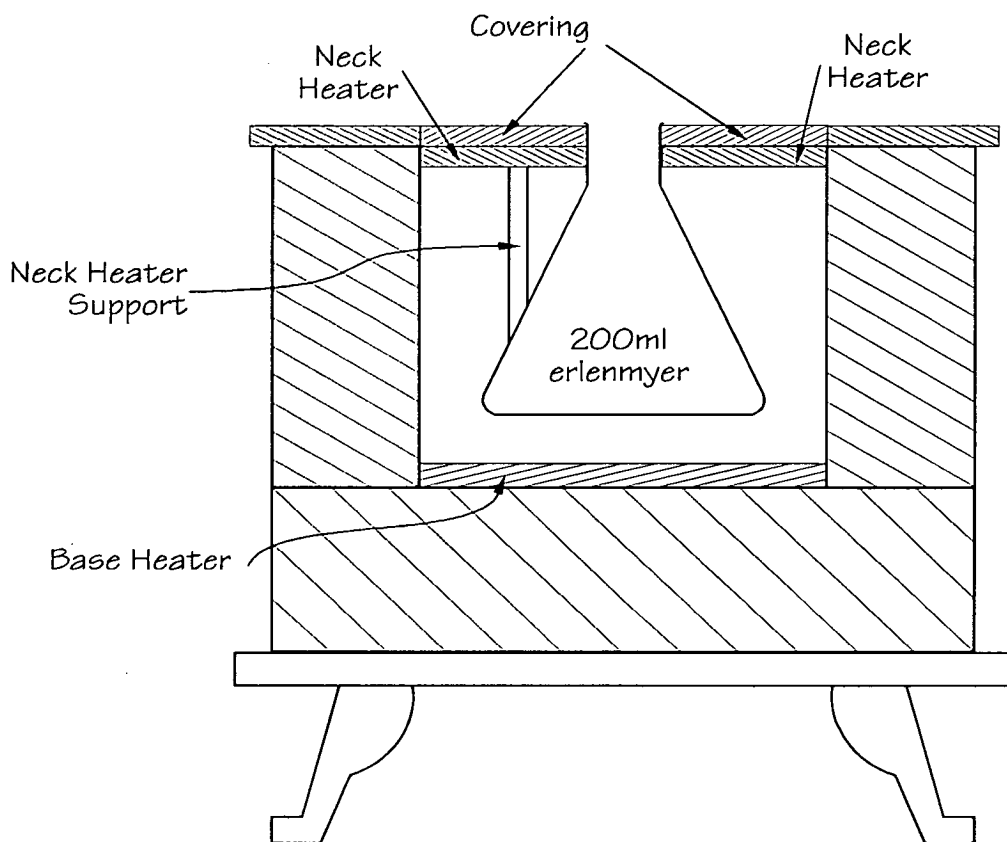
Autoignition is a phenomenon of particular relevance to fire in the chemical industry, because it involves the occurrence of combustion in the absence of an external ignition source. The minimum autoignition temperature is usually the quantity of interest in safety work, especially when combustible mixtures and air can remain in contact for an indefinite period. To assess the autoignition hazard posed by any particular hot surface, or to diagnose the cause of an explosion incident, a knowledge of the critical autoignition temperature is often required. The International Electrotechnical Commission Publication IEC 79-4 (same test method as the BS4056 [2]) is used for the assessment of the minimum autoignition temperature.

In these techniques a determined volume of the product to be tested is injected into a heated 200ml Erlenmeyer borosilicate glass flask containing air. The contents of the flask are observed in a darkened room for 5 minutes following injection of the sample or until ignition occurs. Autoignition is evidenced by a sudden appearance of a yellow or blue flame inside the flask; however, pale blue, white and mixed colour flame could be obtained in some cases. After the lowest flask temperature is obtained, then the test is repeated five times at a temperature 5°C below the lowest one, and if no ignition is obtained this temperature is taken as the autoignition temperature of the combustible mixture in air at one atmosphere (Figure 10 and Figure 11).

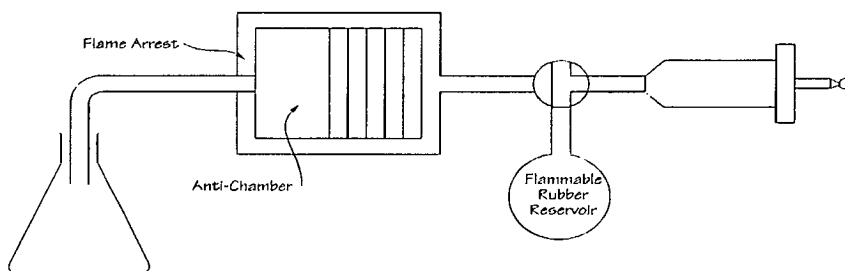
The autoignition temperature does not necessarily represent the minimum ignition temperature in the sense that it is a very apparatus-dependent quantity, since the specification of the vessel, size and wall material have an effect on its values. For example, lower autoignition temperatures tend to be obtained with larger volume apparatus [38]. As a result, the relative values of the autoignition temperature of various compounds yields an indication of allowable surface temperature of equipment and apparatus when exposed to air-vapour mixtures of these compounds. Thus, these rather imprecise and apparatus-dependent autoignition temperatures are useful from a practical standpoint.

Although the standard methods of testing for autoignition temperatures give some idea of the relative ignitability of different flammable gases, they failed to characterise some practical situations. Experience has shown that vapour/air mixtures can come into contact with surfaces which are several hundred of degrees above the published autoignition temperatures without ignition taking place. In a process plant, a hot surface can be present during normal

operation, or may occur as a result of mechanical distress in machinery, such as pumps and motors. On a small scale, one example is a centrifuge in which a volatile flammable liquid is being used. Overheated bearings have been known to cause ignition in this case [20]. Powell [5] has summarised the evidence which shows that the lighter hydrocarbons require surface temperatures of 900°C in the open configuration for ignition to take place, although there is no 'standard test' to measure this. This has become accepted within the petrochemical industry, although it is now clear that 'local confinement' can cause a significant reduction in the temperature at which ignition can take place (see investigation on the Summit Tunnel). No systematic work has been carried out to investigate this effect. The principal objective of this work has been to examine the effect of 'local confinement' in detail, and to provide data which can be used to quantify the process. This information is essential for the safe design of plant and equipment, for the application of quantitative risk assessment and for the fire investigator who has the task of identifying the likely ignition source.



**Figure 10.** Schematic diagram of the autoignition temperature test apparatus.



**Figure 11.** Schematic diagram of the injection of gaseous samples.

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## Chapter 2

### 2. Review of the Experimental and Theoretical Work

#### 2.1 Introduction

Technical and scientific development have been progressive in all fields of science. Most of the knowledge in fire protection and risk analysis started to be developed when electrical energy began to be used in coal mines underground at the end of the last century. Following the efforts of the earliest scientists in investigating gas properties, such as their flammability limits and how they could be ignited, nowadays there are sophisticated tools available such as the ignition mathematical models.

When electrical energy began to be used in coal mines underground in the last century, it was very soon recognised that the gases liberated from the coal and associated strata were flammable. This gas is known as **firedamp** in which the chief constituent is methane. At that time many questions were still unanswered concerning the possible causes of gas ignition in mines. It was therefore necessary to carry out investigations to enable assessment of the hazards to be made and in order to develop protective measures. Several pertained to metallic surfaces that had become heated in some manner. Electric wires and cables were thought of first in this connection. But many other factors, such as improperly lubricated bearings, and sliding car wheels, though perhaps less important, were cause for concern. More potent as possible causes of mine explosions were red-hot cutter bits on mining machines and hot particles and sparks, thrown off during the cutting of coal and rock and from

the impact of a roof fall. Another possible cause of mine explosions was the accidental exposure of lamp filaments. As a consequence, all sorts of questions immediately arise, including the following typical examples. To what temperature must a given heated surface be raised to ignite firedamp? How long must the gas be in contact with that heated surface before it ignites? How does movement of the gas over a heated surface affect the ignition temperature of the gas? Does the ignition temperature vary with different materials? Is the ignition temperature affected by the shape and size of the heated surface? Are some concentrations of this gas in mines ignited more easily than others?

One of the first methods of determining the minimum ignition temperature when a flammable mixture is exposed to a fuel-air mixture was described in 1883 by Mallard and Le Chatelier, who measured the temperature to which the walls of a porcelain vessel had to be heated in order that the mixture undergoing the test should ignite, when it was rapidly admitted to the vessel. In 1922, Wheeler and others [1,2] measured the critical temperature for the ignition of many gaseous mixtures. By using a quartz vessel and the techniques devised by Mallard and Le Chatelier, they showed that as the volume of the vessel decreased the ignition temperature increased. Early in 1940, based on the experimental work carried out by Mallard and Le Chatelier, Semenov [3] proposed the first mathematical representation of the critical conditions of ignition. Today the idea of obtaining the minimum ignition temperature associated with a uniform heating of a volume of mixture enclosed in a vessel is well known as the autoignition temperature. The literature review of the work related to the autoignition temperature will not be included in this present study, but some aspects of the autoignition theory which are relevant to this work are presented in other sections (1.2 and 2.3).

The work carried out by Shell Research Ltd. also will not be presented, as already mentioned (pp 27), since it is related to two- stage ignition.

## **2.2 Review of the published works**

### **Hot wires, rods and strips in a stagnant mixture.**

One of the earliest studies of ignition by a hot surface is connected with the ability of the filaments in a miner's lamp to ignite a methane-air mixture following breakage of the bulb. This was carried out by Heise and Thein, in 1893.

Lemaire (1911) in Belgium and Clark and Hsley (1913) in the U.S.A demonstrated that the filaments of electric lamps operating under normal conditions can readily ignite firedamp-air mixtures that may gain access to them by the breakage of the bulb. They made tests in various ways, i.e., with filaments previously removed from their bulbs and with lighted bulbs smashed by compression or by swinging violently against a hard object. They succeeded in igniting methane or natural gas by 2 volt and 4 volt bulbs; however the current and the temperature of the wire was not measured.

The work carried out by Thornton in 1919 [4] had the objective of investigating to what extent the glowing filament of a miner's lamp might constitute a source of ignition in coal mines. The size of the wires used were 0.1, 0.2 and 0.3 mm in diameter and 30mm long, but only the central 10-15mm glowed brightly. His data were presented as a function of the igniting current. The observations that can be drawn from his tests are:

a) Ignition by heated platinum wire is more difficult than by non-catalytic materials, i.e., tungsten, gold, nickel, iron and silver. Later it was confirmed that the ignition temperature for catalytic surfaces is usually higher than for non-catalytic ones, as explained in section 1.2.

b) He observed that the current required for ignition was insensitive to the mixture concentration. This observation is not consistent with the results presented later by **Shepherd and Wheeler** [5].

Published in 1927 the paper of **Shepherd and Wheeler** [5] dealt with the ignition of methane-air at various concentrations by platinum wires 0.1, 0.2 and 0.3 mm in diameter and tungsten wires 0.1 and 0.065 mm in diameter. A length of 38mm was adopted. The ignition temperature for platinum was estimated in the range of 1,200-1,300 °C. The results for tungsten wires were presented as a function of the igniting current. For tungsten wire they found that the most readily ignitable concentration was 8% of methane/air.

Having in mind that a heated surface may directly or indirectly initiate a gas explosion in coal mines, **Coward and Guest** [6,7], studied ignition of natural gas (93.2% CH<sub>4</sub>, 3.3% C<sub>2</sub>H<sub>6</sub>, 1.5% C<sub>3</sub>H<sub>8</sub>, 0.5% C<sub>4</sub>H<sub>10</sub> and 1.5% N<sub>2</sub>) and air mixture. Horizontally mounted strips 1 mm thick, 108 mm long and of various widths were electrically heated and the maximum temperature monitored by affixing a thermocouple to the centre of the strip. Strips of platinum and nickel were used. The strips were electrically heated by means of a transformer which could deliver a current of as much as 3,000 amperes for a short time, but at a low voltage. The delay before ignition after the current had been applied to the ignition source was reported by them to be around 40 seconds.

The results for nickel demonstrated three important features: a) The ignition temperature in the case of a static mixture was around 940 °C, with a strip 100 mm wide. When the width of the strip lies between 1.9 mm-101.6 mm, it was observed that the temperature necessary to ignite any mixture was found to be higher with narrow strips than with wide ones, as shown in Table 5. b) Ignition probabilities were higher for fuel-lean conditions. The ignition temperature was increased uniformly as the percentage of the gas in the mixture was increased. The difference being about 12 °C for each percentage of change. c) Two tests were carried out with a nickel strip bent into the form of a slotted tube. The tubes were partly open and were heated in the same manner as the nickel strips. The ignition temperatures obtained with these tubes were much lower, i.e. around 724°C, than the ones obtained with flat strips.

**Table 5.** Ignition temperatures of strip of nickel 108 mm long, 1 mm thick [7]

width mm	<i>Ignition Temperature °C - Stagnant Mixture</i>									
	1.9	3.2	6.4	12.7	19.1	25.4	38	57.2	76.2	101.6
4%	1,097	1,073	1,045	1,021	1,005	996	990	978	962	945
7%	1,146	1,122	1,082	1,062	1,042	1,030	1,021	1,005	990	971
10%	1,197	1,163	1,117	1,106	1,087	1,079	1,055	1,031	1,019	933

The platinum temperature went through a maximum at the stoichiometry condition and it was always higher than the nickel temperature. The sharp increase in surface temperature has been explained by postulating a maximum catalytic reaction rate at this condition [8]. Recently these observations were confirmed by Griffin and Pfefferle [9]. Similar results were obtained with a

nickel strip coated with platinum or palladium. These observations showed that these metals are catalytic.

In the early sixties, Silver [10,11,12] carried out some tests with heated copper wires, in flammable atmospheres of pentane-air and ether-air. The results were presented as a function of the electrical current. These tests indicated that copper wires 0.13 mm and 0.11 mm in diameter and with length in the range of 15.9 - 88.9 mm and 12.7 mm respectively when heated to a point of fusion had not caused ignition. The melting point of copper is 1,083°C. However, the ether-air mixture could be ignited by the 0.11mm diameter and 304.8mm long wire, when wound in the form of a spiral. A comparison between Silver's results and those obtained in this work is included in Chapter 3.

As was mentioned at the beginning of this section (pp 40), the very early investigation on ignition by heated surfaces dealt with a flammable mixture in a container with heated walls. The analytical theories developed were called thermal theories. The early concepts on the steady state of these thermal theories were developed by Semenov [3] and Frank-Kamenskii [13]. In 1961 **Ashman and Buchler** [14] conducted an experimental study related to the ignition of gas by electrically heated wires. One of their objectives was to obtain data which could be used to test the validity of the Semenov and Frank-Kamenskii ideas. They conducted an experimental study on the ignition of gases by means of fine tungsten wire with diameters of 0.02mm and 0.05mm and platinum wire 0.04mm in diameter: length was not specified. The temperature was elevated suddenly to a given level by means of a condenser discharge and held within a few degrees of that temperature for 0.1msec. The highest temperature was at the centre of the wire. They investigated the

temperature required to ignite a stoichiometric methane-air mixture. The mixture could be ignited by a tungsten wire at approximately 1470°C. For the platinum wire the temperature appeared to be 50 degrees higher than that observed for the tungsten wire of the same diameter. These ignition temperatures were higher than the ones obtained by Shepherd and Wheeler [5] and Coward and Guest [7], probably due to the small diameter wires used as ignition sources. According to Ashman and Buchler the activation energy of methane was low and it resulted in a high reaction rate near the surface of the wire, so high in fact that it caused a substantial depletion of reactant. They concluded that their results could not be analysed by the thermal theories of Semenov and Frank-Kamenskii, as these require the reaction rate to be small until the ignition temperature is reached. But it is difficult to follow since they used a small wire diameter, which probably led to a short convective time.

The ignition of methane gas in coal mines has been a serious problem since electrical power began to be used underground. As part of a programme conducted by the Ministry of Power Safety in Mines Establishment which had the objective of improving the safety of working conditions in coal mines, **Rae et al** [15] in 1964 carried out experimental work on ignition of gases due to heated surfaces. They studied the influence of surface area and orientation on the ignition of methane-air mixtures. An electrically heated square of alumina was used as an ignition source. Surfaces of several sizes were made, and the minimum surface temperatures required for ignition were obtained with the surface located in the floor, roof or wall of the explosion box. The ignition temperatures were obtained by reducing the temperature of the surface until ignition occurred in about one or more seconds, after the surface had been exposed to the mixture. The surface temperature was measured by an optical pyrometer. The results showed the increase in the minimum ignition

temperature with decreasing surface area for all concentrations. The results for 6% of methane-air are shown in Table 6. The results obtained by them cannot be directly compared with any previous works, but they do not appear to be at variance with any. The influence of the length or width of the surface on the ignition temperature is not clear. For example, the temperatures for a square surface with only one side exposed to the mixture were higher than those obtained by Guest [7] for strip of nickel of the same width, but with both faces exposed.

**Table 6.** Minimum ignition temperature for 6% methane-air mixtures by hot surfaces of different square areas and locations within an explosion box [15].

Areas mm <sup>2</sup>	Minimum Ignition Temperature - °C		
	Floor	Roof	Wall
9 (3x3)	1361	1390	1400
41(6.4x6.4)	1200	-	1264
81(9x9)	1156	1200	1219
169(13x13)	1086	-	1190
324(18x18)	1070	1090	1141

When Semenov [3] deduced the first quantitative theory of thermal explosion, he made use of some assumptions, for instance, that the critical condition of ignition occurs when the rate of heat loss is equal to the rate of heat release. But this idea stated by Semenov was first presented by Van't Hoff in 1884. In 1965 Adomeit [16] carried out experimental work which confirmed the Van't Hoff criterion (Figure 15). The hot surface used by him was a chromium-nickel rod with diameter between 3 and 4 mm and 35 mm long. It was heated

by a capacitor discharge within  $10^{-4}$  seconds, which also was considered to be the interval in which the ignition source reached its maximum temperature. The tests were performed on a mixture of pentane/air and propane/air at various equivalence ratios, and at a gas pressure in the range of 0.5 - 6 atm. According to his work, the time interval between the heated surface reaching its maximum temperature and ignition was 60 milliseconds. It is also his opinion that within such a short time interval free convective flow did not have time to build up. The way the ignition source was heated is similar to the one adopted by other investigators (see Table 9 at the end of this chapter), and they reported a convection mechanism involved in the ignition process.

About thirty years ago, considerable changes occurred in the process industry as a whole, increasing awareness of industrial safety. As potentially hazardous situations can arise when a hot surface is exposed to a flammable mixture, some investigations into the parameters which affect the ignition mechanism have been carried out, such as the ones done by Cutler and Ono et al. which are described in the following two paragraphs.

In 1974 Cutler [17,18] investigated the effect of size, temperature and rate of heating of a tungsten strip on the ignition probability of methane and propane air mixtures. A tungsten strip 31.7 mm long, 0.03 mm thick and with a width varying between 4.8 and 11.9 mm was brought up to a high temperature by a capacitor discharge. The peak temperature was attained in about 0.5 milliseconds. The ignition temperature was measured by means of an optical pyrometer. It was found that the ignition temperature decreased as the width of the strip increased and 7% of methane/air was the most easily ignitable concentration. For propane 3.3% was the most readily ignitable concentration. His data are presented in Table 7 and they will be analysed by the equations

presented in Chapter 4. Cutler suggested that the longer a body is kept at a given temperature in a flammable mixture the greater is the probability of ignition. This conclusion is supported by Rae et al [15], who kept the surface at a steady temperature for approximately one second and found that for 7% of methane-air mixture the ignition temperature was lower (1,200°C) than the one reported by Cutler (1,820°C).

**Table 7.** Ignition temperatures for electrically heated tungsten strips in 7% of methane-air and 3.5% propane-air mixtures [17,18].

Strip Width mm	Ignition Temperatures - °C	
	Methane	Propane
4.8	1850	-
6.4	1820	1373
7.9	1765	-
8	-	1336
9.5	1760	1305
11	-	1273
11.1	1710	-
11.9	1680	-

Onu et al. [19] in 1976 studied the critical ignition temperature in a free convection flow from a vertical heated surface. The heated surface consisted of a 18-8 chromium-nickel steel plate 0.3 mm thick, 40 mm wide and vertical length which varied from 5 to 30 mm. The tests were performed in a stoichiometric mixture of methane and propane with pressures in the range 0.07-1 atm. The ignition source was rapidly heated electrically to just below

the ignition temperature. The surface was then heated slowly until flame propagation occurred away from the hot surface. The temperature immediately before ignition was defined as the ignition temperature. The delay before ignition was not given. The following points were made: For a propane-air mixture the ignition temperature decreased with the concentration, and the lower flammable limit of concentration was 2.25%. The ignition temperature decreased with an increase of the initial temperature of the mixture. For an initial mixture temperature of 60°C, they reported an ignition temperature in the range 927°C-1127°C. At high pressure, i.e. 1 atm, the flow pattern at the surface of the vertical plate approached the one expected for the hydrodynamic boundary layer.

For many years Vinyl acetylene was produced from acetylene as the first step in the manufacture of chloroprene, from which the oil - and chemical - resistant rubber Neoprene is made. Like acetylene, it is a high energy compound which can decompose explosively into elements without the involvement of oxygen. On 25 August 1965 several explosions occurred at Dupont's Louisville works on the banks of the Ohio river, where about 200 tons of vinyl acetylene were stored as a liquid. Twelve people were killed and much of the plant was wrecked. A company investigation [20] showed that the first explosion was caused by the mechanical failure and overheating of a compressor which circulated vinyl acetylene gas. The subsequent explosions which occurred over a period of eight hours were initiated by flying metal fragments and fires started by the first explosion, and by transmission through pipelines. In another accident, on the evening of 23 October 1969, a butadiene purification column in one of Union Carbide's butadiene plants in Texas City exploded. The cause of the accident was an internal explosion of vinyl acetylene. Probably motivated by these accidents, in 1976 Detz [21] was

sponsored by the Union Carbide corporation to carry out work on the ignition of acetylene gas by hot wires. His experiments consisted of igniting pure acetylene at a pressure range from 1.34 atm to 21.41 atm, by means of heated platinum wires, 0.3 mm, 0.2 mm, 0.1 mm in diameter and with lengths of 25 mm and 75mm. One important conclusion stated by him was 'the ignition temperature was independent of the length of the ignition wire but increased as the diameter of the ignition wire decreased'.

In most circuits of interest from the point of view of intrinsic safety, the voltage is less than 100 volts. Then, in order to examine the effects of sparking in low voltage circuits many different types of apparatus were developed in various countries. These apparatus were known as breakflash apparatus. The one adopted in Germany involves four tungsten wires (positive electrodes), which scrape across a grooved cadmium disc (negative electrode). As a consequence of the wires making and breaking contact a discharge is created. If the discharge is powerful enough, they will ignite the flammable atmosphere surrounding the electrodes. During the investigation of the characteristics of this apparatus, it was observed that at certain currents while ignition did not occur during normal operation, nevertheless, if the wire remained in contact with the cadmium disc for some time ignition occurred. It was established that the cause of ignition was the heating of the wire, and it was of great practical importance to know at what current level this hot wire phenomenon became important in the breakflash apparatus. The work carried out by **Zsuzsanna Zborovszky** [22] was concerned with this particular problem. She performed some tests with tungsten and copper wire in a 8.3% methane-air mixture, at atmospheric pressure and ambient temperature. A tungsten wire 11 mm long and 0.2 mm in diameter ignited the mixture with current as low as 4.5 Amperes. The tungsten wire was heated for 100 milliseconds. The

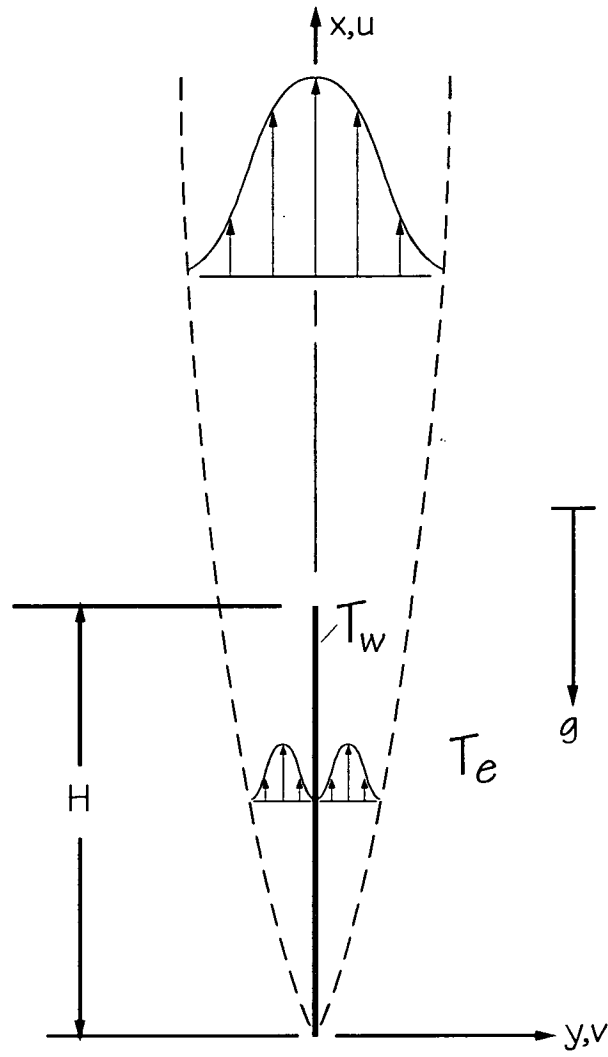


temperature associated with this current was not mentioned. With the copper wires 100 mm long and diameter between 0.25-0.65 mm, ignition was not observed to occur prior to fusion and did not always occur at fusion, either. Above 1,030 °C the wire fused within a few seconds. These observations are in accordance with the test carried out by Silver [9,10]. In her opinion, for the case of ignition when fusion occurred, ignition due to molten copper droplets derived from fusion is unlikely. However, there are indications in the literature [32,33,34] that under certain circumstances ignition can be obtained with hot particles. For example, Silver [32] ignited a mixture of 3% pentane-air, when a 2mm diameter quartz sphere at 1,220°C was thrown into the mixture at a velocity around 4 m/sec.

Vogt [23], who was interested in the conditions in which an electrical circuit could generate a heated surface, and thus become an ignition source, investigated the ignition conditions by electrically heating wires of different materials in a mixture of 6% of methane and air. Although there is no information about his apparatus or experimental procedure, his tests showed that vertical wires were capable of causing ignition at a lower current than horizontal wires. This is consistent with the theory that convective heat transfer plays a role in the ignition process.

The earliest theoretical study on ignition near a vertical heated surface [19] under laminar natural convection conditions adopted the ignition criterion that ignition occurs when the temperature increase of the flow due to reaction is sufficient to cause the temperature gradient normal to the surface to become zero at some point: this is the Van't Hoff criterion. Although this criterion is somewhat arbitrary, agreement between predictions and measurements was satisfactory. In 1981 Chen and Faeth [24-27] examined the theoretical

limitations of this criterion, for a vertical flat plate under free convection conditions. The new feature of their study included the analysis of the flow properties along the surface. According to them, a deflagration wave is formed in the plume above the heated surface, as shown in Figure 12. They called this ignition condition of plume ignition.

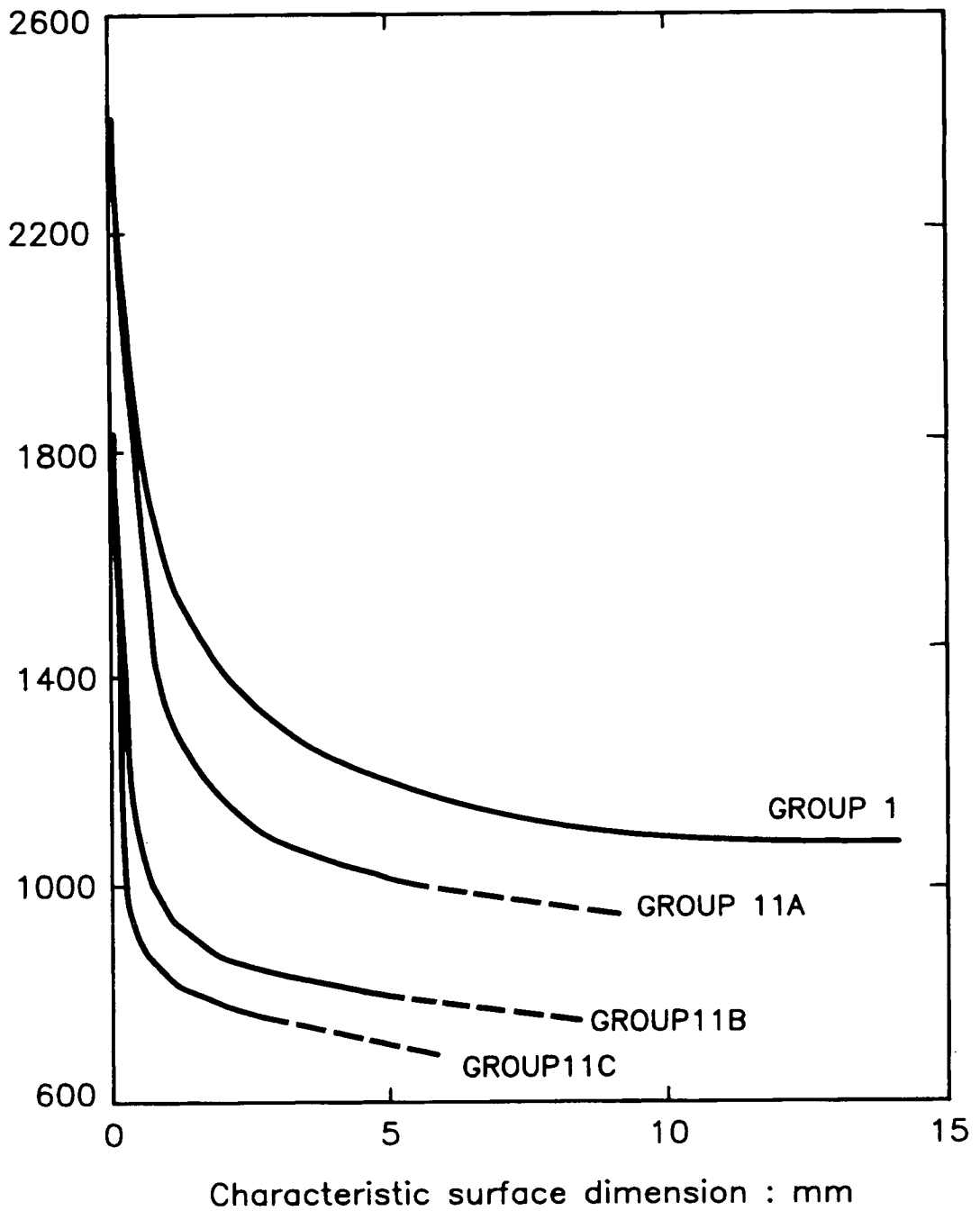


**Figure 12.** The theoretical model of Chen and Faeth [26]. Nomenclature:  $x$  distance along surface;  $u$  velocity parallel to surface;  $y$  distance normal to

surface;  $v$  velocity normal to surface;  $T_w$  wall temperature;  $T_e$  ambient temperature;  $H$  surface height and  $g$  acceleration of gravity.

The Van't Hoff criterion has been employed by other investigators in order to correlate data obtained under forced and free convection conditions [3,16]. These correlations seem to be in agreement with the experimental results. The first limitation of the plume ignition condition is that it only involves convective heat transfer. It has not been used to correlate other experimental data, beside the ones obtained by Onu et al. [19]. Secondly it does not provide an ignition limit directly [27].

Probably with the intention of providing a better understanding of the mechanism and risk of ignition of gases and vapours by hot surfaces, Powell [28] published a literature review on the subject in 1984. Figure 13 shows general trends compiled from many of the results obtained by other investigators to show how the minimum ignition temperature varies with the characteristic surface dimension for particles, spherical and plane surfaces. The previous work included in his review is presented in this section. The upper curve shows results for methane-air mixtures (not all the same concentrations) whilst the others are for the various gases and vapours in their groups. Table 8 shows a comparison between the autoignition temperature obtained according to BS 4056 [29] and Powell's ignition temperatures.



**Figure 13.** Ignition temperatures as a function of the width of the ignition source [28].

**Table 8.** A comparison of ignition temperatures.

	<b>Apparatus Group</b>	<b>Autoignition Temperature °C (BS 4056)</b>	<b>Autoignition<sup>1</sup> Open Surface (Powell)</b>
Methane	I	545	>1,200
Acetone	IIA	535	>1,000
Cyclohexane	IIA	529	>1,000
Ethane	IIA	515	>1,000
Propane	IIA	470	>1,000
Ethylene	IIB	425	>785
Hydrogen	IIC	560	>735

1 - Width > 5mm

The results used by Powell were those where gas flow was by natural convection and low velocity, and where the heated surface tended to be held at a steady temperature. The characteristic dimension of the heated surface is the width, and it was placed in an open configuration. It is clear from Figure 13 and Table 8 that much higher temperatures are generally required for ignition by a hot surface than is evident from the autoignition temperature test [29]. In an experimental study on the hot surface ignition temperature of aircraft fluids, Clodfelter [30] stated that "during the fire safety design of an aircraft engine compartment some companies/designers reduce the autoignition temperature by 10°C to define a safety operating temperature. Some use the autoignition value directly while others select a temperature up to 93°C greater than the autoignition temperature based on hot surface ignition testing under more

realistic conditions ". As was pointed out by Clodfelter there are a range of safety criteria presently used. This becomes evident during the investigation into the Piper Alpha disaster [31], since the surface temperature of some equipment in C module, where the first explosion occurred, was reported to be 500°C - 700°C under normal conditions.

The characteristic length included in the Powell review refers to the width of the ignition sources. Powell's conclusion and other investigations of which the results and conclusions are summarized in Table 9, is that by increasing the width of the ignition source, the probability of ignition increases. The present work and Dezt's work [21], shows that by keeping the width constant and increasing the ignition source lengths the ignition temperatures do not vary. The analysis of the investigation made by Dezt and Powell leads to the conclusion that the width of the heated surface is relevant to the ignition mechanism.

### **Hot sphere**

The reason why Silver, 1937 [32] and Paterson, 1940 [33,34] decided to go into a detailed investigation of the general characteristics of non-burning hot particles in their ability to ignite a flammable mixture may be linked up with the fact that flammable firedamp-air mixture can be ignited when shots are fired to release coal mass. The coal mass was released by shot-firing generators (an alternating current hand generator) connected to detonators. These generators could cause ignition of the firedamp by sparks. This was first confirmed in 1931 at the International Conference on Safety in Mines at Buxton by Dr. E. Beylins. Dr. Beylins suspected that when an open surface or a spark were not the causes of ignition in coal mines, a hot particle of

undecomposed explosive or hot particles of cartridge casing could be the ignition source.

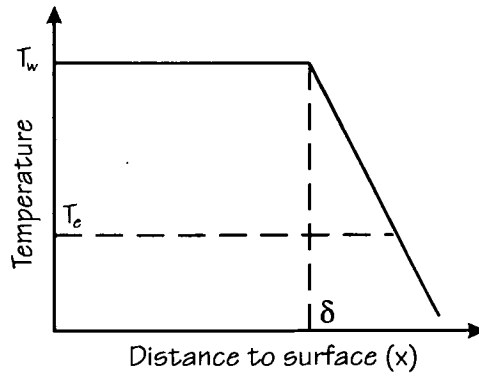
In Silver's experiments [32] a small spherical pellet was heated in a horizontally mounted tube to a pre-determined temperature and was shot by a short air blast into a chamber containing a flammable gas/air mixture, the heating tube serving as a rifle. A timing arrangement opened a sliding gate to permit entry of the pellet into the chamber at the appropriate time. Some air undoubtedly also entered through the gate. But this effect, as well as heat loss from the pellet during its travel through the colder parts of the tube, seems to have been unimportant since variation of the length of the trajectory did not affect the results significantly; it seems probable that any air entering the chamber from the rifle merely diluted the explosive mixture near the gate and that the pellet travelled beyond this disturbance through undiluted mixture. The pellet velocity was not accurately determined. The author states that the speeds used were of the order of 4 m/s. Usually a narrow range of pellet temperature was found below which no ignition occurred and above which ignition occurred instantly on shooting. In the chamber the pellets were stopped by a baffle plate and sometimes were able to ignite the mixture after they had been stopped and fallen to the bottom; such occurrences were considered to be non-ignition.

Paterson [33,34] modified Silver's technique considerably to obtain pre-determined pellet velocity over a wide range. The velocities were determined as a function of a blast pressure by means of a ballistic pendulum. A series of baffle plates prevented the entry of a significant amount of air from the rifle into the chamber at large blasts. The explosion chamber was a tube of 80 cm in length. The pellet traversed the length of the tube and at the end came to

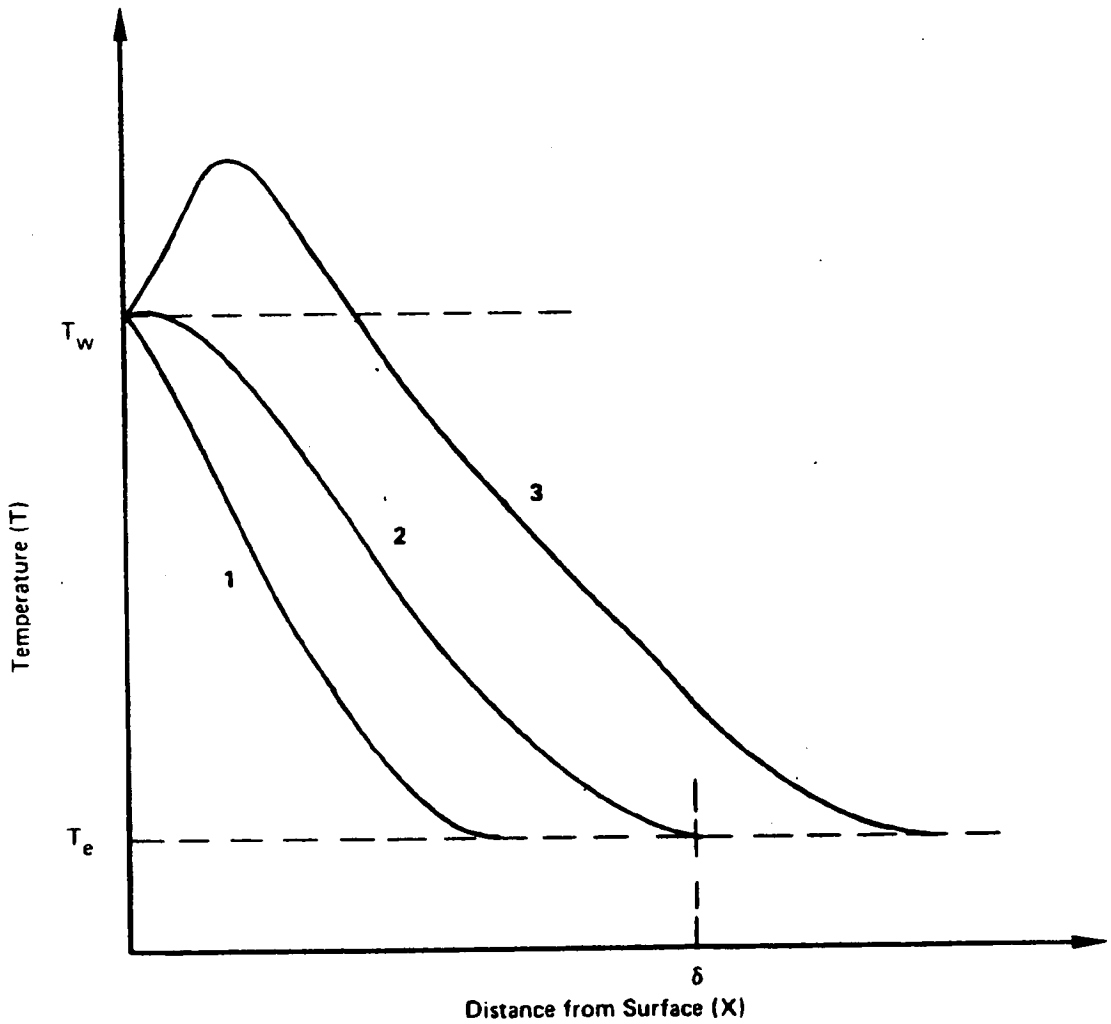
rest in a pad of wet asbestos wool. Since the apparatus was not suitable for very low pellet speeds, another apparatus was designed in which a hot pellet was dropped from a fixed height into an explosion chamber. In an apparatus of this type the velocity increases during the fall of the particle, but since ignition is by low speed it would seem that the velocity at the instant of ignition is reasonably well represented by the velocity at the entrance to the explosion chamber. In these tests the entrance velocity was 1.2 m/s.

Silver [32] and Paterson [33,34] attempted to study methane-air mixtures but found that the ignition temperatures were inconveniently high. Silver obtained ignition of an 8% methane-air mixture with a platinum sphere of 6.5 mm diameter at about 1,200°C. He abandoned further experiments with methane, and instead he, as well as Paterson, used coal gas of the composition 50.1% $H_2$ , 18.8% $CH_4$ , 19.4% $CO$ , 6.5% $N_2$ , 3.4% $CO_2$ , 2.3% $C_nH_m$  and 0.5% $O_2$ . Their data showed that the ignition temperature increases sharply with decreasing sphere diameter. The effect of velocity is demonstrated by the difference between the ignition temperature in runs at about 4 and 1.2 m/sec; the ignition temperature increases as velocity increases.

Silver [32] and Paterson [33,34] failed to find the solution of the conservation equations for the conditions of their tests. Thus they assumed that the critical conditions of ignition took place in a relatively thin layer in the immediate proximity of the sphere wall, in which there was a linear drop of the temperature, Figure 14. A linear drop of the temperature throughout the thin layer does not agree with the Van'Hoff criterion (Chapter 4) which was confirmed experimentally in 1965 by Adomeit, Figure 15. Their analysis was relatively simple, but it seems to be inconclusive as it only succeeds in explaining their results qualitatively.



**Figure 14.** Temperature profile near heated surface surrounded by flammable mixture. Silver and Paterson criteria [32-34].



**Figure 15.** Temperature profile near heated surface surrounded by flammable mixture. Van't Hoff criterion [16]. Legend: 1 before ignition; 2 ignition; 3 after ignition.

## **Hot wires, rods and strips in flowing mixtures**

During and after the Second World War due to the interest in obtaining an optimum design of combustion chamber for propelling aircraft and missiles at high-speed and at great altitude, research and development on high-output combustion were greatly stimulated. The optimum design of combustion chamber for jet propulsion is greatly facilitated if the designer has available information of a fundamental nature concerning ignition, flame propagation and flame stabilization under suitable conditions. One of the important problems encountered in the operation of jet engines was flame blow-out, the extinguishing of flame in the combustion chamber. When blow-out occurs, sufficient energy must be provided by an external source to a local portion of the stream in order to initiate flame. Following ignition, energy must be supplied continually to maintain a stable flame in the main gas stream. The energy requirement either for ignition or for flame stabilization varies with the volume of the portion of the gas stream receiving energy as well as with the fuel type, concentration and velocity; turbulence characteristic; temperature; static pressure and humidity of the gas. In addition, the amount of energy required per unit mass of gas varies with the manner in which the energy is supplied. Therefore for design purposes data were required on the independent effects of each of the variables mentioned in the energy requirement for ignition and flame stabilization. As a result of advances in the development of several types of jet engines the problem connected with ignition of combustion fuel-air mixture under conditions of high velocity flow using a hot surface, particularly electrically heated rods, was addressed by several investigators.

**Mullen and others** [35] in 1948, studied the ignition of streams of pentane-air mixture that were passing over electrically heated cylindrical rods. The rods consisted of metal pipe, i.e., stainless steel, but in order to investigate the chemical nature of the surface they also did some tests with platinum rods. The rods were fitted tightly over two solid copper electrodes about 6.4 mm apart, the rods diameter ranging from 1.6mm to 6.4mm. Current was supplied by a powerful welding generator and the current through the rod was increased slowly until ignition occurred; no information about the time required for ignition to occur was given. The surface temperature was observed by means of an optical pyrometer, and the stream velocity in the range of 24 m/sec to 61 m/sec was obtained from a Pitot tube measurement upstream from the rod. Some of the conclusions are as follows: higher ignition temperature was observed with platinum rods; at lower rod diameter for a given stream velocity; at higher turbulence level; at lower initial gas temperature. The results obtained by them were similar to Paterson's results [33,34].

Parallel to the work developed at the Massachusetts Institute of Technology (Cambridge, Mass) by Mullen and others [35], **Agoston** [36] carried out similar tests using nichrome rods with diameters varying from 6.4mm to 12.7 mm and 65.5mm long, placed horizontally. The tests were conducted at subatmospheric pressure, i.e., 0.5 atm. A stream of a stoichiometric gasoline-air mixture with a velocity in the range 12m/sec - 91m/sec was adopted. The surface temperature just prior to ignition was measured by means of an optical pyrometer. The experimental procedure was similar to the one used by Mullen and others. Agoston confirmed the results of Mullen [35] in the sense that for a given velocity, the ignition temperature increased as the rod diameter decreased.

In the forties the problem of ignition in the high velocity stream of a combustion mixture by means of a hot surface received special attention in the combustion field. In order to further understanding of the ignition mechanism, in 1957 Toong [37] ignited a stoichiometric mixture of ethanol and air moving at 10-20 m/sec using heated strips of nichrome, 50 mm long and unspecified width fitted into a 12mm steel tube. His results were similar to the ones obtained by Mullen et al. [35] and Agoston [36] in the sense that surface temperature for a given set of experimental conditions increased with increase of the stream velocity.

Due to advances in the development of several types of engine considerable attention was given to the problem of ignition of flowing gases by heated wire. Much of the research was conducted by Mullen et al. [35] at velocities ranging from 24m/sec-61m/sec, but in their experiments the flow was always turbulent, although the degree of turbulence was undetermined. **Kimugai and Kimura** [38] examined the problem on a laminar and turbulent flow of city gas of unknown composition. The ignition unit was either a small duct with an inside diameter of 1.2cm or a large one of 3cm in diameter. The degree of turbulence in the ignition unit was varied by placing a perforated plate at different distances upstream. Nichrome rods size 0.3mm to 5mm in diameter and unspecified length were used as ignition sources. The velocity range reported was from 0-30 m/sec. The influence of the degree of turbulence for the velocity range used is not clear. Nevertheless, with both ignition units it was observed that the small rod diameter required a higher ignition temperature.

By that time the relevance of the phenomena of ignition of flowing gas mixture was widespread due largely to its extensive utilization in engineering practice, though there was a lack of scientific analysis of the phenomena. In

1957 **Khitrin and Goldenberg** [39] attempted to correlate the results of Silver, Paterson and Mullen and others [35], by a quantitative analysis of the phenomena in which the Van't Hoff criterion was used as the limiting condition for ignition, which stated that at ignition the rate of heat loss to the surroundings is equal to the rate of heat gain by chemical reaction. In their theoretical investigation of the problem the interaction between the heated body and the flammable mixture was described in terms of two processes: a) The heat generated was expressed as an integral of the rate of reaction with respect to the temperature. This integral was evaluated approximately by assuming that most of the reaction occurs near the body where the temperature is higher; b) The heat losses were assumed to be mainly due to convection. The convection heat loss was expressed as a product of the temperature difference between the mixture outside the boundary layer and the body and a heat transfer coefficient. The coefficient of heat transfer was presented as a function of the Reynold's number . In **Khitrin and Goldenberg** paper the description of the problem was omitted; only the mathematical one was outlined, therefore it became difficult to realise what they had in mind when the model was proposed. Independently of all difficulties in analysing their work, because of the lack of clear definitions of the variables involved, the mechanism of heat loss proposed is far too simple, as the mixture was assumed non-reactive.

In 1956, **Chambré** [40] discussed the problem of the ignition mechanism of a moving combustion mixture. In his analytical investigation the chemical kinetics of the flow were described by a direct first-order reaction and the Van't Hoff criterion was assumed as the critical ignition condition. Fifty years later, in 1970 **Sharma and Sirignano** [40,41] extended the work done by **Chambré** in the sense that they described the reaction kinetics by an overall

single step second-order Arrhenius rate law. Assuming the same ignition criteria as Chambré (i.e. the Van't Hoff criterion), they studied the effects of mixture velocity on the ignition temperature.. As was expected the ignition temperature increased as the velocity increased. They performed the numerical calculations assuming a propane-air mixture in stoichiometric proportions at a temperature of 27°C and 1 atm. They estimated the value of the activation energy and frequency factor which were: activation energy around 71,000 Joule/mole and frequency factor about  $10^4 \text{ m}^3/(\text{mole seconds})$  for  $727^\circ\text{C} < T < 997^\circ\text{C}$  . If  $1327^\circ\text{C} > T > 977^\circ\text{C}$  , then the activation energy was 131,000 Joule/mole and the frequency factor was  $3 \times 10^7 \text{ m}^3/(\text{mole seconds})$ .

Some experimental and theoretical work on ignition of flowing flammable mixture by a hot surface was carried out by others [32-35]. The results presented by them gave correlations between the flow and the ignition temperature. Unfortunately, due to the complexity of the flow patterns the interpretation of the experimental results by analytical methods is not straightforward. In 1971 **Alkidas and Durbetaki** [43,44] carried out a theoretical investigation on the problem of ignition of a flowing combustion mixture over a hot surface. They showed the validity of the Van't Hoff criterion. They found agreement between the Van't Hoff approach and the numerical results obtained by examining a steady-state solution to the conservation equations in the transition region between frozen and equilibrium flow. It is in agreement with the Adomeit's work [16], in which the Van't Hoff criterion was confirmed experimentally.

In the case of accidents involving tankers containing an LNG or other liquefied gases, fire hazards depend on which two possibilities occur in a collision followed by a spill. One is immediate ignition and a subsequent pool fire. For

the period between 1974-1979 the Lloyd's Casualty Report from shipping accidents [45] stated that there were 852 collisions, of which 12 resulted in ignition on collision or spill. In order to assess the risk of ignition where ship tankers carrying flammable cargo were involved in collision, Laurendeau [46,47] in 1982 carried out an experimental and theoretical work about the ignition process of flowing gas, at 1.6 cm/sec. His experiments dealt with ignition by heated tungsten wire of various sizes in a mixture of 7% methane-air, at atmospheric pressure. The ignition source was heated to a very high temperature by an electrical circuit capable of holding the peak temperature for a period of 0-2 seconds. His results were obtained under a pulse heating conditions, i.e., rapid heating to a peak temperature followed by immediate cooling. The peak temperature was obtained after 83 milliseconds, and ignition occurred within 100 milliseconds of the attainment of the peak. He developed simple expressions to estimate the ignition temperature based on the Van't Hoff criterion. The mechanism of heat lost was assumed to be due to convection, and it is dependent on the Nusselt number. His model is consistent with the experimental result obtained by Silver [32], Paterson [33,34], Mullen et al. [35], Rae et al. [15], Cutler [17,18] and Onu et al [19]. The mathematical model suggested by him is similar to the one presented by Alkidas and Durbetaki [43-44], except for the Nusselt number expression. The results obtained by Laurendeau will be analysed using the expressions presented in Chapter 4.

Recently Siccana and Westerterp (1993) published a study about the occurrence of ignition in a mixture of ethane-oxygen-nitrogen, as a function of the gas velocity and the temperature of the electrically heated wire. The tests were carried out on the fuel-rich side, at room temperature and a pressure of 10 atm. The mixture velocity was around 80 cm/sec. It flowed upward through

a test tube made of stainless steel which had an inner diameter of 21mm and a length of 2.5m. The non-catalytic ignition source was a wire of kanthal-A1 (which is an alloy of mainly Fe, Cr and Al) of 0.6mm in diameter and 40mm long. The wire was placed vertically in the tube. The ignition criteria was if the pressure rose more than 0.25 atm ignition was considered to have occurred. It was reported that at the moment of ignition the pressure increased up to 3 atm. The power supply was switched off after ignition. Ignition always occurred within 20 seconds after the beginning of the heating of the wire. During the tests they observed three different regimes, i.e. negligible reaction, local reaction and ignition. Temperature around 700°C characterized the regime of negligible reaction. At a high temperatures 900°C-1,000°C, the mixture near the wire started to react. Ignition occurred almost immediately at temperatures higher than 1,000°C. At the transition of negligible reaction to local reaction a jump of 200°C in the temperature was observed. According to them the transition between local reaction to ignition depended on the balance between the heat production and heat removal, and ignition occurred when the heat generated by the chemical reaction near the wire was larger than the heat removed. The heat loss was mainly due to convection. As similar conclusion was obtained by Coward and Guest [6,7], Cutler [17,18] and Laurendeau [46,47]. It was also observed that the faster the mixture passes the hot wire, the higher is the temperature required to cause ignition. It is their opinion that a certain amount of the gas must reach a certain temperature in order to form radicals and initiate a chemical reaction. Another important observation made by them which has some implications for the design and operation of the process industry is that at the moment the gas flow was stopped ignition occurred. This observation was made during the first tests when a stoichiometric mixture of ethane-air flowed upward through a stainless steel tube with an inner diameter of 50mm, pressure 5 atm and a mixture velocity

of 10 cm/sec. The size and temperature of the ignition source used in these tests were 0.1mm in diameter and 20mm long and 1,200°C respectively.

In conclusion, the problem of ignition by hot surface was first addressed at the beginning of this century when electric power began to be used in coal mines. In the forties the mechanism of ignition by heated surface surrounded by a flowing mixture was particularly important due to the need to develop more efficient engine combustion chambers. The development of the process industry from the sixties gave a new impetus to the subject. In this period the autoignition theory became well accepted. The autoignition temperature was chosen as the minimum ignition temperature for the purpose of design and operation of electrical equipment intended to be used in a flammable atmosphere. However, the autoignition temperature is too conservative in the sense that for a hot surface ignition much higher temperatures are required. As a result there has been a lack of well defined criteria about the minimum temperature. As already mentioned 900°C is accepted as the minimum temperature for ignition due to hot surface. This 900°C was the result of the compilation made by Powell in 1984. During this present review it was noted that very little work was published in the eighties. An interesting observation is that during this period two accidents occurred (Summit Tunnel and Piper Alpha) and the need of information about the ignition process due to heated surface became evident. Recently a work was published which is related to the problem of ignition by a mixture flowing [48]. This work was based on the observation that in an oxidation plant during the recycled phase a hot surface in the reactors or heat exchangers is a possible ignition source.

## 2.3 Autoignition Theory

### 2.3.1. Introduction

The first reasonable analysis of the autoignition phenomenon as defined in section 1.2 was presented by Semenov in 1930, although the basic ideas were stated earlier by Van't Hoff in 1884. The classical theory of autoignition is based on the competition between heat generated in exothermic reaction and the dissipative processes by which heat is removed from the reaction. It is evident that if the heat generated inside the reaction vessel at a rate which is greater than the rate at which heat can be dissipated to the surroundings, the temperature of the reactant mixture will increase, leading perhaps to ignition or explosion.

In his model Semenov [03] assumed a 'lumped thermal capacity analysis' and this assumption is equivalent to saying that the surface convection resistance is large compared with the internal conduction resistance. This implies that the temperature throughout the reactant mixture is uniform [49]. The Semenov model is unrealistic because it assumes no reactant consumption and no temperature gradients. In 1939, Frank-Kamenskii [50] introduced a model in which conductive heat flow in the reactant mixture was taken into account, thus producing temperature gradients in the reactant mixture. The main body of the ideas presented by Semenov and Frank-Kamenskii are regarded as firmly established, although aspects of accuracy and rigour are continually under examination.

This section is primarily concerned with discussing the one-dimensional case of unsymmetrical heating in a plane slab exposed to non-uniform thermal environments as considered by Frank-Kamenskii.

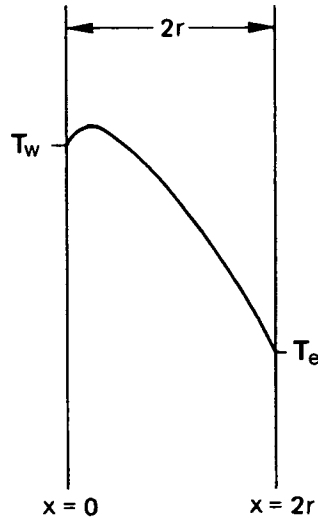
### 2.3.2 Nomenclature

A	frequency factor - $\{[(\text{mole}/\text{m}^3)]^{n-1} \text{sec}^{-1}\}$
$C_1; C_2$	integration constant
E	activation energy - Joule/mole
K	thermal conductivity of the gas - [Joule/(m K sec)]
$q(T)$	rate of heat generation per unit volume at temperature T - [Joule/(m <sup>3</sup> sec)]
Q	heat of combustion - Joule/mole
r	half thickness of the slab - m
R	gas constant
T	temperature - K
$T_e$	ambient temperature - K
$T_w$	hot wall temperature -K
x	spatial coordinate
$X_f$	ambient mole fraction of fuel
$X_o$	ambient mole fraction of oxidizer
z	dimensionless distance , defined as $z = \frac{x}{r}$
$\delta$	Defined as $\delta = \frac{E X_f X_o r^2 Q \rho A}{R T_e^2 K} e^{-\frac{E}{RT}}$

$\delta_c$	Critical value of $\delta$ defined by equation 2.10
$\Delta T$	temperature difference, defined as $\Delta T = T_e - T_w$ and $T_w \gg T_e$
$\varepsilon_w$	Defined as $\varepsilon = \frac{RT_w}{E}$ .
$\theta$	dimensionless temperature rise, defined as $\theta = \frac{E(T - T_w)}{RT_w^2}$ .
$\rho$	density - mole/m <sup>3</sup>

### 2.3.3. Plane Slab

This case consists of plane slab of thickness  $2r$  with one face at a constant high temperature and with the other face maintained at a constant lower temperature. A temperature gradient will become established within the slab whether heat is generated or not and, given heat generation at a rate which increases with temperature, a thermal explosion may take place towards the high temperature face. If heat is generated in the slab and a steady non-uniform temperature distribution is established (Figure 16), then the gain in heat transferred in unit time by conduction across unit area of a volume element of the slab contained between the slab walls separated by a distance  $2r$  and differing in temperature by  $\Delta T$  ( $T_e - T_w$ , where  $T_w > T_e$ ), is equal to the heat generated in unit time in the volume element concerned. This is expressed in general terms by equation 2.1.



**Figure 16.** Temperature distribution in unsymmetrical heated slab. Constant temperature on hot face.

$$-K \frac{d^2T}{dx^2} = q(T) \tag{equation 2.1}$$

It is assumed that,

$$q(T) = X_f X_o Q \rho A e^{\frac{-E}{RT}} \tag{equation 2.2}$$

Equation 2.1 and 2.2 together define the steady-state temperature distribution within the slab. The combination of these equations results in equation 2.3.

$$-K \frac{d^2T}{dx^2} - X_f X_o Q \rho A e^{\frac{-E}{RT}} = 0 \tag{equation 2.3}$$

In order to find the solution for equation 2.3, Frank-Kamenetskii assumed the following dimensionless parameters. The hot face temperature ( $T_w$ ) was adopted as a reference temperature.

$$\frac{-E}{RT} = \frac{-E}{RT_w} + \frac{\theta}{1 + \varepsilon_w \theta}$$

$$\theta = \frac{E(T - T_w)}{RT_w^2}$$

$$\varepsilon_w = \frac{RT_w}{E}$$

provided that  $\varepsilon_w \ll 1$  and  $\theta$  is not large, then

$$\frac{-E}{RT} \approx \frac{-E}{RT_w} + \theta \quad \text{equation 2.4}$$

if  $z = \frac{x}{r}$ , where  $z$  is the dimensionless distance from the hot surface. By combining equation 2.4 with the parameter  $z$  into equation 2.3, it becomes,

$$\frac{d^2\theta}{dz^2} = -\delta e^\theta \quad \text{equation 2.5}$$

$\delta$  is defined as

$$\delta = \frac{E X_f X_0 r^2 Q \rho A}{R T_e^2 K} e^{\frac{-E}{RT}}$$

The solution of equation 2.5 only exists for a certain range of values of  $\delta$ ; in the Frank-Kamenetskii model  $\delta$  is used to investigate the relationship between the system characteristic ( $r$ ) and the critical ambient temperature [51]. In the present study the critical value of  $\delta$ , as defined according to equation 2.10, will be used to investigate the temperature required for ignition in the case of confined configuration (Figure 2) and the depth of the unheated cavity.

The general solution of equation 2.5 [52], is

$$\theta = \ln C_2 - 2 \ln \cosh(z\sqrt{\delta C_2/2} + C_1) \quad \text{equation 2.6}$$

Where  $C_1$  and  $C_2$  are the two integration constants. In order to determine  $C_1$  and  $C_2$  the following boundary conditions are assumed,

$$\theta = 0 \text{ and } \frac{d\theta}{dz} = 0 \text{ at } z=0 \quad \text{equation 2.7}$$

The boundary condition expressed by equation 2.7 is the Van't Hoff criterion (see Chapter 4). With equation 2.7 the constants  $C_1$  and  $C_2$  in the general solution 2.6 are respectively 0 and 1. Equation 2.6 become,

$$\theta = -2 \ln \cosh(z\sqrt{\delta/2}) \quad \text{equation 2.8}$$

Equation 2.9 expressed the second boundary condition,

$$\theta = \theta_e \text{ at } z=2, \text{ where } \theta_e = \frac{E(T_e - T_w)}{RT_w^2} \quad \text{equation 2.9}$$

The boundary condition 2.9 combined with equation 2.8, result in equation 2.10,

$$\delta_c = \frac{(2 \ln 2 - \theta_e)^2}{8} \quad \text{equation 2.10}$$

Wires & Rods Description		Gaseous Media & Flow Type	Ignition Temperature °C	Heating Period <sup>1</sup>	Ignition Delay	Remarks	Authors
Material	Dimensions mm						
Nickel	Length: 108 Width: 12.7 Thickness: 1	4% natural gas (93%CH <sub>4</sub> ) Static	1,021- horizontal 978(vertical) 724(bent)	40sec	40sec	1-Ignition temperature was found higher with narrow strips than wide ones. 2-Higher ignition temperature for platinum. 3-Ignition temperature was lower when convection was reduced.	Coward & Guest 1927 - 1930
Quartz	Diameter: 2.3-5	10%Coal gas-50%H <sub>2</sub> 4m/sec	960-850	-	-	1-Ignition temperature increase sharply with decreasing sphere diameter.	Silver 1937
Quartz	Diameter: 1-5	10%Coal gas-50%H <sub>2</sub> 1.2m/sec	956-800	-	-	1-Ignition temperature increase as velocity increase. 2-Higher ignition temperature with small sphere diameter.	Parteson 1940
Nickel Chrome	Diameter: 6.4-12 Length: 65.5	Stch Gasoline 30m/sec	1407-1383	Current increase until ignition occur	-	1-Higher ignition temperature with small rod diameter. 2-Ignition temperature increase as velocity increase. 3-Ignition temperature increase as initial mixture temperature decrease.	Agoston 1947
Stainless steel	Diameter: 6.35 Length: 6.4	Stch Pentane 29m/sec	1121 - 90° downstream 1232 - 45° downstream	Current increase until ignition occur	-	1-Higher ignition temperature for platinum rods. 2-Higher ignition temperature with small rod diameter. 3-Ignition temperature increase as velocity increase. 4-Ignition temperature increase as initial mixture temperature decrease.	Mullen et al  1948

Wire & Rods Description		Gaseous Media & Flow Type	Ignition Temperature °C	Heating Period <sup>1</sup>	Ignition Delay	Remarks	Authors
Material	Dimensions mm						
Nickel Chrome	Diameter:1.2 Length: unspecified	22% citygas 1m/sec	1027-1094 small chamber 984 large chamber	No information		1-Results depended on the ignition chamber used. 2-Higher ignition temperatures were obtained with small wire diameter.	Kimugai & Kimura 1957
Nickel Chrome	Length:50 Width: unspecified	Stc.Ethanol 13m/sec	425 (ambient 118)	No information	-	1-Ignition temperature increase as velocity increase. 2-Igniton temperature increase as initial mixture temperature decrease.	Toong 1957
Tungsten	Diameter: 0.0508 Length: unspecified	9% Methane Static	2200 1650 1470	0.1 msec	5-10 msec 20-25msec 35-40msec	1-Significantly consumption of reactants near a small ignition source induced high ignition temperature. 2-High ignition temperature for platinum , about 50%.	Ashman & Buchler 1961
Platinum covered with alumina	Length:13 Width:13	9%Methane Static	1,200	-	1 sec	1-Ignition temperature increase if the area exposed to the mixture decrease. 2-Convection affect the ignition temperature.	Rae and others 1964
Chromiun Nickel	Length:35 Diameter:3-4	Stch.Pentane	700-1,200	0.1msec	60msec	1-Van't Hoff criterion was confirmed experimentally.	Adomeit 1965

Wire & Rods Description		Gaseous Media & Flow Type	Ignition Temperature °C	Heating Period <sup>1</sup>	Ignition Delay	Remarks	Authors
Material	Dimensions mm						
Tungsten	Lenght:31.7 Width:6.4 Thickness: 0.03	7%Methane Static	1,820 1,670 1,605 1,535	0.5msec 10msec 100msec 1sec	40msec	1-Ignition temperature increase as the width decrease. 2-Ignition probability increase as the time that heat is transfer to the wire increase.	Cutler 1974-1978
Tungsten	Lenght:50 Width:2-10	7%Methane 0.016 m/sec	1,060-1,010	0-2sec	100msec	1-Ignition temperature increase as the width of the wire decrease.	Laurendeau 1982
Kanthal Al (Fe,Cr,Al)	Lenght: 40 Diameter: 0.6	Fuel-rich ethane 0.8m/sec	900-1,000	20sec	20sec	1-Ignition temperature increase as velocity increase. 2- At 1,200°C ignition occurred at the moment the mixture flow stopped.	Siccana & Westerp 1993

1- The heating period will be related to the temperature rise of the surface, during the time interval that the energy supplied to the ignition source is converted into heat. It depends on the apparatus and the experimental procedures employed.

**Table 9.** Summary of the various studies of ignition by hot surface.

Without doubt the studies on the mechanism of ignition which are presented in this Chapter have been important since they give clear indications about the variables which influence the ignition process at a hot surface. In addition to the review of the published work, some aspects of autoignition theory have been included in this Chapter, as they will be used to analyse the experimental results presented in the next Chapter.

Although previous work carried out has provided some useful information about the ignition process, as discussed in Chapter 1, current knowledge is not sufficient for practical guidelines to be developed for certain applications. A number of questions about the ignition process are still unresolved; in particular, how the effect of 'local confinement' affects the ignition of a flammable vapour/air mixture. The present work was carried out with the intention of obtaining some data and information which could help resolve the issue.

In the next Chapter, the apparatus which was used to obtain the data is described in detail, along with the procedures that were followed in the experiments. The results are also presented.

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## **Chapter 3**

### **3. The Experimental Part of the Present Work**

#### **3.1 Introduction**

The ignition temperature of a flammable mixture is the minimum temperature required to initiate or cause self-sustained combustion without initiation of ignition by spark or flame [1].

The standard ignition temperature measurement [2,3] involves a heated glass flask into which a small measured amount of the flammable mixture is introduced. If ignition occurs, the flask wall temperature is noted as well as the time it takes for ignition to occur after sample introduction. The test is repeated with different wall temperatures until the lowest temperature at which ignition occurs within an ignition delay not greater than 5 minutes is obtained. This lowest temperature is reported as the minimum ignition temperature of the mixture. In some references, this is referred to as autoignition temperature or spontaneous ignition temperature. Data are included in BS 5345 [1].

Although the definition and the method of measuring the autoignition temperature are specific, the value observed under one set of conditions may be changed substantially if these conditions are changed. Experience has shown that unconfined hot surfaces must be hundreds of degrees above the published autoignition temperature to ignite a freely moving flammable mixture in the vicinity. This is not surprising since it constitutes a condition very different from the standard laboratory ignition temperature test.

The ignition of a freely moving combustible mixture in contact with a heated surface has been the object of a considerable number of experimental investigations, but the data obtained are not consistent in that they were obtained by a number of investigators using different techniques over a considerable period of time. On the other hand, there have been no systematic studies dealing with the ignition problem associated with a confined heated surface (as defined in Chapter 1), which is becoming of importance in a number of loss prevention fields. The purpose of the experimental work presented in this chapter is to examine how the degree of confinement, size and orientation of the heated surface affects ignition based on the minimum ignition temperature, while trying to carry out tests which are realistic and repeatable.

The results were obtained with a mixture of 3% of propane/air. The ignition source was an electrically heated strip of nichrome tape 5mm wide and 0.03 mm thick. Two lengths (45 mm and 65 mm) were used at different positions and degree of confinement shown as in Figure 2. It was shown that the local confinement around a heated surface can increase its ability to ignite a flammable mixture.

### **3.2 Apparatus and Instrumentation**

An overview of the apparatus is presented in Figure 17. Basically the system consisted of four components: the reaction vessel, the vacuum line, the ignition detection system and the power supply. This system has three desirable features: it is simple, safe and relatively inexpensive. Specifications

for the major material and instruments are listed in Table 10.

#### 1) Reaction Vessel (6 litre bomb).

This comprised two explosively formed stainless steel hemispheres approximately 22 cm in diameter. In between the halves of the bomb was placed a stainless steel ring (19.2mm thick by 28.5mm wide) which contained (Figure 18): a) grooves for rubber 'O' rings on the upper and lower faces which were required to form an airtight seal between the hemispheres and the ring. b) Two small holes of approximately 3.7 mm internal diameter through which gases could be introduced or extracted from the vessel led to two needle valves (NV1 and NV2). c) Two 6.5 internal diameter holes (tapped on the outside) to carry two copper rods of 4.5 mm diameter which were connected to the power supply by means of screw connectors. In order to fit the copper rods into these holes, two Tufnol insulators were made. There was an 'O' ring between the Tufnol and the outside of the stainless steel ring. In order to extend the insulation into the bomb the copper rods were protected with semi-flexible heat shrinkable tubing, Figure 19. d) A small hole of 3.7 mm internal diameter to allow two thermocouples to be inserted into the bomb.

The top of the bomb had two openings, one closed by a 150 psi graphite bursting disc held in a standard assembly, while a Kistler pressure transducer was fitted in the other.

The bomb sat on a circular frame which had six G-clamps spaced at regular intervals around the circumference. These clamps acted on a steel ring which rested on the upper flange of the top hemisphere and the supporting frame on

which the lower hemisphere sat. They were used to hold the two halves of the reaction vessel firmly together. The clamps were pivoted and so could be swung out of the way to allow the bomb to be dismantled for changing the ignition source and cleaning.

## 2) Vacuum Line

The valve NV2 was connected via a rubber tube to the glass vacuum line (Figure 20). As will be shown in the next section, the system must be airtight to guarantee accuracy in the preparation of the mixture. The vacuum line consisted of a manifold connected to an Edwards vacuum pump through a liquid nitrogen cold trap, a mercury manometer (820mm in height) and a one litre storage bulb. The storage bulb was used to store propane gas. A vacuum pump of 100 litre/min capacity with ultimate vacuum of 0.005 mmHg, model ED100 and manufactured by Edwards High Vacuum was connected via a rubber reinforced PVC tube to a cold trap (Figures 17 and 20).

## 3) Ignition Detector System

Initially the occurrence of ignition was recorded by both a pressure and a temperature rise. It was found that the occurrence of ignition could be satisfactorily detected using just the thermocouples and after some time the pressure measurements were abandoned. The purpose of these tests was not to study the consequences of ignition, and the pressure rise profile was not required.

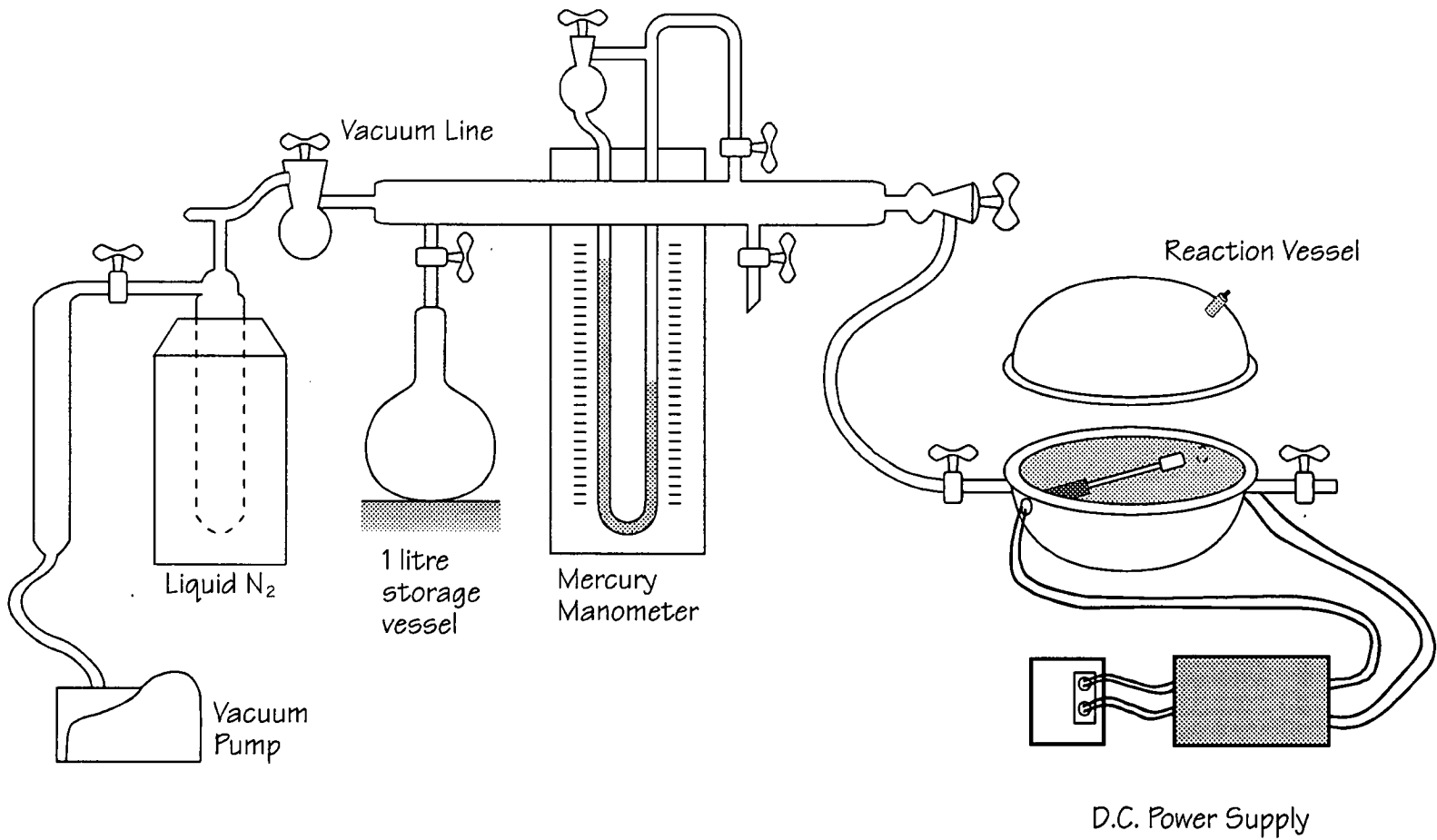
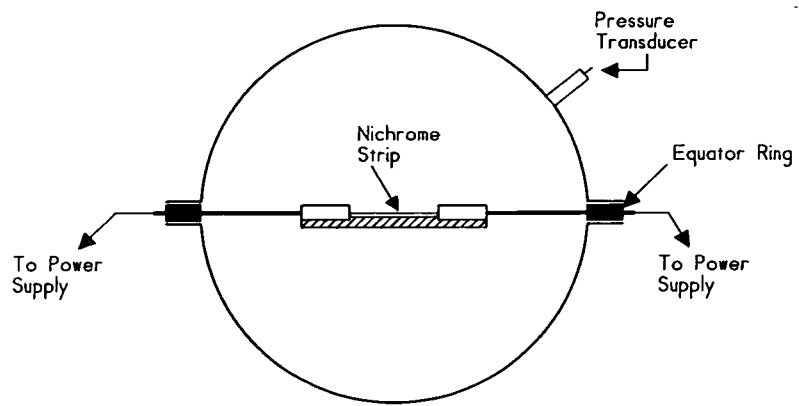
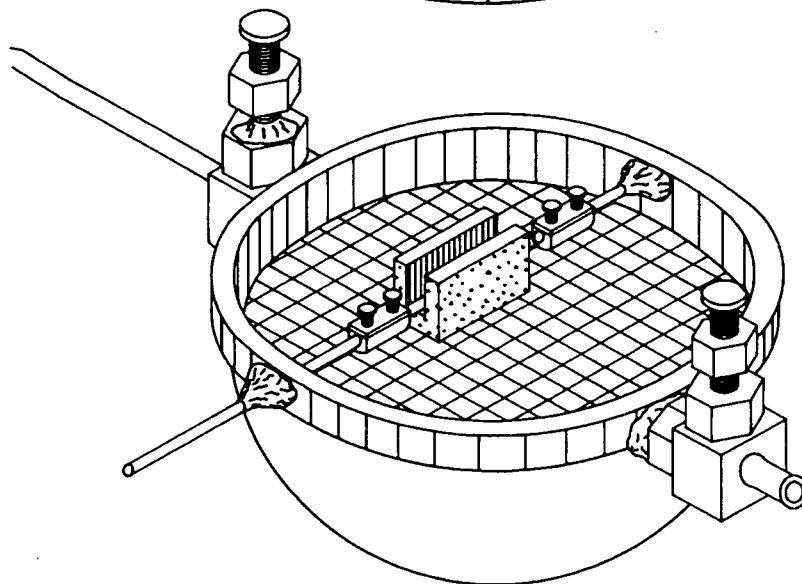
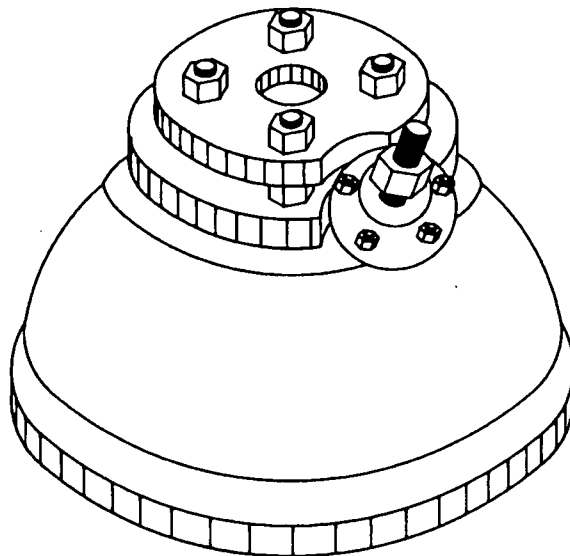


Figure 17. Schematic diagram of the apparatus.



A



B

Figure 18 (A and B). Reaction Vessel , 6 litre bomb.

Figure 19. Tufnol insulator.

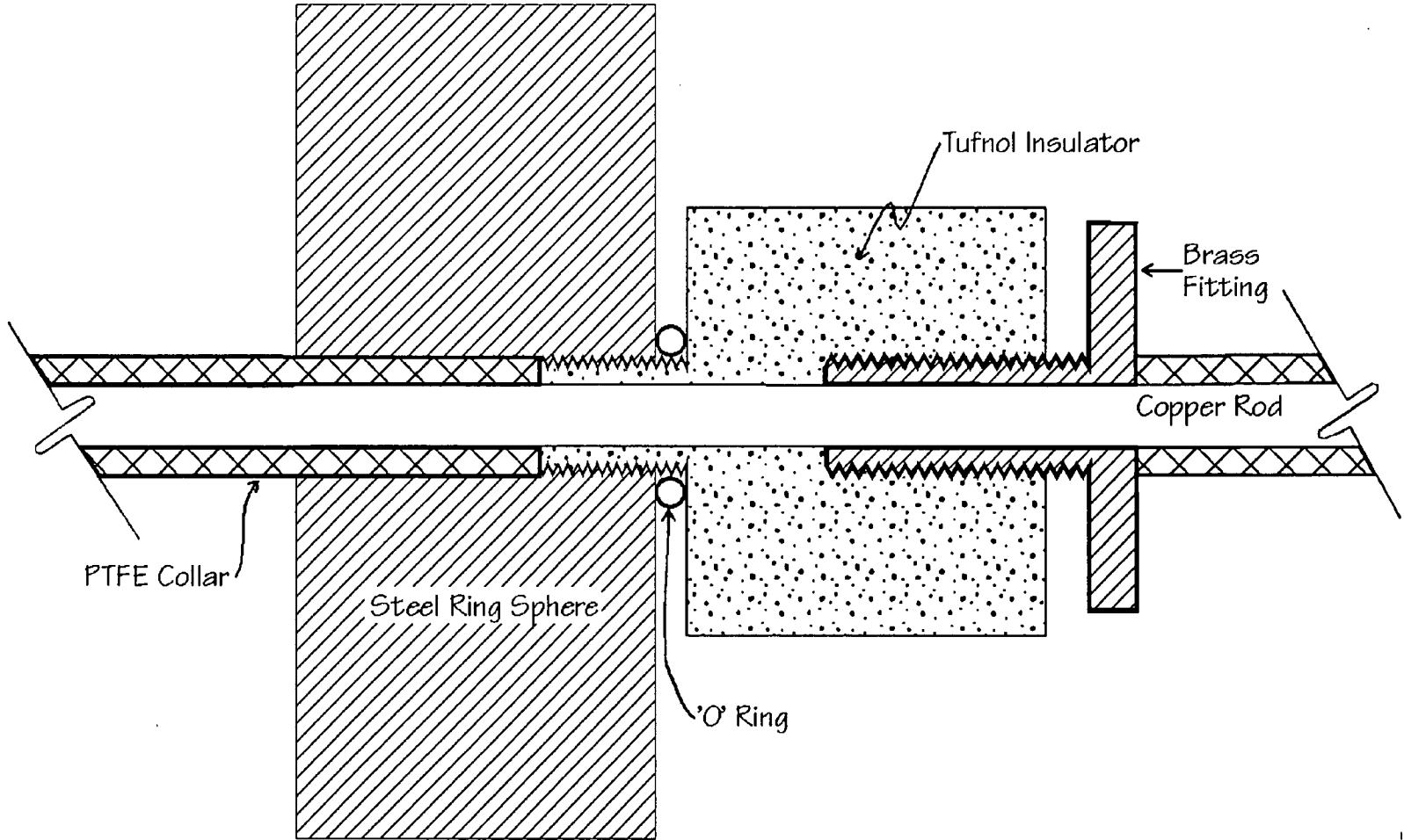
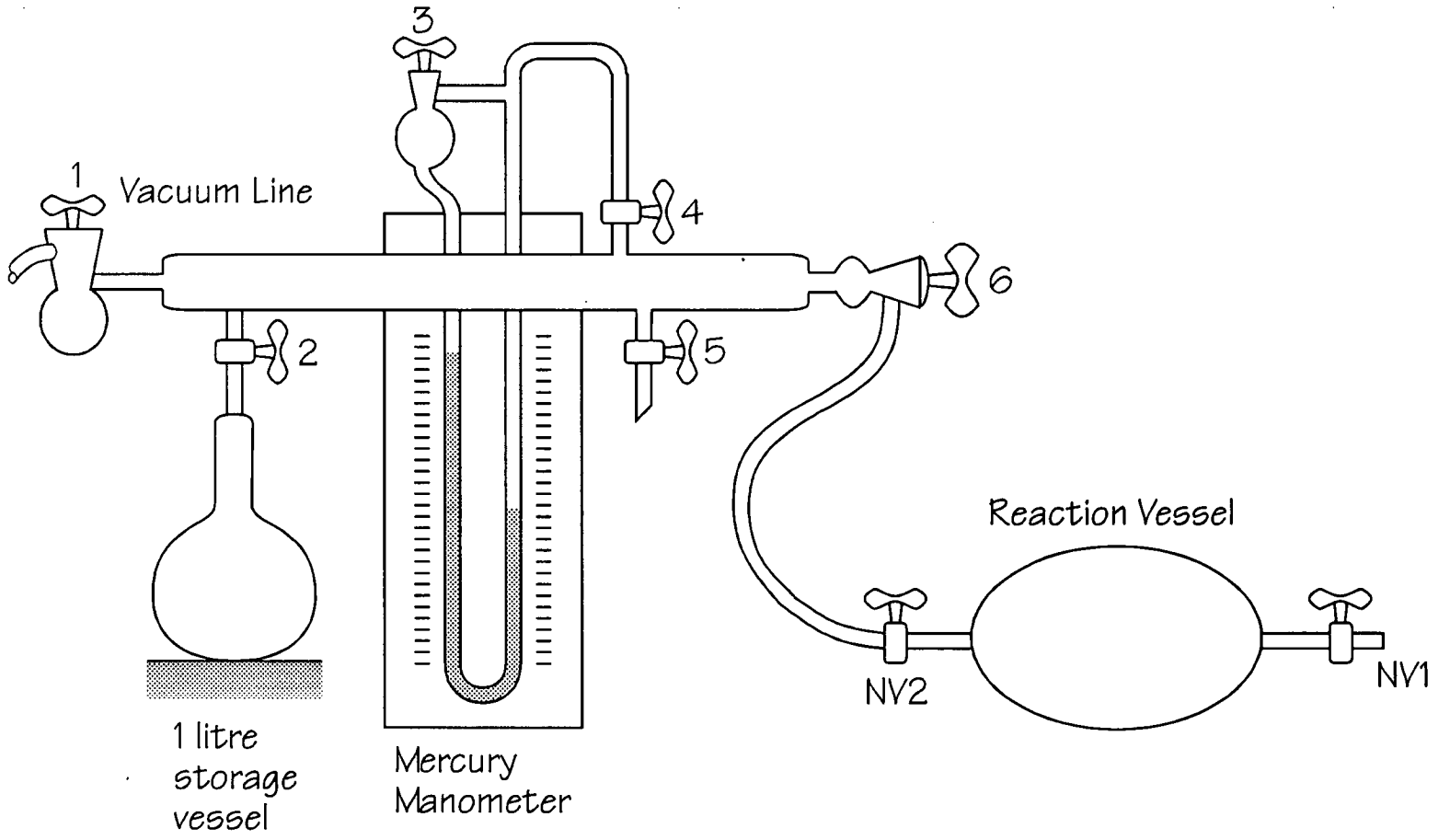


Figure 20. Schematic diagram of the vacuum line.



A Kistler 410B pressure transducer was attached to the bomb by means of an adaptor screwed into the wall of the bomb. An airtight seal was formed by a rubber 'O' ring between the adaptor and the wall of the bomb. A co-axial cable was used to connect the transducer to a charge amplifier model 5001 SN in order to convert the electric charge from the piezo-electric transducer into a proportional voltage. The sensitivity of the transducer was quoted as 3.8 pC/atmosphere. The output of the charge amplifier was fed directly to one channel of a twin beam oscilloscope with an input impedance of approximately  $1\text{M}\Omega$ . The oscilloscope had the facility to store and enhance the display on the screen and could follow very fast writing speeds.

Two type K thermocouples insulated with varnish impregnated glass fibre sleeving 1.5 mm in diameter, were connected to a chart recorder, with a maximum chart speed of 60 cm/min.

#### 4) Power Supply

The ignition source was brought up to a very high temperature by means of a D.C power supply consisting of an 80 amperes service. Temperatures over  $1,000^{\circ}\text{C}$  could be achieved. The circuit of the power supply is shown in Figure 21, and essentially comprises a variable transformer (which could supply up to 100 Amperes at low voltage) connected to a bridge diode which is in parallel with a  $10,000\ \mu\text{F}$  capacitor and a resistance (i.e. the ignition source). A clamp multimeter was used to monitor the current flowing through the Nichrome strip.

**TABLE 10.** Specifications of the equipments and material.

Equipment	Specifications
<p>Power Supply</p> <ul style="list-style-type: none"> <li>- Transformer</li> <li>- Variac</li> <li>- Diode</li> <li>- Capacitor</li> <li>- Shunt</li> <li>- Fuse</li> <li>- Multimeter</li> <li>- ac/dc Clamp Multimeter</li> </ul>	<p>Model: Dalla 40 art/item 1610. 100 amperes;50Hz, 5volts,Thermal Protection IP21, Class of insulation H. Manufactured by: CEBORA</p> <p>Typel :74A; Input: 250V; Volts:50/65 ; Output Volts: 0-275V;Currents: 15AMPS. Manufactured by: ROTARY BERCO REGAVOLTS.</p> <p>Type: 1200 <math>V_{RRM}</math>, <math>V_{RMS}</math> and 80 A. Manufactured by: SEMIKRON.</p> <p>Polar Aluminium Electrolytic Capacitor with screw terminal: 10,000 <math>\mu</math>F, 100VDC. Manufactured by: RS.</p> <p>100 Amperes; 125mVolts and Accuracy <math>\pm</math> 2%.</p> <p>32 Amps; 660 Vac. Supplied by: RS.</p> <p>Model: Fluke 77. Manufactured by: FLUKE.</p> <p>Model: HEME 600. Manufactured by: HEME.</p>
<p>Pressure Transducer</p>	<p>Piezo-Electric Pressure Transducer Type Kister 410B. Manufactured by: KISTLER INSTRUMENT AG.</p>
<p>Charge Amplifier</p>	<p>Type 5001 SN. Manufactured by: KISTLER INSTRUMENT AG.</p>
<p>Oscilloscope</p>	<p>Storage Type DM 64. Manufactured by: TEKTRONIX , UK.</p>
<p>Chart Record</p>	<p>Model: SERVOGOR 120, with two channels. Manufactured by: BBC GOERZ METRAWATT.</p>

<b>Equipment</b>	<b>Specifications</b>
Pyrometer	Model: CYCLOPS 52. Supplied by: INFRARED LIMITED, UK.
Data Logger	Model: MINOLTA/LAND Data Processor DP-C. Supplied by: INFRARED LIMITED, UK.
Vacuum Pump	Model: ED 100. Manufactured by: Edwards High Vacuum.
Thermocouple	Type K

### **3.3 Experimental Procedures**

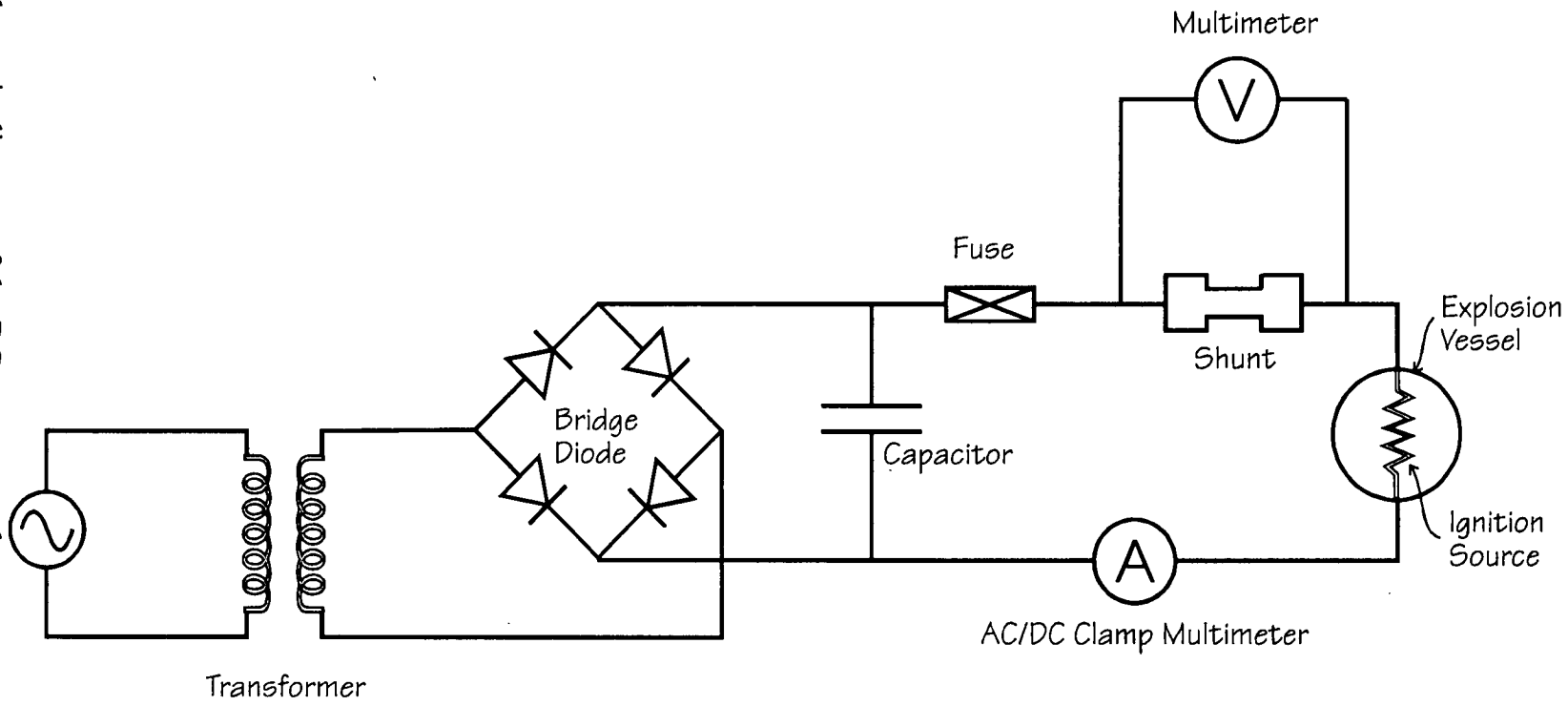
Upon completion of the experimental setup, some preliminary work was conducted to fine-tune the facility and identify the run conditions which would lead to a successful completion of the project. The next sections describe this work as well as procedures and conditions of the experiment.

#### **3.3.1 Calibration of the mixture inside the vessel**

Since one of the common hydrocarbon fuels found in a plant process is condensate, which is a mixture of the lower hydrocarbons, propane was selected as the fuel for these experiments. The propane ( 96% propane, 0.4% ethane, 0.2% propylene, 0.2% butenes and 3.2% C<sub>4</sub>alkenes [4] ) was supplied from in a small cylinder of 10kg.

Whenever it was necessary, the propane cylinder was attached to the vacuum line through the valve number 5 (Figure 20) by a reinforced rubber tube with an internal and external diameter of 6mm and 12mm respectively, in order to transfer propane into the storage bulb. In each test the mixture in the reaction vessel was prepared as follows: With the valves number 2, 3 and 5 closed and

Figure 21. Schematic diagram of the DC power supply.



valves 1, 6, 4 and the valve NV2 open the bomb was evacuated. In order to check if the system (i.e. the vacuum line and the reaction vessel) was airtight, valve number 1 was closed and the pressure in the system was monitored using the mercury manometer for about 15 minutes: If during this period there was no increase in pressure, it was assumed that the system was airtight. This is of importance in order to guarantee that 3% of propane was introduced correctly inside the vessel. The system was checked before each test. The required pressure of propane was introduced into the bomb by opening valve number 2 very carefully and monitoring the pressure rise on the manometer. The valves number 2, 6 and NV2 were closed and the valve NV1 was fully opened to allow the in-rush of air to bring the pressure inside the bomb to atmospheric. A magnetic stirrer was used to mix the contents uniformly. The residual propane inside the vacuum line was removed by the vacuum pump when valve number 1 was opened.

### **3.3.2 Calibration of the pressure transducer**

The needle valve NV1 was securely connected by a rubber tube to an air cylinder and a second rubber tube from a mercury manometer was attached to the valve NV2. With the valve NV2 opened, the rubber tube connected to the air cylinder was pressurised in small stages and the control of the air entering the sphere was through the valve NV1. The pressure transducer was connected to the charge amplifier. The output of the charge amplifier whose sensitivity was set to 1 mechanical unit/volt was fed directly to the oscilloscope. The oscilloscope was set to 1 volt/division. In this case 1 mechanical unit/volt was equal to 0.025 atm. The scales of the amplifier and the

oscilloscope were changed until a pressure rise above 1atm could be detected. The amplifier was set to the sensitivity of the transducer at 3.8 pC/mechanical units (1pC=1mV.1,000pF).

### 3.3.3 Measurement of the Temperature

The surface temperature of the nichrome 80 strip was measured by an optical pyrometer. The temperature along the strip was not uniform, decreasing in the direction of the contacts. It was observed that the maximum temperature is obtained around the centre of the strip; similar observation was made by Onu et al. [5]. Therefore, the pyrometer was set to focus on the middle of the strip. The maximum temperature at the centre of the strip was taken as the strip temperature and it took approximately 15 seconds to achieve its steady temperature. The emissivity was 0.85 [6].

The surface temperature was observed in air at ambient temperature with the same conditions of a closed reaction vessel. The conditions of a closed vessel were simulated by changing the upper part of the bomb by a metal cover with an opening at the top to allow the pyrometer to be introduced. In other words, mainly for safety reasons, in order to measure the temperature of the nichrome 80 strip, the conditions of a closed explosion chamber were simulated, but instead of propane/air mixture inside it there was air. For a mixture 4% propane/air after ignition the maximum pressure inside a reaction vessel with a volume greater than one litre according to Bartknecht [7] is approximately 7 atm; for a 3% propane/air mixture a lower value is expected, but it was assumed that the pressure inside the bomb could reach 7 atm. Thus how to build up an explosion chamber with a glass window that could support the development of such pressure? Facing the difficulties in building such a

reaction vessel and taking into account the safety aspect of the test procedures it was decided to assume as the strip temperature the average temperature of the strip before and after the test.

The temperatures of the nichrome 80 strip were measured under the conditions of a closed sphere but filled with air instead of a mixture of 3% propane-air. It was assumed that the thermal conductivity of pure air was the same as 3% propane-air. The mixture temperature observed before ignition was around  $(60\pm 30)^{\circ}\text{C}$ . According to Weast [08] at  $50^{\circ}\text{C}$  the thermal conductivity of air is  $0.02 \text{ W}/(\text{m}^{\circ}\text{C})$ .

For each experiment a prescribed current was delivered by the DC source for 120 seconds. The temperature time curve of the centre of the strip was recorded by a data logger connected to the optical pyrometer. The power supply was switched off and the sphere closed. The mixture was made up. Due to obvious risks, during the preparation of the flammable mixture special attention was taken in order that it was prepared only inside the reaction vessel. The power supply which was already adjusted to a certain current to bring up the nichrome strip to a certain temperature was switched on. The occurrence of ignition or no ignition was observed. Simultaneously, at the moment that the power supply was switched on a stop-watch clock was triggered to record the ignition delay, in case ignition occurred before the 120 seconds elapsed. Afterwards the needle valve NV2 was opened and the contents of the vessel were evacuated from the sphere through the vacuum line and condensed in the cold trap by the vacuum pump. Then the sphere was opened and with the same current before and during the test, the temperature time curve of the centre of the strip was recorded after the test.

### 3.3.4 Ignition sources

In these experiments a Nichrome 80 tape (80% nickel and 20% chromium), 5mm wide, 0.03mm thick and 45mm or 65mm long was used as an ignition source. The ignition source was placed at the centre of the reaction vessel as shown in Figure 18.

The Nichrome 80 strip was connected to the DC power supply through two copper rods. The connections between the copper rods and the Nichrome strip were made with screw connectors. These connectors were chosen because they could be removed easily after several tests and they provided good electrical contacts. They were changed regularly after 5 tests. After some runs, their electrical contacts tended to become poor, probably due to corrosion by the combustion products. These connectors were protected with the same semi-flexible heat shrinkable tubing as was used on the copper rods.

The Nichrome tape was placed first in one of the configurations as shown in Figure 2. In the open configuration (no "confinement"), it lay directly on the surface of a flat piece of ceramic fibreboard (Kaoboard), 70 mm square. Confinement was provided by placing the Nichrome strip at the foot of a rectangular cavity, also constructed from Kaoboard. The cavity width was kept constant at 5 mm, but the depth varied from 10 mm to 40 mm. Both ends of the cavity were open.

Secondly, in order to investigate the effect of the length and orientation of the ignition source, it was decided to carry out two sets of tests. The first one with a Nichrome strip 65 mm long in an open configuration and the second with

the Nichrome strip of similar length in an inclined configuration, i.e., forming an angle of 30° with the horizontal.

### **3.3.5 Ignition criteria**

The autoignition temperature is important in safety work especially when a flammable vapour/air mixture can remain in contact with a heated surface for an indefinite period. If the temperature of a flammable gas-air mixture is raised in a uniformly heated apparatus at or above the autoignition temperature, combustion occurs in the bulk gas. In the test method measurement of autoignition temperature [2,3] if, 5 minutes after the fuel was injected into a heated flask the appearance of flame was not observed, it is assumed that ignition did not take place.

In experimental work carried out by other investigators (Table 9), the heating period was very short, viz. a few seconds. Such a small heating period is relevant when ignition by a hot surface results from the impact and friction between two surfaces. For example, the most probable source of methane-air ignition during a ship collision comes from the production of a heated surface via frictional heating. The duration of such a hot surface is estimated in the range of 0.5-5.0 seconds [9].

Although the autoignition temperature of most hydrocarbon vapours is in the range of 200-500°C [10] it has been accepted for some time that 900°C [11] can be taken as the minimum ignition temperature for ignition of flammable mixture by an open surface; however this value is based on experimental work which adopted a heating period of several seconds up to 40 seconds. With increasing awareness of industrial safety and considering that the data

available are either related to a long ignition criterion (5 minutes) or a very short heating period, it was thought desirable to investigate the effect of local confinement on the ignition of a flammable mixture by heated surface with heating period of 120 seconds. In the present work, if ignition was not observed within 120 seconds, a non-ignition condition was assumed.

### 3.3.6 Safety Considerations

There are some inherent and evident risks associated with this test procedure, so all equipment and actions adopted were handled carefully. Some of these risks are: a) The potential electrical hazard associated with the D.C source, therefore care such as connecting all equipment to a common ground and provide good insulation for live contacts was taken. b) The risk associated with filling the sphere. The preparation of the mixture was made only inside the sphere. c) Lab coats, glasses and gloves were worn, since flammable liquids and products which cause irritation to the skin (vacuum grease) were in constant use. d) The risk of an undesirable explosion in the vacuum line. Special precaution was taken NEVER to switch off the vacuum pump or open valve number 1, (Figures 17, 20) while the liquid nitrogen was still around the cold trap. If some propane remained condensed in the cold trap and if condensation of oxygen happened, an explosion could have occurred.

When ignition did not occur and the flammable mixture was evacuated from the bomb, only on this occasion was a flammable mixture presented in the evacuation line, but it was safe since the pressure in the evacuation line was low, i.e. less than 20mmHg.

## 3.4 Experimental Results

### 3.4.1 Tests with the Tungsten Wire

At the start of the present experimental work some preliminary tests were carried out with the objective of developing the experimental procedure, verifying some of the previous results and providing some guidelines for the elaboration of the mathematical expressions which will be presented in Chapter 4. These preliminary tests involved an experimental study of the ignition of mixtures of propane and air at various concentrations by heated tungsten wires. They were divided into three sets of data; a) straight wire, b) wire in the form of a vertical U and, c) a wire coil of 4 turns. The results are summarized in Tables 11, 12, 14 and 15 and in the appendix.

The experimental procedure adopted during these preliminary tests was similar to the one followed for the nichrome tape, except for the ignition criteria. For the initial tests the ignition criterion adopted was 15 minutes (900 seconds). Initially a long ignition criterion was chosen, having in mind two observations. First, according to Bradley [12], the oxidation of a hydrocarbon often displays a long induction period (which he defines as the time lag between the exposure of the gas to the heated surface and the subsequent ignition) often lasting for several minutes, which is followed by a much slower build-up in reaction rate. Secondly, in order to compare them with the data presented by Silver [13] who let the ignition source exposed to a flammable mixture to the ignition source approximately 15 minutes.

Researches on the ignition of flammable mixtures have shown two points:

First, the composition of the most readily ignited mixture depends on the ignition source used, i.e., spark ignition or hot wire. The most reactive mixture for the case of a spark ignition lies on the fuel-rich side of stoichiometry [10].

Shepherd and Wheeler [14], Coward and Guest [15], Onu et al. [5] and Cutler [16,17] found that the most readily ignitable mixture for the case of a hot wire seems to be on the fuel-lean side of stoichiometry. The present set of tests with the wire wound in the form of a spiral with 4 turns confirmed the observations of Shepherd and Wheeler, Coward and Guest, Onu et al. and Cutler. For the wire wound in the form of a spiral with 4 turns, the ignition currents were determined for propane-air mixture containing 2.3%, 3%, 3.7%, 4.5%, 5.4%, 6.3% and 6.7% (Table 11). It was observed that 3.7% was the most easily ignitable of these mixtures. Cutler [17] with a straight tungsten wire 57mm long and 6.4mm wide, found that the most easily ignitable mixture of propane and air was at 3.3%.

**Table 11.** Preliminary set of results with tungsten wire 0.5mm in diameter wound in the form of a spiral.

Concentrations (%Vol)	Ignition Current Range (A)	Number of Tests	Number of Ignitions
2.3	13.9±0.1	2	2
3.0	14.1±1.1	17	11
3.7	13.6±1.2	11	8
4.5	14.2±0.4	5	3
5.4	15.1±1.3	13	10

Concentrations (%Vol)	Ignition Current Range (A)	Number of Tests	Number of Ignitions
6.3	14.3±0.3	4	2
6.7	15.2±1.2	7	5

**Table 12.** Estimated minimum ignition temperature for the tungsten wire 0.5mm in diameter wound in the form of a spiral with 4 turns.

Concentrations (%Vol)	Estimated Ignition Temperature 1,2 (°C)
2.3	-
3.0	(980±40)
3.7	(790±50)
4.5	960±60
5.4	890±40 <sup>3</sup>
6.3	-
6.7	960±30

1- The temperatures were obtained either with the pyrometer or calculated from the voltage and current, but they were not recorded for all the tests carried out (see appendix). In order to estimate an ignition temperature the values of the temperatures recorded were considered, and by assuming a probability of 50% of non-ignition the ignition temperatures were estimated.

2- The values outside the parenthesis refer to the temperature obtained with the pyrometer. The values inside the parenthesis refer to the temperature calculated from the resistance curve.

3- This value includes both temperatures, i.e. either the one obtained with the pyrometer or the one calculated from the resistance curve.

Secondly, ignition could be affected by the shape of the hot wire. Tests conducted by Silver [13] showed that when the wire was wound in the form of a spiral, ignition was obtained more easily than when it was straight. His data are reproduced in Table 13.

It is important to observe that Silver, comparing the probability of ignition between the straight wire and the one wound in the form of a spiral, used wires with the same diameter, but different lengths. The present results shown in Tables 14 and 15, confirmed Silver's observation, since only the wire diameter is maintained constant. On the other hand, the set of data related to the U vertical wire and the 4 turns wire, in which the tungsten wires had the same diameter and length, are not consistent with Silver's results.

**Table 13.** Ignition obtained for a mixture of 4.8 -5.1% ether-air, with copper wires [13].

Diameter (mm)	Length (mm)	Currents (A)	Ignition Delay <sup>1</sup> (seconds)	Results
0.16	15.9	7.5	900	NI
0.13	25.4	4.2	900	NI
0.13	12.7	5	20 <sup>2</sup>	NI

Diameter (mm)	Length (mm)	Currents (A)	Ignition Delay <sup>1</sup> (seconds)	Results
0.11	15.9	4.5	900	NI
0.11	304.8 <sup>3</sup>	4	1	I

1- Ignition delay is defined as the time period between the exposure of the gas to the heated surface and subsequent ignition.

2- The wire fused after 20 seconds, but ignition was not observed.

3- 304.8 mm was formed into a spiral.

**Table 14.** Preliminary set of results with tungsten wire 0.5mm in diameter, 3% propane-air.

Set of Tests	Ignition Current Range (A)	Number of Tests	Number of Ignitions
Straight wire (45mm long)	16±1.4	23	15
U vertical wire (175mm long)	14.4±1.1	17	9
4 turns wire (175mm long)	14.1±1.1	17	11

**Table 15.** Estimated ignition temperature of the preliminary set of results with tungsten wire 0.5mm in diameter, 3% propane-air.

Set of Tests	Estimated Ignition Temperature <sup>1</sup> (°C)
Straight wire (45mm long)	1200±50
U vertical wire (175mm long)	950±50
4 turns wire <sup>2</sup> (175mm long)	980±50

1- The temperatures were obtained either with the pyrometer or calculated from the voltage and current. But they were not recorded for all the tests carried out, as shown in the appendix. In order to suggest an ignition temperature, the values of the temperatures recorded were considered, and by assuming a probability of 50% of non-ignition, the ignition temperatures were estimated.

2- Diameter of each turn 10mm. Distance between turns 5mm.

Although this preliminary set of data with tungsten wire could not be analysed theoretically, it was important. It showed that the ignition delay was not reproducible.

### 3.4.2 Tests with the Nichrome 80 Tape

The main purpose of the data presented in this section is to study how the degree of confinement affects the ignition temperature. It was felt that the use of experimentally acquired knowledge would lead to a better understanding of the ignition process, as well as leading to a more accurate diagnosis of practical hazards.

The results were obtained using a Nichrome 80 strip as the ignition source. A constant current was passed through the strip for a period of 120 seconds. During the first 20 seconds of the heating period, the temperature rose rapidly to a near constant value which was maintained until the end of the experiment (120 seconds) as shown in Figures 22-24 and 29-31. As was mentioned in section 3.3.3, the strip temperature time curves during the tests were obtained from the average of the values recorded before and after each test. In order to be on the conservative side, the values presented in Tables 17-19 and 21-23 (see pages 120-138) are the highest values calculated. The data that were obtained showed a considerable scatter. Taking the open configuration as an example, ignition was investigated in the temperature range 870 - 960°C. It was not possible to identify a well-defined minimum surface temperature below which ignition did not occur. To resolve this problem, the results were inspected in temperature bands ( for the open configuration 870-890°C, 890-910°C and 930-960°C) and the number of ignitions and non-ignitions noted. The results for the open configuration are presented in this way in Table 17.1. These results were used to calculate the probability of ignition in each temperature band. These probabilities were then plotted against the mid-point of each temperature band, and the temperature corresponding to a 50% probability of ignition was interpolated (see Figure 25). The other results are

shown in Tables 18.1, 19.1, 21.1, 22.1, 23.1 and Figures 25, 26, 27, 32, 33, 34. A large number of data were obtained on separate days ensuring data repeatability. The tests showed that true ignition temperatures can be obtained with sufficient effort.

The time-temperature curves of these bands are shown in Figures 22-24,29-31. These bands were calculated from the average of all time-temperature curves of the tests included in the respective band. Some of the time-temperature curves represented the tests in which ignition occurred (I) in the respective band, others curves represented the tests in which ignition did not occur (NI) in the respective band. The Figures 25-27, 32-34 show the probability of ignition for each band.

#### **3.4.2.1 'Open configurations' results**

The ignition temperature for the 45mm and 65mm long nichrome 80 strip placed in the horizontal position were respectively 880-900°C and 895-915°C. The results are consistent with Powell's compilation that the minimum ignition temperature for a class IIA vapour (for which propane is the representative fuel) at an open surface is of the order of 900°C. On the other hand, the previous work carried out and summarized in Table 9 (Chapter 2), showed that a lower ignition temperature is expected for a wide ignition source, but the present tests showed that if the width is kept constant there is no difference in the ignition temperature, if the length is increased from 45mm to 65mm.

The review of the published material (Chapter 2) indicated that the ignition temperature tends to decrease if convection effects are reduced. In order to verify this conclusion with the ignition criteria adopted and also to provide

data that allow a comparison between the present set of tests in which the nichrome 80 strip was placed horizontally, a nichrome 80 strip 65 mm long was placed in an inclined position 30° to the horizontal. The test results obtained with the inclined configuration showed an ignition temperature of 890-920°C, similar to the ones obtained with the nichrome 80 strip 45 mm and 65 mm long placed horizontally.

The results related to the 'open configuration' are summarized in Tables 17-19 and Figures 22-27.

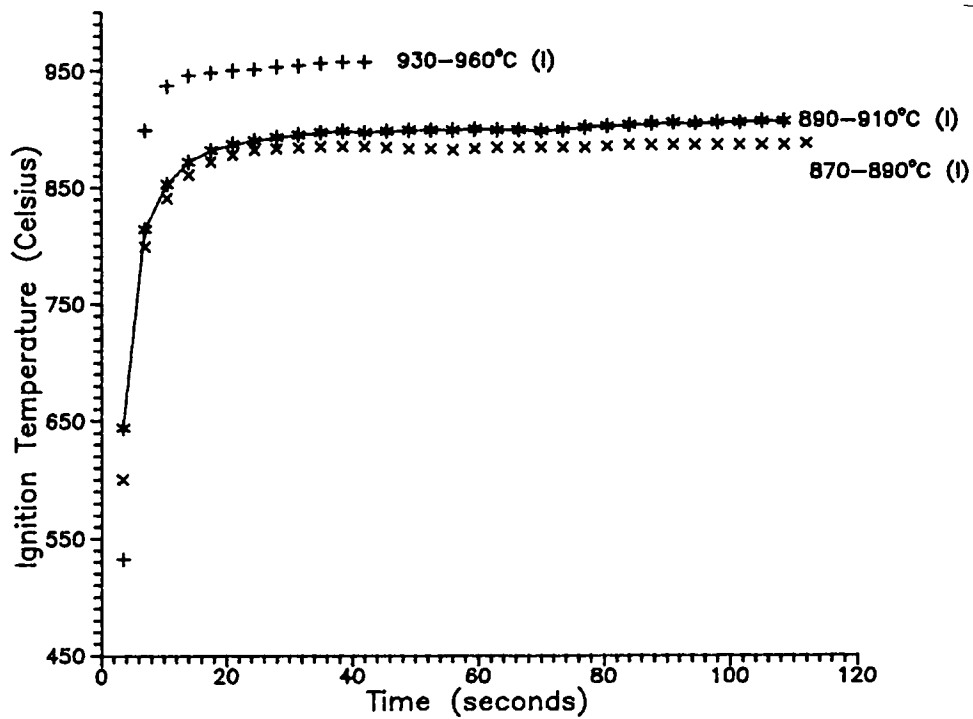
**Table 16.** Open configuration results

Strip Description		Ignition Temperatures <sup>1</sup> °C
Dimensions mm	Position	
Length: 45 Width: 5 Thickness:0.03	Horizontal	880-900
Length: 65 Width: 5 Thickness:0.03	Horizontal	895-915
Length: 65 Width: 5 Thickness:0.03	Inclined 30°	890-920

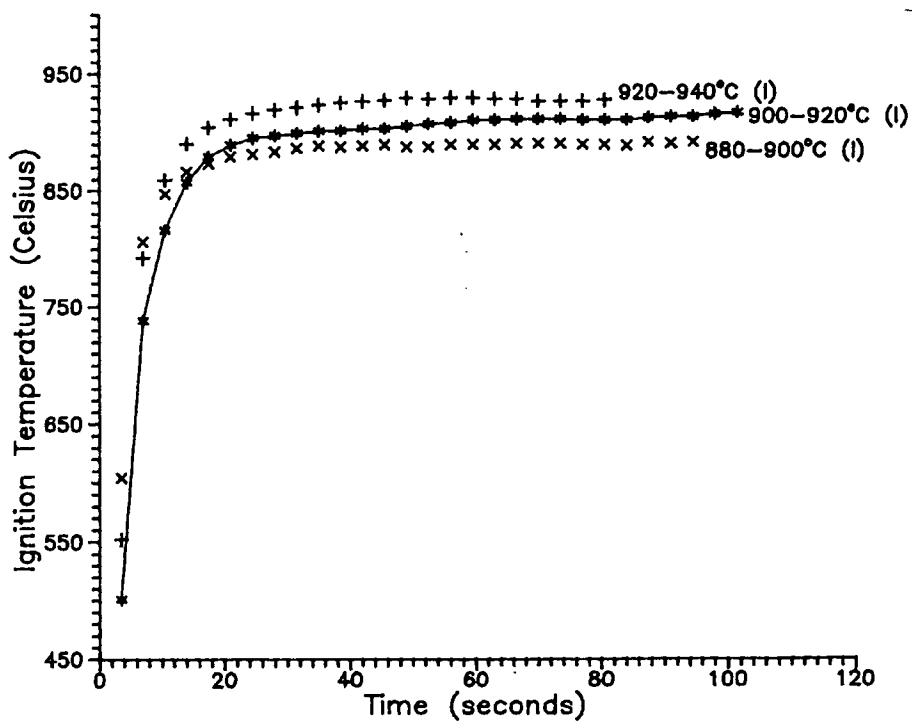
1- Temperature bands in which the probability of ignition was 50%. The values were obtained by interpolating the data presented in Figures 25-27.

### 3.4.2.2 'Local confinement' results

There have been many investigations into the ignition temperature required to ignite a flammable mixture by heated surfaces. It is surprising that there has been no systematic investigation into the effect of the 'local confinement' of the hot surface on the ignition temperature. The results related to the 'local confinement' which are summarized in Table 20, were obtained with strips of Nichrome 45mm long, 5mm wide and 0.03mm thick placed in rectangular



**Figure 22.** Time-temperature curves related to the horizontal Nichrome strip 45mm long. Open configuration.



**Figure 23.** Time-Temperature curves related to the horizontal Nichrome strip 65mm long. Open configuration.

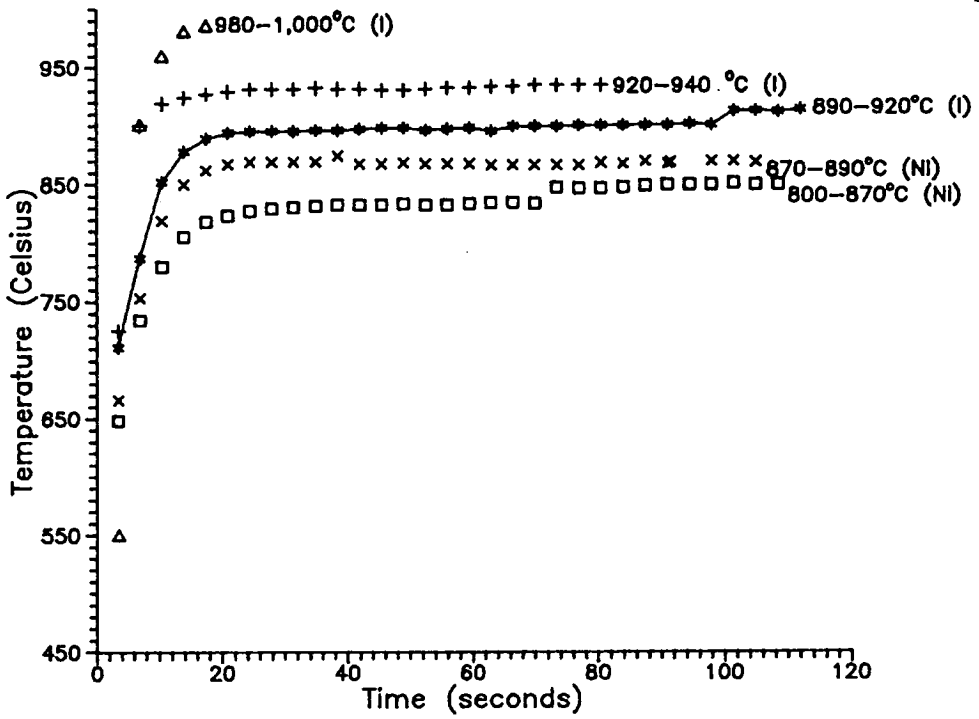


Figure 24. Time-temperature curves related to the inclined Nichrome strip 65mm long. Open configuration.

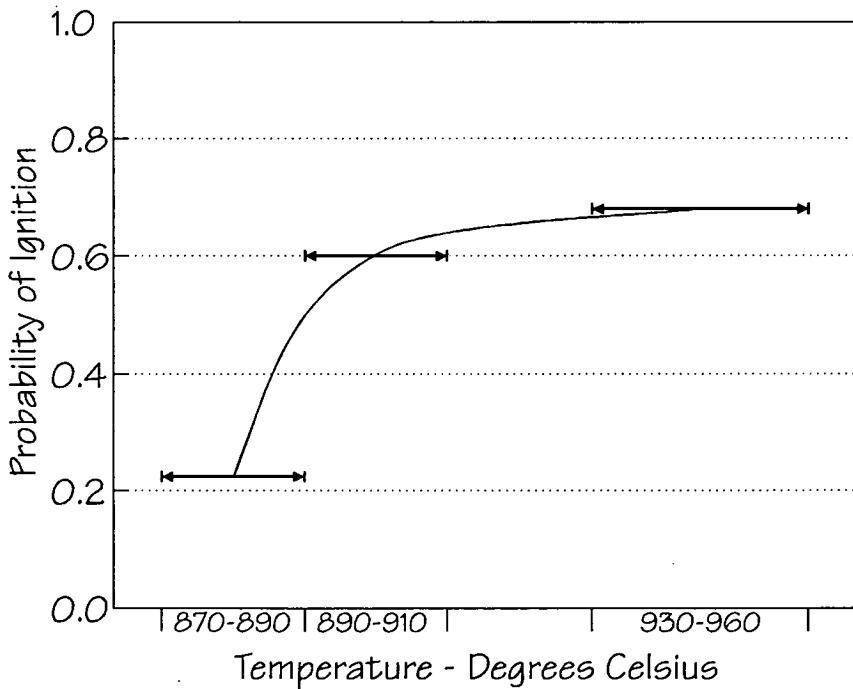
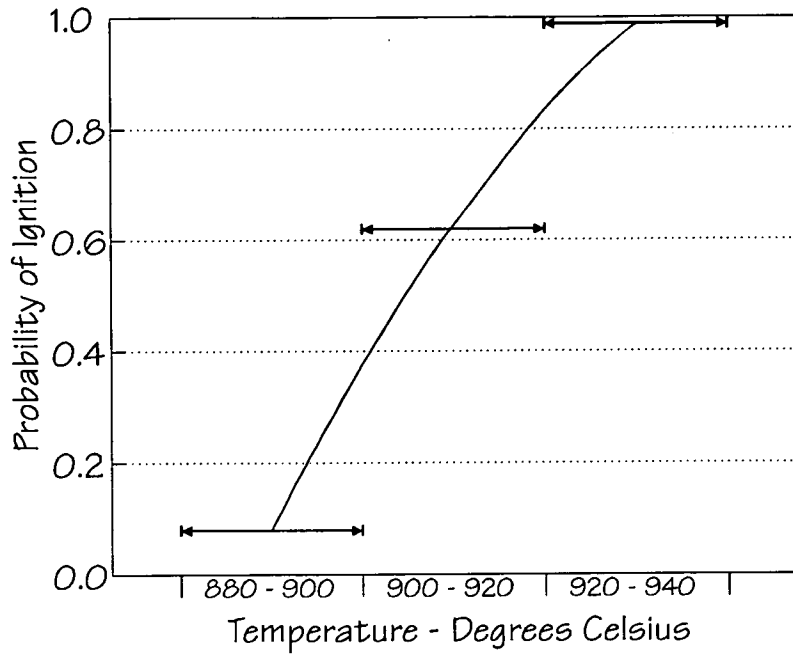
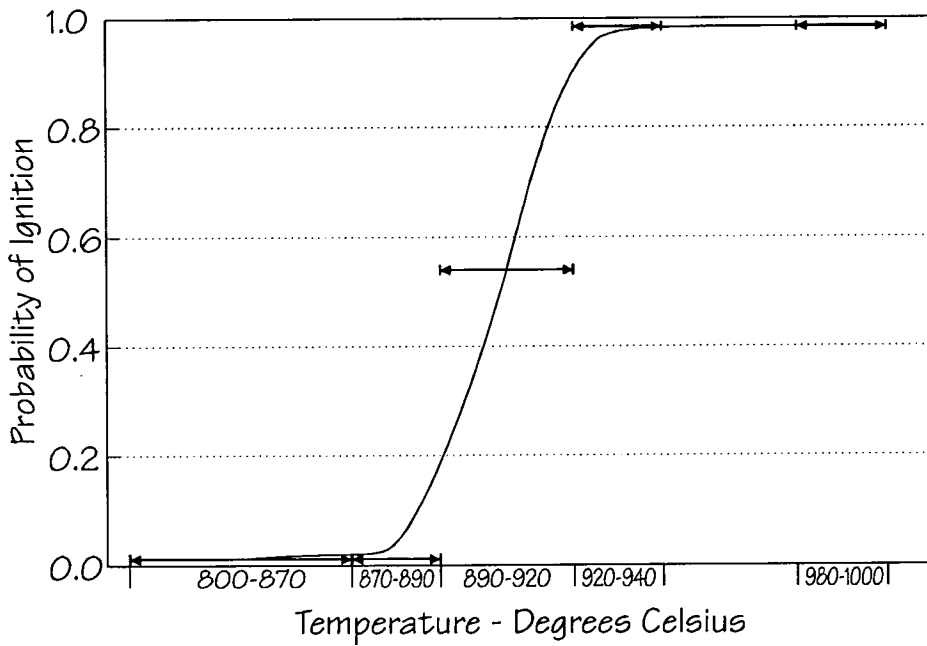


Figure 25. Probability of ignition for each band selected. Horizontal Nichrome strip 45mm long. Open configuration.



**Figure 26.** Probability of ignition for each band selected. Horizontal Nichrome strip 65mm long. Open configuration.



**Figure 27.** Probability of ignition for each band selected. Inclined Nichrome strip 65mm long. Open configuration.

unheated cavities constructed with Kaoboard. The cross sections of these cavities are shown in Figure 2. The cavity widths were constant at 5mm, but the depths varied from 10mm - 40mm. The 'local confinement' results are summarized in Tables 21-23 and Figures 29-34.

**Table 20.** 'Local confinement' results

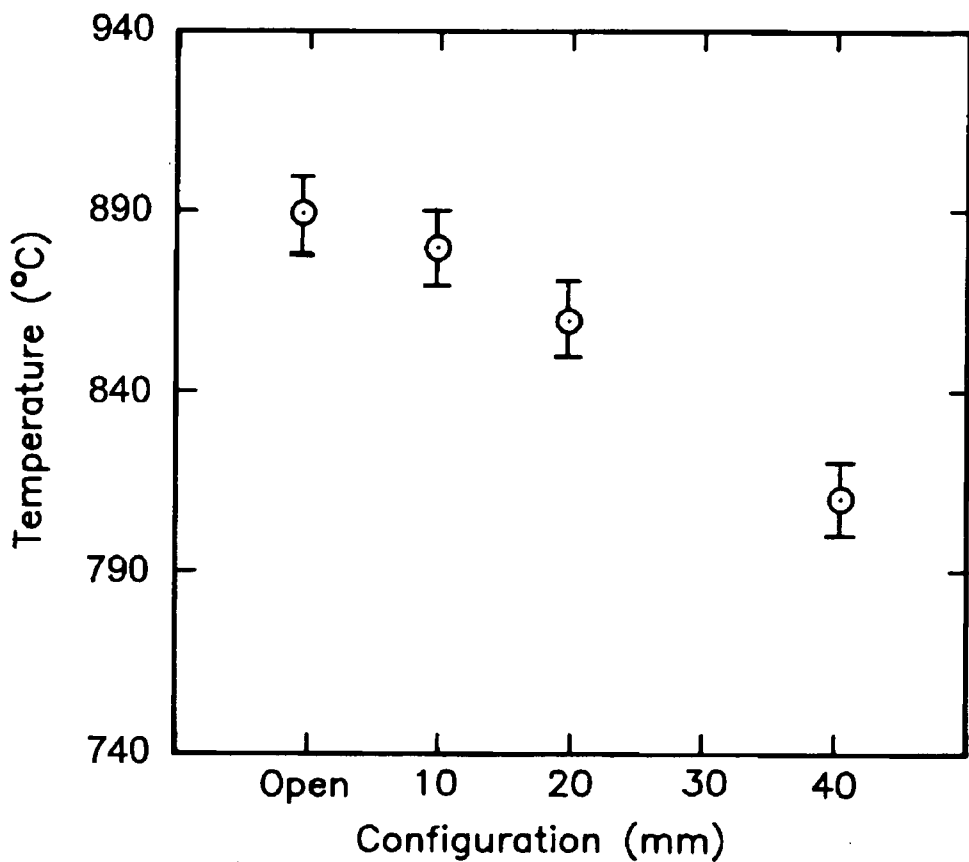
'Local Confinement'	Ignition Temperature <sup>1</sup> °C
10 mm deep	870-890
20 mm deep	850-870
40 mm deep	800-820

1- Temperature bands in which the probability of ignition was 50%. The values were obtained by interpolating the data presented in Figures 32-34.

A comparison between the ignition temperature obtained with an open (45mm long Nichrome strip) and 'local confinement' configuration is shown in Figure 28. It shows that 'local confinement' around a heated surface can increase its ability to ignite a 3% propane/air mixture. The ignition temperature of the 'local confinement' configuration depended on the depth of the cavity.

Cutler [16,17] observed that the longer the heated surface is kept at a given temperature in a flammable mixture the greater is the probability of ignition. With the objective of verification, the ignition criterion adopted initially of 120 seconds was modified. With an ignition criterion of 180 seconds the ignition

temperatures of a 'local confinement' 20mm and 40mm were observed. This change in the ignition criteria confirmed Cutler's observations. Thus, for the 'local confinement' 20mm deep, the ignition temperature band either for the ignition criteria 120 seconds or 180 seconds was 850-870°C. For the 'local confinement' 40mm deep, the ignition temperature band for an ignition criterion of 120 seconds was 800-820°C, and for 180 seconds was 790-810°C.



**Figure 28.** Comparison between the ignition temperatures of the open and 'local confinement' configurations.

The results shown in Figure 28 indicate clearly the effect of 'local confinement' around a heated surface on the temperature required for the

ignition of a flammable vapour air mixture. They are consistent with the results of the experiments carried out after the Summit Tunnel fire.

Considering the information obtained in other studies which were described in Chapter 2, and also taking into account the results obtained during this investigation, the next Chapter will present a qualitative and quantitative analysis of the ignition process by a heated surface.

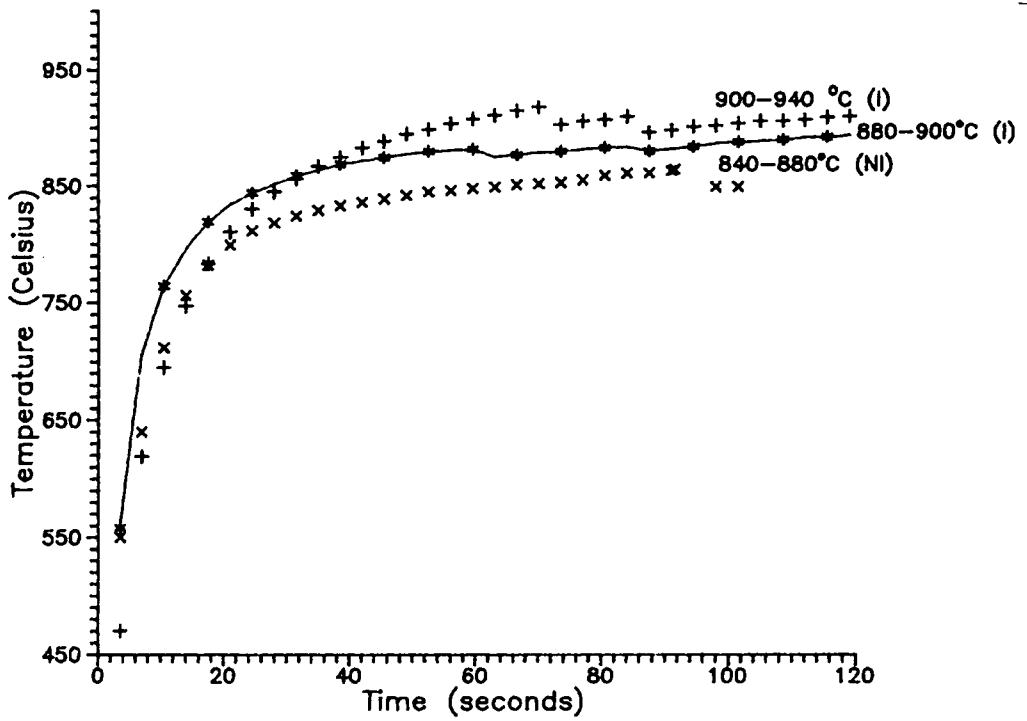


Figure 29. Time-temperature curves related to 'local confinement' configuration 10mm deep.

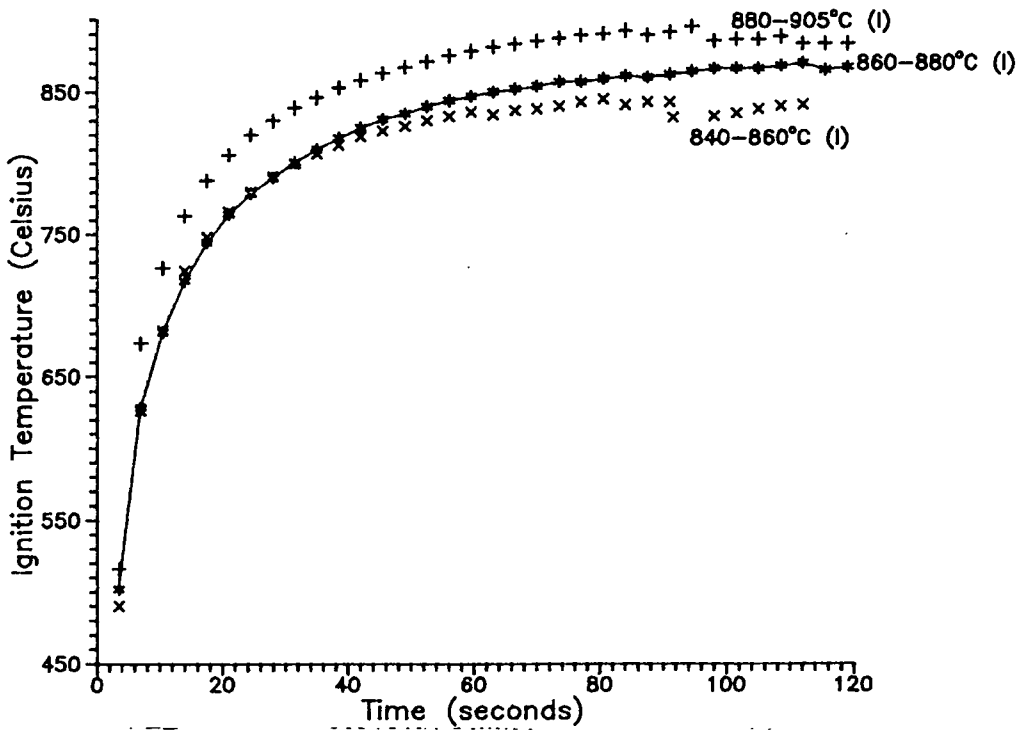


Figure 30. Time-temperature curves related to 'local confinement' configuration 20mm deep.

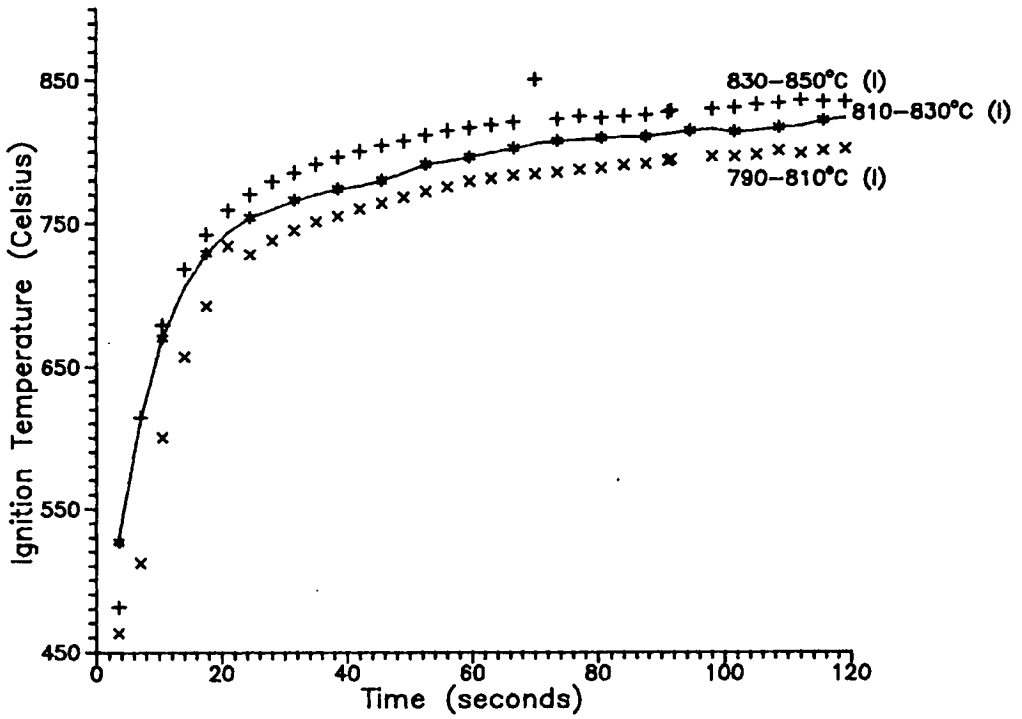


Figure 31. Time-temperature curves related to 'local confinement' configuration 40mm deep.

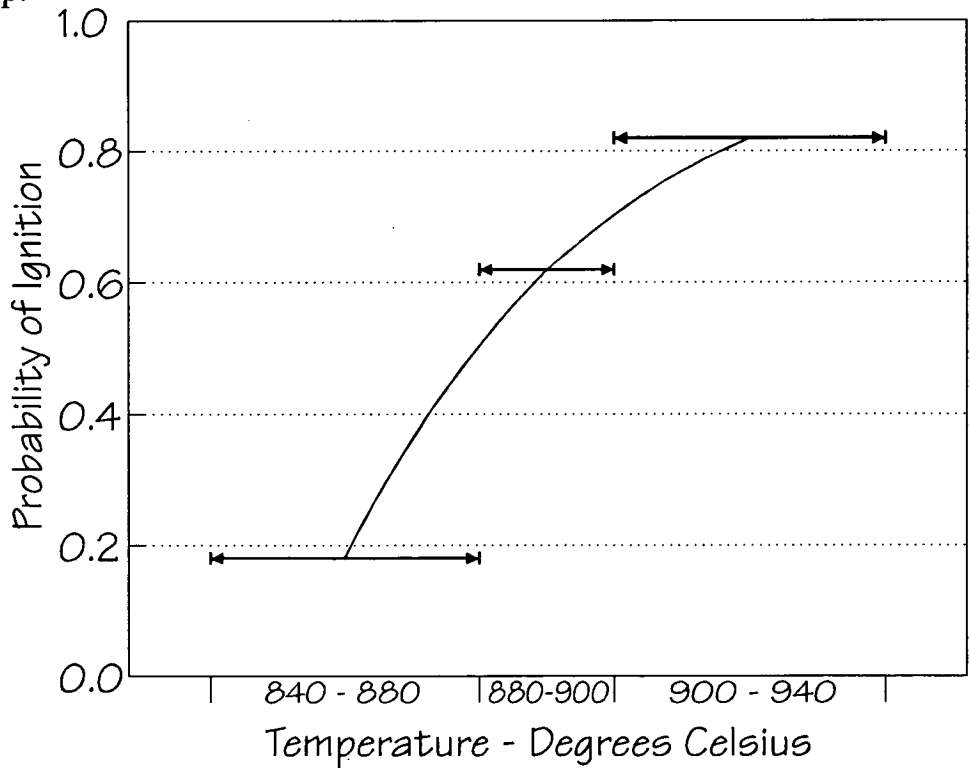
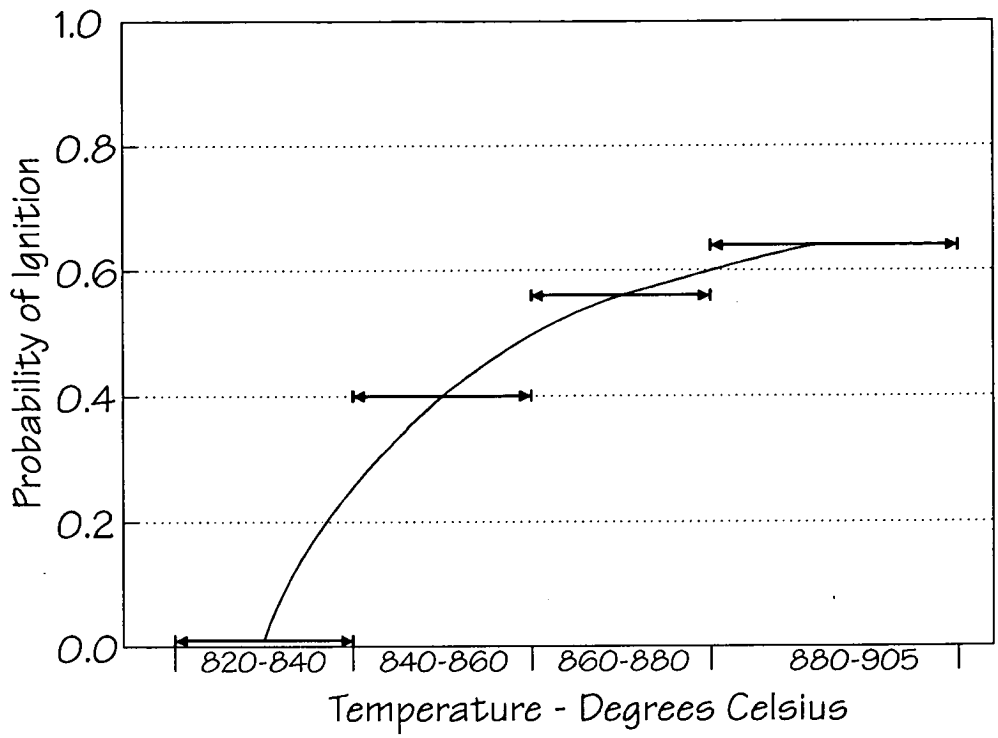
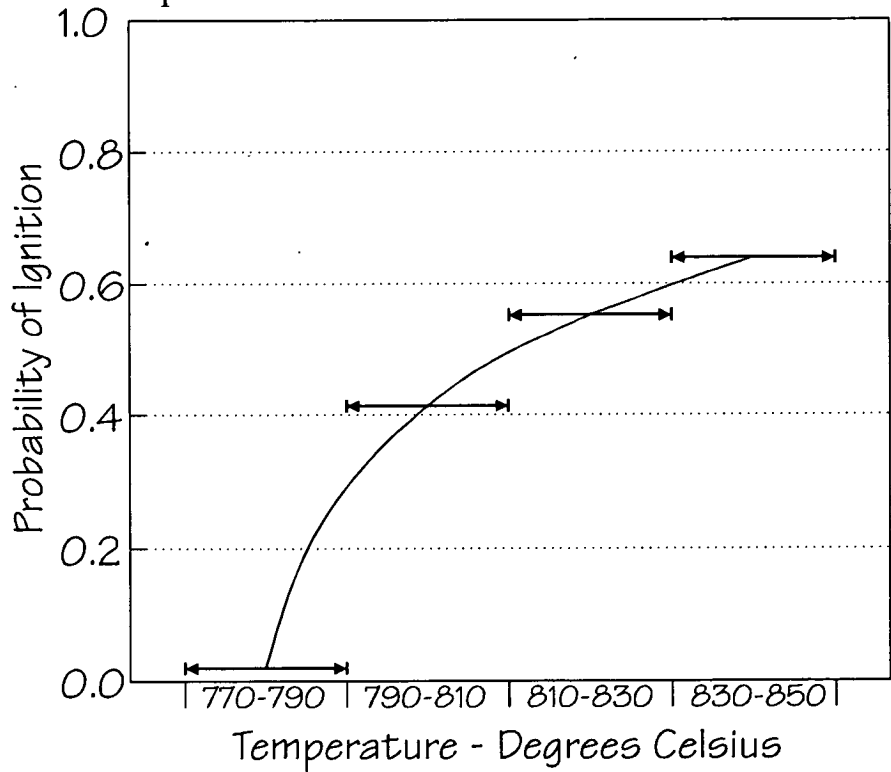


Figure 32. Probability of ignition for each band selected. 'Local confinement' configuration 10mm deep



**Figure 33.** Probability of ignition for each band selected. 'Local confinement' configuration 20mm deep.



**Figure 34.** Probability of ignition for each band selected. 'Local confinement' configuration 40mm deep.

**Table 17.** Results of the tests related to the horizontal Nichrome strip 45mm long. Open configuration (see also Table 17.1).

<b>Test Number<sup>1</sup></b>	<b>Temperature (°C)<sup>2</sup></b>	<b>Ignition Delay (seconds)<sup>3</sup></b>	<b>Results<sup>4</sup></b>
16AHS45	939 ± 2.0	-	NI
19AHS45	951 ± 6.0	31	I
19HS45	904 ± 3.0	65	I
20AHS45	913 ± 4.0	-	NI
20.1AHS45	913 ± 4.0	-	NI
20HS45	908 ± 5.0	88	I
20.1HS45	911 ± 5.0	108	I
21AHS45	937 ± 2.0	-	NI
21HS45	901 ± 19	-	NI
21.1HS45	901 ± 19	115	I
22AHS45	957 ± 1.0	42	I
22HS45	908 ± 5.0	-	NI
22.1HS45	835 ± 8.0	-	NI
23AHS45	952 ± 4.6	23	I
23.1AHS45	947 ± 4.6	15	I
23HS45	885 ± 40	80	I
23.1HS45	887 ± 40	111	I
24HS45	877 ± 20	-	NI
24.1HS45	877 ± 20	-	NI
25HS45	885 ± 32	-	NI
25.1HS45	885 ± 32	-	NI
26HS45	881 ± 30	-	NI

Test Number <sup>1</sup>	Temperature (°C) <sup>2</sup>	Ignition Delay (seconds) <sup>3</sup>	Results <sup>4</sup>
26.1HS45	881 ± 30	-	NI
37HS45	897 ± 4.0	75	I
37.1HS45	897 ± 4.0	66	I
38HS45	887 ± 14	-	NI

1-The test number identifies the run number, configuration ,i.e., HS is horizontal surface and the length of the nichrome tape in millimetres.

2- The highest temperature from the time-temperature curve, which was obtained as described in section 3.3.3.

3- Ignition delay is the time lag between the exposure of the gas to the ignition source and the subsequent ignition.

4- The results are either ignition (I) or no ignition (NI).

**Table 17.1.** Results of the tests related to the horizontal strip 45mm long, temperature group into bands.

<b>Temperature Band - °C</b>	<b>Ignitions</b>	<b>Non-ignitions</b>	<b>Probability of Ignition</b>
<b>870-890</b>	23HS45	24HS45	0.22
	23.1HS45	24.1HS45	
		25HS45	
		25.1HS45	
		26HS45	
		26.1HS45	
		38HS45	
<b>890-910</b>	19HS45	20AHS45	0.6
	20HS45	20.1AHS45	
	20.1HS45	21HS45	
	21.1HS45	22HS45	
	37HS45		
	37.1HS45		
<b>930-960</b>	19AHS45	16AHS45	0.67
	22AHS45	21AHS45	
	23AHS45		
	23.1AHS45		

**Table 18.** Results of the tests related to the horizontal Nichrome strip 65mm long. Open configuration (see also Table 18.1).

Test Number <sup>1</sup>	Temperature (°C) <sup>2</sup>	Ignition Delay (seconds) <sup>3</sup>	Results <sup>4</sup>
39HS65	908 ± 3.0	-	NI
40HS65	887 ± 30	-	NI
40.1HS65	887 ± 30	-	NI
41HS65	893 ± 5.0	-	NI
41.1HS65	893 ± 5.0	-	NI
42HS65	908 ± 30	-	NI
43HS65	906 ± 12	-	NI
44HS65	906 ± 14	-	NI
45HS65	887 ± 15	-	NI
46HS65	893 ± 23	-	NI
47HS65	894 ± 30	-	NI
48HS65	891 ± 25	93	I
48.1HS65	891 ± 25	-	NI
49HS65	913 ± 30	-	NI
50HS65	927 ± 30	74	I
50.1HS65	930 ± 20	60	I
51HS65	931 ± 25	47	I
51.1HS65	926 ± 25	77	I
51.2HS65	927 ± 25	79	I
52HS65	912 ± 28	99	I
52.1HS65	881 ± 28	-	NI
53HS65	909 ± 3.0	35	I

Test Number <sup>1</sup>	Temperature (°C) <sup>2</sup>	Ignition Delay (seconds) <sup>3</sup>	Results <sup>4</sup>
54HS65	913 ± 20	-	NI
55HS65	905 ± 20	54	I
55.1HS65	922 ± 20	111	I
56HS65	906 ± 20	39	I
56.1HS65	903 ± 20	30	I
56.2HS65	903 ± 20	30	I
56.3HS65	903 ± 20	20	I
57HS65	907 ± 30	54	I
57.1HS65	906 ± 30	47	I
58HS65	896 ± 20	-	NI
59HS65	920 ± 10	33	I
59.1HS65	925 ± 10	53	I
59.2HS65	920 ± 10	34	I

1-The test number identifies the run number, configuration ,i.e., HS is horizontal surface and the length of the nichrome tape in millimetres.

2- The highest temperature from the time-temperature curve, which was obtained as described in section 3.3.3.

3- Ignition delay is the time lag between the exposure of the gas to the ignition source and the subsequent ignition.

4- The results are either ignition (I) or no ignition (NI).

**Table 18.1.** Results of the tests related to the horizontal strip 65mm long, temperature group into bands.

<b>Temperature Band - °C</b>	<b>Ignitions</b>	<b>Non-ignitions</b>	<b>Probability of Ignition</b>
<b>880-900</b>	48HS65	40HS65	0.09
		40.1HS65	
		41HS65	
		41.1HS65	
		45HS65	
		46HS65	
		47HS65	
		48.1HS65	
		52.1HS65	
		58HS65	
<b>900-920</b>	52HS65	39HS65	0.63
	53HS65	42HS65	
	55HS65	43HS65	
	55.1HS65	44HS65	
	56HS65	49HS65	
	56.1HS65	54HS65	
	56.2HS65		
	56.3HS65		
	57HS65		
	57.1HS65		
<b>920-940</b>	50HS65		1
	50.1HS65		
	51HS65		
	51.1HS65		
	51.2HS65		
	59HS65		
	59.1HS65		
	59.2HS65		

**Table 19.** Results of the tests related to the inclined Nichrome strip 65mm long. Open Configuration (see also Table 19.1).

<b>Test Number<sup>1</sup></b>	<b>Temperature (°C)</b>	<b>Ignition Delay (seconds)<sup>3</sup></b>	<b>Results<sup>4</sup></b>
1IS65	807 ± 7	-	NI
2IS65	896 ± 21	-	NI
2.1IS65	896 ± 21	-	NI
3IS65	986 ± 7	15	I
3.1IS65	981 ± 11	13	I
3.2IS65	981 ± 11	14	I
4IS65	926 ± 6	22	I
4.1IS65	929 ± 7	34	I
5IS65	913 ± 22	115	I
5.1IS65	913 ± 22	-	NI
6IS65	937 ± 17	35	I
6.1IS65	935 ± 16	29	I
7IS65	934 ± 9.0	79	I
7.1IS65	932 ± 9.0	57	I
8IS65	891 ± 25	-	NI
8.1IS65	889 ± 25	99	I
9IS65	898 ± 26	25	I
9.1IS65	906 ± 26	58	I
9.2IS65	905 ± 26	48	I
10IS65	892 ± 22	38	I
10.1IS65	894 ± 22	49	I

Test Number <sup>1</sup>	Temperature (°C)	Ignition Delay (seconds) <sup>3</sup>	Results <sup>4</sup>
11IS65	874 ± 35	-	NI
11.1IS65	874 ± 35	-	NI
12IS65	869 ± 36	-	NI
12.1IS65	869 ± 36	-	NI
13IS65	899 ± 25	-	NI
13.1IS65	899 ± 25	-	NI
14IS65	887 ± 25	67	I
14.1IS65	893 ± 25	-	NI
15IS65	850 ± 35	-	NI
15.1IS65	850 ± 35	-	NI
16IS65	926 ± 18	18	I
17IS65	878 ± 20	-	NI
17.1IS65	878 ± 20	-	NI
18IS65	873 ± 20	-	NI
18.1IS65	873 ± 20	-	NI

1-The test number identifies the run number, configuration ,i.e., IS is inclined surface and the length of the nichrome tape in millimetres.

2- The highest temperature from the time-temperature curve, which was obtained as described in section 3.3.3.

3- Ignition delay is the time lag between the exposure of the gas to the ignition source and the subsequent ignition.

4- The results are either ignition (I) or no ignition (NI).

**Table 19.1.** Results of the tests related to the inclined Nichrome strip 65mm long, temperature group into bands.

<b>Temperature Band - °C</b>	<b>Ignitions</b>	<b>Non-ignitions</b>	<b>Probability of Ignition</b>
<b>800-870</b>		1IS65	0
		15IS65	
		15.1IS65	
<b>870-890</b>		11IS65	0
		11.1IS65	
		12IS65	
		12.1IS65	
		17IS65	
		17.1IS65	
		18IS65	
<b>890-920</b>	5IS65	2IS65	0.53
	8.1IS65	2.1IS65	
	9IS65	5.1IS65	
	9.1IS65	8IS65	
	9.2IS65	13IS65	
	10IS65	13.1IS65	
	10.1IS65	14.1IS65	
	14.1IS65		
<b>920-940</b>	4IS65		1
	4.1IS65		
	6IS65		
	6.1IS65		
	7IS65		
	7.1IS65		
	16IS65		
<b>980-1,000</b>	3IS65		1
	3.1IS65		
	3.2IS65		

**Table 21.** Results of the tests related to the 'local confinement' configuration 10mm deep (see also Table 21.1).

<b>Test Number<sup>1</sup></b>	<b>Temperature (°C)</b>	<b>Ignition Delay (seconds)<sup>3</sup></b>	<b>Results<sup>4</sup></b>
13ACC10	969 ± 8.0	23	I
15ACC10	940 ± 4.0	85	I
17ACC10	906 ± 22	105	I
24ACC10	900 ± 7.0	60	I
25ACC10	860 ± 7.0	-	NI
25.1ACC10	860 ± 7.0	-	NI
26ACC10	942 ± 18	68	I
26.1ACC10	942 ± 18	68	I
27ACC10	885 ± 17	-	NI
27CC10	895 ± 17	59	I
27.1CC10	889 ± 17	53	I
27.2CC10	892 ± 17	55	I
28.1ACC10	901 ± 17	-	NI
28CC10	888 ± 37	82	I
28.1CC10	888 ± 37	82	I
29ACC10	910 ± 22	120	I
29CC10	882 ± 31	75	I
30ACC10	894 ± 6.0	-	NI
30CC10	879 ± 25	94	I
30.1CC10	852 ± 8.0	76	I
30.2CC10	849 ± 15	101	I
31CC10	864 ± 32	-	NI

Test Number <sup>1</sup>	Temperature (°C) <sup>2</sup>	Ignition Delay (seconds) <sup>3</sup>	Results <sup>4</sup>
32CC10	838 ± 5.0	-	NI
33CC10	853 ± 23	-	NI
34CC10	862 ± 24	-	NI
34.1CC10	862 ± 24	-	NI
35CC10	877 ± 6.0	-	NI
35.1CC10	877 ± 6.0	-	NI
36CC10	880 ± 15	-	NI
36.1CC10	880 ± 15	-	NI
81ACC10	840 ± 40	-	NI
82ACC10	877 ± 40	-	NI
83ACC10	894 ± 28	120	I
83.1ACC10	894 ± 28	-	NI
112ACC10	871 ± 20	-	NI
113ACC10	857 ± 30	-	NI

1-The test number identifies the run number, configuration, i.e. CC is 'confined configuration' also referred to as 'local confinement' and the depth of the cavity (Figure 2).

2- The highest temperature from the time-temperature curve, which was obtained as described in section 3.3.3.

3- Ignition delay is the time lag between the exposure of the gas to the ignition source and the subsequent ignition.

4- The results are either ignition (I) or no ignition (NI).

**Table 21.1.** Results of the tests related to the 'local confinement' configuration 10mm deep, temperature group into bands.

<b>Temperature Band - °C</b>	<b>Ignitions</b>	<b>Non-ignitions</b>	<b>Probability of Ignition</b>
<b>840-880</b>	30CC10	25ACC10	0.19
	30.1CC10	25.1ACC10	
	30.2CC10	31CC10	
		32CC10	
		33CC10	
		34CC10	
		34.1CC10	
		35CC10	
		35.1CC10	
		81ACC10	
		88ACC10	
		112ACC10	
		113ACC10	
<b>880-900</b>	24CC10	27ACC10	0.62
	27CC10	30ACC10	
	27.1CC10	36ACC10	
	27.2CC10	36.1CC10	
	28CC10	83.1ACC10	
	28.1CC10		
	29CC10		
	83ACC10		
<b>900-940</b>	15ACC10	28ACC10	0.83
	17ACC10		
	26ACC10		
	26.1CC10		
	29ACC10		

**Table 22.** Results of the tests related to the 'local confinement' configuration 20mm deep (see also Table 22.1).

Test Number <sup>1</sup>	Temperature (°C) <sup>2</sup>	Ignition Delay (seconds) <sup>3</sup>	Results <sup>4</sup>
33CC20	894 ± 15	-	NI
34CC20	905 ± 32	96	I
34.1CC20	905 ± 32	96	I
35CC20	903 ± 3.0	85	I
35.1CC20	903 ± 3.0	85	I
36CC20	899 ± 13	-	NI
37CC20	857 ± 7.0	79	I
38CC20	868 ± 17	102	I
38.1CC20	868 ± 17	102	I
39CC20	858 ± 22	-	NI
40CC20	883 ± 24	89	I
41CC20	871 ± 30	-	NI
42CC20	873 ± 13	-	NI
42.1CC20	873 ± 13	-	NI
43CC20	852 ± 32	-	NI
44CC20	849 ± 30	58	I
45CC20	872 ± 8.0	120	I
46CC20	871 ± 16	-	NI
47CC20	871 ± 28	-	NI
48CC20	855 ± 11	91	I
49CC20	862 ± 5.0	120	I
50CC20	877 ± 34	73	I

Test Number <sup>1</sup>	Temperature (°C) <sup>2</sup>	Ignition Delay (seconds) <sup>3</sup>	Results <sup>4</sup>
51CC20	868 ± 19	107	I
52CC20	883 ± 18	120	I
53CC20	873 ± 28	-	NI
54CC20	892 ± 25	110	I
55CC20	886 ± 21	-	NI
56CC20	878 ± 8.0	113	I
56.1CC20	878 ± 8.0	113	I
60CC20	841 ± 26	110	I
61CC20	816 ± 17	-	NI
62CC20	836 ± 21	-	NI
63CC20	871 ± 10	-	NI
64CC20	875 ± 12	-	NI
65CC20	863 ± 21	-	NI
66CC20	866 ± 15	110	I
66.1CC20	866 ± 15	110	I
67CC20	882 ± 30	-	NI
68CC20	875 ± 4.0	97	I
69CC20	849 ± 15	-	NI
70CC20	842 ± 23	-	NI
71CC20	880 ± 24	87	I
80CC20	842 ± 17	-	NI
84CC20	834 ± 30	-	NI
85CC20	841 ± 4.0	-	NI
86CC20	838 ± 12	-	NI
87CC20	839 ± 9.0	-	NI

- 1-The test number identifies the run number, configuration; i.e. CC is 'confined configuration' also referred to as 'local confinement' and the depth of the cavity (Figure 2).
- 2- The highest temperature from the time-temperature curve, which was obtained as described in section 3.3.3.
- 3- Ignition delay is the time lag between the exposure of the gas to the ignition source and the subsequent ignition.
- 4- The results are either ignition (I) or no ignition (NI).

**Table 22.1.** Results of the tests related to the 'local confinement' configuration 20mm deep, temperature group into bands.

<b>Temperature Band - °C</b>	<b>Ignitions</b>	<b>Non-ignitions</b>	<b>Probability of Ignition</b>
<b>820-840</b>		61CC20	0
		62CC20	
		84CC20	
		86CC20	
		87CC20	
<b>840-860</b>	37CC20	39CC20	0.4
	44CC20	43CC20	
	48CC20	69CC20	
	60CC20	70CC20	
		80CC20	
		85CC20	
<b>860-880</b>	38CC20	41CC20	0.57
	38.1CC20	42CC20	
	45CC20	42.1CC20	
	49CC20	46CC20	
	50CC20	47CC20	
	51CC20	53CC20	
	56CC20	63CC20	
	56.1CC20	64CC20	
	66CC20	65CC20	
	66.1CC20		
	68CC20		
	71CC20		
<b>880-905</b>	40CC20	33CC20	0.64
	52CC20	36CC20	
	54CC20	55CC20	
	34CC20	67CC20	
	34.1CC20		
	35CC20		
	35.1CC20		

**Table 23.** Results of the tests related to the 'local confinement' configuration 40mm deep (see also Table 23.1).

<b>Test Number<sup>1</sup></b>	<b>Temperature (°C)<sup>2</sup></b>	<b>Ignition Delay (seconds)<sup>3</sup></b>	<b>Results<sup>4</sup></b>
57CC40	786 ± 16	-	NI
58CC40	817 ± 8.0	-	NI
59CC40	832 ± 12	99	I
72CC40	823 ± 14	-	NI
73CC40	839 ± 10	119	I
74CC40	832 ± 25	70	I
74.1CC40	836 ± 25	75	I
75CC40	845 ± 29	-	NI
76CC40	845 ± 24	-	NI
77CC40	833 ± 25	109	I
77.1CC40	833 ± 25	-	NI
78CC40	816 ± 32	-	NI
79CC40	838 ± 19	-	NI
88CC40	833 ± 40	112	I
88.1CC40	834 ± 40	119	I
89CC40	818 ± 40	80	I
89.1CC40	827 ± 40	99	I
90CC40	797 ± 27	98	I
90.1CC40	808 ± 27	107	I
91CC40	817 ± 21	120	I
91.1CC40	814 ± 21	113	I
92CC40	814 ± 17	-	NI

Test Number <sup>1</sup>	Temperature (°C) <sup>2</sup>	Ignition Delay (seconds) <sup>3</sup>	Results <sup>4</sup>
93CC40	801 ± 19	-	NI
94CC40	787 ± 15	-	NI
95CC40	801 ± 7.0	119	I
96CC40	823 ± 23	119	I
97CC40	797 ± 20	-	NI
98CC40	801 ± 15	120	I
99CC40	818 ± 20	116	I
100CC40	806 ± 10	-	NI
101CC40	783 ± 23	-	NI
102CC40	807 ± 9.0	-	NI
103CC40	813 ± 18	-	NI
104CC40	803 ± 9.0	-	NI
105CC40	797 ± 14	-	NI
106CC40	800 ± 10	97	I
107CC40	802 ± 15	-	NI
108CC40	785 ± 7.0	-	NI
109CC40	771 ± 10	-	NI
110CC40	769 ± 17	-	NI

1-The test number identifies the run number, configuration, i.e. CC is 'confined configuration' also referred to as 'local confinement' and the depth of the cavity (Figure 2).

2- The highest temperature from the time-temperature curve, which was obtained as described in section 3.3.3.

3- Ignition delay is the time lag between the exposure of the gas to the ignition source and the subsequent ignition.

4- The results are either ignition (I) or no ignition (NI).

**Table 23.1.** Results of the tests related to the 'local confinement' configuration 40mm deep, temperature group into bands.

<b>Temperature Band - °C</b>	<b>Ignitions</b>	<b>Non-ignitions</b>	<b>Probability of Ignition</b>
<b>770-790</b>		57CC40	0
		94CC40	
		101CC40	
		108CC40	
		109CC40	
		110CC40	
<b>790-810</b>	90CC40	93CC40	0.42
	90.1CC40	97CC40	
	95CC40	100CC40	
	98CC40	102CC40	
	106CC40	104CC40	
		105CC40	
		107CC40	
<b>810-830</b>	89CC40	58CC40	0.54
	89.1CC40	72CC40	
	91CC40	78CC40	
	91.1CC40	92CC40	
	96CC40	103CC40	
	99CC40		
<b>830-850</b>	59CC40	75CC40	0.64
	73CC40	76CC40	
	74CC40	77.1CC40	
	74.1CC40	79CC40	
	77CC40		
	88CC40		
	88.1CC40		

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## Chapter 4

### 4. Simple Mathematical Model - Open Configuration

#### 4.1 Scope and Objectives

This section considers the qualitative and quantitative analysis of the ignition process by a heated surface in an open configuration.

Previous experimental works which were published had different objectives. As a result different experimental procedures were adopted, but some observations appear to be common to them all. The qualitative and quantitative analysis presented in this section is based on some of these aspects.

#### 4.2 Description of the Mechanism

Ignition is a transition from a nonreacting to a reacting state in which external stimuli lead to thermochemical runaway followed by a rapid transition to self-sustained combustion [1]. The ignition process is very complex and involves many intricate physical and chemical steps. In order to predict or interpret the ignition process, detailed chemical kinetics must be known, however the measurement of species concentration in a short time interval is very difficult. As a result, the mechanism of chemical kinetics during the ignition process is not known in advance. The development of an

interpretation of the ignition mechanism presented in the following paragraphs is supported by the experimental data available.

Concerning the practical aspects of ignition by a heated surface, the following sequence of events may take place:

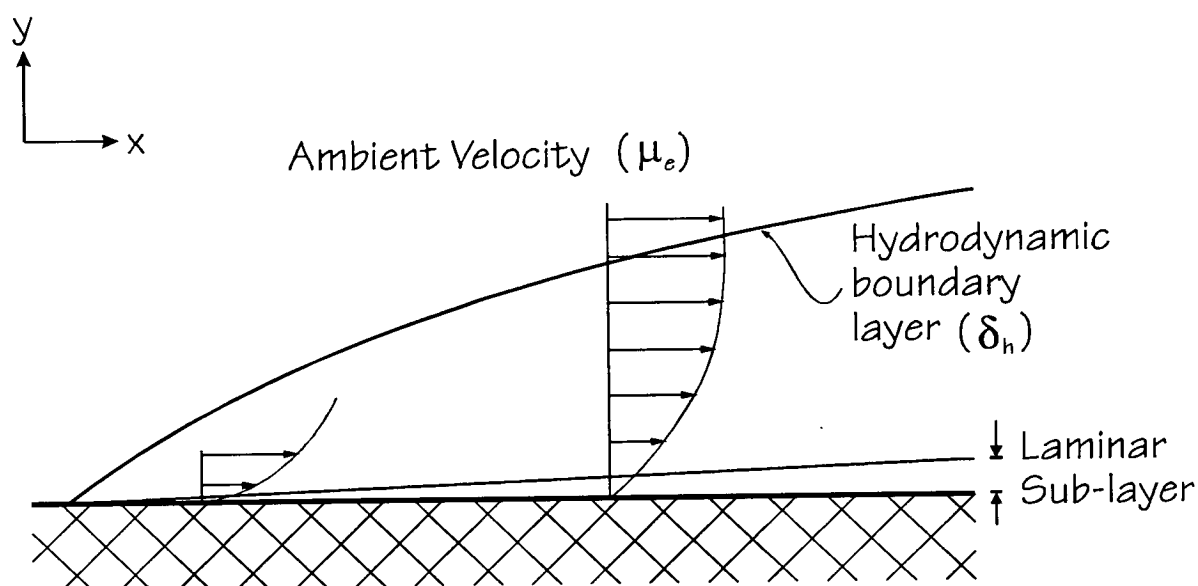
#### **A) Heating the surface**

The electrical energy that is supplied to the ignition source is converted into heat. The ignition source was heated electrically by a constant voltage for the required heating period (as defined in Table 9). Typical temperature-time curves are shown in Figures 22, 23 and 24. The ignition source is heated to a high temperature and as a consequence the adjacent gas layer which is initially at ambient temperature is also heated.

#### **B) The path of contact between the gas and the heated surface**

Before examining the mechanism of heat transfer to the gas, it will be helpful to discuss briefly the concept of "boundary layers". Figure 35 illustrates the concept of a hydrodynamic boundary layer. Consider a flat, thin, rigid stationary plate situated parallel to the flow in a stream of isothermal fluid flowing at a velocity  $u_e$ . At the wall, there is no relative motion between the fluid and the solid surface; this is the "no slip" condition. Frictional viscous forces tend to retard the motion of the fluid in a thin layer near the wall. In that thin layer the velocity of the fluid increases from zero at the wall to its "free stream" value ( $u_e$ ), which corresponds to the external frictionless flow. The layer under consideration is known as hydrodynamic boundary layer. For small values of  $x$  the flow within the boundary layer is

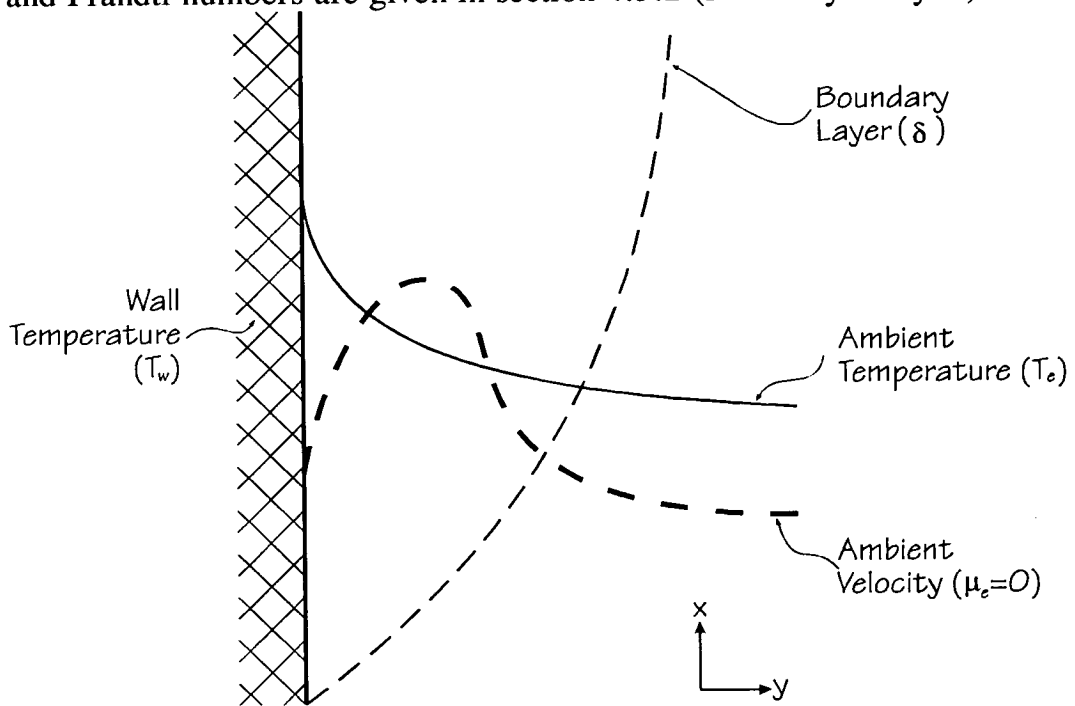
laminar, but this could develop turbulence, although a laminar sublayer will always exist near the surface. In addition to the hydrodynamic boundary layer if the fluid and the plate are at different temperatures, there is also a thermal boundary layer. The concept of the thermal boundary layer is very similar to the hydrodynamic boundary layer except that the thickness of the thermal boundary layer is smaller. In the context of the present work the thickness of the hydrodynamic boundary layer will be assumed to be equal to that of the thermal boundary layer. And they will be referred to from now on simply as the boundary layer. This assumption is roughly true for convective flows [2].



**Figure 35.** Flow and hydrodynamic boundary layer [2].

A thin flat plate whose temperature is  $T_w$  is shown in Figure 36 standing vertically in a infinite stagnant medium of gas ( $u_e=0$ ) at a temperature  $T_e < T_w$ . If one measures the temperature of the mixture as a function of the distance from the surface one observes that an increase in velocity occurs in the boundary layer. The density of the heated gas in the boundary layer is lower than the ambient density. Due to the decreased density in the boundary layer, the local fluid rises upward, inducing an upward flow. Such an

upward flow a near heated surface is known as free convective flow. If one measures the upward velocity, one discovers that it is zero at  $x=0$ , reaches a maximum somewhere in the boundary layer and falls to the ambient value ( $u_e=0$ ) at a distance far way from the wall. The flow field is strongly dependent on the temperature. The thickness of the boundary layer is defined as the distance from the wall beyond which the velocity is unmeasurable close to the 'free stream' value, i.e.  $u(y)=0.99u_e$  [3]. The thickness of the free convective boundary layer at any value of  $x$  can be estimated by an analysis of the energy equation in the boundary layer. Thus, the free convective boundary layer thickness is inversely proportional to the Grashof and the Prandtl numbers [2] (see equation 4.15). The definitions of Grashof and Prandtl numbers are given in section 4.3.2 (similarity analysis).



**Figure 36.** Approximate profiles of a free convective boundary layer about a vertical surface [2].

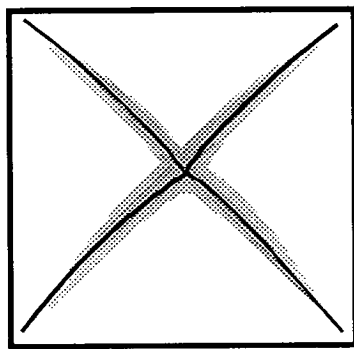
The previous studies which are summarized in Table 9 suggest that the way in which the flammable mixture comes into contact with the heated surface plays a role in the ignition mechanism.

Husar and Sparrow [4] made a visual study of the patterns of free convection flow adjacent to horizontal upward heated surfaces. They used various planforms such as square, rectangle and triangle, to study the influence of the shape of the heated surface on the free convection flow field. They found that there occurs a partitioning of the flow field with the partitions very nearly coinciding with the bisectors of the angles of the planforms. These behaviour are illustrated in Figure 37. In the case of the rectangle, the central partition is a longitudinal symmetry line. The authors stated that there is no flow across a partition line, and in fact, each partition line is the central element of a vertical ascending buoyant plume. The partition lines are created by the interaction of the flows streaming inward along the plate surface from the separate edges, and the flows in each separated region of the plate could be independent of one another. They noticed that the flow within the partitioned sections moves inward in a parallel path, perpendicular to the edge of the plate. When the flow approaches the region of the partition lines, it is formed into a vertical ascending buoyant plume. Also the flow field in each of the partitioned-off sections of the plates appears to be a mirror-image of that in the neighbouring one.

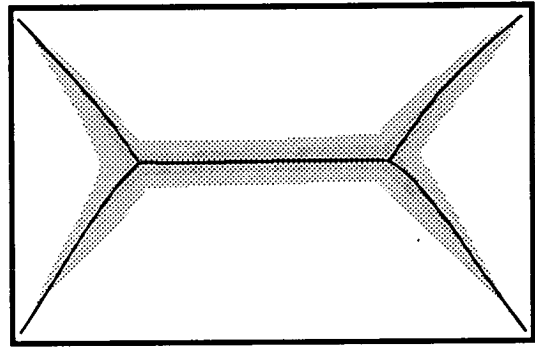
For the square planform, the fluid moves inward from the sides and the upward flow takes place at the centre of the plate [4]. With increase of the angle of inclination with the horizontal the position of upward flow is shifted from the centre to the upper edge; when the angle exceeds about 10 degrees

with the horizontal the position of the upward flow is at the trailing edge of the plate [5,6].

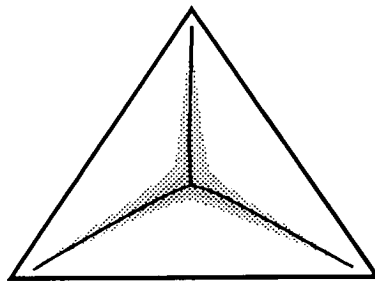
The study carried out by Wragg and Loomba [7] to describe the free convection of heat and mass transfer at horizontal upward facing electrodes, draws attention to the fact that the diameter of the electrodes is an important factor in determining the convection behaviour. A representation of the probable velocity and concentration profiles at any point in the boundary layer before the ascending plume, which generally occurs in the case of smaller diameter electrodes, according to Wragg and Loomba is reproduced in Figure 38.



Square  
(Husan & Sparrow)

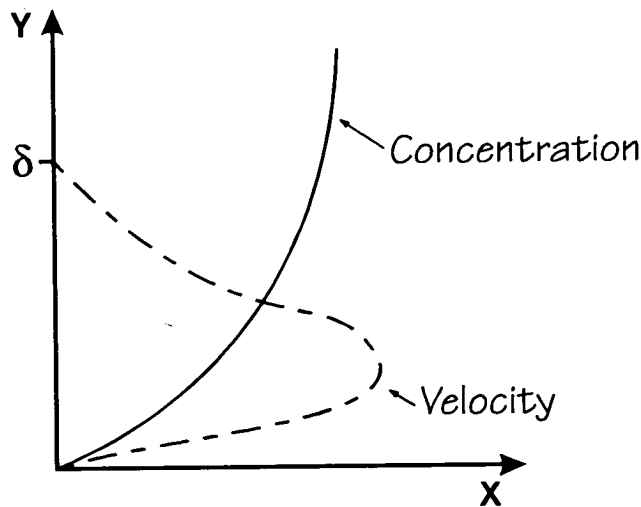


Rectangle  
(Husan & Sparrow)



Triangle  
(Husan & Sparrow)

**Figure 37.** Partitioning and flow patterns of the flow field [4].



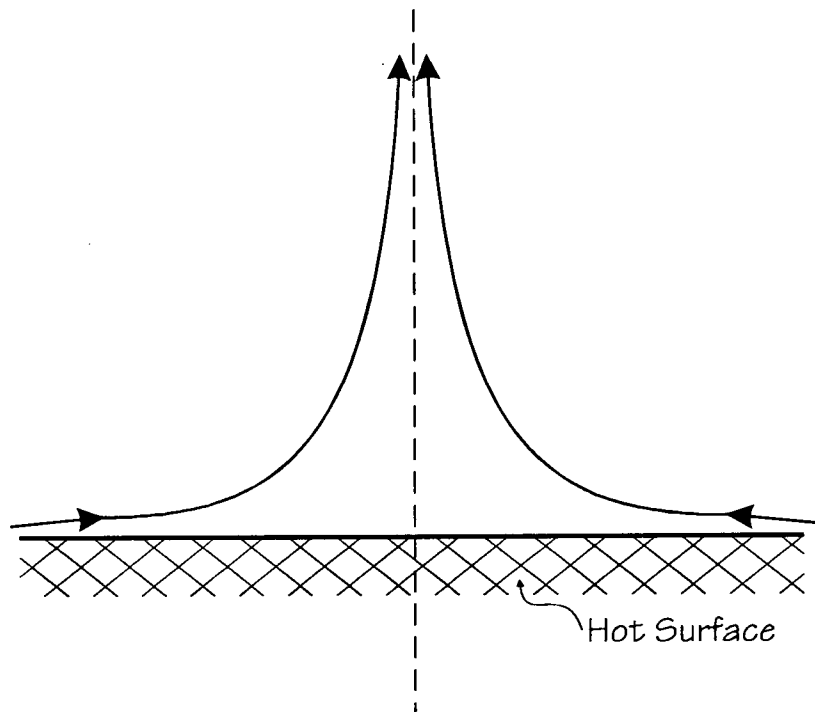
**Figure 38.** Approximate velocity and concentration profiles of a free convective boundary layer of a small diameter electrode [7].

The published works for ignition by heated surface were not able to draw a clear line between the influence of the width and the length of the ignition source. Instead, some have suggested that the ignition source area is a fundamental variable, but in all cases the ignition source area was increased by increasing its width. The ignition temperature was found to increase as the width decreased. In the present work the heated surface area was increased by increasing its length. The results showed that by increasing the length while the width is kept constant the ignition temperatures obtained were similar. This leads to the conclusion that the width rather than either the area or the length of the surface should be considered as the characteristic length.

The following sequence of events based on what was mentioned above was adopted.

A boundary layer is formed at the surface of the Nichrome tape in the open configuration. Fresh mixture comes into contact with the solid surface as it

moves at right angles to the length, Figure 39. It forms a buoyant plume above the centre line of the strip. The temperature of the strip is at a maximum at the mid-point, and it is expected that it will be above the mid-point that chemical reaction will first be initiated and that ignition will occur. Therefore, an upward bulk motion of the mixture, a chemical reaction and a flux of fresh mixture entrainment are established in this boundary layer, while the rest of the mixture outside the boundary layer is not affected by these processes.



**Figure 39.** Flow patterns of a horizontal upward facing heated surface.

### C) The Van't Hoff criterion

The so-called Van't Hoff ignition criterion is shown in Figure 15. Curve 1 represents heat transfer into the surrounding boundary layer before ignition. Curve 3 represents the temperature-time profile near the surface

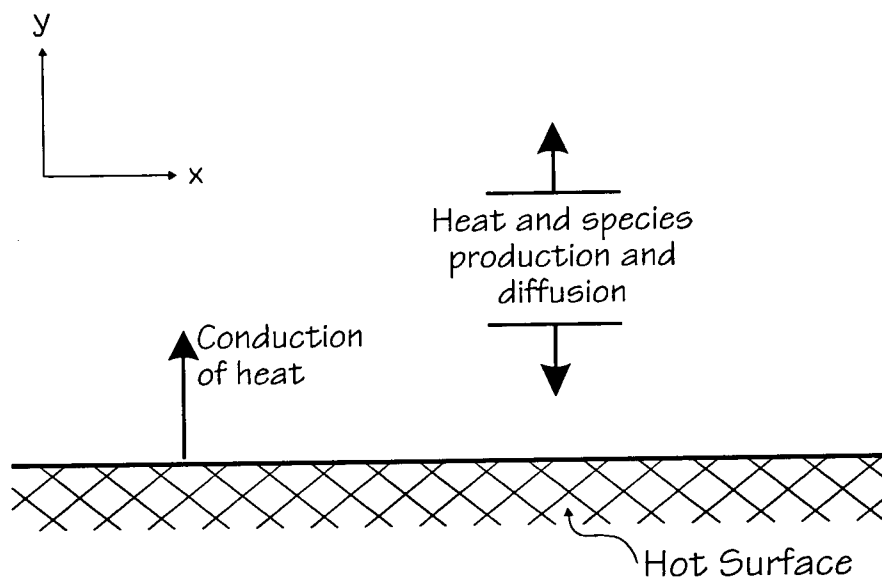
when chemical reaction has been initiated in the boundary layer. Curve 2 represents the ignition criterion. The idea expressed in curve 2 is that ignition by a hot body takes place when the temperature gradient in the gaseous medium near the wall, i.e.,  $(dT/dx)_w$ , becomes greater than zero. The limiting condition of the stationary state is  $(dT/dx)_w = 0$ , unless the wall possesses catalytic properties. This condition implies that there is no flow of heat from the wall to the gas and that the heat released by the reaction near the wall is sufficient to compensate for the quantity of heat lost to the surrounding unheated gaseous medium, i.e., the chemical heat flux is equal to the loss heat flux. The heated wall merely brings the adjacent gas layer to a temperature such that an additional increment of temperature causes local spontaneous ignition with formation of a flame which then spreads in all directions from the heated body through the flammable mixture.

#### **D) Heat Exchanged Between the Gas and the Heated Surface**

Heat is transferred whenever there is a temperature gradient, from the region of higher temperature. Heat will flow by conduction from the surface to the adjacent laminar sublayers of the gas near the surface, thus heat transfer ceases when there is no longer a temperature gradient in the boundary layer. The high temperature in the boundary layer causes chemical reactions to occur at a significant rate. As a result, both a convective flow and a chemical reaction are established in the boundary layer, while the mixture outside the boundary layer is at rest in the free convection system.

The time interval between the exposure of the gas to the heated surface and the subsequent ignition, will be referred to as ignition delay. It depends on the temperature of the solid surface and fluid properties, such as heat capacity, thermal conductivity and absolute viscosity.

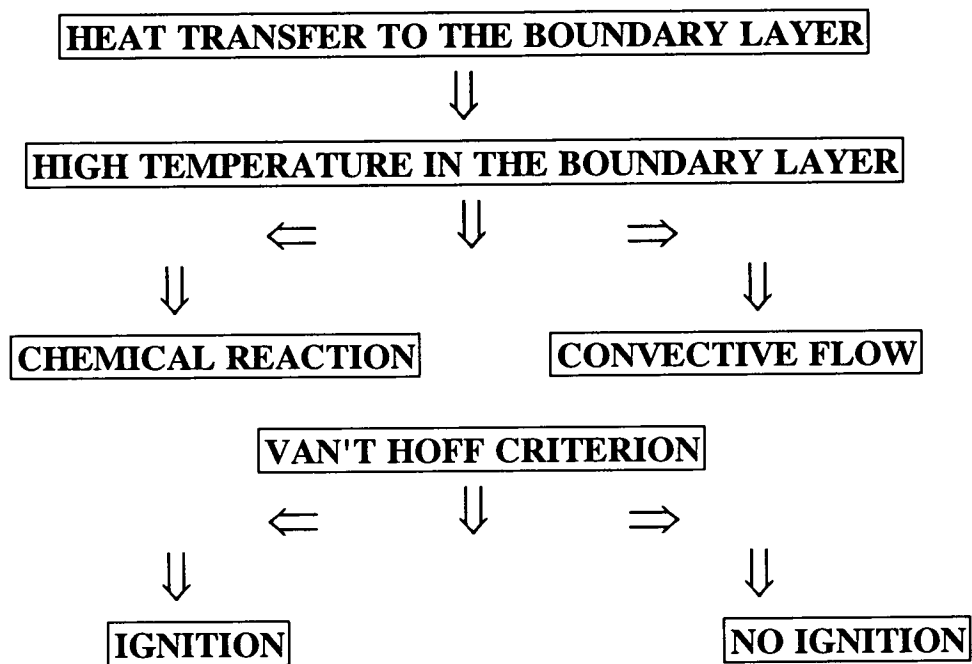
The mechanism of heat and mass exchange between the flammable mixture and the heated surface is very complex. It is not intended here to give a comprehensive treatment. Only some of the variables will be considered, to allow an understanding of the ignition process. Figure 40 shows a schematic diagram of the ignition model, which will be described quantitatively in next the section.



**Figure 40.** Schematic diagram of the physical ignition model.

The sequence of events by which a flammable mixture is ignited by a heated surface has been a matter of speculation and has suffered several reinterpretations in the light of various experimental works. The present

work reopens the discussion. The sequence of events which would lead to the ignition of a flammable mixture is shown in Figure 41.



**Figure 41.** Schematic diagram of the sequence of events of the ignition model.

## 4.3 Simple Mathematical Model

### 4.3.1 Nomenclature

A	frequency factor $\{[(\text{moles}/\text{m}^3)]^{n-1}\text{sec}^{-1}\}$
$C_i$	mass fraction of $i$ th chemical species
$C_{p,i}$	heat capacity at constant pressure of $i$ th chemical species- Joule/(mole K)
$C_p$	heat capacity at constant pressure, per unit mass -Joule/(mole K) $\left( C_p = \sum_i^N C_i C_{p,i} \right)$
$D_1$	First Damkohler number
$\overline{D_1}$	Modified First Damkohler number, defined as $\overline{D_1} = D_1 e^{\frac{-E}{RT_w}}$
$D_2$	Second Damkohler number
$D_{1,2}$	binary coefficient of diffusion - $\text{m}^2/\text{sec}$
E	activation energy - Joule/mole
$E^*$	dimensionless activation energy
g	gravitational acceleration - $\text{m}/\text{sec}^2$
h	static enthalpy, defined as $h = \sum_i^N C_i h_i$ - Joule/mole
$h^*$	dimensionless static enthalpy
$h_i$	enthalpy of $i$ th chemical species - Joule/mole
$h_i^0$	standard enthalpy of formation of $i$ th chemical species - Joule/mole
$h_e$	ambient enthalpy - Joules /mole
$h_w$	enthalpy of the gas - Joules /mole
i	$i$ th chemical species

K	thermal conductivity of the gas - [Joules/(m K sec)] (evaluated at the local surface temperature)
L	characteristic length (width) - m
L*	dimensionless characteristic length (width)
m <sub>f</sub>	partial order with respect to fuel
m <sub>O</sub>	partial order with respect to oxidizer
N	total number of chemical species present
n	overall reaction order - $n = m_f + m_O$
P	pressure - atm
Pr	Prandtl number, defined as $(\gamma_w / \alpha)$
Q	heat of combustion - Joule/mole
q <sub>ch</sub>	chemical heat flux - [Joule/(m <sup>2</sup> sec)]
q <sub>loss</sub>	heat loss flux - [Joule/(m <sup>2</sup> sec)]
r <sub>f</sub>	molar reaction rate - [moles/(m <sup>3</sup> sec)]
R	gas constant
T	temperature - K
T <sub>e</sub>	ambient temperature - K
T <sub>w</sub>	wall temperature or ignition temperature - K
u	velocity - m/sec
V <sub>i</sub>	scalar diffusion velocity of ith chemical species - m/sec
x,y	spatial coordinate
X <sub>f</sub>	ambient mole fraction of fuel
X <sub>O</sub>	ambient mole fraction of oxidizer
$\alpha$	thermal diffusivity - m <sup>2</sup> /sec
$\gamma_w$	kinematic viscosity of the wall - m <sup>2</sup> /sec
$\delta$	boundary layer thickness - m

$\theta$	dimensionless wall temperature or dimensionless ignition temperature
$\rho$	density - moles/m <sup>3</sup>
$\rho_e$	ambient density - moles/m <sup>3</sup>

### 4.3.2 Similarity Analysis

The similarity analysis rests on the postulate that the real laws of nature cannot depend on the choice of the system of units of measurement. Thus, any real law can be represented in the form of a relation between dimensionless parameters.

Based on the similarity analysis the following dimensionless parameters are defined:

- a) **Nusselt number** =  $\frac{\text{convective heat transfer}}{\text{thermal conductivity of the gas}}$
- b) **Prandtl number** =  $\frac{\text{kinematic viscosity}}{\text{thermal diffusivity}}$
- c) **Schmidt number** =  $\frac{\text{kinematic viscosity}}{\text{diffusion coefficient}}$
- d) **Lewis number** =  $\frac{\text{rate of energy transport}}{\text{rate of mass transport}} = \frac{\text{Prandtl number}}{\text{Schmidt number}}$
- e) **Reynold number** =  $\frac{\text{inertia forces}}{\text{viscous forces}}$
- f) **Grashof number** =  $\frac{\text{buoyancy forces X inertia forces}}{\text{viscous forces}^2}$
- g) **Biot number** =  $\frac{\text{external resistance of heat convection}}{\text{internal resistance of heat conduction}}$

The physical properties of the medium in which the transfer of heat and mass takes place are characterized by the Prandtl and Schmidt numbers. The

character of the motion of medium in forced convection and natural convection is represented by the Reynolds and Grashof numbers respectively.

The similarity parameters presented are of relative importance in non-reactive mixtures. In reacting mixtures two additional variables are required to describe a process: heat of reaction and the source term describing the kinetics of the mixture. In real systems the kinetics are described by a number of elementary reactions, and an equal number of dimensionless parameters are required. The present analysis was simplified by considering one overall reaction, which was assumed to be representative of the chemical kinetics of the process. The similarity parameters that characterize the chemical changes in the process are the First and Second Damkohler numbers [8,9].

$$D_1 = \frac{\text{convective time}}{\text{chemical time}} \quad \text{where convective time} = \frac{\text{boundary layer thickness}}{\text{velocity}} \quad \text{and}$$

$$\text{chemical time} = \frac{\text{density}}{\text{molar reaction rate}}$$

$$D_2 = \frac{\text{heat addition by chemical reaction}}{\text{heat associated with convection of enthalpy}}$$

The convective time refers to the period of time that the mixture remains in the reaction zone, and the chemical time is the effective duration of the reaction. If  $D_1 \ll 1$  the convective time is much shorter than the chemical time, and the mixture does not have time to react. If  $D_1 \gg 1$  the chemical time is much shorter than the convective time, and reaction is possible.

The other dimensionless parameters which are used in the next sections are:

$$D_1 = \frac{\delta r_f}{u \rho}$$

$$\overline{D_1} = D_1 e^{\frac{-E}{RT_w}}$$

$$D_2 = \frac{Q}{C_p T_e}$$

$$E^* = \frac{E}{RT_e}$$

$$\theta = \frac{T_w}{T_e}$$

$$L^* = \frac{\delta}{L}$$

$$h^* = \frac{h_w}{h_e}$$

### 4.3.3 Mathematical Description

A rigorous mathematical description of the ignition process always results in a series of complex equations for which no analytical solution exists. On the other hand, to obtain an analytical solution, an unrealistically simplistic approach is required in which so many factors are neglected that a reasonable understanding of the phenomenon cannot be achieved. Nevertheless, the objective of the present mathematical description is to find a simple model with which it is possible to evaluate the ignition temperature due to a heated surface. The form of this mathematical interpretation is supported by the experimental data available. The variables included in the present mathematical formulation which are required to estimate the ignition temperature can be found in the literature.

The steady-state analysis presented in this section is an expansion of the original work of Khitrin and Goldenberg [10] and similar contributions by Adomeit [11,12], Alkidas and Durbetaki [13,14], Laurendeau [9] and Kumar [15]. The basic premise of this development is the so-called Van't Hoff ignition criterion as shown in Figure 15. This condition states that a combustible mixture near the non-catalytic surface of a hot body will ignite when the temperature gradient normal to the wall is zero. It implies that ignition will occur when the heat lost to the surroundings is equal to the heat generated by the chemical reaction. The physical meaning can be understood by considering the heat transfer process resulting when a reactive mixture comes in contact with a hot surface. Due to the higher temperature of the wall, heat will be transferred to the gas, resulting in an increase of the gas temperature. This temperature rise will bring about an increase in the self-heating of the gas, where the rate of heat release by chemical reaction is proportional to the exponential term  $e^{\frac{-E}{RT}}$ . The heat generated in turn will further raise the temperature of the gas, thus reducing the net flux from the wall. Hence the adiabatic condition of the wall is an indication that the temperature in the boundary layer of the mixture has risen sufficiently to sustain chemical reaction.

The applicability of the Van't Hoff criterion is consistent with the work done by Adomeit [12], Alkidas and Durbetaki [13,14,15], Law [17-20] and Laurendeau[13].

Adomeit [12] measured the temperature field surrounding a rapidly heated 3-4mm diameter chromium-nickel rod using a Mach-Zehnder interferometer. The temperature profiles immediately before, during and after ignition were

similar to those shown in Figure 15, in accordance with the Van't Hoff criterion.

Alkidas and Durbetaki [13,14,15] found a good agreement between the Van't Hoff approach and the numerical results obtained by examining steady state solutions to the conservation equations in the transition region between frozen and equilibrium flow.

Law [17-20] developed an analytical steady-state solution for both stagnation point ignition [17] and ignition by a stationary particle [18]. In both cases, the flowfield surrounding the particle could be divided into two regions, an inner diffusive-reactive zone near the hot surface and an outer diffusive-convective zone away from the hot surface. A Damkohler number ignition criterion was developed which proved to be independent of the momentum equation and thus applicable to both stagnant and convective flowfields. The Damkohler number criterion was found to imply zero heat transfer between the surface and the gas and hence to be equivalent to the Van't Hoff criterion.

Laurendeau [9] assessed the ignition temperature by assuming that the energy produced at the surface was independent of the energy lost to the ambient. The energy lost to the ambient was expressed as a function of the Nusselt number. He suggested some expression for the Nusselt number for the case of stagnant mixture, free and forced convection. In these expressions the Nusselt number was constant for the case of stagnant mixture and as function of the characteristic length for the later two cases. The characteristic length was defined as the surface width. The critical condition obtained took into account the Van'Hoff criterion; good agreement between the theoretical and the experimental data was obtained

The mathematical analysis makes use of the following assumptions:

- 1) Ignition can be described by the Van't Hoff criterion.
- 2) The reaction occurs in a thin film at rest near the wall and the temperature drop across the stagnant film is  $T_w - T_e$ .
- 3) The thickness of the thermal boundary layer is the same as the hydrodynamic layer.
- 4) The mechanism of heat transfer is independent of the chemical reaction.
- 5) The chemical kinetics are described by a one-step overall reaction.  $F + \nu_o O_x \rightarrow \nu_p P$  where F,  $O_x$  and P represent fuel, oxidizer and product respectively, and  $\nu_o$  and  $\nu_p$  are the molar stoichiometric coefficient for oxidizer and products. According to Harrison and others [21] the approach of representing the chemical kinetics by a one step reaction for temperature below 500°C is inappropriate. As the temperatures required for ignition of a flammable vapour/air mixture by a hot surface are well above 500°C the one-step overall reaction was assumed.
- 6) The heat capacities are constant with temperature changes.
- 7) The Lewis number is equal to one.

The biggest contribution to the reaction is assumed to be near the wall where the temperature is the highest. The heat transfer at the surface due to chemical reaction was assessed by integrating the energy conservation equation at the moment of ignition.

$$-k \cdot \frac{d^2T}{dy^2} + Q \cdot r_f = 0 \quad \text{equation 4.1}$$

$$r_f = X_f^{m_f} \cdot X_o^{m_o} \cdot \rho^n \cdot A \cdot e^{\frac{-E}{RT}} \quad \text{equation 4.2}$$

Equations 4.1 and 4.2 together define the steady state temperature distribution in the boundary layer. The second term of equation 4.1 is similar to the rate of heat generation per unit volume at temperature T as defined in equation 2.1. Combining equations 4.1 and 4.2,

$$K \cdot \frac{d^2T}{dy^2} = A \cdot X_f^{mf} \cdot X_o^{mo} \cdot Q \cdot \rho^n \cdot e^{\frac{-E}{RT}} \quad \text{equation 4.3}$$

Integrating equation 4.3 with respect to temperature. The appropriate boundary conditions are given by,

$$\begin{aligned} y = 0 & \quad T = T_w \\ y = \delta & \quad T = T_e \end{aligned}$$

$$K \int_0^\delta \left( \frac{d^2T}{dy^2} \right) \left( \frac{dT}{dy} \right) dy = \int_{T_e}^{T_w} A \cdot X_f^{mf} \cdot X_o^{mo} \cdot Q \cdot \rho^n \cdot e^{\frac{-E}{RT}} dT \quad \text{equation 4.4}$$

Since  $\frac{dT}{dy} \left( \frac{d^2T}{dy^2} \right) dy = \frac{1}{2} \frac{d}{dy} \left( \frac{dT}{dy} \right)^2 dy$ , therefore equation 4.4 becomes

$$\frac{K}{2} \left( \frac{dT}{dy} \right)_w^2 = A \cdot X_f^{mf} \cdot X_o^{mo} \cdot Q \cdot \rho^n \cdot \int_{T_e}^{T_w} e^{\frac{-E}{RT}} \cdot dT \quad \text{equation 4.5}$$

But,

$$\rho = \frac{P}{R \cdot \sqrt{T_w \cdot T_e}} \quad \text{and} \quad \rho_e = \frac{P}{R \cdot T_e} \quad \text{equations} \quad 4.6.1$$

$$\int_{T_e}^{T_w} e^{\frac{-E}{RT}} \cdot dT \approx \frac{R \cdot T_w^2}{E} e^{\frac{-E}{RT_w}} \quad \text{equation} \quad 4.6.2$$

(see references [13] and [14])

Using equations 4.6 into equation 4.5 , it became,

$$K \left( \frac{dT}{dy} \right)_w^2 = 2 \cdot A \cdot X_f^{m_f} \cdot X_o^{m_o} \cdot Q \cdot \rho_e^n \left( \frac{T_e}{T_w} \right)^{n/2} \cdot \frac{R \cdot T_w^2}{E} \cdot e^{\frac{-E}{RT_w}} \quad \text{equation 4.7}$$

The heat flux due to the chemical reaction is given by,

$$q_{ch} = K \left( \frac{dT}{dy} \right)_w = \sqrt{2 \cdot K \cdot A \cdot X_f^{m_f} \cdot X_o^{m_o} \cdot Q \cdot \rho_e^n \left( \frac{T_e}{T_w} \right)^{n/2} \cdot \frac{R \cdot T_w^2}{E} \cdot e^{\frac{-E}{RT}}} \quad \text{equation 4.8}$$

For most hydrocarbon  $n = 2$  [9], thus equation 4.8 becomes,

$$q_{ch} = \sqrt{2 \cdot K \cdot A \cdot X_f \cdot X_o \cdot Q \cdot \rho_e^2 \left( \frac{T_e}{T_w} \right) \cdot \frac{R \cdot T_w^2}{E} \cdot e^{\frac{-E}{RT}}} \quad \text{equation 4.9}$$

The mechanism of heat losses is represented mathematically by equation 4.10,

$$q_{\text{loss}} = \underbrace{-K \frac{dT}{dy}}_{\text{conduction}} + \underbrace{\rho \sum_i^N h_i C_i V_i}_{\text{diffusion}} \quad \text{equation 4.10}$$

Assuming the Fick's form for the diffusion  $V_i = \left( \frac{-D_{1,2}}{C_i} \cdot \frac{dC_i}{dy} \right)$ , then equation

4.10 becomes,

$$q_{\text{loss}} = - \left( K \frac{dT}{dy} + \rho \cdot D_{1,2} \sum_i^N h_i \frac{dC_i}{dy} \right) \quad \text{equation 4.11}$$

Where  $h_i = \int_0^T C_{p,i} dT + h_i^0$ . The complete static enthalpy includes both the

thermal and chemical enthalpies [22], and is defined by  $h = \sum_i^N C_i h_i$ , therefore

$$dh = d \overline{C_p} dT + \sum_i^N h_i dC_i \quad \text{where } \overline{C_p} = \sum_i^N C_i C_{p,i} \quad \text{and equation 4.11 for}$$

$q_{\text{loss}}$  is rewritten as follows,

$$q_{\text{loss}} = \underbrace{\frac{-K}{C_p} \left( \frac{dh}{dy} - \sum_0^N h_i \frac{dC_i}{dy} \right)}_{\text{conduction}} + \underbrace{\frac{-K}{C_p} \left( \frac{\rho D_{1,2} \overline{C_p}}{K} \sum_0^N h_i \frac{dC_i}{dy} \right)}_{\text{diffusion}}$$

equation 4.12

In the boundary layer, the temperature rise leads to a chemical reaction which will generate more than one chemical species. When a reacting mixture contains more than one chemical species, the heat energy is transported not only by heat conduction but also by diffusion currents carrying enthalpy [23]. The first and the second term of equation 4.12 expresses the energy flux due to conduction away from the surface and the net energy flux due to the diffusion of chemical species. The term  $\left(\frac{\rho D_{1,2} \overline{C_p}}{K}\right)$  is the Lewis number, which was defined in the previous section. In the case of Lewis number equal to one the convective heat transfer in the boundary layer is independent of the model of the chemical reaction [22].

Assuming,  $\left(\frac{\rho D_{1,2} \overline{C_p}}{K}\right) = 1$ , then

$$q_{\text{loss}} = \frac{-K}{C_p} \left(\frac{dh}{dy}\right) \quad \text{equation 4.13}$$

If  $\left(\frac{dh}{dy}\right)_w \approx \frac{h_e - h_w}{\delta}$  [22], therefore, equation 4.13 becomes

$$q_{\text{loss}} = \frac{-K}{C_p} \left(\frac{h_e - h_w}{\delta}\right) \quad \text{equation 4.14}$$

The flow pattern over a heated surface in the case of a free convection flow approximates to the one expected for the hydrodynamic boundary layer [24], therefore the expression for the boundary layer thickness is defined as follows:

- 1) For the case of free convection by equation 4.15 [2]

$$\delta = 1.681 L \text{Pr}^{-1/4} \left( \frac{\gamma_w^2 \rho}{g L^3 (\rho_e - \rho)} \right)^{1/4} \quad \text{equation 4.15}$$

The dimensionless parameter  $\left( \frac{g L^3 (\rho_e - \rho)}{\gamma_w^2 \rho} \right)$  which appears in the right hand side of equation 4.15 is the Grashof number.

2) For the case of laminar flow by equation 4.16 [25]

$$\delta \approx \sqrt{\frac{\gamma_w L}{u}} \cdot \sqrt{\frac{1}{\text{Pr}}} \quad \text{equation 4.16}$$

According to the Van't Hoff criteria  $q_{\text{ch}} = q_{\text{loss}}$ , then combining equation 4.9 and 4.14 the critical condition of ignition is given by,

$$\sqrt{2 \cdot K \cdot A \cdot X_f \cdot X_o \cdot Q \cdot \rho_e^2 \left( \frac{T_e}{T_w} \right) \cdot \frac{R \cdot T_w^2}{E} \cdot e^{\frac{-E}{RT_w}} = \frac{-K}{C_p} \left( \frac{h_e - h_w}{\delta} \right)}$$

equation 4.17

When the dimensionless parameters ,which were defined in section 4.3.2, enthalpy of the gas ( $h_w = C_p \cdot T_w$ ) , velocity  $\left( u = \frac{2 \alpha}{\delta} [2] \right)$  and the thermal diffusivity coefficient  $\left( \alpha = \frac{K}{\rho C_p} \right)$  are used in equation 4.17, it becomes:

$$\frac{4 \overline{D_1 D_2}}{E^*} \cdot e^{\frac{-E^*}{\theta}} = \left(1 - \frac{1}{h^*}\right)^2 \quad \text{equation 4.18}$$

Equation 4.18 demonstrates that the ignition temperature is determined solely by the first and second Damkohler number, the dimensionless activation energy ( $E^*$ ) and the dimensionless enthalpy ( $h^*$ ).

The influence of the first Damkohler number on ignition temperature and extinction characteristics of initially unmixed gases was first demonstrated by Fendell [26]. He considered the ignition and extinction of a diffusion flame near the stagnation region, when an oxidant is blown from upstream infinity at a fuel reservoir with a surface perpendicular to the stagnation stream-line . A direct one-step second order reaction of the Arrhenius type was used to describe the chemical kinetics of the flow. The flow was assumed to be inviscid. The dependence of the maximum temperature (flame temperature) on the first Damkohler number established the ignition and extinction characteristics. According to him a small First Damkohler number implies a vanishingly small chemical activity, while a large Damkohler number established that an intense chemical reaction occurs. The intermediate values of Damkohler number accounted for the phenomena of ignition and flame extinction.

Despite the simplifying assumptions, when equations 4.15 and 4.17 are applied to the experimental results of Cutler [27,28] (Figures 42, 43) and equations 4.16 and 4.17 to those of Laurendeau [9] (Figure 44), a good correlation was obtained.

Laurendeau [9] mentioned that Lifshitz et al [27] and Tsuboi and Wagner [28] found  $E/R=25,000K$  for methane air mixture at an equivalence ratio  $([fuel/air]/[fuel/air]_{stoich})$  in the range of 0.2 -2.0 and a temperature between  $925^{\circ}C - 1825^{\circ}C$ . For a mixture of 7% methane-air [9,29] the activation energy was assumed to be in the range  $21, 600K < E/R < 26,000K$ . The value for the frequency factor was estimated based on the one suggested by Lewis and von Elbe [31], which is  $A=1.3 \cdot 10^8 \text{ m}^3/(\text{mole second})$ . In the present analysis the frequency factor was assumed to be in the range  $10^7 < A < 2.5 \cdot 10^8 \text{ m}^3/(\text{mole second})$ . The other variables were obtained from Weast [32] and they are listed in the appendix. The error expected was estimated around  $55^{\circ}C$ , based on equation 4.17.

Sharma and Sirignano [33,34], who performed an analytical analysis of the ignition process by a hot surface considering a mixture of 4% propane/air, observed two distinct temperature regimes, i.e. before and after ignition, and estimated the activation energy and frequency factor in the ranges  $39,500 < E < 62,000 \text{ Joule/mole}$  and  $10^4 < A < 3 \cdot 10^7 \text{ m}^3/(\text{mole second})$  respectively. These ranges are somewhat arbitrary since they were chosen in order to justify their model. Due to the lack of information about the activation energy and the frequency factor of the propane, in the present study the activation energy and the frequency factor were estimated in the range of  $39,500 < E < 62,000 \text{ Joule/mole}$  and  $10^5 < A < 3 \cdot 10^7 \text{ m}^3/(\text{mole second})$ . The other variables are listed in the appendix. For Cutler's data [30] the error expected was around  $55^{\circ}C$ . As will be shown in the next section the error expected for the results obtained in the present study was estimated around  $77^{\circ}C$ .

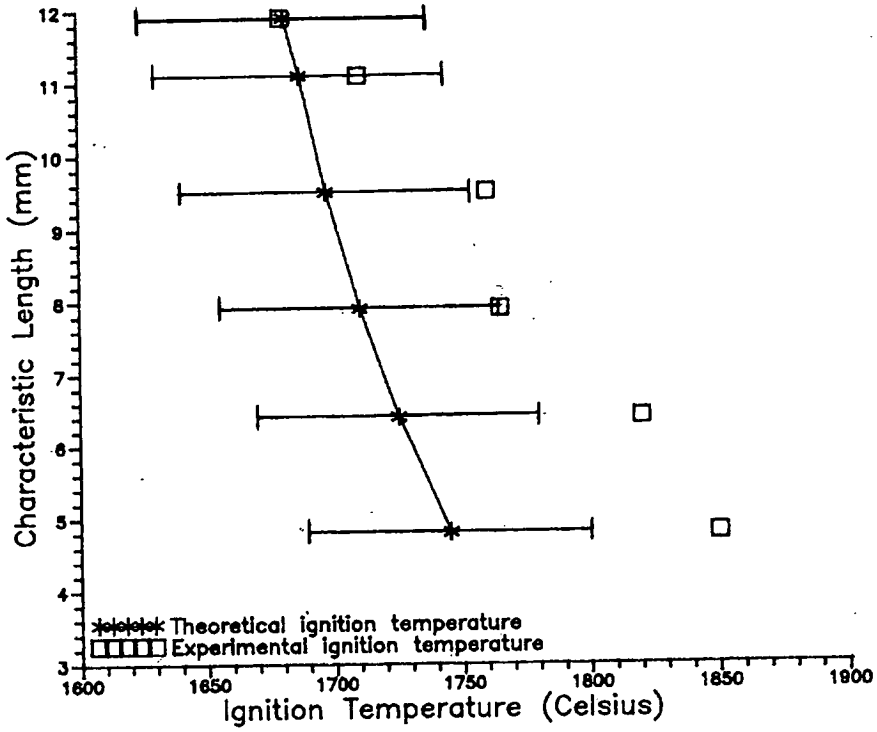


Figure 42. Influence of the characteristic length on the ignition temperature for a static mixture of 7% methane-air [27].

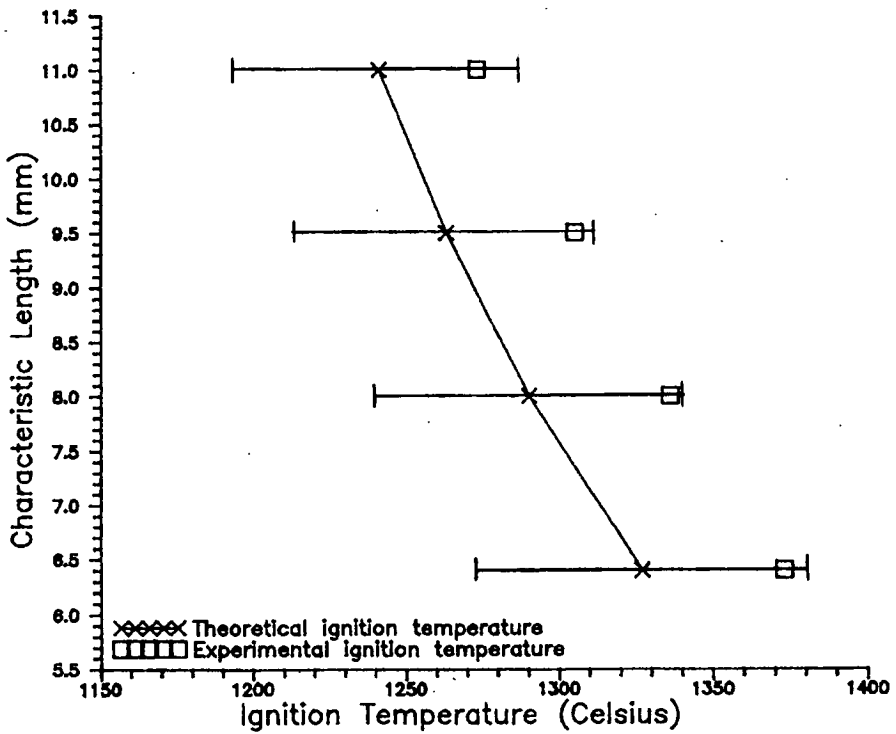


Figure 43. Influence of the characteristic length on the ignition temperature for a static mixture of 3.5% propane-air [28].

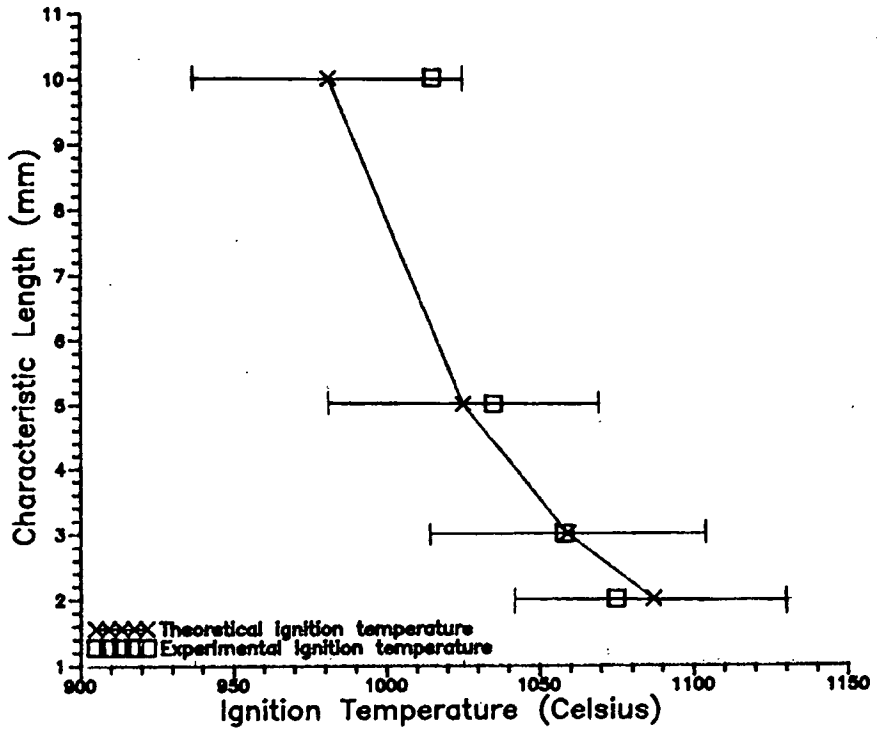


Figure 44. Influence of the characteristic length on the ignition temperature for a flowing mixture of 7% methane-air [9].

## **4.4 Analysis of the results of the present work**

Initially this work had two objectives. Firstly, to investigate how the length and orientation of the ignition source consisting of a heated surface 5mm wide affected the ignition temperature. Secondly, to study the influence of 'local confinement' on the ignition temperature, by placing the heated surface at the base of an unheated cavity.

The theoretical determinations of the ignition temperature obtained with the open configuration will be based on the model proposed and presented in section 4.3. For the results related to the confined configuration a qualitative description is given by the autoignition theory presented in Chapter 2.

### **4.4.1 Open configuration**

A common observation throughout the published works on ignition indicated that the ignition temperature increases as the width of the surface is decreased. The results obtained in an open configuration are presented again in Table 24. They showed that if the surface width is kept the same, its length did not affect the ignition temperature significantly.

### **4.4.2 'Local confinement' configuration**

Although the autoignition theory presented in Chapter 2 (section 2.3) was developed as a model for explosions in static reacting gases inside a closed vessel, it has been used in many areas of practical experience. For example the autoignition theory has proved to be successful in the assessment of hazards due to self-heating ( section 1.2, autoignition). Its application to the

ignition of unconfined gases would not seem to be appropriate as the theory does not take into account convective flow of the reactant mixture.

However, the ignition of the vapour-air mixture within the cavity was treated as a slab, to examine the effect of cavity depth, and compare it with the experimental trends. The same trend was observed (Table 25), but the predicted ignition temperatures are higher than the measured ones. Agreement was not expected in view of the convective flow associated with the ignition process, and in any case the Arrhenius parameters are not known with any certainty. However, as will be seen from the flow pattern and temperature distributions for the 20mm and 40mm deep cavities obtained using a computational fluid dynamics package, a region exists near the mid-point of the heated surface in which the velocity of the mixture was extremely low and within which the flammable vapour/air mixture was maintained at a high temperature.

Having this in mind, it might be possible to model the 'local confinement' conditions using the Frank-Kamenetskii equations, but further computational analysis would be necessary to explore this.

As the experimental result for the 'local confinement' 10mm deep was similar to the one obtained for the horizontal Nichrome strip 45mm long in an open configuration, this study seems to indicate that for the case of 'local confinement' there is a critical depth beyond which the ignition temperature decreases drastically. But in order to verify this more tests are required.

**Table 24.** Ignition temperatures for the open configuration.

<b>Strip Description</b>		<b>Experimental Ignition Temperature °C</b>	<b>Theoretical Ignition Temperature<sup>1</sup> °C</b>
<b>Dimensions mm</b>	<b>Position</b>		
Length: 45 Width: 5	Horizontal	890±10	900±77
Length: 65 Width: 5	Horizontal	905±10	900±77
Length: 65 Width: 5	Inclined 30°	905±15	900±77

1- Equations 4.15 and 4.17 were used.

**Table 25.** Ignition temperatures for the 'local confinement' configuration.

<b>'Local Confinement'</b>	<b>Experimental Ignition Temperature -°C</b>	<b>Theoretical Ignition Temperature -°C</b>
10mm deep	870-890	970
20mm deep	850-870	891
40mm deep	800-820	835

## 4.5 Computational Fluid Dynamics analysis

### Introduction

The experimental results show clearly that 'local confinement' promotes ignition at a hot surface. The explanation for this effect cannot be deduced from the results alone. There are several relevant factors, including:

- (i) The presence of the walls of the cavity reduce the entrainment of cold vapour/air mixture into the buoyant plume rising above the heated surface, thus reducing the rate of cooling of the hot mixture.
- (ii) The insulating cavity will also help to reduce the rate of cooling.
- (iii) The cavity walls inhibit the upward movement of the buoyant gases, thus increasing the 'residence time' (during which the combustion process can develop).

These are difficult to examine experimentally, but by using computational fluid dynamics (CFD) it is possible to analyse the flows set up in the vicinity of the hot strip. This technique has developed rapidly over the last two decades as powerful computers have become available. Computational fluid dynamics has been applied to a large number of industrial problems involving fluid flows (e.g. aerodynamics design of cars, etc), but more recently it has been used successfully to model accident escalation patterns. One such computational fluid dynamics model is Harwell's Flow 3D [35] which was used to study the fire development pattern in the King's Cross underground accident enquiry [36] with great success.

The Harwell Flow 3D software has been developed over a number of years by AEA Technology to simulate laminar and turbulent flow problems for a

wide variety of applications. The Flow 3D software package was used to model the flow patterns and the temperature distribution in the vicinity of the heated Nichrome strip in the 'open configuration' (Nichrome 80 strip 45mm long in the horizontal position, see Figure 2 and Table 16) and in the 'local confinement' conditions corresponding to the cavities 20mm and 40mm deep (see Figure 2 and Table 20).

The full details of the software may be found in references [37,38]. Flow 3D uses a finite-difference or finite-volume representation of the physical laws governing conservation of mass, momentum and energy in three dimensions. With this technique the region of interest is divided into a large number of cells and the Navier-Stokes equations are solved iteratively to give values of the fluid velocity, the pressure and the temperature in each cells, given that suitable boundary and initial conditions have been specified.

### **Assumptions**

In these simulations the following assumptions were made:

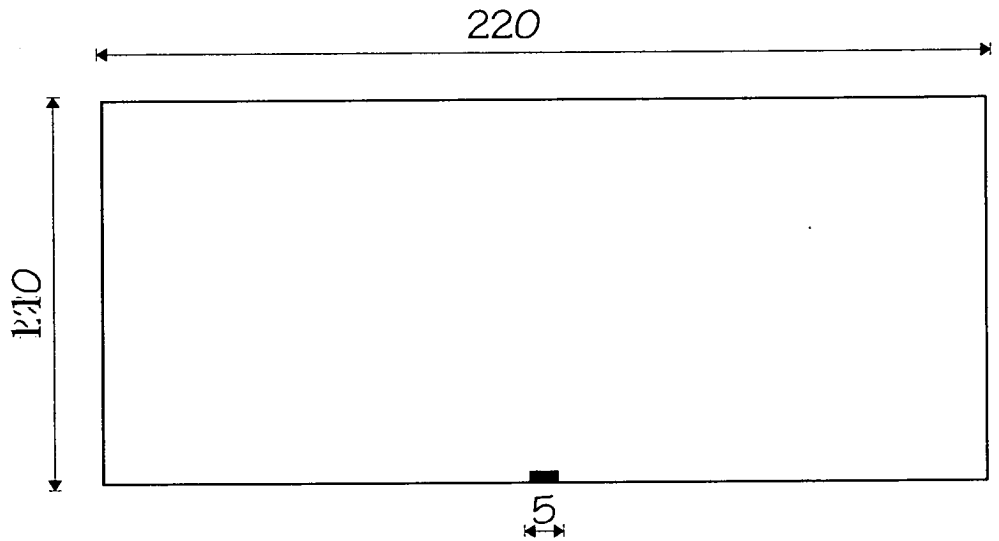
- (i) The steady state condition was achieved before ignition (i.e. it was not necessary to model the combustion process)
- (ii) The walls of the unheated cavity (Figure 2) could be treated as adiabatic (i.e. there was no heat loss through the walls). Radiation effects were not considered.
- (iii) As was mentioned in Section 3.4.2, during the first 20 seconds of the heating period (120 seconds), the temperature rose rapidly to a constant value which was maintained until the end of the heating period. The temperature used in these simulations were the steady state 'ignition temperatures' of the Nichrome strip defined in sections 3.4.2.1 and 3.4.2.2.

(iv) The relevant thermophysical properties of the propane/air mixture could be approximated by those of air.

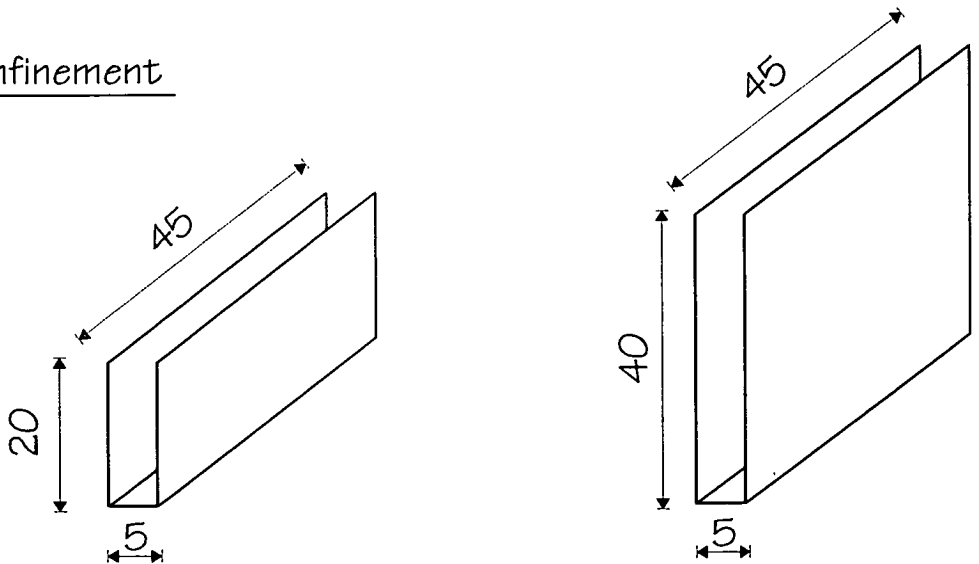
**Geometry representation**

GEOMETRY CONFIGURATION (dims. mm)

Open Configuration



Local Confinement



## Computation Details

The heat transfer model for the buoyant flow utilised the 'Boussinesq' approximation [37]. With this approximation the fluid was assumed to be incompressible. The buoyancy term in the vertical-momentum equation used the simple equation of state to model the influence of temperature upon the density

## Computation Results

The computation gave temperatures in degrees absolute (Kelvin), and are presented as contour maps in Figures 46, 50 and 54. The contours are spaced at 15K (note that the temperatures in the text are in degrees Celsius (°C)). The scaled velocity vectors are displayed in Figures 45, 48, 49, 52 and 53, the velocities given in m/sec.

### Open Configuration run

The characteristic dimension of the heat source was chosen to be the width of the Nichrome, since the experimental results gave a clear indication that the width is a fundamental variable in the ignition process. In the computational fluid dynamics simulation, it was assumed that the flows could be considered in two dimensions in a plane at right angles to the major axis of the strip.

In this run the predicted flow pattern and velocity (Figure 45) and the predicted temperature contours (Figure 46), are seen to confirm the

mechanism described qualitatively in Section 4.2. In particular the flow pattern of the horizontal upward facing heated surface as shown in Figure 39 which should be compared with Figure 45.

It is difficult to identify a 'boundary layer' in these results, but Figure 46 shows that the temperature of the heated vapour/air mixture is greater than 745°C for a vertical distance of approximately 1.5mm. The corresponding residence time of vapour/air mixture entrained into the base of the buoyant column of gas cannot be estimated with any certainty, but it will be of the order of 50msec.

#### 'Local confinement' runs

In these simulations the 'local confinement' results corresponding to the cavities 20mm deep and 40mm deep were considered. The flow was examined in three dimensions within the rectangular space defined by the cavity.

#### 20mm deep cavity run

The results related to the 20mm deep cavity simulation are shown in Figures 47-50.

Figure 47 shows a section through the mesh, in which the x-axis lies along the long axis of the nichrome and the y-axis is perpendicular to the plane of the strip.

Figures 48 and 49a show the velocity contours and the flow pattern respectively. They indicate that there is a central region close to the strip where the velocity is extremely low: This is also shown in Figure 49b which

is the vertical plane at right angles to the centre line of Figure 49a. These low velocities should be compared with the velocity of incoming gas through the ends of the cavity (Figure 49a).

The flammable mixture flowing into both ends of the cavity forms boundary layers which interact towards the centre producing a near-stagnant region, while turning to form a single vertical plume. The 'residence time' of the vapour/air mixture in the high temperature region is influenced by this flow pattern (Figure 49), as well as by the factors itemised on page 172.

The temperature contour curves (Figure 50) show that in the regions regarded as 'boundary layers' the gas temperature is high ( $>733^{\circ}\text{C}$ ).

#### 40mm deep cavity run

The results related to the 40mm deep cavity simulation are shown in Figures 51-54.

Figure 51 shows a section through the mesh, in which the x-axis lies along the long axis of the nichrome and the y-axis is perpendicular to the plane of the strip.

Figures 52 and 53 show the velocity contours and the flow pattern respectively. These figures show the same relatively stagnant central region formed by the inflow of mixture from both ends of the cavity. The results are qualitatively similar to those from the 20mm cavity, except that there appear to be regions of recirculation approximately 28mm above the hot surface (Figure 53). This may be a real effect, but to ensure that it was not a result of the computational grid size, further work would be necessary.

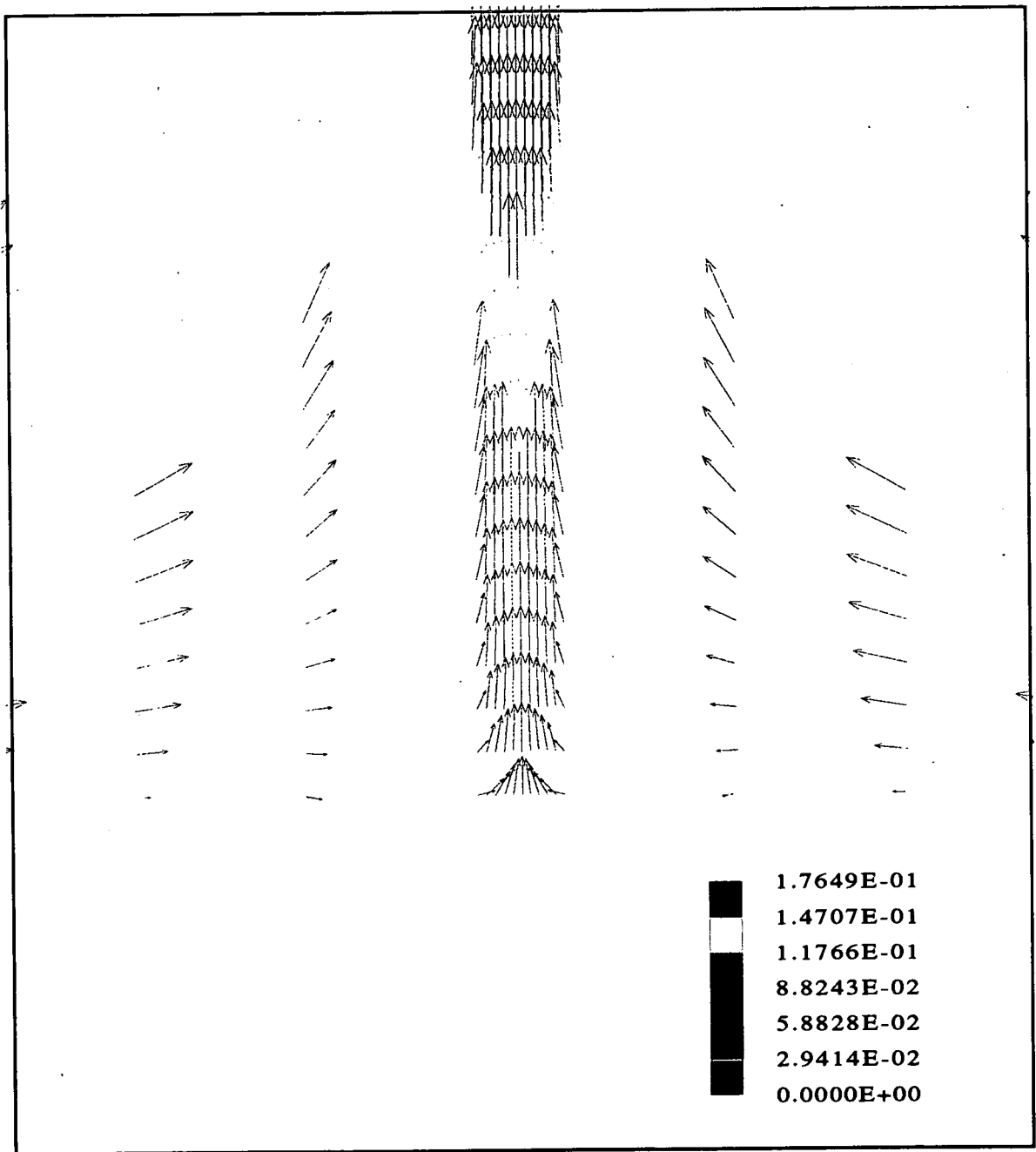
Figure 54 shows that the temperature in the regions regarded as the 'boundary layer' is high, ensuring relatively long residence times for the flammable vapour/air mixture in the region of high temperature.

## **Discussion**

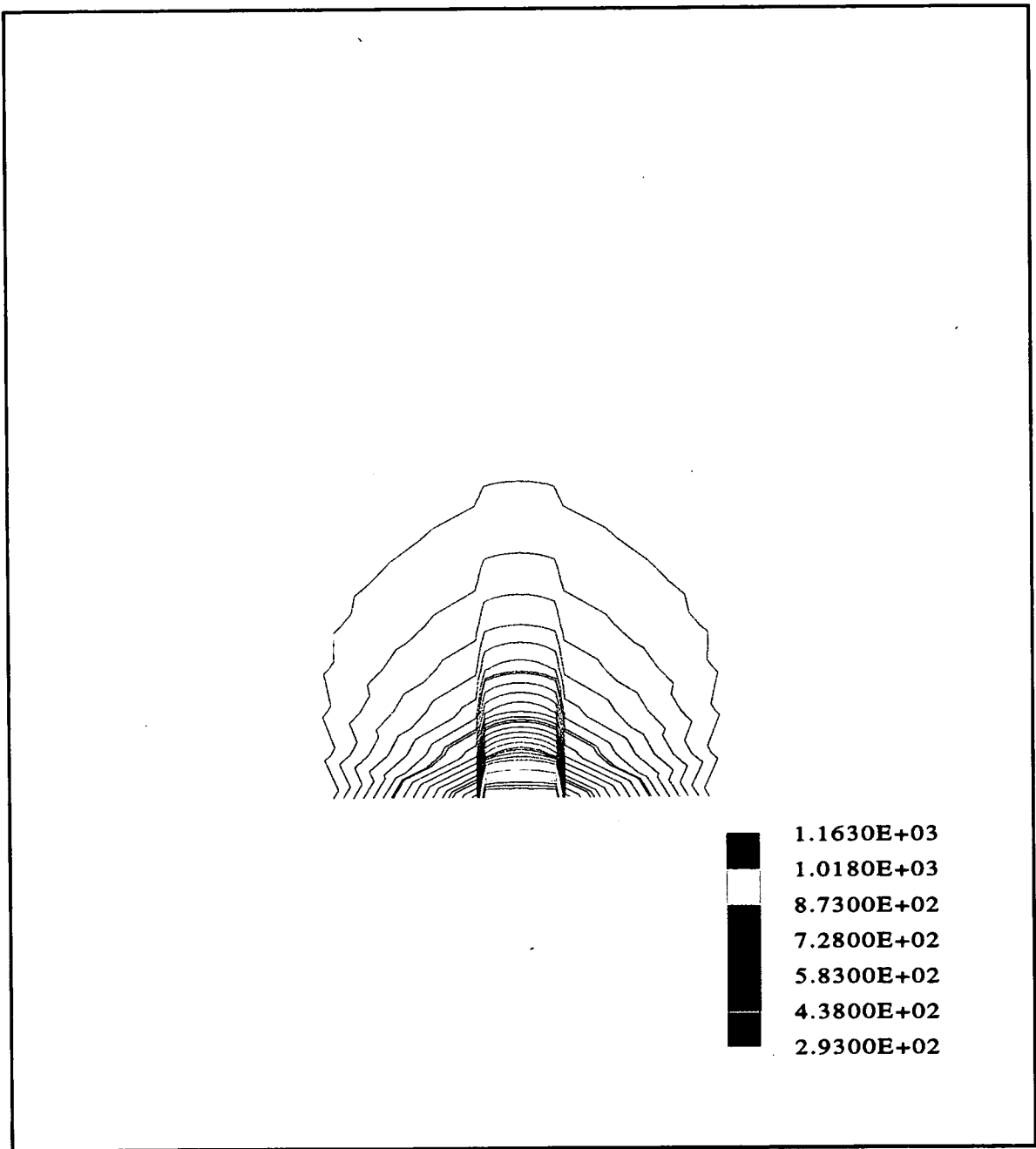
The results from the computational fluid dynamics calculations show marked differences between the flow patterns in the open configuration and the configuration of 'local confinement' (compare Figures 45 and 49b). With 'local confinement', the flows of vapour/air mixture within the cavity provide much longer residence times during which the combustion process develop. In qualitative terms, this will permit ignition to occur at lower temperatures, if ignition is interpreted as a critical value of the First Damkohler number, which is the effectively the ratio of the 'residence time' to the 'chemical time' (see page 155).

The flow pattern within the confined space is complex , indicating that the mechanism leading to ignition is complex. More experimental and computational work is necessary to resolve these details. Further discussion of the results is presented in the next Chapter.

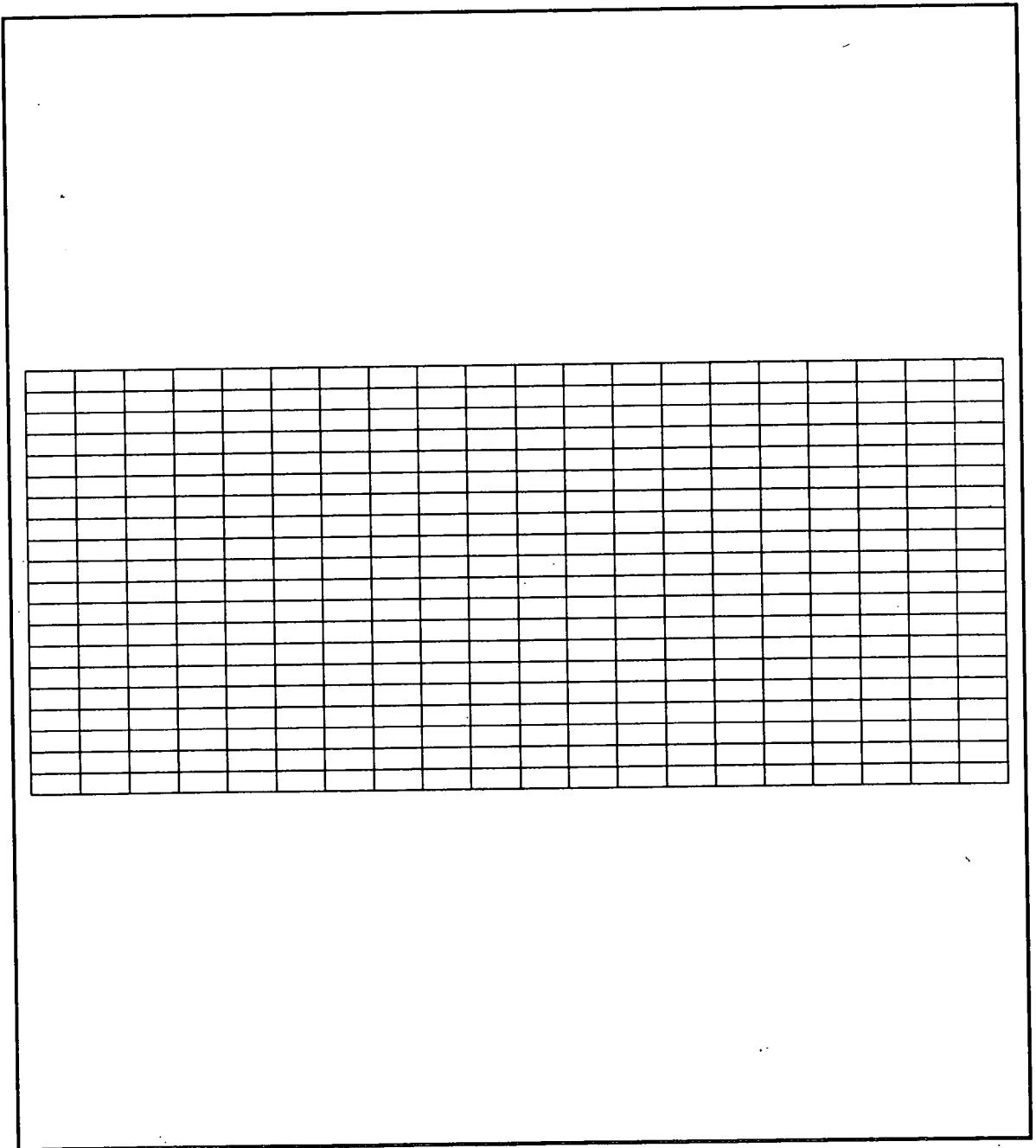
**Figure 45.** Predicted flow pattern and velocity on the open configuration.



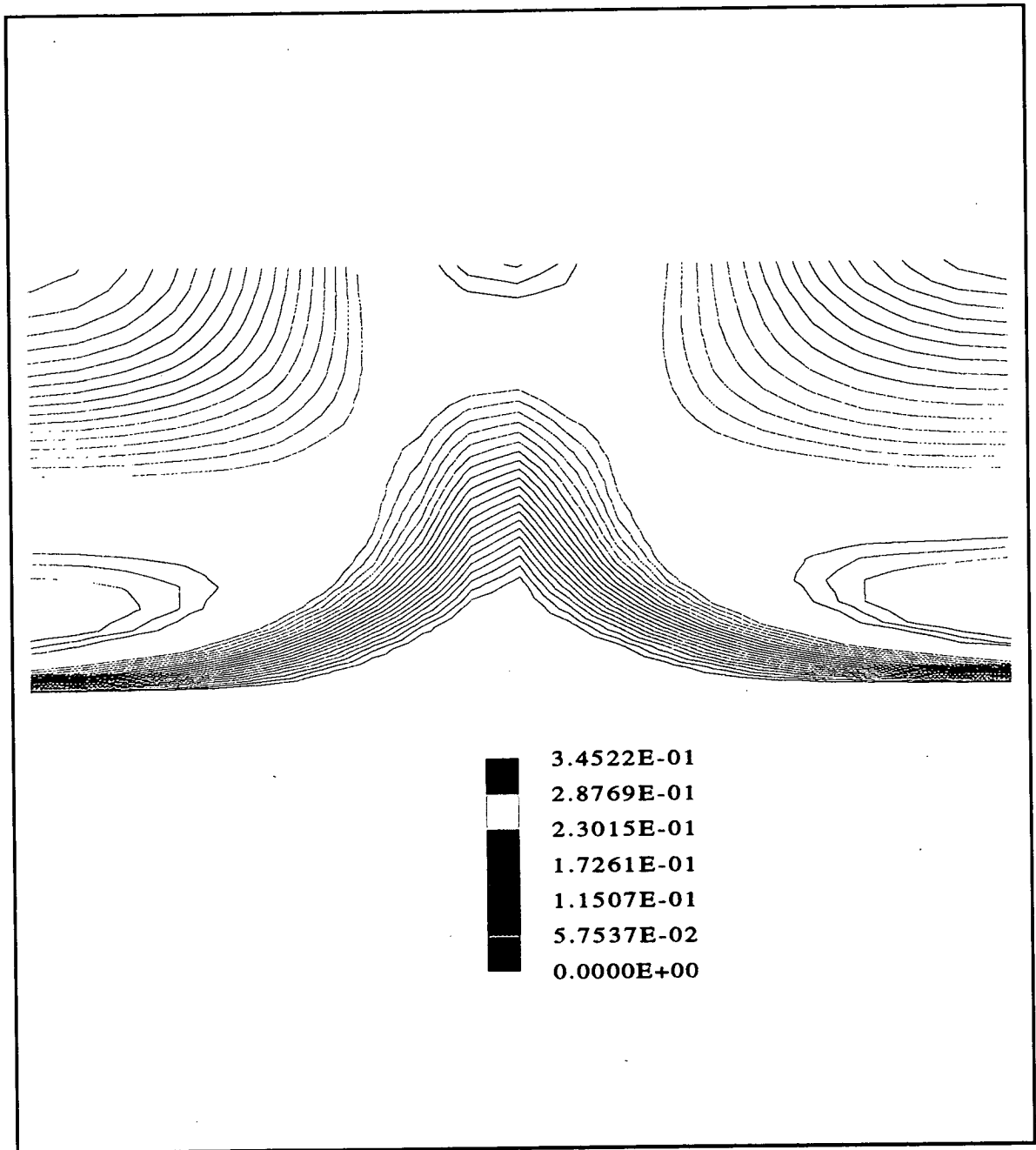
**Figure 46. Predicted temperature contours on the open configuration.**



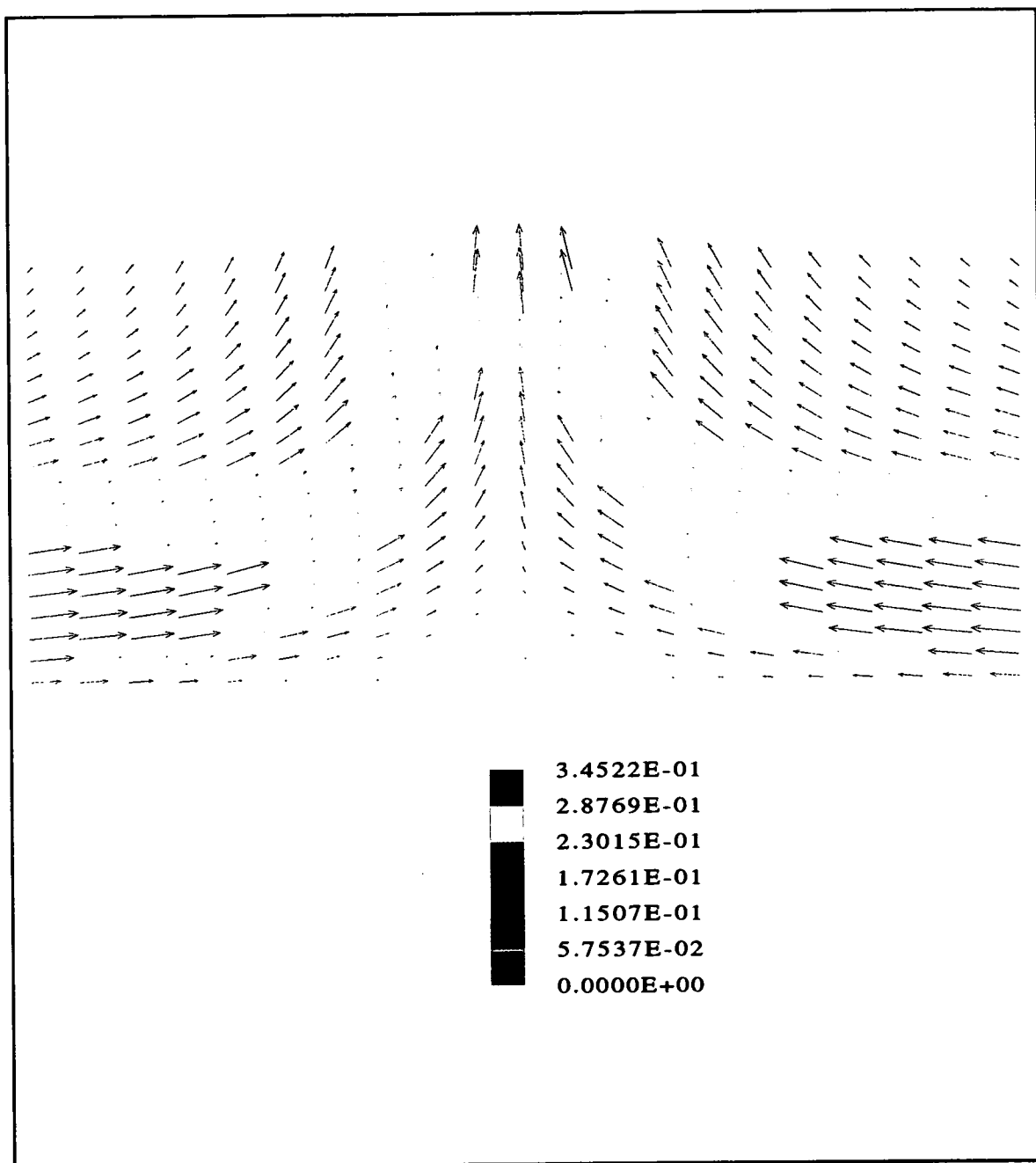
**Figure 47.** Mesh of the 20mm deep cavity.



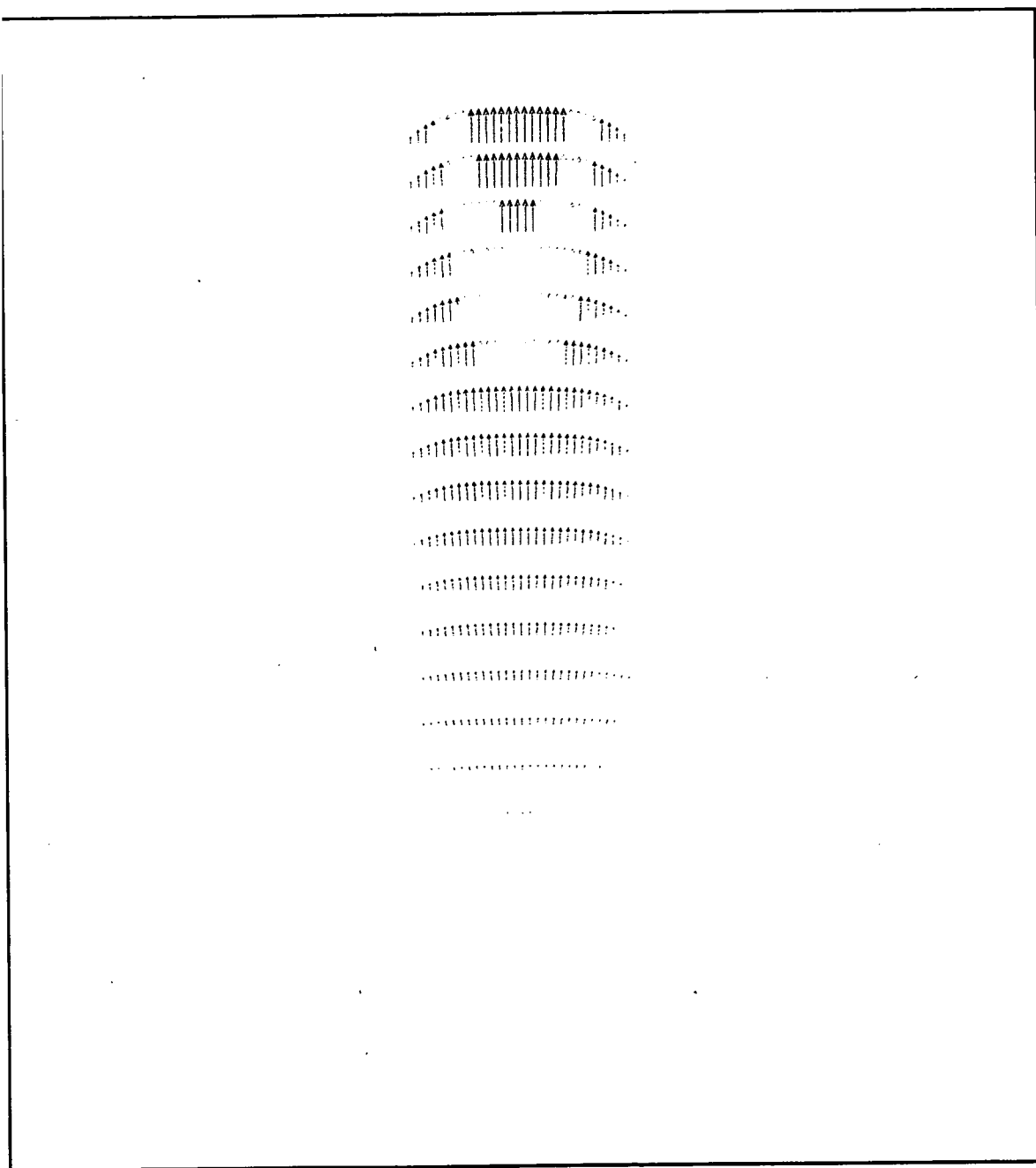
**Figure 48.** Predicted velocity contours on the 20mm deep cavity.



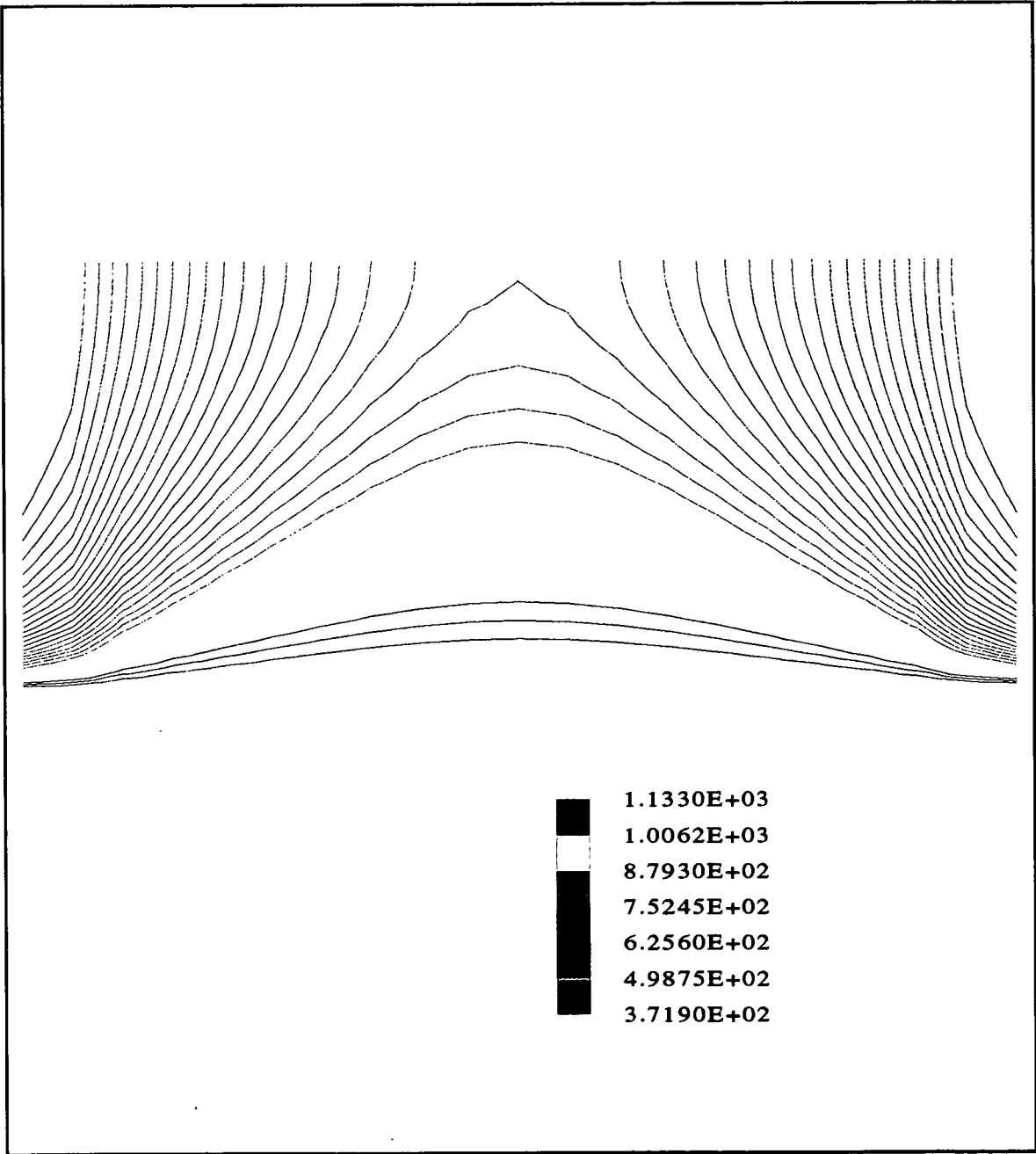
**Figure 49a.** Predicted flow pattern on the 20mm deep cavity.



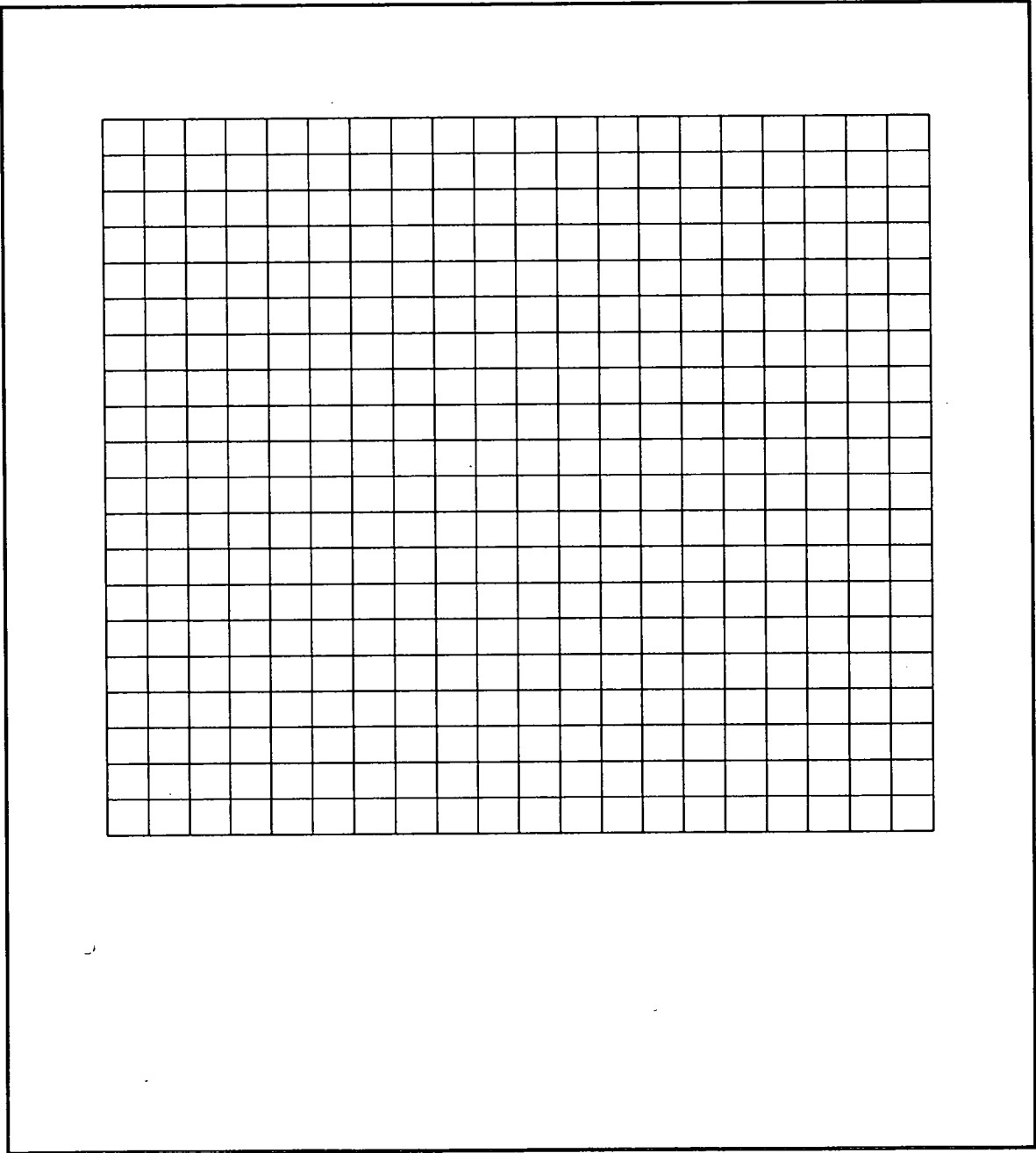
**Figure 49b.** Predicted flow pattern on the 20mm deep cavity (vertical plane at right angles to the centre line of Figure 49a).



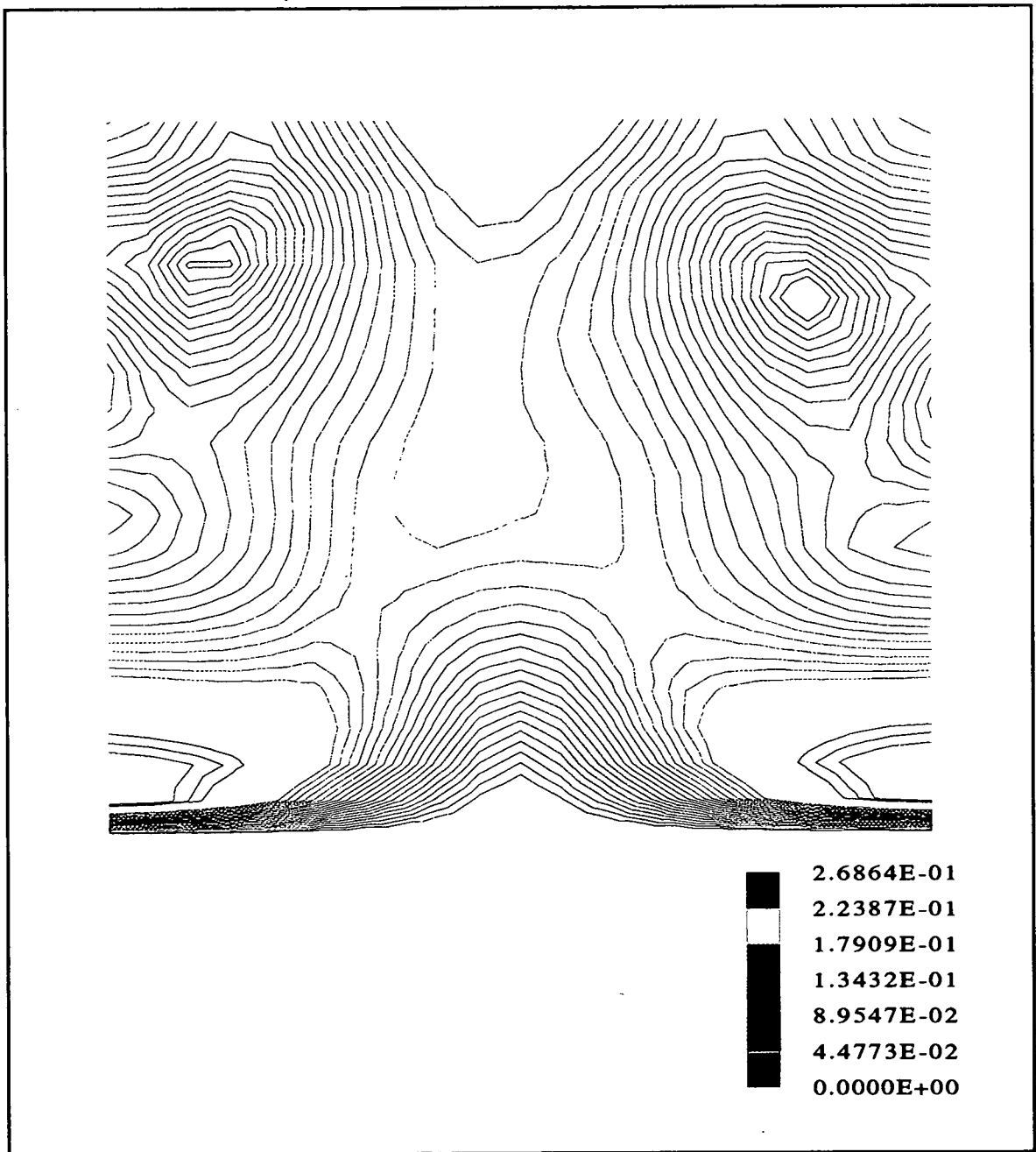
**Figure 50.** Predicted temperature contours on the 20mm deep cavity.



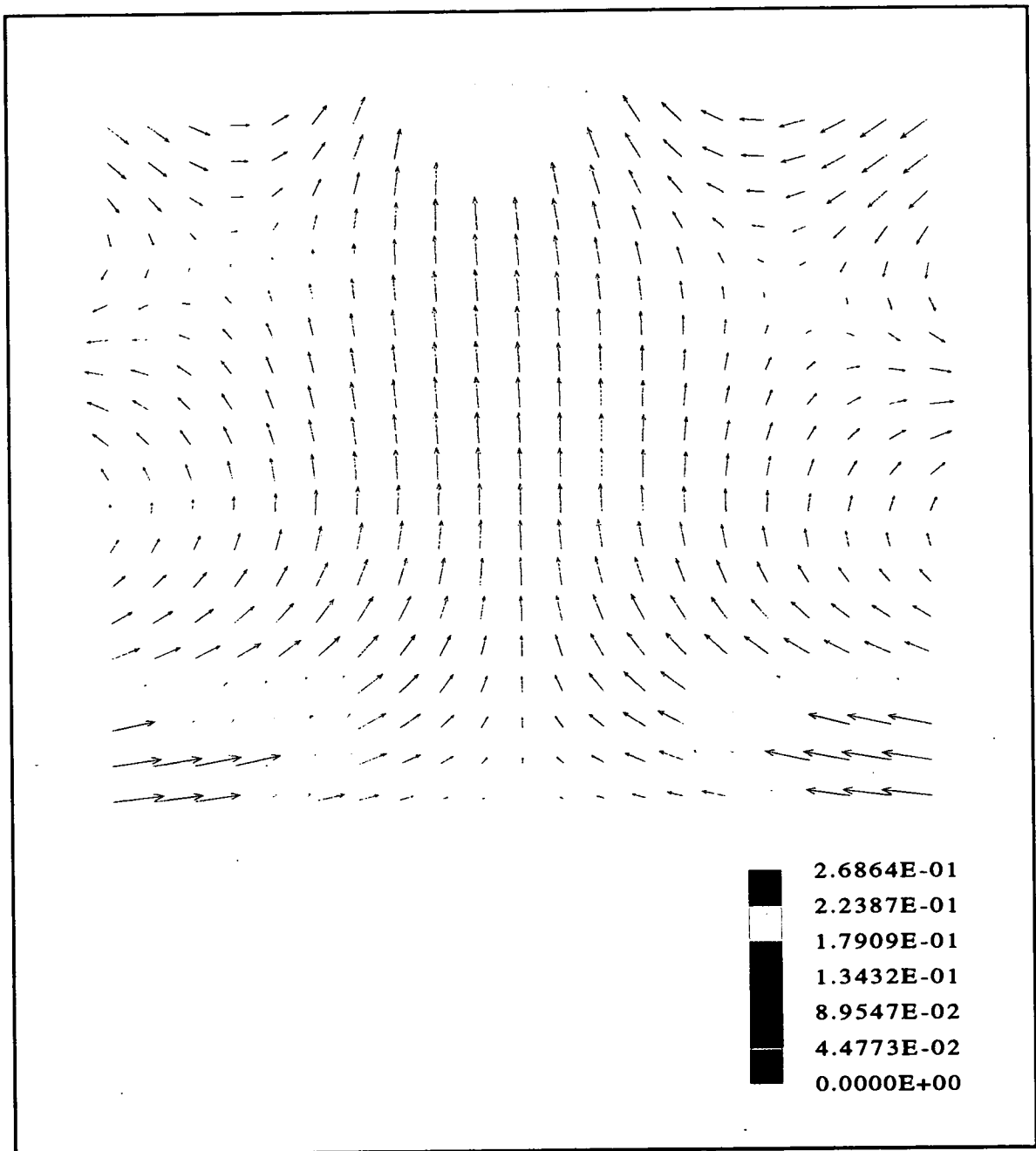
**Figure 51.** Mesh of the 40mm deep cavity.



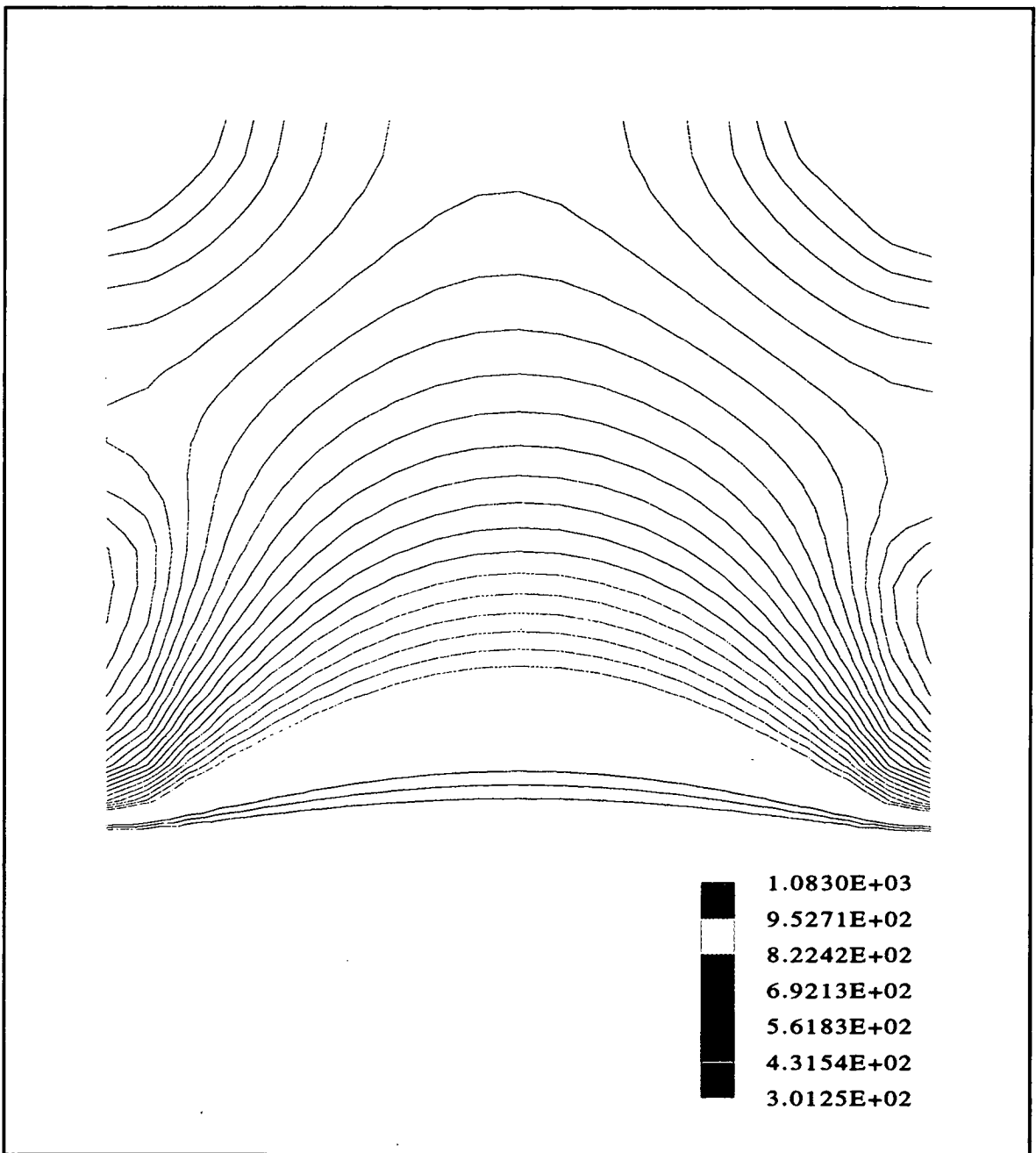
**Figure 52.** Predicted velocity contours on the 40mm deep cavity.



**Figure 53.** Predicted flow pattern on the 40mm deep cavity.



**Figure 54.** Predicted temperature contours on the 40mm deep cavity.



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## **Chapter 5**

### **5. Discussion and conclusions of the results obtained and recommendations for future work.**

#### **5.1 Introduction**

The initial objective of the present work was to investigate how the 'local confinement' of the ignition source affects the ignition temperature of a flammable mixture of 3% propane and air. Surprisingly this had not previously been investigated systematically, and it was felt that the data resulting from this work would lead to a better understanding of the ignition process and would allow existing models of ignition to be tested. But during the development of this work other variables were also studied, such as the length and orientation of the ignition source. In this chapter a discussion of the results obtained will be presented, followed by some recommendations for future work.

#### **5.2 Discussion of the preliminary tests with tungsten wire**

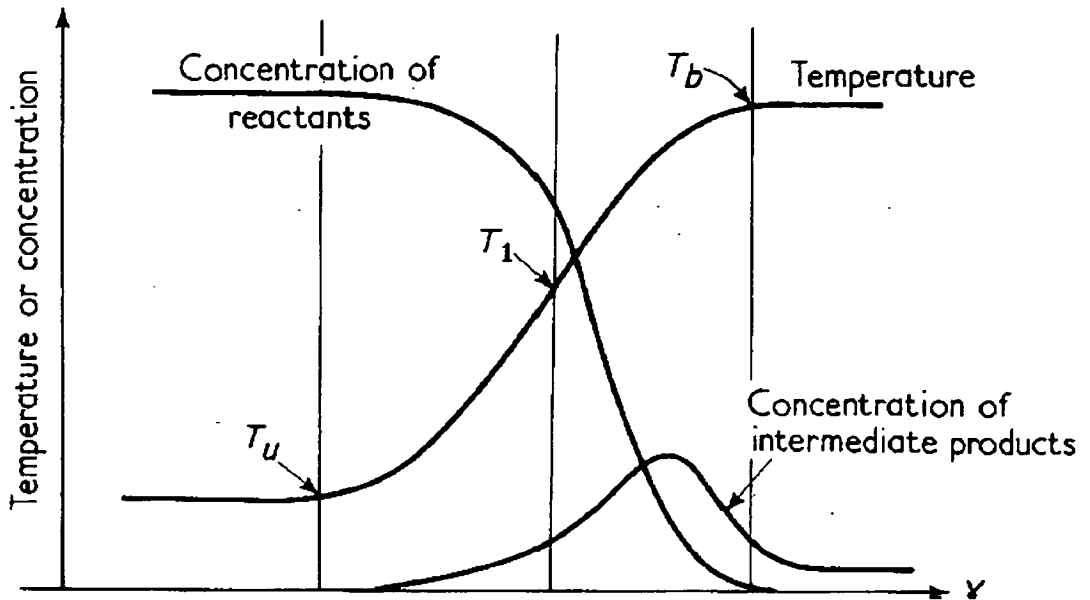
Flame can be initiated by a source of energy such as an electric spark or a hot surface which raises the local temperature enough to start the chemical reaction and cause thermal run-away.

In spark ignition, the spark discharge causes electrical breakdown of the vapour/air mixture generating a plasma at high temperature. This establishes

a small spherical volume of gas, known as a flame kernel which is rich in free atoms and radicals. For flame to propagate, the energy should be sufficient and the flame kernel must exceed a critical size, otherwise the ambient unburned gas itself serves as a quenching agent by dissipating the heat of the reaction zone. Such quenching by the unburned gas is associated with divergent flame propagation, when the flame radius is small and "flame stretch" is high. In other words, in spherical flame propagation a mass element on its passage through the reaction zone loses more heat to the unburned gas than it had gained prior to the entrance into the reaction.

During plane flame propagation, an element of gas ahead of the flame front can receive heat in two ways: either by conduction from the reaction zone or from chemical reactions occurring within it. In the plane flame, the flow is not divergent and the transfer of heat through the element leads to stable flame propagation.

A schematic diagram of the concentration and temperature profiles through a plane flame is shown in Figure 45. Heat flows from the boundary **b** of the burned gas to the boundary **u** of the unburned gas, while the mass flows from **u** to **b**. A mass element passing through the flame at first receives by conduction more heat from the downstream hotter element than it loses to the upstream cooler element, therefore its temperature increases. At **T<sub>1</sub>** the chemical reaction becomes significant, releasing heat which causes further temperature rise to **T<sub>b</sub>**. Similar considerations apply to the concentration change in that the reactants diffuse towards the reaction zone, while products diffuse in the opposite direction. However the intermediate active species (free radical) diffuse in both directions; those diffusing ahead of the flame contribute to the flame propagation mechanism.



**Figure 55.** Temperature and concentration profiles through plane flame [1].

The high concentration of free radicals observed in the reaction zone is due to the branching reaction ( $\text{H} + \text{O}_2 = \text{HO} + \text{O}$ ), which is the most important reaction in the ignition process. When the temperature is high enough for the branching reaction to give rapid chain branching, ignition has occurred. The most significant active species are hydrogen atoms which diffuse very rapidly, particularly ahead of the flame front, and will promote flame propagation. The concentration of hydrogen atoms is higher in the fuel-rich side than in the fuel-lean side of the stoichiometry, which accounts for the fact that the maximum burning velocities lie on the fuel-rich side [2].

In the case of spark ignition the most readily ignitable mixture tends also to lie on the fuel-rich side of the stoichiometry. However, in the preliminary

experiments with hot wire ignition in this study, it was observed that the most ignitable mixtures were on the lean side of the stoichiometry, in agreement with previous work, as mentioned in section 3.4.1.

When ignition occurs at a hot surface, the reaction begins in the boundary layer. The branching reaction will become important when the temperature is high enough, but as hydrogen atoms will diffuse rapidly to the surface, the surface itself acts as an inhibitor. It is possible that the destruction of these free radicals at the surface accounts for the fact that the most ignitable mixture lies on the fuel-lean side.

During the preliminary tests, in addition to the observation that 3.7% propane/air mixture was the most ignitable mixture, it was also noted that the ignition temperature for the wire wound in the form of a spiral (Table 12) was similar to the one obtained for the vertical U wire (Table 15); those temperatures were lower than the one estimated for the straight wire (Table 15). In the case of the wire wound in the form of a spiral, a lower ignition temperature is anticipated, since the spiral simulated a semi-confined space, which allowed the hot gases to stay longer at an elevated temperature. As was shown in the literature review, the longer the mixture stayed in contact with the hot surface, the greater was the probability of ignition.

The ignition temperature in the case of the vertical 'U' wire was similar to the spiral, and less than the horizontal straight wire. An explanation for this observation is that for the horizontal straight wire the heat transfer boundary layer is small, and is modelled as free convection around a horizontal cylinder [3]. On the other hand, the vertical 'U' wire had two vertical sections 50mm long. The heat transfer boundary layer is extended, similar to

free convection at a vertical plate [3]. The convective time involved is greater for the vertical wire than for the horizontal wire, and there is a lower ignition temperature.

### **5.3 Discussion of the tests carried out in an open configuration.**

Either in static tests in which only gas movement due to natural convection occurred or in tests with low or high velocity gas stream, a marked difference in ignition temperature was observed when the width of a horizontal heated surface changed in dimension [4-8]. In Table 9 some of the common observations from the experimental work that has been published are summarized. They showed that the ignition temperature tended to increase if the width of the heated surface was decreased, when the length was maintained constant.

Since each investigator had a different objective in mind when they conducted their experiments, any attempt to find an indication of how the length of the heated surface affects the ignition temperature by comparisons between the previous results can lead to incorrect conclusions, Table 26.

Despite the fact that the experimental works of Mullen et al [4] and Agoston [5] had similar objectives, they used different initial temperatures and pressures. As an increase in either the initial temperature or pressure tend to decrease the ignition temperature [5], it is impossible to conclude if the differences between their results are due to the length of the rods or either temperature or pressure. Another example is shown in the results of Coward and Guest [6] and Laurendeau [8]: the difference observed in their ignition

temperatures for 2mm and 3mm wide strips is in the range 64-71°C. This difference could be attributed to the experimental conditions, rather than difference in length. They used different heating periods and gas stream velocities. The longer heating period in Coward and Guest tests, which were carried out in a stagnant mixture, could decrease the temperature required for ignition [7], while the flow velocity in Laurendeau's runs tended to increase the ignition temperature [4]. The difference between the results obtained by Cutler [7] and Laurendeau [8] is enormous, despite the fact that they conducted their tests with a mixture of 7% methane-air, using the same ignition source (tungsten wire) with similar dimensions. It is likely that the difference between the results obtained by Cutler [7] and Laurendeau [8] could be related to the experimental procedures adopted by them. As a result a clear distinction between the factors that affect the ignition mechanism is extremely difficult to identify. Therefore the previous work can only give some indications about these factors if they are analysed separately.

From the previous experimental work it is evident that if the length of the heated surface is constant and its width varied, under different experimental conditions a higher ignition temperature was achieved with narrow strips (Table 26). In order to have a clear idea how the length of the heated surface affects the ignition temperature two sets of tests were carried out, in which the width of the strip was kept constant at 5mm and the length varied.

**Table 26.** Comparison of the ignition temperature for the open configuration obtained by previous studies.

Dia-meter mm	Ignition Temperature °C				
	Mullen <sup>1</sup> Length:6.4mm	Agoston <sup>2</sup> Length:63.5mm	Coward&Guest <sup>3</sup> Length:108mm	Cutler <sup>4</sup> Length:57mm	Laurendeau <sup>5</sup> Length:50mm
1.6	1,329	-	-	-	-
2.0	-	-	1,146	-	1,075
3.2	1,160	-	1,122	-	1,058
4.8	-	-	-	1850	-
5.0	-	-	-	-	1,035
6.4	-	1,407	1,082	1820	-
7.9	-	-	-	1765	-
8.9	-	1,396	-	-	-
9.5	-	-	-	1760	-
10	-	-	-	-	1,015
11.1	-	-	-	1710	-
11.9	-	-	-	1680	-
12.2	-	1,383	-	-	-

1- Mixture:velocity 30m/sec; Stch pentane.Initial temperature:74°C.  
Pressure: 0.003-0.01atm.

2-Mixture:velocity 30m/sec; Stch gasoline.Initial temperature:85°C.  
Pressure: 0.5 atm.

3- Mixture:stagnant; 7% natural gas (93%CH<sub>4</sub>). Heating period: 40 seconds.

4-Mixture:stagnant; 7% methane.Heating period: 0.5milliseconds.

5- Mixture:velocity 1.6cm/mim; 7% methane. Heating period: 0-2 seconds.

The data obtained in the present work with Nichrome strips 45mm and 65mm long placed in the open configuration indicated that the length of the ignition source did not affect ignition temperature as shown in Table 24, leading to the conclusion that the length of the strip was not a fundamental variable in the ignition mechanism. The explanation for this observation could be related to the path of contact between the gas and the heated surface, as described in section 4.2. Therefore, the mechanism by which the gas-air mixture comes into contact with the surface is greatly affected by its width. The area of contact between the hot gases and the ignition source (i.e. the extent of the boundary layer) may be increased by increasing the width of the surface rather than its length. However, there are no data on the effect of reducing the length until it equals the width. It seems likely that there will be an effect if the length is the same magnitude as the width. Rae and others [9] who studied the effect of area by square surfaces and showed that there was a large dependence on area for surface areas less than 50mm<sup>2</sup>.

Table 24 also shows that the orientation of the ignition source did not produce a significant change in the ignition temperature. The angle of inclination was 30°. On the other hand, it should be noted that the width of the ignition source was kept constant. The experience obtained during the development of the present work seems to indicate that the width of the ignition source is a fundamental variable in the ignition mechanism, but a clear picture of how it affects the ignition process is required, and to obtain a better understanding further studies are required.

Another variable that could possibly affect the ignition temperature, as indicated in the preliminary tests, is the destruction of the free radicals at the

surface. A way to quantify indirectly the destruction of the free radicals could be obtained by taking into account the variation of the concentration of species  $i$  within the distance from the surface. In fact this parameter was included in the simple model presented in section 4.3, but due to the lack of information available it was eliminated. However, a qualitative explanation may be proposed, involving competition between the branching reaction ( $H+O_2$ ) and the termination reaction ( $H+surface$ ). This competition does not exist for spark ignition, provided that the electrodes are far enough apart. However, a detailed analysis of the kinetics of the reaction would be necessary to test the hypothesis.

The simple model for the case of free convection and low velocity gave a reasonable correlation between the experimental and the predicted ignition temperature, if the steady state condition is assumed. But its limitation is that the ignition delay cannot be estimated.

In a detailed review of ignition at a hot surface Powell [10] in 1984 concluded that the minimum temperature of an open surface for ignition of Group IIA vapour, in which propane is the main representative, was  $900^{\circ}C$  for a 'characteristic surface dimension' of 10-15 mm. The conclusions presented by Powell resulted from a compilation of many experimental results obtained with hot surfaces held at a steady temperature in natural or low velocity flows; the characteristic surface dimensions included the diameter of particles (or sphere), the area of plane surfaces and the surface width. As most of the work included in his review considered the width of the strip as the characteristic surface dimension, it is reasonable to assume that 10-15 mm was the width. A further gradual increase in the ignition temperature would be anticipated with a decrease in the surface dimension,

but the tests conducted during this project showed that it is not the case, since the ignition temperature around 900°C for a small surface width was obtained. The previous studies as well as the present one confirmed that 900°C is the minimum ignition temperature due to a hot surface for the case of an open configuration, if the surface is exposed to a flammable mixture only during a short period of time, which could be between 0-120 seconds.

#### **5.4 Discussion of the tests carried out in the 'local confinement' configuration**

It was observed that when the ignition source was placed inside a semi-confined space, such as the ones shown in Figure 2, which were referred to throughout the Chapters as 'local confinement', the ignition temperature decreased and it was related to the depth of the cavity, see Table 25.

The results obtained with the 'local confinement' configuration were analysed using the Frank-Kamenetskii thermal theory. The Frank-Kamenetskii model was formulated for a static flammable mixture within a closed vessel and is not strictly applicable to the present situation where buoyant flow occur. The flows were shown clearly in the computational fluid dynamics simulations. However the Frank-Kamenetskii model predicted the trend observed in ignition temperature as a function of the cavity depth.

There are several difficulties in obtaining a formula for predicting the temperature in the case of 'local confinement' configuration, caused by factors such as either the temperature or the density distribution inside the unheated cavity not being uniform. Considering a heated element, at the

same time that it travels from the bottom to the top of the cavity, i.e. in the direction of the decreasing temperature gradient, it is influenced by the fresh mixture which enters the cavity through the ends. All these effects are difficult to quantify and the effect of lowering the ignition temperature by an amount related to the 'depth' of the cavity may be influenced by one or more of the following factors: Firstly, with the hot surface horizontal and facing upwards, the proximity of the sides of the cavity will inhibit the buoyancy induced flow and increase the convective time of the hot propane/air mixture in the vicinity of the surface. Secondly, the presence of the sidewalls will prevent entrainment of fresh mixture into the buoyant flow through the sides, which would have a cooling effect - thus maintaining a higher temperature until the flow clears the cavity. Finally, the ceramic fibreboard used in the experiments is an excellent thermal insulating material through which heat losses will be low. If the sidewalls were at the same temperature as the heated strip, an even lower ignition temperature would be anticipated.

The present work revealed some relevant points. Firstly, the width of the ignition source seem to be an important variable in the ignition mechanism. Secondly, the ignition temperature decreased considerably when the heated surface was presented in some kind of semi-confined space. The ignition temperature appears to be a function of the degree of confinement. Thirdly, in the absence of a more specific model the thermal theory of Frank-Kameneskii has indicated of the trend of ignition temperature variation for the reasons stated in section 4.4. Fourthly, the computational fluid dynamics simulations showed clear differences between the open configuration and the configurations of 'local confinement'. The latter results are qualitatively consistent with the experimental data. These points should be considered carefully, as they are important in the context of ignition prevention and

control in the chemical and petrochemical industries. The above discussion clearly indicates the importance of local confinement in identifying hot surfaces as potential ignition sources.

### **5.5 Recommendations for future work**

Although the present work has thrown light on some of the questions related to the ignition of a flammable mixture at a hot surface, which are important in the fire protection field, it has also left some questions without definite answers. Therefore, in order to test the hypothesis suggested in the previous sections and mainly to provide a better understanding of the ignition process, some work is suggested for future research.

The preliminary tests (see section 3.4.1) showed that for the case of ignition of a flammable mixture at a hot surface, the most ignitable mixture lies in the fuel-lean side. As was suggested in section 5.2 it could be due to the destruction of free radicals at the surface. It was not the objective of this work to study this aspect of the ignition process. The review of the published work indicated that information about this aspect is not available. It is clear, therefore, that a detailed investigation is required.

The analysis which took into account the previous work and the present one emphasises two points: a) the length of the horizontal straight wire had no apparent effect in the minimum ignition temperature, and b) the diameter of the horizontal straight wire was an important variable in determining the ignition temperature. These observations could be related to the hypothesis that the main path of contact between the mixture and the heated surface is

the width. However, as shown in Figure 37 the mixture also has contact with the heated surface through its length, but it seems have a minor effect on the ignition temperature. It could be an indication that there is a ratio length/width beyond which the width becomes predominant. It would be interesting to study to what extent this ratio affects the minimum ignition temperature.

Measurements should be made of the effect of the width of the heated strip on the ignition temperature, for both open and 'local' configurations.

The tests carried out for the situation in which the ignition source was placed inside an unheated cavity, indicated that there exists a cavity depth beyond which the ignition temperature decreases drastically (see Figure 28). In order to determine this critical cavity depth more data need to be obtained.

Experiments should also be carried out to investigate the effect of heating the entire cavity. This would require a modified design of apparatus. The equipment used by Bull and others (Shell Research) would be suitable, but a vapour with a lower ignition temperature (such as acetaldehyde) would have to be used. Experimental results would be easier to obtain, but the theoretical interpretation would be more difficult, particularly if two-stage ignition had to be considered.

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## **APPENDIX A**

### **Results Obtained with the Tungsten Wires**

**Tungsten Wire - Straight Wire**  
0.5mm in diameter and 45mm long

<b>Test Number<sup>1</sup></b>	<b>Current Range (Amperes)</b>	<b>Ignition<sup>2</sup> Delay (seconds)</b>	<b>Temperature<sup>3</sup> (°C)</b>	<b>Results<sup>4</sup></b>
1T3	17.4±0.1	50	-	I
4T3	17.4±0.1	70	-	I
5T3	17.4±0.1	70	-	I
11T3	14.4±0.1	-	-	NI
13T3	17.4±0.1	60	-	I
14T3	17.4±0.1	176	-	I
17T3	16.9±0.1	104	-	I
18T3	14.4±0.1	-	-	NI
19T3	16.9±0.1	152	-	I
24T3	13.3±0.1	-	-	NI
25T3	12.5±0.1	-	-	NI
26T3	16.4±0.1	192	-	I
27T3	16.4±0.1	168	-	I
29T3	16.4±0.1	320	-	I
30T3	16.4±0.1	320	-	I
31T3	16.4±0.1	448	-	I
77T3	15.9±0.1	695	1226±35(1224)	I
78T3	15.1±0.2	-	-	NI
92T3	15.1±0.1	-	-	NI
93T3	15.1±0.2	-	-	NI
97T3	15.9±0.1	864	1272±38(1268)	I
146T3	14.8±0.2	565	(1305±121)	I
147T3	14.3±0.1	-	(1225±45)	NI

1- The test number identifies the run number, tungsten wire and the mixture concentration.

2- Ignition delay is the time lag between the exposure of the gas to the ignition source and the subsequent ignition.

3- The values outside the parenthesis were obtained with the pyrometer (emissivity value equal to 0.39). The average of the temperatures recorded during the test was assumed as the wire temperature. The value inside the parenthesis were calculated. The average of the voltages and currents recorded during the test were translated into temperature using the resistivity curve of the tungsten.

4- The results are either ignition (I) or no ignition (NI).

**Tungsten Wire**  
0.5mm in diameter and 175mm long  
Form of U vertical

Test Number <sup>1</sup>	Current Range (Amperes)	Ignition <sup>2</sup> Delay (seconds)	Temperature <sup>3</sup> (°C)	Results <sup>4</sup>
49T3	12.5±0.1	-	-	NI
50T3	13.8±0.1	-	-	NI
51T3	13.8±0.1	-	-	NI
52T3	13.8±0.1	-	-	NI
90T3	14.3±0.2	-	-	NI
81T3	14.9±0.1	256	1152±19 (1143±47)	I
84T3	14.9±0.1	256	1152±19 (1143±47)	I
88T3	14.9±0.1	304	1077±13 (1143±47)	I
87T3	14.9±0.1	552	1163±9 (1143±47)	I
139T3	13.7±0.5	856	(1049±94)	I
150T3	14.9±0.2	-	(906±47)	NI
151T3	14.5±0.3	240	(972±71)	I
152T3	14.5±0.3	-	(952±67)	NI
153T3	15.5±0.1	7	(994)	I
154T3	14.4±0.3	204	(1014±77)	I
159T3	14.4±0.2	-	(918±37)	NI
161T3	15.4±0.2	17	(934±52)	I

1- The test number identifies the run number, tungsten wire and the mixture concentration.

2- Ignition delay is the time lag between the exposure of the gas to the ignition source and the subsequent ignition.

3- The values outside the parenthesis were obtained with the pyrometer (emissivity value equal to 0.39). The average of the temperatures recorded during the test was assumed as the wire temperature. The value inside the parenthesis were calculated. The average of the voltages and currents recorded during the test were translated into temperature using the resistivity curve of the tungsten.

4- The results are either ignition (I) or no ignition (NI).

**Tungsten Wire**  
0.5mm in diameter and 175mm long  
wound in the form of a spiral with four turns,  
the space between the turns was 0.5mm

Test Number <sup>1</sup>	Current Range (Amperes)	Ignition <sup>2</sup> Delay (seconds)	Temperature <sup>3</sup> (°C)	Results <sup>4</sup>
58T2.3	13.9±0.1	740	(1008)	I
59T2.3	13.9±0.1	512	(1008)	I
20T3	14.9±0.1	5	-	I
37T3	13.8±0.1	350	-	I
38T3	13.8±0.1	144	-	I
39T3	13.8±0.1	568	-	I
40T3	13.8±0.1	504	-	I
46T3	12.5±0.1	-	-	NI
47T3	12.5±0.1	-	-	NI
48T3	12.5±0.1	-	-	NI
53T3	13.8±0.1	256	-	I
54T3	13.8±0.1	672	-	I
55T3	13.8±0.1	784	-	I
127T3	13.2±0.1	-	848±52(830)	NI
144T3	13.4±0.4	420	(977±33)	I
149T3	14.9±0.1	25	(1075±16)	I
155T3	13.9±0.1	-	991±69 (968±28)	NI
156T3	14.0±0.2	-	(999±36)	NI
158T3	15.1±0.1	9	(1148±5)	I
112T3.7	14.4±0.1	132	(1040)	I
118T3.7	14.0±0.1	32	(1057)	I
118AT3.7	14.5±0.5	8	-	I
119T3.7	13.8±0.2	160	-	I
120T3.7	13.1±0.1	-	760±20(741)	NI
121T3.7	13.1±0.6	334	848±52 (855±56)	I
122T3.7	13.7±0.1	122	(1008±34)	I
123T3.7	13.5±0.1	820	-	I
140T3.7	13.1±0.3	-	(776±38)	NI
142T3.7	13.4±0.1	-	(1005±48)	NI
143T3.7	13.4±0.3	678	(1033±62)	I

Tungsten Wire, 0.5mm in diameter and 175mm long  
wound in the form of a spiral with four turns

CONTINUATION

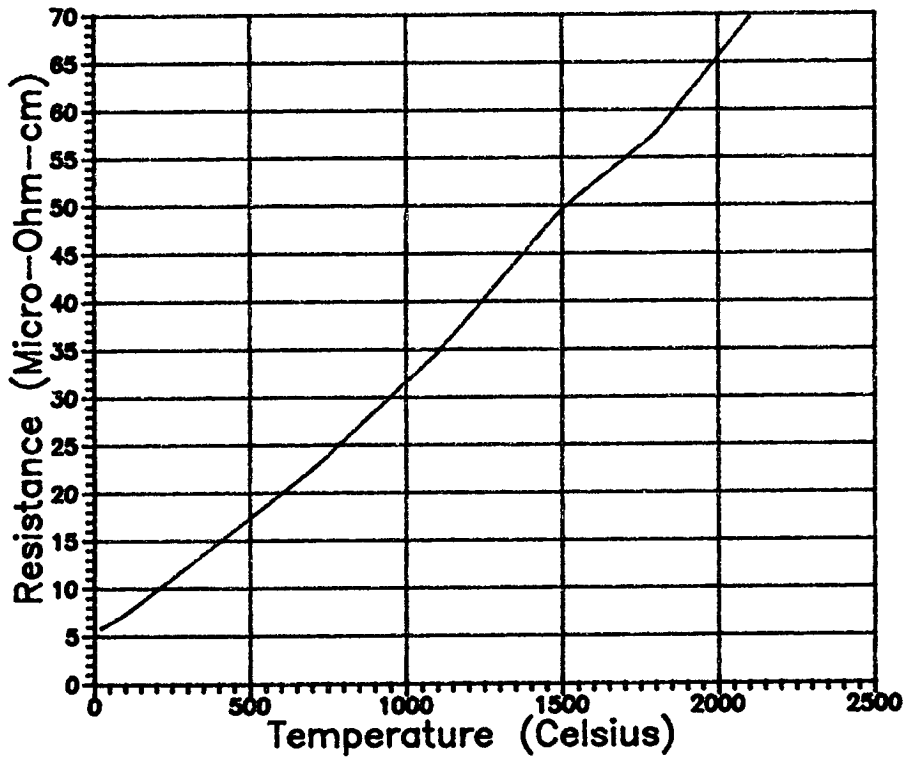
Test Number <sup>1</sup>	Current Range (Amperes)	Ignition <sup>2</sup> Delay (seconds)	Temperature <sup>3</sup> °C	Results <sup>4</sup>
106T4.5	13.9±0.1	-	-	NI
107T4.5	14.0±0.2	236	-	I
113T4.5	14.4±0.2	400	962±58 (1011±69)	I
115T4.5	14.1±0.3	784	-	I
125T4.5	13.4±0.2	-	768±20	NI
63AT5.4	16.4±0.1	5	-	I
64AT5.4	14.6±0.1	105	-	I
66T5.4	13.9±0.1	-	991±69 (978±9)	NI
67T5.4	14.4±0.1	184	(920)	I
68T5.4	15.0±0.1	7	-	I
69T5.4	14.6±0.1	32	-	I
70T5.4	13.9±0.1	756	(1003)	I
71T5.4	13.9±0.1	704	1008±34(1003)	I
72T5.4	13.2±0.1	-	890±21	NI
73T5.4	13.2±0.1	-	872±18	NI
104T5.4	14.1±0.1	448	(920)	I
105T5.4	13.9±0.1	408	1005±23(1003)	I
126T5.4	13.3±0.2	-	848±52	NI
111T6.3	14.3±0.3	696	-	I
114T6.3	14.0±0.1	528	-	I
116T6.3	13.7±0.3	-	-	NI
128T6.3	13.4±0.2	-	813±21	NI
63AT6.7	16.4±0.1	5	-	I
64AT6.7	14.4±0.1	45	-	I
65T6.7	13.9±0.1	-	-	NI
108T6.7	14.4±0.2	400	-	I
109T6.7	14.4±0.2	752	960±25(1010)	I
110T6.7	14.3±0.2	336	-	I
117T6.7	13.8±0.2	-	-	NI

- 1- The test number identifies the run number, tungsten wire and the mixture concentration.
- 2- Ignition delay is the time lag between the exposure of the gas to the ignition source and the subsequent ignition.
- 3- The values outside the parenthesis were obtained with the pyrometer (emissivity value equal to 0.39). The average of the temperatures recorded during the test was assumed as the wire temperature. The value inside the parenthesis were calculated. The average of the voltages and currents recorded during the test were translated into temperature using the resistivity curve of the tungsten.
- 4- The results are either ignition (I) or no ignition (NI).

## APPENDIX B

### Curve of the Electrical Resistivity of the Tungsten Wire

The curve of the Electrical resistivity of the tungsten wire that was used to estimate the temperatures during the preliminary tests, as mentioned in Chapter 3, section 3.4.1.



#### References

- Goodfellow, Data Sheet W1. England.

## APPENDIX C

### Data for the Ignition Temperatures Calculations

The following symbols were defined in Chapter 4, section 4.3.

Symbols	Propane	Methane
$C_p$	217.6 Joule/(mole K)	87.864 Joule/(mole K)
$g$	9.8 m/sec <sup>2</sup>	9.8 m/sec <sup>2</sup>
$h_e$	96.6 10 <sup>3</sup> Joules /mole	84.47 10 <sup>3</sup> Joules /mole
$h_w$	209.2 10 <sup>3</sup> Joules /mole	87.864 10 <sup>3</sup> Joules /mole
$k$	25.4 10 <sup>-3</sup> Joules/(m K sec)	44.64 10 <sup>-3</sup> Joules/(m K sec)
$Pr$	0.74	0.74
$Q$	2044 10 <sup>6</sup> Joule/mole	8 10 <sup>5</sup> Joule/mole
$T_e$	293 K	293 K
$\gamma_w$	1.6 10 <sup>-5</sup> m <sup>2</sup> /sec	9.5 10 <sup>-5</sup> m <sup>2</sup> /sec

#### References

- CRC Handbook of Chemistry and Physics (58th edition). CRC Press.
- Alkidas, A. and Durbetaki, P. (1973). 'Ignition of a gaseous mixture by hot surface'. Combustion Science and Technology, volume 7, 135-140.
- Drysdale, D. (1986). An Introduction to Fire Dynamics, chapter 1, pp 21. John Wiley and Sons.