An Experimental Investigation on the Effect of Nitrogen Enriched Air and Heat Transfer on the Maximum Experimental Safe Gap for Propane Gas Explosions

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Abstract

Electrical apparatuses for use in potentially explosive gas atmospheres are required to be enclosed. There are two main requirements in the design of such enclosures. Firstly, they are required to withstand the pressure generated in an internal explosion. Secondly, any gap openings must be small enough to quench flames and to cool combustion products to prevent re-ignition of a surrounding explosive gas atmosphere. The largest gap opening that just prevents transmission of an internal explosion to a surrounding explosive gas atmosphere is called the maximum experimental safe gap (MESG). The MESG values is determined from standardised experiments.

The purpose of the conducted experimental work was to investigate the influence of the gap material on the MESG value. Another aim was to find out if partial inertisation of the explosive gas influences the maximum experimental safe gap.

The combustible gas used in the experiments was propane. The experiments were conducted in an apparatus with an interchangeable and adjustable gap opening. The gap materials tested was carbon steel, brass, aluminium and polyoxymethylene.

The experiments with metal gaps show that the properties of the metals do not have a significant influence on the MESG value. However, a decrease of 0.01 mm was achieved when a flame gap of brass was used, compared to the value obtained using a steel gap. Temperature measured above the orifice of the gap opening supports the finding. At equal gap opening, a higher temperature was measures above brass gaps than above steel gaps. An increase of the MESG was achieved by partial inertisation of the explosive gas atmosphere. The MESG value of propane was doubled when the oxygen content of air was lowered to 15.04 volume percent.

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1 Introduction

Over 90 % of the energy used by humans is developed through combustion processes [1]. Knowledge of how to deal with the hazards of combustion processes, and how to achieve high operational safety is of great importance. Efforts to develop technology and to gain knowledge of how to prevent explosions have taken place over time. In the coal mining industry, firedamp could be ignited when miners used lamps with open flames. Sir Humphry Davy developed a safety lamp in 1815 which was able to provide light without causing risk of an explosion [1]. Following the development of the Davy lamp, several technical solutions have been made to prevent accidental ignition of explosive atmospheres. However, fires, explosions and processes running out of control still occur occasionally. Recent major incidents in the petroleum industry include Piper Alpha (1988), BP Texas City (2005), Buncefield fire, UK (2005), Puerto Rico gas plant explosion (2009) and Deepwater Horizon (2010) [2]. All accidents resulted in damaged property, financial loss, loss of company reputation and large environmental damage. Some even resulted in fatalities. In March 2012 a gas leakage at Elgin WHP, in the British sector of the North Sea, led to a great risk of a major explosion. Evacuating the workers and shutting down the platform avoided this.

Explosive atmospheres may occur where flammable gas, dust, mist or spray mix with air. To reduce the risk of an explosion, protective measures must be taken. Actions with objective of avoiding explosions can be divided into *primary*, *secondary* and *tertiary* explosion protection measures [3].

The *primary* explosion protection consists of actions performed to prevent the formation of a potentially explosive atmosphere. Numerous methods can be effective:

- Avoidance of flammable substances.
- Limitation of concentration in range below or above explosive limits.
- Inertisation; lowering the proportion of oxygen by adding an inert gas in the mixture.
- Ventilation.

Secondary explosion protection is actions performed where primary measures have been exhausted, and hazardous areas with explosive atmospheres still occur. Protective measures which render ignition sources ineffective are applied. These measures include all explosion protection measures for electrical apparatuses used in hazardous areas.

Tertiary explosion protection is constructional explosion protection limiting the extent of an accidental explosion. An example of this is equipment designed to withstand the maximum explosion pressure. If equipment is not able to withstand the pressure, pressure relieves can be used.

In many cases electrical equipment must be used and operated in areas where an explosive atmosphere might occur. Thus representing a hazard, because of electric sparks and parts with high temperatures, which can serve as an ignition source. A secondary explosion protection measure is to place electrical equipment inside flameproof enclosures to exclude them from being sources of ignition. The flameproof enclosure serves as a safety barrier between the surrounding atmosphere and the electrical equipment. Gaps in the enclosure, even though small, are necessary. They are needed to permit assembly, installation and maintenance of the equipment. These gaps may cause explosive gas to penetrate into the enclosure; hence a requirement is that pressure developed during an internal explosion must be withstood. It is of importance to identify the critical dimensions of gaps and joints through which an internal explosion can be transmitted to a surrounding explosive atmosphere. The maximum gap between two close-fitting, flat surfaces, which prevents transmission of an internal explosion to a surrounding explosive gas atmosphere, is called the maximum experimental safe gap, MESG. The value of MESG is determined experimentally and is dependent on the composition and properties of the exploding atmosphere, as well as the specification of the gap.

Partial inertisation is a term referring to lowering the oxygen content in air. This is a protective measure for fire and a mitigating measure for explosions occurring. The present work aims to investigate two factors of the maximum experimental safe gap. One objective is to study how nitrogen enrichment of air, in an explosive mixture with propane, influences the safe gap, using an experimental approach. This is done to investigate if standards applying for flameproof enclosures which are intended for use in fuel in air, can be used in atmospheres with fuel in nitrogen enriched air. As well as to investigate the impact on the MESG.

A parameter for the determination of MESG values is the heat transfer occurring inside the safe gap. The heat transfer cools the combustion products from an explosion. The present work aims to investigate if varying the gap material, in terms of its thermal conductivity, influence the MESG value. Temperature measurements of the combustion gas exiting the orifice of the safe gap can indicate if gap material is of importance.

The rest of the thesis is organised as follows: Chapter 2 outlines the relevant literature. A review of explosion theory and classification of explosion proof equipment is presented, followed by an explanation of the operating principles of flameproof enclosures. Next, in Chapter 3, the experimental equipment used throughout the present work is presented, and then Chapter 4 consists of the experimental results and discussions of these. Finally, in the Appendix, details of the experimental procedures are given, along with specifications of the equipment used.

2 Relevant literature

This section is a review of the relevant literature for this thesis. An outline of explosion theory and classification of explosion proof equipment is presented, followed by an explanation of the operating principles of flameproof equipment.

2.1 Explosion theory

There are several definitions of the term explosion. Some focus on the noise due to the sudden release of a pressure wave, while some focus on the sudden release of chemical energy. In Eckhoff [4], a definition of the term is given:

"*An explosion is an exothermal chemical process that, when occurring at constant volume, gives rise to a sudden and significant pressure rise*".

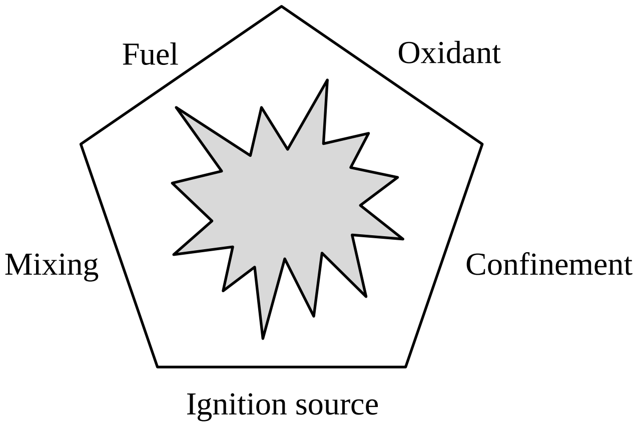


Figure 2-1: Explosion pentagon showing the requirements for a gas, liquid or dust explosion to occur.

The explosion pentagon in Figure 2-1 illustrates the five components required for a gas, liquid or dust explosion to occur. Removal of any element prevents an explosion, but a fire might still take place.

- Fuel – a combustible gas, liquid or dust; will function as the reducing agent.
- Oxidant – air/oxygen; will function as the oxidizing agent.
- Mixing – concentration of fuel within explosion limits.
- Confinement – some degree of confinement to ensure pressure rise.
- Ignition source – source providing sufficient ignition energy to initiate explosion.

The combustible material can be flammable gas, dust, mist or spray. The ability the material has to form an explosive atmosphere depends on its flammability and concentration.

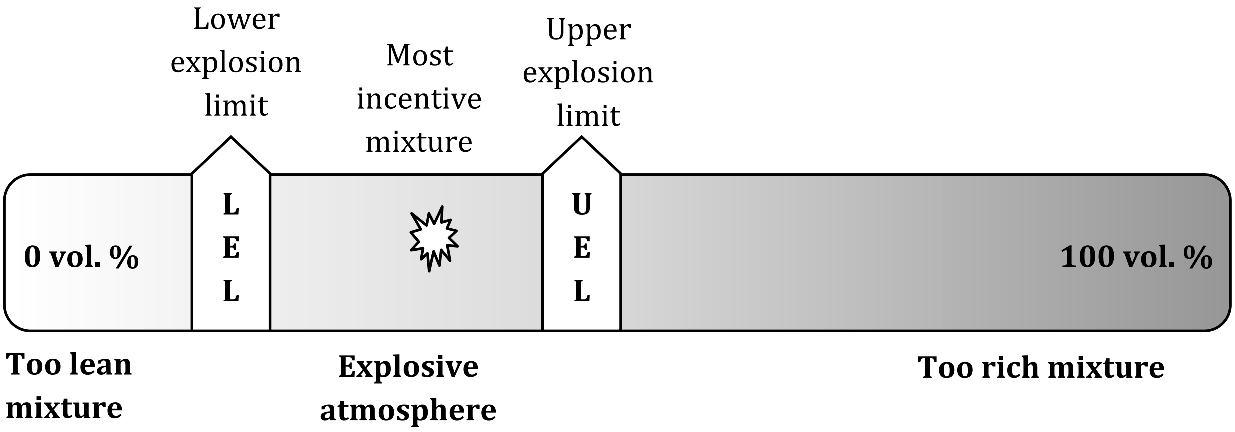


Figure 2-2: Explosion limits for combustible material in volume percentage.

Figure 2-2 demonstrates the explosion limits for a combustible material. The concentration of the combustible material must lie between the lower explosion limit (LEL) and the upper explosion limit (UEL). In order to be ignited, the mixture must contain a concentration of fuel within this range. These limiting values are commonly expressed in volume percent (vol. %) of the total mixture, and depends on the initial pressure and temperature. A concentration of the most incentive mixture of fuel and air is bounded by LEL and UEL. This concentration is experimentally determined, and lies near the stoichiometric fuel-air concentration for gas mixtures [5].

2.2 Classification of explosion proof equipment

Explosion proof equipment is classified according to its intended use. Three factors which are important for this classification can be summarized as follows:

- The probability of a potential flammable atmosphere occurring.
- The flammable substance which the equipment potentially will be exposed to.
    - Gases, vapors and mists or dust.
- The properties of the flammable atmosphere.

2.2.1 Zone classification

A hazardous area can be defined as "*an area in which an explosive atmosphere is present, or may be expected to be present, in quantities such as to require special precautions for the construction, installation and use of electrical apparatus*" [6].

Areas are classified according to the probability of the presence of flammable atmosphere. The classification is done to establish adequate means of explosion protection. Furthermore, the areas are subdivided into zones based on the likelihood of occurrence and duration of a flammable atmosphere [4]:

- Zone 0: Area where a flammable atmosphere is present continuously or for long periods
- Zone 1: Area where a flammable atmosphere is likely to occur in normal operation.
- Zone 2: Area where a flammable atmosphere is not likely to occur in normal operation. If occurring, it will only exist for short periods.

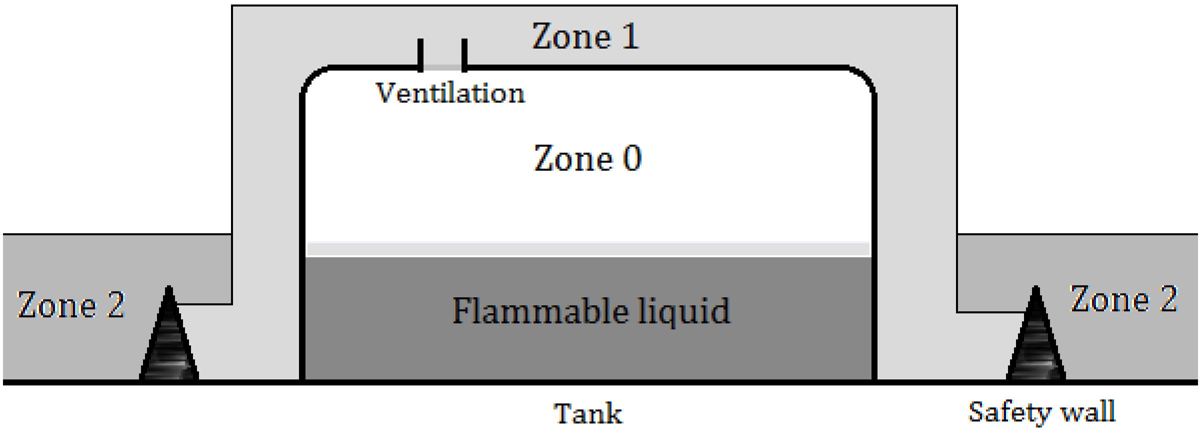


Figure 2-3: Example of the zone classification of explosive atmospheres.

Figure 2-3 exemplifies a zone classification of a tank containing a flammable liquid. Inside the tank, above the liquid, is an area classified as Zone 0, where a flammable vapour is expected to be present. Outside the tank, an area classified as Zone 1 is situated where ventilation from the tank creates a hazardous area in normal operation. Safety walls contain the flammable vapour, assuming it is heavier than air. If leakage or spills occur, the safety walls may not be able to contain the vapour, leading to an area classified as Zone 2. Flammable atmosphere in this area is likely to be a rare occurrence.

2.2.2 Explosion groups

Electrical equipment used in an explosive atmosphere is classified in the following groups [7]:

- Group I: Equipment intended for use in mines, susceptible for firedamp.
- Group II: Equipment intended for use in places with an explosive gas atmosphere other than firedamp.
- Group III: Equipment intended for use in places with an explosive dust atmosphere.

Group II is subdivided, based on the nature of the explosive gas atmosphere in which they are intended to be used.

- IIA – a typical gas is propane.
- IIB – a typical gas is ethylene.
- IIC – a typical gas is hydrogen.

2.2.3 Temperature classes

The auto ignition temperature of an explosive gas atmosphere is the lowest temperature of a heated surface which, under specified conditions, will ignite a flammable substance in the form of a gas or vapour mixture with air [6]. The auto ignition temperature of some gases is presented in Table 2-1.

Table 2-1: Auto ignition temperature for some hydrocarbons and hydrogen in air [5].

Gas	Auto ignition temperature (°C)
Methane (firedamp)	595
Propane	450
Ethylene	440
Hydrogen	560

The highest surface temperature of equipment used in hazardous areas, must be lower than the ignition temperature of the surrounding flammable gas. Electrical equipment used in explosion group II has been classified according to its maximum permissible surface temperature, shown in Table 2-2.

Table 2-2: Temperature classes for electrical equipment of explosion group II [4] .

Temperature class	Maximum permissible surface temperature of electrical equipment (°C)	Auto ignition temperature of surrounding flammable gas (°C)
T1	450	T > 450
T2	300	300 < T < 450
T3	200	200 < T < 300
T4	135	135 < T < 200
T5	100	100 < T < 135
T6	85	85 < T < 100

2.2.4 Type of protection

Different protection measures are carried out on electrical equipment subjected to an explosive gas atmosphere. Several types of protections are used; all based on different protection concepts. The most common types of protections are shown in Table 2-3.

Table 2-3: The most common secondary explosion protection measures for electrical equipment used in an explosive gas atmosphere [7].

Type of protection	Marking	Used in Zone		
		0	1	2
Increased safety	Ex ‘e’		●	●
Flameproof enclosure	Ex ‘d’		●	●
Pressurized enclosure	Ex ‘p’		●	●
Intrinsic safety	Ex ‘i’	●	●	●
Oil filled enclosure	Ex ‘o’		●	●
Sand filled enclosure	Ex ‘q’		●	●
Encapsulation	Ex ‘m’	●	●	●

Only two types of protection concepts are allowed used in a Zone 0 environment, as Table 2-3 highlights. The two types are intrinsic safety and encapsulation. Any sparks in equipment with intrinsic safety has insufficient energy to be an ignition source. When encapsulation is used as a protection concept, equipment is molded inside a material to prevent any contact with the surrounding atmosphere.

2.3 Propane as fuel in an explosion

Combustion is a self-sustainable chemical reaction which requires no additional energy when initiated. Combustion with hydrocarbon gas as fuel can be described by reaction (2-1).

$$Fuel + Oxidant \rightarrow Water + Carbon\ dioxide + Heat \tag{2-1}$$

Stoichiometric mixtures are mixtures of fuel and oxidant which support complete combustion of the fuel. A combustible mixture is lean or rich in reference to its stoichiometric mixture. Rich mixtures have an excess of fuel and combustion will result in incomplete combustion because of lack of oxidant. Mixtures are lean if there are excess of oxidant.

A reaction where all the fuel is consumed is a stoichiometric reaction. Propane, the gaseous fuel used in this thesis, gives the stoichiometric reaction (2-2).

$$C_3H_8 + 5O_2 \rightarrow 4H_2O + 3CO_2 + Heat \tag{2-2}$$

Reaction (2-2) is a simplification of the chemical reactions taking place in a combustion reaction.

The stoichiometric mixture consists of 4.02 vol. % propane in air, when air is the oxidiser. See Appendix G for calculations. Table 2-4 summarizes values for propane as fuel in an explosion.

Table 2-4: Tabulated values for propane [5].

Attribute	Value
Equipment group	IIA
Temperature class	T2
MIC ratio	0.82
MESG (mm)	0.92 mm
Most incentive mixture (vol. % in air)	4.2
Auto ignition temperature (°C)	450
Relative density to air (air = 1)	1.56
Adiabatic flame temperature in air (°C)	1977

2.4 Ignition source

In order to prevent ignition of explosive atmospheres, it is important to identify possible ignition sources. Some of the ignition sources which can set off an explosion are [3]:

- Hot surfaces.
- Flames and hot gases.
- Mechanically generated sparks.
- Electrical equipment.
- Stray electric current.
- Static electricity.
- Adiabatic compression.

2.4.1 Ignition of explosive atmosphere

Ignition can be defined as the initiation of a self-sustained combustion [8]. Ignition occurs when the rate of heat generation exceeds the rate of heat loss in a fixed volume.

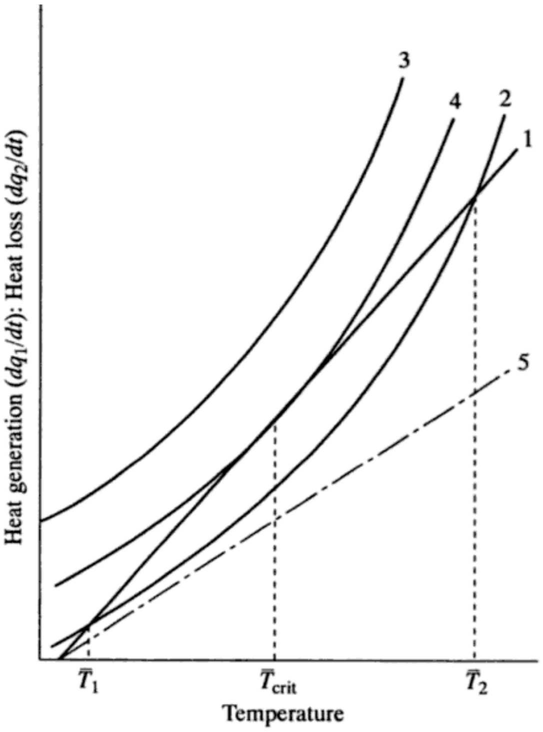


Figure 2-4: Heat generation and heat loss as a function of temperature. [9]

Figure 2-4 illustrates three possible scenarios of heat generation in opposition to heat loss:

- Case 1 – Line 1 represents the heat loss line and curve 2 the heat generation curve.

  The heat generation curve intersects the heat loss line in three points, two of them shown in the figure. These represent points of stationary states. Increase in temperature over $\bar{T}_1$ will be counteracted by an increase in rate of heat loss greater than rate of heat generation. This leads to cooling of the system if heating is stopped; the temperature will decrease to $\bar{T}_1$. The other intersection point, $\bar{T}_2$, represents an unstable stationary state. If the temperature is raised at this point, the rate of heat generation will exceed the rate of heat loss and explosion ensues. If the temperature is lowered the opposite occurs. Heat loss rate exceeds heat generation rate and temperature reverts to $\bar{T}_1$, the stable stationary point.

- Case 2 – Line 1 represents heat loss line and curve 3 the heat generation curve

  There are no intersection points. The heat generation curve lies above the heat loss line and only explosive states can exist. The same applies to the case where line 5 is the heat loss line and curve 2, 3 or 4 is the heat generation curve. The relation between line 1 and 5 can in this case represent reactants with different concentrations.

- Case 3 – $\bar{T}_{\text{crit}}$ is the intersection point between line 1 and curve 4.

  This point is the last possible stationary state before explosion occurs. This is called the critical state.

As long as the rate of heat generation exceeds rate of heat loss, the reactant will self-heat.

2.5 Flameproof enclosures

This section will give an outline of the principles behind and the function of flameproof enclosures.

2.5.1 History

In 1815 Sir Humphry Davy discovered that iron wire gauze prevents ignition of firedamp by the flame of an oil lamp. The thermal conductivity of the gauze was sufficient to cool the combustion residuals [10]. The close meshed screen prevented the flame to propagate to the surroundings and ignite any firedamp present.

Ninety years later Carl Beyling, a mining engineer, conducted fundamental experiments leading to development of flameproof enclosures. He discovered that ignited firedamp caused an overpressure in a closed enclosure, and that joints of suitable dimensions prevented flame transmission to the surrounding firedamp.

2.5.2 Working principle

A flameproof enclosure, Ex “d”, is an enclosure containing electric parts which can ignite an explosive atmosphere. It is a requirement that the enclosure is able to withstand the pressure developed during an internal explosion. It must also prevent explosion transmission to an explosive gas atmosphere surrounding the enclosure.

To decrease the maximum explosion pressure of an internal explosion, the enclosure can have gaps or joints with narrow openings. These joints must be narrow enough to prevent penetrating combustion products igniting a surrounding explosive atmosphere. Joints have two purposes; to relieve the pressure and to cool down hot combustion products. The shortest path through the joint, from the inside to the outside of the enclosure, is defined as the width of the flameproof joint.

Flameproof enclosure “d” is defined by The International Electrotechnical Commission as an “enclosure in which parts which can ignite an explosive atmosphere are placed and which can withstand the pressure developed during an internal explosion of an explosive mixture and which prevents the transmission of the explosion to the explosive atmosphere surrounding the enclosure” [11].

2.5.3 Quenching distance

For a flame to be able to propagate trough a narrow gap, the heat generated by the combustion reaction must be greater than the heat loss to the wall. The quenching distance (QD) is the smallest gap width a flame can propagate through, without extinguishing [12].

2.5.4 Maximum experimental safe gap

Hot combustion products are able to cause re-ignition if they are not cooled down sufficiently when passing through a gap opening. This can cause re-ignition at smaller gap openings than the quenching distance, if an explosive gas atmosphere is present.

The maximum experimental safe gap (MESG) is defined as the maximum gap, of a joint of 25 mm in width, which prevents any transmission of an explosion [6]. Gap openings in flameproof enclosures must therefore be narrower than the MESG, as illustrated in Figure 2-5. This will ensure that hot combustion products are sufficiently cooled down and re-ignition not possible.

MESG values are determined experimentally. The values are dependent on the fuel-air ratio; therefore the most incentive mixture is tested. That is the fuel-air ratio providing the smallest MESG value. The initial pressure and temperature are also of relevance. Table 2-5 summarizes values for some combustible gases in air at atmospheric pressure and normal temperature.

Table 2-5: The MESG values of some combustible gases in air at atmospheric pressure and normal temperature [5].

Gas	MESG value (mm)	Explosion group	Most incentive mixture (vol. % in air)
Methane (firedamp)	1.14	I	8.2
Propane	0.92	IIA	4.2
Ethylene	0.65	IIB	6.5
Hydrogen	0.29	IIC	27

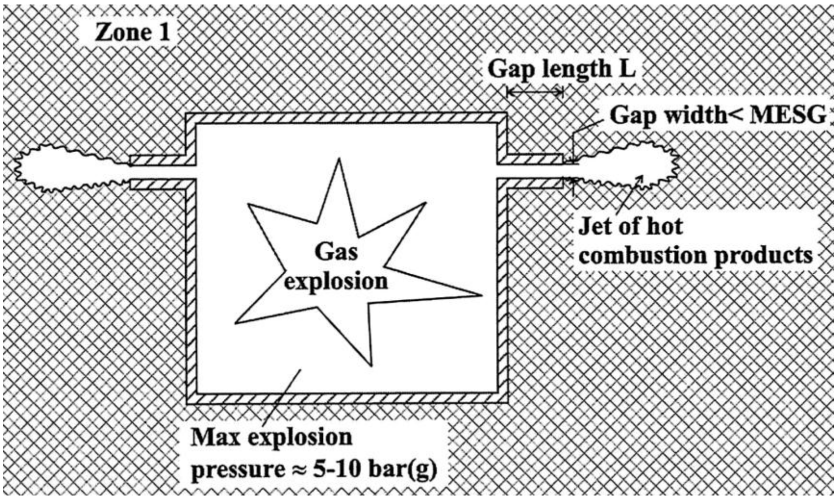


Figure 2-5: Illustration of a flameproof enclosure (Ex ‘d’) from [4].

2.5.5 Test method for maximum experimental safe gap

The International Electrotechnical Commission (IEC) is the leading international standards organization. They prepare and publish international standards for all electrical, electronic and related technology. IEC provide an international standardized test method, used to determine maximum experimental safe gap for different gases [5]. The apparatus used consist of an internal and an external chamber, shown in Figure 2-6. The chambers are connected through a circumferential gap with adjustable gap opening and a gap length of 25 mm. Average roughness of the gap surface is required to be < 6.3 µm. The apparatus is filled with a known mixture of gas and air, under normal temperature and pressure. The mixture is ignited and the flame propagation is observed. By adjusting the gap in small steps, he MESG value for the gas is determined.

10 explosion tests at each gap opening, at a number of concentrations around the most incentive mixture, are performed to confirm MESG values.

Probability of ignition is used as an indication of the accuracy of values found. Experimental results give values for the highest gap, g_0, at which there is 0 % probability of ignition, and the lowest gap, g_{100}, giving 100 % probability of ignition. The gap opening of 0 % probability of ignition, g_0, is defined as the MESG value of the gas.

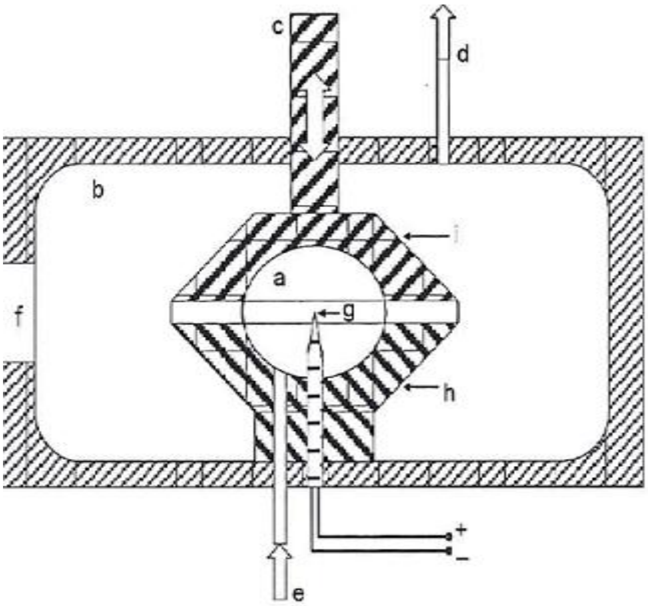


Figure 2-6: Illustration of the test apparatus used by IEC for determination of the maximum experimental safe gap [13].

2.6 Explosion transmission through narrow gaps

Gaps or joints in a flameproof enclosure have two purposes, as emphasised in section 2.5.2:

- The flame resulting from an internal explosion has to be quenched.
- The hot products of combustion have to be cooled down sufficiently to not cause ignition of an explosive atmosphere surrounding the enclosure.

2.6.1 Flame quenching by a cold wall

The quenching distance, as discussed in section 2.5.3, is the smallest width of a gap that a flame can propagate through. Williams introduced two ignition criteria [12]:

- *Ignition will occur only if enough energy is added to the gas to heat a slab about as thick as a steady propagating laminar flame to the adiabatic flame temperature.*
- *The rate of liberation of heat by chemical reactions inside the slab must approximately balance the rate of heat loss from the slab by thermal conduction.*

By using these two criteria for ignition and quenching, an energy balance for quenching can be made. In this simplified energy balance heat loss due to convection is neglected.

$$\dot{Q}_{G,flame}V = \dot{Q}_{\text{cond}} \tag{2-3}$$

$\dot{Q}_{G,flame}V$ - Volumetric heat release rate from the flame
$\dot{Q}_{cond}$ - Heat loss by conduction to walls

The flame quenching is illustrated in Figure 2-7.

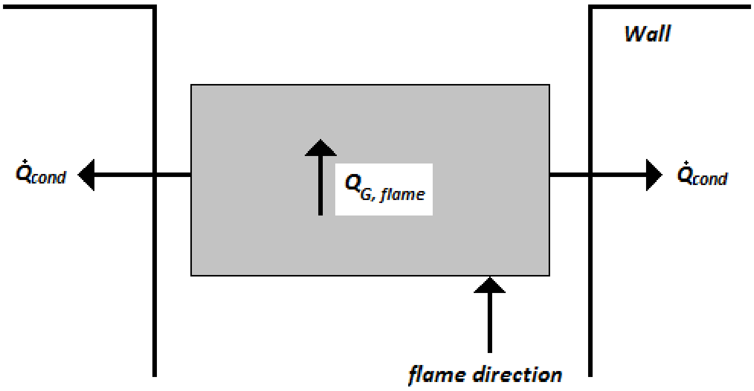


Figure 2-7: Flame quenching in a gap opening between two parallel walls.

A flame arrestor is a device which prevents breakthrough of an explosion flame by extinguishing the flame. The quenching effect is based on the amount of heat transferred from the combustion zone to the gap walls. Experiments with flame arresting devices have not shown significant influence of the wall material or the thermal conductivity on their flame arresting capabilities [1].

2.6.2 Heat transfer to gap wall

When a fluid is flowing through a gap, heat can be transferred by *convection* and *conduction*.

Convection is heat transfer due to movement of fluid. A high temperature combustion gas flowing through a gap with lower temperature will result in heat transfer from the gas to the surface of the gap.

Newton's Law of cooling given in equation (2-4) states that the difference between the surface temperature and the temperature of the fluid is proportional to the heat loss [14].

$$\frac{q}{A} = h\left(T_s - T_f\right) \tag{2-4}$$

q - Rate of heat flow (W).
A - Surface area of the heat being transferred (m^2).
T_s - Surface temperature (K).
T_f - Fluid temperature (K).
h - Heat-transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$).

The fluids heat-transfer coefficient depends on both the flow patterns determined by fluid mechanics and the thermal properties it has.

Convection can further be subdivided into free convection and forced convection. Free convection is when a fluid is put in motion because of density gradients in the fluid. Forced convection can be described as fluid flow caused by an external source. The explosion experiments performed in this study leads to temperature and density variations within the fluid flow. Hence, both types of convection occur within the flame gap.

Conduction is heat transfer in a continuous substance due to a temperature gradient. Fourier's Law states that the heat flux is proportional to the temperature gradient but with opposite sign. For one dimensional heat flow, Fourier's Law is given by equation (2-5) [14]:

$$\frac{dq}{dA} = -k\left(\frac{dT}{dx}\right) \tag{2-5}$$

q - Rate of heat flow in direction normal to the surface (W).
A - Surface area (m^2).
k - Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$).
T - Temperature (K).
x - Distance normal to surface (m).

In metals, thermal conduction results from motion of free electrons. Because of this there is close correspondence between thermal conductivity and electrical conductivity.

2.6.3 Effect of wall roughness on fluid flow and heat transfer

The velocity of a fluid flow is zero at the interface between the fluid and the wall surface. This is caused by friction. A rough surface leads to higher friction, which is quantified using a dimensionless number called the friction factor *f*. If a rough surface is smoothed, the friction factor is reduced.

The relative roughness of a wall is a measure of how smooth the wall is. Relative roughness of a pipe wall is the ratio between *k* and *D*, where *k* is a measure of the height of a groove, and *D* is a measure of the diameter of the pipe extending from the bottom of the grooves.

Turbulence in a flow can be described using the dimensionless Reynolds number (Re) which is a measure of the ratio between the viscous forces and the inertial forces. The Reynolds number is defined as [14]:

$$Re = \frac{\rho \overline{V} D}{\mu} \tag{2-6}$$

ρ - Density of the fluid (kg·m^{-3}).
$\overline{V}$ - Average velocity of the fluid (m·s^{-1})
D - Diameter of the pipe (m).
μ - Dynamic viscosity of the fluid (N·s·m^{-2}).

Re>4000 indicates a turbulent flow, while Re<2100 indicates laminar flow.

A moody diagram shows the relation between friction factor, relative roughness and Reynolds number for flow in circular pipes, shown in Figure 2-8.

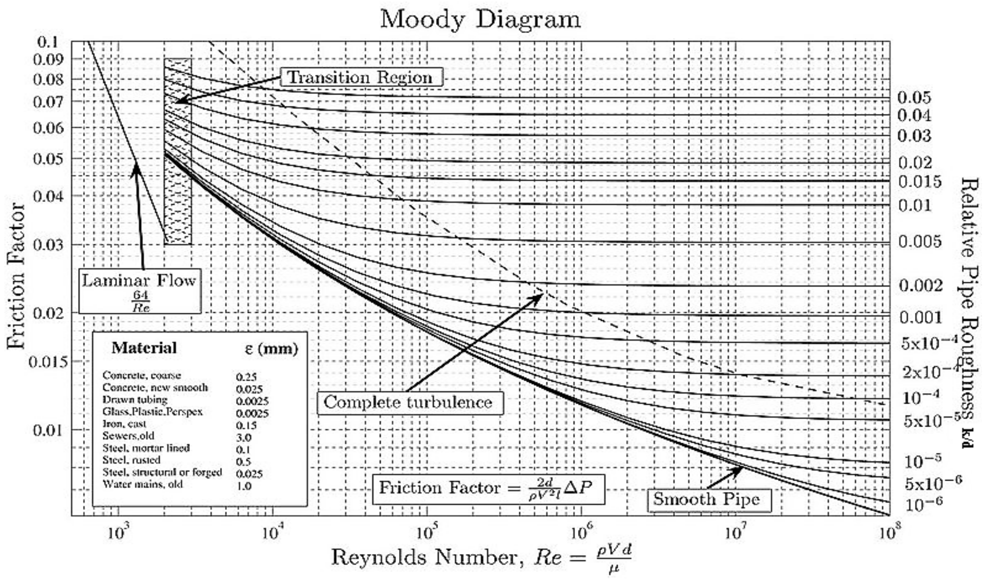


Figure 2-8: Friction factor plot for circular pipes [14].

The equivalent diameter for a non-circular pipe is defined as [14]:

$$D_{eq} = 4\frac{S}{L_p} \tag{2-7}$$

S - Cross sectional gap area (m^2).
L_p - Perimeter of gap (m).

The flow through a safe gap with temperature difference between the walls of the gap and the combustion gas leads to heat transfer. This can be described as a fluid stream in flow parallel to a plate. The flow will develop boundary layers close to the interface of the plate. The velocity at the plate surface is zero and increase to the outer boundary of the layer. This difference in velocity within the fluid is called the hydrodynamic boundary layer. The fluid temperature is higher than the plate temperature. Heat will be transferred from the fluid to the plate and create a temperature gradient in the fluid. This difference in temperature within the fluid is called the thermal boundary layer.

The Nusselt number is ratio of convective and conductive heat transfer across the boundary layer [14]:

$$Nu = \frac{hD}{k} \tag{2-8}$$

h - Convective heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$).
D - Diameter of the pipe (m).
k - Thermal conductivity of the fluid ($W \cdot m^{-1} \cdot K^{-1}$).

If the Nusselt number is close to 1, the convection and conduction terms have relatively similar order of magnitude and thus laminar flow. A large Nusselt number means that the convective heat transfer dominates, hence the flow is turbulent.

The relationship between the thicknesses of the thermal boundary layer and the hydrodynamic boundary layer at a given point along the plate is the dimensionless Prandtl number (Pr). It is the ratio of the viscous diffusion rate and the thermal diffusion rate [14]:

$$\mathrm{Pr} = \frac{c_p \mu}{k} \tag{2-9}$$

c_p - Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$).
μ - Dynamic viscosity ($N \cdot s \cdot m^{-2}$).
k - Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$).

When Pr <<1, conductive transfer is dominant, the thermal diffusion rate is much larger than the viscous diffusion rate. Convective transfer is dominant when Pr >>1. Temperature has little influence on the Prandtl number of gases, since viscosity and thermal conductivity increase with temperature approximately with the same rate.

Roughness leads to change in conditions of heat transfer. The Gnielinski correlation states that the Nusselt number for forced convection in turbulent pipe flow is [15]:

$$\mathrm{Nu} = \frac{\left(\frac{f}{8}\right)(Re-100)Pr}{1+12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}}-1\right)} \qquad \text{2-10}$$

Where f is the friction factor and $3000 \leq \mathrm{Re} \leq 5 \cdot 10^6$. A larger friction factor, hence rougher surface, will increase the heat transfer coefficient and lead to increased heat loss.

2.6.4 Cooling of a jet by mixing with unburned gas

Hot gas flowing through a gap, from a primary explosion chamber to an external chamber, creates a jet. Due to the high pressure in the primary chamber, the jet becomes turbulent with velocity fluctuations. The velocity fluctuations cause the jet to mix with the unburned explosive gas in the external chamber.

The flow field of a turbulent jet can be divided into three different regions as illustrated in Figure 2-9; the core region, the transient region and the fully developed turbulent jet region [16]. If the jet of hot gas achieves favourable conditions and enough energy in any of the regions, it will cause re-ignition in the external chamber.

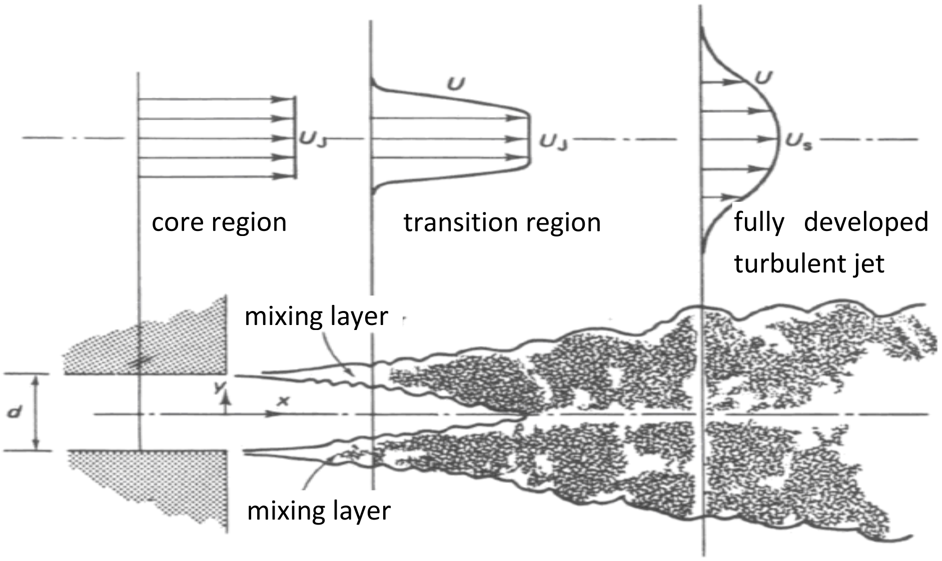


Figure 2-9: Illustration of the flow field of a turbulent jet [16].

The core region is characterized by constant temperature, velocity and concentration, and consists of burned gas. The high velocity of the region provides little contact with the surrounding unburned gas and contact time is often too short to ignite the unburned gas.

In the transition region, the core region develops into a fully developed turbulent jet. The interface between the burnt and unburned gas will increase and the jet will lose velocity. The ratio between the heat generation and the heat loss determines whether ignition occurs.

In the fully developed turbulent jet region, the interaction between the hot and cold gas is at its maximum, hence the cooling of the hot gas is at its maximum. If the heat generation exceeds the heat loss, ignition will occur in this region. The other outcome is that mixing causes the energy of the jet to dissipate to the extent that heat generation does not exceed the heat loss, in which case the explosive unburned gas will not ignite.

2.7 Adding inert gas to an explosive atmosphere

Inert gases, such as nitrogen, argon and helium, are gases that do not readily react with other elements. When added to an explosive atmosphere, it displaces oxygen and thus decreases the danger of oxygen dependant explosions.

2.7.1 Flammability limits

A fuel-air mixture may be described as flammable if it is possible to initiate combustion with an ignition source. Critical flammability concentrations of fuel in air decide the limits of where combustion is possible as pointed out in 2.1.

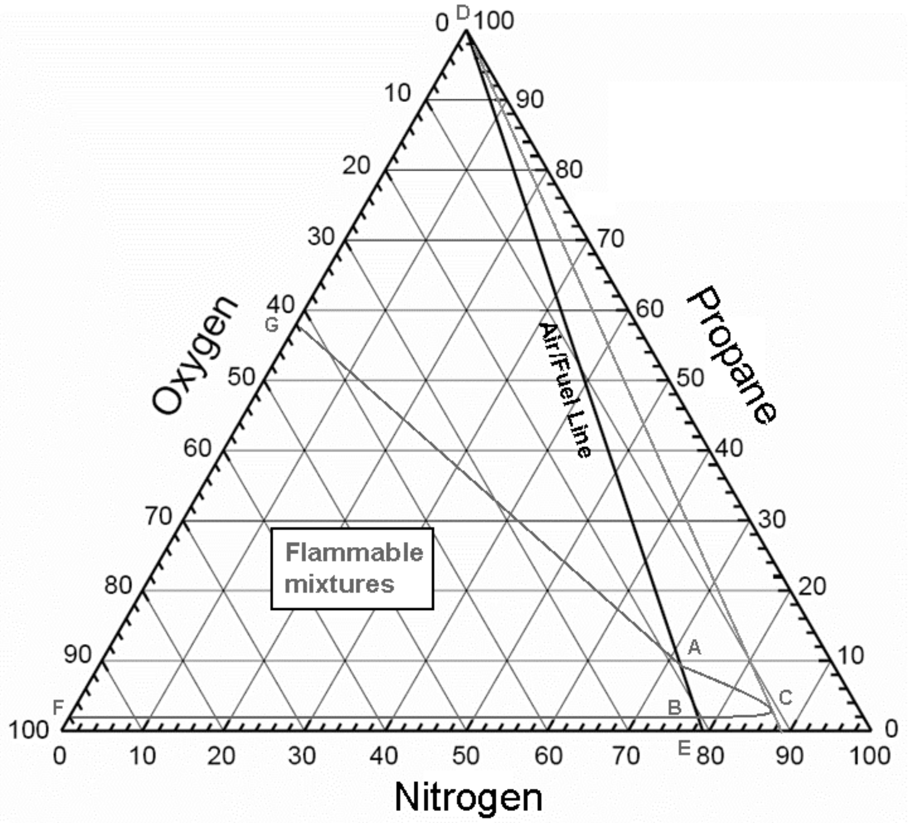


Figure 2-10: Flammability diagram for propane (in vol. %) [17].

Each point in the flammability diagram in Figure 2-10, describes different concentrations of oxygen, nitrogen and propane. The diagram area of which the mixture is flammable is limited by the lines between point G-A-C-B-F. Air – fuel combinations are found along the air/fuel line from point D (100 % propane) to point E (air – 79 % nitrogen, 21 % oxygen, 0 % propane.) The lower flammability limit (LFL) and the upper flammability limit (UFL) for propane in air are plotted at points B and A respectively. The line from point D, tangential to point C is the limit line. Along this line the ratio between nitrogen to oxygen is fixed. Below this, flame propagation is not possible for any amount of propane. This line meets the nitrogen axis at the limiting oxygen concentration (LOC).

In this thesis, the flammable area between A-C-D is evaluated. The area consists of an explosive mixture of propane and air with reduced oxygen content.

Table 2-6: Flammability limits of propane in air at atmospheric pressure and normal temperature. Based on [18].

Flammable substance	Vessel	LFL (vol. % in air)	UFL (vol. % in air)	LOC (N_2) (vol. %)
Propane	Flam. tube [a]	2.1	9.5	11.5
	12-L [b]	2.0	10.0	10.5

[a] Flammability tube data by **[19]**.

[b] Data from 12-L spherical flask by **[20]**.

Table 2-6 show the lower and upper flammability limits in terms of vol. % propane in air. Limiting oxygen concentration (LOC) is defined as the minimum oxygen concentration in a mixture of fuel, air and an inert gas which will propagate flame [18]. The LOC is dependent on pressure, temperature and type of inert gas. The tabulated values are found at atmospheric pressure and normal temperature, using nitrogen as the inert gas.

2.7.2 Partial inertisation

It is not always cost-effective to add the amount of inert gas necessary to reach the LOC value for air-fuel mixtures. One of the focus areas of this thesis is to study how atmospheres with permanently low oxygen concentration (LO), or hypoxic air, affects the MESG value of flameproof enclosures. Reduction of oxygen in air by replacement of nitrogen is an effective measure to prevent fire. Oxygen concentration at 13-15 vol. % prevents many materials being ignited and functions as a mitigating measure for explosions occurring. [18]

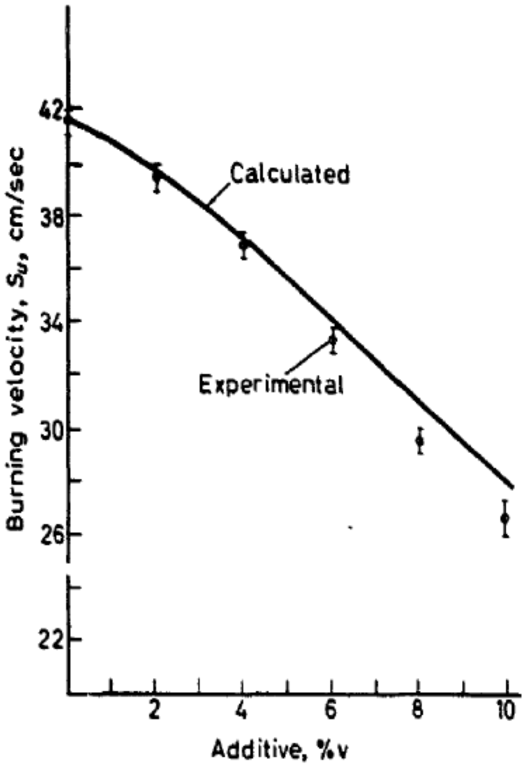


Figure 2-11: Effect of nitrogen on the burning velocity of a propane-air mixture. [21]

LO atmospheres influence the flammability of explosive mixtures. The LFL value increase and the UFL value decrease, creating a smaller interval of ignitable gas mixture with respect to the concentration of the combustible gas. In [21] Yumlu performed experiments in a conical flame burner, adding nitrogen to a 4.2 vol. % propane in air mixture, causing decreased burning velocity as shown in Figure 2-11.

In [22] Movileandu et al. did a study concerning effects of various additives (Ar, N_2, and CO_2) on the burning velocity of ethylene-air mixtures. It was concluded that both burning velocity and maximum flame temperature decreased with increased amount of additive, making the explosion less fierce.

2.7.3 Hypoxic environment

Environment containing hypoxic air where humans can operate at a normal level of activity, for short or extended durations, is called a hypoxic environment. Angerer and Nowak [23] performed a study of the physiological effects on healthy persons working in a room with an oxygen concentration of 13–15 vol. %. It was concluded that the atmosphere did not impose a health hazard. However, their conclusion emphasized that mood, cognitive and psychomotor functions might be mildly impaired in those conditions. They recommended close monitoring of the health problems of people working in low oxygen atmospheres.

A British standard for hypoxic air fire prevention systems defines hypoxic risk categories [24]. In the standard, no risk is associated with respiration of air containing minimum 14.8 % oxygen for healthy persons. With a limitation of 4 hour exposure, healthy persons can work in areas containing 13.0–14.7 % oxygen. Oxygen concentration below 13 % leads to risk of acute mountain sickness and special precautions are necessary.

2.7.4 Effect of oxygen concentration on the MESG

This thesis investigates the influence of nitrogen enrichment of air on the MESG for propane gas. In [25] Lunn studied the effect of oxygen enrichment of air on the MESG values for several flammable gases. It was found that oxygen enrichment had a notable effect on the MESG, which decreased as the oxygen enrichment increased, as seen in Figure 2-12.

The study pointed out that the MESG value depends on three factors:

- The temperature of the jet of hot combustion gas.
- The rate of combustion, hence the composition of the flammable mixture.
- The relative rate of entrainment of ambient mixture into the jet, relative to the mass of the jet.

The relative rate of entrainment depended on three factors: The jet velocity, the density of the hot jet and the size of the jet orifice (dependent on the MESG). High jet velocity and small jet orifice increased the rate of entrainment, reducing chance of re-ignition.

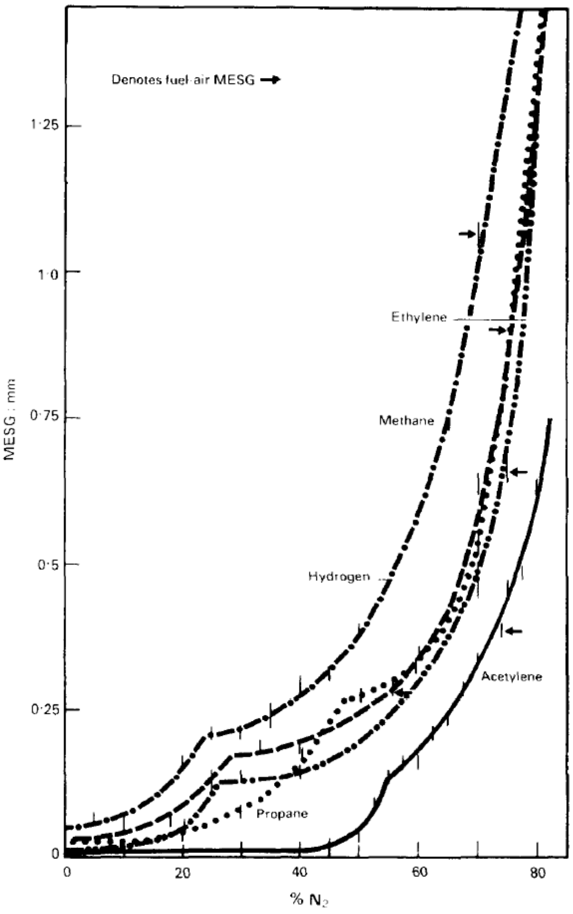


Figure 2-12: MESG measurements for fuel-oxygen in stoichiometric proportions with added oxygen [25].

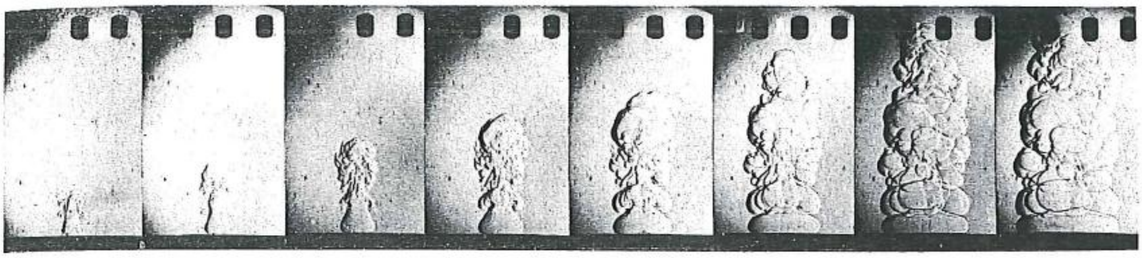
Increasing oxygen concentration in the mixture led to higher rate of combustion and an increase of the internal explosion pressure. The higher explosion pressure increases jet velocity through the safe gap. As pointed out, this reduced the chance of re-ignition. However, both the rate of combustion and the temperature are higher, increasing the probability of re-ignition. To counteract this, a smaller jet orifice is necessary to increase the rate of entrainment to prevent re-ignition. Lowering the safe gap opening does this.

When the oxygen concentration is increased to a relative high level, the flow through the safe gap is choked. As the nitrogen content of the gas mixture decreases, the reactivity of the gas mixture increases and the internal explosion pressure at which the hot jet ejects through the safe gap increases.

2.8 Relevant experimental background

A number of experimental trials have been conducted to investigate the mechanism of flame transmission through a narrow gap.

In [26] Phillips studied why the safe gap of a flameproof enclosure behaves as it does. Based on experimental research he developed a model which calculates the size of the maximum experimental safe gap. Furthermore, to establish the location of the ignition point above the safe gap, a schlieren system was used. This system visualizes density variations in a medium. Experiments showed that with 100 % ignition probability, the external ignition occurred close to the orifice. To find the ignition point within the range of the MESG, the gap opening was reduced to achieve ignition probability of 50 %. This led to an ignition point a distance away from the orifice, varying from 5 to 80 mm. The schlieren photographs showed that the flame first appeared as a sphere at the head of the jet of hot combustion products, shown in Figure 2-13.


(a) Ignition at 100 per cent probability

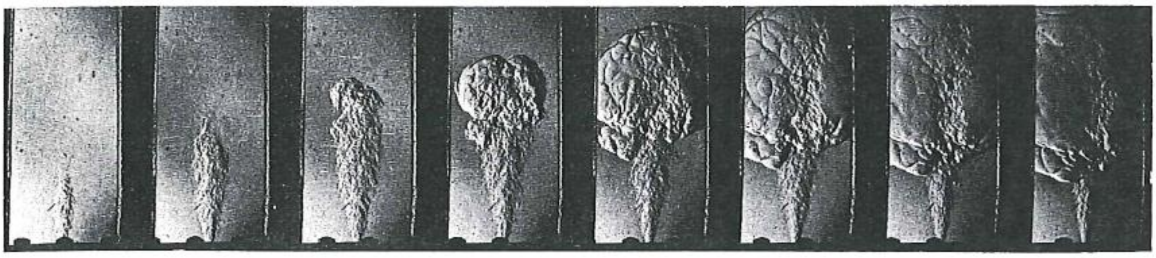

(b) 50 per cent probability

Figure 2-13: Schlieren photography showing difference in ignition position for 100 % and 50% re-ignition position [26].

It was established that heat transfer from hot combustion products were significant. Schlieren photographs of combustion products emerging from a flame arrestor showed visible jets emerging from each channel, showed in Figure 2-14. Phillips explained this as possible to observe because of the temperature gradient in the jets, due to heat transfer to the channel wall. If there were no heat transfer the emerging gas would appear as a single jet.

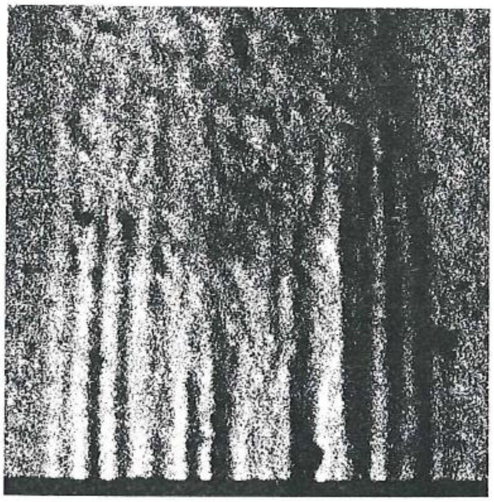


Figure 2-14: Schlieren photography of hot gas ejected through a flame arrestor showing the effect of heat transfer [26].

2.8.1 Previous experiments performed with the PRSA

The apparatus used in the study presented here was constructed by Eckhoff and Larsen [27].

In [27] Larsen studied gas explosion transmission, from the primary to the external chamber, through holes with varying diameters. It was stated that the experimental set-up, the mixture concentration and the ignition position in the primary chamber was of importance when finding the maximum experimental safe diameter, MESD. The volume of the primary chamber was of importance when finding the ignition position giving most re-ignitions. This was explained by pressure rise being coupled to chamber volume. Low explosion pressure may lead to quenching of the flame, because of heat loss to the channel wall. Due to high explosion pressure, turbulence and entrainment of cold un-burnt gas into the combustion zone may extinguish the flame.

The MESD decreased to a minimum when moving the ignition source a certain distance from the hole-inlet. As ignition distance was further increased, the MESD increased as shown in Figure 2-15.

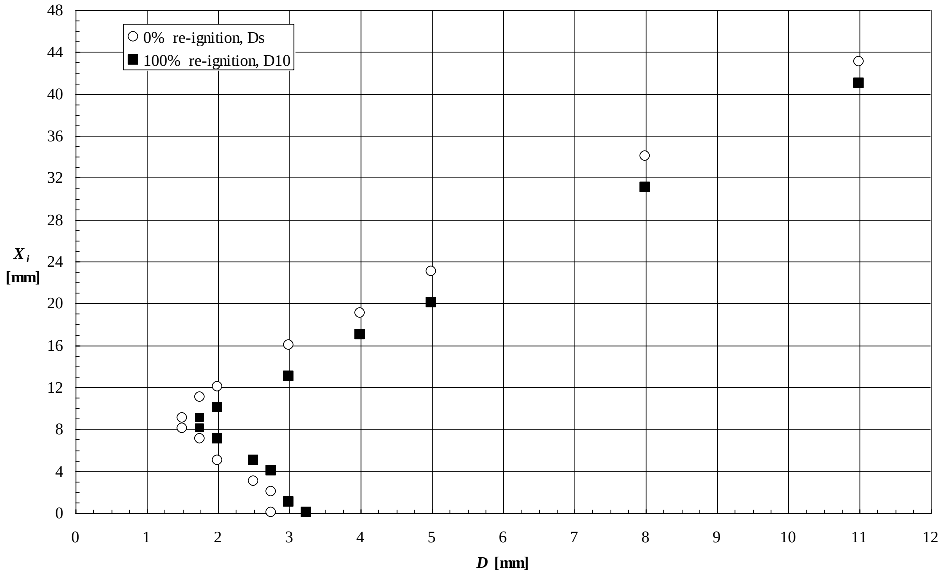


Figure 2-15: Safe diameter D_s *and* D_{10} *for various ignition-distances* X_i*. Primary volume V=1-l and 4.2 vol. % propane-air.[27]*

The concentration that gave the smallest safe diameter, called the optimal concentration, was found to be dependent on the experimental set-up. Larsen used 4.2 vol. % propane in air when conducting his experiments. This was found to be the most incentive mixture in the PRSA.

In [28] Einarsen modified the PRSA to be able to perform experiments with both parallel slits and cylindrical holes. He investigated the relation between gap length and MESG, as well as hole length and MESD. It was found that an increase in gap length led to a systematic increase of the MESG. The same result was found for the experiments with cylindrical holes.

In [29] and [30] Opsvik and Grov conducted experiments with the PRSA and an apparatus with a circular flame gap, the plane circular flange apparatus (PCFA). Experiments were carried out with 4.2 vol. % propane in air. The ignition distance most favourable for re-ignition, in the external chamber in the PRSA, was found to be 14 mm, shown in Figure 2-16.

It was also investigated how surface damages on the flame gap influence the MESG value. Flame gap surfaces were damaged using several methods. Milled grooves, both lengthwise and crosswise the flow direction, were examined. Sets of flame gaps were also exposed to sea water to investigate the influence of rust. Flame gaps with crosswise grooves led to an increase of the MESG value, from 0.98 mm to 1.10 mm in the PRSA. Compared to experiments with undamaged flame gap surfaces, the damaged flame gaps gave higher pressure measurements in the primary chamber. It was suggested that the grooves led to increased turbulence and velocity in the flame gap, giving rise to a more efficient cooling of the combustion jet.

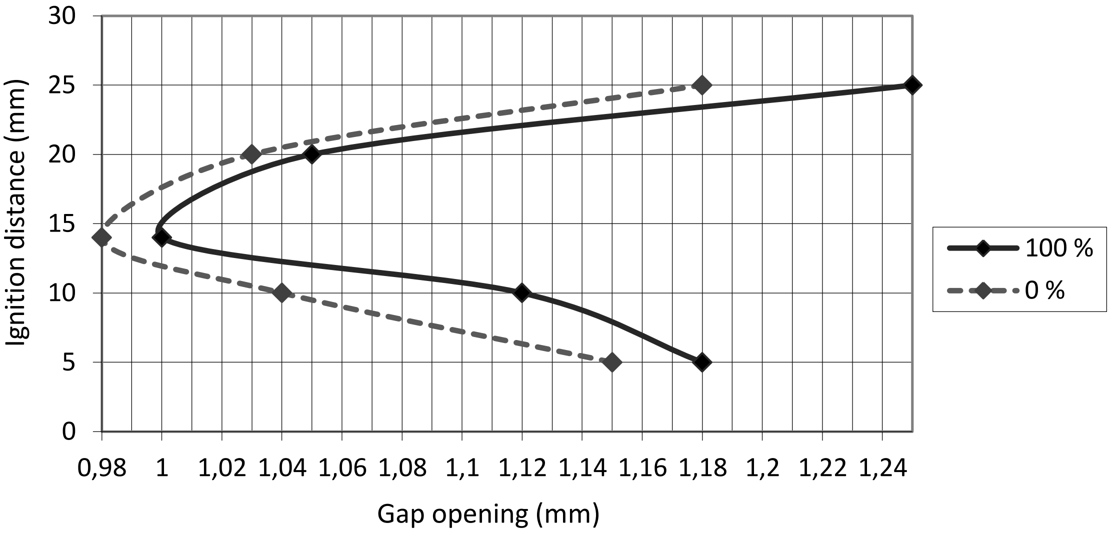


Figure 2-16: Determination of the ignition position most favourable for re-ignition in the external chamber in the Plane Rectangular Slit Apparatus with 4.2 vol. % propane in air. The solid line is the gap opening giving re-ignition for ten experiments for the given ignition position, the dotted line is the gap opening giving no re-ignition for ten experiments for the given ignition position [29].

In [31] Solheim continued the experimental work with the PRSA using 4.2 vol. % propane in air as test gas. He studied temperature deviance over undamaged flame gap and flame gap with multiple milled crosswise grooves, with a gap opening of 0.98 mm. Measurements over undamaged steel slits gave temperature readings of 317°C and 221°C, respectively 2 and 4 cm over the orifice. Temperatures over the damaged flame gap were measured to be 131°C and 86°C, respectively 2 and 4 cm above orifice. The significant deviance was explained with the increased friction factor due to the crosswise grooves. The conclusion was in disagreement with the conclusion given by Opsvik and Grov. The increased relative roughness, k/D (see section 2.6.3), leading to a decrease of flux and velocity of combustion gases flowing through the gap. The combustion products were therefore cooled down significantly more, due to the increased retention time inside the flame gap.

A flame gap of Plexiglas with seven crosswise grooves was made to investigate the influence of heat transfer in slits with low thermal conductivity. During experiments, the slit bent and the walls between the grooves melted. No conclusions could be drawn; it was suggested to make flame gaps of a more robust material with low thermal conductivity for future experiments.

3 Experimental apparatuses

The experimental part of the present work has been done in The Plane Rectangular Slit Apparatus (PRSA). The apparatus was originally designed by Larsen [27] and Eckhoff and has previously been used in experimental work by Larsen [27], Einarsen [28], Grov [29] and Solheim [31].

A list of the experimental apparatuses used in the present work is given in Appendix A.

3.1 The Plane Rectangular Slit Apparatus

The Plane Rectangular Slit Apparatus, denoted PRSA, consists of a cylindrical primary and external chamber as shown in Figure 3-1.

The primary chamber has a volume of 1 litre and is made out of steel. It contains an ignition source with variable ignition position and a piezoelectric pressure transducer. The external chamber is 3 litres and made out of Perplex. This makes is possible to visually confirm re-ignition in the chamber. It contains two thermocouples mounted directly above the flame gap orifice. Explosion ventilation is at the top of the external chamber.

The interchangeable flame gap is mounted on a removable plate between the primary and the external chamber. The external chamber can easily be removed by unscrewing it from the primary chamber, releasing the flame gap plate, making inspection and adjustments easy.

Experimental procedure for the PRSA is described in Appendix D.

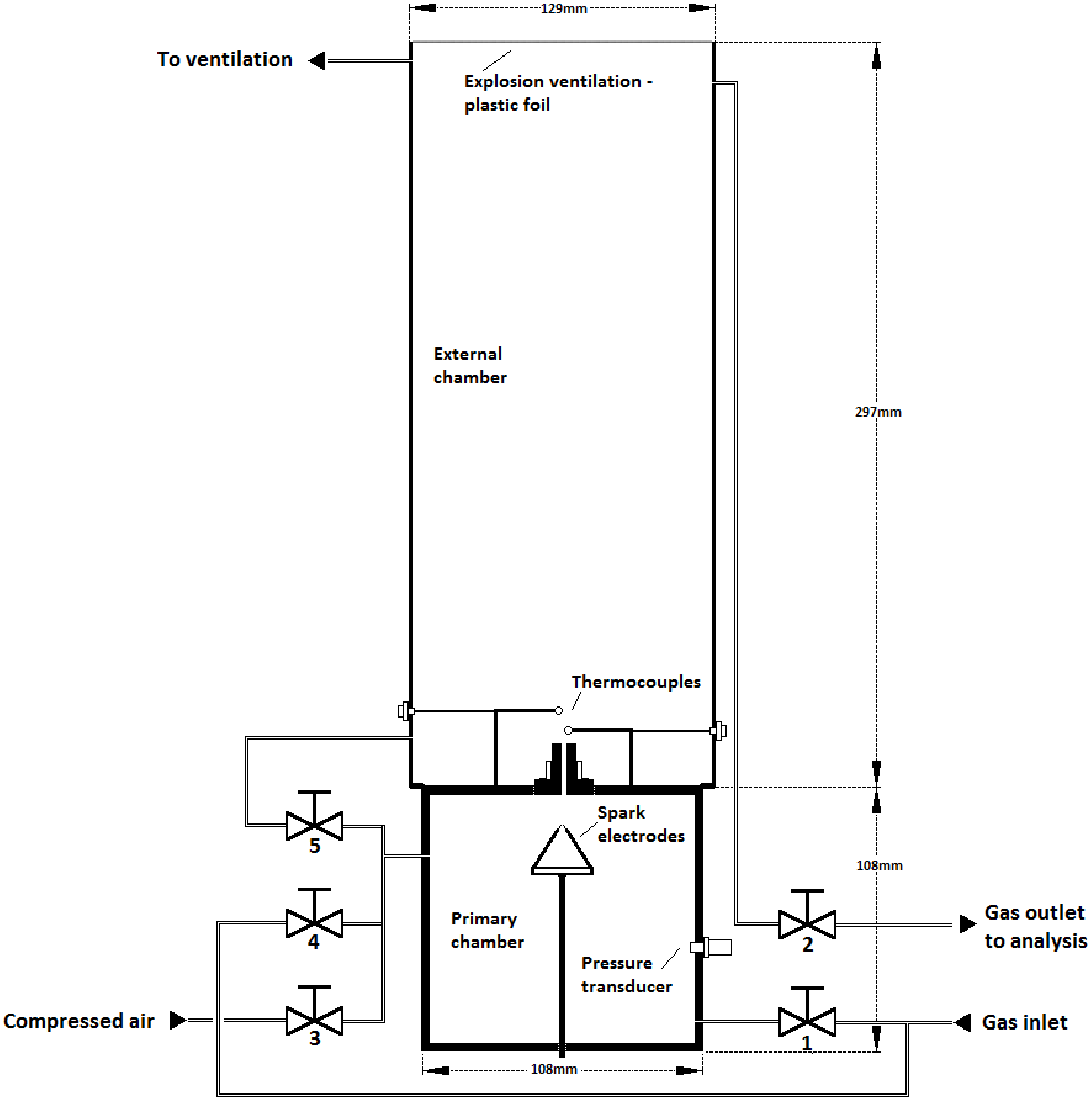


Figure 3-1: The Plane Rectangular Slit Apparatus, shown with tubing. Compressed air inlet is connected to the compressed air system of UoB. The gas inlet and outlet is connected to the gas analyser.

3.1.1 Ignition source

Spark electrodes in the primary chamber function as the ignition source in the PRSA. The spark electrodes are connected to a spark generator with an external trigger device. An electric spark in the primary chamber is provided when the spark generator is triggered.

The position of the ignition source in the primary chamber is vertically adjustable. The ignition position is referred to as the distance from the top of the spark electrodes to the flame gap entrance. Experiments Grov [29] and Solheim [31] conducted showed that an ignition position of 14 mm gave most re-ignitions in the external chamber. This distance is used in the experimental work in this thesis, as the most incentive ignition position.

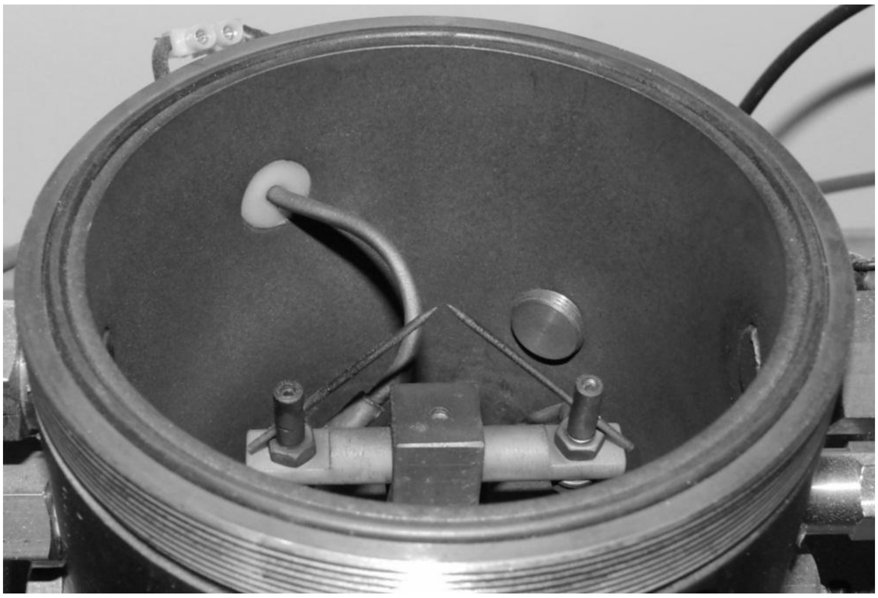


Figure 3-2: Spark electrodes shown in the centre of the primary chamber.

3.1.2 Thermocouples

Thermocouples are used to measure the temperature of combustion products leaving the flame gap. Two thermocouples were mounted on steel rods inside the external chamber, vertical above the gap opening, as shown in Figure 3-3. The heights of the steel rods are adjustable and secured that the thermocouples were at the same height and position throughout the execution of the experiments. The height was controlled to not have been altered after each set of explosions.

Thermocouple specifications and welding procedure are given in Appendix F.

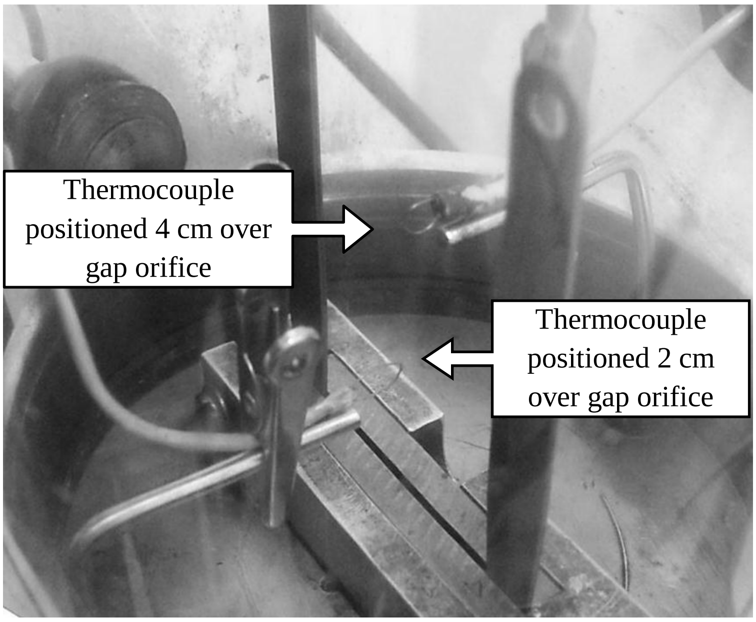


Figure 3-3: Thermocouples fastened at two distances directly over the flame gap opening in the external chamber. At each side of the gap orifice, distance shims are viewed.

3.1.3 Flame gap

The flame gap consists of a pair of plane slits with equal material characteristics. The slits are mounted between the primary chamber and the external chamber on the flame gap plate, creating a passage between the chambers. This distance is referred to as the flame gap opening.

Distance shims with variable thicknesses, from 0.03 mm to 1.00 mm, are used to adjust the distance between the slit pairs. Shims are placed at each side and throughout the gap to ensure uniform and controlled gap opening. Low torque is used when fastening the flame gap on the flame gap plate to not squeeze the flame gap together, making the gap opening smaller than intended or not uniform.

The procedure for adjustment of flame gap opening is given in Appendix B.

All slits used in the experimental work has equal dimensions. Slits shown in Figure 3-4 have the dimensions tabulated in Table 3-1.

Table 3-1: Dimensions of slits used to create the flame gap in this thesis.

Specification	**Measure**
Length of slit (mm)	25.0
Width of slit (mm)	56.3
Thickness of slit (mm)	5.0

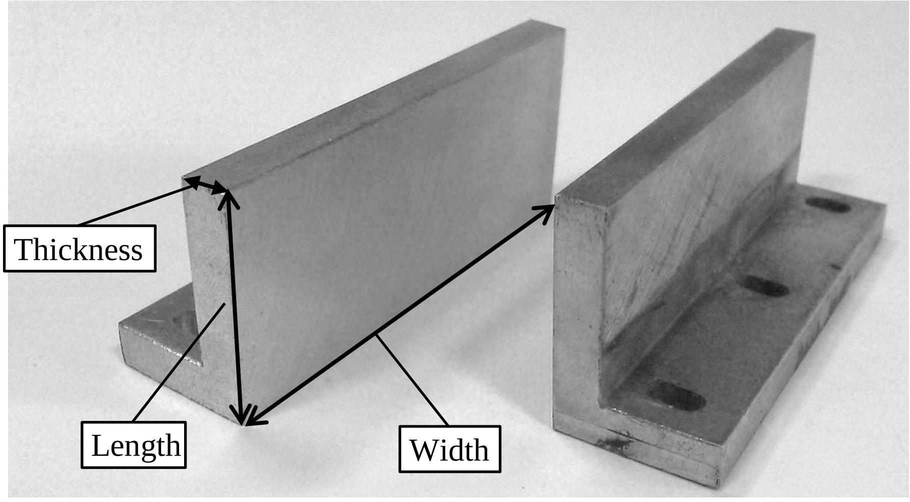


Figure 3-4: A pair of slits with dimensions tabulated in Table 3-1.

Different materials have been used to fabricate slits used in this thesis. Some material and slit specifications are presented in Table 3-2.

Table 3-2: Properties of the different slits materials used. Values from [14] and [32].

Material property (25°C)	**Slit material**			
	Carbon steel	**Brass**[1]	**Aluminium**	**Polyoxy-methylene (POM)**
Weight of slit pair (g)	159.0	169.4	53.2	28.0
Thermal conductivity (W/m°C)	45	96	202	0.36
Specific Heat (J/g°C)	0.49	0.38	0.90	1.46

3.1.4 Flow in the PRSA

Ignition in the primary chamber leads to spherical flame propagation. The flame front drives unburned reactants through the flam gap due to expansion of the hot combustion products. Pressure increases as the flame front approach the flame gap entrance. The flame is quenched if the flame gap opening is less than the quenching distance. Hot combustion products penetrates the gap and into the secondary chamber. An illustration of the flame front propagation, at time t, is given in Figure 3-5.

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[1] The brass consists of an alloy of 58 % copper, 39 % zinc and 3 % lead.

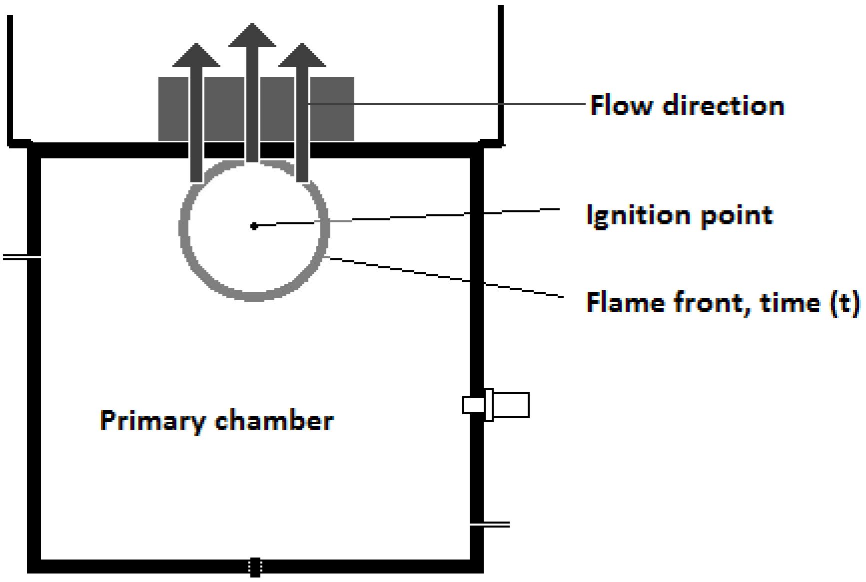

Figure 3-5: Propagation of the flame front from the ignition point at time (t).The flame front develops as a sphere from the ignition point.

3.1.5 Gas composition

The gas composition used in the experiments conducted, is mixed and analysed in the Servomex 4200 gas analyser. The premixed gas is fed to the bottom of the primary chamber and to the bottom of the external chamber. This is done to make the filling more efficient, as opposed to having one filling point. Ventilation from the top of the external chamber helps reduce the pressure in the apparatus, during filling, to a level the plastic foil can withstand. Gas is taken from the top of the external chamber and led to the gas analyser where it is continuously analysed for oxygen and propane content. When the analysed values stabilize, the gas feed is closed.

The gas mixtures used in this thesis consist of propane and air, and propane mixed with three compositions of nitrogen enriched air. Air was taken from the pressurised air system of the laboratory, while the nitrogen enriched air were premixed on bottles.

Operation instructions and calibration procedure of the gas analyser, Servomex 4200, is given in Appendix C and Appendix D.

3.2 Measurement and control system

A tailor made data acquisition and control system for the PRSA is illustrated in Figure 3-6. This was used in the experiments to measure temperature and pressure, and to control the ignition source.

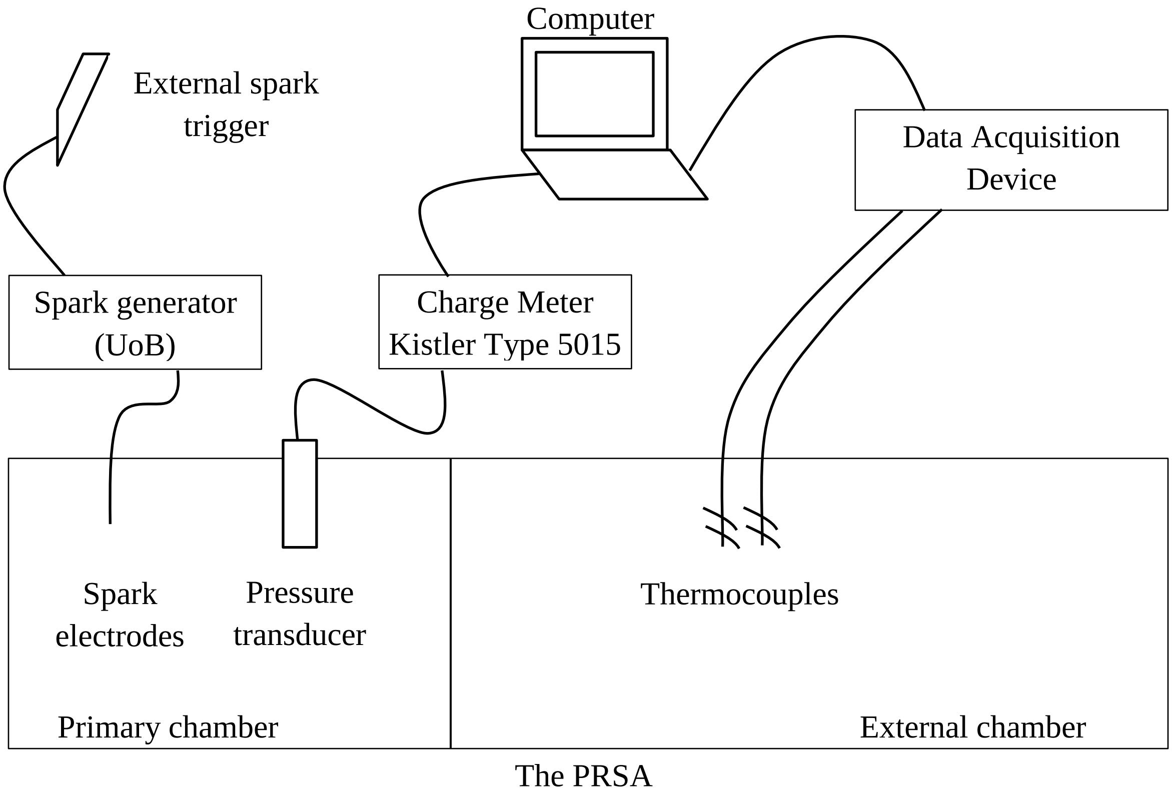

Figure 3-6: The measurement and control system of the PRSA.

Operational procedures for the data acquisition system are given in Appendix E.

3.3 Sources of error

This chapter is based on chapter 3.9 in [31].

3.3.1 Data Acquisition system

The experience from the work performed in this thesis shows that the amplification of the measured signal is of importance. The analogue/digital converter reads all the channels and have switches inside which chooses which channel to read. If one channel is not satisfactorily amplified, the signal from this channel influences the signal from the next reading.

3.3.2 Gas concentration measurements

Calibration of the propane analyser was done with a certified gas containing 5.00 vol. % propane in nitrogen. Calibration of the oxygen analyser was done with regular air, according to the manufacturer, with a calibration value of 20.95 vol. % oxygen. Zero calibration of the analyser was done with gas containing 99.999 vol. % nitrogen. The measurements close to these values would have the highest accuracy and as the gas mixture departs from these values the accuracy would be somewhat lower. For mixtures far from the reference point, the accuracy depends on the linearity between the two points or the extrapolation towards a richer mixture. The alternative is how well the analyser calibrates for nonlinearity.

Insufficient calibration could result in uncertainties with respect to concentration measurements. All calibration of the gas analyser has been executed in accordance with the calibration procedure enclosed in Appendix C.

Another parameter which can have an influence on the actual gas concentration both in the primary and external chamber is that the mixture in the chambers may not always be homogenous.

3.3.3 Air humidity

The propane used in the experiments is mixed with air from the local pressurised air system. No measurements of humidity are done, but the air is filtrated and dried in a unit downstream the air compressor. In any case the quality of the air is not documented and pollution in form of oil, dust particles or water may exist in the supplied air. This may have effects on the results.

3.3.4 Pressure

There is uncertainty in the pressure readings due to the resolution of the pressure transducer. Kistler, the manufacturer of the piezoelectric transducer and amplifier, states that the accuracy of the measurement is ≤ ± 0.08 % of Full Scale Output when the calibration range is in the area of 0 to 25 bar. This gives an accuracy of ± 0.02 bar at the used measuring range, which is well within acceptable limits.

The pressure transducer is mounted a fixed distance at the vertical chamber wall of the primary chamber. The transducer does not detect local pressure gradients in the chamber.

3.3.5 Temperature

The thermocouples used in this work are not constructed to measure temperatures in explosions (or jets). The extremely rapid increase in temperature, due to the explosion, causes some uncertainty to the measured temperature. It is assumed that the temperature difference measured between different experiments is valid.

3.3.6 Condensed water

After a few explosions water will typically condense on the inside of the walls of the primary chamber and may represent a significant source of error. Water may evaporate from the warm vessel walls during gas filling and the subsequent period of turbulence settling, altering the gas composition. Water in the gas mixture may affect reaction mechanisms and heat capacity, whereas a small portion of the water at the vessel walls may evaporate during the explosion. It is assumed that the explosions will be too rapid for significant amounts of water to evaporate.

3.3.7 Experiments

There are uncertainties due to construction tolerances in size of volumes, ignition positions and flange diameters and distances. In addition, there is accuracy related to the experimental work, although good experimental procedures would counteract this.

The dimension of the distance shims is observed to have a variation of approximately +/- 1 hundredth of a millimetre.

4 Experimental results and discussion

In this chapter the results and discussions from the experimental work are presented. The experiments have been carried out in the Plain Rectangular Slit Apparatus with propane as the fuel gas. Figure 4-1 shows an example of an explosion propagated from the primary chamber to the external chamber. Combustion gas from the explosion in the primary chamber ignites the explosive atmosphere in the external chamber.

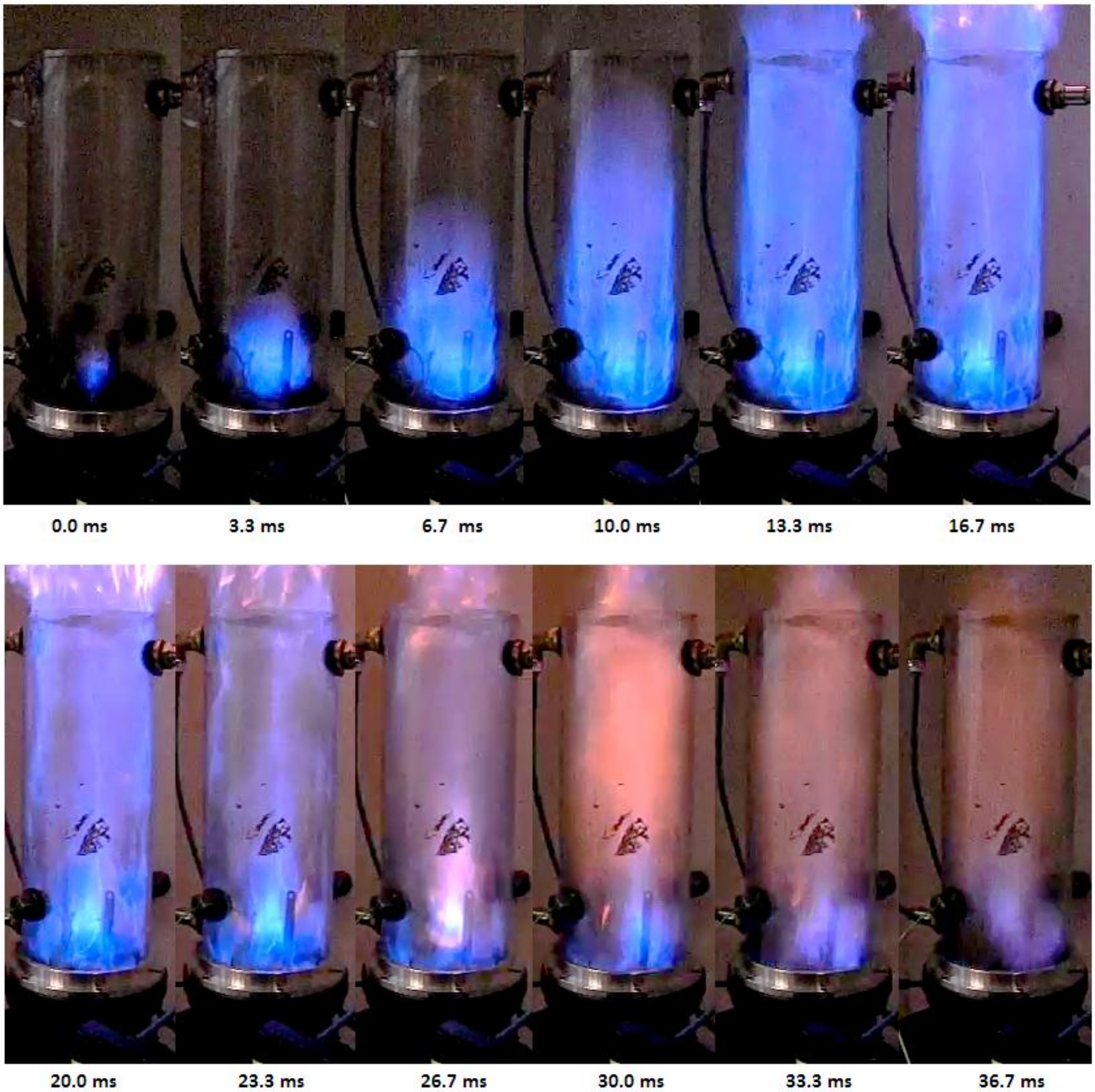

Figure 4-1: Explosion propagation in the PRSA. Experiment performed using steel-slits with 1.01 mm gap opening, in air with 4.20 vol. % propane. The black spot on the external chamber is due to fastening of thermocouples during assembling.

The two main objectives of this study have been:

- To investigate the effects of heat transfer on the maximum experimental safe gap by varying the flame gap material, hence the thermal conductivity. The experiments were performed with a test gas consisting of 4.2 vol. % propane in air.

In this study the temperatures over the flame gaps has been measured while varying the gap material. The objective was to investigate any significant temperature deviations related to material specifications. The temperature deviations observed was further investigated to find out whether this influenced the MESG value or not. Sections 4.1 and 4.2 consist of results and discussion of the experimental data obtained.

- To investigate the influence on the MESG when performing experiments with various mixtures of propane and nitrogen enriched air.

The study was performed by finding the most incentive mixtures of propane and nitrogen enriched air, followed by a determination of the MESG value for the different mixtures. Section 4.3 consists of results and discussion of the experimental data obtained.

4.1 Temperature measurement above flame gaps

Slits with different thermal properties were fabricated and tested in the PRSA. Some of the material properties are listed in Table 3-2. A combustible gas consisting of 4.2 vol. % propane in air was used for the tests.

Temperature measurements in the external chamber were performed at two altitudes, 2 cm and 4 cm, directly over the flame gap opening. A minimum of 5 consecutive experiments was conducted to ensure the temperature measured was repetitive. The temperatures presented are mean values from experiments not causing re-ignition in the external chamber.

4.1.1 Results

Slits made out of brass, aluminium and carbon steel were examined at two gap openings. Brass slits with gap opening of 0.98 mm caused re-ignition in the external chamber and is not included in Table 4-1.

Table 4-1: Mean temperature measured over the flame gap in the external chamber of the PRSA. Test gas of 4.2 vol. % propane in air.

		Temperature (°C) at measuring distance	
Gap opening (mm)	**Slit material**	**2 cm**	**4 cm**
0.95	Brass	316.3	246.0
0.95	Aluminium	298.7	225.9
0.95	Steel	285.1	209.6
0.98	Aluminium	325.2	241.8
0.98	Steel	316.3	228.1

Slits made out of brass gave the highest temperature readings and steel slits gave the lowest readings, as seen in Table 4-1. With a gap opening of 0.95 mm, the temperature 2 cm over the flame gap was 316.3°C for brass slits, while for steel slits a temperature of 285.1°C was obtained. When increasing the gap opening to 0.98 mm, use of brass slits caused re-ignition in the secondary chamber, and the results could not be used. Aluminium slits gave temperature readings between values for steel slits and brass slits, when the gap opening was 0.95 mm.

Slits of polyoxymethylene (POM) were temperature measured using two gap openings, 0.98 mm and 1.01 mm. Experiments were conducted 3 times at each gap opening. The reason for this was that when examining the POM slits after 3 consecutive trials, melting had started to occur at the gap entrance. The surface of the gap was smoothed by the heat of the combustion products, compared to new slits. No re-ignitions in the external chamber were observed while testing POM slits at these gap openings.

Table 4-2: Temperature measurements over flame gap of POM.

Gap opening (mm)	Test number	Slit material	Temperature (°C) at measuring distance 2 cm	4 cm
0.98	1	POM	365.6	298.8
0.98	2	POM	370.0	295.1
0.98	3	POM	382.2	309.0
1.01	1	POM	407.3	N/A
1.01	2	POM	412.5	N/A
1.01	3	POM	438.7	N/A

Table 4-2 shows temperature measured over the POM flame gap, using two measuring distances and conducting three tests for each gap opening. The experiments show an increase of temperature during the test series.

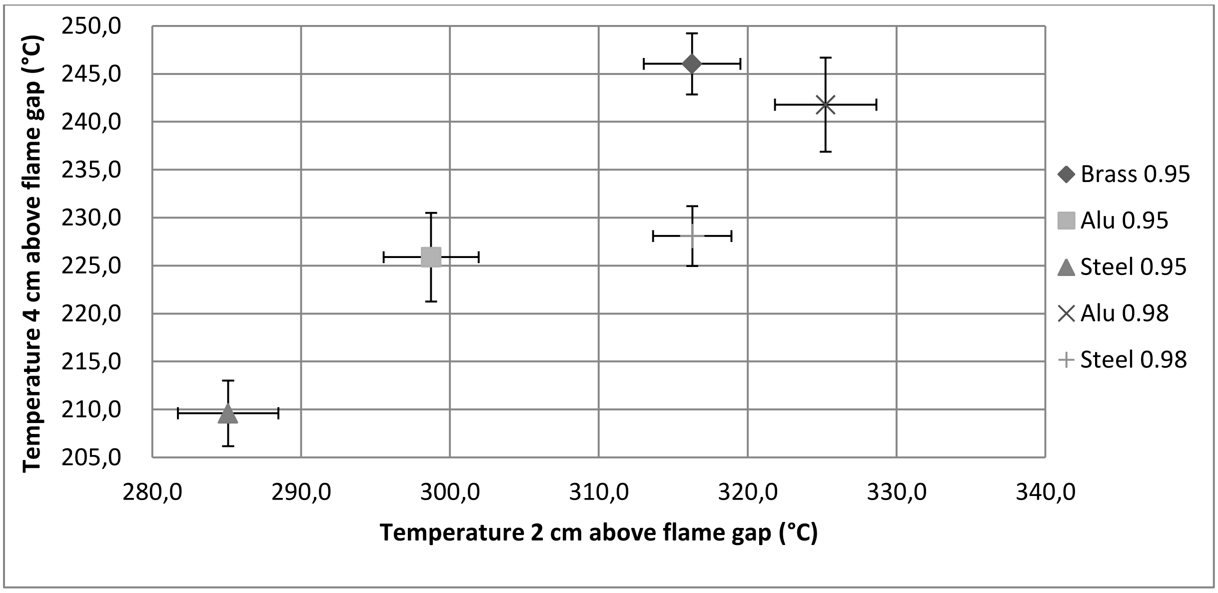

Figure 4-2: Temperature measurements over flame gaps made of different materials, using two measuring distances and two gap openings. The figure shows the mean temperature and standard deviation.

Figure 4-2 show mean temperatures measured at the two heights above the gap orifice. Temperature values for steel, brass and aluminium are included, while temperature values for POM is not included in Figure 4-2 because of the varying measurements tabulated in Table 4-2.

4.1.2 Discussion

Temperature measurements of the hot combustion gas in the external chamber gave dissimilar temperature measurements, with different flame gap materials. Measurements over brass slits, with a gap opening of 0.95 mm showed higher readings of temperature than over aluminium and brass. Heat transfer across materials of high thermal conductivity occurs at a higher rate than across materials of low thermal conductivity, see section 2.6.2.

The thermal conductivities of the flame gap materials are tabulated in Table 3-2. With carbon steel having 45 W/m°C, brass 96 W/m°C and aluminium 202 W/m°C. It could be expected that flame gaps made of metals with high thermal conductivity has higher conductive heat transfer, compared to materials with low thermal conductivity. The high thermal conductivity should then cause the jet to lose some of its energy, and emerge with a lower temperature. It is clear that other factors influence the heat transfer to the gap and that conductivity is of minor importance. A possible explanation for the findings of higher temperatures over brass slits is oxidation of the gap surface of the brass. Oxidation of brass occurs when the copper molecule comes in contact with oxygen. This process may affect the heat transfer ability of the brass surface in such way that the heat loss of the jet decrease.

The temperature of a jet emerging from a gap is of importance of the MESG value of the gas. The re-ignition occurring at 0.98 mm, when brass slits were used, supports the findings of higher temperatures over brass slits, compared to slits of steel and aluminium, at gap opening of 0.95 mm.

Temperature values measured, using the same gap opening, can be compared. When comparing the data in Table 4-1 and Table 4-2, it can be seen that temperatures measured above POM slits, with gap opening of 0.98 mm, are larger than comparable temperatures over the metal gaps. Thermal conductivity of POM is 0.36 W/m°C, 1/125 of the value of steel. This may cause the jet to emerge at a higher temperature, thus having insulating properties.

Table 4-2 show a systematic increase of measured temperature over POM slits, from test number 1 to test number 3. Electro microscopic photos show a smoothing of the gap surface occurring during tests. See Appendix J for comparable photos of new and tested POM slits. From 2.6.3, a smoother surface, will decrease the heat transfer coefficient and lead to decreased heat loss. The increase of temperature may be the result of reduced friction inside the gap, due to the smoothing.

When increasing the gap opening, a temperature increase for both the steel slits and the aluminium slits are observed. The temperature of the jet is a result heat loss to the walls and heat generated in the combustion. When the gap opening is increased, the wall area in contact with the jet, relative to the mass of the jet is decreased. Hence the temperature of the jet is increased.

4.2 Experiments with slits in mixture of propane and air

Of the metal gaps examined, steel and brass flame gaps gave temperature readings with the largest spread. The slits were examined further to find out what influence they had on the MESG value. The value was found according to the IEC test method for maximum experimental safe gap, described in section 2.5.5. Ten explosion experiments were performed at each gap opening. The highest value of gap, g_0, at which there is 0 % probability of ignition in the external chamber, is defined as the MESG value of the gas.

Obtained MESG value using steel-slits in regular air was 0.98 mm as shown in Table 4-3. The value coincide with the MESG previously reported by Solheim [31]. A gap opening of 0.97 mm gave two re-ignitions, while a gap opening of 0.98 mm gave zero re-ignitions. The lowest gap, g_{100}, giving 100 % probability of ignition was 1.01 mm.

Table 4-3: Experiments with steel-slits.

Gap opening (mm)	**Ignition distance (mm)**	**Number of experiments**	**Number of re-ignitions**	**Mean pressure (barg)**
0.97	14	10	0	2.32
0.98	14	10	0	2.29
0.99	14	10	2	2.22
1.00	14	10	8	2.23
1.01	14	10	10	2.33

The MESG value found using brass-slits in regular air was found to be 0.97 mm as shown in Table 4-4. The gap opening of 0.98 mm gave three re-ignitions while gap opening of 0.97 mm gave zero re-ignitions. The lowest gap, g_{100}, giving 100 % probability of ignition was 1.00 mm.

Table 4-4: Experiments with brass-slits.

Gap opening (mm)	**Ignition distance (mm)**	**Number of experiments**	**Number of re-ignitions**	**Mean pressure (barg)**
0.97	14	10	0	2.34
0.98	14	10	4	2.31
0.99	14	10	9	2.18
1.00	14	10	10	2.23
1.01	14	10	10	2.34

From Table 4-3 and Table 4-4, it can be seen that values for g_{100} and g_0 are 0.01 mm less for brass compared to the experimental data of steel. This indicates equally reliable values, according to IEC [5].

4.2.1 Discussion

The MESG value obtained, for the most incentive mixture of propane in air, when using brass slits compared to value obtained when using steel slits are not equal. MESG value using steel slits were observed to be 0.98 mm, while using brass slits 0.97 mm, a deviation of 0.01 mm. Brass gives a lower value, as expected from experiments discussed in 4.1.2.

When examining the slit surface of the two flame gaps, there are no readily apparent deviations between the two surfaces. The slits are milled using the same equipment; the surface roughness is of equal dimension, 2.0 µm [29]. This value is well within the IEC requirement of < 6.3 µm. Electro microscopic photography of the two slit surfaces show no significant deviance between the surfaces. See Appendix J for comparable photo. There may be some small surface damages on the steel slit surface which can be related to increased turbulence in the flame gap. This can lead to increased heat loss to the gap walls and explain the higher MESG value.

According to the IEC standard, the maximum gap opening for flameproof enclosures, with the dimensions of the test apparatus used in this thesis, is 0.40 mm [5]. The material properties of the flameproof gaps of metal, tested in this thesis, are of minor importance to the MESG value of propane.

The pressure measurements show that the mean minimum pressure is obtained when probability of re-ignition is between 20 % and 9 0%. For steel slits the value is obtained at 0.99 mm and 20 % re-ignition probability while for brass slits it is obtained at 0.99 mm and 90 % re-ignition probability. When re-ignition probability is 100 %, measurements show that the maximum pressure in the primary chamber increases, despite a larger gap opening. Re-ignition in the external chamber increases the pressure above the gap orifice resulting in a decreased pressure difference between the primary chamber and the external chamber. Fluids moves from high pressure toward low pressure areas. The pressure difference leads to a higher maximum pressure in the primary chamber, which may be caused by the increased pressure in the external chamber. The same phenomenon can be seen in pressure measurements in the following section, 4.3.

4.3 Experiments with steel slits in mixture of propane and nitrogen enriched air

The experiments were done with three nitrogen-oxygen mixtures with unlike mixture rates. These mixtures contained less oxygen than air. Propane was used as fuel gas, in all trials, and mixed with nitrogen-oxygen according to the experimental procedure in Appendix D.

Due to limited amount of the nitrogen enriched air, trials performed has not been done with 10 consecutive trials for each tested gap opening. However, the MESG value found is verified with 10 consecutive tests.

The procedure done to find the MESG value is in accordance with the IEC Standard [5] for gas and vapour classification, regarding test methods and data. Pressure measurements were conducted using a fixed gap opening and varying the concentration of propane starting at a concentration around stoichiometric value. See Appendix G for calculation of the stoichiometric values of propane in the three nitrogen-oxygen mixtures. The pressure measurements were done to find the concentration value of propane providing the maximum pressure, indicating the most incentive mixture [27].

Preliminary tests were made by adjusting the gap opening several times and varying the concentration of propane. The tests were done to establish the highest gap with 0 % probability of ignition and the lowest gap with 100 % probability of ignition. The indicated most incentive mixture, found using pressure measurements, was used as a basis for propane concentration in the mixture.

The highest gap, g_0, found during preliminary tests was examined with 10 consecutive trials, using concentrations close to the most incentive mixture found in the preliminary test, as specified in the IEC Standard. If no re-ignition occurred during these test series, g_0 was established as the gas MESG value.

4.3.1 Measurements of oxygen content in test gas

Three test gases, containing different ratios of N_2 and O_2 were used in the following experiments. The oxygen content was measured using the gas analyser, succeeding two complete calibration procedures. The two measurements were done one week apart and found to be equal. Values are tabulated in Table 4-5.

Table 4-5: Measured oxygen content and calculated nitrogen content in the three test gases.

Mixture	**Vol. % O_2**	**Vol. % N_2**
ii.	19.00	81.00
iii.	16.77	83.23
iv.	15.04	84.96

The stoichiometric values of propane in the three mixtures are presented in Table 4-6. Calculations are described in Appendix G. As shown in section 2.5.4, the stoichiometric mixture may differ from the most incentive mixture.

Table 4-6: Stoichiometric mixtures of fuel and nitrogen enriched air.

Mixture	**Vol. % C_3H_8**	**Vol. % O_2**	**Vol. % N_2**
ii.	3.66	18.30	78.03
iii.	3.25	16.23	80.53
iv.	2.92	14.60	82.48

4.3.2 Oxygen content of 19.00 volume percentage

Figure 4-3 shows pressure measurement in experiments with mixture ii from Table 4-5, and variable propane concentration. The most incentive mixture, basis for propane concentration is found to be 3.85 vol. % propane.

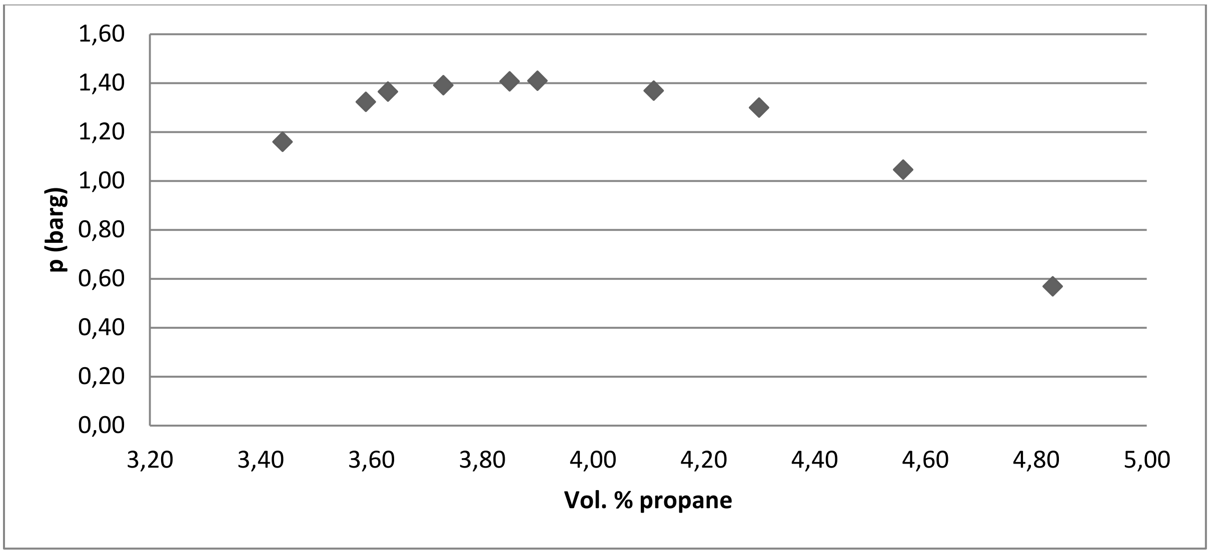

Figure 4-3: Pressure measurements in explosion experiments with mixture containing propane and air with 19.00 vol. % oxygen. A gap opening of 1.00 mm and ignition distance of 14 mm were used.

Experiments were conducted as described in section 4.3, varying the gap opening to find value for g_0. Ten consecutive experiments with concentrations neighbouring the most incentive mixture with gap opening of 1.21 mm gave no re-ignitions, shown in Table 4-7. The MESG value found is therefore 1.21 mm.

Table 4-7: Experiments with steel-slits in mixture of propane and air with 19.00 vol. % oxygen.

Gap opening (mm)	Ignition distance (mm)	Number of experiments	Number of re-ignitions	Mean pressure (barg)
1.20	14	3	0	1.23
1.21	14	10	0	1.21
1.22	14	13	4	1.22
1.23	14	7	3	1.24
1.25	14	3	3	1.19

Figure 4-4 show pressure measurements during preliminary tests. Pressure increase is observed when increasing the gap opening from g_0 to g_{100}, then decrease from g_{100}.

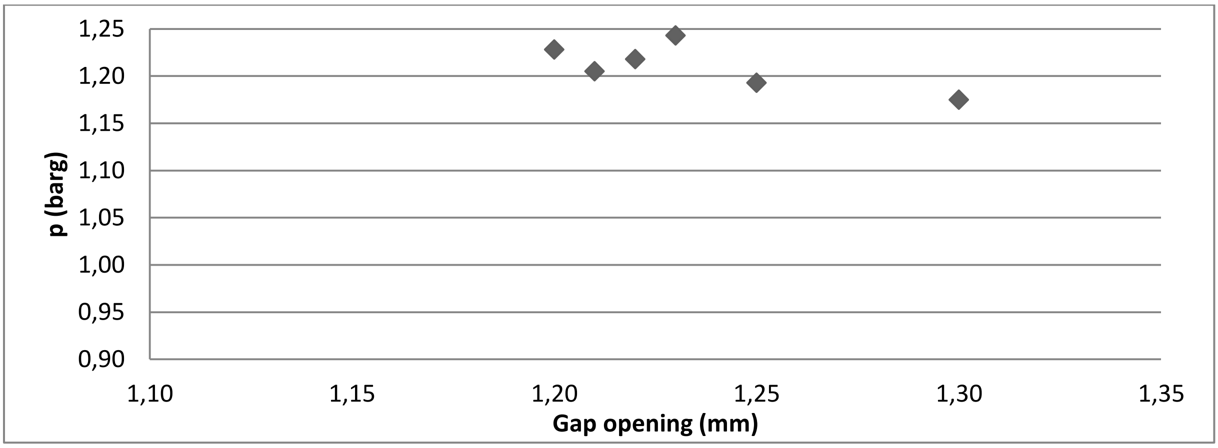

Figure 4-4: Pressure measurements with 3.85 vol. % propane in mixture.

4.3.3 Oxygen content of 16.77 volume percentage

Figure 4-5 shows pressure measurements in experiments with mixture iii from Table 4-5, and variable propane concentration. The most incentive mixture, basis for propane concentration is found to be 3.45 vol. % propane.

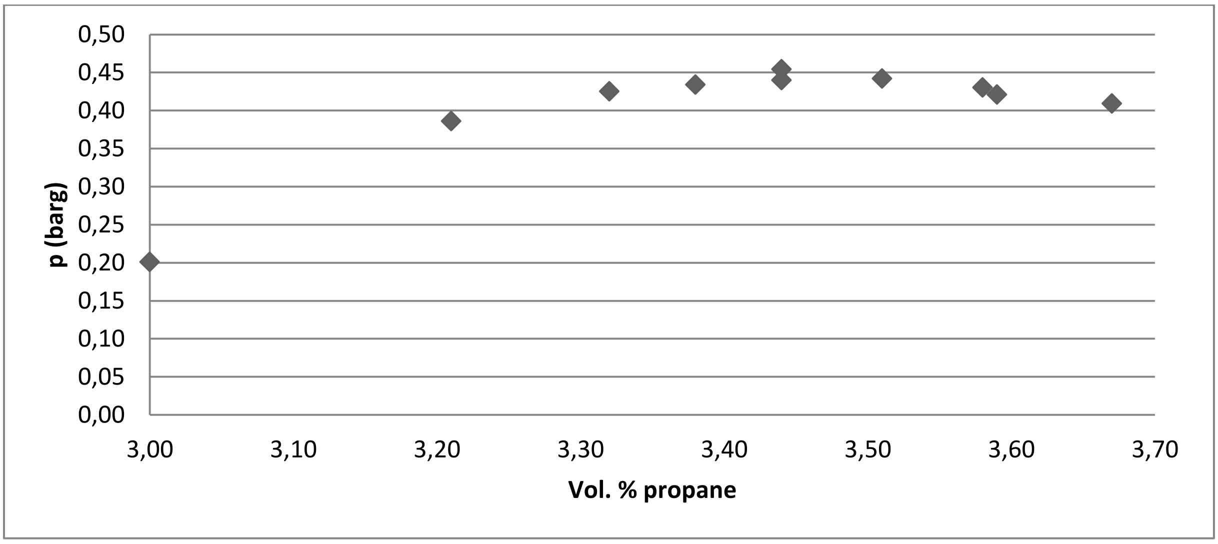

Figure 4-5: Pressure measurements in explosion experiments with mixture containing propane and air with 16.77 vol. % oxygen, using a gap opening of 1.20 mm and ignition distance of 14 mm.

Ten consecutive experiments with concentrations neighbouring the most incentive mixture with gap opening of 1.55 mm gave no re-ignitions, shown in Table 4-8. The MESG value found is therefore 1.55 mm.

Table 4-8: Experiments with steel-slits in mixture of propane and air with 16.77 vol. % oxygen.

Gap opening (mm)	Ignition distance (mm)	Number of experiments	Number of re-ignitions	Mean pressure (barg)
1.50	14	1	0	0.30
1.55	14	10	0	0.28
1.56	14	6	1	0.27
1.57	14	3	2	0.27
1.58	14	8	3	0.27
1.59	14	10	4	0.26
1.60	14	22	7	0.25
1.61	14	5	5	0.26
1.62	14	1	1	0.29
1.65	14	1	1	0.26
1.70	14	1	1	0.23

Figure 4-6 shows pressure measurements during preliminary tests.

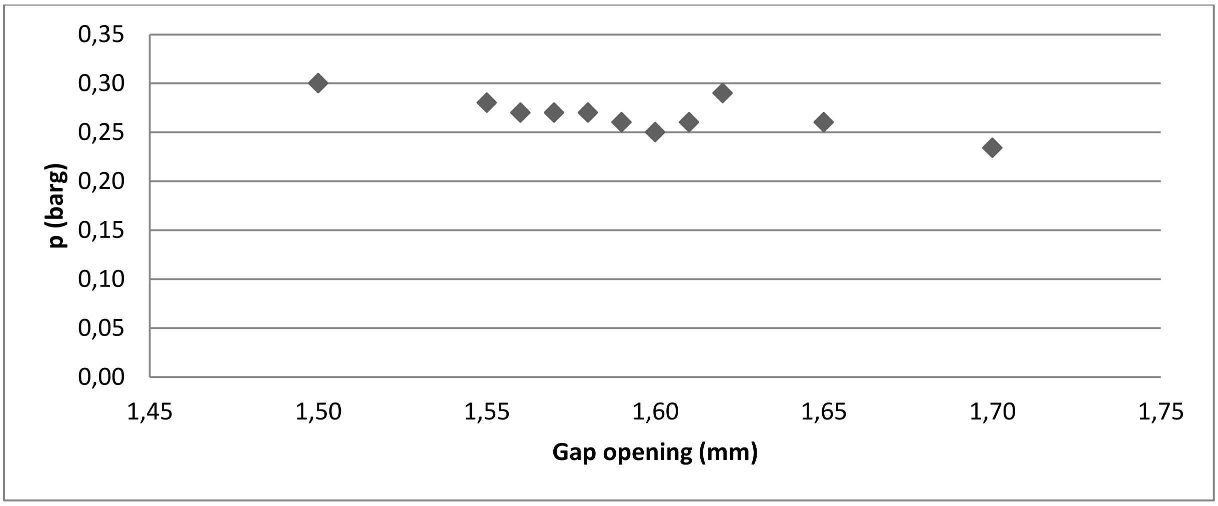

Figure 4-6: Mean pressure measurements with 3.45 vol. % propane in mixture.

4.3.4 Oxygen content of 15.04 volume percentage

Figure 4-7 shows pressure measurements with mixture containing propane in air with 15.04 vol. % oxygen. Concentrations lower than 3.08 vol. % propane in air were not possible to ignite. The highest pressure measured was close to the un-ignitable mixture. The most incentive mixture was chosen to be the mixture consisting of 3.15 vol. % propane. This was based on the pressure measured and the preceding tests, and with regards to the stoichiometric value.

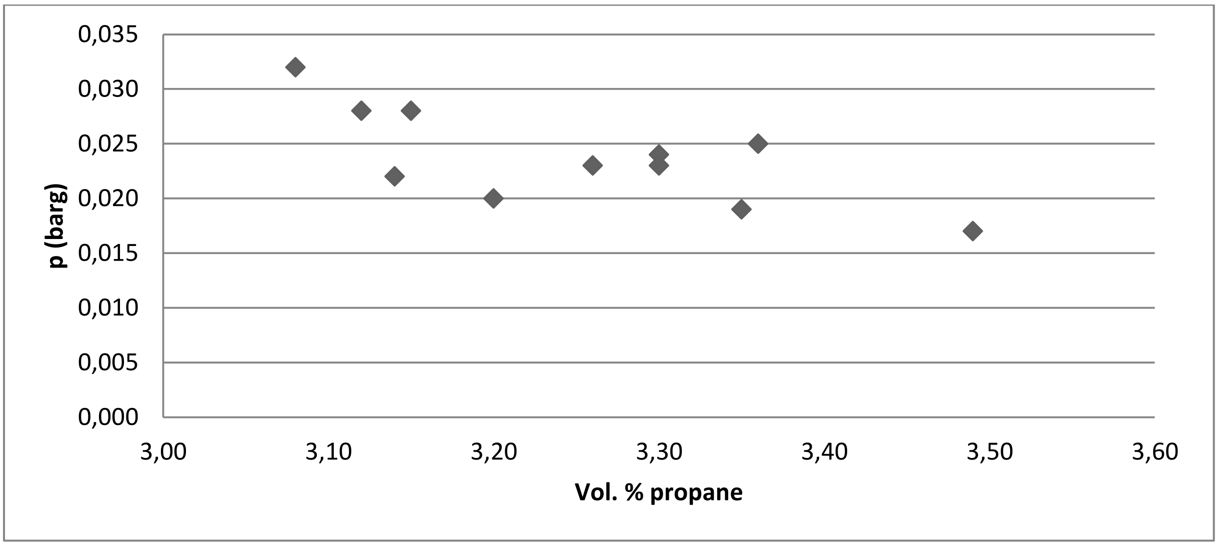

Figure 4-7: Pressure measurements in explosion experiments with mixture containing propane and air with 15.04 vol. % oxygen, using a gap opening of 2.00 mm and ignition distance of 14 mm.

Due to limited amount of gas, gap opening could not be changed by small steps. However, a sufficient number of experiments were conducted to establish the MESG value. With concentrations neighbouring the most incentive mixture, gap opening of 2.00 mm gave no re-ignitions for 11 consecutive experiments, as shown in Table 4-9. Thus the MESG value is 2.00 mm.

Table 4-9: Experiments with steel-slits in mixture of propane and air with 15.04 vol. % oxygen.

Gap opening (mm)	Ignition distance (mm)	Number of experiments	Number of re-ignitions	Mean pressure (barg)
2.00	14	11	0	0.024
2.05	14	9	1	0.027
2.10	14	10	2	0.032
2.15	14	2	1	0.025
2.25	14	3	2	0.022
2.45	14	1	1	0.022

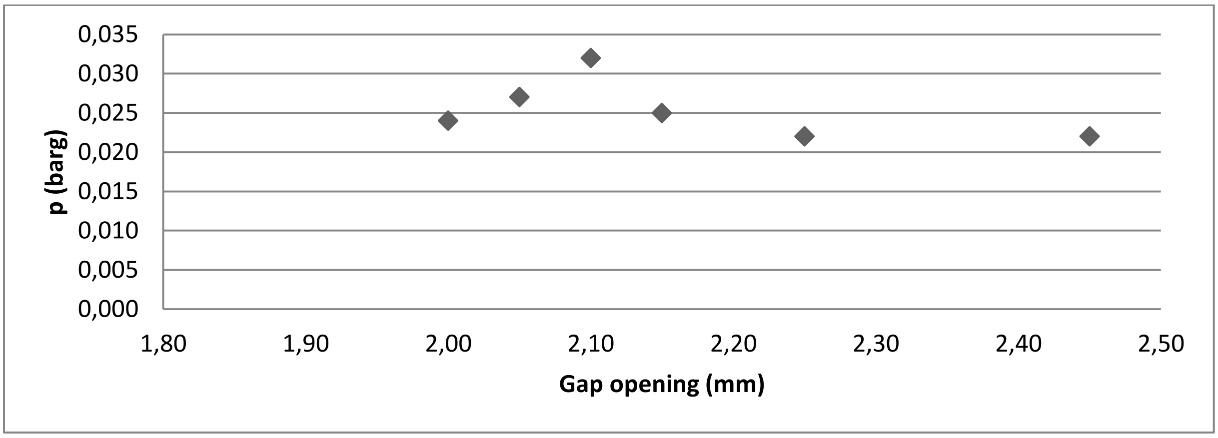

Figure 4-8: Pressure measurements with 3.15 vol. % propane in mixture.

In Figure 4-9 a typical pressure development in the primary chamber during experiments with 3.15 vol. % propane in mixture is shown. The occurrence of two pressure tops followed by a pressure reduction can be seen.

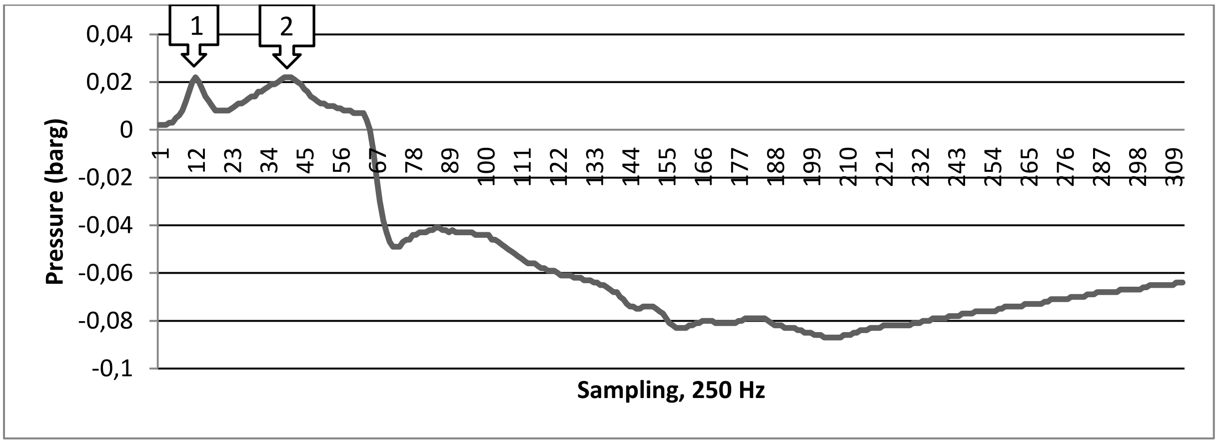

Figure 4-9: Typical pressure measurement in the primary chamber during experiments with 3.15 vol. % propane in mixture.

4.3.5 Discussion

As pointed out in section 2.7.4 the MESG is dependent on three factors;

- The temperature of the jet of hot combustion gas.
- The rate of combustion.
- The relative rate of entrainment of ambient mixture into the jet, relative to the mass of the jet.

The main observation from the experiments is that when decreasing the oxygen concentration and increasing the nitrogen concentration in the mixtures, the MESG value increase, as shown in Figure 4-10.

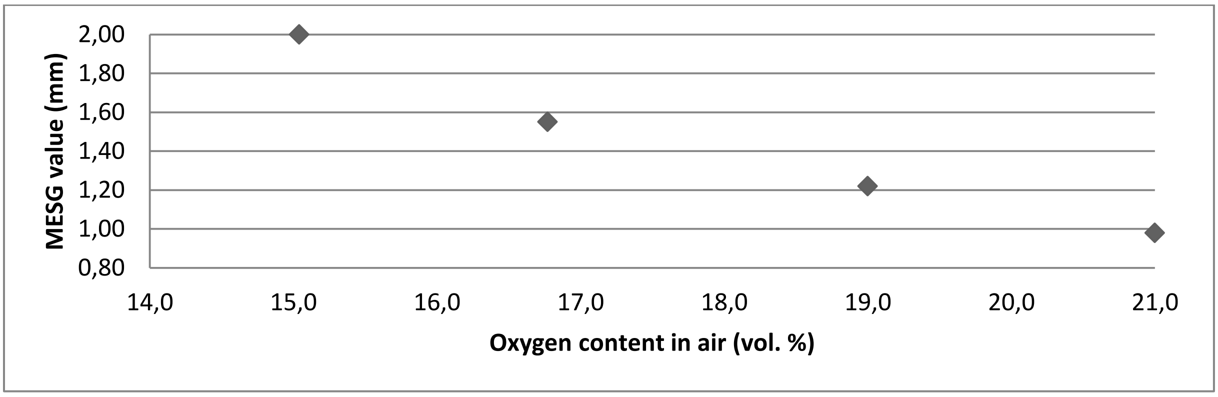

Figure 4-10: MESG values for propane in nitrogen enriched air, in terms of oxygen concentration in the air.

Table 4-10 shows a summary of the results obtained in present section. The most incentive mixtures are tabulated with their respectable MESG values, determined experimentally. It can be mentioned that the most incentive mixture value of propane is found to be above the stoichiometric value for all mixtures.

According to the IEC standard, the maximum gap opening for flameproof enclosures, with the dimensions of the test apparatus used in this thesis, is 0.40 mm [13]. For equipment intended to be used in a hypoxic environment, the requirement of maximum gap opening can be said to be strict. This requirement comes with a large margin of safety, if implemented in a future standard for hypoxic environments.

Table 4-10: MESG values and most incentive mixtures of propane and different nitrogen-oxygen mixtures.

Mixture	**Vol. % C_3H_8**	**Vol. % O_2**	**Vol. % N_2**	**MESG (mm)**
i.	4.20	20.07	75.73	0.98
ii.	3.85	18.27	77.88	1.22
iii.	3.45	16.19	80.36	1.55
iv.	3.15	14.57	82.28	2.00

Increasing nitrogen content in the mixture decreases the reactivity, hence lowers the explosion pressure in the primary chamber. A pressure difference of approximately 2.25 barg is measured at MESG values of mixture i and mixture iv. As indicated in section 2.7.4, when nitrogen content is at the levels examined, the flow through the flame gap is subsonic. A decrease in explosion pressure causes lower jet velocity and a decreased relative rate of entrainment. This contributes to increased probability of ignition. The jet temperature and the reactivity of the mixture are reduced when increasing the nitrogen content because of the effect on the combustion rate. This contributes to decreased probability of ignition. When increasing the gap opening, this results in a bigger jet orifice. The relative rate of entrainment is then increased so that ignition occurs at a bigger gap opening.

Pressure measurements in experiments with propane in mixture with an oxygen content of 15.04 vol. % resulted in two pressure tops in the primary chamber. An ignition of an explosive mixture in the primary chamber will lead to a spherical flame front propagating toward the flame gap, shown in section 3.1.4. The explosion products cause pressure to increase in the primary chamber. When the flame front reaches the flame gap, a pressure top can be seen in Figure 4-9, labelled 1. The flame front propagates through the flame gap and is quenched, followed by explosion products flowing through the gap. Escaping explosion products causes lowering of pressure in the primary chamber. A sudden pressure drop might induce turbulence causing the burning rate to increase, causing another pressure top, labelled 2. This result might indicate that the ignition position is not optimal. If the ignition source were positioned further from the gap entrance, the maximum pressure could be higher. This as a result of a larger spherical flame front developing prior the flame front reaching flame gap entrance, hence more combustion products.

Comparing experimental MESG values from this thesis and values by Lunn [25], a good correlation is found. From Table 2-6 the limiting oxygen concentration for propane is found to be 10.5-11.5 vol. % oxygen, depending on the test method. At this value, the MESG will have a value of infinite. Lunn used stoichiometric values for his experimental work. This may lead to higher MESG values compared to values found using the most incentive mixtures. The reason for this is that the most incentive mixture is the mixture providing the smallest MESG value as emphasised in section 2.5.4.

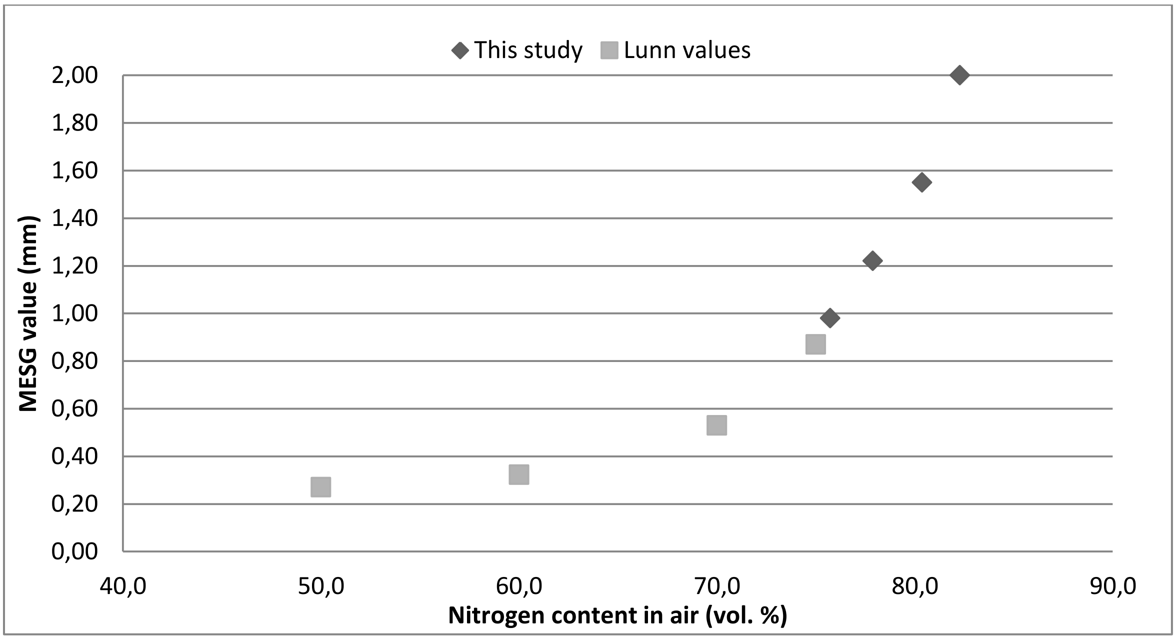

Figure 4-11: MESG values for propane in nitrogen enriched air and oxygen enriched air, in terms of nitrogen concentration in the air. Experimental values from present work seen in context with experimental values from Lunn. Lunn using stohiciometric values of propane in oxygen enriched air [25].

4.4 Adhesive tape with polyethylene coating situated in the primary chamber

Some test experiments with hydrogen as fuel was done in the PRSA. Hydrogen is a more reactive gas with MESG value of 0.29 mm. To make sure tests were not influenced by leaks at the side of the flame gap, adhesive tape was attached to the flame gap plate inside the primary chamber. Experiments resulted in variable and unreliable MESG values obtained. This indicated that the adhesive tape influenced the combustion process.

Experiments with adhesive tape inside the primary chamber were also conducted with steel slits in 4.20 vol. % propane in air. This was done to see how melting of plastic influence the re-ignition in the external chamber. The experiments with adhesive tape inside the primary chamber led to decreased MESG value for all slits tested. The gap opening providing ignitions were inconsistent. The value of ($g_{100} – g_0$) were in some cases as high as 7. According to IEC, a value of 4, when conducting experiments with fuel in air, is to be considered an acceptable limit for results to be reliable [5].

Table 4-11: Possible MESG values obtained for experiments with adhesive tape with polyethylene coating situated in the primary chamber

Gap material	Lowes gap with probability of ignition > 0 % (mm)	Possible MESG value (mm)
Steel	0.98	0.97
Brass	0.95	0.94
Aluminium	0.97	0.96
POM	1.20	1.19

Table 4-11 gives an indication of the minimum gap opening obtained in the PRSA, with variable slit material, providing explosion in the external chamber. Possible MESG values are tabulated.

A readily available explanation for the results is hard to find. Melting of the polyethylene coating was observed; hence gases may interfere with the combustion process, increasing the reactivity of the reaction.

5 Conclusion

An experimental investigation on the ability of flame gaps to prevent transition of explosions has been conducted. The influence of two parameters has been investigated experimentally. The conclusions from the investigation can be summarized as follows:

The influence on the MESG value by the heat transfer within a flame gap in a propane-air mixture:

- Three metal flame gaps have been investigated. The experiments with these have not shown significant influence of the wall material or the thermal conductivity on the heat transfer from the jet of hot combustion products. The temperature measurements over flame gaps show that the thermal conductivity of the metal flame gaps is of second importance.
- The use of POM as flame gap material resulted in high temperature readings in relation to measurements over the flame gaps of metal. This may be the result of the low thermal conductivity of the material.

The influence of partial inertisation of propane on the MESG value:

- Three mixture ratios of nitrogen enriched air have been used to partial inert propane. Experiments have shown that when increasing the nitrogen concentration in the mixtures, the MESG value increase. A doubling of the MESG value was achieved compared to that of propane-air, when conduction experiments with nitrogen enriched air containing 15 vol. % oxygen. This leads to large margins of safety if current standards for electrical equipment are implemented in future international standards for hypoxic environments.

Experiments with adhesive tape with polyethylene coating situated in the primary chamber were conducted. The influence of the adhesive tape decreased the MESG value for propane gas, when using flame gaps of steel, aluminium, and brass. This emphasises that explosion transmission through a flame gap depends on many parameters.

6 Recommendations for further work

The experimental work in this thesis has showed some of the effects material properties have on the efficiency of flame gaps. It has also shown the effects of lowering oxygen concentration, in an explosive gas mixture, on the MESG value. Verification experiments and experiments with other flame gap materials and gas properties are needed to provide final conclusions. Suggestions for further work in conjunction with experimental work done in this thesis:

- Experiments with other flame gap material. Usage of flame gaps made of more heat resistant material with low conductivity, to further investigate the relation between heat transfer within the flame gap and the MESG value.
- Investigate the effect of groves milled in materials of low thermal conductivity. Grooves leads to increased turbulence in the flame gap which may contribute to larger heat loss.
- Simulate experiments using computational fluid dynamics.
- Redesign the apparatus in such way that temperature measurements inside the flame gap are possible. This can help to better understand where the heat transfer occurs, and if the main cooling of the jet is situated in the external chamber.
- Investigate the effect of obstructions or plastics inside the primary chamber. Preliminary experiments showed that the MESG were affected by adhesive tape inside the primary chamber of the PRSA.
- Conduct experiments with nitrogen enriched air, to further investigate the effect of increased reactivity on the MESG value.
- Examine the influence of the ignition position in the primary chamber. To investigate the effect of increased and reduced distance between the ignition source and the flame gap entrance, on the MESG values obtained for nitrogen enriched air.

Suggestions for further work using experimental apparatus and procedures in this study:

- Investigate the effect of metal dust inside the flame gap, and the influence it may have on re-ignition in the external chamber.
- Perform experiments with obstructions just outside the flame gap orifice, to see if it affects the MESG value and the re-ignition in the external chamber.

7 References

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Appendix A Experimental apparatus and procedures

Experimental apparatus	**Type**
Explosion apparatus	The Plane Rectangular Slit Apparatus
Gas analyser	Servomex 4200, industrial gas analyser
Computer	Dell Latitude D630
DAQ	NI USB 6008
Pressure transducer	Kistler 701A
Charge amplifier	5015A000
Spark generator	Tailor made, estimated energy 50mJ
Thermocouples	Tailor made
Welding apparatus for thermocouples	Tailor made
Camera	Casio Exilim Ex-F1
Test gas 1	Propane (99.95 %)
Test gas 2	19 vol. % O_2/ rest N_2
Test gas 3	17 vol. % O_2/ rest N_2
Test gas 4	15 vol. % O_2/ rest N_2
Calibration gas	Nitrogen, quality 5.0 (99.999 %)

Appendix B Adjustment of gap opening in the PRSA.

The adjustment of flame gap opening must be done before any experimental procedure.

1. Disconnect all tubing from the external chamber and unscrew from primary chamber.
2. Remove the flame gap plate from the top of the external chamber.
3. Place distance shims on both sides of the gap. The shims must be placed on the sides and to the bottom of the gap. This will ensure uniform gap opening.
4. Fasten screw 1 and 2 at the upper part of the gap. Use a torque of 20 cNm. Shown in Figure 7-1.
5. Fasten screw 3 – 6 at the lower part of the gap. Use a torque of 20 cNm. Shown in Figure 7-1 and Figure 7-2.
6. Fasten screw 7 – 12 at the underside of the gap. Use a torque of 1 Nm.

The reasons for using low torque on screws are to not damage the screw threads and to not squeeze the flame gap together, making the gap opening smaller than intended or not uniform.

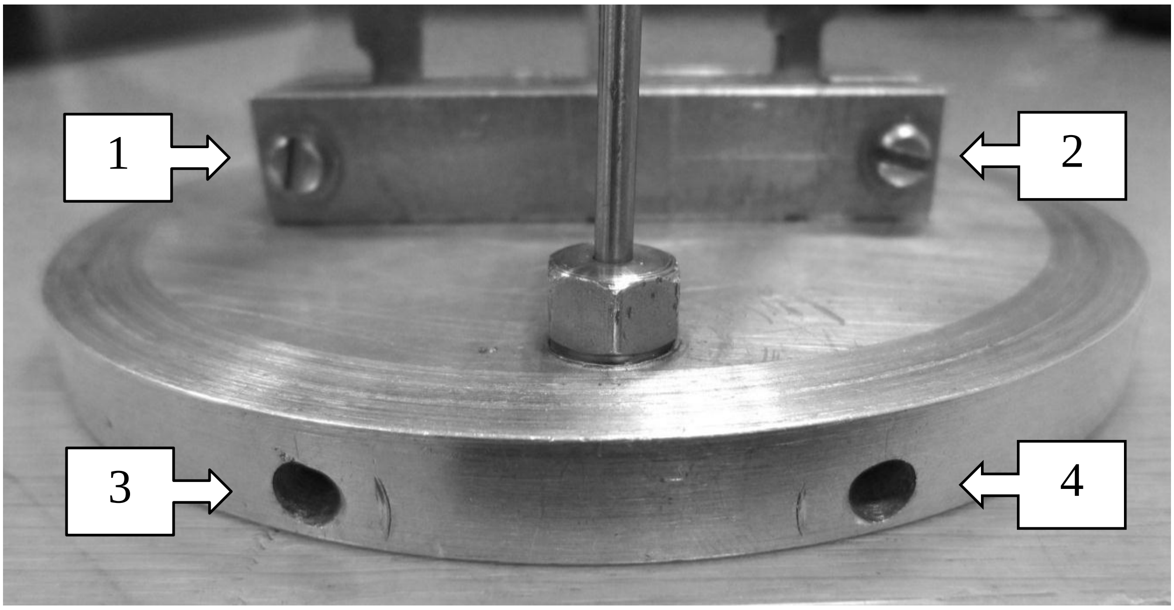


Figure 7-1: Screws on the fastening clamp at the upper part of the flame gap plate.

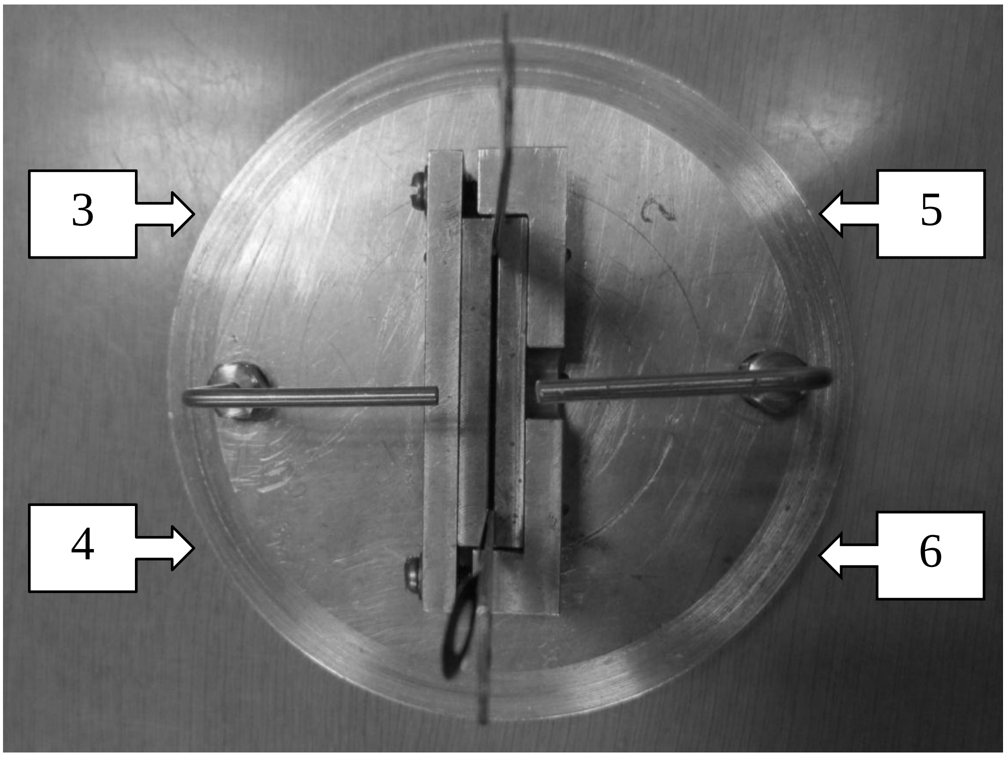


Figure 7-2: Screws on the lower part of the flame gap plate.

Appendix C Calibration of gas analyser, Servomex 4200.

The gas analyser is able analyse two components in the gas composition. It can measure oxygen concentration and propane concentration. To obtain correct volume percent values, the gas analyser must be calibrated. Two calibrations for each component are necessary.

Low level calibration:

- Nitrogen gas with quality of 5.0 must be used to calibrate for a zero-level concentration. This consists of 99.999 vol. % nitrogen.

High level calibration:

- To calibrate for high level, gas with known level of oxygen/propane is used. To calibrate for high level of oxygen, regular air can be used.

The flow to analyse must never exceed 100 ml/minute. This may ruin the paramagnetic oxygen sensor or give false measurements.

The calibration procedure follows, see Appendix H for numbered figure of gas analyser:

1. Connect calibration gas to calibration gas inlet and turn valve (4) to “calibration gas”.
2. The first arrow (1) must be turned “to exhaust fan”, the second (2) to “calibration test gas” and the third (3) “to HC analysis”.
3. Make sure the calibration gas inlet is chosen, and then turn on the “flow HC gas”.
4. Turn on the analysis pump.
5. The display shows the measured volume percentage of oxygen and propane in the calibration gas. Wait for values to stabilize.
6. To correct the values press the following button combination quickly: “enter”, “quit”, “right arrow”, “measure”, arrow up”, “menu”.
7. Choose “calibrate” by pressing “enter”. Enter the password: 1812 using the arrows, then press “enter”.
8. Choose manual calibration, and then either oxygen or propane.
9. Choose low calibration to calibrate for 0.0000 vol. % oxygen/propane. Choose high calibration using gas with known volume percentage of oxygen/propane.

Appendix D Experimental procedure

Before execution of experiments:

1. Perform procedure for adjusting the gap opening in the PRSA.
2. Ensure that the tubing from the gas analyser to the PRSA is connected according to Figure 3-1.
3. Calibrate the gas analyser. It is necessary to perform a high level calibration of the oxygen sensor on the Servomex 4200 every day used, to obtain correct readings. It is prudent to also perform a low level calibration once a week to ensure zero-point has not been altered.
4. Turn on spark generator and pressure measuring device.

Experimental procedure for an experiment set.

1. Install flame gap plate in the PRSA and screw the external chamber onto the primary chamber.
2. Attach temperature sensor above flame gap.
3. Fasten plastic foil on top of the external chamber using a rubber band.
4. Open valve 1, 2, 4 and 5 on the PRSA. Shown in Figure 7-3
5. Turn valves on analyser (1) to “to apparatus” and valve (2) to “from apparatus”, valve (3) to “to HC analysis” and valve (4) to “HC-gas”.
6. Turn pressure regulator for air inlet slowly clockwise until the pressure gauge indicates 0.2 barg.
7. Turn needle valve for air counter clockwise. Flow meter labelled “air” measures the air flow to apparatus.
8. Open valve for flow HC-gas.
9. Turn valve (6) to “Extra flow meter open” and adjust HC-gas flow.
10. Wait for values to stabilize. Approximately 8-10 minutes for the PRSA. Adjust flow if necessary.
11. Turn off analyser pump.
12. Turn off HC-gas flow, turn (1) to “to exhaust”
13. Close valve 1, 2, 4 and 5 on the PRSA.
14. Secure area and wear ear protection.
15. Activate the spark generator.
16. Activate Labview program for temperature and/or pressure measurements.
17. Ignite gas mixture.
18. Store Labview files with measturements.
19. Flush apparatus with air by opening valve 3 on the PRSA.
20. Turn off air and gas supply when experiment set is completed.

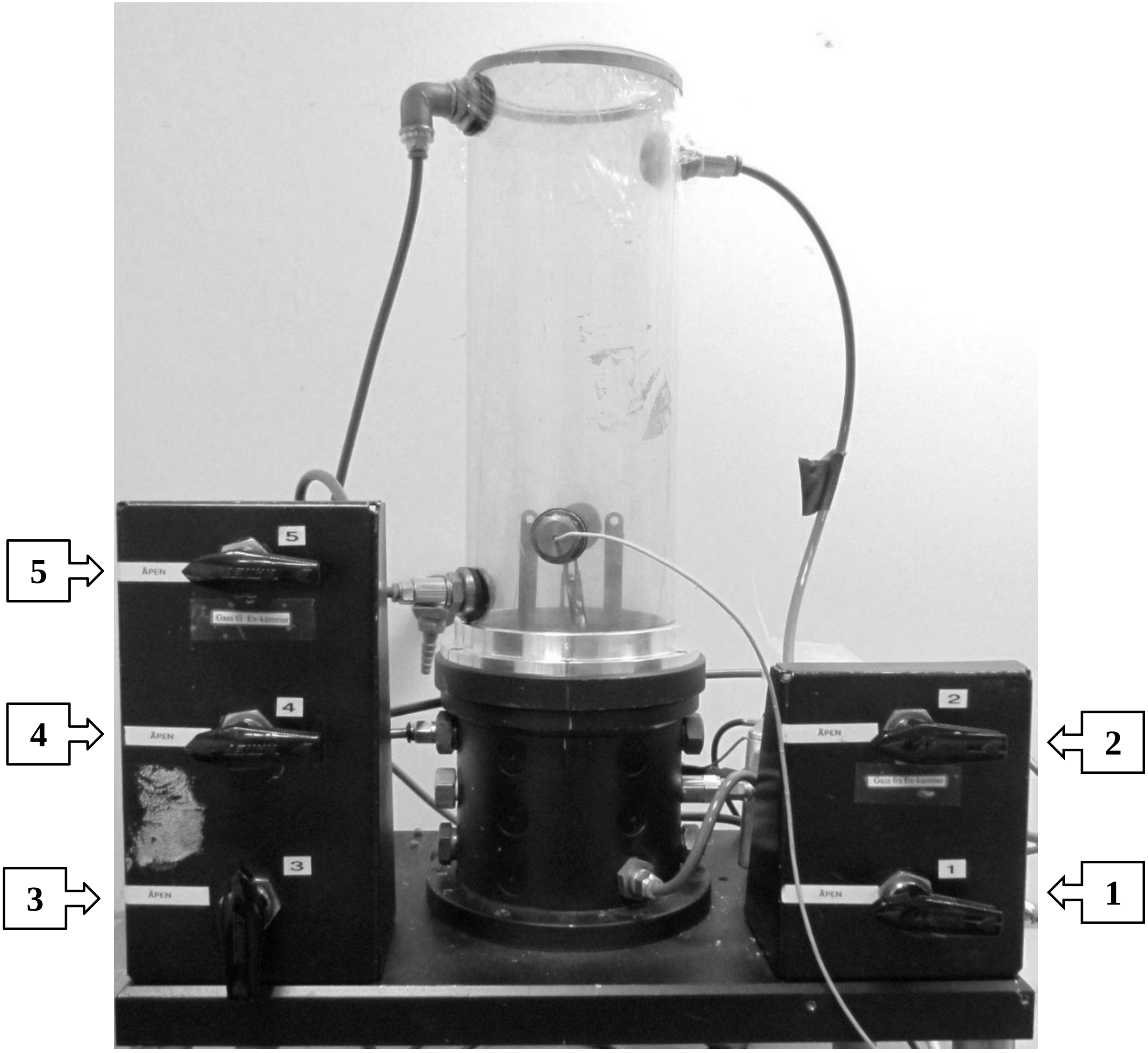


Figure 7-3: The PRSA. Showing apparatus completely assembled with plastic foil on top of the external chamber. Temperature sensor mounted and valve 1, 2, 4 and 5 in the open position. Valve numbers indicated.

Appendix E Data acquisition system

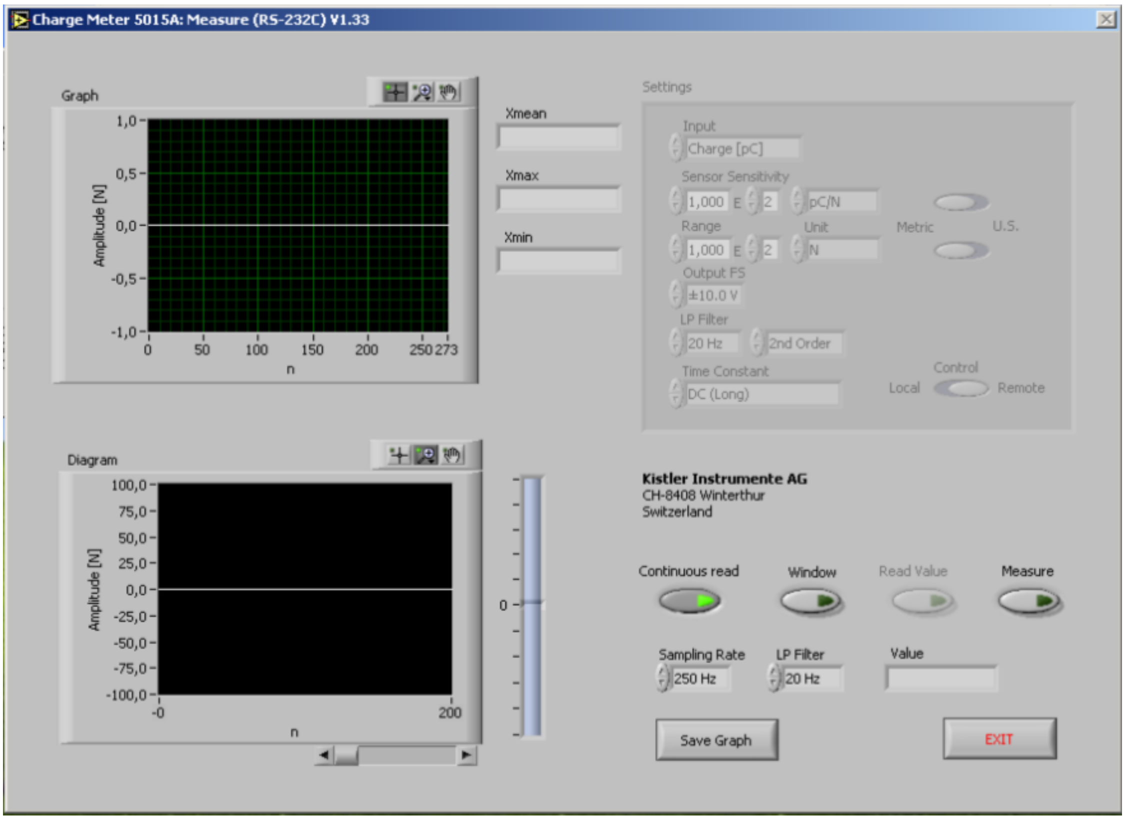
To measure pressure in the primary chamber, the computer program following Kistler Type 5015A Charge Meter, V1.33 was used. The program was based on LabVIEW V8.5.

A computer programs, based on LabVIEW V8.5, was made to be able to measure temperature in the external chamber during experiments.

A simplified guide for these programs follows:

Pressure measurements:

1. Choose a sensitivity of 6 bars.
2. Press continuous read measure at a chosen sampling rate. The highest sampling rate for the charge meter used is 250 Hz.
3. Press measure to start measurement.
4. Press measure again to end measurement.
5. Press save graph, and save results as a *.txt file. This enables easy reading of data.



Input: Charge [pC]
Sensor Sensitivity: 1,000 E 2 pC/N
Range: 1,000 E 2
Unit: N
Metric / U.S.
Output FS: ±10.0 V
LP Filter: 20 Hz, 2nd Order
Time Constant: DC (Long)
Control: Local / Remote

Kistler Instrumente AG
CH-8408 Winterthur
Switzerland

Sampling Rate: 250 Hz
LP Filter: 20 Hz

Figure 7-4: Screen shot of Charge Meter 5015A V.133 program, used for pressure measurements.

Temperature measurements:

The thermocouples are connected to the data acquisition device NI USB 6008. A computer program developed to measure readings are shown in figure

1. Press run, shown in Figure 7-6.
2. After 5 seconds a dialogue box appears which enables saving of measurements as a *.txt file.
3. Readings is displayed as a waveform graph in the program.

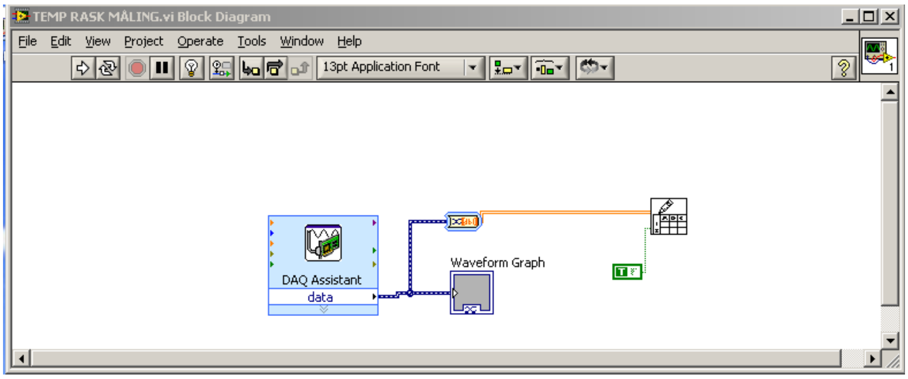


Figure 7-5: Block diagram LabVIEW program used for temperature measurements.

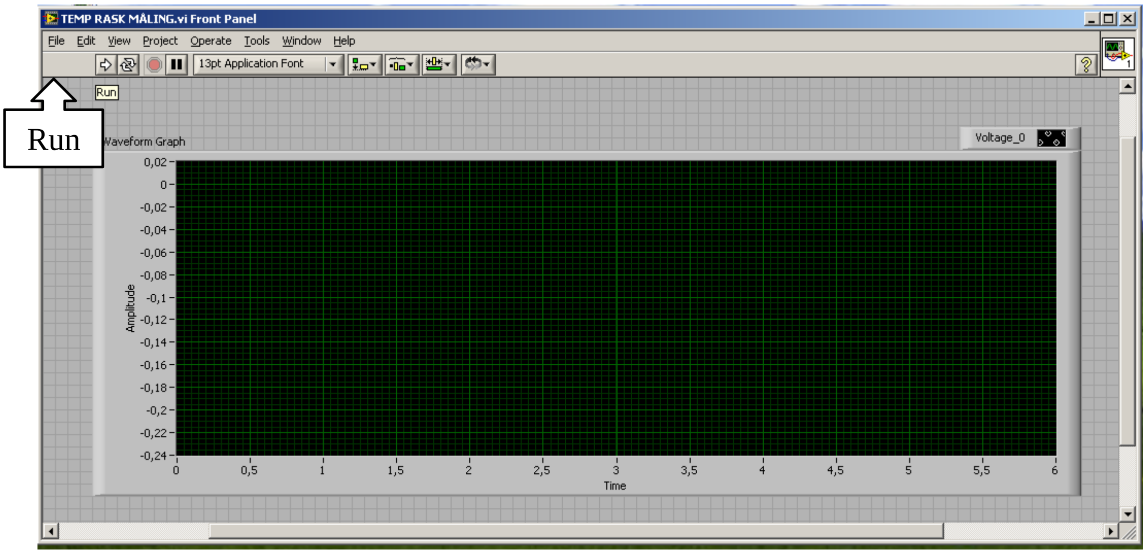


Figure 7-6: Screen shot of LabVIEW program used for temperature measurements.

Appendix F Thermocouples

Thermocouples are a device consisting of a wire with two different metals and a conjunction point between them. When the junction point is heated or cooled, a voltage is produced that can be correlated to the temperature. The thermocouples used in the present work are of type k and consist of nickel-chromium (+) and nickel-aluminium (-). Their temperature range is -200°C to 1100°C. The thickness of the metal wires is 0.3 mm. Sensitivity is approximately 41 µV/°C and accuracy of ±2.5°C. The voltage produced from the thermocouples was amplified through a tailor made amplifier (AD597), connected to a data acquisition device (NI USB 6008) and logged using a computer program (see Appendix E).

The welding apparatus for the thermocouples are tailor made [33]. The principle of the apparatus is to charge a condensator via a rectifier, and to discharge across the two metal wires. The wires are connected to the condensator, one at the positive side and one to the negative side. The opposite ends of the wires are gently pushed together until contact is made and the condensator discharge through the wires creating a welding point. Argon is added to the welding point during the procedure to prevent combustion and make the welding the more dominant process.

Appendix G Calculation of stoichiometric concentrations

Calculation of stoichiometric concentrations of propane in mixtures with various ratios of nitrogen/oxygen:

Table 7-1: Gas mixtures with different oxygen/nitrogen concentrations.

Mixture	Vol. % O_2	Vol. % N_2
i.	20.95	79.05
ii.	19.00	81.00
iii.	16.77	83.23
iv.	15.04	84.96

Stoichiometric

$$C_3H_8 + mixture = H_2O + CO_2 + N_2 \tag{7-1}$$

Stoichiometric calculation for mixture i:

$$C_3H_8 + 5\left(O_2 + \frac{79.05}{20.95}N_2\right) = 4H_2O + 3CO_2 + 5\left(\frac{79.05}{20.95}N_2\right) \tag{7-2}$$

Molar ratio of propane and oxygen reactant is:

$$\frac{X_{C_3H_8}}{X_{O_2}} = \frac{1}{5} \tag{7-3}$$

$$X_{C_3H_8} = \frac{X_{O_2}}{5} \tag{7-4}$$

Molar ratio of nitrogen and oxygen reactants is:

$$\frac{X_{N_2}}{X_{O_2}} = \frac{79.05}{20.95} \tag{7-5}$$

$$X_{N_2} = \frac{79.05}{20.95}\,X_{O_2} \tag{7-6}$$

Using that:

$$\sum reactants = 1 \tag{7-7}$$

$$X_{O_2} + X_{N_2} + X_{C_3H_8} = 1 \tag{7-8}$$

Substituting molar ratios of propane and nitrogen:

$$X_{O_2} + \frac{79.05}{20.95} X_{O_2} + \frac{X_{O_2}}{5} = 1 \tag{7-9}$$

$$\left(1 + \frac{79.05}{20.95} + \frac{1}{5}\right) X_{O_2} = 1 \tag{7-10}$$

$$X_{O_2} = 0.2011 = 20.11\% \tag{7-11}$$

Knowing the stoichiometric oxygen concentration, nitrogen and propane concentrations can be found using:

$$X_{N_2} = \frac{79.05}{20.95} X_{O_2} = 75.87\% \tag{7-12}$$

$$X_{C_3H_8} = \frac{X_{O_2}}{5} = 4.02\% \tag{7-13}$$

Calculation of stoichiometric mixtures of propane and the other three oxygen/nitrogen mixtures made using same method.

Table 7-2: Stoichiometric values for fuel/air and fuel/nitrogen enriched air.

Mixture	**Vol. % C_3H_8**	**Vol. % O_2**	**Vol. % N_2**
i.	4.02	20.11	75.87
ii.	3.66	18.30	78.03
iii.	3.25	16.23	80.53
iv.	2.92	14.60	82.48

Table 7-3: Values for concentration with regards to most incentive mixture.

Mixture	**Vol. % C_3H_8**	**Vol. % O_2**	**Vol. % N_2**
i.	4.20	20.07	75.73
ii.	3.85	18.27	77.88
iii.	3.45	16.19	80.36
iv.	3.15	14.57	82.28

Appendix H Photography of gas analyser with valve numbers

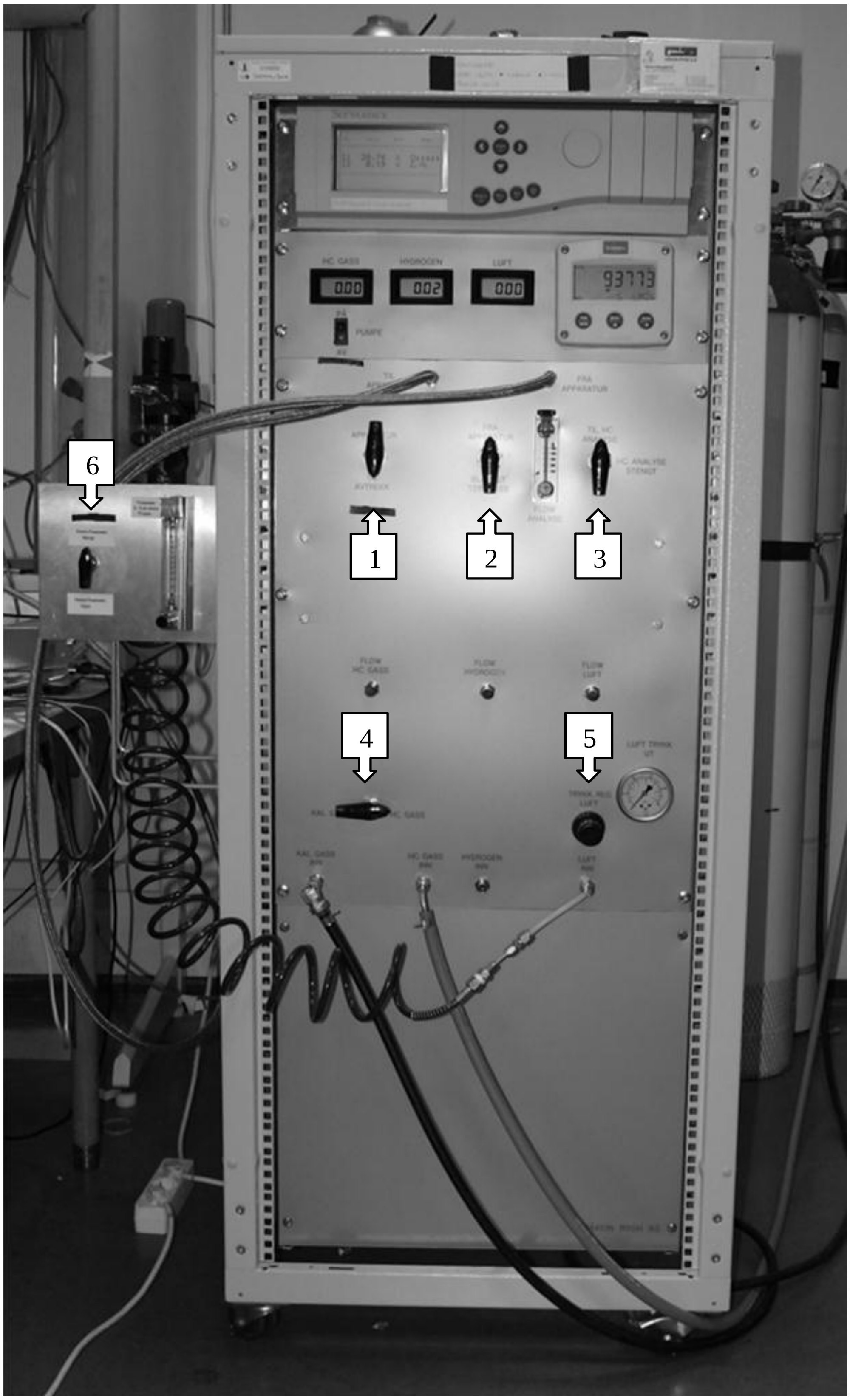
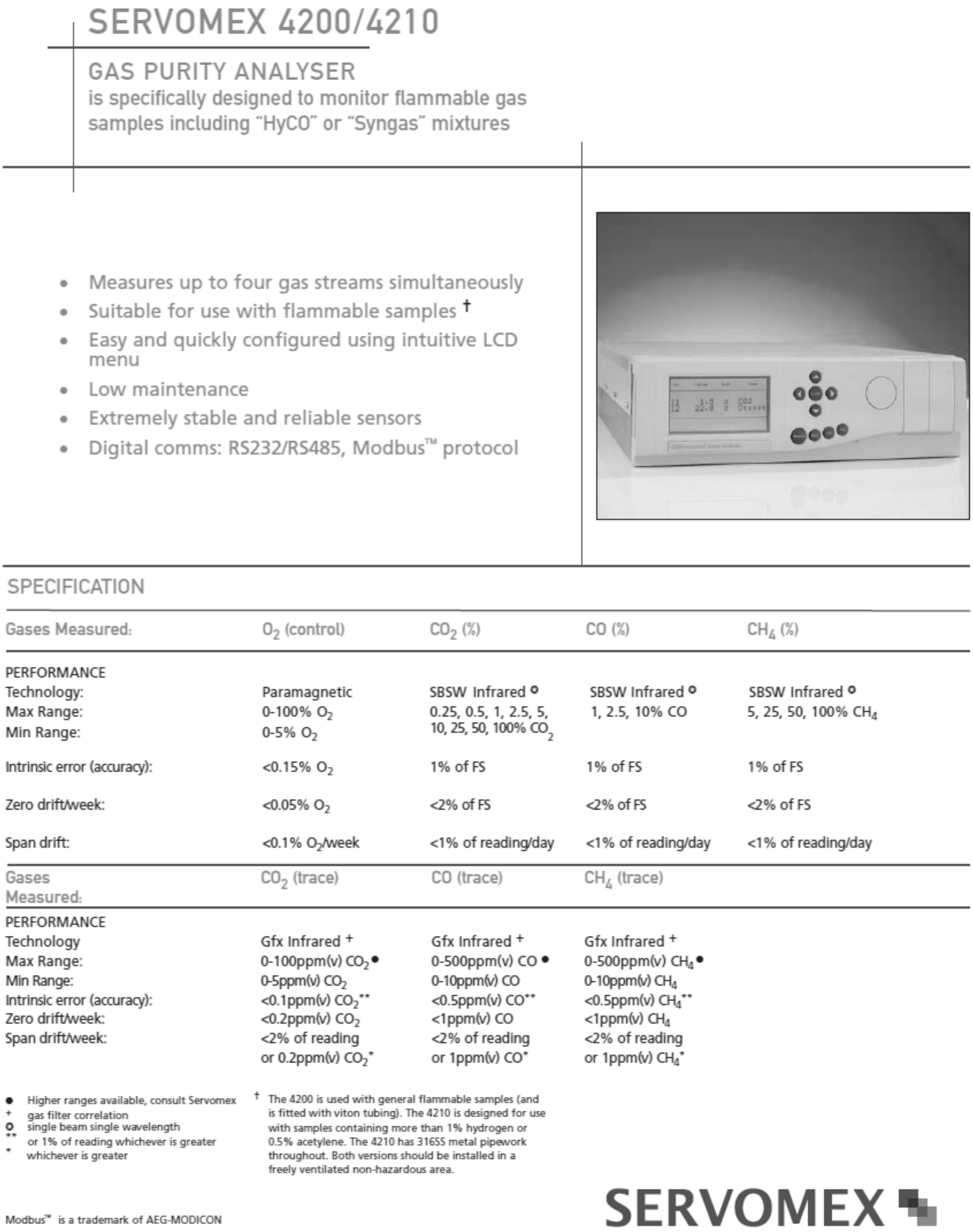


Figure 7-7: Photography of gas analyser, Servomex 4200.

Appendix I Gas analyser specifications



SERVOMEX 4200/4210

GAS PURITY ANALYSER

is specifically designed to monitor flammable gas samples including "HyCO" or "Syngas" mixtures

- Measures up to four gas streams simultaneously
- Suitable for use with flammable samples †
- Easy and quickly configured using intuitive LCD menu
- Low maintenance
- Extremely stable and reliable sensors
- Digital comms: RS232/RS485, Modbus™ protocol

SPECIFICATION

Gases Measured:	O_2 (control)	CO_2 (%)	CO (%)	CH_4 (%)
PERFORMANCE				
Technology:	Paramagnetic	SBSW Infrared ○	SBSW Infrared ○	SBSW Infrared ○
Max Range:	0-100% O_2	0.25, 0.5, 1, 2.5, 5, 10, 25, 50, 100% CO_2	1, 2.5, 10% CO	5, 25, 50, 100% CH_4
Min Range:	0-5% O_2			
Intrinsic error (accuracy):	<0.15% O_2	1% of FS	1% of FS	1% of FS
Zero drift/week:	<0.05% O_2	<2% of FS	<2% of FS	<2% of FS
Span drift:	<0.1% O_2/week	<1% of reading/day	<1% of reading/day	<1% of reading/day

Gases Measured:	CO_2 (trace)	CO (trace)	CH_4 (trace)
PERFORMANCE			
Technology	Gfx Infrared +	Gfx Infrared +	Gfx Infrared +
Max Range:	0-100ppm(v) CO_2 ●	0-500ppm(v) CO ●	0-500ppm(v) CH_4 ●
Min Range:	0-5ppm(v) CO_2	0-10ppm(v) CO	0-10ppm(v) CH_4
Intrinsic error (accuracy):	<0.1ppm(v) CO_2^{**}	<0.5ppm(v) CO^{**}	<0.5ppm(v) CH_4^{**}
Zero drift/week:	<0.2ppm(v) CO_2	<1ppm(v) CO	<1ppm(v) CH_4
Span drift/week:	<2% of reading or 0.2ppm(v) CO_2^{*}	<2% of reading or 1ppm(v) CO^{*}	<2% of reading or 1ppm(v) CH_4^{*}

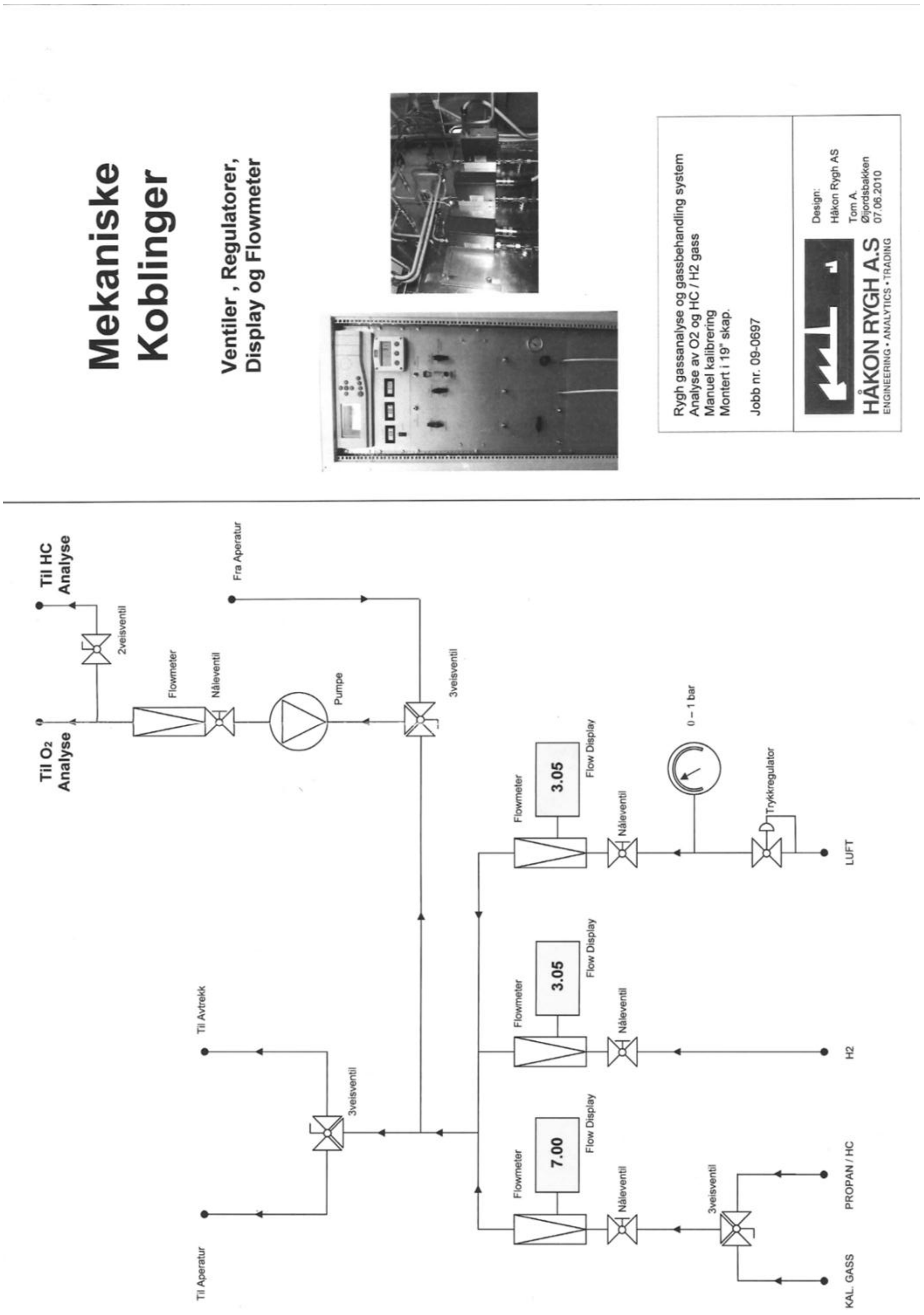
● Higher ranges available, consult Servomex
\+ gas filter correlation
○ single beam single wavelength
** or 1% of reading whichever is greater
* whichever is greater

† The 4200 is used with general flammable samples (and is fitted with viton tubing). The 4210 is designed for use with samples containing more than 1% hydrogen or 0.5% acetylene. The 4210 has 316SS metal pipework throughout. Both versions should be installed in a freely ventilated non-hazardous area.

Modbus™ is a trademark of AEG-MODICON

SERVOMEX

Figure 7-8: Specifications of gas analyser.



Mekaniske Koblinger

Ventiler , Regulatorer, Display og Flowmeter

Rygh gassanalyse og gassbehandling system
Analyse av O2 og HC / H2 gass
Manuel kalibrering
Montert i 19" skap.

Jobb nr. 09-0697

HÅKON RYGH A.S
ENGINEERING • ANALYTICS • TRADING

Design:
Håkon Rygh AS
Tom A.
Øijordsbakken
07.06.2010

Figure 7-9: The mechanical couplings of the gas analyser.

Appendix J Magnified photos of slits

The photos were taken at the Laboratory for Electron Microscopy at UoB, using a Zeiss Supra 55VP electron microscope.

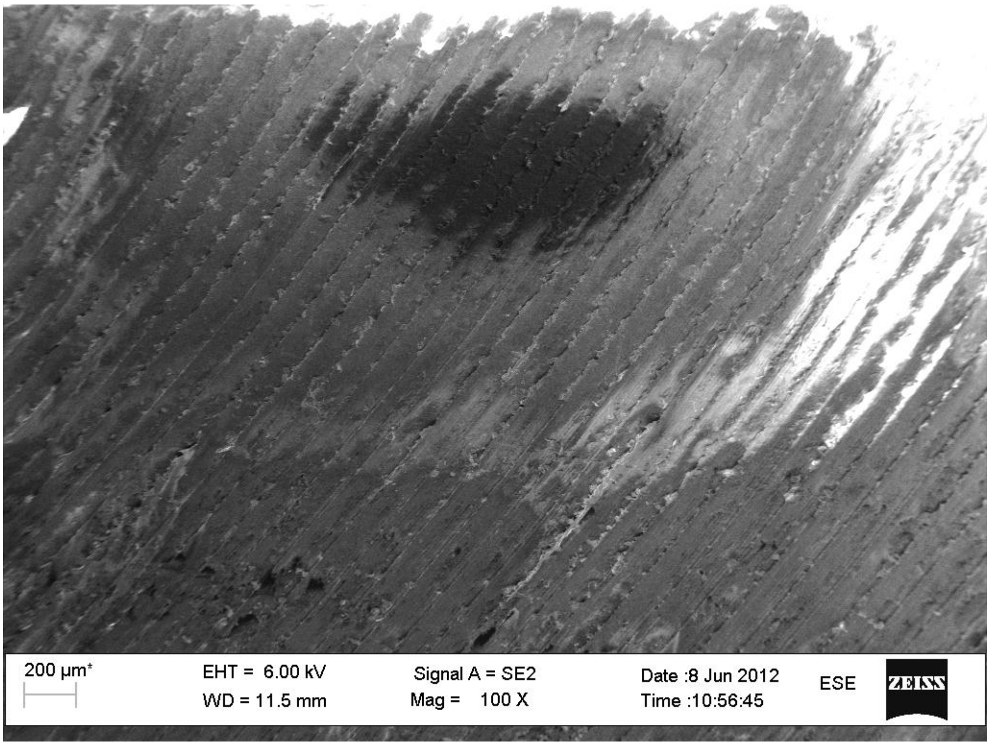


Figure 7-10: POM slit surface, new and unexposed of heat.

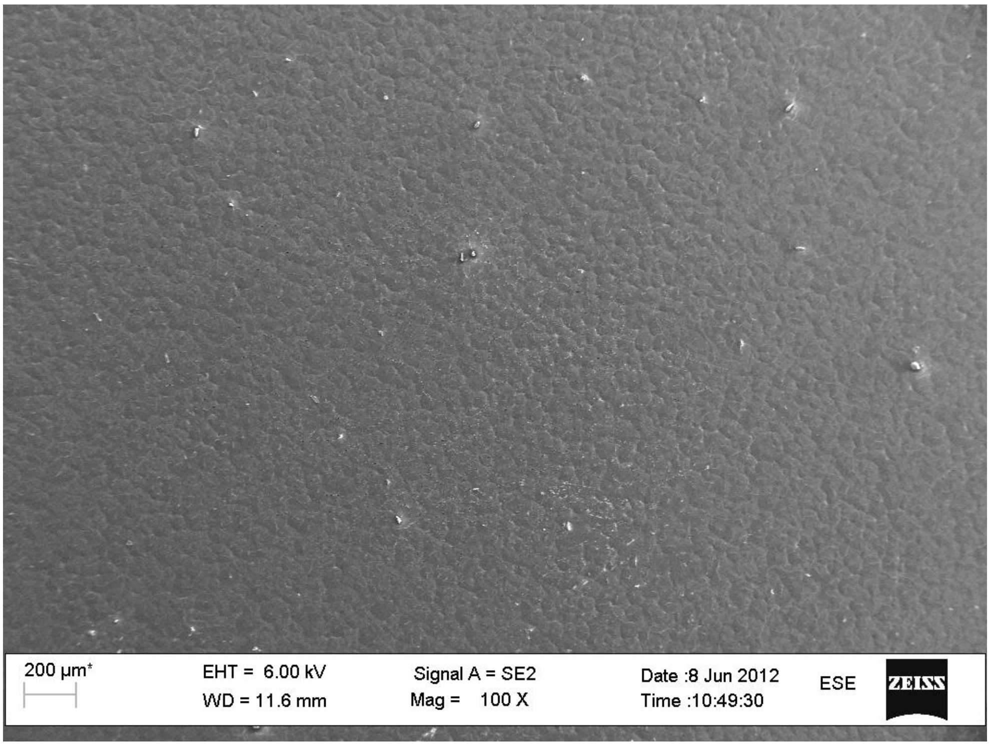


Figure 7-11: POM slit surface, after 3 consecutive explosion experiments, lower part of gap surface.

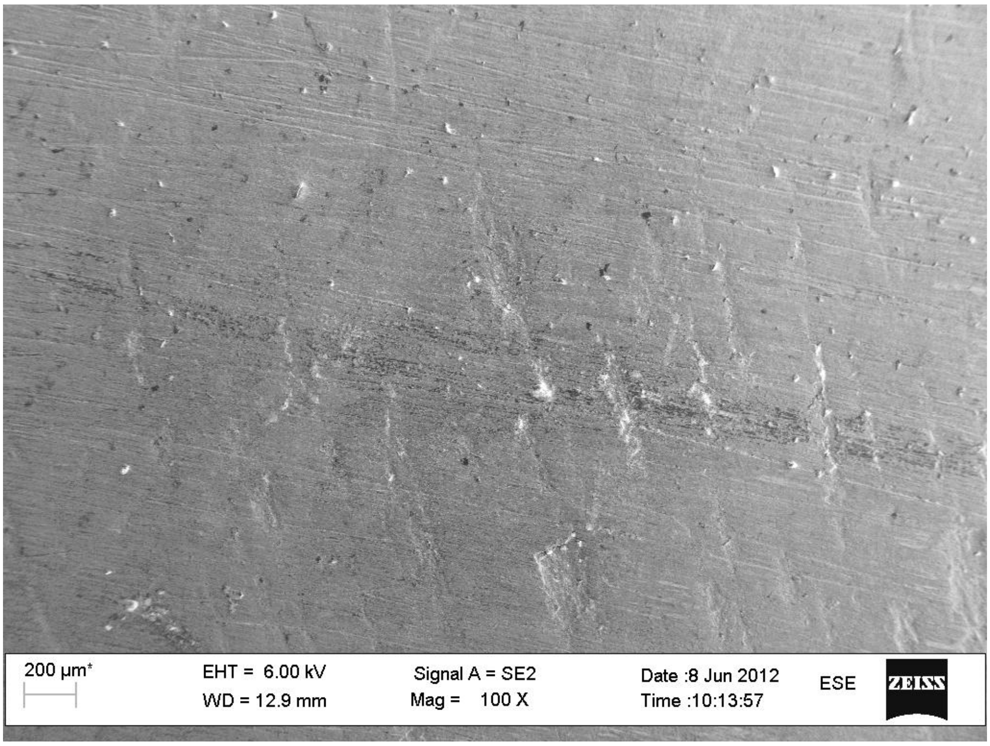


Figure 7-12: Surface of carbon steel slit.

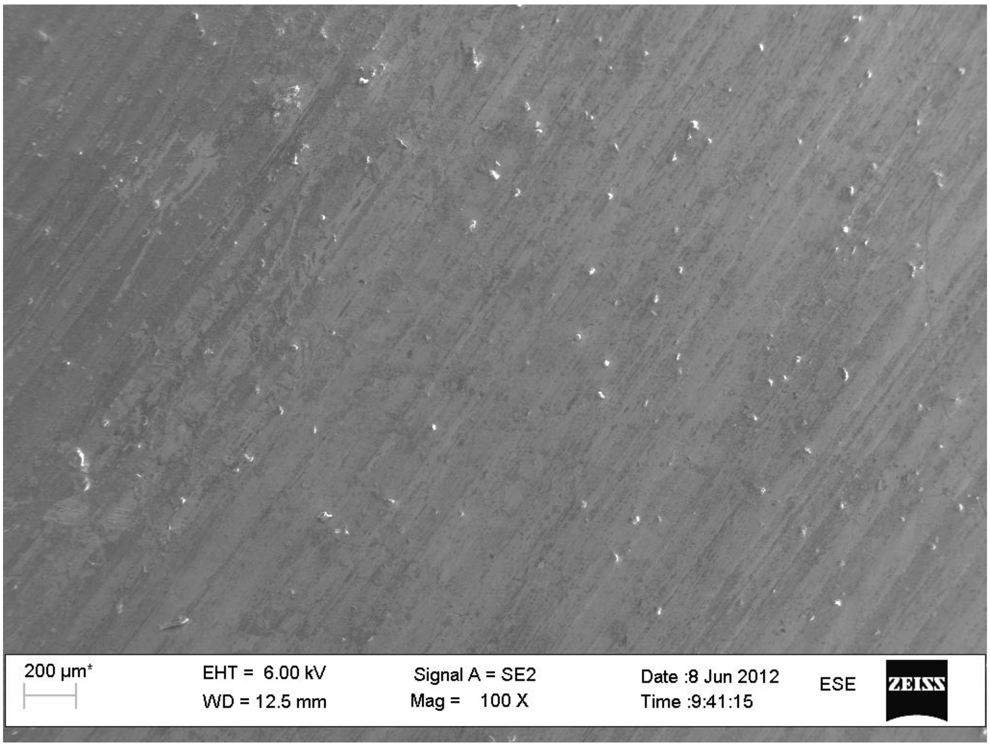


Figure 7-13: Surface of brass slit.

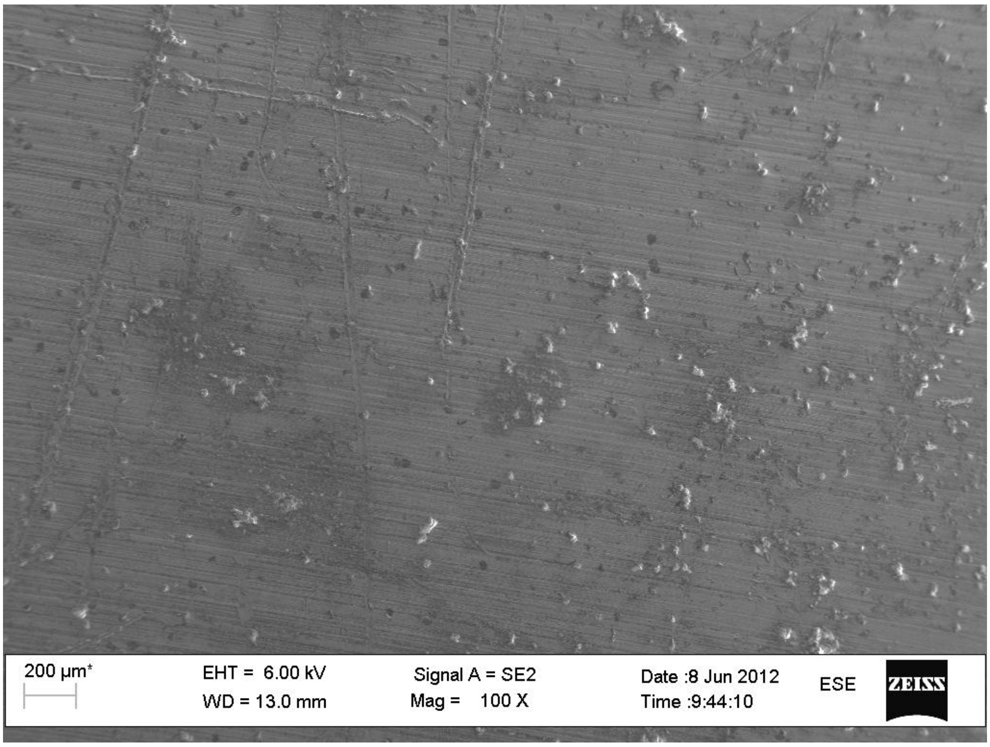


Figure 7-14: Surface of aluminium slit.

Appendix K Experimental data

An excerpt from the measurement data, not presented in the results section, obtained through the experimental work is presented in this section.

Gap opening	Trials	Re-ignition	Pressure	Mean pressure
0,97	Steel	0	2,33	
0,97	Steel	0	2,31	
0,97	Steel	0	2,30	
0,97	Steel	0	2,30	
0,97	Steel	0	2,32	
0,97	Steel	0	2,31	
0,97	Steel	0	2,31	
0,97	Steel	0	2,32	
0,97	Steel	0	2,34	
0,97	Steel	0	2,32	
Mean		**0**	**2,32**	**2,32**
0,98	Steel	0	2,29	
0,98	Steel	0	2,29	
0,98	Steel	0	2,29	
0,98	Steel	0	2,30	
0,98	Steel	0	2,31	
0,98	Steel	0	2,31	
0,98	Steel	0	2,28	
0,98	Steel	0	2,27	
0,98	Steel	0	2,29	
0,98	Steel	0	2,28	
Mean		**0**	**2,29**	**2,29**
0,99	Steel	1	2,22	
0,99	Steel	0	2,22	
0,99	Steel	0	2,20	
0,99	Steel	0	2,22	
0,99	Steel	0	2,21	
0,99	Steel	1	2,19	
0,99	Steel	0	2,23	
0,99	Steel	0	2,22	
0,99	Steel	0	2,21	
0,99	Steel	0	2,23	
Mean		**2**	**2,22**	**2,22**
1,00	Steel	0	2,19	
1,00	Steel	1	2,24	
1,00	Steel	1	2,20	
1,00	Steel	1	2,22	
1,00	Steel	1	2,25	
1,00	Steel	1	2,26	
1,00	Steel	0	2,23	

	1,00	Steel	1	2,26	
	1,00	Steel	1	2,25	
	1,00	Steel	1	2,22	
Mean			**8**	**2,23**	**2,23**
	1,01	Steel	1	2,29	
	1,01	Steel	1	2,33	
	1,01	Steel	1	2,33	
	1,01	Steel	1	2,34	
	1,01	Steel	1	2,34	
	1,01	Steel	1	2,34	
	1,01	Steel	1	2,31	
	1,01	Steel	1	2,32	
	1,01	Steel	1	2,34	
	1,01	Steel	1	2,34	
Mean			**10**	**2,33**	**2,33**

	Gap opening	Trials	Re-ignition	Pressure	Mean pressure
	0,97	Brass	0	2,36	
	0,97	Brass	0	2,34	
	0,97	Brass	0	2,36	
	0,97	Brass	0	2,31	
	0,97	Brass	0	2,31	
	0,97	Brass	0	2,32	
	0,97	Brass	0	2,35	
	0,97	Brass	0	2,36	
	0,97	Brass	0	2,34	
	0,97	Brass	0	2,31	
Mean			0	**2,34**	2,34
	0,98	Brass	1	2,34	
	0,98	Brass	1	2,34	
	0,98	Brass	0	2,37	
	0,98	Brass	0	2,26	
	0,98	Brass	0	2,25	
	0,98	Brass	0	2,29	
	0,98	Brass	1	2,31	
	0,98	Brass	1	2,33	
	0,98	Brass	0	2,29	
	0,98	Brass	0	2,36	
Mean			4	**2,31**	2,31
	0,99	Brass	1	2,17	
	0,99	Brass	1	2,18	
	0,99	Brass	1	2,19	
	0,99	Brass	1	2,18	
	0,99	Brass	1	2,19	
	0,99	Brass	1	2,17	
	0,99	Brass	0	2,20	
	0,99	Brass	1	2,15	
	0,99	Brass	1	2,19	

	0,99	Brass	1	2,15	
Mean			9	**2,18**	2,18
	1,00	Brass	1	2,22	
	1,00	Brass	1	2,23	
	1,00	Brass	1	2,25	
	1,00	Brass	1	2,23	
	1,00	Brass	1	2,20	
	1,00	Brass	1	2,26	
	1,00	Brass	1	2,21	
	1,00	Brass	1	2,22	
	1,00	Brass	1	2,22	
	1,00	Brass	1	2,23	
Mean			10	**2,23**	2,23
	1,01	Brass	1	2,36	
	1,01	Brass	1	2,31	
	1,01	Brass	1	2,31	
	1,01	Brass	1	2,35	
	1,01	Brass	1	2,30	
	1,01	Brass	1	2,36	
	1,01	Brass	1	2,37	
	1,01	Brass	1	2,37	
	1,01	Brass	1	2,35	
	1,01	Brass	1	2,31	
Mean			10	**2,34**	2,34

Temperature measurements over flame gaps (°C):

0.95	**Brass**	**2 cm above gap**	**4 cm above gap**
		314,5	242,4
		311,5	246,5
		319,6	251,0
		317,6	245,9
		318,1	244,4
		316,3	**246,0**
	Std dev	3,243917385	3,192647804

0.95	**Aluminium**	**2 cm above gap**	**4 cm above gap**
		301,1	228,1
		294,1	218,4
		296,7	225,0
		300,8	230,6
		301,0	227,3
		298,7	**225,9**
	Std dev	3,186377253	4,63540721

0.95	**Steel**	**2 cm above gap**	**4 cm above gap**
		284,5	213,8
		280,4	206,2
		289,1	212,3
		287,5	209,3
		284	206,4
		285,1	**209,6**
	Std dev	3,369718089	3,421257079

0.98	**Aluminium**	**2 cm above gap**	**4 cm above gap**
		322,2	242,9
		326,8	243,1
		330,4	248,1
		322,6	234,7
		324,2	240,1
		325,2	**241,8**
	Std dev	3,404115157	4,896120914

0.98	**Steel**	**2 cm above gap**	**4 cm above gap**
		315,0	225,3
		314,0	228,1
		316,6	232,5
		315,1	229,5
		320,7	225,0
		316,3	**228,1**
	Std dev	2,63950753	3,113197713

Mixture with 19.00 vol. % oxygen in nitrogen/oxygen:

Trial	C3H8	p (barg)	Opning
1	4,56	1,045	1,00
2	4,83	0,567	1,00
3	4,30	1,298	1,00
4	3,90	1,408	1,00
5	3,85	1,405	1,00
6	3,63	1,363	1,00
7	3,59	1,322	1,00
8	3,44	1,158	1,00
9	3,73	1,390	1,00
10	4,11	1,367	1,00

Gap opening	Trials	Re-ignitions	Re-ignitions	Pressure	Mean pressure
1,20	**3**	**0**	0	1,26	**1,23**
1,20			0	1,22	
1,20			0	1,21	
1,21	**10**	**0**	0	1,21	**1,21**
1,21			0	1,22	
1,21			0	1,21	
1,21			0	1,22	
1,21			0	1,19	
1,21			0	1,19	
1,21			0	1,20	
1,21			0	1,22	
1,21			0	1,20	
1,21			0	1,20	
1,22	**13**	**4**	0	1,24	**1,22**
1,22			0	1,20	
1,22			0	1,19	
1,22			1	1,21	
1,22			1	1,20	
1,22			1	1,22	
1,22			0	1,21	
1,22			0	1,20	
1,22			1	1,24	
1,22			0	1,23	
1,22			0	1,22	
1,22			0	1,23	
1,22			0	1,21	
1,23	**7**	**3**	0	1,26	**1,24**
1,23			1	1,26	
1,23			0	1,23	
1,23			0	1,24	
1,23			1	1,24	
1,23			1	1,24	
1,23			0	1,23	
1,25	**3**	**1**	1	1,19	**1,19**
1,30	**1**	**1**	1	1,18	**1,18**
1,33	**1**	**1**	1	1,17	**1,17**
1,40	**1**	**1**	1	1,12	**1,12**
1,50	**1**	**1**	1	0,98	**0,98**

Mixture with 16.77 vol. % oxygen in nitrogen/oxygen:

Forsøk	C3H8	p (barg)	Opning
1	3,00	0,201	1,2
2	3,21	0,386	1,2
3	3,32	0,425	1,2
4	3,38	0,434	1,2
5	3,44	0,440	1,2
6	3,51	0,442	1,2
7	3,58	0,430	1,2
8	3,67	0,409	1,2
9	3,59	0,421	1,2
10	3,44	0,454	1,2

Gap opening	Trials	Re-ignitions	Re-ignitions	Pressure	Mean pressure
1,50	1	0		0,30	0,30
1,55	10	0	0	0,27	0,28
1,55		0		0,29	
1,55		0		0,28	
1,55		0		0,27	
1,55		0		0,29	
1,55		0		0,28	
1,55		0		0,29	
1,55		0		0,27	
1,55		0		0,29	
1,55		0		0,31	
1,56	6	0	1	0,26	0,27
1,56		0		0,25	
1,56		0		0,27	
1,56		1		0,29	
1,56		0		0,28	
1,56		0		0,28	
1,57	3	1	2	0,27	0,27
1,57		1		0,27	
1,57		0		0,28	
1,58	8	0	3	0,24	0,27
1,58		1		0,25	
1,58		1		0,28	
1,58		0		0,28	
1,58		0		0,28	
1,58		0		0,25	
1,58		1		0,29	
1,58		0		0,26	
1,59	10	0	4	0,27	0,26

1,59		0		0,25	
1,59		0		0,22	
1,59		1		0,26	
1,59		1		0,24	
1,59		1		0,27	
1,59		0		0,23	
1,59		1		0,46	
1,59		0		0,22	
1,59		0		0,22	
1,60	22	0	7	0,19	0,25
1,60		1		0,22	
1,60		1		0,22	
1,60		0		0,26	
1,60		1		0,25	
1,60		0		0,26	
1,60		0		0,25	
1,60		0		0,26	
1,60		1		0,24	
1,60		0		0,25	
1,60		0		0,27	
1,60		0		0,26	
1,60		0		0,27	
1,60		1		0,26	
1,60		0		0,26	
1,60		0		0,27	
1,60		0		0,27	
1,60		1		0,25	
1,60		0		0,26	
1,60		0		0,25	
1,60		1		0,25	
1,60		0		0,26	
1,61	5	1	5	0,25	0,26
1,61		1		0,29	
1,61		1		0,27	
1,61		1		0,28	
1,61		1		0,24	
1,62	1	1	1	0,29	0,29
1,65	1	1	1	0,26	0,26
1,70	1	1	1	0,23	0,23

Mixture with 15.04 vol. % oxygen in nitrogen/oxygen:

Forsøk	C3H8	p (barg)	Opning
1	3,30	0,024	2,00
2	3,20	0,020	2,00
3	3,26	0,023	2,00
4	3,49	0,017	2,00
5	3,30	0,023	2,00
6	3,35	0,019	2,00
7	3,14	0,022	2,00
8	3,12	0,028	2,00
9	3,08	0,032	2,00
10	3,15	0,028	2,00
11	3,36	0,025	2,00

Gap opening	Trials	Re-ignitions	Re-ignitions	Pressure	Mean pressure
2,00	11	0	0		0,024
2,05	9	0	1	0,028	0,027
2,05		0		0,030	
2,05		0		0,029	
2,05		0		0,025	
2,05		0		0,023	
2,05		1		0,025	
2,05		0		0,026	
2,05		0		0,025	
2,05		0		0,027	
2,10	10	0	2	0,027	0,032
2,10		1		0,038	
2,10		1		0,029	
2,10		0		0,040	
2,10		0		0,038	
2,10		0		0,022	
2,10		0		0,035	
2,10		0		0,031	
2,10		0		0,026	
2,10		0		0,029	
2,15	2	1	1	0,028	0,025
2,15		0		0,022	
2,25	3	0	2	0,023	0,022
2,25		1		0,023	
2,25		1		0,021	
2,45	1	1	1	0,022	0,022