THE UNIVERSITY OF CALGARY

EXPERIMENTAL INVESTIGATION OF A JET DIFFUSION FLAME AND FLAME FLASHBACK WITHIN STREAMS OF HOMOGENEOUS FUEL-AIR MIXTURES

by

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ABSTRACT

Flashback and blowout phenomena in a system involving a jet diffusion flame within laminar and turbulent co-flowing streams of air or homogeneous fuel-air mixtures were investigated experimentally using methane, ethylene, propane and hydrogen as fuels.

Two types of flames, lifted and attached, were observed before blowout depending on the stream velocity and the jet nozzle diameter. Generally, lifted flames had higher blowout limits than attached flames. Also, the blowout limits of lifted flames decreased as the stream velocity was increased while those of the attached flames were almost independent of the stream velocity in the range considered. Procedures for correlating the observed blowout limits of both types of flame are proposed.

The flame flashback limits for binary fuel mixtures and fuel-diluent mixtures involving hydrogen were determined experimentally and the observed limits were found to be in good agreement with those calculated according to the proposed procedures.

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NOMENCLATURE

a_D	experimental constant for hydrogen-diluent mixtures
d_j	diameter of the jet nozzle (mm)
FB_C	calculated value of the flashback limit for the fuel mixture (% by volume)
FB_D	flashback limit of "diluted" hydrogen in air (% by volume)
FB_E	experimental value of the flashback limit for the fuel mixture (% by volume)
FB_F	flashback limit of single fuels in air (% by volume)
FB_m	flashback limit of fuel mixtures in air (% by volume)
$H_{P_i\,F}$	changes in the enthalpies of the product components of fuel-air mixtures (kJ/kg)
$H_{R_i\,F}$	changes in the enthalpies of the reactant components of fuel-air mixtures (kJ/kg)
$H_{P_i\,M}$	changes in the enthalpies of the product components of the fuel-air-diluent mixtures (kJ/kg)
$H_{R_i\,M}$	changes in the enthalpies of the reactant components of the fuel-air-diluent mixtures (kJ/kg)
M_a	molecular weight of air (kg/kmol)
M_g	molecular weight of gas (kg/kmol)
P_a	atmospheric pressure (kPa)
P_u	absolute pressure upstream of choked nozzle (kPa)
Q_j	volumetric flame blowout limit (m^3/h)
Q_{jo}	volumetric flame blowout limit with only air in surrounding (m^3/h)
Q_a	flow rate of air through choked nozzle (m^3/h)

Q_g flow rate of gas through choked nozzle (m^3/h)

S_L maximum laminar burning velocity in air (m/s)

t_D mixing time (s)

t_C characteristic chemical time (s)

T_a atmospheric temperature (K)

T_f final temperature attained in the fuel-air-diluent mixtures after combustion (K)

T_o initial temperature of fuel-air-diluent mixtures (K)

T_u temperature upstream of choked nozzle (K)

U_S stream velocity (m/s)

$U_{S,L}$ limiting stream velocity for flame liftoff (m/s)

$U_{S,M}$ maximum stream velocity for which flame flashback could be determined (m/s)

y_{H_2} hydrogen concentration in hydrogen-diluent mixtures (% by volume)

y_i concentration of the "i"th fuel component in the mixture (% by volume)

α correlation blowout limit parameter $(\frac{m^2}{mm^2})(\frac{s}{h})$

ρ_j density of the jet fuel (kg/m^3)

ρ_S density of air (kg/m^3)

θ dimensionless stream velocity, U_S/S_L

λ ratio of specific heats (C_p/C_v)

γ variable defined as $P_u/\sqrt{T_u}$

CHAPTER ONE

INTRODUCTION AND OBJECTIVES

1.1 GENERAL

A jet diffusion flame is one of the simplest ways to burn hydrocarbon fuels. Such a flame develops within a thin region where the fuel and the oxidizer, initially separated, are mixed with each other to form a flammable mixture of varying composition across any section. Since the rate of chemical reaction in diffusion flames is usually relatively fast, the flames are generally considered to be controlled by the rate of mixing between the fuel, air and the re-entrained hot products of combustion.

A lot of work has been done by many researchers on the stability of the jet diffusion flame over a wide range of operating conditions. Two combustion phenomena that are commonly used to characterize the stability of the flame are flame flashback and flame blowout. Flashback involves the propagation of a flame, from a suitable ignition source, into the homogeneous fuel-air stream in a direction opposite to the direction of flow. The minimum fuel concentration in the stream at which such a flame propagation occurs is known as the lean flashback limit. Flame blowout, on the other hand, occurs when the jet velocity is so high that a stationary flame cannot be maintained anywhere in the jet and the flame is thus blown out. The minimum jet flow rate at which the flame suddenly goes out of the combustor entirely defines the blowout limit. Flame liftoff may be observed before the flame is blown out under certain conditions. Liftoff refers to the situation where the base of the jet flame is blown away from the jet nozzle exit and is stabilized at a finite distance downstream of the nozzle exit.

Information about flame flashback is very important for a safe handling and use of gaseous fuels and for the prevention of fire in situations where a flowing homogeneous fuel-air mixture may be present. Such data is also relevant to the study of the stability of the jet flame in a stream of lean homogeneous fuel-air mixture. It is known that the stability of a jet diffusion flame can be improved significantly, under certain conditions, if the surrounding stream contains some fuel already premixed with air. The amount of fuel that can be introduced into the stream is however limited by the onset of flashback through the whole stream.

Adequate knowledge of the blowout limit of the jet diffusion flame of a given fuel is necessary to ensure a continuous combustion operation in many thermal systems. Such knowledge is especially vital in aerospace applications where a stable flame is to be maintained over a wide range of flight conditions.

1.2 JUSTIFICATION FOR THE PRESENT WORK

An examination of the literature on flame flashback revealed that most of the available information are limited to relatively low stream velocities (≤ 0.6 m/s). Although, some results for certain fuels are now available at stream velocities reaching up to 1.3 m/s, more studies are necessary to establish the effect of the stream velocity on the flashback limit for relatively high Reynolds number flows. Also, there is still not enough information on how the fuel composition affect the flashback limits of various mixtures of gaseous fuels and diluents, especially at stream velocities greater than about 0.6 m/s.

Most of the earlier investigations on flame blowout involved a jet diffusion flame in a quiescent environment. Although, blowout of the jet flame within co-flowing streams of air or air homogeneously mixed with fuel have been investigated recently by a few researchers, most of such investigations were done at relatively low stream velocities. However, many practical applications employ a jet diffusion flame in turbulent co-flowing air streams. Information is therefore needed about the effect of the various conditions of the co-flowing stream (velocity, composition, etc) on the stability of the jet flame.

1.3 OBJECTIVES

The specific goals set to be achieved in the present investigation fall under two major categories as follows:

A. Flame flashback within homogeneous fuel-air mixtures

1. To investigate the effect of the stream velocity on the flashback limits of homogeneous fuel-air mixtures.
2. To establish the flashback limits of binary fuel mixtures involving hydrogen and to develop guidelines for predicting them.
3. To study the effect of the addition of diluents to hydrogen on the flame flashback limits.
4. To develop guidelines for predicting the flame flashback limits of hydrogen-diluent mixtures in air.

B. Blowout of the jet diffusion flame

1. To establish the effect of the velocity of the surrounding co-flowing air stream on the blowout limit of a jet diffusion flame.
2. To determine the effect of the jet nozzle diameter on the blowout limit of the jet flame.
3. To investigate the effect of the surrounding co-flow stream composition on the blowout limit of the jet flame.

CHAPTER TWO

LITERATURE SURVEY

2.1 FLASHBACK WITHIN HOMOGENEOUS FUEL-AIR MIXTURES

If the fuel concentration in a homogeneous stream of air and fuel is within the flammable range, a flame initiated by a suitable ignition source, will propagate in either upstream or downstream direction, depending on the relative magnitudes of the velocity of the flame front (or burning velocity) and the stream velocity. If the stream velocity exceeds the burning velocity, the flame will propagate downstream and may eventually be blown out of the combustor. It is also possible for the flame to appear to be stationary at any location if the local burning velocity is equal to the local stream velocity. If however, the burning velocity is greater than the stream velocity, the flame will propagate upstream against the direction of flow. This upstream propagation of the flame is known as flame flashback, and the minimum fuel concentration in the stream at which it occurs defines the lean flashback limit. It can be expected therefore that the flashback limit will be influenced by all the physical parameters that affect the burning velocity of the homogeneous fuel-air mixture.

Flame flashback is an important characteristic of a fuel and the determination of the flashback limit of different fuels has been the subject of several investigations. However, most of these investigations were limited to small diameter tubes and burners [6,7,19,31,34]. But for a few studies, there is limited information in the literature about flame flashback limits in large channels and at high stream velocities. The flashback in large diameter tubes (~150 mm), using a small diffusion pilot flame as the source of ignition, were studied by Karim et al [16,19] and Kibrya [20] at relatively low (up to 0.55 m/s) stream velocities. The results obtained from their investigation showed that the flashback limit of methane and hydrogen were influenced by the stream velocity over the whole range of stream velocities considered while those of ethylene and propane were only affected at velocities lower than about 0.1 m/s. They also reported that the flashback limit was not affected by the type of fuel in the pilot flame, its rate of flow or the axial location of the pilot flame inside the combustor.

Quite recently, flashback in a vertical square cross-section (132 mm x 132 mm) combustor and at stream velocities reaching up to 1.3 m/s were studied by Wierzba et al [32] and Kar [15]. Compared to the results of Karim et al, their results at corresponding low stream velocities (≤ 0.55 m/s) were in the order of 20 - 35% higher. Since the cross sectional area of the combustors used in both cases are very close to each other (within 1.5%), the difference in the results obtained from the two combustors indicates that the geometry of the combustor probably influences the flashback limit.

There is a wide area of practical applications where the gaseous fuels in use represent mixtures of gaseous fuels and diluents. A few examples are processes utilising different natural gases, industrial or bio-gases. In this regard, it is important to know the flashback limits of different fuel mixtures. Some limited data on the flashback limits of fuel mixtures primarily involving methane have been published [15,32]. It was shown that an adapted form of Le-Chatelier's approach for predicting the flammability limits of fuel mixtures can be used to predict the flashback limits of the fuel mixtures. The flashback limits of methane-diluent-air mixtures were also established at stream velocities in the range of 0.51 - 0.6 m/s [15]

2.2 BLOWOUT OF JET DIFFUSION FLAMES

The stability of a jet diffusion flame has been the subject of many investigations. In particular, the liftoff and blowout phenomena of such flame have been studied extensively in attempts to identify the underlying physical mechanisms that are responsible for these stability limits and to develop procedures for predicting both phenomena [2,7,8,9,12,13,14,23,24,27,31]. Many competing theories have been proposed to account for the observed liftoff and blowout limits in a system involving a simple fuel jet issuing into a quiescent medium. An assessment of these theories have been reported to show that none of them are completely satisfactory in providing explanations of the experimental results [27].

One popular view, proposed by Vanquickenborne and van Tiggelen [31], assumes that a homogeneous mixture of fuel and air is formed at the base of the lifted jet flame. Flame stabilization is considered to be maintained by a balance of turbulent flame speed for the premixed fuel and air mixture and the local flow velocity. Near the nozzle exit, the average flow velocity everywhere exceeds the burning velocity. The flame thus lifts off to be stabilized downstream at a position where the condition of equality of these velocities is satisfied. This position defines the liftoff height. As the jet exit velocity is increased further, the local average flow velocity increases and the stabilization plane moves further downstream. At a certain level of the jet exit velocity, this stabilization plane is so far downstream that the average composition becomes fuel-lean across the entire jet and the burning velocity starts to drop sharply. Blowout then occurs either due to inability to satisfy the requirement of velocity balance or due to the mixture concentration being below the lean flammability limit. Kalghatgi [13,14] used this approach to correlate his experimental results on the liftoff and blowout limits of lifted jet flames of different fuels over a range of jet nozzle diameters. The model has also been used by several other researchers to explain various experimental findings on flame liftoff and blowout [3,9,29].

Peters and Williams [24] have questioned this view and pointed out that the assumption of a uniform fuel-air mixture at the base of the lifted flame is not consistent with the known mixing behaviour of axisymmetric jets. In their view, the time required for flow of a fluid element from the nozzle exit to the base of the lifted flame is not sufficient for mixing of the element to approach local uniformity prior to reaching the flame. They proposed instead, a model in which the turbulent diffusion flame is considered as an ensemble of laminar diffusion flamelets which can be quenched if stretched beyond a critical value in the presence of turbulence. It was suggested that the flamelets are more stretched as the jet velocity increases. For a nozzle attached flame, this may lead to a large fraction of the laminar diffusion flamelets being quenched at the rim for liftoff to occur. The flame will be stabilized somewhere downstream of the nozzle exit where the strain rates are low enough for a reasonable fraction of the laminar diffusion flamelets to remain unextinguished. Assessment of this theory with a view to delineate clearly the regime of validity of the theory in flames and combustors has been done by Bilger [1]. The theory has also been successfully applied to the modelling of jet diffusion flames of hydrocarbon fuels [22]. In the work of Peters [25], it was suggested that it is possible that both premixed combustion and laminar flamelet extinction by stretching are important for flame stabilization.

A different model, based on the behaviour of large-scale turbulent structures in the turbulent flow field, has been proposed by Broadwell et al [2] to explain the flame extinction phenomena. According to this model, hot combustion products expelled to the edge of the jet during the passage of earlier large-scale turbulent structures reenter the jet together with fresh air and initiate the reaction in the flame sheets that are formed between the air and the jet fluid. Blowout is expected to occur when the reentrained, hot combustion products are mixed so rapidly with the unburned jet fluid that there is insufficient time for ignition before the temperature and radical species concentrations drop below some critical value. The criterion for flame extinction is proposed to be that the ratio of the local mixing time, t_D, to a characteristic chemical time, t_C, is less than some critical value. This model was applied by the authors to correlate the experimental observations of Kalghatgi [13] on flame blowout for different gaseous fuels over a range of jet nozzle diameters and a good agreement was reported [2].

As mentioned earlier, the theories discussed above have all been proposed based on a jet diffusion flame in a quiescent environment. With this type of flame, liftoff is generally observed before the incidence of blowout. However, it is well known that many important applications involve the jet flame within co-flowing streams, for example, gas turbine combustors, furnaces, etc. For such jet flames, liftoff may or may not occur before flame blowout depending on the stream velocity and the diameter of the jet nozzle

[15,34].

Dahm and Dibble [7] applied the theory of Broadwell et al [2] to explain their blowout results on methane and propane jet flames in co-flowing air streams of velocity reaching up to 1 m/s. By performing the necessary non-linear scaling of the flow field, they were able to show that the flame will be blown out when the ratio of the mixing time to the characteristic chemical time, t_D/t_C, is less than about 4.3. The values of the predicted blowout limits from their analysis were shown to be in good agreement with their experimental results. However, considering the jet nozzle diameters used in their work (3.3 and 5.2 mm) and the relatively low range of stream velocities considered (up to 1 m/s), liftoff of the jet flame must have been observed before blowout in all their experiments.

Thus the literature describes, in some detail, the possible physical mechanisms responsible for the observed stability behaviour of the lifted flame but lacks similar information on the nozzle attached flame. More studies are thus needed to provide pertinent information that may be used to develop suitable guidelines for predicting the stability limits of the nozzle-attached flame.

It is known that the blowout limit of a jet diffusion flame in co-flowing streams is generally lower than the corresponding limit for the jet flame in quiescent environment. Several methods for improving the stability of the flame in co-flowing streams have been investigated in the literature [4,20,30]. One of such methods is the introduction of some auxiliary fuel into the co-flowing stream of air. The studies conducted at relatively low stream velocities up to 0.5 m/s [11,17,18,20] indicated a significant improvement in the stability of the jet diffusion flame when a small amount of fuel was added to the co-flowing stream. Recently, similar studies were carried out on methane jets at significantly higher stream velocities reaching up to 1.4 m/s [15,34]. The results obtained indicate that the effect of the auxiliary fuel on the stability of the jet diffusion flame depends on the type of the fuel, its concentration and the level of the stream velocity. They confirm that the stability of the jet flame was improved by adding the auxiliary fuel to the stream at low stream velocity ($\simeq$ 0.3 m/s) for all common gaseous fuels. However, such an addition had a complex effect on the blowout limit of the jet flame at relatively higher stream velocities ($\geq$ 1.0 m/s) and did not always enhance the blowout limits.

CHAPTER THREE

APPARATUS AND EXPERIMENTAL PROCEDURE

3.1 APPARATUS

The schematic diagram of the experimental set up is presented in Figure 3.1. The experiments were conducted in a vertical square cross-section steel combustor (132 mm x 132 mm) fitted with quartz windows on two opposite sides for viewing the flame. Two separate fuel lines were available. One line delivered fuel to the pilot flame while the other was used to introduce the auxiliary fuel into the co-flowing air stream well upstream of the combustor. This arrangement ensured thorough mixing of the fuel with the air such that a homogeneous mixture was formed before the stream reached the combustor. The air stream was generated using a centrifugal blower driven by an induction motor. The stream passed through a honeycomb flow straightener before entering the combustor. The jet fuel was discharged vertically along the centreline of the combustor from a sharp edged circular nozzle held by a 6.2 mm outer diameter brass tube at a height of 70 mm above the base of the combustor. The jet nozzles employed were of diameters 1.0, 1.5 and 2.0 mm.

The flow rate of air was measured using a sharp edged orifice plate while the flow rates of fuels and diluents were measured using calibrated choked nozzles. The choked nozzles were calibrated using wet test meters. The accuracy of the results for very small flow rates was later checked using a soap bubble meter. The calibration was conducted with air as the working fluid and correction factors were applied to adapt the calibration for the different gases used in the experiments. The accuracy of the correction factors was

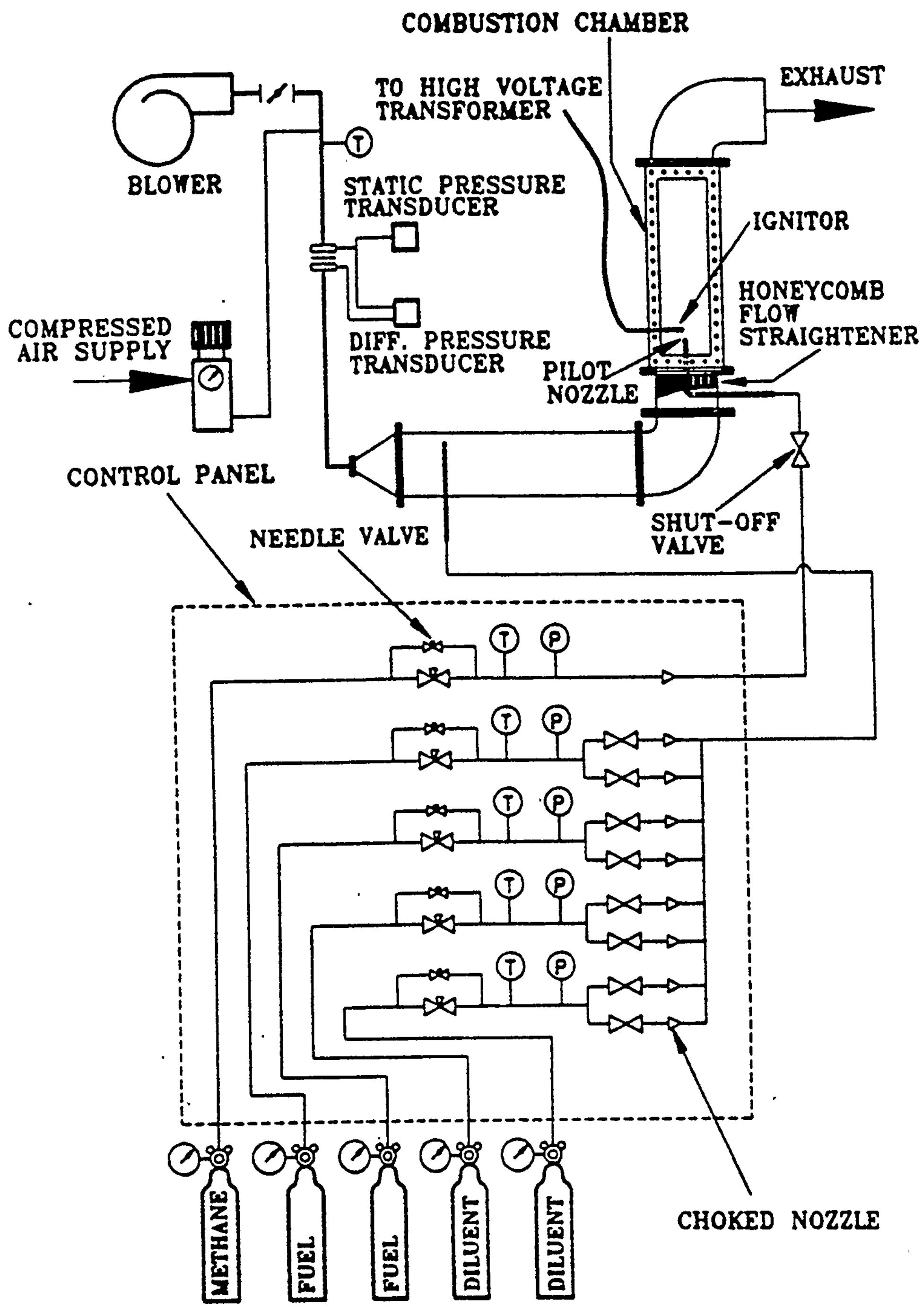

Figure 3.1: Schematic diagram of the experimental set-up

checked by conducting calibration tests over a few points with the actual gases that were to be used in the experiments.

Gaseous fuels employed in the experiments were methane, ethylene, propane and hydrogen, while nitrogen and carbon dioxide were used as diluents. Flashback of the flame was established visually and also with the help of a thermocouple located close to the base of the combustor. A sudden increase in the temperature reading of the thermocouple indicates the arrival of a flame at the base of the combustor and thus helps to detect the onset of flame flashback.

3.2 EXPERIMENTAL PROCEDURE

To establish the flashback limits within the stream of homogeneous air-fuel or air-fuel-diluent mixture, the following steps were followed:

1. The stream velocity was first set to a very small value and, with the pilot jet set to a very small flow rate, the jet was ignited to produce a small flame. The stream velocity was then increased to the desired level.
2. The surrounding fuel was next introduced very gradually into the air stream until a critical value was reached at which flashback of the mixture occurred.
3. In establishing the flashback limit of binary fuel mixtures involving hydrogen in air, the other fuel was first introduced into the air stream at the desired flow rate. Hydrogen was then introduced into the stream and its flow rate was increased gradually until flashback of the mixture occurred. The same procedure was then repeated for different binary fuel mixtures and at different velocities

of the stream.

4. Flashback limits of hydrogen-diluent mixtures in air were determined by first setting the air to the desired flow rate and then introducing the required concentration of the diluent into the air stream. Hydrogen was finally added to the stream and its flow rate was gradually increased until the flashback limit of the mixture was reached.

The blowout limits of the jet flames were determined at different stream velocities and different surrounding fuel concentrations by following the procedure described below:

1. The stream velocity was first set at a small value and the jet fuel ignited. The stream velocity was then set to the desired value and the jet flow rate was gradually increased until blowout of the jet flame occurred. The volumetric flow rate of the jet at which the flame suddenly went out of the combustor entirely was recorded as the blowout limit. Sufficient time was allowed between successive increase of the jet flow rate to allow for steady flow conditions in the combustor.
2. The blowout limits of the jet flames within co-flowing stream of air and fuel were established by first setting the flow rate of air as desired and then introducing the required quantity of the surrounding fuel into the air stream. The jet flow rate was then increased very slowly until blowout of the flame occurred.

CHAPTER FOUR

FLASHBACK LIMITS: RESULTS AND DISCUSSION

4.1. GENERAL

The flame flashback limits of single fuels, binary fuel mixtures, and fuel mixed with diluents in air were determined in a combustion chamber opened to the atmosphere. The temperature of the flowing stream was about 25°C for all the experiments while the combustor pressure was approximately atmospheric. The fuels used included methane, ethylene, propane, and hydrogen while nitrogen and carbon dioxide were employed as diluents.

The flashback limits of single fuels in air are reported in section 4.2 while those of the binary fuel mixtures of hydrogen with methane, ethylene and propane follow in section 4.3. The limits for flame flashback of hydrogen-diluent mixtures in air are discussed in section 4.4. Procedures for calculating the flashback limits of fuel-diluent mixtures are described in section 4.5.

4.2. FLAME FLASHBACK LIMITS OF SINGLE FUELS IN AIR

The use of a pilot jet flame as an ignition source limited the range of stream velocities over which the flashback limit of the fuel-air stream can be determined. At certain values of the stream velocities and fuel concentrations, the flame would propagate from the pilot flame through the stream downstream in the direction of flow. Often simultaneously, the blowout of the pilot flame would occur. In such cases, it was not possible to achieve flame flashback by simply increasing the fuel concentration in the stream, since the ignition source was lost.

The flashback limits of methane, ethylene, propane and hydrogen at different stream velocities are shown in Figure 4.1. A symbol * on each curve in the figure indicates the maximum (limiting) stream velocity, $U_{S,M}$, for which flame flashback could be determined. It was observed that the value of this maximum velocity depends on the type of fuel in the stream and generally increases in order of increasing maximum laminar burning velocity of these fuels in air as follows: 0.39 m/s for methane, 0.45 m/s for propane, 0.75 m/s for ethylene and 3.06 m/s for hydrogen [13].

The experimental results showed that the flame flashback limit was influenced differently in different ranges of the stream velocity. However, as the stream velocity approaches zero, the value of the flashback limit for each fuel approaches the corresponding value of the lean flammability limit for that fuel in air for downward flame propagation [5]. With methane, ethylene and propane in the stream, the flame flashback limit was found to decrease with increase of the stream velocity up to about 0.4 m/s. Beyond this level, a slight increase in the flashback limit was observed as the stream velocity was increased further until the limiting value for each fuel was reached. With hydrogen in the stream, the flame flashback limit was more significantly influenced by changes in the stream velocity. As shown in the figure, the flashback limit initially decreased as the stream velocity was increased and reached a minimum at a stream velocity of about 1.6 m/s. A further increase in the stream velocity beyond this level resulted in a significant increase in the flame flashback limit until the limiting stream

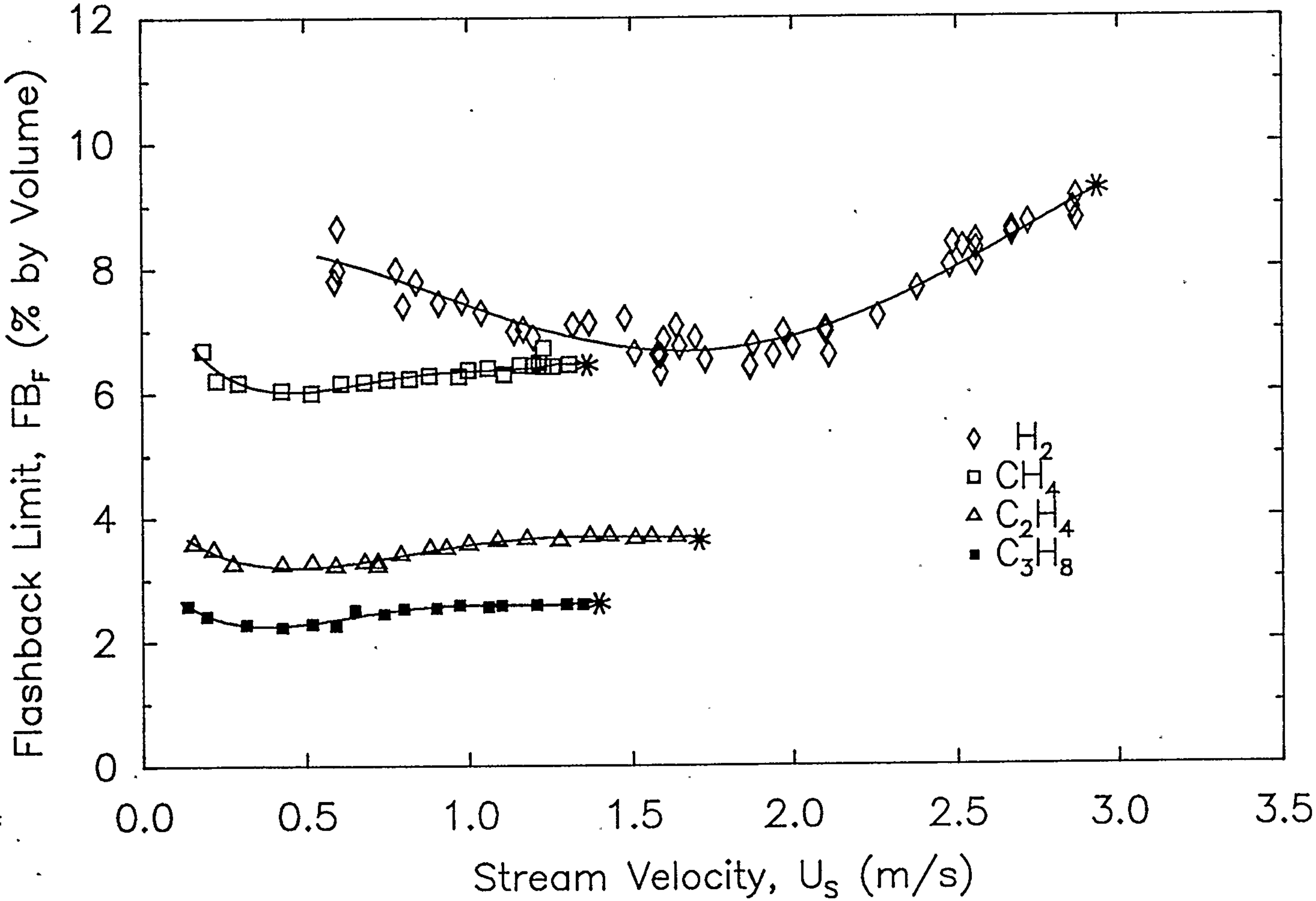

Figure 4.1 - Flashback limits of pure fuels in air. * indicates the maximum stream velocity for which flame flashback could be determined for each fuel

velocity of about 2.9 m/s was reached.

It has been suggested that the initial decrease of the limit results from an increase of flame burning velocity promoted by higher turbulence intensity associated with the increase of stream velocity [36]. A lower fuel concentration is thus needed to achieve flame flashback. As the stream velocity is increased beyond a certain level however, it is possible that the resulting increase in the burning velocity, due to higher turbulence intensity, is not sufficient to compensate for the increase in the stream velocity. A higher fuel concentration in the stream is therefore needed to raise the burning velocity in excess of the stream velocity for the flame to propagate against the flow.

4.3. FLASHBACK LIMIT OF BINARY FUEL MIXTURE

Since the flashback limit of hydrogen in air tends to behave differently from that of methane, ethylene or propane as discussed in the previous section, it is practically important to establish how the addition of hydrogen to any of these fuels will affect the flashback limit. Tests were conducted at different stream velocities and the fuels were mixed together prior to their introduction into the air stream. Figure 4.2 shows the results at a relatively low stream velocity of 1 m/s at which, for all individually employed fuels, flame flashback limits were determined. As shown in the figure, the limit for fuel mixture falls somewhere between the corresponding limits for the individual fuels making up the mixture.

It is expected that some similarity exists in the nature of lean flame flashback and lean flammability limit. Hence, Le Chatelier's rule, often used to predict the flammability

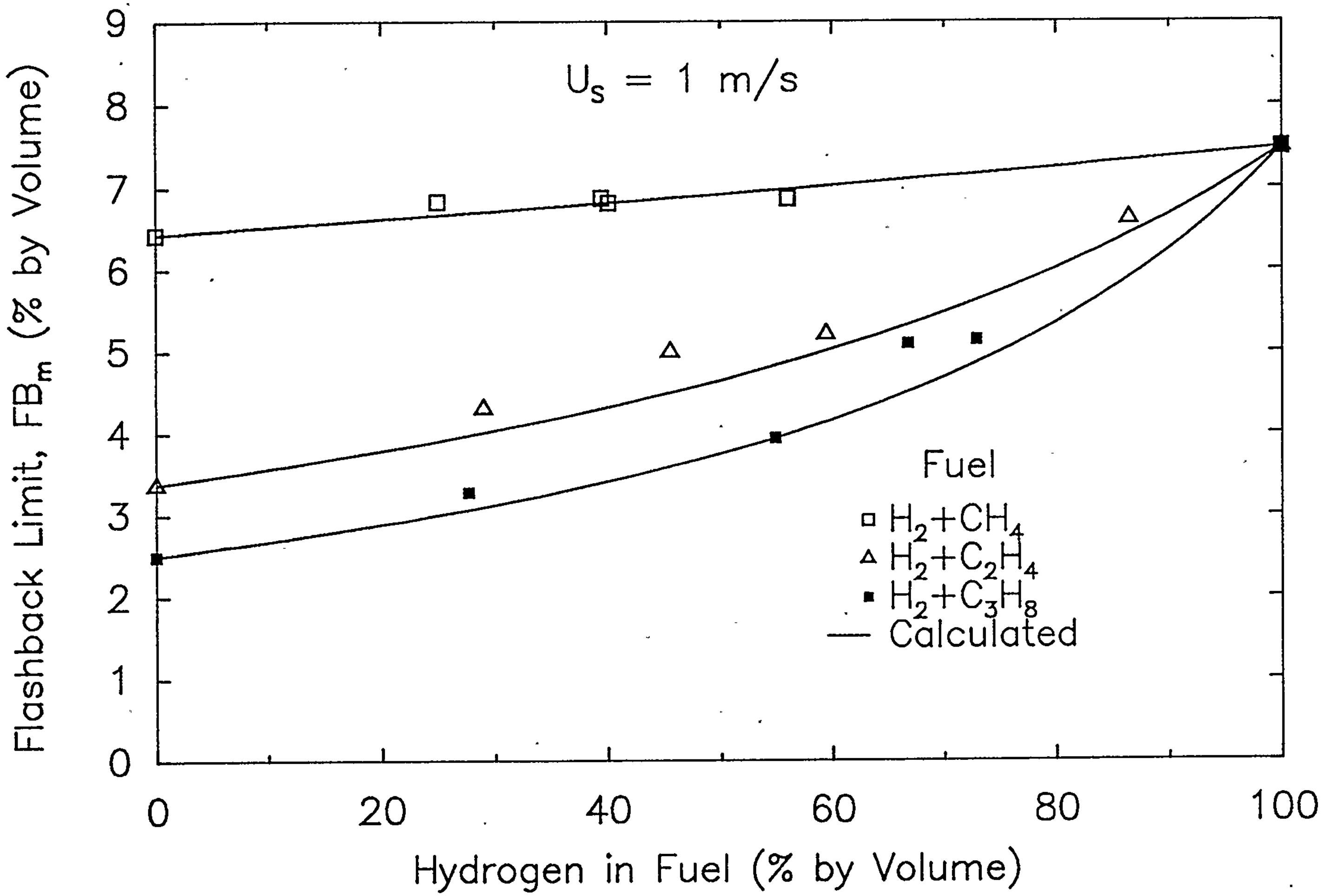

Figure 4.2 - Flashback limits of binary fuel mixtures involving hydrogen in air.

limits of fuel mixtures in air, can be adapted to predict the flame flashback limit of the fuel mixture in the form:

$$FB_m = 100[\sum \frac{y_i}{FB_i}]^{-1} \tag{4.1}$$

where

FB_m is the flashback limit for the fuel mixture (% by volume)
FB_i is the flashback limit for the "i"th fuel component on its own in air (% by volume)
y_i is the "i"th fuel component concentration in a fuel mixture (% by volume)

The flashback limits calculated using the above equation are also shown in Figure 4.2 for comparison. The deviation of the calculated limits, FB_C from the experimental values, FB_E defined as $(FB_C - FB_E)/FB_E$, are shown in Figure 4.3. The deviations fall within 7.5% for all but two of the fuel mixtures and appear to have been influenced mainly by experimental errors.

It was noted in section 4.2 that the limiting stream velocity for flame flashback was highest for hydrogen compared to methane, ethylene and propane. The addition of hydrogen to these fuels will generally increase the range of the stream velocities at which flame flashback could be observed. The limiting stream velocity for the binary fuel mixture will fall somewhere between the corresponding limiting stream velocities for the individual fuels making up the mixture depending on the mixture composition. This is shown, for the different fuel mixtures investigated, by the symbol * on the curves shown in Figures 4.4 - 4.6.

The calculated flashback limits, using equation 4.1, for the binary fuel mixtures

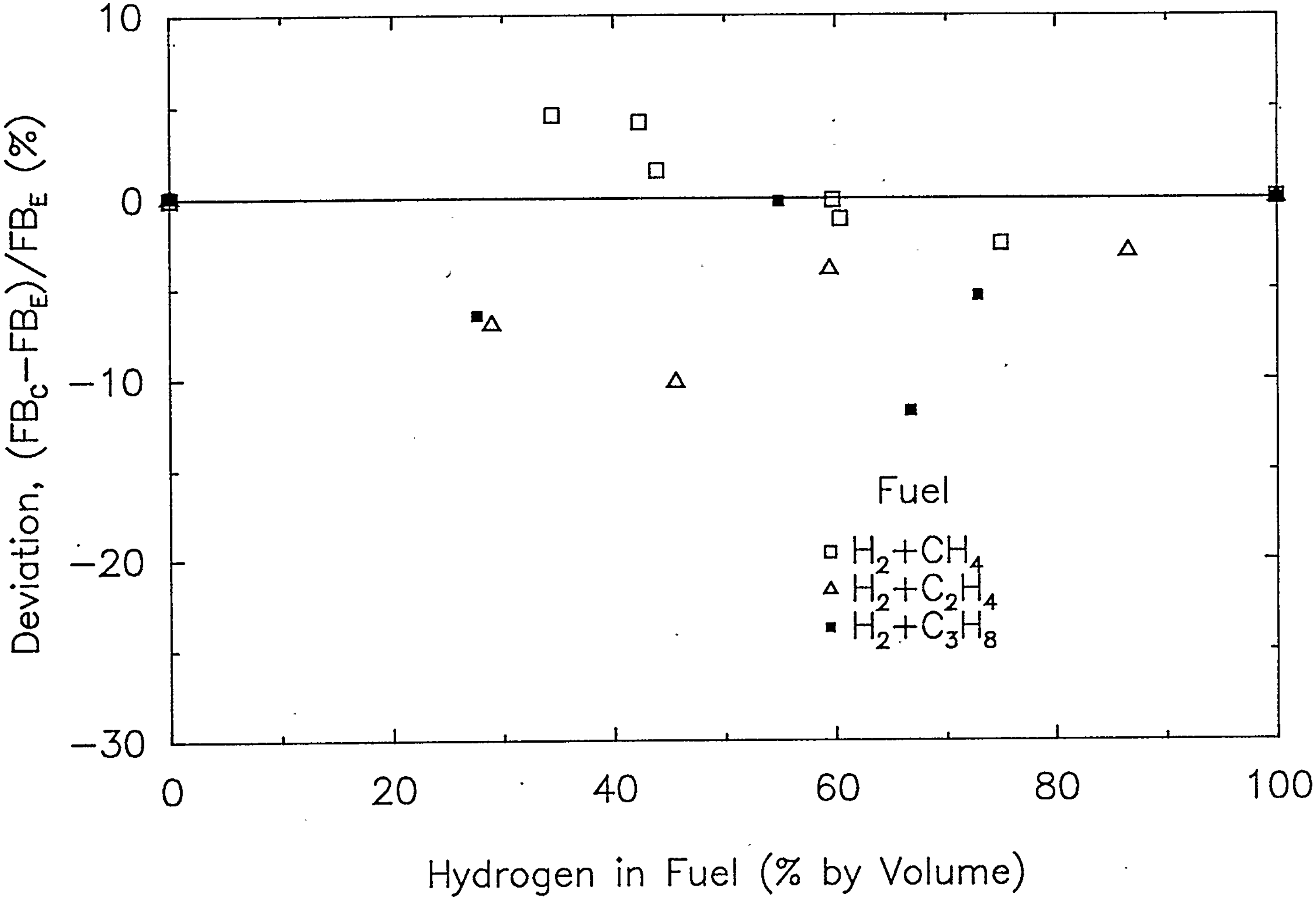

Figure 4.3 - The extent of the deviation of the calculated flashback limits of binary fuel mixtures from the experimental values

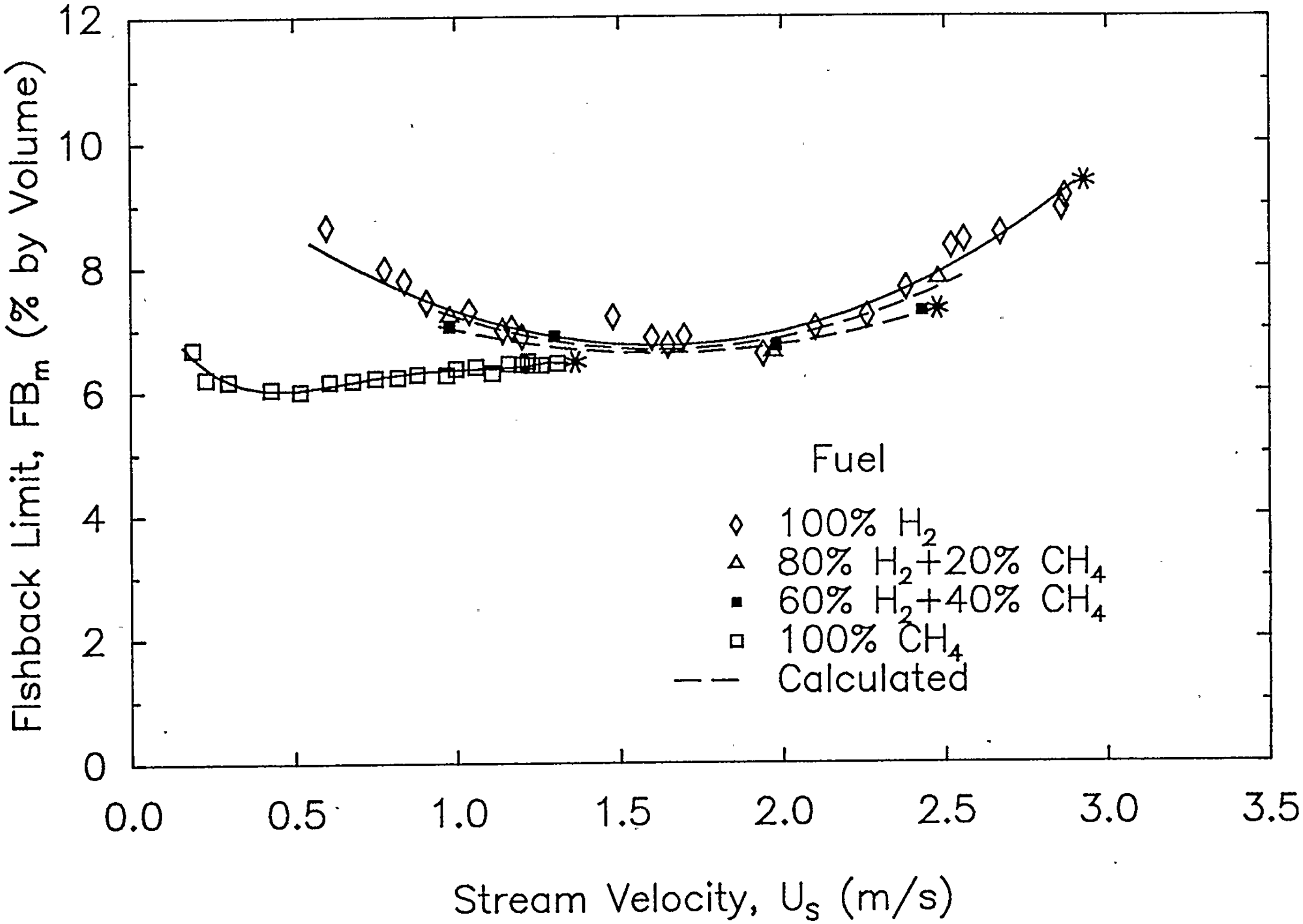

Figure 4.4 - Flashback limits of methane-hydrogen fuel mixtures in air. * indicates the limiting stream velocity beyond which flame flashback could not be observed

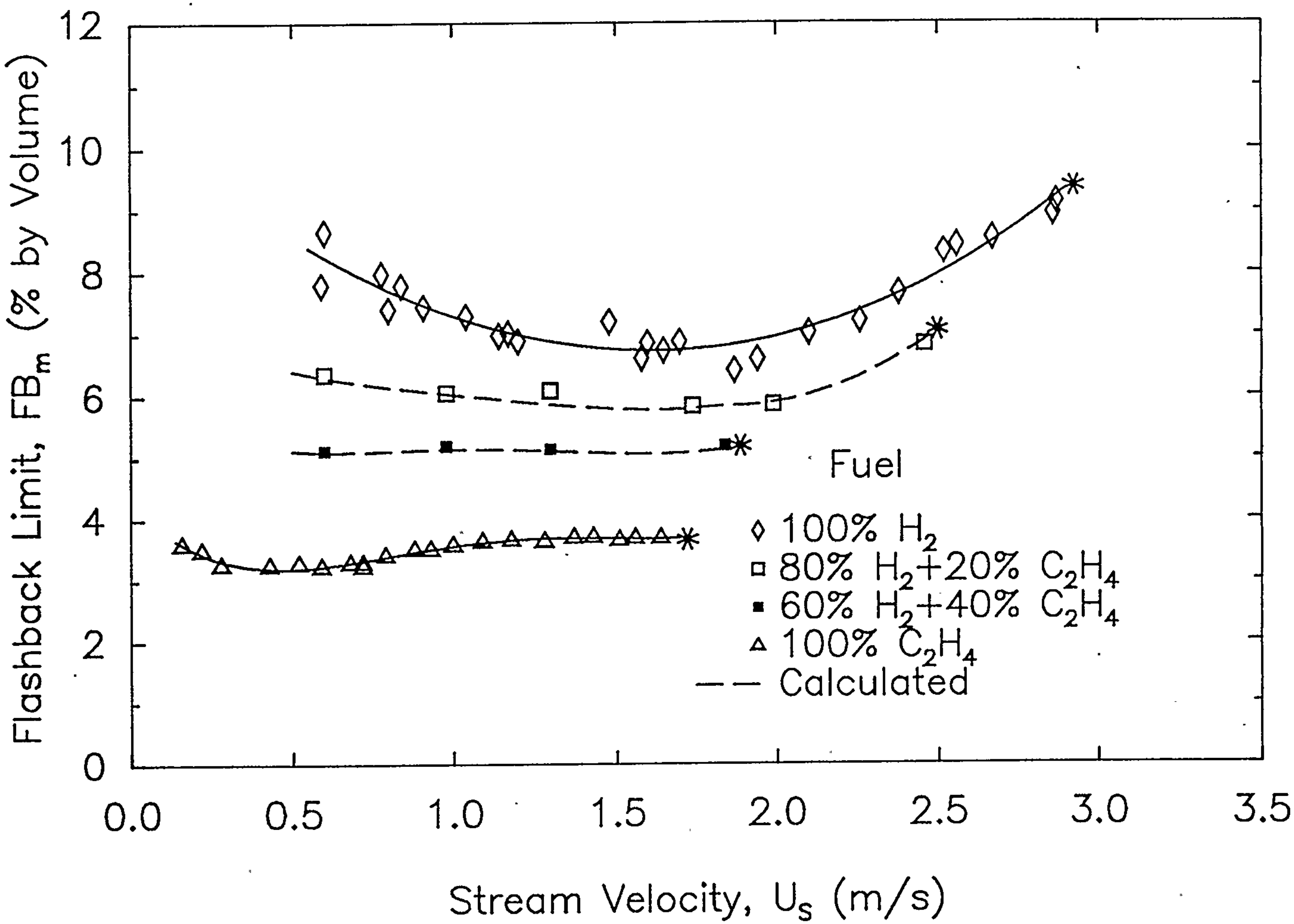

Figure 4.5 - Flashback limits of ethylene-hydrogen fuel mixtures in air. * indicates the limiting stream velocity beyond which flame flashback could not be observed

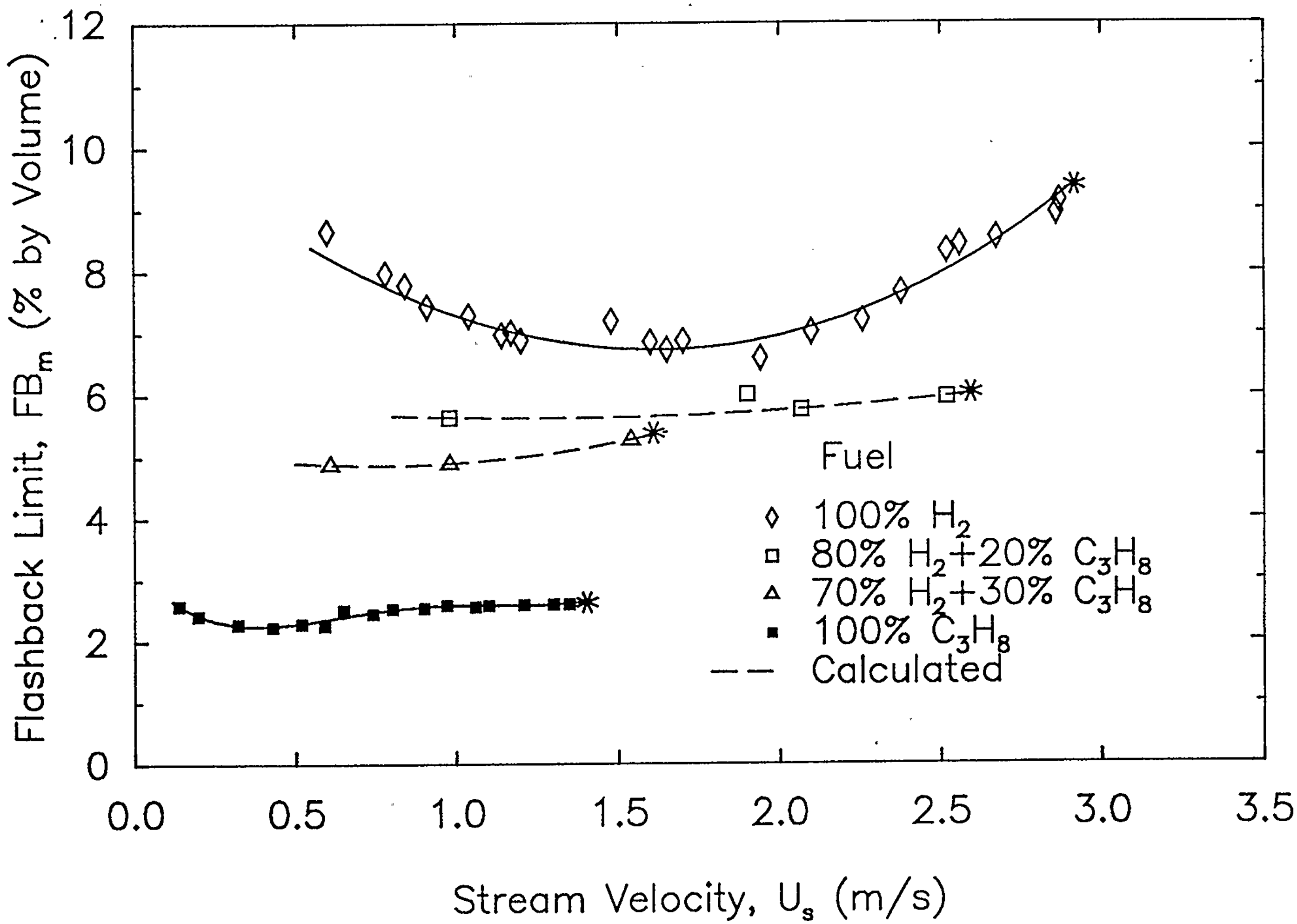

Figure 4.6 - Flashback limits of propane-hydrogen fuel mixtures in air. * indicates the limiting stream velocity beyond which flame flashback could not be observed

are also shown in Figures 4.4 - 4.6 (dashed lines). At stream velocities below the limiting velocity for both fuel mixture components, the flashback limits were calculated according to equation 4.1. When the stream velocity exceeds the limiting velocity for methane, ethylene or propane, the following flashback limits of the individual fuel mixture components were used: for hydrogen, the actual value of the flashback limit at the corresponding stream velocity and for methane, ethylene and propane, the so-called "apparent" flashback limits corresponding to the value at the limiting stream velocity. Agreement between the calculated and the experimental values was very good, the deviation falling within 5% in all cases.

Experiments showed that the limiting stream velocity for flashback of methane-hydrogen binary fuel mixtures is linearly dependent on the methane concentration in the mixture, Figure 4.7. Similar data for ethylene-hydrogen and propane-hydrogen mixtures are plotted in Figure 4.8. It is evident from the figure that the relationship is not linear as in the case with methane.

4.4 FLASHBACK OF HYDROGEN-DILUENT MIXTURES

Since diluents can be present in a significant proportion in many low grade fuels, it is important from a practical point of view to establish the flashback limits of fuel-diluent mixtures. Such data, if available, can be of great help in industry for the prevention and control of fire. In this study, the flame flashback limits were established for hydrogen-nitrogen and hydrogen-carbon dioxide mixtures in air for a stream velocity of 1.6 m/s. The typical results obtained are shown in Figure 4.9. As can be seen in the

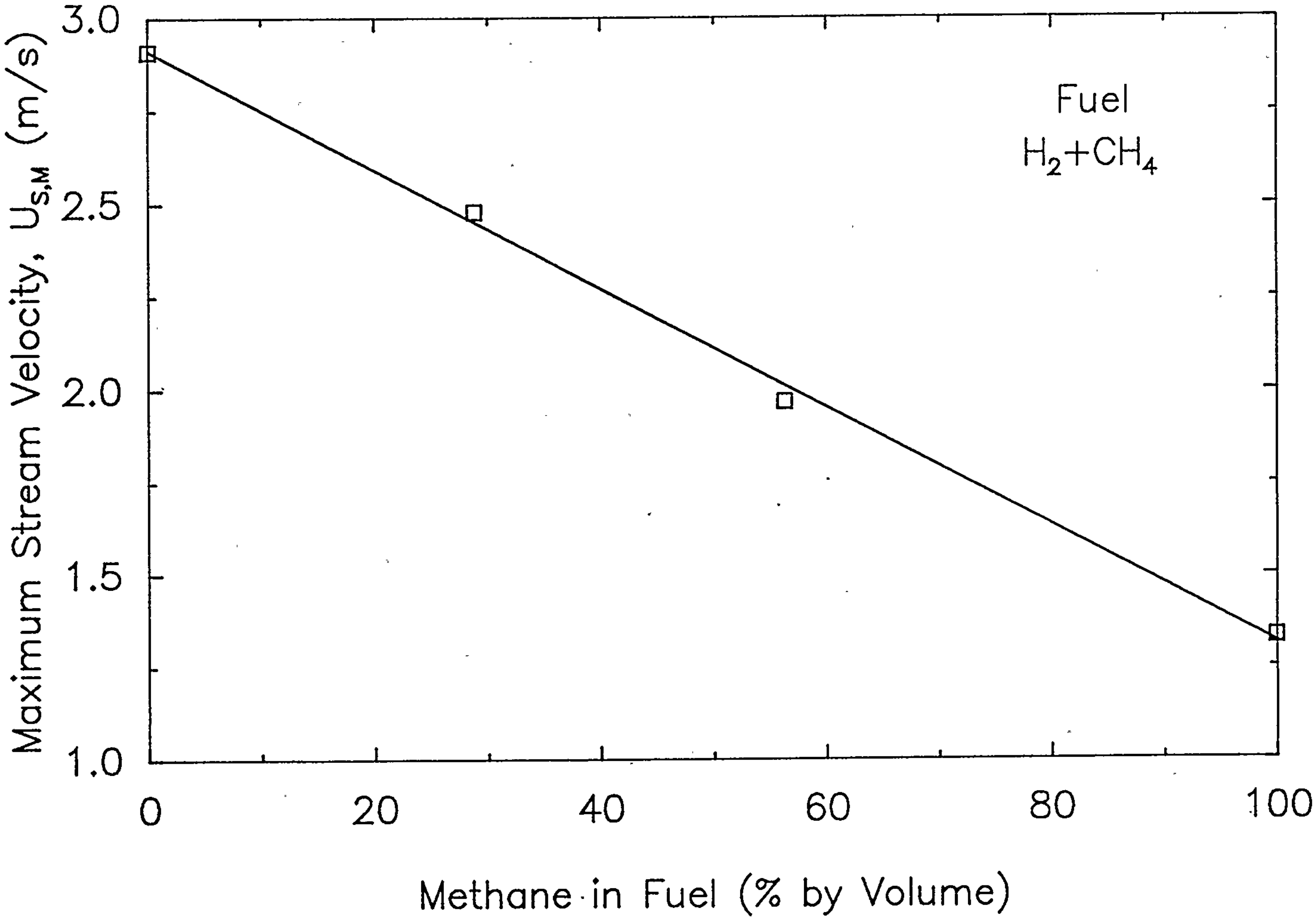

Figure 4.7 - The limiting stream velocity for flame flashback as a function of methane concentration in methane-hydrogen fuel mixtures

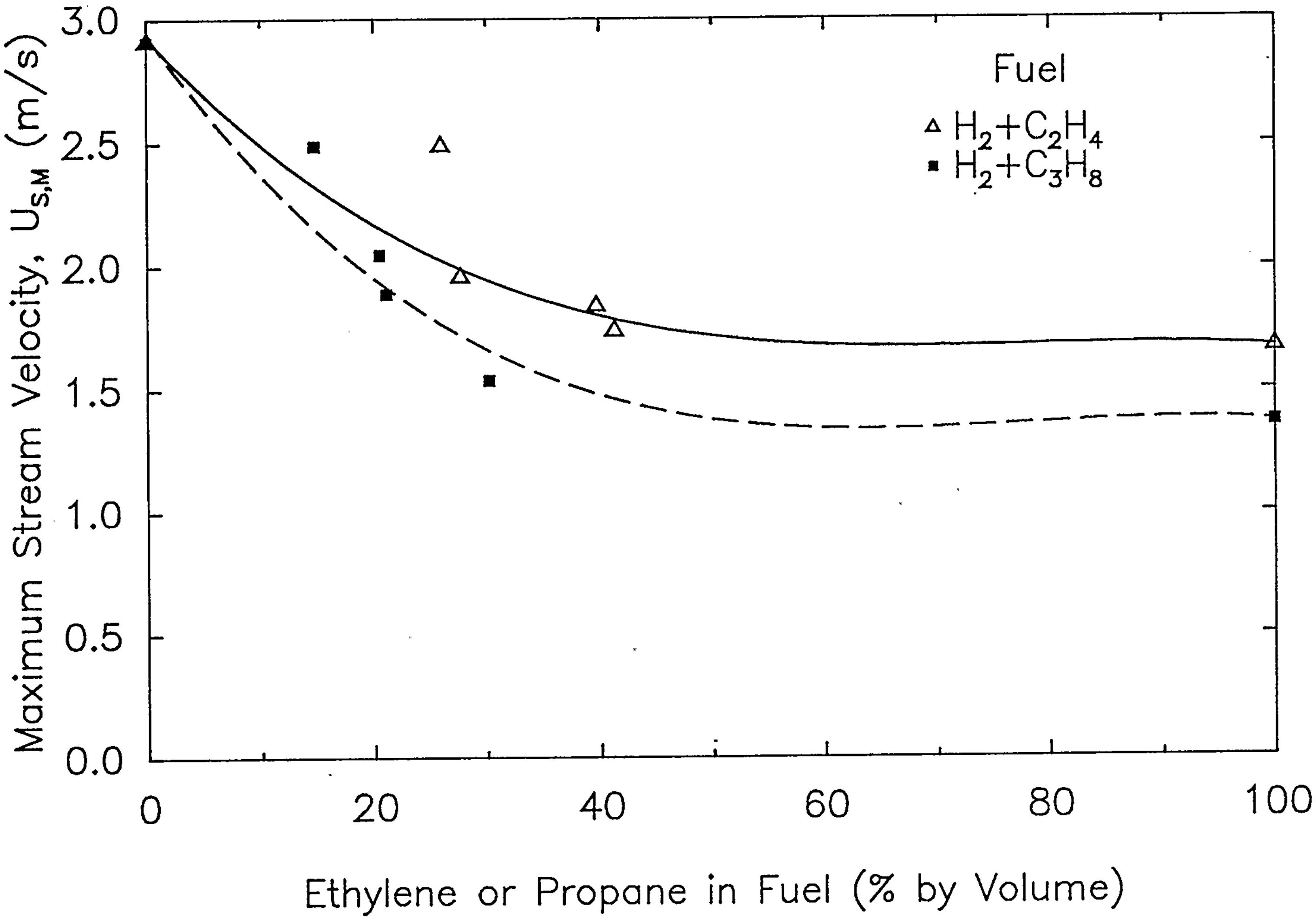

Figure 4.8 - The limiting stream velocity for flame flashback as a function of ethylene or propane concentration in binary fuel mixtures involving hydrogen

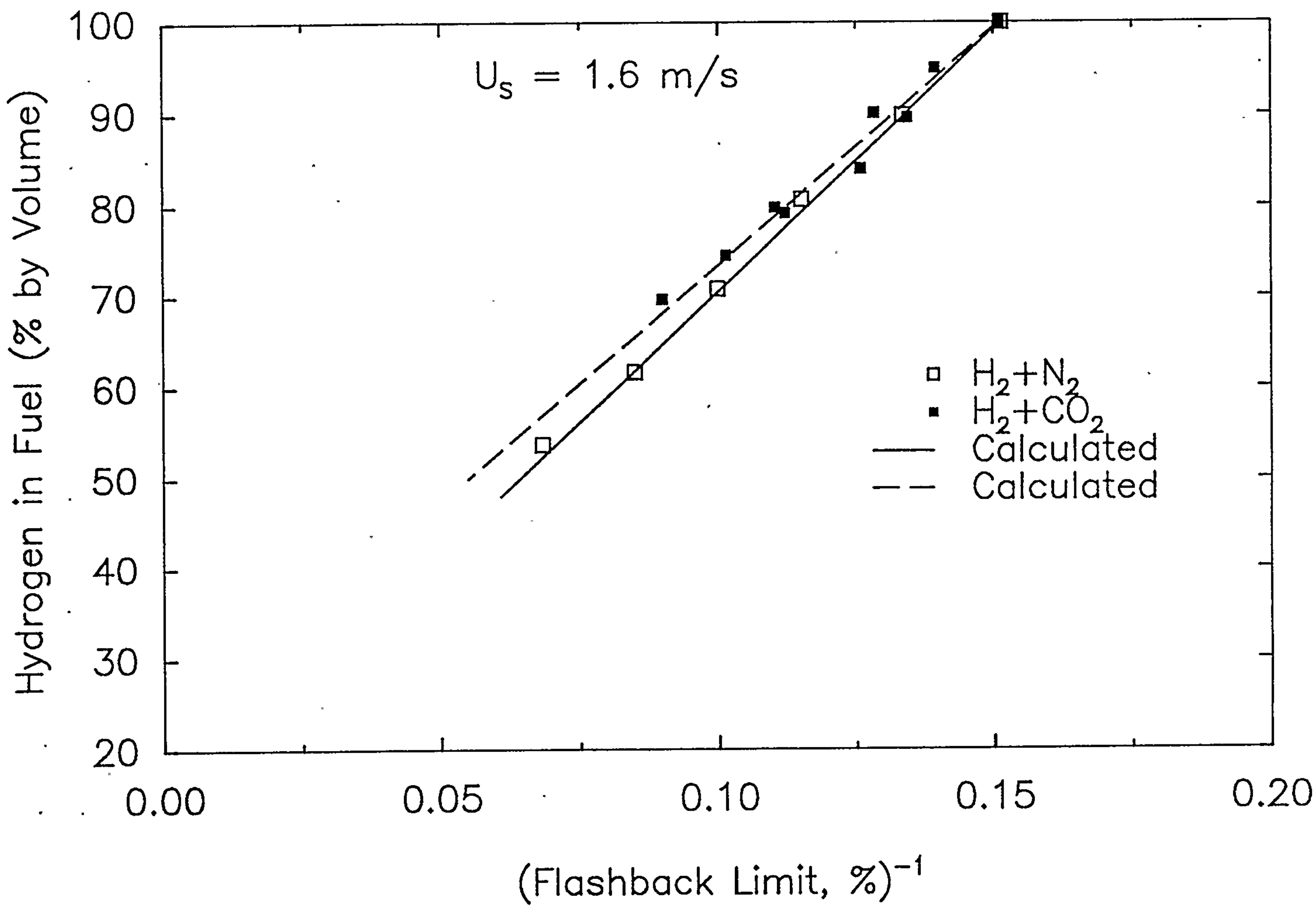

Figure 4.9 - The flashback limits of hydrogen-diluent mixtures in air.

figure, the flashback limit increases with diluent concentration in the mixture and is generally higher with carbon dioxide as diluent than with nitrogen. Addition of a diluent reduces the flame speed by acting as a heat "sink" absorbing part of the heat released by the combustion process. A higher fuel concentration in the stream is thus needed to compensate for this. Since the heat capacity of carbon dioxide is higher than that for nitrogen, the "cooling" effect of carbon dioxide will be stronger resulting in the higher flashback limits observed.

It was proposed in [36] that the flashback limits of hydrogen-diluent mixtures can be calculated using the approach developed earlier for predicting the flammability limits of fuel-diluent mixtures [35]. Following this approach, the flashback limit of hydrogen-diluent mixture is given as:

$$FB_D = 100\left[\frac{y_{H_2}}{FB_{H_2}} + a_D(100 - y_{H_2})\right]^{-1} \tag{4.2}$$

where

FB_D is the flashback limit of the diluted hydrogen in air (% by volume)

FB_{H_2} is the flashback limit of hydrogen on its own in air (% by volume)

y_{H_2} is the hydrogen concentration in the fuel mixture (% by volume)

a_D is a constant

The experimentally obtained values of the constant a_D at the stream velocity of 1.6 m/s are as follows:

for H_2 - N_2 mixture, $a_D = -0.02276$

for H_2 - CO_2, $a_D = -0.04120$

Experiments conducted at lower velocities ($\approx$ 0.6 m/s) [15] gave the following results:

for H_2 - N_2 mixture, $a_D = -0.004$

for H_2 - CO_2, $a_D = -0.012$

Comparing the results, it may be concluded that the constant a_D decreases with increase of the stream velocity.

The flashback limits calculated using equation 4.2 and the appropriate values of the constant a_D are shown in Figure 4.9 for comparison. The deviation of the calculated results from the experimental values, shown in Figure 4.10, is within 5% and can be considered to have originated mainly from experimental errors.

4.5. PROCEDURE FOR CALCULATING FLASHBACK LIMITS OF FUEL-DILUENT MIXTURES

It was mentioned earlier that the procedures developed for predicting the lean flammability limits of fuel-diluent mixtures can be used successfully to predict the lean flame flashback limits. Hence, it was decided to apply, for the flashback limit calculation, a simple concept of constant adiabatic flame temperature used earlier for lean flammability limits calculations [33]. It is assumed that the adiabatic flame temperature of the "diluted" fuel in air at the flashback limit is equal to the adiabatic flame temperature of the same pure fuel in air at the flashback limit at the corresponding conditions.

At the lean flashback limit, the mixture concentration is fuel-lean, and it is thus possible to assume that the products of combustion will be water vapour, nitrogen, some

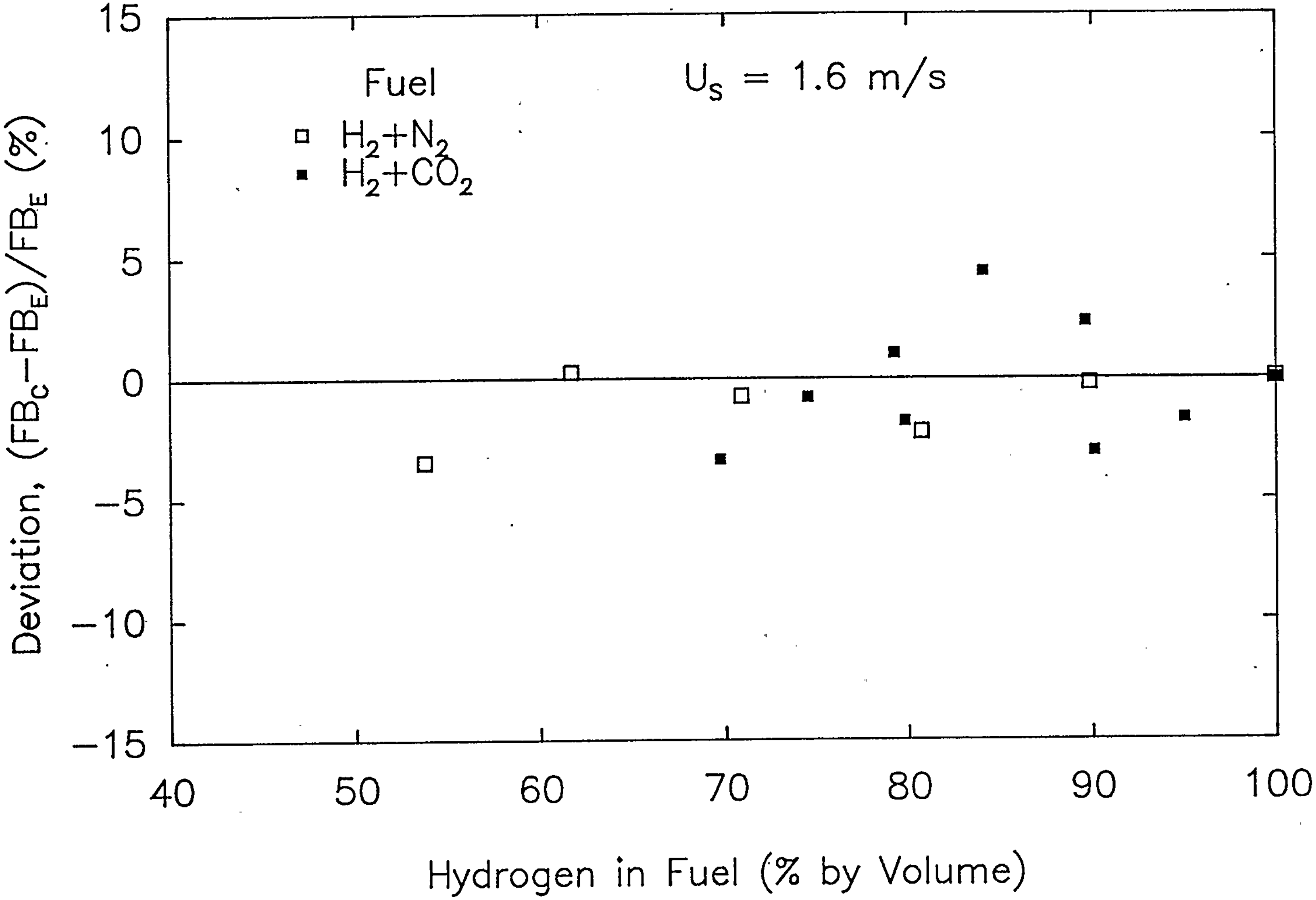

Figure 4.10 - The extent of the deviation of calculated flashback limits of hydrogen-diluent fuel mixtures from the experimental results

excess oxygen and carbon dioxide (depending on the type of fuel and/or diluent). Following this assumption about the products, the combustion equations can be written as follows:

for pure hydrocarbon fuel in air

$$\begin{aligned} &FB_F(C_mH_n) + (100-FB_F)(0.21O_2 + 0.79N_2)= \\ &mFB_FCO_2 + \frac{n}{2}FB_FH_2O + [0.79(100-FB_F]N_2 \\ &\qquad + [21-(0.21+m+\frac{n}{4})FB_F]O_2 \end{aligned} \tag{4.3}$$

for nitrogen as diluent

$$\begin{aligned} &FB_D(yC_mH_n+(1-y)N_2) + (100-FB_D)(0.21O_2+0.79N_2)= \\ &ymFB_DCO_2 + \frac{n}{2}yFB_DH_2O + [79+(0.21-y)FB_D]N_2 \\ &\qquad +[21-(0.21+ym+\frac{n}{4}y)FB_D]O_2 \end{aligned} \tag{4.4}$$

and for carbon dioxide as diluent

$$\begin{aligned} &FB_D(yC_mH_n+(1-y)CO_2) + (100-FB_D)(0.21O_2+0.79N_2)= \\ &[(ym-y+1)FB_D]CO_2 + [21-(0.21+ym+\frac{n}{4}y)FB_D]O_2 \\ &\qquad + \frac{n}{2}yFB_DH_2O + [79-0.79FB_D]N_2 \end{aligned} \tag{4.5}$$

where

FB_D is the flashback limit of the fuel-diluent mixture (% by volume)

FB_F is the flashback limit of the fuel on its own in air (% by volume) y is the molar fraction of the fuel in the fuel-diluent mixture

The adiabatic flame temperature reached with the fuel on its own in air can be calculated using the energy equation in the form:

$$(\sum H_{R_i\,F})_{T_o} = (\sum H_{P_i\,F})_{T_f} \qquad (4.6)$$

where $H_{R_i\,F}$ and $H_{P_i\,F}$ are changes in the enthalpies of the various components of the reactants and products in equation (4.3) at temperatures T_o and T_f respectively. The calculated T_f together with the known flashback limit, FB_F of the pure fuel in air can now be used to evaluate the flashback limit, FB_D of the fuel-diluent mixture in air using the energy equation for the mixture in the form:

$$(\sum H_{R_i\,M})_{T_o} = (\sum H_{P_i\,M})_{T_f} \qquad (4.7)$$

where $H_{R_i\,M}$ and $H_{P_i\,M}$ are the changes in the enthalpies of the reactants and products of the various components in equation (4.4) or (4.5) at temperatures T_o and T_f respectively.

Table 4.1 shows the calculated flashback limit, FB_D, for H_2 - N_2 and H_2 - CO_2 fuel mixtures in air at a stream velocity of 1.6 m/s, using this concept. The lean flashback limit for pure hydrogen in air at this velocity was determined experimentally as 6.61%. In the table the fuel concentration is listed as the percentage by volume of the fuel in the fuel-diluent mixture while the flashback limits are listed as the percentage by volume of the fuel-diluent mixture in the total mixture of fuel, diluent and air. The corresponding experimental values of the flashback limit of the mixtures have been included in the table for comparison.

As can be seen in the table, the approach gives a very good prediction of the flashback limit of fuel-diluent mixtures, especially when the diluent concentration in the fuel is not very high. With the exception of diluent concentrations in excess of about 30%, the deviation of the calculated limits from the experimental values is within 7%.

Table 4.1

Calculated Lean Flashback limit of Hydrogen-Diluent Mixtures

$FB_F = 6.61\%$, $U_S = 1.6$ m/s

Fuel Mixture					
H_2 - N_2			H_2 - CO_2		
y_F(%)	$FB_{D,C}$ (%)	$FB_{D,E}$ (%)	y_F (%)	$FB_{D,C}$ (%)	$FB_{D,E}$ (%)
53.78	12.28	14.62	69.77	9.63	11.13
61.74	10.70	11.77	74.60	8.98	9.86
70.92	9.32	10.01	79.25	8.43	8.90
80.73	8.19	8.68	79.84	8.36	9.06
89.87	7.35	7.50	89.66	7.41	7.45
-	-	-	90.16	7.37	7.80
-	-	-	95.08	6.97	7.18

CHAPTER FIVE

BLOWOUT OF A JET DIFFUSION FLAME: RESULTS AND DISCUSSION

5.1 GENERAL

The blowout limits of a jet diffusion flame in a co-flowing stream of air or homogeneous fuel-air mixture were determined at approximately atmospheric pressure. The initial temperature of the surrounding stream and the jet were in the range of 18 - 25°C. Blowout of the jet flame in co-flowing air streams was examined with methane, ethylene, propane and hydrogen used as the jet fuels. Similarly, ethylene was used as the jet fuel in the investigation of flame blowout within homogeneous fuel-air streams while methane and hydrogen were used as the surrounding fuels. In order to investigate the effect of the jet nozzle diameter on the blowout limit of the jet flame, three different jet nozzles of diameters 1.0, 1.5 and 2.0 mm were employed.

The effect of the stream velocity and the diameter of the jet nozzle on the blowout limit of the jet flame within co-flowing air streams are discussed in sections 5.2 and 5.3 respectively while the blowout limits of ethylene jet flames with the addition of methane and hydrogen to the surrounding stream follow in sections 5.4.

5.2 EFFECT OF STREAM VELOCITY ON THE BLOWOUT LIMIT

Generally, two different types of the jet flame were observed depending on the velocity of the co-flowing stream. "Lifted" flames, stabilized at a finite distance downstream of the nozzle exit were always observed before the incidence of blowout at values of the stream velocities below a certain limit, herein referred to as the limiting stream velocity, $U_{S,L}$. When the level of the stream velocity exceeded this limiting value, "attached" flames, stabilized close to the nozzle exit (appeared to be attached to the nozzle rim) were always observed at any jet flow rate up to the blowout limit.

The experimental results showed that the value of the limiting stream velocity depends on the type of the jet fuel and the diameter of the jet nozzle as indicated in Figure 5.1. Generally, the higher the laminar burning velocity of a fuel in air, the higher the value of the limiting stream velocity for flame liftoff for that fuel. For a given fuel, the limiting velocity also increases with increase of jet diameter.

The effect of the stream velocity on the lifted and the nozzle attached flame can be seen in Figures 5.2 - 5.5. The range of stream velocities over which each type of flame was observed before blowout are also shown in the figures. For the lifted flame, the blowout limit was found to decrease with increase of the stream velocity. This decrease in the blowout limit became much more significant when the diameter of the jet nozzle was increased from 1.5 to 2 mm. An increase in the stream velocity relative to the jet velocity reduces the rate of entrainment of air into the jet and negatively affects the mixing process. This probably leads to the decrease in the jet blowout limit.

Comparing the values of the blowout limits for different fuels as illustrated in Figures 5.5 and 5.6, it can be seen that, for a given stream velocity and jet nozzle diameter, the blowout limit of the lifted flame was highest for hydrogen, followed by ethylene and then propane with methane jet flames being the least stable of the four. This trend is in agreement with the order of the laminar burning velocity, S_L, of these fuels in air.

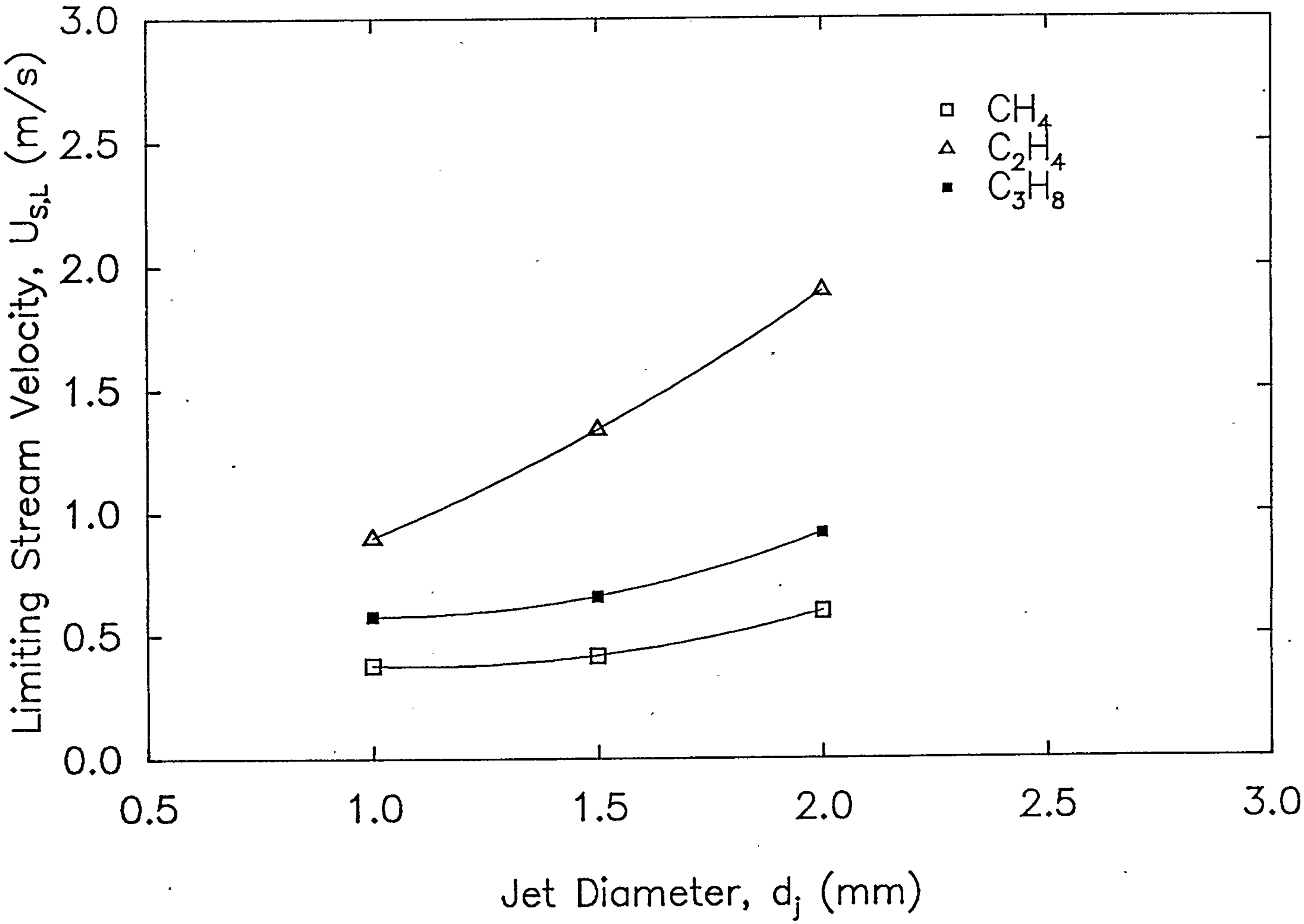

Figure 5.1 - Variation of the limiting stream velocity for liftoff with jet diameter for different fuels

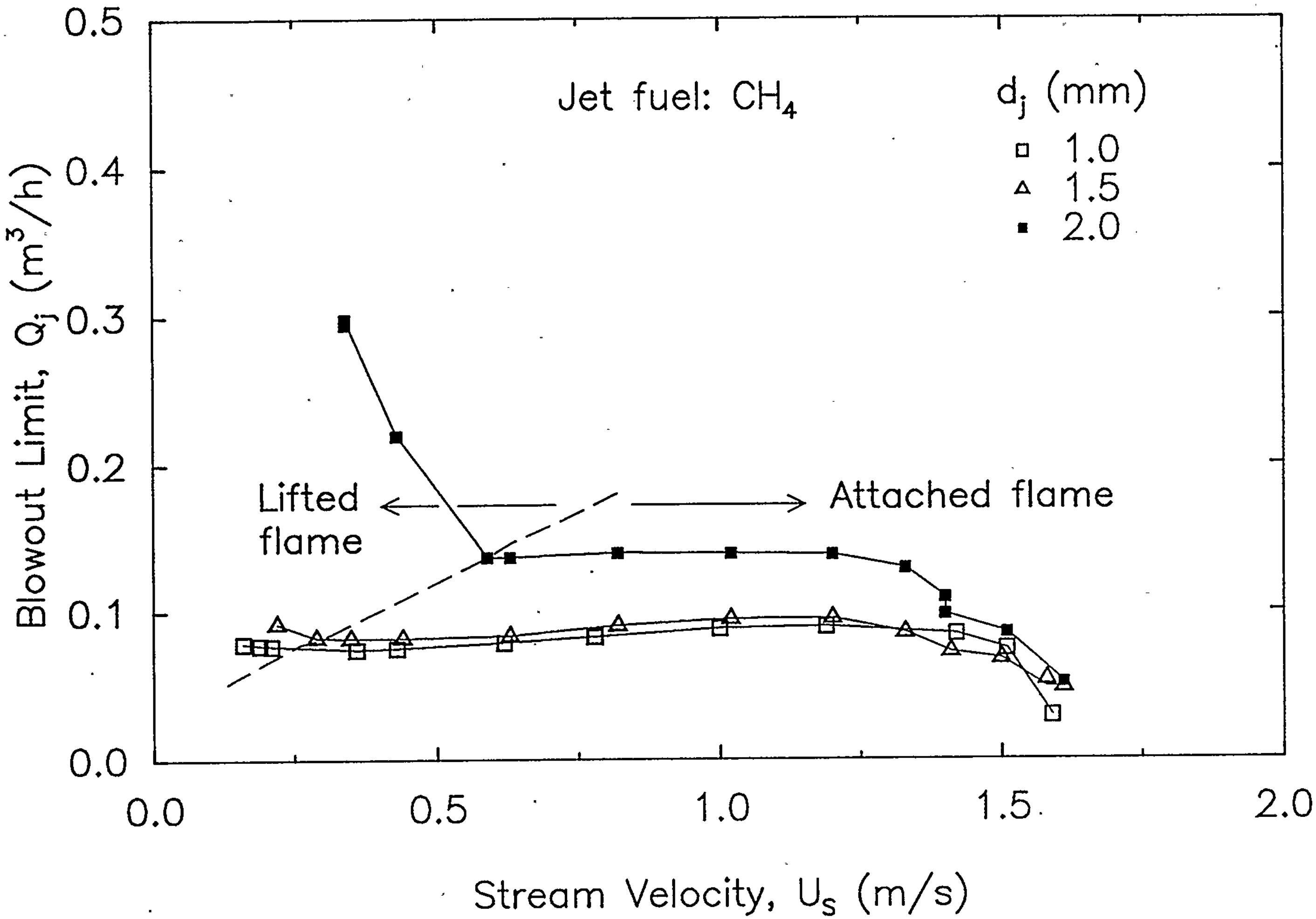

Figure 5.2 - Volumetric blowout limit of methane jet diffusion flame as a function of stream velocity at different diameters of the jet nozzle

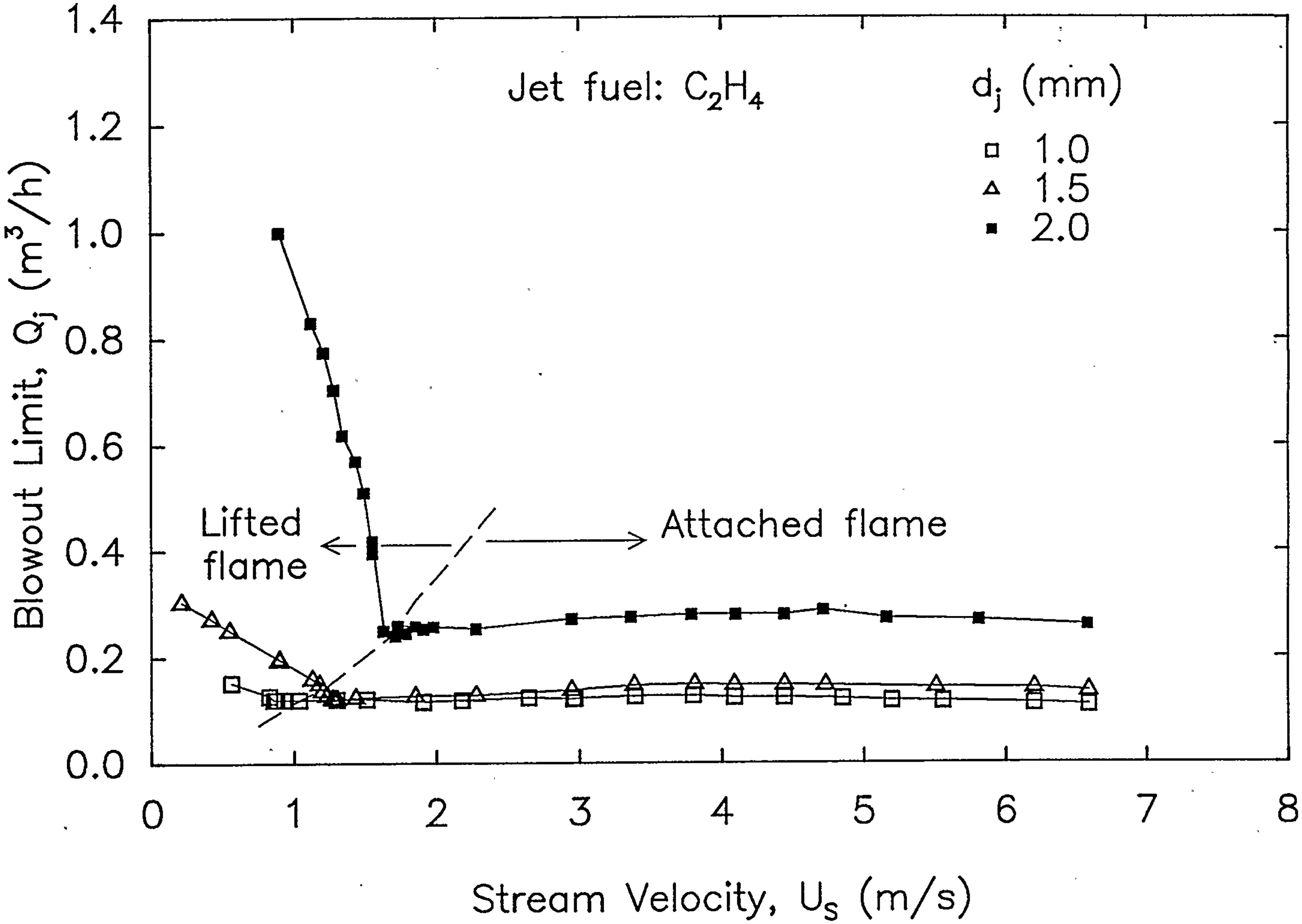

Figure 5.3 - Volumetric blowout limit of ethylene jet diffusion flame as a function of stream velocity at different diameters of the jet nozzle

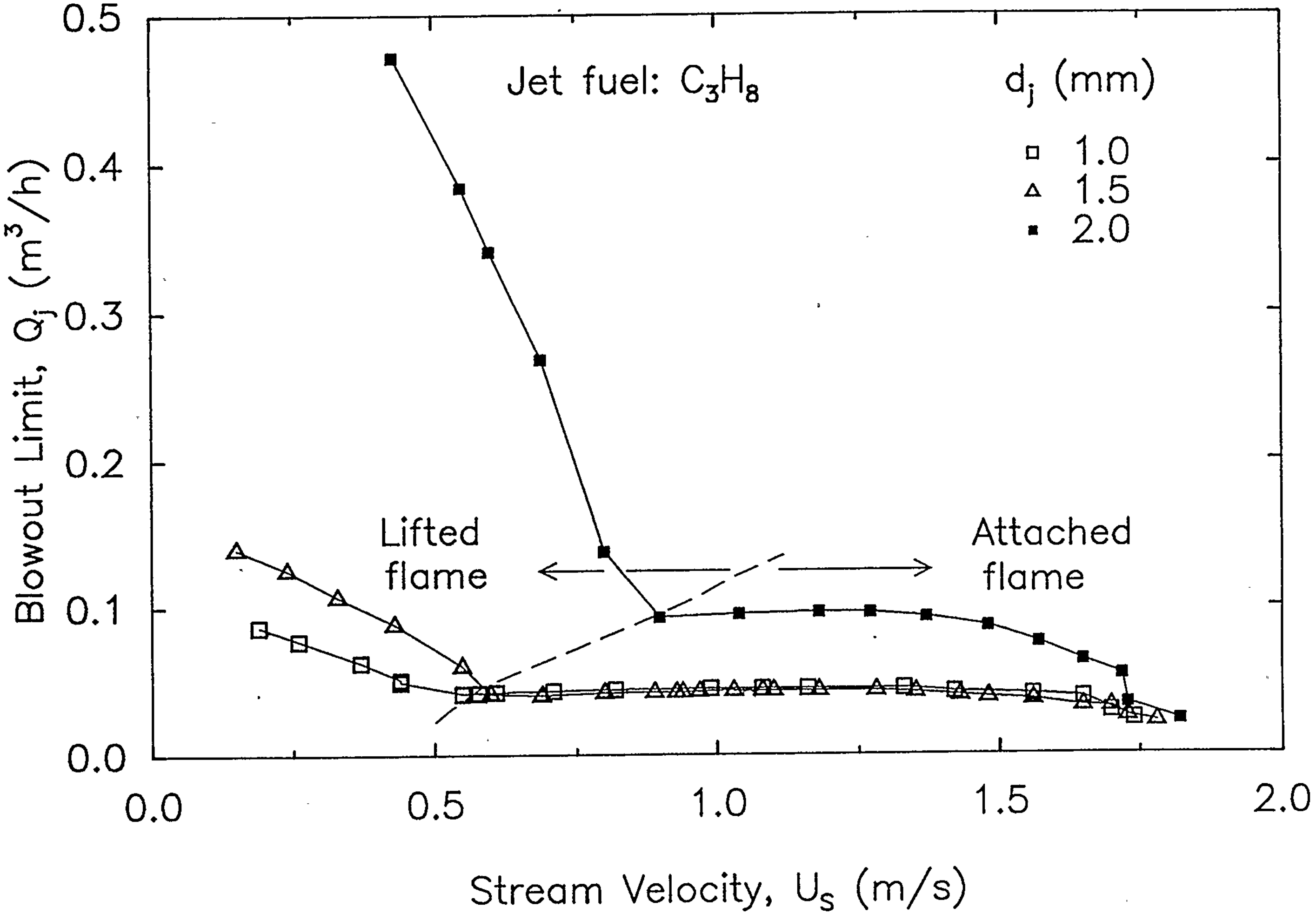

Figure 5.4 - Volumetric blowout limit of propane jet diffusion flame as a function of stream velocity at different diameters of the jet nozzle

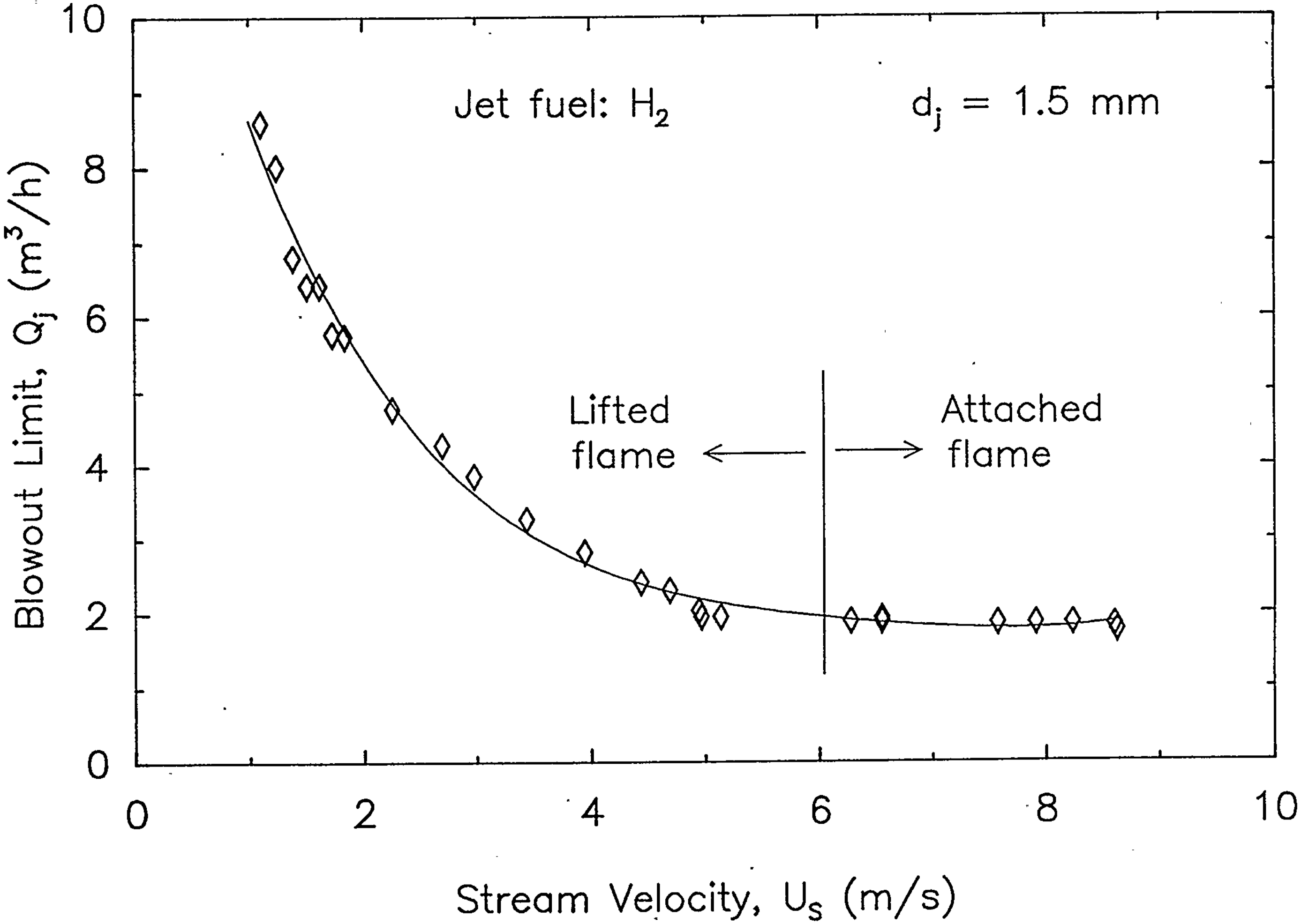

Figure 5.5 - Volumetric blowout limit of hydrogen jet diffusion flame as a function stream velocity

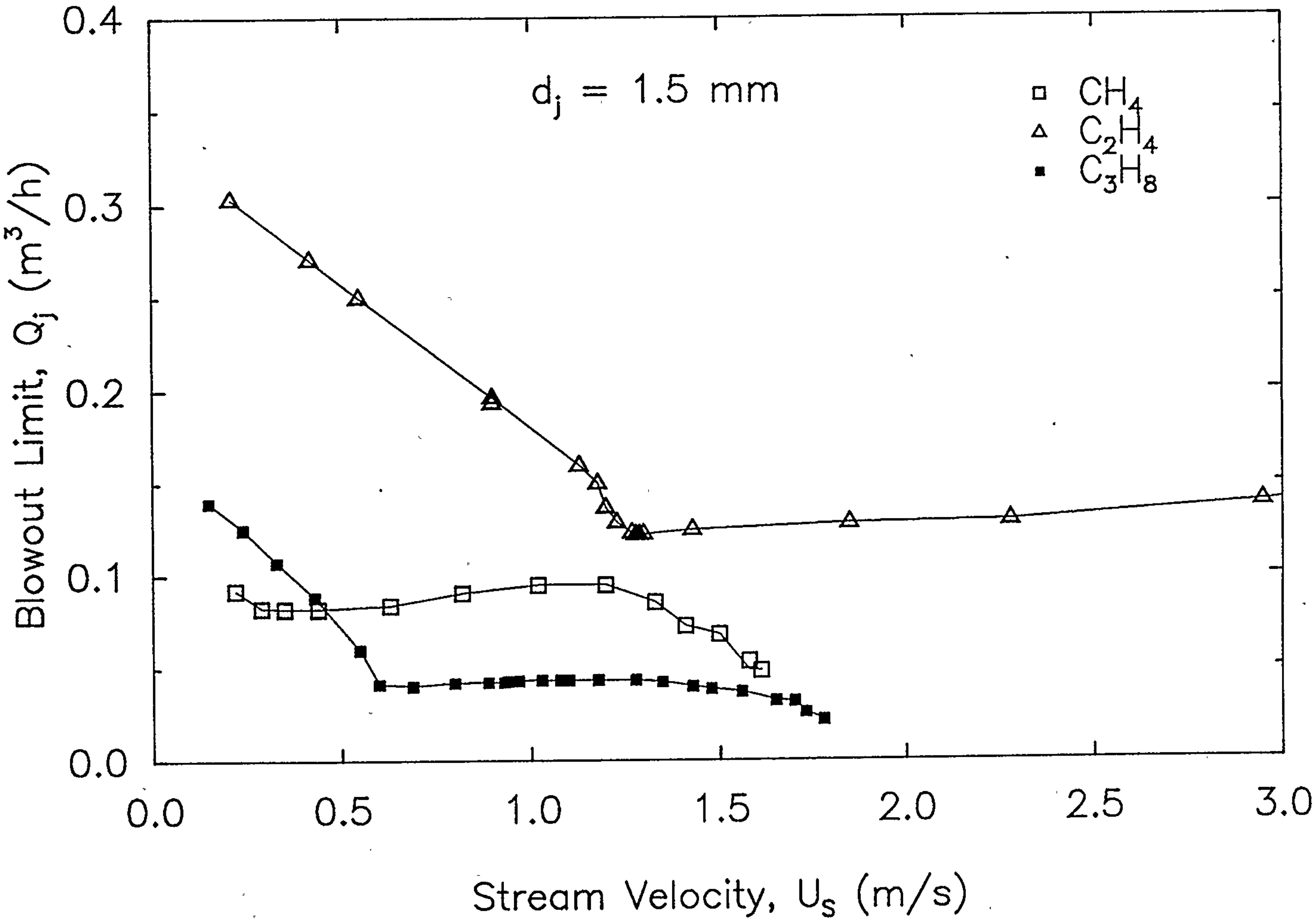

Figure 5.6 - Volumetric blowout limit of different hydrocarbon gaseous fuel as a function the stream velocity

The stability pattern of the nozzle attached jet flame is quite different. It can be observed from the figures that the blowout limits of this type of flame were generally lower than those of the lifted flame. It has been reported [28] that in the case of the attached flame, mass entrainment rates are lower due to a slower growth rate of the shear mixing layer. This would probably account for the lower blowout limits observed with the nozzle attached flames.

Observing the effect of the stream velocity on the stability of the nozzle attached flame, it is seen that an increase in the stream velocity does not have a significant effect on the blowout limit of the flame initially. However, as the stream velocity was increased further, a certain level was reached beyond which a decreasing trend in the flame blowout limit was observed with methane and propane jets. For instance, for a jet nozzle diameter of 1.0 mm, this trend set in for the two fuels when the stream velocity exceeded about 1.2 and 1.3 m/s, respectively. For ethylene and hydrogen jets however, no significant changes in the blowout limit of the attached flame was observed as the stream velocity was increased up to the maximum level considered (about 6.5 m/s for ethylene and 8.6 m/s for hydrogen).

A similar comparison of the blowout limits of the nozzle attached flame for different fuels from Figures 5.5 and 5.6 shows that while hydrogen and ethylene jet flames are still the two most stable, propane jets now have lower flame blowout limits compared to methane jets. This trend is in contrast to the one observed with lifted flames.

5.3 EFFECT OF JET NOZZLE DIAMETER ON THE BLOWOUT LIMIT

The blowout limit of the lifted and the nozzle attached flame are influenced differently by changes in the jet nozzle diameter. For the lifted flame, the blowout limit was found to increase with increase of the jet nozzle diameter. This increase in the blowout limit became much more significant when the diameter of the jet nozzle was increased from 1.5 to 2.0 mm.

For the nozzle attached flame, a significant increase in the blowout limit with increase of the jet nozzle diameter was only observed when the diameter was increased from 1.5 to 2.0 mm. The observed blowout limits increased only slightly for methane and ethylene attached jet flames with increase of the jet nozzle diameter from 1.0 to 1.5 mm and were not noticeably different for propane jet flames.

It was found that the experimentally observed blowout limits of the lifted flame of different gaseous fuels can be correlated based on a dimensionless form of the stream velocity ($U_S/U_{S,L}$), herein referred to as the relative stream velocity, and a parameter α which is proportional to the square root of the momentum ratio between the jet and the air stream at the blowout conditions and is defined as:

$$\alpha = \left(\frac{\rho_j}{\rho_S}\right)^{\frac{1}{2}} \frac{Q_j}{U_S d_j^2} \tag{5.1}$$

where

ρ_j is the density of the jet fuel (kg/m^3)
ρ_S is the density of the air stream (kg/m^3)
Q_j is the observed blowout limit of the jet flame (m^3/h)
d_j is the diameter of the jet nozzle (mm)

U_S is the stream velocity (m/s)

The plot of the parameter α against the relative stream velocity for different jet nozzle diameters are shown in Figures 5.7 - 5.9. It can be seen in the figures that a good agreement was obtained for all the experimental results.

A different correlation was proposed for the attached flame because its behaviour is distinctly different from that of the lifted flame. It was found that a plot of the parameter α (defined earlier) against a dimensionless stream velocity term θ ($\theta = U_S/S_L$), as shown in Figures 5.10 - 5.12, can be used quite well to correlate the observed blowout limits of some fuels. For instance, for the jet nozzle diameters of 1.0 and 1.5 mm, this simple approach gave a good correlation of the observed blowout limits of methane, ethylene and hydrogen but cannot be used for correlating the observed results for propane jet flames.

Attempt was made to correlate the observed blowout limits of the nozzle attached flame for different fuels and at different diameters of the jet nozzle on a single curve by replotting Figures 5.10 - 5.12 in the form:

$$\left(\frac{\rho_j}{\rho_S}\right)^{\frac{1}{2}} \frac{Q_j}{U_S d_j} = f\left(\frac{U_S}{S_L}\right) \qquad (5.2)$$

where

ρ_j is the density of the jet fuel (kg/m^3)
ρ_S is the density of the air stream (kg/m^3)
Q_j is the observed blowout limit of the jet flame (m^3/hr)
d_j is the diameter of the jet nozzle (mm)
U_S is the stream velocity (m/s)

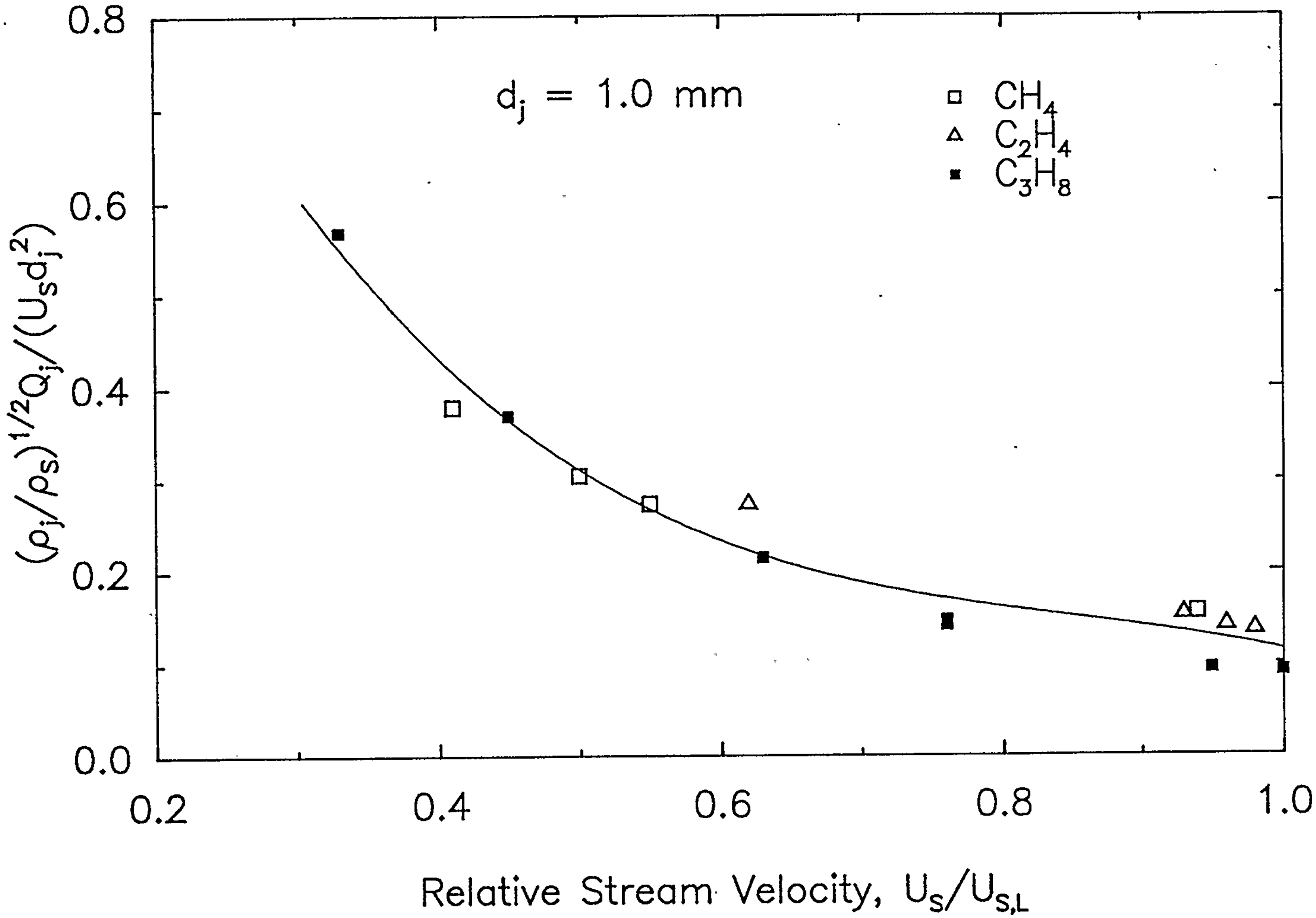

Figure 5.7 - Blowout limits of a jet diffusion flame of different fuels in the flame liftoff region for a jet nozzle diameter of 1 mm

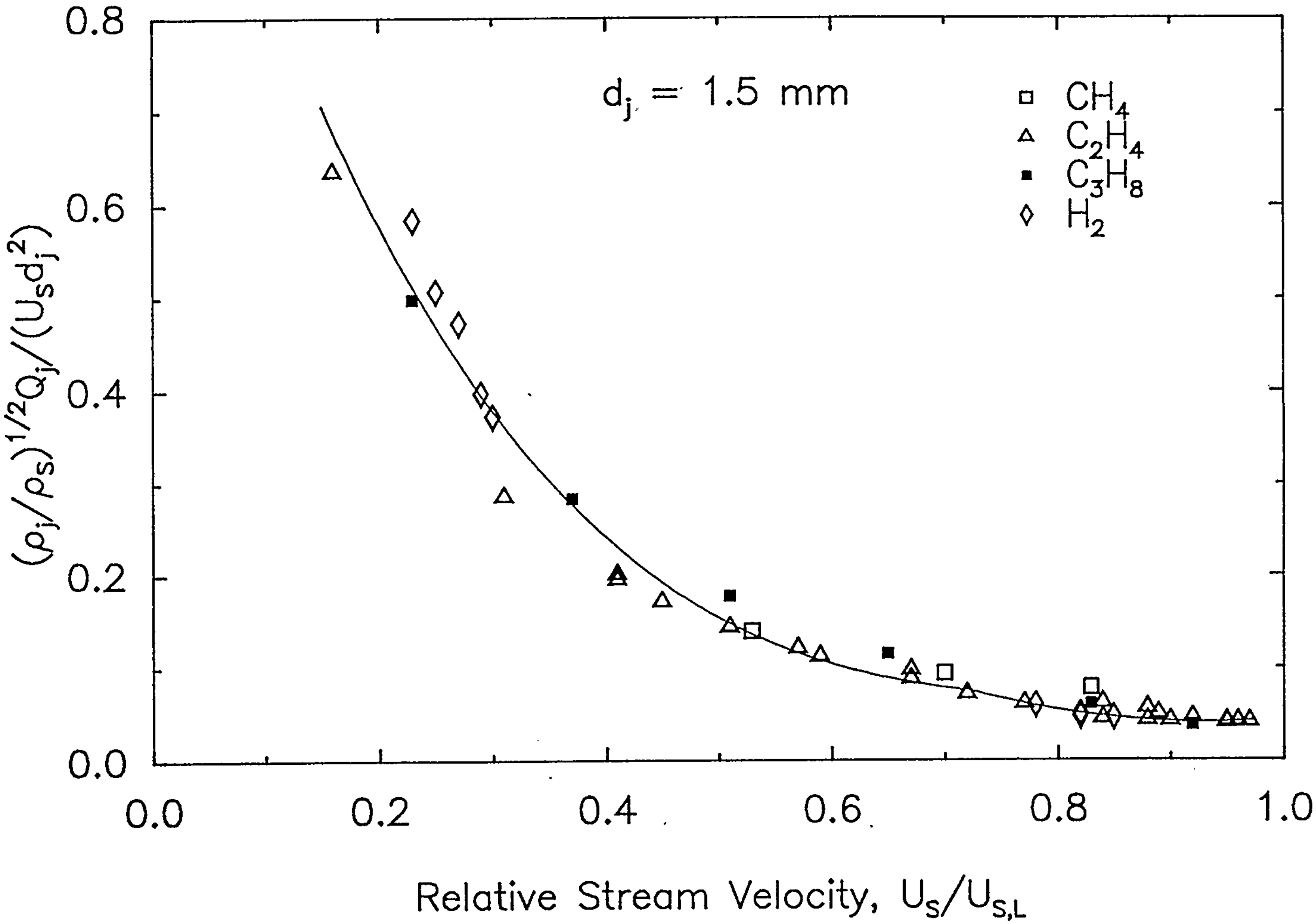

Figure 5.8 - Blowout limits of a jet diffusion flame of different fuels in the flame liftoff region for a jet nozzle diameter of 1.5 mm

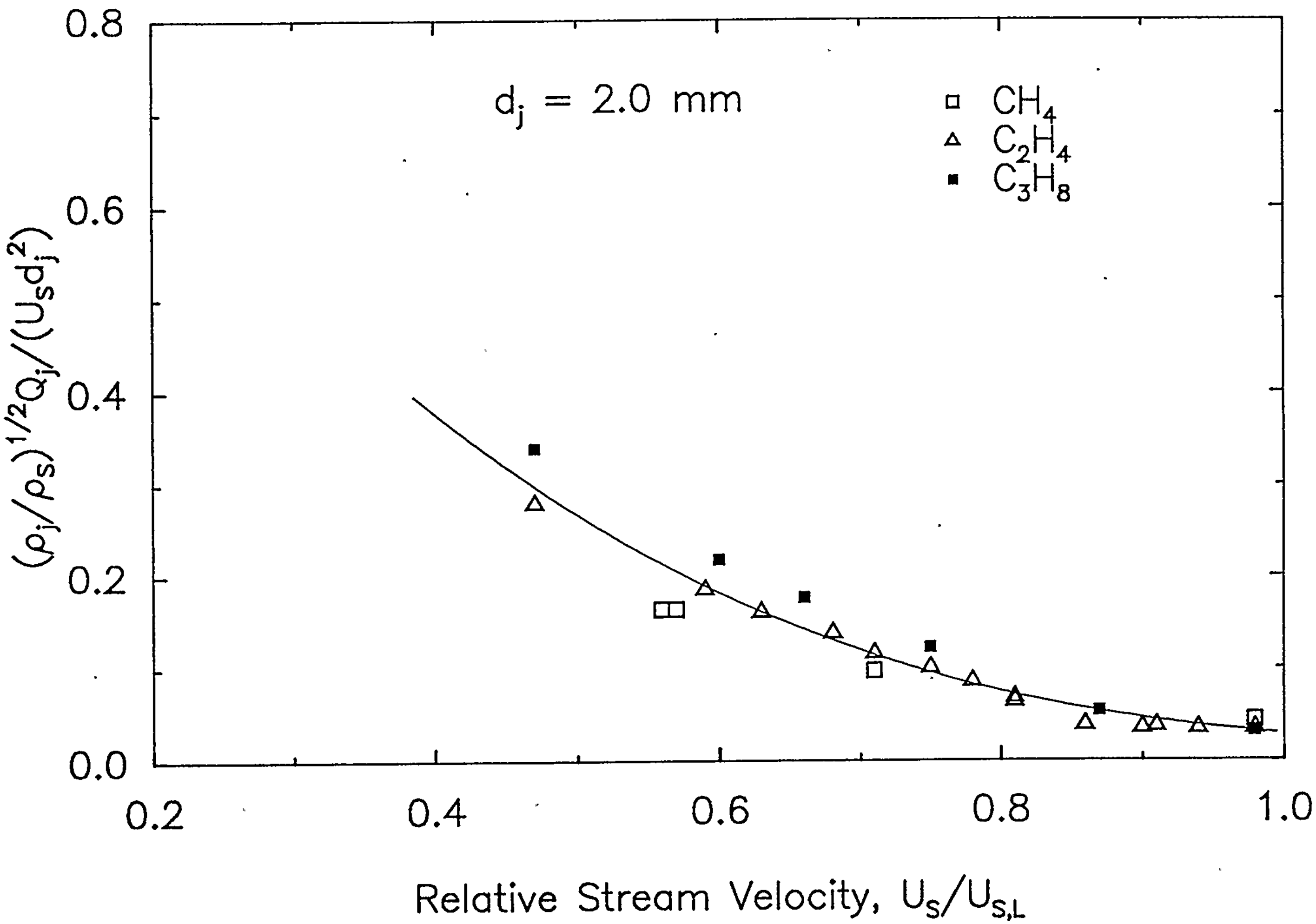

Figure 5.9 - Blowout limits of a jet diffusion flame of different fuels in the flame liftoff region for a jet nozzle diameter of 2 mm

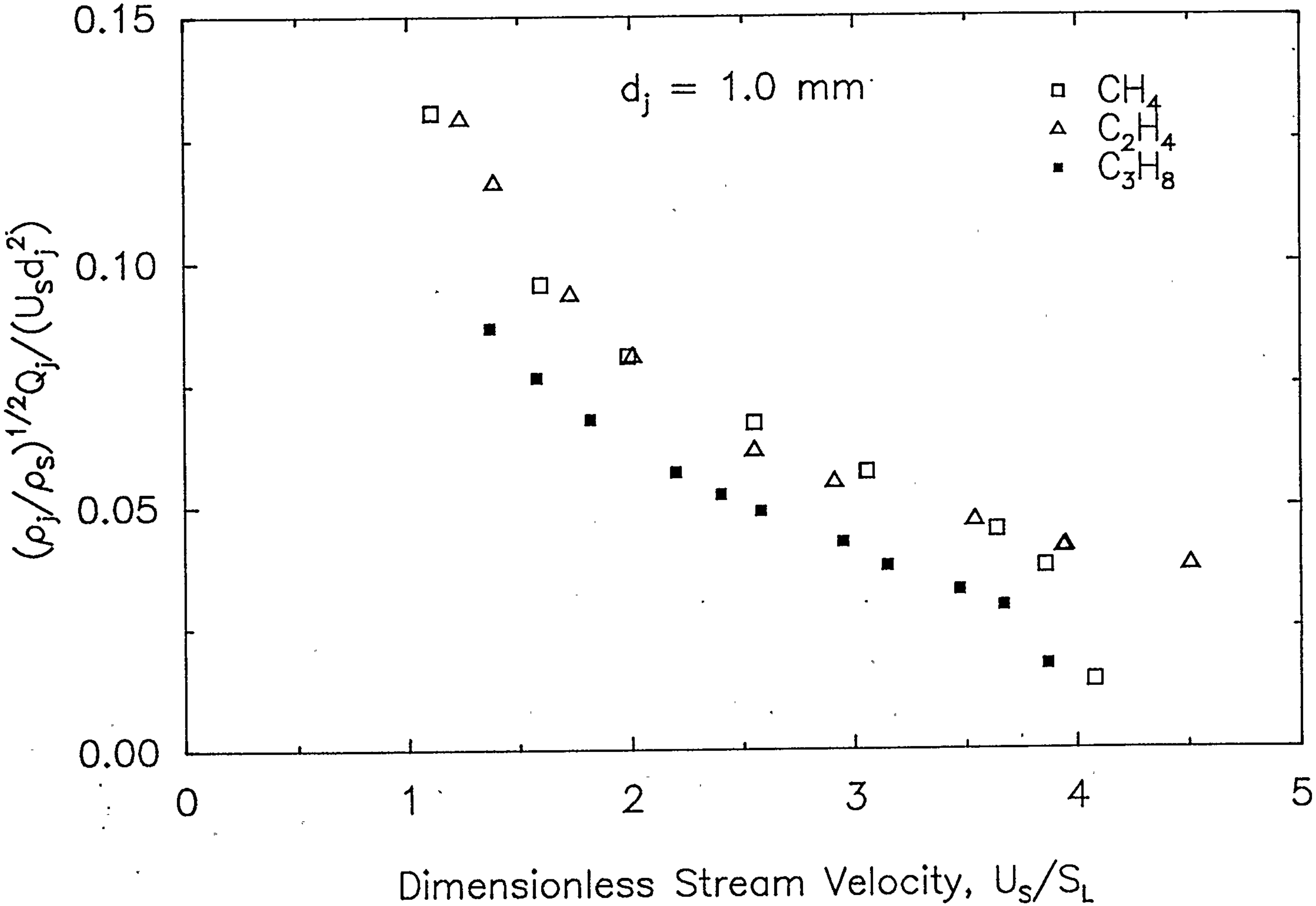

Figure 5.10 - Blowout limits of a jet diffusion flame of different fuels in the attached flame region for a jet nozzle diameter of 1 mm

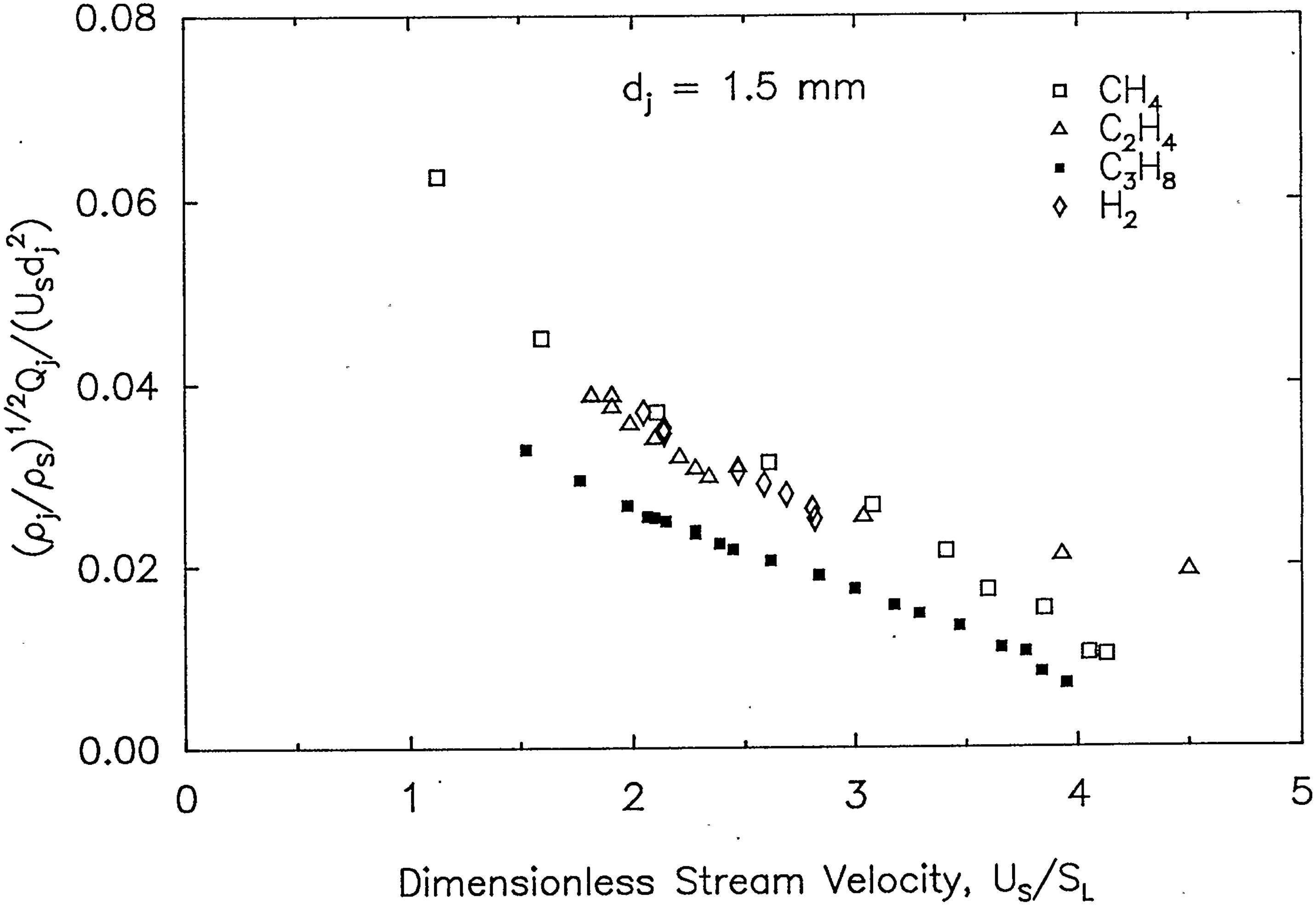

Figure 5.11 - Blowout limits of a jet diffusion flame of different fuels in the attached flame region for a jet diameter of 1.5 mm

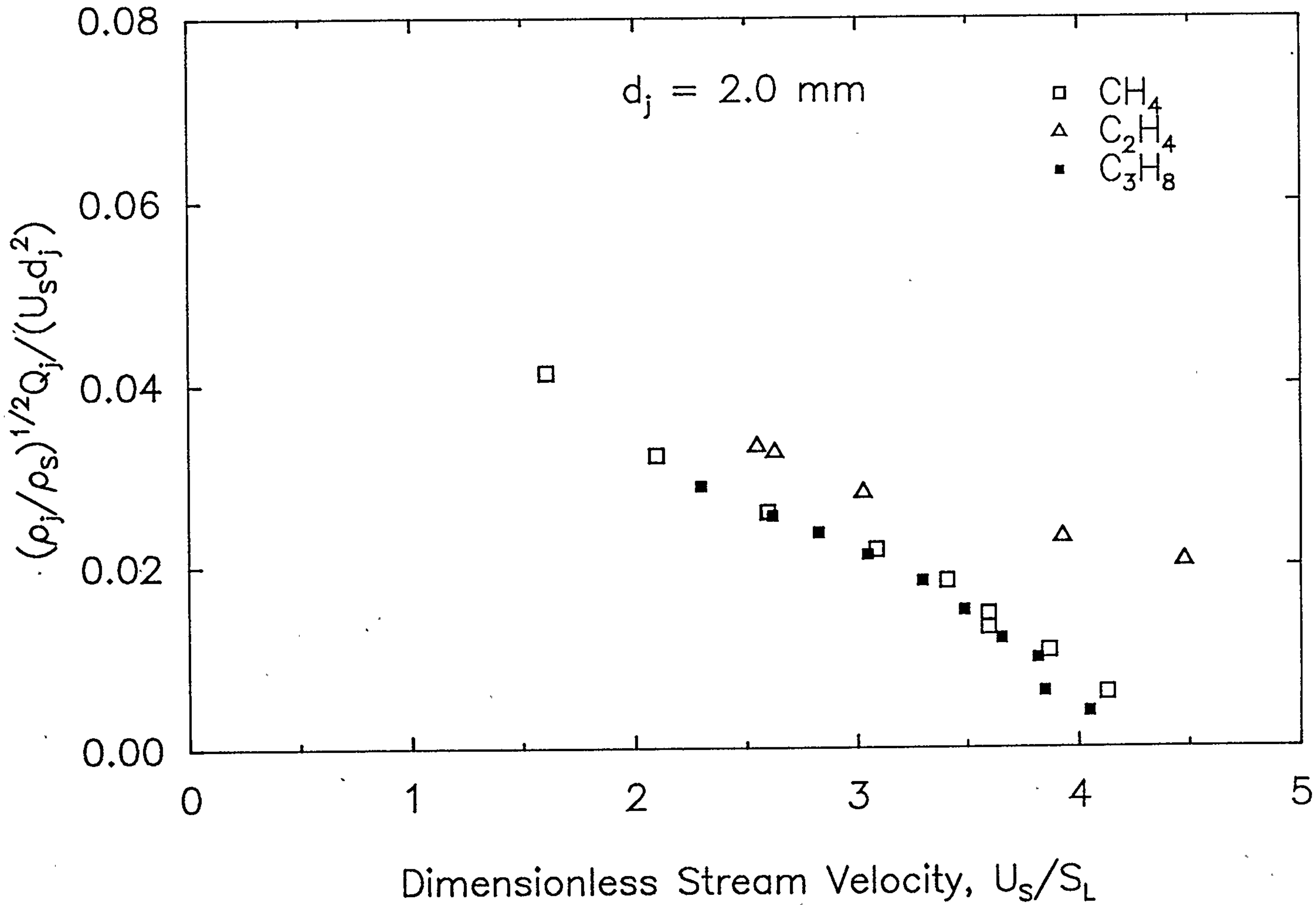

Figure 5.12 - Blowout limits of a jet diffusion flame of different fuels in the attached flame region for a jet diameter of 2 mm

S_L is the maximum burning velocity in air (m/s)

As shown in Figure 5.13, the proposed correlation according to equation 5.2, fits the majority of the experimental data quite well.

5.5 EFFECT OF THE SURROUNDING STREAM FUEL CONCENTRATION

The addition of fuel into the surrounding air stream has different effect on the stability of the jet diffusion flame depending on the velocity of the stream, its concentration, and the type of fuel added to the stream. It is already known that the blowout limit of the jet flame is enhanced considerably when the surrounding stream contains some fuel homogeneously mixed with the air [17,18]. However, it was reported recently [15,34] that the addition of some fuels to the co-flowing air stream under certain conditions can have a detrimental effect on the stability of the jet flame. The experiments in [34] were conducted with methane as the jet fuel and such detrimental effect were observed at stream velocities higher than 1.4 m/s with methane, ethylene and propane as the auxiliary fuel in the surrounding co-flow stream.

In order to improve the understanding of the mechanism that leads to this adverse effect, the blowout of ethylene jet diffusion flame at stream velocities ranging from 0.31 - 2.52 m/s were investigated with methane or hydrogen added into the surrounding air stream. The diameter of the jet nozzle was 1.5 mm. Ethylene was chosen as the jet fuel because of its better stability at high stream velocities compared to methane and propane, and because it was relatively easier to observe ethylene flames than hydrogen flames.

Lifted flames were observed before blowout with either methane or hydrogen as

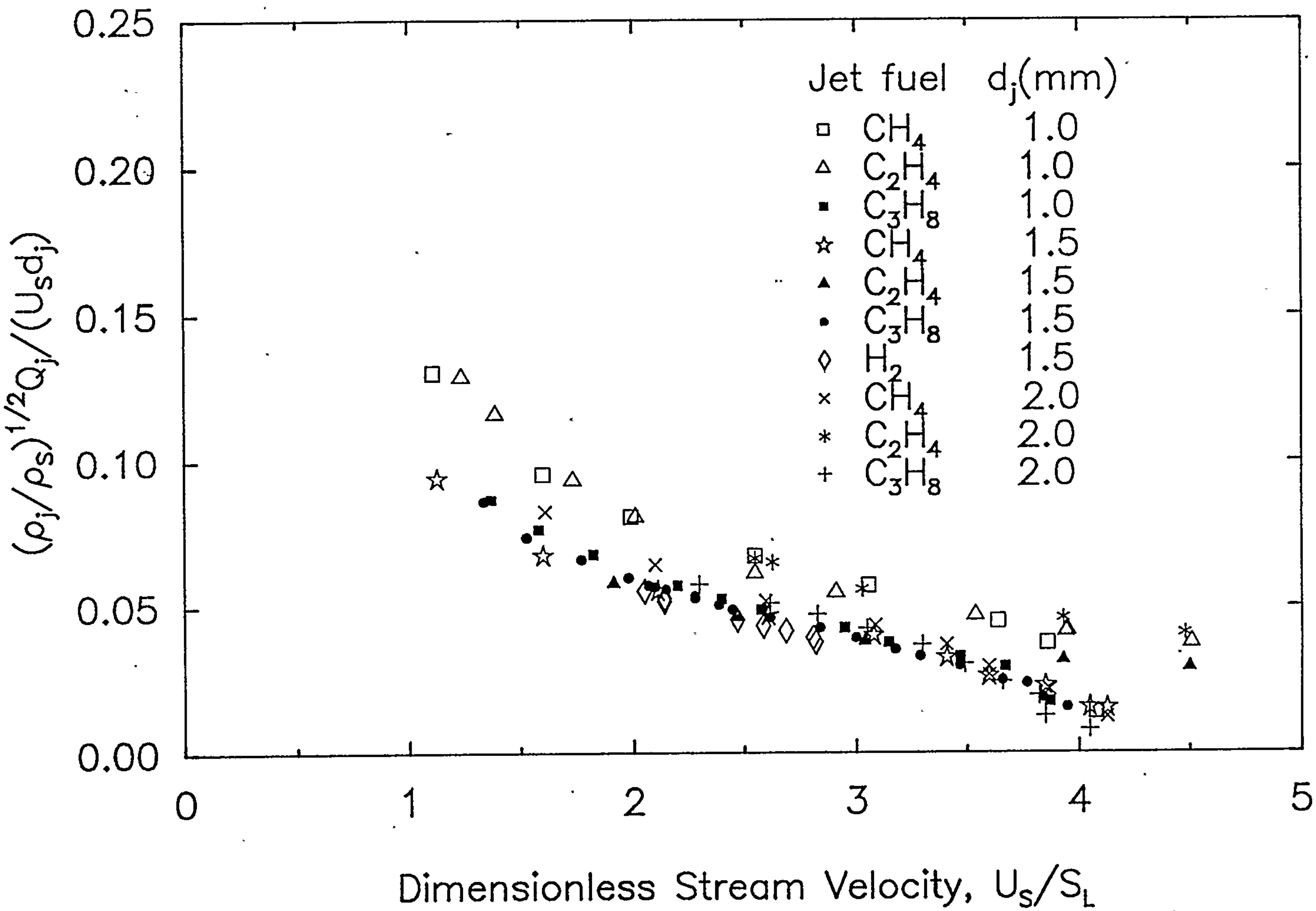

Figure 5.13 - Blowout limits of a jet diffusion flame of different fuels at different jet diameters in the attached flame region

the surrounding fuel for stream velocities reaching up to 1.40 m/s. At 2.50 m/s however, attached flames were observed for the whole range of methane concentrations employed but only up to about 5.6% concentration with hydrogen as the surrounding fuel. Above this level of hydrogen concentration, liftoff suddenly set in and the blowout limit of the lifted jet flame improved very significantly with every small increase in hydrogen concentration.

The effect of the addition of methane or hydrogen to the surrounding stream on the blowout limit of the jet flame at low stream velocity (0.31 and 0.70 m/s) can be seen in Figure 5.14. As shown, the blowout limit increases slightly at low surrounding fuel concentration with both fuels. The amount of any surrounding fuel that can be added into the surrounding air stream is limited by the flashback limit of the fuel in air. However, when the stream velocity is low, the concentration of methane or hydrogen that could be introduced in the surrounding stream before the mixture started to burn were much lower than the corresponding flashback limit. As the jet velocity was increased relative to the stream velocity, mixing between the surrounding fuel, air and the jet fuel in the space between the lifted flame base and the nozzle exit improved. It is possible that the contribution of the jet fuel to the fuel concentration in the stream made the mixture become flammable at a surrounding fuel concentration well below the corresponding flashback limit. Any increase in the jet flow rate under this condition raised the mixture concentration upstream of the flame even further resulting in the flame being propagated upstream against the flow until finally, flashback occurred.

At a stream velocity of 1.4 m/s, the addition of methane has a negligible influence

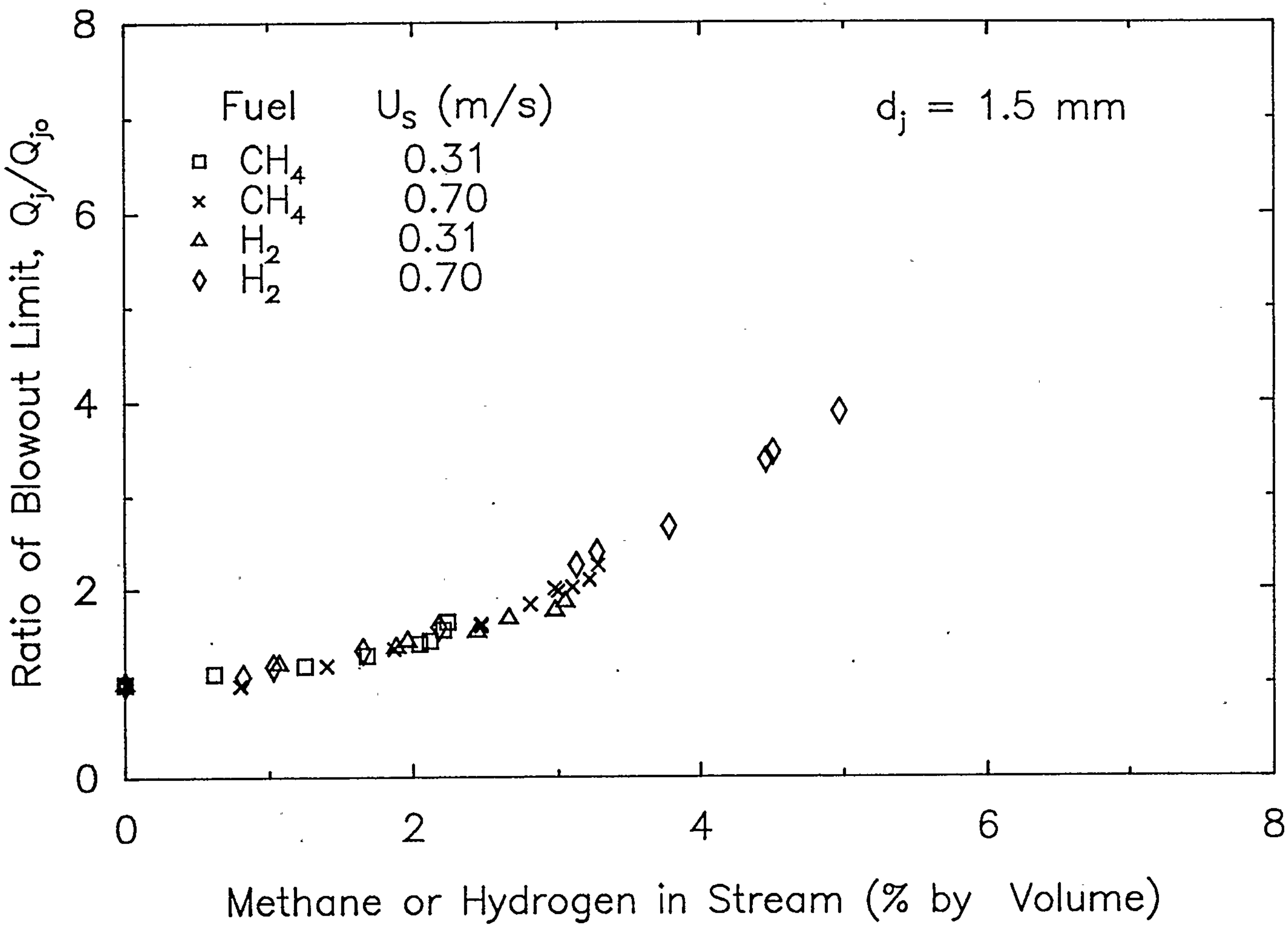

Figure 5.14 - Ratio of blowout limits of ethylene jet diffusion flame at different concentration of methane or hydrogen in the surrounding stream

on the blowout limit of the lifted flame at low concentration (less than 3.0%) as can be seen in Figure 5.15. At higher concentration however, the limit increased very significantly with a relatively small increase in concentration. With hydrogen as the surrounding fuel however, the blowout limit of the flame increased steadily as the hydrogen concentration was increased. Also the addition of hydrogen to the surrounding stream improved the blowout limit the most at this stream velocity in the concentration range of up to about 4.7%.

At higher stream velocity (2.5 m/s), experiments showed that the addition of methane or hydrogen to the surrounding air stream at relatively small concentrations has no significant effect on the blowout limit of the jet flame. The ratio of blowout limits was approximately unity for methane and hydrogen concentrations up to about 4.6 and 5.5% respectively. As mentioned earlier, nozzle attached flames were always observed at this velocity except at hydrogen concentrations higher than about 5.6%, hence the blowout limit can be expected to be smaller than for the lifted flames as observed. Increasing the methane concentration beyond 4.6% brought about a significant drop in the blowout limit of the jet flame. On the other hand, increase in the concentration of hydrogen beyond 5.5% resulted in lifted flames for which the blowout limit increased very significantly with every small increase in concentration.

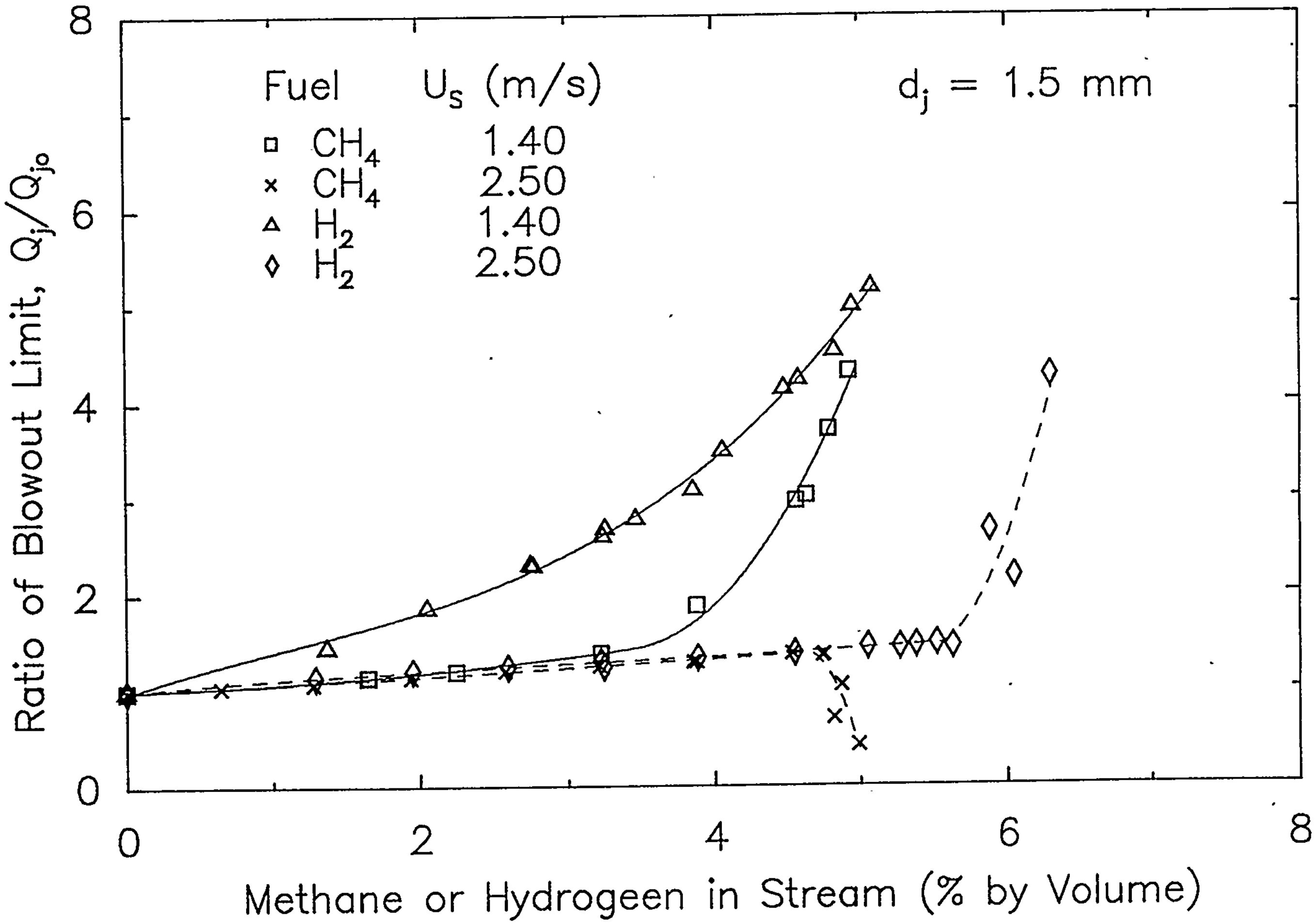

Figure 5.15 - Ratio of blowout limits of ethylene jet diffusion flame at different concentrations of methane or hydrogen in the surrounding stream

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

1. The lean flashback limits of methane, ethylene, propane and hydrogen in air have been determined at different stream velocities. It was found that the flashback limits of hydrogen in air were generally the most significantly affected by changes in the stream velocity while those of the other fuels were only affected at low stream velocities.
2. Flashback limits of different binary fuel mixtures of hydrogen with methane, ethylene and propane in air were established at different stream velocities. The limits were also established for hydrogen-diluents mixtures in air at a stream velocity of 1.6 m/s.
3. The flashback limits of binary fuel mixtures of gaseous fuels can be predicted reasonably well on the basis of a modified form of Le-Chatelier's rule. The deviation of the predicted limits from the experimental limit values for the most cases appeared not to exceed 7.5%.
4. A simple approach was proposed for calculating the lean flashback limits of fuel-diluent mixtures. The deviation of the flashback limits of hydrogen-diluent mixtures calculated according to this approach compare very well with the experimental results especially at diluent concentrations below 30%.
5. The blowout limits of a jet diffusion flame in a co-flowing stream of air were determined for methane, ethylene, propane and hydrogen fuels at different stream velocities and three different diameters of the jet nozzle. Two types of flames, lifted

and attached, were observed depending on the stream velocity and the jet nozzle diameter.

6. The observed flame blowout limits were found to be higher for the lifted jet flames than for the attached flames. The limits for lifted flames decreased with increase of the stream velocity while those of the attached flames were almost independent of the stream velocity for the most part of the range considered.
7. It was also observed that the flame blowout limits increase significantly with increase of the jet nozzle diameter from 1.5 to 2 mm but less significantly with a similar increase from 1.0 to 1.5 mm. The measured blowout limits of the lifted flames of different fuels were correlated quite well using the proposed procedures.
8. The blowout limits of ethylene jet diffusion flames in co-flowing streams of air mixed with methane or hydrogen were determined at different stream velocities. Lifted flames were observed before blowout at stream velocities reaching up to 1.4 m/s. At 2.5 m/s however, attached flames were observed for the whole range of methane concentrations employed but only up to about 5.6% with hydrogen as the surrounding fuel. The stability of the jet flame was found to improve with the introduction of a small amount of fuel into the surrounding stream at relatively low velocities. At higher velocities up to 2.5 m/s however, a decrease in the blowout limit of the jet flame was observed with methane as the surrounding stream at concentrations higher than about 4.6%. No such drop in the blowout limit was observed with hydrogen as the surrounding fuel.

6.2 RECOMMENDATIONS

1. It is recommended that a more stable source of ignition be provided for the flowing homogeneous fuel-air mixture so that the possibility of flame flashback can be investigated at higher stream velocities than were reached in the present study.
2. Schlieren photography of the flame is also recommended since this can reveal some detail structures of the flame and provide useful insights into the mixing processes inside the combustor. This knowledge may be used to explain the difference in behaviour exhibited by the lifted flame and the nozzle attached flame. The variations of microscopic structure within the flame at different jet and stream velocities may indicate the behaviour of the eddies within the jet diffusion flame. Such information can then be linked to the stability of the flame to develop some predictive procedures for the stability phenomena.
3. The turbulence intensity within the flame at different stream velocities can give an indication of the relation between the degree of turbulence and the blowout jet velocity. Such information can be very useful in predicting the blowout limit at different stream velocities. It is therefore recommended that the turbulence intensity within the flame be measured possibly using a Laser - Doppler Velocitymeter (LDV).

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APPENDIX

1. GENERAL

The choked nozzles used to measure the flow rates of the fuels and the diluents were calibrated in air and suitable correction factors were applied to the calibration curves to obtain the actual gas flow rate. Denoting the absolute pressure and temperature upstream of the nozzle as P_u and T_u respectively, it can be shown that for a choked nozzle:

$$Q \propto \frac{P_u}{\sqrt{MT_u}} \left(\frac{T_a}{P_a}\right) f(\lambda)$$

where,

$$f(\lambda) = \sqrt{\frac{2\lambda}{\lambda+1} \left(\frac{2}{\lambda+1}\right)^{\frac{1}{\lambda-1}}}$$

λ is the ratio of specific heats (C_p/C_v) and

M is the molecular weight.

If Q_g and Q_a are the volume flow rate of the gas and air through the choked nozzle respectively, it follows that,

$$\frac{Q_g}{Q_a} = \frac{f_g(\lambda)}{f_a(\lambda)} \sqrt{\frac{M_a}{M_g}} = F(\lambda, M)$$

or $\quad Q_g = F(\lambda,M)\, Q_a$

A calibration curve based on air can therefore be corrected for a given gas by applying the appriopriate correction factor $F(\lambda, M)$.

2. VALUES OF THE CORRECTION FACTORS FOR DIFFERENT GASES

Gases	$F(\lambda, M)$
Air	1.0000
Nitrogen	1.0180
Carbon dioxide	0.7914
Methane	1.3146
Ethylene	0.9780
Propane	0.7510
Hydrogen	3.8146

3. CALIBRATION EQUATION FOR DIFFERENT CHOKED NOZZLE

Size (mm)	Equation of Line $(\gamma = P_u/\sqrt{T_u})$
0.14	$Q_a = 0.0020714\gamma - 0.0013$
0.20	$Q_a = 0.006281\gamma - 0.004$
0.41	$Q_a = 0.0162721\gamma$
0.64	$Q_a = 0.0348484\gamma$
0.91	$Q_a = 0.0842105\gamma$
1.09	$Q_a = 0.1101449\gamma$
1.32	$Q_a = 0.186764\gamma$