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The effect of co-flow stream velocity on turbulent non-premixed jet flame stability

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Abstract

The stability behaviour of non-premixed jet flames in a co-flowing air stream was investigated experimentally. The experimental data obtained indicate that there exists a range of co-flow velocity where two distinctly different extinction limits can occur at the same co-flow velocity depending on whether the flame is lifted or attached at ignition. Results show that co-flow velocity has a much greater effect on the blowout limits of lifted flames than on the blowoff limits of attached flames. The blowout limit of lifted flames initially increase linearly with co-flow velocity independent of nozzle diameter until a peak value is reached, after which it decreases rapidly with increasing co-flow velocity. Such behaviour appears to be governed by two different mechanisms. A model for predicting lifted flame blowout limits has been developed. It is based on the ratio of the Kolmogorov time scale and the chemical time scale as a function of a jet similarity parameter. The model was used to predict the blowout limits for methane as well as the effect of diluents in either fuel or co-flow stream. Results show very good agreement with experimental data in the current investigation.

Keywords: Turbulent non-premixed jet flames; Flame stability; Blowout limits; Co-flow; Diluents

1. Introduction

The stabilization of turbulent non-premixed jet flames has been the subject of many research efforts in the past few decades. It is well-known that as the jet velocity increases, a non-premixed jet flame would first lift off from the burner rim (lifted flame) and a continuous increase in the jet velocity would result in flame blowout [1]. It has also been observed in the past that a jet flame can also be extinct while it is still attached to the rim [2]. This phenomenon is referred to as flame blowoff [1]. Understanding of the physics which govern these phenomena is crucial for determining the operating conditions at which flame instability will occur in practical devices.

The stabilization mechanism of lifted flames has received much attention in the past [3–7]; however, there is still a limited amount of information available on predicting the blowout limits of lifted flames. Kalghatgi [8] and Broadwell et al. [5] each proposed a model for predicting the blowout limits of free jet flames. Kalghatgi's model is based on the notion that fuel and air are completely premixed at the base of a lifted flame. On the other hand, the model proposed by Broadwell et al. is based on the concept that large-scale mixing is the stabilization mechanism of lifted flames.

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Their stability criterion is defined as the ratio of the characteristic large-scale mixing time to the chemical time. Chao et al. [9] recently showed that both models could accurately predict their experimental blowout data for pure and diluted fuels; however, the large-scale mixing model required a modification to account for the effect of the Reynolds number.

In many practical combustion systems, a co-flow air stream is often added to increase the efficiency of the combustion process, shorten the flame length and reduce the residence time for NO_x formation [10]. However, it was shown that a very small increase in the co-flow stream velocity can lead to a very dramatic decrease in the lifted flame blowout limit [7,11,12] and a lifted flame can only be stabilized at low co-flow velocities $< 3\ S_L$ [7]. Thus it is important to have a model that can predict the effect of co-flow velocity on blowout limits accurately. Dahm and Dibble [12] extended the model of Broadwell et al. for jet flames in a co-flow stream for limited blowout data. Along a different line, Karbassi [13] proposed a different stability criterion based on the eddy dissipation concept [6] for predicting lifted flame blowout limits in co-flow.

The stability of attached flames and their extinction limits (blowoff) have received less attention than the blowout limits of lifted flames. There is currently no model available in the open literature that can predict the blowoff limits. There are also very few detailed studies which include the flame stability behaviour for both attached and lifted flames in a co-flowing stream.

This work consists of two parts. The first objective is to investigate the effect of co-flow on the stability limits of both attached and lifted jet flames experimentally. In particular, it is of interest to determine how the stability limits of lifted and attached flames vary with the co-flow velocity. The second objective is to develop and validate a method for predicting blowout limits of lifted flames in order to gain a better understanding on the effects of co-flow velocity and dilution in the fuel or in the co-flow stream on these limits.

2. Experimental procedure

Experimental blowout limits were determined in a vertical stainless steel chamber with a square cross-section (127 × 127 mm) and quartz windows installed on the chamber sides. Co-flowing air was driven by a centrifugal blower equipped with a variable frequency drive for accurate control of the flow rate. A honeycomb straightener at the base of the chamber ensured uniform velocity of the air stream, which was confirmed by velocity measurements at the chamber base using hot-wire anemometry. The fuel and diluents were supplied from high pressure cylinders, which were mixed homogeneously in a tube 2 m long prior to discharge from a circular nozzle fitted onto a stainless steel tube in the center of the chamber. Diluents can also be added to the co-flowing air at a location upstream of the entrance into the chamber base. Fuel was ignited with an electrical spark placed near the nozzle rim for all experiments. Mass flow rates of all fuel (methane) and diluents (nitrogen and carbon dioxide) were measured by separate choked nozzles and the co-flowing air mass flow rate was measured using a sharp-edged orifice. Uncertainties of the flow measurements were within ±5%.

A stable jet flame was initiated with spark ignition at an initial fuel discharge velocity and a fixed co-flow velocity. The fuel velocity was then increased gradually until one of the stability limits (liftoff, blowout or blowoff) could be observed visually. Liftoff occurred when an attached flame jumped from the nozzle suddenly and re-stabilized itself at some downstream location as a stable lifted flame. This flame would extinguish with further increase in the fuel velocity at the blowout limit. However, the blowoff limit occurs instead when an attached flame lifts off and gets extinguished simultaneously. All stability limits cited in this paper are the mean fuel velocity at the instance when one of the events described above occurred. All experiments took place under atmospheric conditions in Calgary ($P = 89$ kPa and $T = 20$ °C).

3. Experimental observations on non-premixed jet flame stability

3.1. Methane stability behaviour

Figure 1 shows a typical behaviour of the stability limits of a methane jet discharging into a co-flow stream. The nozzle diameter (d_o) is 2 mm

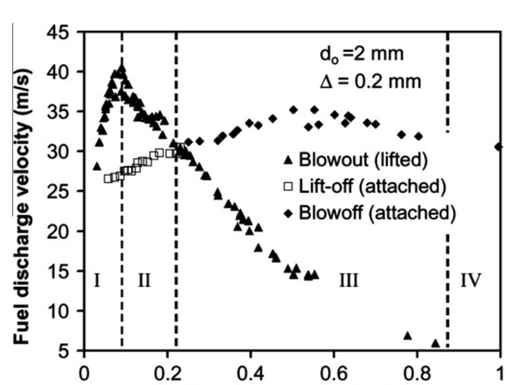

Fig. 1. Stability limits of a methane non-premixed jet flame as a function of co-flow stream velocity.