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Stability of Turbulent Diffusion Wake Flames behind Bluff-Bodies with Fuel Injection

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Abstract

Stability of wake flames formed behind a cylindrical bluff-body with two fuel injection slits was investigated experimentally in three kinds of bluff-bodies with 10, 15 and 20 mm diameter fitted in an air stream. The range of air flow velocities were 5-60 m/s. Fuels used here were propane, methane, ethylene and butane, and were injected upward into the air stream from the slits at the surface of the flame holder with an angle of 30° against the air flow direction. Flame stability limits, length of the recirculation zone and excess air ratio in the zone were measured for various fuels and air velocities.

The results show that the recirculation zone length depends on the flame holder dimension and is independent of the chemical properties. The excess air ratio in the recirculation zone is influenced only by the approaching air velocity at blow-off. Further it is suggested that the stability curves for each fuel and flame holder dimension are generallized by use of $U_f \cdot A_{st.}$ and $U^* \sqrt{d}/Su$ where U^* is a corrected approaching air velocity, d the flame holder diameter, Su the laminar burning velocity, U_f the fuel flow rate and $A_{st.}$ the stoichiometric air-fuel ratio.

1. Introduction

The mechanism of flame stabilization in high velocity uniform gas streams has long been under investigation and presented by many researchers [1], [2]. The use of a bluff-body as a flame holder is one of the most effective flame stabilization techniques. The recirculation zone is formed in the near wake of the body and works as an ignition source of the fresh fuel-air mixture. Then a stable flame is held in this region. These studies on bluff-body flame stabilization have been carried out almost entirely with homogeneous premixed fuel-air flow and were well summarized by Williams [3]. Contrary to the large number of investigations of flame stabilization with gaseous premixtures, only a few investigations with fuel supply from bluff-bodies have been reported [4]. In these studies new problems related to the characteristics of diffusion flames, e. g., turbulent diffusion of the fuel, naturally come about in addition to the problems on premixture flow.

In the present study gaseous fuels were supplied to the approaching air flow from two slits on the upstream surface of the bluff-body. Flames in this study

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were a kind of turbulent diffusion flame, however, they showed the characteristics of premixed fuel-air flames in terms of flame propagation. This was the result of turbulent diffusion of fuels mixed with the through air flow immediately after injection. Therefore these flames substantially differ from the turbulent diffusion flames held on the usual round jet burner. In order to discuss the flame stabilization mechanism, it is assumed that there is no difference in the characteristic flow pattern between the premixed and diffusion flames stabilized by the same flame holder. Premixture flame stabilization studies have been directed to explain the mass exchange between the through flow and the recirculating flow [5]. The same as with the premixed flame stabilization study, the quantity of the air entrained into the recirculation zone behind a bluff-body is a fairly important parameter in this study.

The purpose of the present study is to clarify experimentally the effects of the fuel injection rate and the flame holder dimensions on the stability limits of flames formed behind bluff-bodies and display the relation between the stability limits and various physical quantities such as the recirculation zone length and the excess air ratio in the recirculation zone.

2. Experimental apparatus

The experimental apparatus employed here is schematically shown in Fig. 1. The air was supplied by two blowers, through a calming section consisting of a diffuser, two 50-mesh screens and a 9 to 1 concentration-ratio nozzle, and introduced into a combustion chamber with a fully developed turbulent flow and a flat velocity profile. The test section entrance velocities could be adjusted from 5 to 60 meters per second. The test section had a constant cross section (50 × 75 mm) and a length of 622 mm. One side of the test section consisted of a pyrex glass to observe the flame configulation.

Three flame holders used in this experiment were cylindrical tubes of brass with a length of 50 mm and a diameter of 10, 15 and 20 mm and were fitted with it's axis normal to the air flow direction. The flame holder had two rectangular slits (0.5 × 20 mm) to inject the fuel.

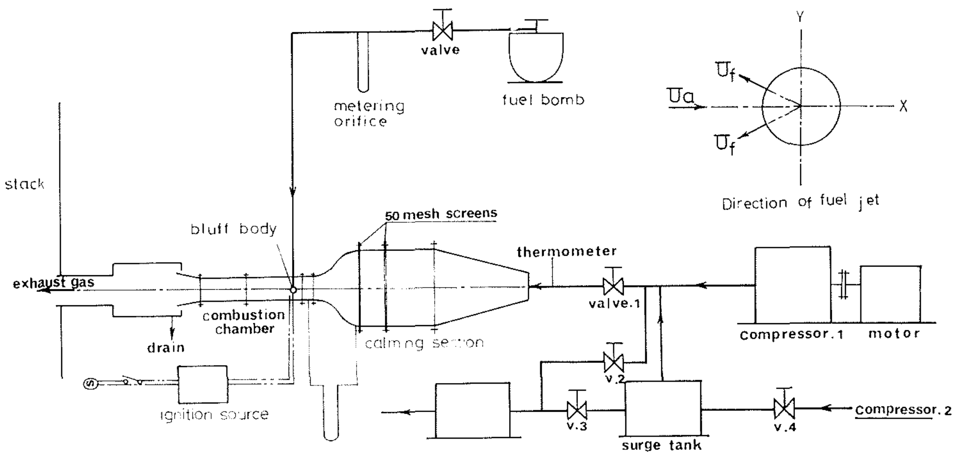

Figure 1. Schematic diagram of experimental apparatus and the direction of fuel jet from a bluff-body

Propane, methane, ethylene and butane used as gaseous fuels were introduced to the flame holder and injected from the slits, which were directed into the upstream of the air flow at an angle of 30 degrees against the air flow direction at the surface of the flame holder, as shown in Fig. 1.

Although there is a large difference in length between the bluff-body and the fuel injecting slits the two-dimensionality of this flame was ascertained previously at the vicinity of the center plane of the chamber.

3. Experimental results and discussion

3.1 Flame configuration

A actual photograph of a typical example of a stabilized flame behind a bluff-body is shown in Fig. 2. In this figure a dotted line shows the cylindrical bluff-body and the luminous area corresponds to the flame zone. Ignition fronts of upper and lower flames appear immediately downstream of the separation points on the flame holder. Premixed flames stabilized by bluff-body propagated to the combustion chamber walls at an angle. In the present study there is no obvious flame front propagating to the chamber walls with the premixed flames. Assuming that the flame is held within the shear layer between the through flow and the recirculating flow, the region closed by the upper and lower flame front corresponds to the recirculation zone. In premixed flame, the shear layer between the through flow and the recirculating flow acted as a mixing layer of unburned mixtures and burned gases. In the present flame the shear layer seemed to act also as a fuel mixing layer with through air. This difference between premixed and present flames appears in the difference of flame propagation mechanism.

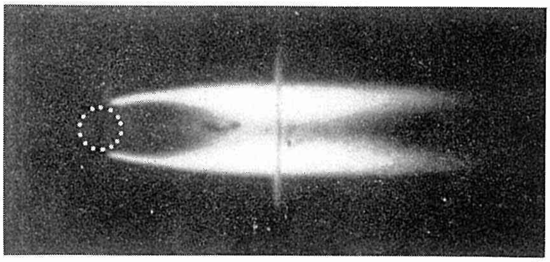

Figure 2. Photograph of flame configulation, stabilized by a 12.5 mm bluff-body, $U_a=28$ m/s, $U_f=2.2$ m/s

3.2 Stability limits

In the present experiment the stability limits were determined by the approaching air velocity at which the flame blew-off for fuel injection rates. No fuel rich limit appeared in this experiment and only the lean limits were obtained by the above procedure. These results are shown in Figs. 3, 4, 5 and 6, for propane, methane, ethylene and butane, respectively. Stabilized flames were obtained in the right-hand region of the stability curves in these figures. The stability curves in this study are very similar to those in the case of a bluff-body wetted by liquid fuels reported by Gross [4].

Figs. 3, 4, 5 and 6 show that the fuel injection rate decreases by decreasing the flame holder diameter for an arbitrary approaching air velocity. No stability curve intersects and the gradient of the curve decreases with an increase of the flame holder diameter. It is also shown that there is no significant difference in both tendency and quantity for propane, ethylene and butane. In comparison with the above fuels, methane indicates considerably low stability limits but the same tendency with the other fuels for the change of flame holder diameter.

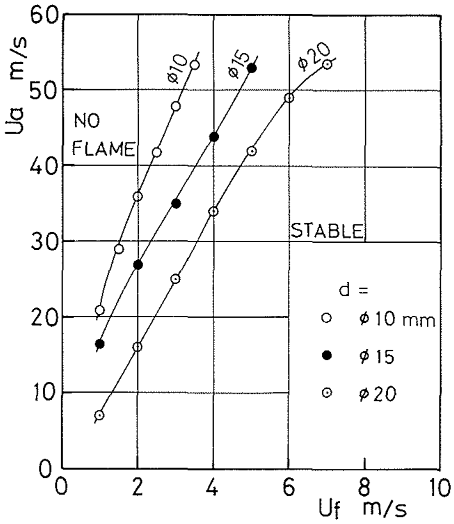

Figure 3. Stability limits for propane flames stabilized on cylindrical flame holders

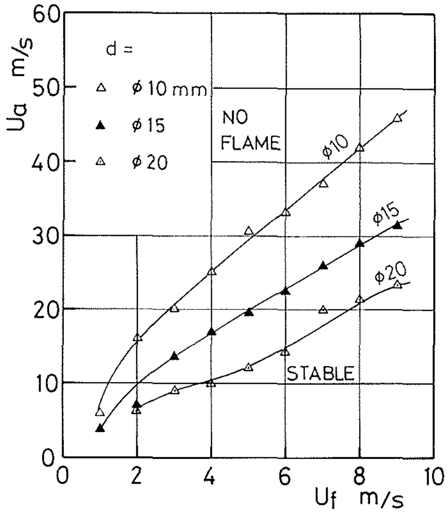

Figure 4. Stability limits for methane

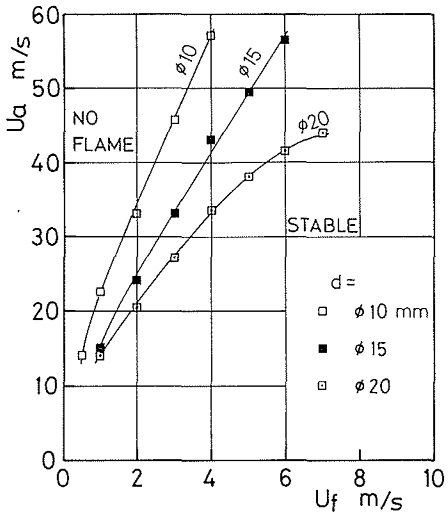

Figure 5. Stability limits for ethylene

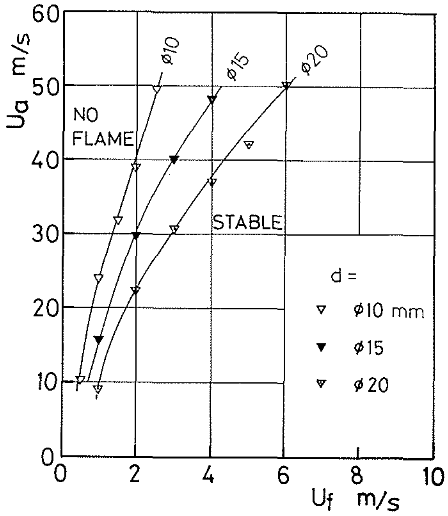

Figure 6. Stability limits for butane

Fig. 7 shows the stability limits of propane and methane with the correlation of characterized blow-off air velocity $U^*\sqrt{d}$ versus fuel injection rate U_f, where d is flame holder diameter. U^* was defined as the air velocity past the edge of the flame holder at blow-off and expressed as

$$U^* = \frac{1}{1-B} U_a,$$

where B is the blockage ratio d/H (H; the height of combustion chamber). This figure suggests that the characterized blow-off air velocity is approximately constant with various flame holder diameters for a same fuel injection rate for each fuel. The blow-off air velocity decreases with an increase of the flame holder diameter as shown above and the relation is represented as follows. The blow-off air

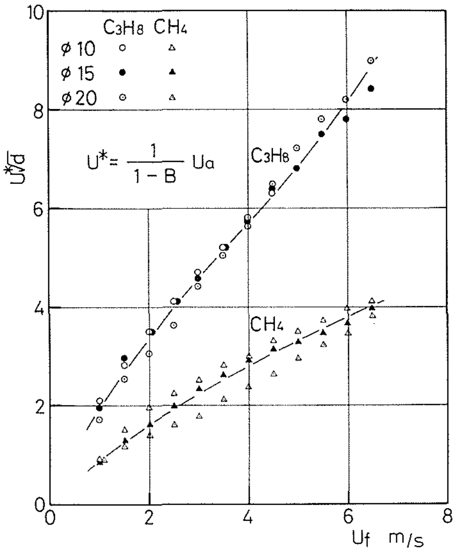

Figure 7. Characterized blow-off air velocity versus fuel injection rate for propane and methane

velocity is inversely proportional to the square root of the flame holder diameter. This relation is also confirmed to be valid for ethylene and butane. This result is evidently different from that of premixed flame stabilization study, for example, where Scurlock [6] reported that the blow-off air velocity is approximately proportional to the square root of the flame holder diameter.

3.3 Recirculation zone length

The recirculation zone length and the temperature in this region play a important role for premixed flames stabilized by bluff-bodies. It is nessesary to find the influence of various physical factors on the recirculation zone length. Zukoski [2] and many other authors reported that the recirculation zone length was decided only by aerodynamic factors such as the flame holder dimension and approaching air velocity and was independent of chemical factors.

In this study the measurement of the recirculation zone length was performed using the flame reaction to salt solution which was injected with low velocity into the wake from a very small injection tube. Measuring condition was near the blow-off limits.

The results of these measurements are shown in Figs. 8, 9, 10 and 11 for propane, methane, ethylene and butane, respectively. These four figures clearly show the same tendency both qualitatively and quantitatively for the variety of the air velocity and the characteristic dimension of the flame holder. This results shows that the recirculation zone length is independent of the choice of fuel.

From these figures it is shown that the recirculation zone length increases with an increase of the flame holder diameter. As shown in the lower part of each figure a characteristic parameter $L_{RZ}/\sqrt{d}$ seems to be constant for the change of the flame holder diameter, where L_{RZ} is the recirculation zone length. Namely the recirculation zone length is proportional to the square root of the flame holder diameter. This result is equivalent to that of Zukoski [2] for premixed

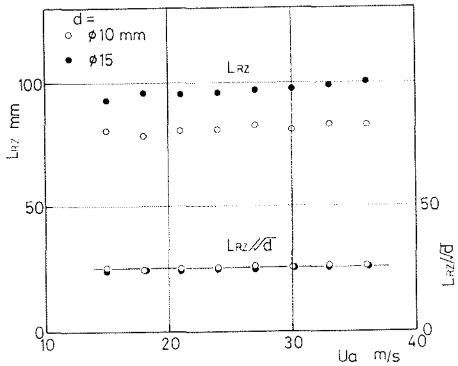

Figure 8. Actual and characterized recirculation zone length versus approaching air velocity for propane

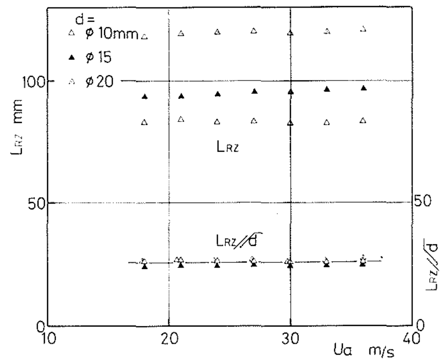

Figure 9. Recirculation zone length for methane

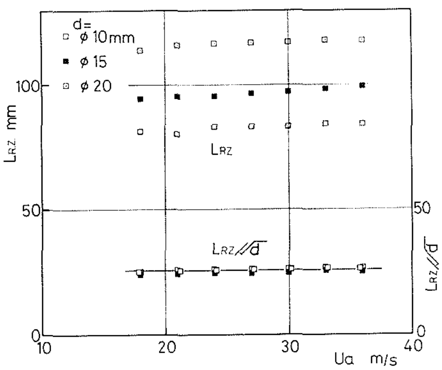

Figure 10. Recirculation zone length for ethylene

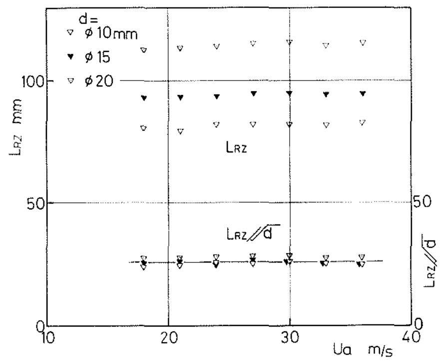

Figure 11. Recirculation zone length for butane

flame stabilization. It could be regarded that the recirculation zone length is independent of the approaching air velocity although it slightly increases with increasing air velocity.

It may be assumed that the recirculation zone length is essentially independent of chemical characteristics and only governed by aerodynamic ones. Thus these results are adequately similar between diffusion and premixture flames.

3.4 Excess air ratio in the recirculation zone

The gas analysis in the recirculation zone is an effective means to grasp the burning condition in this region. In this experiment the result of gas analysis was represented by the excess air ratio. The gas analysis was carried out at the vicinity of the blow-off limit. Experimental procedure was as follows. Gas samples were withdrawn with a thin quartz probe at a point 25 mm downstream from the trailing edge of the flame holder on the center axis for 10mm-bluff-body and at similar distances downstream for 15 and 20 mm-bluff-body, respectively. These samples were analized by using gas chromatograph and the excess air ratio was calculated by using the normal method. The homogeniety in the recirculation zone was discussed previously and the measurements were carried out at a point where the representative gas composition was obtained.

The experimental results at the vicinity of the stability limits are shown in

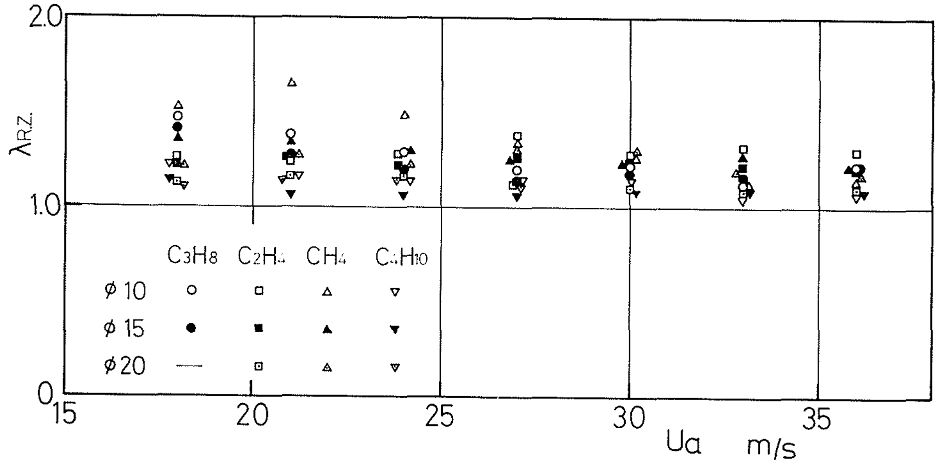

Figure 12. Excess air ratio in the recirculation zone versus approaching air velocity at a vicinity of blow-off for propane, methane, ethylene and butane

Fig. 12. This figure shows that the excess air ratio in the recirculation zone decreases as the approaching air velocity increases and has a tendency to converge to the stoichiometry value. This tendency qualitatively corresponds to the lean limit stability curves of premixture flame. Relatively large scattering of the results is seen in the lower part of the air velocity for the change of fuels and the flame holder diameter. The scattering decreases with increasing air velocity. However, it is not difficult to recognize the excess air ratio is independent of the variety of fuels and the flame holder diameter.

4. Consideration on blow-off limits

The recirculation zone contains some essential factors which govern the flame stabilization by bluff-bodies. In these factors, the excess air ratio is taken into account when considering the blow-off condition here, for the excess air ratio distinctly indicates the burning condition in the recirculation zone. As shown above it can be thought to be valid that the excess air ratio in the recirculation zone is independent of the variety of fuels and diameters of flame holders and has a fixed value for each air velocity. The excess air ratio is decided by the air entrainment rate into the recirculation zone and the fuel injection rate in this study. To consider the blow-off limit, it will be very effective to introduce the quantity of air entrainment into the recirculation zone if the following assumptions are made; (1). the volumetric air entrainment rate is independent of the variety of fuels and the fuel injection rate and influenced by the change of the flame holder dimension and the approaching air velocity, (2). all the fuel injected enters the recirculation zone.

The excess air ratio in the recirculation zone λ_{RZ} can be expressed as follows,

$$\lambda_{RZ}=Q_a/Q_f/A_{st.} \qquad (1),$$

where Q_a is the volumetric air exchange rate, Q_f the fuel feed rate and $A_{st.}$ the stoichiometric air-fuel ratio. As shown above, the air exchange rate can be assumed to be constant for the variety of fuels and the changes of the fuel injection rates. Further, at blow-off condition the excess air ratio in the recirculation zone also can be thought to be independent of the variety of fuels

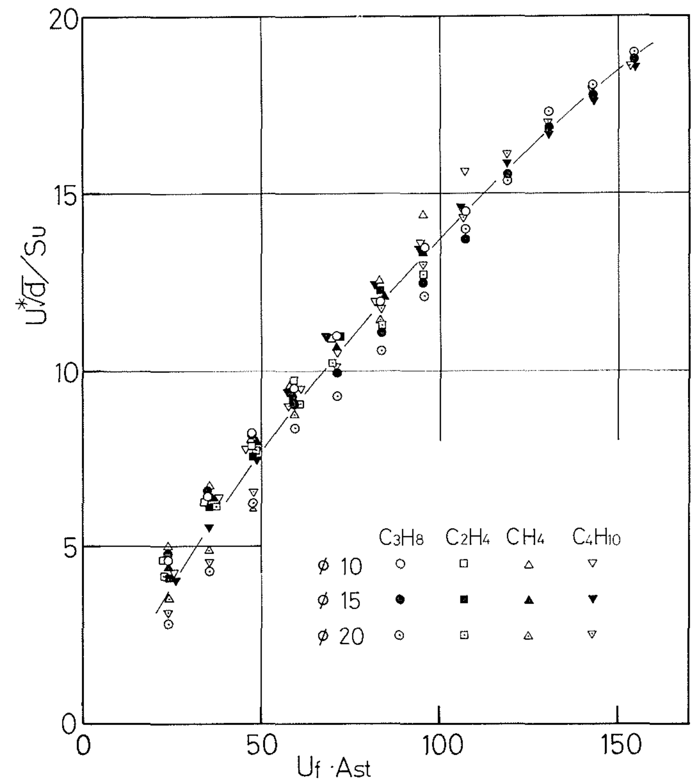

Figure 13. Generallized stability limit with the axis of $U_f \cdot A_{st.}$ and $U^* \sqrt{d}/Su$ for different kind of fuels and flame holders

and the flame holder diameters. Under these considerations, Eq. (1) can be arranged and following equation is obtained on blow-off limits.

$$Q_f \cdot A_{st.} = Q_a / \lambda_{RZ} = \text{Const.} \qquad (2).$$

Eq. (2) shows that the fuel injection rate is generallized by the parameter of $Q_f \cdot A_{st.}$ for the different kind of fuels.

Then it may be nessesary for the consideration on blow-off to discuss the effect of the chemical reaction rate on the blow-off air velocity. In this paper it is assumed that the blow-off air velocity is proportional to the chemical reaction rate and that the chemical reaction rate is represented by the laminar burning velocity Su. Under the above assumption, the stability curver are modified and shown in Fig. 13 using coordinates $U_f \cdot A_{st.}$ as an abscissa and $U^* \sqrt{d}/Su$ as an ordinate. In this figure the stability curves are well generallized for different kind of fuels and flame holder diameters. Further, it is ascertained that the approaching air velocity at blow-off is proportional to the laminar burning velocity.

From these results the approaching air velocity increases with an increase in the laminar burning velocity. And for a constant approaching air velocity, a stable flame is obtained at a lower fuel injection rate, when the stoichiometric air-fuel ratio is larger.

5. Conclusions

The main considerations to be drawn in this work may be summarized as follows.

(1) Stability limits increase with a decrease in the flame holder diameter. And a parameter of $U^*\sqrt{d}$ represents the effect of the flame holder dimension and the approaching air velocity on the stability limits.

(2) The recirculation zone length is only determined by the flame holder dimension and proportional to the square root of the flame holder diameter.

(3) The excess air ratio in the recirculation zone is independent of the variety of fuels and the flame holder dimension and it depends on the main air velocity.

(4) Stability limits increase as the laminar burning velocity increases. Stability curves are well generallized on the axis of $U_f \cdot A_{st.}$ and $U^*\sqrt{d}/Su$ for an arbitrary fuel and a cylindrical flame holder.

Acknowledgement

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