Blowoff Stability of Methane-Air Premixed Flame on Tube Burners

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ABSTRACT
Stability of premixed flames is important in applications involving industrial and domestic impingement heat transfer processes, gas turbine combustion chamber and others. Blowoff limits of premixed methane-air flames stabilised on an uncooled Bunsen type burner is considered in the present experimental work. The effect of burner material, wall thickness and burner exit shape on the blowoff limits is presented. Burner materials covered in this study are stainless steel, brass and pyrex. Wall thicknesses considered are 1 mm, 2 mm and 3 mm for pyrex tubes of 10 mm inside diameter. The burner exit shapes covered in this study are circle, triangle, square and hexagon. The operating mixture Reynolds number range is 800 – 4000. It is found that the burners with low thermal conductivity, larger wall thickness and minimal sided polygon shapes provide better lean blowoff stability. Critical velocity gradient parameter defined on the basis of hydraulic diameter collapses the blowoff limits for all shapes covered in the present study. Correlations for Karlowitz number (*Ka*) are suggested for the blowoff stability for the various cases studied. The Karlowitz number is found to increase steeply with increase in fuel richness when equivalence ratio (ϕ) is greater than 1. This is attributed to the secondary reaction zones that provide additional heating of the tube at the stabilisation region. For equivalence ratio less than 1, the dependence of Karlowitz number with equivalence ratio is relatively weak. For turbulent flow, the Karlowitz number is found to be independent of the tube material, thickness and shape.

Key words:blowoff limits, premixed flame, methane-air, critical velocity gradient, Karlowitz number

NOMENCLATURE

Symbol	Meaning
C	Skin friction coefficient, $C_f = \dfrac{\tau_w}{\rho \bar{u}^2 / 2}$
d	Tube inside diameter (mm)
f	Friction factor
g_b	Critical velocity gradient parameter, $g_b = \dfrac{8\bar{u}}{d}$ (1/s)
Ka	Karlowitz number, $Ka = \dfrac{\alpha\, g_b}{Su^2}$
l	Length (mm)
M	Molecular weight
r	Radial coordinate
R	Tube radius (mm)
Pe	Peclet number, $Pe = \dfrac{ud}{\alpha}$
Re	Reynolds number, $\mathrm{Re} = \dfrac{\rho_m u_m d}{\mu_m}$

Su	Burning velocity, $Su = \frac{r}{l} u_m$ (m/s)
t	Tube wall thickness (mm)
u	Velocity (m/s)
X	Mole fraction
Y	Mass fraction

Greek symbols

α	Thermal diffusivity (m/s^2)
μ	Absolute viscosity (Pa.s)
η	Preheat zone thickness (mm)
ε	Emissivity
ρ	Density (kg/m^3)
τ	Shear stress (N/m^2)
ϕ	Equivalence ratio

Subscripts/ Superscripts

–	Average value
+	For non-dimensional turbulent quantities, *u* and *y*
b	Blow off
i	Component of mixture
J	Isothermal jet
f	Flame
m	Mixture
w	Wall
c	Circle

1. INTRODUCTION

Burner stability finds importance in industrial heating applications, gas turbine combustor applications, boiler furnaces, glass forming, domestic water heater and others. A stable flame is observed on a tube burner for certain proportions of fuel and oxidizer mixtures (equivalence ratio) at a certain mixture flow rate (Reynolds number). Beyond a certain proportion the flame flashes back (for low *Re*) or blows off. These limits are called as flame stability limits. These limits are important from energy saving and management point of view as the type of material of the tube, wall thickness and exit shape have influence on the minimum fuel richness (equivalence ratio) required for a given Reynolds number to have a stable flame. Use of richer fuel mixture implies more fuel usage which may not always result in higher heating efficiency. Moreover, lean mixtures result in lesser emissions of soot and NOx.

The phenomenon of flame stability is attributed to the following theories reported in literature.

i) Critical velocity gradient theory
ii) Flame stretch theory
iii) Flame base curvature effects (for inverted flames)

Lewis and Elbe [1] proposed the critical velocity gradient theory and inferred that the velocity gradient at the burner wall is the sole parameter that determines the flame stability limits of a burner. Figure 1 is a schematic illustration of the blowoff limits.

The blowoff limit governed by critical velocity gradient (g_b) is defined by Eq.(1). For laminar flow through circular tubes the velocity profile is given by Eq.(2) and accordingly the critical velocity gradient parameter is given by Eq.(3).

$$g_b = \lim_{r \to R}\left(-\frac{du}{dr}\right) \tag{1}$$

$$u(r) = 2\bar{u}\left(1 - \left(\frac{r}{R}\right)^2\right) \tag{2}$$

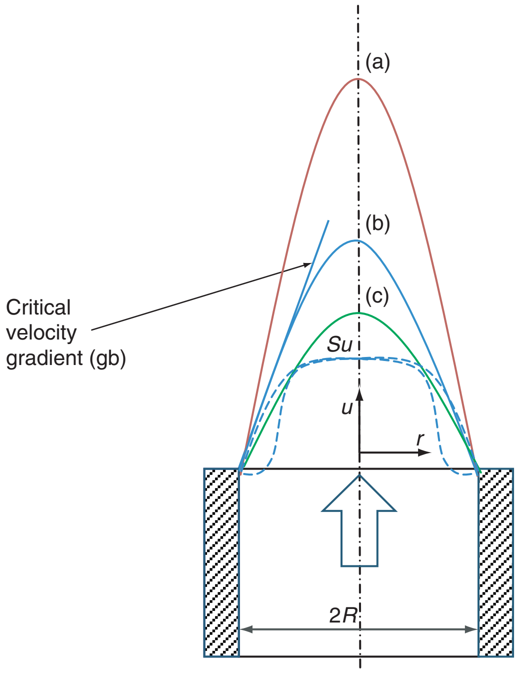

Figure 1. Illustration of flame stability criteria (Blowoff limit) showing the critical velocity gradient and mixture velocity profiles; (a) Unstable, (b) Stability limit and (c) Stable.

$$g_b = \frac{8\bar{u}}{d} \tag{3}$$

Harris *et al*. [2] reported stability limits of methane-air and propane-air mixtures on the basis of critical velocity gradient. The critical velocity gradient parameter is independent of the diameter of the burner. The burner stability limits are also found to depend on parameters like wall thickness and burner material as reported by Bollinger and Edse [3]. They used hydrogen and oxygen gases to generate the flame and measured the burner tip temperature with a thermocouple. The burner tip temperature is higher for burner material made of lower thermal conductivity (stainless steel) than that of higher thermal conductivity (copper). Accordingly, the critical velocity gradient is higher for burner made from Stainless steel as compared to copper burner. The higher burner tip temperatures would ensure a better chemical reaction progress at the wall and therefore the magnitude of burning velocity is higher. This is benevolent to flame stability. They further reported that the flame stability is better for uncooled burner as compared to a cooled burner. Dugger [4] reported the effect of initial mixture temperature on the burner stability limits for propane –air mixture. They found that increasing the initial mixture temperature results in better blowoff stability, however, this also narrows the stability region between flashback and blowoff limits. This implies that the stable operating region for the burner is reduced. Bonilla and Maccullum [5] reported the stability data on rectangular burners for methane-air and butane-air mixtures. They found that the flashback data correlate well by the critical velocity gradient normal to wall on longer side of the port. This data is also found to correlate well by average critical velocity gradient on both the sides of the rectangular port. They found that the blowoff data correlates well by the average critical velocity gradient around the port for laminar and turbulent flows. Mishra [6] reported stability of mixtures of compressed natural gas (CNG) and air on two rectangular port burners based on the critical velocity gradient parameter. CNG-air mixture is widely used in new automobiles.

As per the flame stretch concept (Karlowitz criterion), the excessive stretching of the flame at the base is considered to be the criterion for blowoff. This is explained by the parameter (β) of Karlowitz criterion expressed as $\beta = \left(1 + \frac{\eta_0}{U}\frac{dU}{dy}\right)$. At blowoff condition, near the wall, the velocity gradient is very high and the mixture velocity is low implying a high value of β.

This would result in a low value of burning velocity (Su) compared to the non blowoff condition. This increased stretch at blowoff condition would therefore result in flame extinction due to significant reduction of the burning velocity. The Karlowitz number is related to the critical velocity gradient and is expressed in Eq. (4). η_0 is the penetration distance (preheat zone thickness) defined by $\eta_0 = \alpha\ /Su$.

$$Ka = \frac{\eta_0}{U}\frac{du}{dy} = \frac{\alpha\, g_b}{Su^2} \tag{4}$$

Reed [7] proposed a single expression based on flame stretch concept given by Eq. (5) for blowoff limits that correlated well for methane, propane, hydrogen, butane and natural gas fuels with air and oxygen as oxidisers.

$$g_b = 0.23\rho Cp \times \frac{Su^2}{k} \times (1-(1-Z^{6.4})\alpha) \tag{5}$$

In Eq. (4), a = 0 for lean fuel mixtures and a = 1 for rich fuel mixtures. The Karlowitz number calculated by Reed [7] from the experimental data is found to be a constant of 0.23 for lean fuel mixtures. However, for fuel rich mixtures, the experimental data showed remarkable deviation in the Karlowitz number and this data is correlated by the introduction of fraction of volume of fuel in mixture (Z) to the stoichiometric value. Reed [7] explained this deviation as an outcome of flame interaction with secondary reaction zone in a fuel rich mixture. The presence of secondary reaction zone increased the heat conducted to the base and therefore a higher stretch can be accommodated.

Edmondson and Heap [8] reported blowoff data based on flame stretch concept for inverted flames of methane, ethane, propane, butane and ethylene fuels with air as oxidiser. They found that the critical Karlowitz number is a constant (0.95 ± 0.15) for inverted flames stabilised on a thin plate (0.03 cm). However, they reported that the critical Karlowitz number is not a constant for cylindrical tube burners even for lean fuel mixtures. They attributed this inconsistency to the inaccuracies in the burning velocity measurement due to flame interaction with the surrounding air dilution and secondary reaction zone.

Putnam and Jensen [9] suggested that Peclet number is a more generalised representation of flashback data which takes care of variations in mixture composition and burner pressure. They arrived at simple expressions based on Peclet number of isothermal jet and Peclet number of flame jet to predict the flashback criterion. One such expression is given by Eq. (6).

$$Pe_J = \frac{1}{8K'} Pe_F^2 \tag{6}$$

Putnam and Jensen [9] used the experimental data of acetylene-air, ethylene-air and natural gas mixtures reported by other researchers and found that the data is very well correlated based on Peclet number representation. Melvin and Moss [10] reported contradictions in the critical velocity gradient theory and proposed that Damkholer number is the parameter that influences the stability limits rather than the critical velocity gradient.

Kawamura *et al.* [11] proposed the Area increase concept as the influencing parameter for blowoff stability of inverted methane-air and ethylene-air flames stabilised on thin plates in a rectangular flow passage. The Area increase parameter is given by $A = \eta_0/R$. η_0 is the preheat zone thickness which is computed as $\eta_0 = \alpha/Su$ and R is radius of curvature of flame base near the stabilisation plate. The radius of curvature of the flame base decrease with increase in the velocity gradient (flow velocity) along with the increase in the distance of the flame base from the stabilisation plate. These two effects reduce the burning velocity at the stabilisation point and therefore the flame blows off. Kawamura compared the Karlowitz number and Area increase parameter for different plate thicknesses at varying mixture composition at blowoff. They found that the area increase parameter is a constant while the Karlowitz number is found to vary significantly. In a subsequent work reported by Kawamura *et al.* [12] they experimentally measured the local flame stretch of the inverted flame and found that there is no stretching of the flame near the stabilisation point at blowoff. This further confirmed that the Karlowitz criterion is not the proper parameter to represent the blowoff phenomenon for inverted flames.

Methane is a major constituent of natural gas which is widely used in industrial and domestic heating applications. Therefore, the study on the parameters that influence the stability of methane air flames is essential. Although, the effect of burner material, wall thickness and shape of burner exit is reported for other fuels [3], a comprehensive study of effect of these parameters for methane gas is not available in the literature. Also, there is a need for correlation to identify the stability limits for different tube materials, thickness and shape. Furthermore, experimental data on turbulent flow is limited [4] and hence requires attention. The aim of the present work is to study the influence of tube material (stainless steel, brass and pyrex), wall thickness (1, 2 and 3 mm) for pyrex tubes and burner exit shape (circle, triangle, square and hexagon) on blowoff limits for methane air mixtures.

2. EXPERIMENTAL SETUP AND PROCEDURE

Figure 2a is the schematic of the flow controls and instrumentation for studying the flame stability of methane-air premixed flames. Venturimeters and orificemeters are used to meter flow of methane gas (99.5% purity) and air from compressed air storage tank. The venturimeters are calibrated by water initially and then compared *in situ* at the tip of the burner with DryCal (DCLITE H) calibrator, BIOS International make. The orifice meters is directly calibrated with DryCal. A maximum of 2% deviation is found over the entire range of flow rate requirement. The operating pressure for the flow-meters is maintained at 2 bar (gage) so as to minimise effect of back pressure. The flow meters are changed accordingly for low and high flow rate requirement. Methane and air are then mixed in a mixing tube as shown in Fig 2b. The Stainless Steel balls ensure that the two fluids find enough time for mixing and reduced flow fluctuations. The ratio of burner tube length to diameter is maintained atleast 50 so as to ensure fully developed flow condition. The flame is manually blownoff after every reading and the burner is cooled by allowing air to pass through it, for at least 2 to 3 minutes.

2.1. Data reduction

The chemical balance equation for combustion of methane and air is as per Eq. (7).

$$CH_4 + a\left(O_2 + 3.76\ N_2\right) \rightarrow xCO_2 + yH_2O + zCO + wO_2 + 3.76aN_2 \tag{7}$$

For ϕ = 1, a = 2 and when ϕ is not equal to 1, $a = 2 / \phi$. Here, ϕ is the equivalence ratio defined as $\phi = (A/F)_{stoich}/(A/F)_{actual}$ .The mixture density is calculated from Eq. (8), the mixture viscosity is calculated from Eq. (9) and the mixture Reynolds number (*Re*) is calculated from Eq. (10).

$$\rho_m = \sum Y_i \rho_i \tag{8}$$

$$\mu_m = \frac{\sum \mu_i X_i \sqrt{M_i}}{\sum X_i \sqrt{M_i}} \tag{9}$$

$$\mathrm{Re} = \frac{\rho_m u_m d}{\mu_m} \tag{10}$$

The uncertainties in the measured parameters are estimated by the method of Moffat [13]. Table 1 shows the maximum uncertainties in various parameters reported in the present study.

2.2. Validation of the experimental setup

The experimental procedure is validated by measurement of the critical velocity gradient and the burning velocity.

2.2.1. Critical Velocity Gradient

Harris *et al*. (1948) reported blow off and flashback limits of methane-air mixtures for burners made of pyrex tube for varying oxygen proportions. In the present work, study on blowoff limits of methane-air

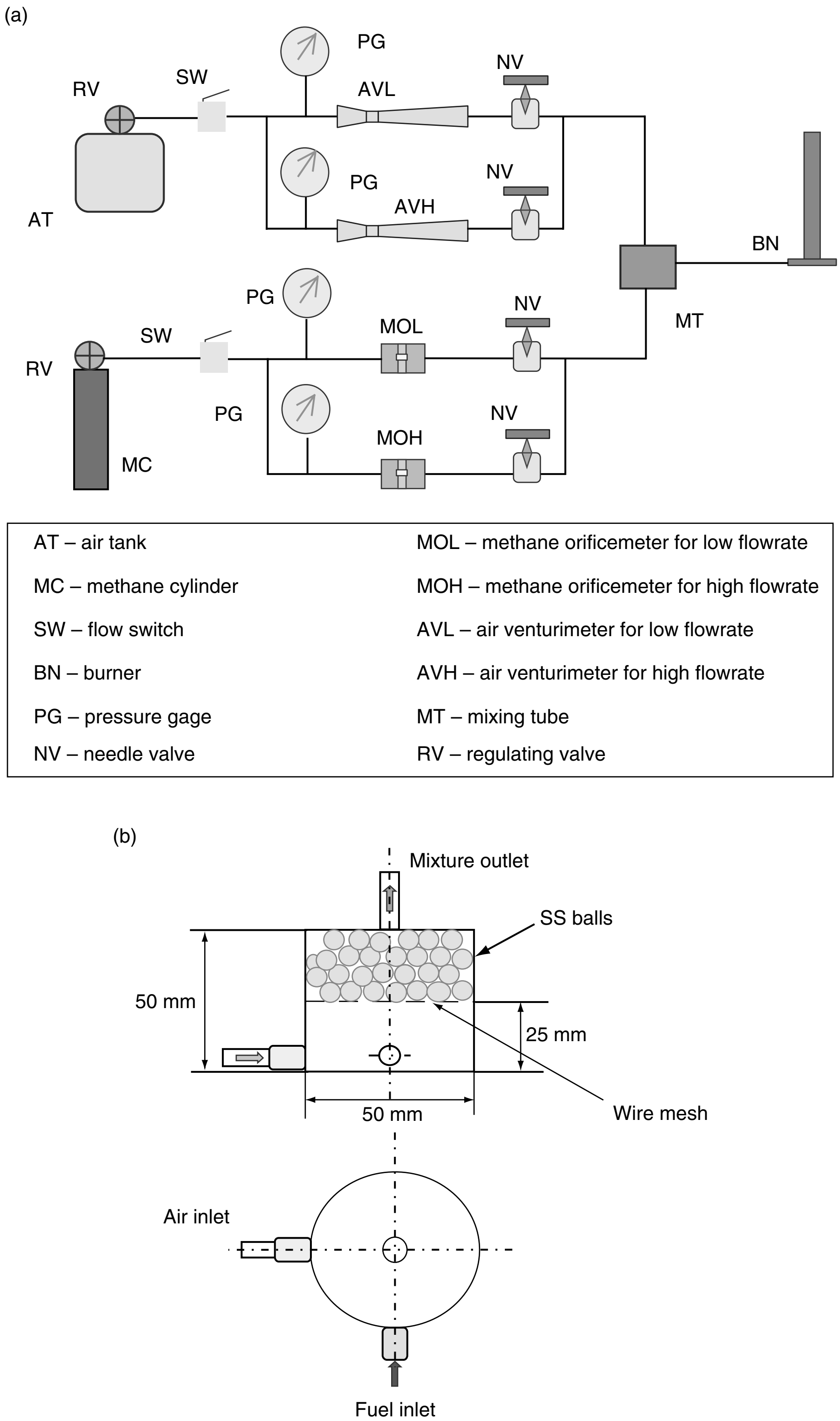

Figure 2. Schematic diagram of the experimental setup; (a) Flow controls (b) Mixing tube.

flame on circular pyrex tube burners of 1mm wall thickness is carried out. The present results are validated with that of Harris *et al*. [12] as shown in Fig. 3. Present results are in reasonably good agreement with that of Harris *et al* [12].

Table 1. Maximum uncertainties in various parameters reported in the present study.

Sl No.	Parameter	Minimum uncertainty (%)	Maximum uncertainty (%)
1	Equivalence ratio	10.76	13.1
2	Reynolds number	9.88	11.21
3	Critical velocity gradient parameter	8.92	10.37
4	Burning velocity	9.09	10.37
5	Karlowitz number	15.65	17.96

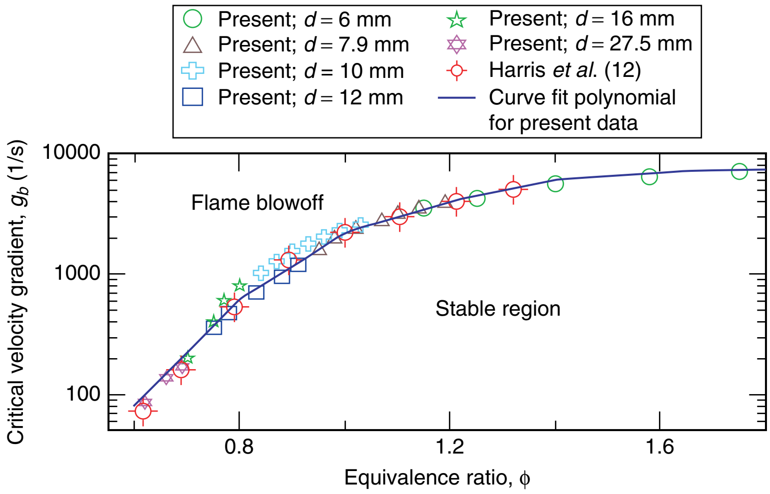

Figure 3. Variation of critical velocity gradient parameter with equivalence ratio.

2.2.2. Burning Velocity

Laminar burning velocity is measured in the present study by area method (Fig. 4). The inner cone is approximated as a right circular cone with base radius (r) and slant height (l). On applying a mass flux balance would result in an expression for burning velocity, $Su = \frac{r}{l} u_m$.

Andrews and Bradley [14] measured burning velocity of methane air premixed flames with spherical bomb calorimeter. In the present work, area method is used to measure the burning velocity of

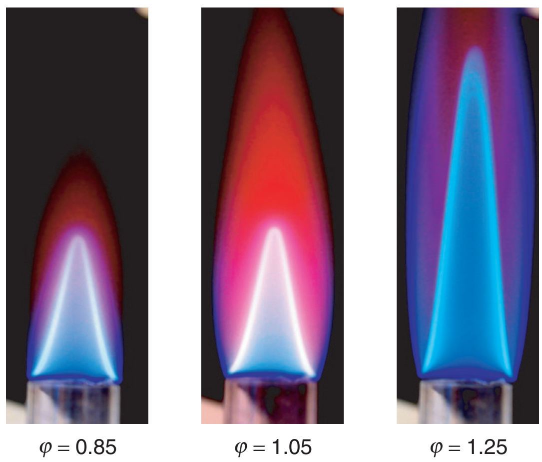

Figure 4. Photographic pictures of premixed methane-air flames at different equivalence ratios stabilised on pyrex tube burner of d = 12 mm and t = 1 mm.

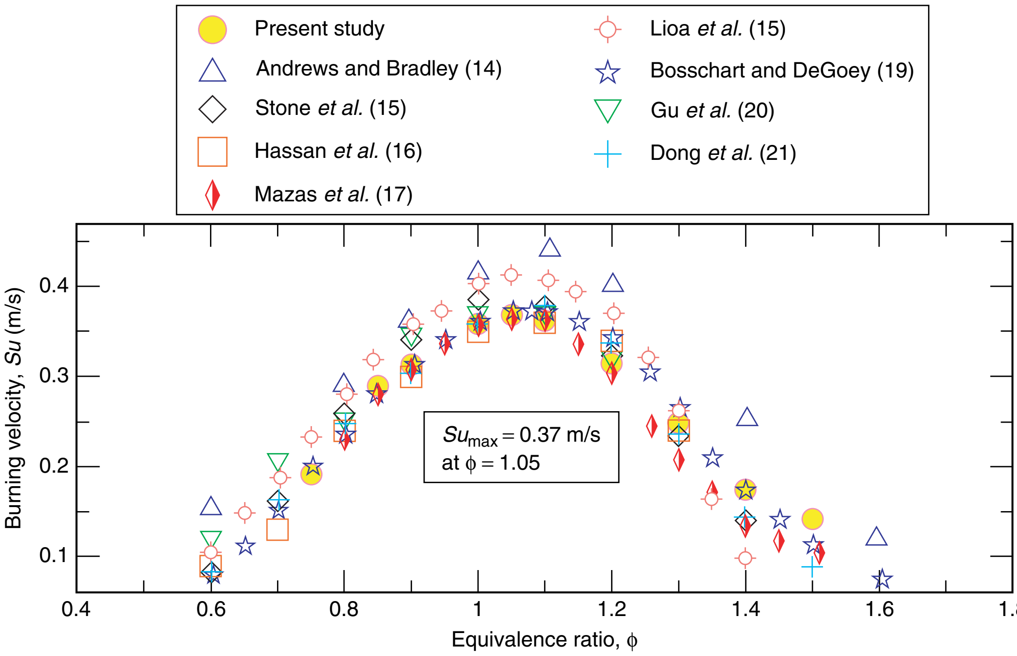

Figure 5. Variation of the measured burning velocity with equivalence ratio.

methane-air mixtures. The measured burning velocities are compared with that of Andrews and Bradley [14] and more recent data of Stone *et al.* [15], Hassan *et al.* [16], Mazas *et al.* [17], Liao *et al.* [18], Bosschaart and De Goey [19], Gu *et al.* [20], Dong *et al.* [21] and Galmiche *et al.* [22]. The comparison is reasonably good as shown in Fig. 5. In the present study, the maximum burning velocity is found to be 0.37 m/s at an equivalence ratio of 1.05. Following correlations for burning velocity are suggested from the present study

$$Su = 0.5798 \text{ In } \phi + 0.369, \text{ for } \phi < 1. \tag{11}$$

$$Su = -0.684 \text{ In } \phi + 0.4201 \text{ , for } \phi > 1. \tag{12}$$

The above correlations predict the experimental burning velocity within 5.6 % for $\phi < 1$ and 8.6 % for $\phi > 1$.

3. RESULTS AND DISCUSSIONS

3.1. Blowoff limits for laminar flow

The blowoff limits of methane-air mixture for different burner material, wall thicknesses and burner exit shapes is studied for $800 < Re < 2000$.

3.1.1. Effect of Burner Material

The thermophysical properties of burner material are found to influence the flame stability limits as shown in Fig. 6. Pyrex tube is found to have better stability than the stainless steel and brass tubes. This behaviour can be explained by the fact that burner with higher thermal conductivity would diffuse heat faster to its base thus keeping the tip relatively cooler than that of burner made of lower conductivity material. The entraining air from the surrounding therefore gets heated by lesser amount for higher conductivity tube material and would hamper the blowoff limit because of improved convective quenching.

3.1.2. Effect of Burner Wall Thickness

The wall thickness is found to influence the flame stability limits as shown in Fig.7. It is imperative from the figure that for the same inside diameter and same material of tube, thick walled burner has better blowoff stability. Intuitively, with larger wall thickness, the heating length for the diffusing surrounding air is more and therefore the air entraining the flame from the base near the wall is hotter. This would result in higher burning velocity near the wall and improved blowoff stability limit.

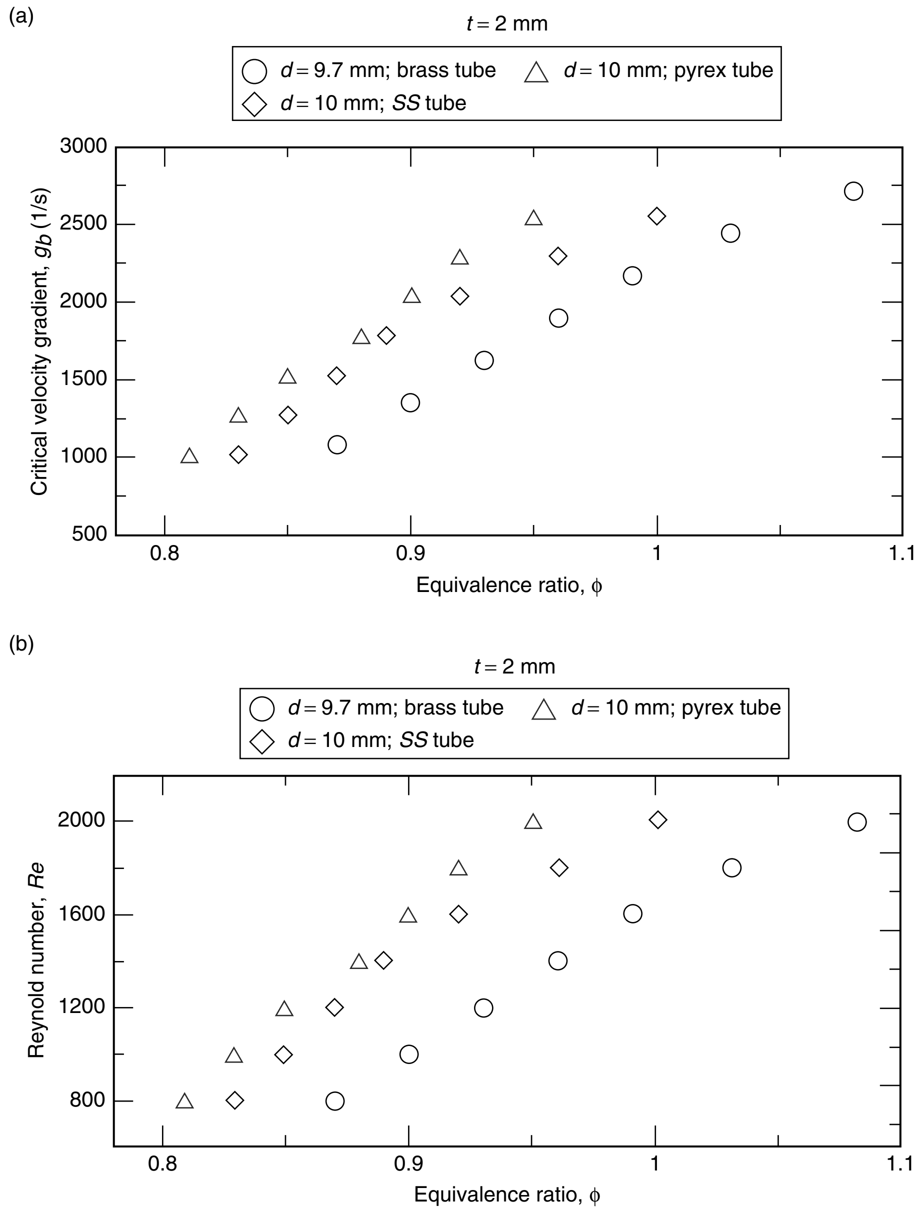

Figure 6. Effect of tube material; (a) Variation of g_b with φ, (b) Variation of *Re* with φ.

3.1.3. Effect of Burner Exit Shape

For non-circular shapes, the critical velocity gradient can be obtained by selecting proper expressions for friction factor [23] and substituting in Eq. (15). The laminar friction factors for square, triangle and hexagonal shape is listed in Table 2.

Figure 8 shows the effect of burner exit shape on the blowoff stability. The critical velocity gradient parameter is found to be independent of the exit shape of the burner. However, from Fig. 8b, it is clear that square shaped exit is preferable over hexagonal and circular for a common hydraulic diameter of 7.8 mm, while triangle shape is preferred over circular shape for the hydraulic diameter of 4 mm. It can be inferred that minimal sided polygon of same hydraulic diameter would provide better lean blowoff stability for a given *Re*.

3.2. Blowoff limits for turbulent flow

Blowoff limits for 2000 < *Re* < 4000 is studied for different burner material, wall thickness and burner exit shapes. For turbulent flow, the velocity profile near the wall is given by Eq. (11). The expression for g_b is derived in adequate steps through Eq.s (11) to (18). On substituting $f = 64/Re$, Eq. (18) reduces to Eq. (3).

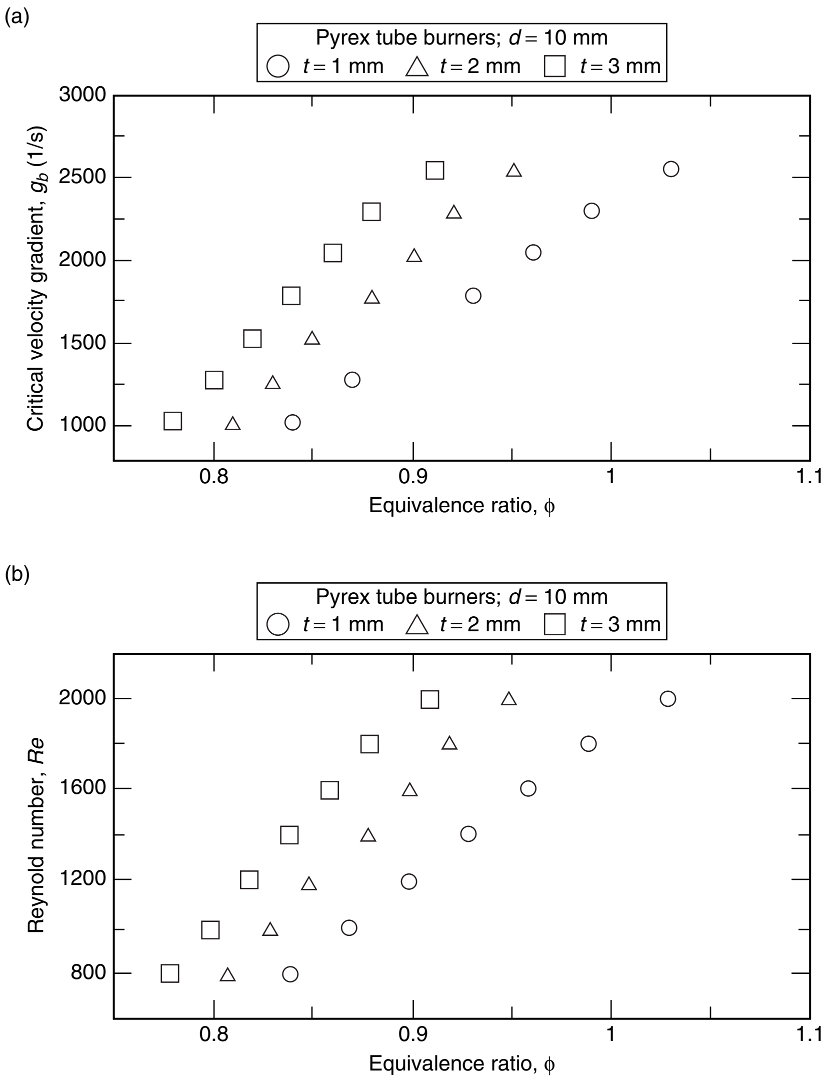

Figure 7. Effect of burner wall thickness (a) Variation of g_b with φ, (b) Variation of Re with φ.

Table 2. Laminar friction factors for noncircular ducts.

Shape	Expression for laminar friction factor
Circular	$f_c = \dfrac{64}{Re}$
Equilateral triangle	$f_{tria} = \dfrac{53.2}{Re}$
Square	$f_{sq} = \dfrac{56.8}{Re}$
Hexagon	$f_{hex} = \dfrac{60.22}{Re}$

$$u^+ = y^+ \tag{11}$$

$$\Rightarrow \frac{u}{u_{shear}} = \frac{y u_{shear}}{\upsilon} \tag{12}$$

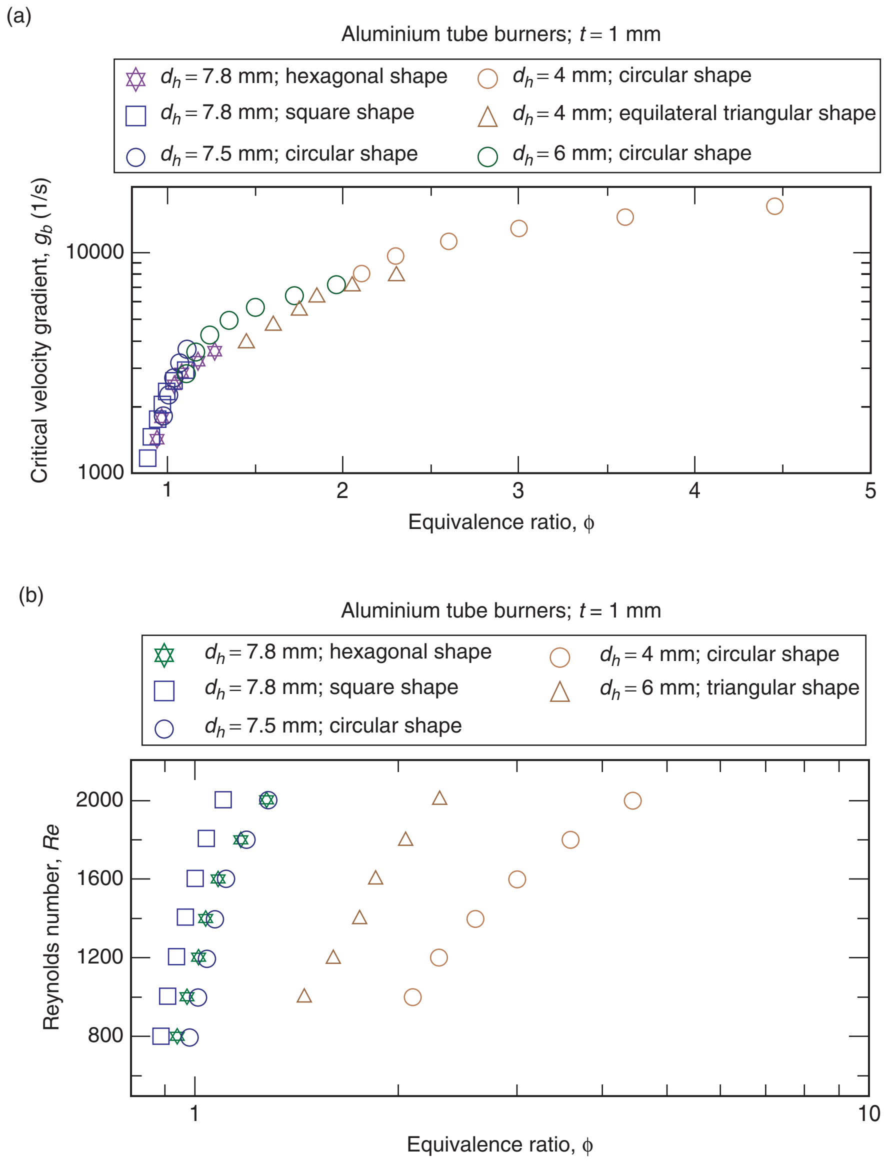

Figure 8. Effect of burner shape (a) Variation of g_b with φ, (b) Variation of Re with φ.

$$\therefore \frac{du}{dy} = \frac{u_{shear}^2}{\upsilon} = \frac{\tau_w}{\rho\upsilon} = \frac{\tau_w}{\mu} \tag{13}$$

$$C_f = \frac{\tau_w}{\rho \bar{u}^2 / 2} \tag{14}$$

$$\therefore f = 4C_f = 8\frac{\tau_w}{\rho \bar{u}^2} \tag{15}$$

$$\Rightarrow \tau_w = \frac{f \rho \bar{u}^2}{8} \tag{16}$$

$$g_b = \lim_{r \to R}\left(\frac{-du}{dy}\right) = \lim_{r \to R}\left(\frac{\tau_w}{\mu}\right) = \lim_{r \to R}\left(\frac{f \rho \bar{u}^2}{8\mu}\right) \tag{17}$$

Table 3. Turbulent friction factors for noncircular ducts.

Shape	Expression for turbulent friction factor
Circular	$f_c = 4.7602\times10^{-15} Re^4 - 6.2662\times10^{-11} Re^3 + 3.0305\times10^{-7} Re^2$ $-6.3122\times10^{-4} Re + 0.50857$
Equilateral triangle	$f_{triangle} = 0.9504 f_c$
Square	$f_{square} = 0.997 f_c$
Hexagon	$f_{hexagon} = 0.904 f_c$

$$\Rightarrow g_b = \frac{f}{8}\frac{\rho\bar{u}d}{\mu}\frac{\bar{u}}{d} = \frac{f\,\mathrm{Re}}{8}\frac{\bar{u}}{d} \tag{18}$$

The friction factor for non-circular ducts for transition to turbulent flow range (2300< Re < 4000) is computed from the multichannel method proposed by He and Gotts [24]. For circular duct, the friction factor is obtained from the data of Nikuradse as reported by Cheng [25] and is listed in Table 3.

3.2.1. Effect of Burner Material

For turbulent flow the effect of burner material is similar to that of laminar flow as shown in Fig. 9. However, the spread in stability limit widens at higher turbulent flow conditions.

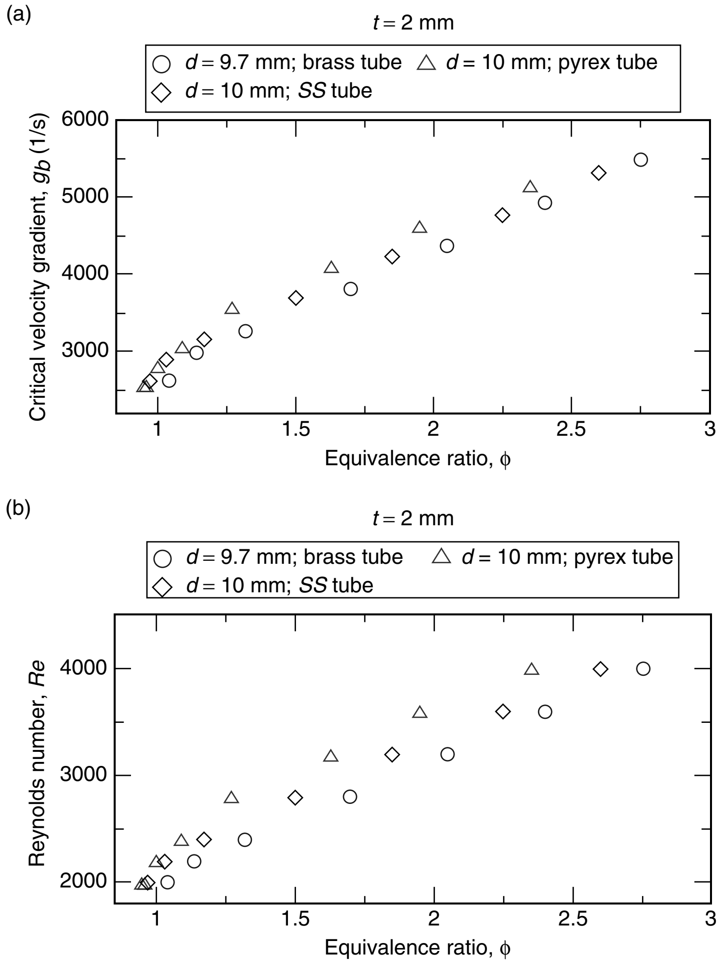

Figure 9. Effect of burner material (a) Variation of g_b with ϕ, (b) Variation of Re With ϕ.

3.2.2. Effect of Wall Thickness

For turbulent flow the effect of wall thickness is also similar to that of laminar flow as shown in Fig. 10. Larger wall thickness provides better lean blowoff stability.

3.2.3. Effect of Burner Exit Shape

From Fig. 11a it is clear that the dependency of critical velocity gradient parameter on the shape of the burner exit is absent. However, the scatter is more pronounced in turbulent region as compared to laminar flow region of Fig. 8a.

4. CORRELATIONS FOR BLOWOFF STABILITY

The stability parameter in terms of Karlowitz number (*Ka*) is used to correlate the present experimental data.

4.1. Laminar flow (800 < *Re* < 2000)

For pyrex tubes (present experimental data from Fig. 3), the dependency of Karlowitz number on equivalence ratio has a distinct pattern for equivalence ratio greater and less than 1 as expressed in Eqns. (19 and 20).

$$Ka = 0.4698\phi - 0.1445\ ,\ 0.75 < \phi < 0.99 \tag{19}$$

$$Ka = 0.3\phi^6,\ 1.02 < \phi < 1.32 \tag{20}$$

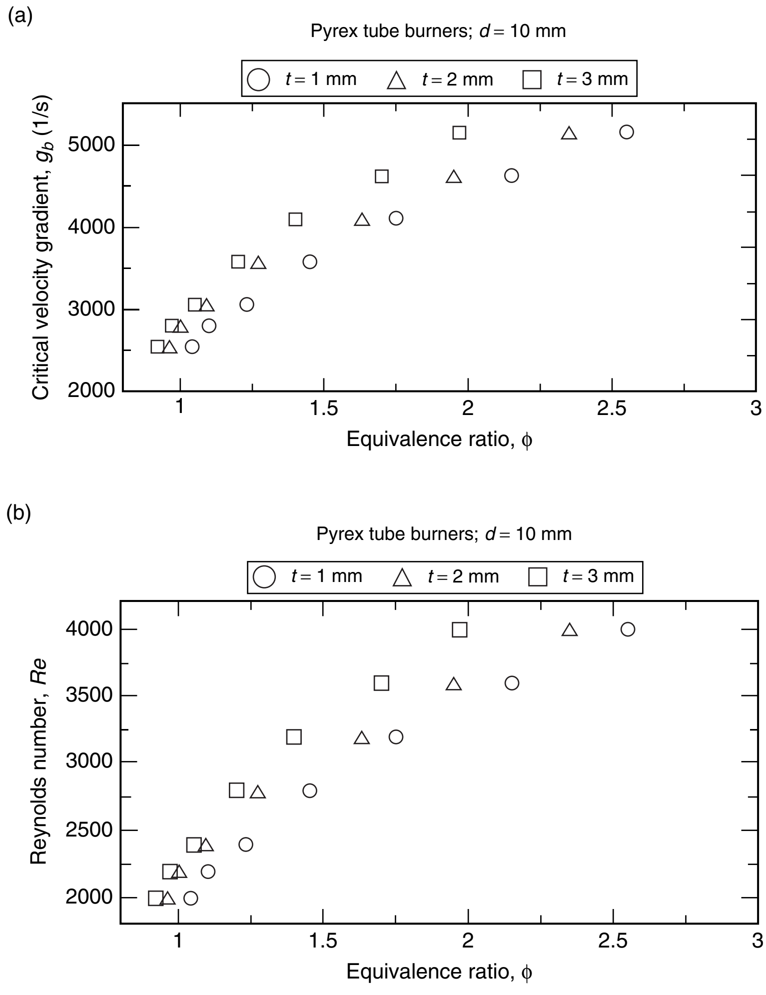

Figure 10. Effect of wall thickness (a) Variation of g_b with ϕ, (b) Variation of *Re* With ϕ.

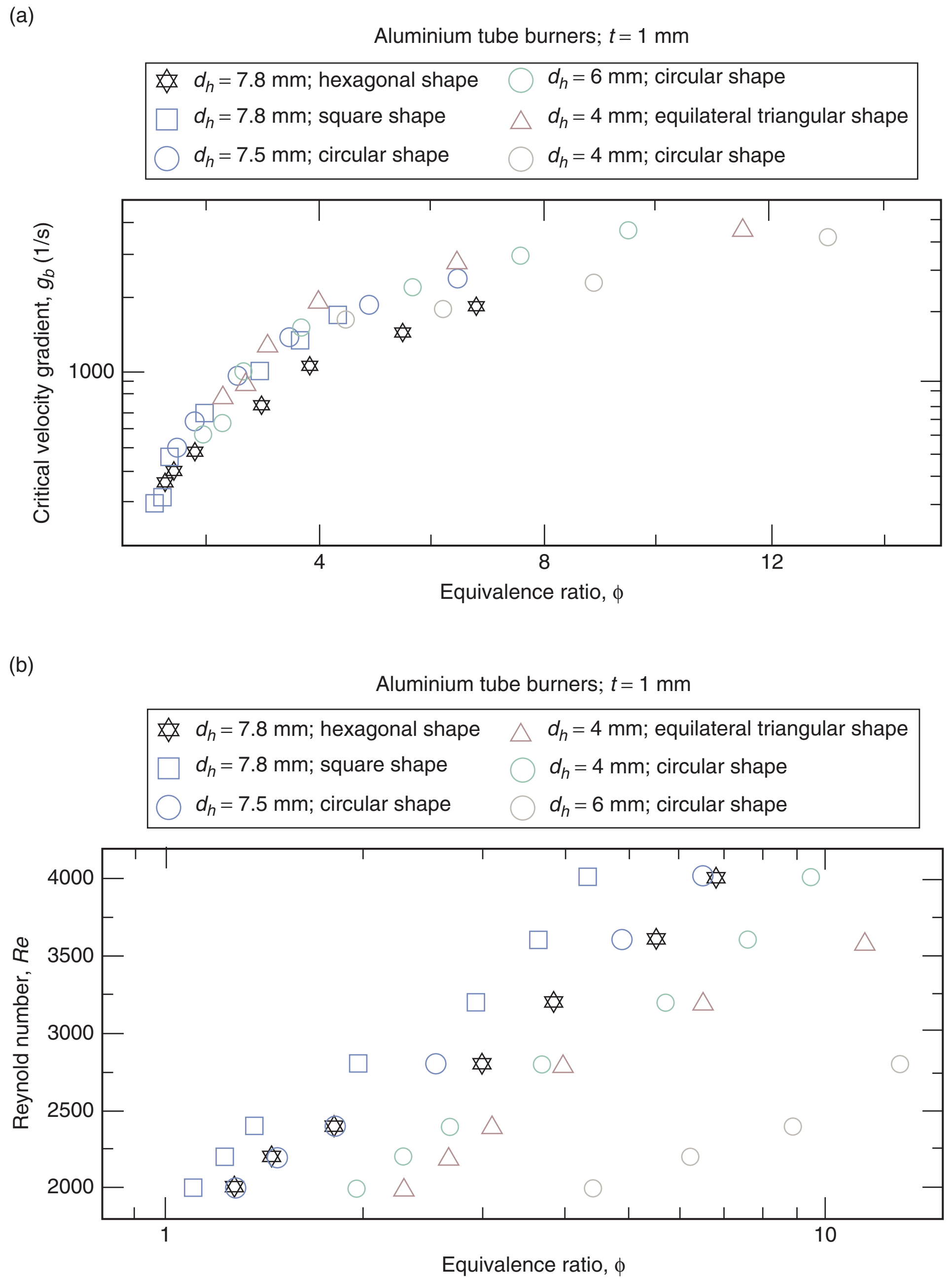

Figure 11. Effect of burner shape (a) Variation of g_b with ϕ, (b) Variation of Re With ϕ.

The maximum deviation in Eqns. (19 and 20) with present experimental data is 17% and 16% respectively. For laminar flow and lean mixtures ($\phi < 1$), the Karlowitz number increases marginally with the increase in equivalence ratio. However, for $\phi > 1$, there is a steep increase in *Ka* with the increase in equivalence ratio. Reed [7] reported similar behaviour and attributed the secondary reaction zones as responsible for remarkable increase in Karlowitz number for $\phi > 1$. Another explanation that may be given is the magnitude of burning velocity that starts to decrease after $\phi = 1.05$. Since, Karlowitz number is inversely proportional to square of burning velocity, the Karlowitz number increases significantly. For lean fuel mixtures, the burning velocity increase with the equivalence ratio counters the effect of secondary reaction zones. Therefore, the Karlowitz number increases marginally. Reed's correlation [7] predicts the present experimental data with a deviation of 35% for $\phi < 1$ and 28% for $\phi > 1$. This may be attributed to the variations in tube material properties, thicknesses and cooled/uncooled burner conditions.

The effect of variations in material property (thermal diffusivity of tube (α)) and tube thickness (t) on stability for the present experimental data (Figs. 5 & 6) are correlated by Eqs. (21) and (22).

$$Ka = 0.13\phi^{1.77}\alpha^{-0.094} \quad (21)$$
$$0.87 < \phi < 1.08$$
$$7.54 \times 10^{-7}\ \mathrm{m^2/s} < \alpha < 9.71 \times 10^{-5}\ \mathrm{m^2/s}$$

$$Ka = \phi^{1.35}\left(\frac{t}{d}\right)^{0.46} \quad (22)$$
$$0.81 < \phi < 1.03$$
$$0.1 < t/d < 0.3$$

Equations 21 and 22 predict the experimental data within 10%. It is observed that the shape of the burner exit does not influence the stability parameter (Ka). Hence, the above correlations generated for circular tube are found to be valid for square, triangle and hexagon. A generalised correlation for $\phi < 1$ which holds good for all the tube materials, thicknesses and shapes covered in the present study is given by Eq. (23).

$$Ka = 0.4\left(\frac{t}{d}\right)^{0.46}\alpha^{-0.063}\phi^{1.6} \quad (23)$$

Equation 23 predicts the experimental data within 20%.

4.2. Turbulent flow (2000 < *Re* < 3200)

For turbulent flow, a single expression fits all the present experimental data (Figs. 8 through 10) suggesting insensitivity of Karlowitz number to change in material, tube thickness and shape of the tube. However, the variation of Karlowitz number with ϕ is different for $\phi < 1$ and $\phi > 1$ as expressed in Eqs. (24) and (25).

$$Ka = -0.56\phi + 0.975$$
$$0.9 < \phi < 1$$
$$7.54 \times 10^{-7}\ \mathrm{m^2/s} < \alpha < 9.71 \times 10^{-5}\ \mathrm{m^2/s} \quad (24)$$
$$0.1 < t/d < 0.3$$

$$Ka = \frac{e^{3.36\phi}}{83}$$
$$1 < \phi < 1.32$$
$$7.54 \times 10^{-7}\ \mathrm{m^2/s} < \alpha < 9.71 \times 10^{-5}\ \mathrm{m^2/s} \quad (25)$$
$$0.1 < t/d < 0.3$$

These correlations predict the experimental results within 6% for $\phi < 1$ and 16% for $\phi > 1$. An interesting observation is that the Ka decreases with increase in equivalence ratio for lean fuel mixtures contrary to laminar flow region.

5. CONCLUSIONS

A study on the blowoff limits of premixed methane-air flames is done for 800 < Re < 4000. The effect of burner tube material (SS, brass and pyrex), wall thickness (1, 2, 3 mm) and burner exit shape (circle. triangle, square and hexagon) on the blowoff limits is carried out. Following conclusions may be drawn from the present study.

i) Burner of lower thermal conductivity (thermal diffusivity) is found to have a better lean blowoff limits for laminar flow. Tubes with high thermal conductivity diffuse more heat to the base of the tube. Hence, the tip temperatures are lower resulting in lower burning velocity which results in leaner blowoff stability.

ii) Larger wall thickness is found to improve lean blowoff limits for laminar flow. Larger wall thickness tubes provide longer heating lengths for the entraining air at the cone base. Hence, higher mixture temperature at the tip of the tube is experienced which ensures leaner blowoff stability.
iii) Critical velocity gradient parameter expressed in terms of hydraulic diameter for tubes of different exit shapes collapses to that of circular tube. This behavior is more consistent for laminar flow than in the turbulent flow region.
iv) The Karlowitz number is found to be independent of tube material type, thickness and exit shape for turbulent flow.
v) The Karlowitz number increases linearly with increase in equivalence ratio for $\phi < 1$ for laminar flow. However, for turbulent flow, Karlowitz number decreases linearly with increase in equivalence ratio for $\phi < 1$.
vi) For laminar and turbulent flows, the Karlowitz number increases exponentially for $\phi > 1$.
vii) Correlations are suggested for burning velocity and Karlowitz number (stability parameter) for tubes of different materials, thicknesses, shapes, equivalence ratio and laminar/turbulent flows.

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REFERENCES

[1] Lewis, B. and Elbe V. G., "Stability and structure of burner flames", Journal of Chemical Physics, 11 (1943), 75–97.

[2] Harris E. M., Grumer J., Elbe V. G. & Lewis B., "Burning velocities, Quenching and stability data on non turbulent flames of methane and propane with oxygen and nitrogen", Third symposium on combustion, Flame and explosion phenomena (1948), 80–89.

[3] Bollinger E. L. and Edse R., "Effect of burner-tip temperature on flashback of turbulent hydrogen- oxygen flames", Industrial and Engineering Chemistry, 48 (4) (1956), 802–807.

[4] Dugger G. L., "Flame stability of preheated propane- air mixtures", Industrial and Engineering chemistry, 47 (1) (1955).

[5] Bonilla A. R. and McCullum R. L.N., "Flame stabilization on rectangular burners", Combustion and Flame, 12 (1968), 492–498.

[6] Mishra D. P., "Experimental studies of flame stability limits of CNG–air premixed flame", Energy Conversion and Management 48 (2007), 1208–1211.

[7] Reed B. S., "Flame stretch – A connecting principle for blow-off data", Combustion and Flames, 11 (1967), 177–189.

[8] Edmondson H. and Heap P. M., "The correlation of burning velocity and blowoff data by the flame stretch concept", Combustion and Flame, 15 (1950), 179–187.

[9] Putnam A. A. and Jensen A. R., "Application of dimensionless numbers to flashback and other phenomena", Third symposium on combustion, Flame and explosion phenomena, (1948), 89–98.

[10] Melvin A. and Moss J.B., "Evidence for the failure of flame stretch concept for premixed flames", Combustion Science and Technology, 7 (1973), 189–196.

[11] Kawamura T., Asato, K. Mazaki T., Hamaguchi T. and Kayahara H., "Explanation of the blowoff of inverted flames by Area-increase concept", Combustion and Flame, 35 (1979), 109–116.

[12] Kawamura T., Asato, K. and Tomotsu mazaki, "Re-examination of the blow limits of premixed flames – Inverted flames", Combustion and Flame, 45 (1982), 225–233.

[13] Moffat, R.J. "Using uncertainty analysis in the planning of an experiment" Journal of Fluids Engineering, Transactions of the ASME, (1986).

[14] Andrews E. G. and Bradley D., "The burning velocity of methane-air mixtures", Combustion and Flame, 19 (1972), 275–288.

[15] Stone R. Clarke A. and Beckwith P., "Correlations for the Laminar-Burning Velocity of Methane/Diluent/Air Mixtures Obtained in Free-Fall Experiments", Combustion and Flame, 114 (1998), 546–555.

[16] Hassan I. M., Aung T. K. and Faeth M. G., “Measured and Predicted Properties of Laminar Premixed Methane/Air Flames at Various Pressures”, Combustion and Flame, 115 (1998), 539–550.

[17] Mazas N. A., Fiorina B., Lacoste, A. D. and Schuller T., “Effects of water vapor addition on the laminar burning velocity of oxygen-enriched methane flames”, Combustion and Flame, 158 (2011), 2428–2440.

[18] Liao Y. S., Jiang M. D. and Cheng, Q., “Determination of laminar burning velocities for natural gas”, Fuel, 83 (2004), 1247–1250.

[19] Bosschaart J. K. and L. P. H. de Goey, “The laminar burning velocity of flames propagating in mixtures of hydrocarbons and air measured with the heat flux method”, Combustion and Flame, 136 (2004), 261-269.

[20] Gu J. X., Haq Z. M., Lawes M. and Woolley R., “Laminar Burning Velocity and Markstein Lengths of Methane–Air Mixtures”, Combustion and Flame, 121 (2000), 41–58.

[21] Dong, Y., Vagelopoulos M. C., Spedding R. G. and Egolfopoulos, N. F., “Measurement of laminar flame speeds through digital particle image velocimetry: mixtures of methane and ethane with hydrogen, oxygen, nitrogen, and helium”, Proceedings of the Combustion Institute, 29 (2002), 419–426.

[22] Galmiche, B., Halter F., Foucher F. and Dagaut P., “Effects of Dilution on Laminar Burning Velocity of Premixed Methane/Air Flames”, Energy and Fuels, 25 (2011), 948–954.

[23] Rohsenow M. W., Hartnett P. James, Cho I. Young, “Handbook of heat transfer”, McGraw Hill, 3rd edition (1998).

[24] He S. and Gotts, A. J., “Calculation of Friction Coefficients for Noncircular Channels”, Journal of Fluids Engineering, ASME, 126 (2004), 1033–1038.

[25] Cheng N. S., “Formulas for friction factor in transitional regimes”, Journal of Hydraulic Engineering, ASCE, 134(9) (2008), 1357–1362.