# COMPUTATIONAL ANALYSIS ON THE STABILITY AND CHARACTERISTICS OF PARTIALLY PREMIXED BUTANE-AIR OPEN FLAMES IN TUBULAR BURNER

by

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*Partially premixed combustion is one of the developing areas of combustion research that has the advantages of both premixed and diffusion mode of combustion. The present work involves a computational study on the stability and characteristics of partially premixed butane-air flames. The effect of operating parameters like fuel-air ratio, primary aeration, and the presence of co-flow and co-swirl on the stability and flame characteristics has been studied. The simulation results show that the height of the flame decreases with an increase in primary aeration and also in the presence of a co-swirl stream. It has also been found that the stability of flames increases with co-swirl air but deteriorates with the presence of the co-flow air. The flame temperature increases with primary aeration and it has been observed that the peak flame temperature shifts away from the burner mouth for lower primary aeration. It has been observed that the flame stability improves with co-swirl air which is attributed to the re-circulation zone created due to the swirl motion which acts as a heat source. The poor stability in the presence of co-flow air is attributed to flame stretching and aerodynamic quenching of the stretched flamelets. The lift-off velocity and the stable operating range increases with equivalence ratio and also with co-swirl air.*

Key words*: flames, lift-off, blow-out, equivalence ratio, primary aeration, re-circulation zone*

## Introduction

Many industrial combustors employ jet flames which operate in premixed or diffusion combustion mode. In some situations, the flame is partially premixed, as it is necessary to avoid sooting. Bunsen burners, staged combustors, gas turbine combustors and Diesel engines are some devices, which encounter partially premixed flames. These flames ensure non-sooting stable combustion. Non-sooting and low pollution technologies are important to address the current energy crisis and stringent emission norms [1, 2]

High flame stability is one of the important concerns in any burner design. It should operate stably over varied operating conditions, *viz*., turn down ratios with specific fuel-air ratios. Further, these flames encounter instabilities, which are characterized by lift, blow-off, and flashback limits. In stable operation, the mixture flow velocity and the local burning velocity should be correctly matched to have safe operation.

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Partially premixed flames are formed when fuel is mixed with only a sub-stoichiometric amount of oxidizer (referred to as primary air) encounters a flame front where it burns with the deficit oxidizer (secondary air). Many domestic and industrial applications employ partially premixed flames which are chosen for their stability. An elaborated understanding on the combustion and stability characteristics of partially premixed flames are necessary for practical and technological applications.

Important design criteria for gas burners are the avoidance of instabilities like flash back and lift-off. Equivalence ratio and burning velocity are parameters which significantly affect the stability of flame. The flame jet burns stably due to the balance between the local flame speed and the jet velocity at the flame-base and flame blow-out occurs when such a balance is disturbed with increasing jet velocity. Based on the equivalence ratio and port velocity, the flame may exhibit phenomenon of lift-off or flash back. The phenomenon of flame flash back occurs when the gas-flow velocity (port velocity, $U_P$) is less than laminar burning velocity, $U_L$, where the flame enters upstream in the fuel tube. For $U_P > U_L$, the flame lifts off from the burner rim and may eventually blows off.

In real burners, flame instability is undesirable as it leads to incomplete combustion and explosion. It also leads to flame extinguishment beyond lifting limit as the ambient air entrains near the lifted flame base leading to localized reduction in equivalence ratio and hence flame blow-out. Lifted flames are noisy and cause poor heat transfer and combustion efficiency. It has been observed that the flame blow-out occurs due to local extinction of the flame-lets caused by sufficiently large strain rates in the flow. The partially premixed flames can be stable only in a range of primary aeration and beyond that the flame detaches itself from the port and blows off leading to poor thermal and fuel efficiency [3, 4]. To overcome the issues created due to incomplete combustion, co-flow or co-swirl air enveloping the central jet is traditionally used [5]. Swirl stabilization is frequently used in industrial burners and gas-turbine combustors for both premixed and non-premixed modes of combustion.

An extensive research on the stability of partially premixed flames has been carried out and published in [6-8]. With increase in the port velocity, the flame lifts off from the burner mouth and further increase in the port velocity causes the flame to blow out and blow off. The flame sometimes blows off without lifting off and this has been observed at some port velocity and mixture strength was explained using the flame-stretch theory according to which flame extinction occurs due to the stretching of the combustion wave when it is exposed to steep boundary velocity gradient at the burner rim. This process, also known as aerodynamic quenching causes the flame front to lose more heat to the unburned mixture, and it gets extinguished suddenly due to severity of aerodynamic quenching [9]. Also, it is observed that fuel-rich flame can withstand higher port velocity compared to lean flame prior to flame-lift. This is attributed to the effect of secondary combustion occurring at the stabilization zone: the additional energy released at the flame base due to the entrainment of oxygen from the ambience offsets the heat loss caused by aerodynamic quenching [9].

The stability of tubular burner flames in quiescent and cross-flow conditions for burners operating in vertical and horizontal configurations has been carried out. The study observes the cross-flow and buoyancy effects of hot gases enhance flame stability at fuel rich conditions [10]. An experimental study of partially premixed flames at atmospheric and sub atmospheric pressures reported shrinking of blow out limit curve at lower ambient pressure [11]. A visualization study of methane and nitrogen diluted methane flames at blow out condition indicated that the diffusion flame shortens and disappears as the flame proceeds towards blowout [12].

A stability study with air dilution reported that at a constant jet velocity, the lift-off height of the flame increases with air-dilution and is attributed to the increase in the stoichiometric mixture fraction value, which resides in the higher velocity region [13]. A numerical study on the lift-off and blow-out behaviour of non-premixed syngas flames reported that with nitrogen dilution the flame lifts off and propagated downstream along the stoichiometric mixture fraction-line with the flame structure changing from diffusion double flame [14].

A detailed study on the flame characteristics on partially-premixed $CH_4$-air jet flame performed for different fuel-flow rates and equivalence ratio showed that the average height, flame length and flame base area decreased while the lift-off distance increased with the amount of air injected [15].

The scope of this study is to investigate the stability and flame characteristics of partially premixed flames. The outcome of this study will help in understanding the primary aeration required for any practical burners for efficient, safe and clean burning.

## Computational study

Flame mathematical models are tools used in engineering and science to predict functional relationships between certain input and output variables. The CFD has become an essential tool in all branch of fluid dynamics which offers numerical solution by computation solving of governing equations that describe fluid-flow and associated energy or species transport. This tool has found its vast importance in combustion in the design and analysis of burner, furnace and gas-flow by reducing the time, effort and money involved in doing expensive and time consuming pilot scale or full scale testing processes. In using CFD, approximated results can be obtained by choosing appropriate models. In the present case, an axi-symmetric geometry has been used to simulate a partially premixed flame issuing from open circular burner port. The governing equations used to define combustion process [16] are defined in the following section.

Continuity equation:

$$\frac{\partial}{\partial x_{\mathrm{i}}}\left(\rho u_{\mathrm{i}}\right)=0 \tag{1}$$

Continuity equation for the ax-symmetric geometry is given:

$$\frac{\partial}{\partial x_i}(\rho u)+\frac{\partial}{\partial x_i}(\rho v)+\frac{\rho v}{r}=0 \tag{2}$$

where $x$ is the axial co-ordinate, $r$ – the radial co-ordinate, $u$ – the axial velocity, and $v$ – the radial velocity.

Momentum conservation equations:

Conservation of momentum in the i direction is described:

$$\frac{\partial}{\partial x_i}\left(\rho u_i u_i\right)=-\frac{\partial p}{\partial x_i}+\rho g_i+F_i+\mu\frac{\partial^2 u_i}{\partial x_j} \tag{3}$$

where $p$ is the static pressure and $\rho g_i$ and $F_i$ are the gravitational body force and external body forces (*e.g.*, forces that arise from interaction with the dispersed phase) in the $i$ direction, respectively. The $F_i$ also contains other model-dependent source terms such as porous-media and user-defined sources. For axisymmetric geometries, the axial and radial momentum conservation equations are given:

$$\frac{1}{r}\frac{\partial}{\partial x}\left(r\rho u^2\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho uv\right)=-\frac{\partial p}{\partial x}+F_x \tag{4}$$

$$\frac{1}{r}\frac{\partial}{\partial x}\left(r\rho uv\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho v^2\right)=-\frac{\partial p}{\partial r}+F_r \tag{5}$$

where

$$\nabla\bar{\mathrm{v}}=\frac{\partial u}{\partial x}+\frac{\partial v}{\partial r}+\frac{v}{r} \tag{6}$$

Energy equation:

$$\frac{\partial}{\partial x_i}\left(\rho U_i h\right)=\frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right)+U_i\frac{\partial p}{\partial x_i}+\tau_{ij}\frac{\partial U_i}{\partial x_j}+\frac{\partial}{\partial x_i}\left(\sum_j D_j h_j\frac{\partial m_j}{\partial x_i}\right) \tag{7}$$

where $k$ is the specific turbulent kinetic energy (= $k_\mathrm{l}+k_\mathrm{t}$), where $k_\mathrm{t}$ is the turbulent thermal conductivity, defined according to the turbulence model being used. Also, $D_j$ is the mass diffusivity of species $j$ through the mixture and $h_\mathrm{t}$ is the enthalpy of the mixture denoted by $h$.

## Tangential momentum equation for swirl flows

It is important to note that while the assumption of axisymmetry implies that there are no circumferential gradient in the flow, there may still be non-zero swirl velocities. The tangential momentum equation for 2-D swirling flows may be written:

$$\frac{1}{r}\frac{\partial}{\partial x}\left(r\rho U_t\right)=\frac{1}{r}\frac{\partial}{\partial x}\left[r\mu\frac{\partial U_t}{\partial x}\right]+\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^3\mu\frac{\partial}{\partial r}\left(\frac{U_t}{r}\right)\right] \tag{8}$$

where $x$ is the axial co-ordinate and $r$ – the radial co-ordinate.

The simulation in the present work is carried out using multiple species model. In this approach, transport equations for individual species are not solved. Instead, individual component concentrations for the species of interest are derived from the predicted mixture fraction distribution. The mixing and transport of chemical species in combustion can be modeled by solving conservation equations describing convection, diffusion, and reaction sources for each component species. Physical properties of chemical species and equilibrium data are obtained from the chemical database. The influence of the reaction rate is taken into account by employing the Magnussen and Hjertagar model called eddy dissipation model. In this model the reacting flow is simulated using infinitely fast chemistry assumption. The eddy dissipation model relates the rate of reaction the rate of dissipation of the reactant and product containing eddies.

The eddy dissipation model is based on the concept that chemical reaction is fast relative to the transport processes in the flow. The model assumes that the reaction rate may be related directly to the time required to mix reactants at the molecular level. In turbulent flows, this mixing time is dominated by the eddy properties, and therefore, the rate is proportional to a mixing time defined by the turbulent kinetic energy, $k$ and dissipation, $\varepsilon$:

$$\text{Reaction rate}=\alpha\frac{\varepsilon}{k} \tag{9}$$

Domain discretization is achieved by first choosing a fitting co-ordinate system and then dividing the region of interest into small sub-domains by drawing lines which coincide with constant co-ordinate lines. The GAMBIT is a preprocessor, which can be used for grid generation within the flow domain. In this work meshing has been done using map scheme with quadrilateral cells. In the present study, RNG $k$-$\varepsilon$ model has been employed for modelling the turbulent flow features [16].

The process of creating the grid system is called grid generation. Two distinct types of grid generation methods are possible, namely, structured and unstructured grid generation. In the present study structured, quadrilateral and non-uniform grid is used. For better convergence and higher resolution, quadrilateral structured mesh has been used. The grid is fine close to the flame front and coarse in the far field. Grid independence study has been carried out to study the effect of grid size on the result. Numerical analysis of this model has been carried out with different mesh sizes like 565750, 77500, and 90680 quadrilateral cells. The variation in the predicted maximum temperature is very small *i.e.*, within ±15 K with the three chosen grid size. This has been done to establish that there are no variations in the solution with the size of the mesh. Hence, assuming that the solution is independent of mesh size, further analysis was done with 77500 cells.

The model consists of two concentric tubes and an outer nozzle head. Through the central tube fuel and air mixture is passed. The co-flow air is passed through the outer tube and the nozzle head is fitted at the end to have a uniform velocity near the vicinity of the burner port. The central feed tube of this burner is 9.5 mm inner diameter and 12 mm outer diameter. To study the effect of secondary stream, a co-flow tube having two tangential entries for imparting swirl has been concentrically placed around the central feed tube. The outer pipe is fitted with a nozzle of diameter 30 mm provides an annular gap of around 10 mm between the concentric pipes. The specifications of the test burner used for the experiemental investigation has been used for the present numerical study. The reaction is assumed to be single step process. Also, for the sake of simplification of the calculations, combustion is assumed to be complete, which may not be the case in reality. For doing numerical simulations, an axi-symmetric geometry, shown in fig. 1, is created using the GAMBIT and simulation has been carried out using FLUENT.

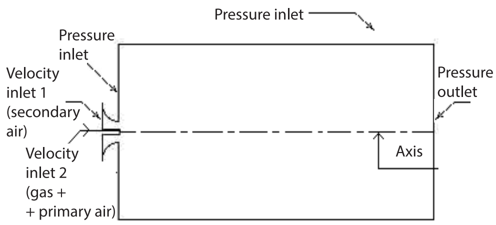


**Figure 1. Computational domain with boundary conditions**

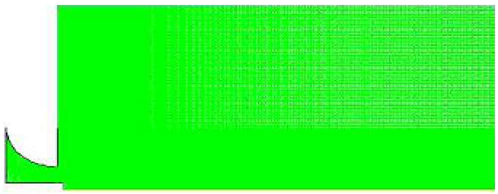

**Figure 2. Structured, quadrilateral and non-uniform grid**

The flow and transport equations have been solved in the present work using FLUENT software. Axi-symmetric burner geometry is created using the GAMBIT preprocessor module and a structured, non-uniform grid with 77500 cells is employed as shown in fig. 2. The solver employed is a segregated, implicit, steady-state and finite rate reaction method with multiple species model. The RNG $k$-$\varepsilon$ turbulence model has been adopted with eddy dissipation. The two transported variables are turbulent kinetic energy, $k$, which determines the energy in turbulence, and turbulent dissipation rate, $\varepsilon$, which determines the rate of dissipation of turbulent kinetic energy. The specific heat of the mixture is assumed to be governed by mixing law, whereas the individual specific heats are prescribed as piecewise polynomial functions of temperature for accurate prediction of heat release by combustion. As the flow is turbulent, turbulent intensity and hydraulic diameter are also specified to calculate $k$ and $\varepsilon$. Mixture fraction of the species is also given as a boundary condition at the inlets and at the downstream boundary, in case of reverse flow. First order upwind discretization scheme has been used for momentum, swirl velocity, turbulent kinetic energy, turbulent dissipation rate and energy. Constant property values (at average temperature and mixture composition) have been employed for fluid thermal conductivities, viscosities, *etc*. The analysis has been done for base and co-stream flow conditions for various equivalence ratios [17]. The fuel flow rate was maintained constant as 0.21 $m^3$ per hour and port velocity is kept fixed at the boundary for varying primary aeration. The influence of secondary flow was studied at two secondary flow velocities (1.45 m/s and 2.28 m/s) for co-flow and co-swirl cases. The velocities were chosen to observe significant effect and are arbitrarily chosen.

## Results and discussion

The numerical investigation has been carried out on partially premixed flames with the primary aeration ranging from 20-60% of stoichiometric air fuel ratio to observe the flame characteristics such as flame shape, length, mixing intensity and the flame stability. The primary aeration in any practical burner lies normally in the range 30-60%. Below 20% it behaves more like diffusion flames and beyond 60% it inherits the characteristics of a premixed flame. Therefore, primary aeration of 20-60% lies well within the range adopted in practical burners has been used. The species contours of the fuel, oxidizer and the burnt products are shown in fig. 3. The species contour shows the species concentration near the burner mouth and in the far flow field. The concentration of the fuel is the maximum when the partially aerated fuel jet emerges out of the port. The concentration gradient appears when the fuel is consumed and is zero in the downstream, away from the flame zone in the far field. The concentration of oxygen is the minimum in the intense flame zone as it gets depleted in the vicinity of the flame due to combustion. The oxygen concentration is the maximum in the far field. The contours of the products of combustion show, the concentration of $CO_2$ and water vapour appears in the flame zone and a gradient appears which shows that the concentration of the burnt products gradually reduces and disappears in the far field. The species concentration contours for the various primary aeration shows that the consumption rate is faster at higher primary aeration and the species concentration gradient is steep.

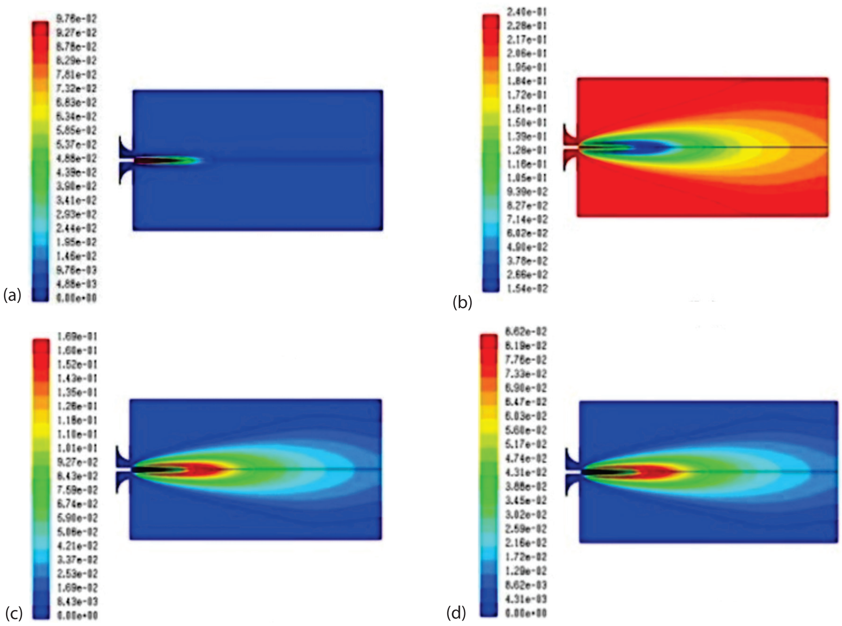


**Figure 3. Species mass fraction; (a) butane, (b) oxygen, (c) $CO_2$, and (d) water vapor**

The contours of turbulence and reaction rate are shown in fig. 4. The intensity of turbulence is higher in the mixing zone where the aerated fuel mixes with the secondary oxidizer. The reaction rate which is the rate of consumption of fuel is higher in the primary reaction zone nearer to the burner port. The intense reaction rate zone gets longer for less primary aeration as the flame stretches far for the thirst of oxygen. The intensity of mixing shown as turbulence intensity is observed to be shorter and broader for cases with co-swirl air and is attributed to the formation of re-circulation zone. The presence of co-flow does not have significant effect on the mixing zone.

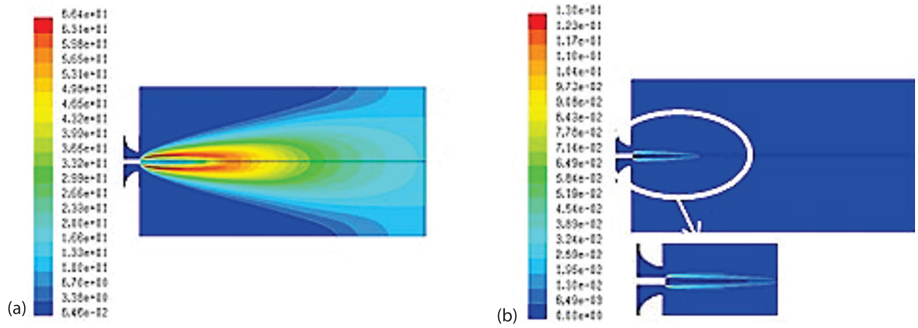


**Figure 4. Contours of turbulence [$m^2s^{-2}$] and reaction rate [$kgmolm^{-3}s^{-1}$]**

The effect of primary aeration on flame length was investigated numerically with 20%, 40%, and 60% primary aeration. The characteristic flame length is approximated as the zone with peak temperature in the static temperature contours. The effect of primary aeration is shown in fig. 5. The computational results compared with the earlier experimental study [18] are in good agreement with the experimental data. The maximum temperature zone in the static temperature contour matches proportionaly with the premixed blue zone portion of the practical flame. The flame length decreases with increase in primary aeration is because with increase in primary aeration, the amount of secondary air required for complete combustion lessen and can be attained in a shorter axial distance from the burner port. If the primary aeration is only 20%, 80% oxidizer requirement has to be met by acquiring it from the flame proximity and hence a longer flame length.

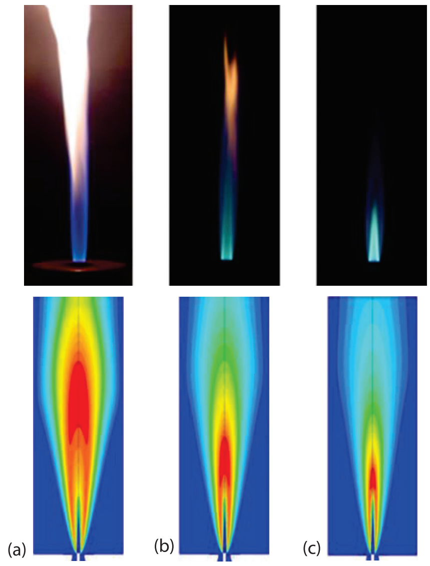


**Figure 5. Effect of primary aeration on the characteristic flame length; experimental data comparison [18] with computational result at (a) 20%, primary aeration, (b) 40% primary aeration, and (c) 60% primary aeration**

The effect of secondary stream of air on the stability of partially premixed flames is shown in fig. 6. The results show that the flame length decreases with co swirl-air and increases for co-flow air. Also, for a given fuel-flow rate, the lift-off velocity is also found to be higher with co-swirl air due to the formation of re-circulation zone. The flame stability is deteriorated with co-flow air due to flame stretch and weakening of the flame at the anchor point. The measured temperature along the axis and at different radius are plotted in 3-D using sigma plot and compared with the experimental flames with and without secondary air stream.

The input velocity given at the boundary is increased in small intervals until the flame lifts-off from the burner mouth. The velocity at which the incipient lift occurs is called the lift-off velocity. If the velocity is increased further, the flame blows out of the burner and finally blows-off. Before the flame blows-out, the velocity of the lifted stable flame when reduced brings the flame back on the burner mouth which is termed as drop back velocity.

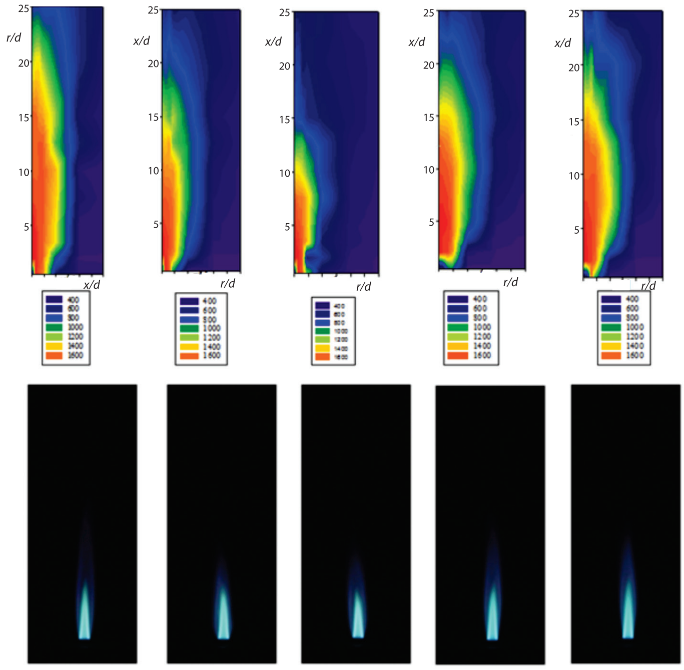


**Figure 6. Effect of co-flow and co-swirl air on flame length**

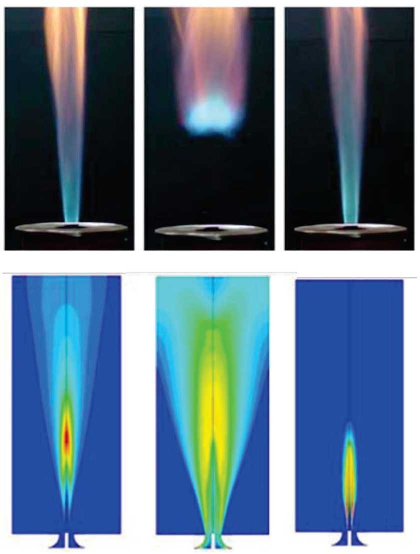

**Figure 7. Stable, lifted and drop back flame with 60% primary aeration**

The lift-off velocity has been observed for flames with and without secondary air. The lift-off velocity increases with increase in primary aeration and with co-swirl air. Figure 7 shows the computational result for lift-off flame and comparison against the experimental flame. The drop back velocity has been experimentally found to be higher than lift-off. The results obtained with the effect of increase in primary aeration and with co-flow and co-swirl air are in good agreement with the results obtained from previous studies [19-21].

The flame temperature obtained from the computational study has been plotted in *xy* co-ordinates and shown in fig. 8(a). The axial temperature profile shows that the temperature increases with increase in primary aeration and also the distance at which the maximum temperature is attained closer to the burner port as the stoichiometry can be attained closer to the port at higher primary aeration. The static temperature comparison for flames without secondary flow (base case) and with co-flow and co-swirl has been made in fig. 8(b). The graph shows the temperature is almost the same with the secondary air. However, the maximum temperature point shifted towards the burner mouth with co flow and co swirl air. The maximum temperature is higher for swirl case compared to co-flow and base case. The comparison of base, co-flow and co-swirl also indicates that the flame becomes shorter with co-swirl and co-flow does not have significant effect.

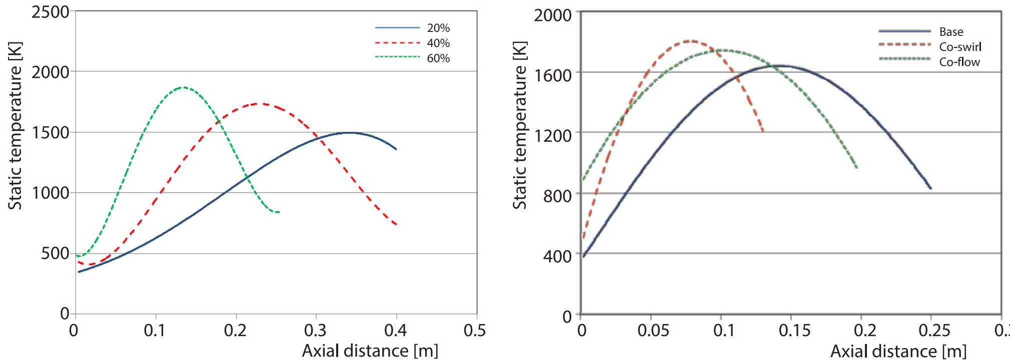


**Figure 8. Axial temperature profile; (a) static temperature at 20%, 40%, and 60% primary aeration and (b) static temperature for base, co-flow and co-swirl cases**

## Conclusion

A computational investigation on the stability and flame characteristics of partially premixed butane air flames with primary aeration ranging from 20-60% of the stoichiometric air has been carried out. The effect of operating parameters like primary aeration and the presence of secondary flow on the stability and flame characteristics has been studied. The simulation shows that the flame height of the flame decreases with increase in primary aeration and in the presence of co-swirl. It has also been found that the stability of flames increases with co-swirl air but deteriorates with the presence of the secondary co-flow air. The flame temperature increases with primary aeration and it has been observed that the peak flame temperature shifts away from the burner mouth for lower primary aeration. It has been observed that the flame stability improves with co-swirl air which is attributed to the re-circulation zone created due to the swirl motion which acts as a heat source. The poor stability in the presence of co-flow air is attributed to flame stretching and aerodynamic quenching of the stretched flamelets.The lift-off velocity and the stable operating range increases with equivalence ratio and also with co-swirl air.

## Nomenclature

$k$ – specific turbulent kinetic energy [$m^2s^{-2}$]
$F_i$ – body force, [N]
$U_L$ – laminar flame speed, [$ms^{-1}$]
$U_P$ – port velocity, [$ms^{-1}$]
$u$, $v$ – velocity vector in $x$-, $y$-direction [$ms^{-1}$]

*Greek symbols*

$\varepsilon$ – turbulent kinetic energy dissipation rate, [$m^2s^{-3}$]
$\mu$ – dynamic viscosity, [$Nsm^{-2}$]

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