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On The Role of Entrainment Phenomena on Flaming Combustion

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Abstract: **Flaming combustion is sub-classified into premixed and diffusion flames, the type of flames that are ubiquitous. From jet engines to rocket engines these types of flames are utilized to generate thrust for our vehicles. With careful observation and inference it can be clearly stated that in real time applications it's a combination of these two flames in unison that is in work, rather than either one alone. Although innumerable work has been done in the past that concern the two types of flames individually very few research works exists that concerns the transition between these two regimes nor their combined effect on the efficiency of combustion. Current work is aimed at gaining fundamental knowledge of transition, by studying a few of the many factors that influence transition and their corresponding effects on the physical parameters. A butane cylinder fitted with nozzle containing 3 equidistant sets of 4 holes each that have an equal diameter for air entrainment is used for carrying out the study. Parameters like entrainment area, the orientation of nozzle, the mass flow rate of fuel and various positions and combinations of air entrainment holes are manually varied to observe the physical changes in the flame like flame height and intensity. Image processing is used as a potential resource along with regular CCD camera. The phenomenon is systematically video-graphed and image segmentation is carried out to obtain desired characteristics. These methods are jointly used utilized to establish a non-dimensional parameter that theoretically characterizes transition phenomena. The results obtained from this experiment could be easily applied to combustion chambers present in jet engines as the experiment is aimed to mimic jet engine combustion chamber to a certain extent. Further, the results can provide a prospective understanding of the physics behind transition phenomena and a concept of premixed strength that can in the near future pave way for greener and efficient propulsion systems.**

Keyword- Premixed flames, Transition, Diffusion flames, Air-entrainment Enclosure area, Location of enclosures, Combinations of location of enclosures, Flame length

I. INTRODUCTION

Combustion deals with exothermic chemical reaction by using fuel and oxidizer associated with a reaction zone. Fuel and oxidiser mix in required proportions and combustion occurs through an intricate sequence of reaction steps. Combustion is critically important and the resultant energy interactions and governing phenomenon sources close to 80% of the world energy requirements in form of like propulsion, heating, electricity production. This branch of physics is broadly classified into smoldering and flaming. The classification is based on the manifestation of flames resulting from highly exothermic reactions yielding high flame temperatures depending on the fuel-oxidizer ratio. Different types of flames can result from the way in which the fuel and oxidant are mixed. Combustion can occur in premixed or diffusion modes. Diffusion flame represents diffusion-controlled combustion with diffusion rate greater than the reaction rate. In diffusion flame, fuel and oxidiser concentration vanishes at flame front and the flame region is very thin. In premixed flames, fuel such as natural gas, commercial and industrial liquid fuels, usually termed fuel oils and air mixture kept in an open tube is lighted by a spark and the propagation of the flame is observed at a certain velocity. In comparison to the premixed flames (short and blue), diffusion flames are longer and yellow with higher stability range, luminosity, sooty and flame temperature is not very high. When the fuel flow rate is relatively low, the incoming gaseous flow of fuel and air is laminar, as is the flame however; high fuel flows may lead them to being turbulent.

Thus, flames are generally identified as to be laminar premixed, laminar diffusion, turbulent premixed or turbulent diffusion. In addition, they can also be categorized into stationary or propagating flames. Partially premixed flames contain a rich premixed fuel-air mixture in a stream, and, for complete combustion to occur, they require the transport of oxidizer from an appropriately oxidizer rich mixture that is present in another stream. The stationary flames are widely used in domestic or industrial burners, the propagating flames being involved in explosions. An important aspect of the combustion research is investigation of the behaviour of flames in response to numerous parametric variations and external influences. The premixed and diffusion flames had been extensively studied and explored owing to the strong physical presence and applications. Combustion systems are one of the most important and complex highlighting an interesting aspect of the presence of partially premixed flames as a coupled resentment between premixed flame and diffusion flame. Flames in most practical applications cannot be described as purely premixed or non-premixed. Understanding the behaviour of flame in response to multiple air-entrainments to fuel on its path to produce flame is important because of its wide range applicability i.e. ring pool fire, perforated liner in combustors, furnace burner rims, Bunsen burners, perforated exhausts and culinary flame torches. This study could be very effective for fire safety purpose of a multiple-windowed tall infrastructure.

The parametric study of flaming combustion characteristics for ring pool fires and perforated liners has been done by researchers for decades. Scientists have stratified, classified and quantified the traits of flame in influence of amount of passive air-entrainment, forced air-entrainment, variation of composition of fuel and oxidiser and induced instabilities. Sohrab and Law [1] studied characteristics of polyhedral flames of propane and butane in influence of burner rim aerodynamics by illuminating the effects of atmospheric entrainment, inner wall boundary layer, and conductive heat loss to the burner. They found burner tips are unable to to support polyhedral structure and rise in surrounding atmospheric Nitrogen enhances the propensity of polyhedral structure. The rotational speeds based linear velocities at times in excess of laminar propagation velocity corresponding to the same mixture. Wadia [2] gave a brief review on advanced liner cooling techniques focusing more on laminated porous wall cooling, angled-multihole (effusion) cooling and composite metal matrix liner by defining the concept of heat transfer considering material and fabrication problems associated with it. Jing and Sun [3] worked on and found that in a perforated liner in presence of a bias flow, significantly gives rise in absorption coefficient and effective absorption bandwidth. The plate thickness also has a major significance on acoustic reactance and thus on resonating frequency. Eldredge and Dowling [4] investigated on effectiveness of cylindrical perforated liner with mean bias flow in its adsorption of planar acoustic waves in a duct. Each aperture was subjected to a harmonic pressure difference resulting vortex shedding from the rim. When the system included in a duct whose termination allows most acoustic energy to reflect upstream for further interaction with the liner, can absorb as much as 83% of incident energy at certain frequencies, and prevent 100% of the outgoing energy from reflecting back to the source. Lei, et al. [5] worked for controlling combustion instability by the effects of perforated liners with bias flow and by analytically and experimentally found that perforated liners can largely supress the combustion instabilities. Heuwinkel, et al. [6] studied liner configuration under bias and grazing flow condition was performed in three different test facilities and with three different measurement techniques. Results show the influence of the flow dominates the damping behaviour of the circular module and plane configuration shows an additional resonance effect. Though, the behaviour outside of the resonance range is similar to the circular configuration. Rodrigues and Fernades [7] analysed methane and propane flame stabilization on matrix-hole plate burner optimising effects of hole diameter, distance between holes and number of holes of the flow distribution plate as function of the relative velocity gradient. Shows that flames are less stable as large is the distance between holes on the distribution plate and that the flame stability is almost insensible to the other number of holes of the plate and the hole diameter and finally characterised the reacting propane airflow around burner plate. Lei, et al. [8] investigated the detailed behaviours of the temperature, velocity (in axial and tangential directions) and air entrainment in fixed-frame type fire whirl plume. The radial temperature follows the decaying exponential function and the power exponent „n" decreases from 2 to 1 with height in the intermittent flame and plume. In continuous flame, drop in increment rate of centreline axial velocity was observed comparative to buoyant flame. Recently Wang, et al. [9] studied the flame height and air entrainment coefficient of double buoyancy-controlled jet fires having two identical rectangular nozzles with same mass flow rate but varying distances. They found the flame height increases with the heat release rate, and it decreases with the distances between two nozzles if the distance is small. The flame height remains unchanged when the distance is large enough. Hu, et al. [10] experimentally investigated the evolution of flame height produced by line-source buoyant turbulent non-premixed jets with air entrainment constraint by two parallel side walls at various separation distances. Resulting in little flame height change with side walls separation distance when the longer side of the line-source nozzle is perpendicular to the side walls, flame height decreases with increase in side walls separation distance and finally approaches the value of a free jet when the separation distance beyond a critical value when the shorter side of the line-source nozzle is perpendicular to the sidewalls. In 2018, Tao, et al. [11] experimentally investigated on effects of various diameters for ring pool fire resulting flame height of ethanol changes slightly and for n-heptane, it increases with equivalent diameter. They also found a classic correlation for n-heptane and ethanol for plotting the evolution of flame height. Rahul, et al. [12] experimentally investigated on transitional flaming from premixed to diffusion flame with varying inlet air-entrainment area and varying orientation in first quadrant. Images of transitional flaming acquired and phenomenally presented. The results obtained clearly quantify flaming transition as a strong function of inlet air-entrainment enclosure area with linear dependence on orientation. Present work primarily focuses on simplifying and understanding the behaviour of flames with varying location and for various sets of locations of air-entrainment zones of equal enclosure

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Vol 3, Issue 3, March 2018

area. The motivation for this work is initiated by the idea of understanding flames as a function of various air-entrainment enclosure locations and simultaneous multiple air-entrainment enclosure locations in varying sets and utilising it wide range applications of flames associated with perforated channels for stabilizing it and further exploration of flame dynamics. The specific objectives of the work are:

(a) To investigate the effect of varying air-entrainment enclosure area locations vertically on flame structure and characteristics.

(b) To study the effect of varying combination of sets for air-entrainment enclosure area and the flame response.

(c) To study the effect of fuel flow rate on flame characteristics.

II. EXPERIMENTAL SETUP AND SOLUTION METHODOLOGY

To address the subject, an experimental setup was upraised comprising of (a) Butane cylinder with nozzle (Fig. 1(a)), (b) Orientation reference chart, (c) Height reference chart, (d) Camera, (e)Support enclosure Apparatus; (please see Fig 1(b)). Selected nozzle contains 3 sets of 4 holes (diameter 4.87 mm each) which are radially symmetric and placed with a pitch distance 33.0 mm vertically for required air entrainment. The top entraining array of holes‟ set (E1), the bottom one (E3) and the intermediate one (E2) are as displayed in Fig. 3

(a) .The experiments were carried out for vertically upward configuration of nozzle and in normal gravity (21% oxygen concentration) environment. The nozzle consists of three removable sub-parts as shown in Fig.2.The top parts host air entrainment holes and the bottom part allows fuel flow from the cylinder through an orifice of 0.5mm.The flow velocity measurement is done as shown in Fig.3(b). By keeping the regulating knob fixed for three configurations considering low, medium and high flow rates of butane as 1.217, 2.4335 and 3.65 (in mg/s). The various combinations of set of holes are well defined and represented in Fig. 4. The aerodynamic interactions between flow inside the nozzle with surrounding air is shown as a schematic diagram in Fig. 4 as initially butane posses high kinetic energy and low pressure, air is sucked into nozzle through E3 and E2, as the flow proceeds forward wall friction reduces kinetic energy and increase in pressure which leads to exhaust of gas from E1 and the remaining flow transforms into flame.

For a fixed butane flow rate, 8 sets of combination of air-entraining holes exist, which are separately video-graphed for 20 seconds each by a 60 fps camera. And at an equal time interval of 4 seconds, 5 pictures are taken from each case. The experiment is then repeated for all three mass flow rates and pictures are comparatively analyzed with different flow rates having combination constant and different combinations having butane flow rate constant. It must be noted that all the experiments have been done by enlighten the burner from the top opening of nozzle by a matchstick as shown in Fig. 5.

Fig. 1 (a): Premixed

Fig. 1 (b): Complete butane gas cylinder experimental with nozzle setup

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International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 3, Issue 3, March 2018

Fig.2: Removable sub-parts of nozzle

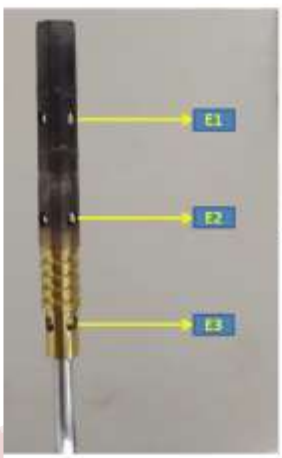

Fig. 3 (a): Air-entraining holes Fig. 3(b): Anemometer

Fig. 4: Cases of various combination of location of air-entrainment enclosure area by enclosing holes: (a) All holes open, (b) only E3 closed, (c) only E2 closed, (d) only E1 closed, (e) only E1 open, (f) only E3 open, (g) only E2 open and (h) All closed.

Fig. 5: Enlighting the burner from the top opening of the burner by a matchstick

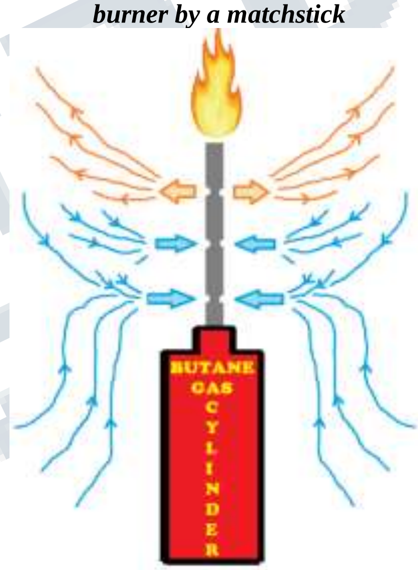

Fig. 6: Airflow field interactions between system and surrounding through entraining holes.

III. RESULTS

The experimentation is systematically categorized into 4 configurations entitled as „SRV" for air entraining enclosure area obstruction by operating 12 holes in three configuration cases as:

a) SRV-I: Represents the case for all 12 holes open.
b) SRV-II: Represents the case for 4 out of 12 holes closed.
c) SRV-III: Represents the case of 8 out of 12 holes closed.
d) SRV-IV: Represents the case for all 12 holes closed.

SRV-I and SRV-IV defines the extreme cases for flaming combustion under present conditions. SRV-II and SRV-III are expected to experience momentous variations in the flame response with cases leading to transition. The

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Vol 3, Issue 3, March 2018

experimentation was repeated for all three mass flow rates and images are comparatively analyzed with different flow rates with fixed combination and different combinations having fixed butane flow rate constant. First, the experiments were carried out for high butane flow rate of 3.65 mg/s. Fig. (6 –12) shows images corresponding to different cases.

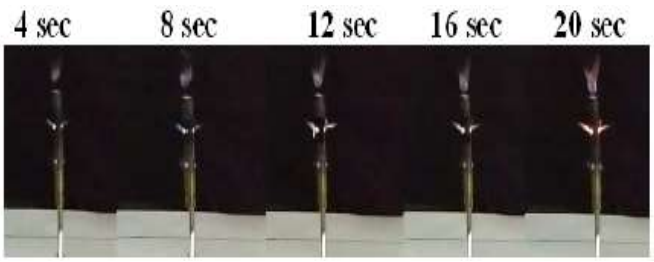

Fig. 6: All Opened Case

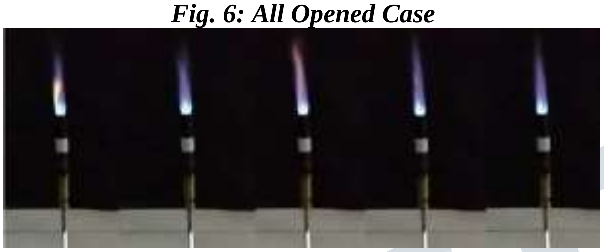

Fig. 7: Only E1 Closed Case

Fig. 8: Only E2 Closed Case

Fig. 9: Only E3 Closed Case

The observations are taken by insight analyzing of pictures as shown in Fig. 6, all the holes kept open representing SRV-I configuration and a small fluttering lifted off double tipped partially premixed flame is observed from the top opening of nozzle. The E3 set allows high velocity air entrainment to the butane flow path and get rich oxygen to diffuse combust but till the flow reaches top opening of nozzle due to viscous boundary layer formation on the walls it increases the velocity more due to induced convergent path for flow. Hence the velocity is much higher to unable the effective diffusion for combustion. This in turn generates a lift off flame which is on the verge of blow off limit. Along with it 4 small conical tilted flames are coming out of E1 holes, representing the high speed air entrainment from all four opposite enclosures at set E3 meet at a point and stagnate the oxygen concentration for diffusion with butane flow and due to the metallic walls heat from the flame transfer in forward direction i.e. low temperature fuel, giving rise to flame formation just above the stagnant point of airflow which clearly visible from E2. Flame heat the air particles and it propagates upwards due to driving forced fuel flow and hot air particles build the pressure inside the duct and due to the temperature and pressure gradient between flow in duct and surrounding, flow throw the flame out through 4 holes of E1 set whose velocity is very high sets flame on the edge of blow off limit due to huge temperature loss by high speed outward flows and insufficient time for proper diffusion of oxygen and butane at such velocity.

Next, SRV-II is represented in Fig. 7, Fig. 8 and Fig. 9. The case of only E1 set closed as represented in Fig. 7 a conical blue jet flame is observed from top opening of nozzle which seems to be structurally stable but intermediate yellow flames witnessed for fraction of seconds. Here the E3 set holes allow strong air entrainment to the butane flow inside duct made the mixture oxygen rich and due to relatively low velocity airflow near E2 set just because the cylinder venturi is at much distance from E2 set than E3 the velocity loses its potential as it goes up hence lower velocity air entrainment takes place at E2 and at top opening of nozzle have enough time to diffuse the oxygen with butane flow and finally ignition at this point gives rise to complete combustion of butane and a premixed flame comes into picture. The yellow flames produced for very short period of time few times because of inter energy transfers and flow readjustment to make the flame stable. By observing the Fig 8, where closing only E2 set a blue color jet flame is seen from top opening of nozzle having lighter color and lesser yellow flames‟ special appearances observed than E1 set closed case as shown in Fig 7. Even in this case E3 set allows air-entrainment at high velocity inside the duct and due to frictional effects and induced shearing forces it loses velocity as it goes upwards and a little entrainment happen at E2 due to lesser pressure gradient than E3 location. Ultimately enough pressure build at the top opening of the nozzle and ignition by matchstick gives premixed flame formation associated with unsteady

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 3, Issue 3, March 2018

yellow flame appearances for fraction of seconds lesser time than it appeared in E1 closed case due to less internal energy transfer required to equilibrate the systems conserved energy and hence less flow adjustment inside the duct happen and at few time intervals the flow lacks oxygen to make proper combustion and gives sooty flame formation.

By closing only E3 set a completely diffusion flames from E2 set are longer and E3 are relatively shorter are produced and mixed with the large diffusion flame from the top nozzle opening and starts flickering as shown in Fig. 9. The high velocity airflow is obstructed here, along the height of duct the velocity loses in overcoming the frictional forces. The E2 set gets little air-entrained due to less pressure gradient between flow in duct and surrounding which results in lacking oxygen in the flow to diffuse with butane making the mixture rich. When it goes upwards with rich mixture the high concentrated oxygen from the flow tend to flow out through E1 set along with losing butane also to atmosphere and the rest of the flow goes through top opening of nozzle, which when ignited a diffusion large flame occur due to lack of oxygen the incomplete combustion takes place forming large sooty flames, which starts flickering due to inter-energy conversions and to get sustained flame exposes itself to get in the vicinity of more atmospheric oxygen. This flame eventually transfer its heat to low temperature fuel in downward direction through hot radicle transfers and though conduction by metallic wall of nozzle. Hence, heating of butane flow takes place at both the sets of E1 and E2 resulting formation of diffusion flames which tries to get more oxygen and come out of duct and due to buoyancy it mixes with the large diffusion flame from the top opening of nozzle.

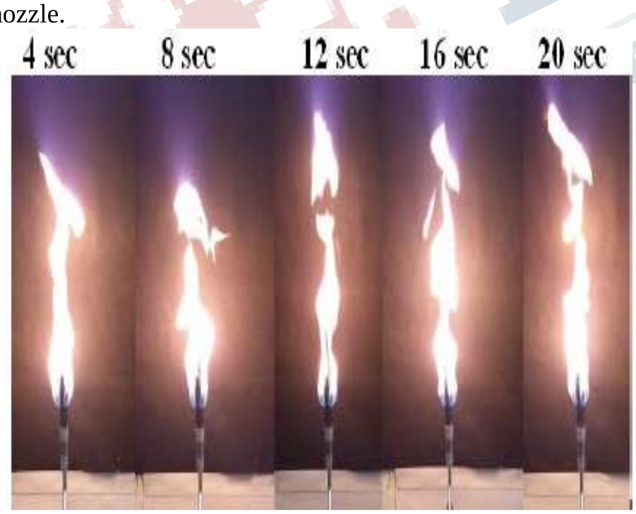

Fig. 10: Only E1 Opened Case

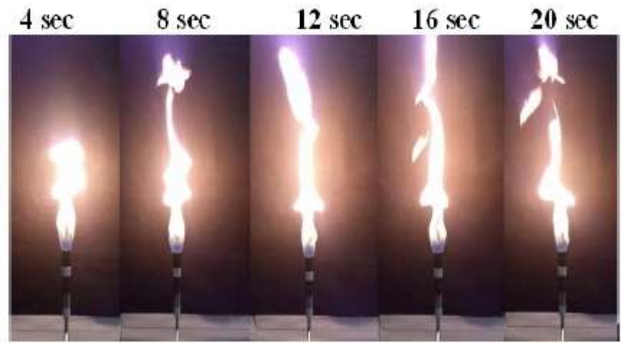

Fig. 11: Only E2 Opened Case

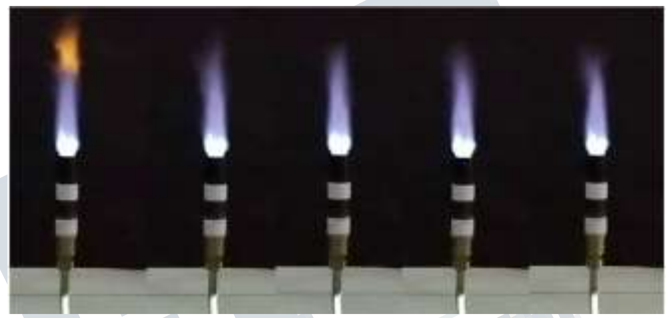

Fig. 12: Only E3 Opened Case

Fig. 13: All Closed Case

Fig. 10, Fig. 11 and Fig. 12 shows flame behavior for SRV-III. Enclosing E2 and E3 sets in Fig. 10, long yellow flames produced by E1 set holes mixed with the large diffusion flame from top opening of nozzle and flickering phenomenon is observed. The only air-entrainment occurs through E1 set of holes where the flow velocity significantly decreased and pressure build is enough to start combustion. Here a very less velocity air is drawn into the flow in duct for diffusion with butane flow, this makes the mixture rich and incomplete combustion happen on ignition at the top opening of nozzle. Due to forward heat transfer and conduction by metal walls the heating of butane occur at E1 and flame generated here lacks oxygen and to sustain it comes out of ducts through holes and goes up by the virtue of buoyancy mixes with the

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International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)

Vol 3, Issue 3, March 2018

large diffusion flames. Due to inter-energy transfers and in starve of oxygen the flow exposes itself to more atmospheric oxygen in compensating rise in length (or flame area) giving rise to high flickering phenomenon at much larger amplitudes.

Enclosing E1 and E3 sets the larger diffusion flame from the top opening of nozzle observed and it‟s associated with high range of flickering heights as shown in Fig. 11. The velocity of the butane flow decreases as it got influenced by the friction at the location of E2 the pressure gradient is more than only E1 opened case and the airflow velocity is more than the previous case. Resulting in more oxygen rich and till the mixed flow reach the top opening of nozzle the flow pressurization takes place and when ignited the combustion occurs giving rise to sooty flames but lesser air-entrainment is required to diffuse with the butane flow to make the flame sustain. So the inter-energy transfer takes place giving rise to lesser flickering phenomenon than the only E1 closed case.

The only E3 hole opened case is shown in Fig. 12, by closing E1 and E2 sets obstruction of air-entrainment takes place where low velocity airflow supposed to place. Here the high velocity butane flow makes a greater pressure gradient between butane flow in duct and surrounding and drawing a high airflow from surrounding takes place which when ignited at the top of nozzle the properly oxidized flow sets a blue conical jet flame from top opening of nozzle.
For SRV-IV only Fig. 13 comes in picture where all the three sets of holes are closed, no air-entrainment is entertained giving leading to make rich mixture. A largest and brightest diffusion flame associated with flickering phenomenon for longest height range is observed from top opening of nozzle. Because to compensate with oxygen deficiency, flame takes a broader region by increasing its height (and/or area) by inter-energy conversions giving rise to greater unsteady flickering rates.
Fig. 14 – Fig. 21 show variation of flame structure with different configurations for low mass flow rate of 1.217 mg/s at time steps of 4 seconds from 0 to 20 seconds.

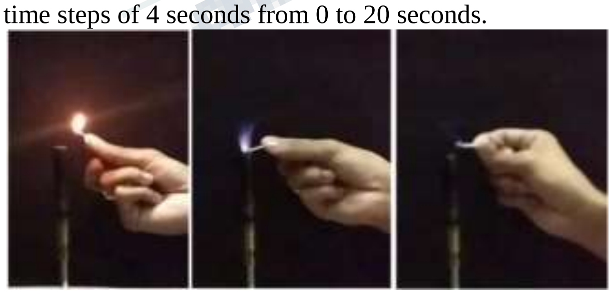

Fig.14 – All opened case

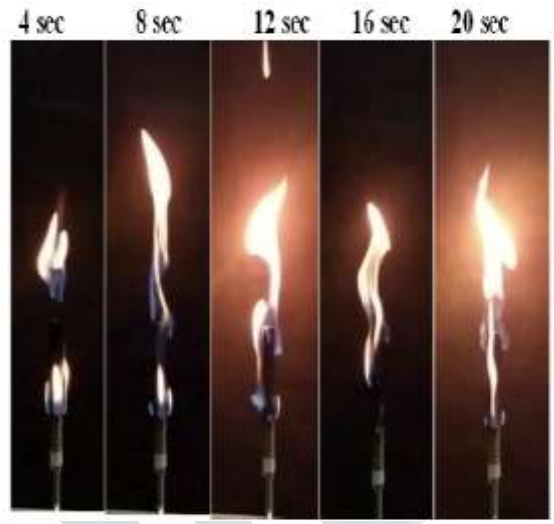

Fig.15: Only E3 closed case

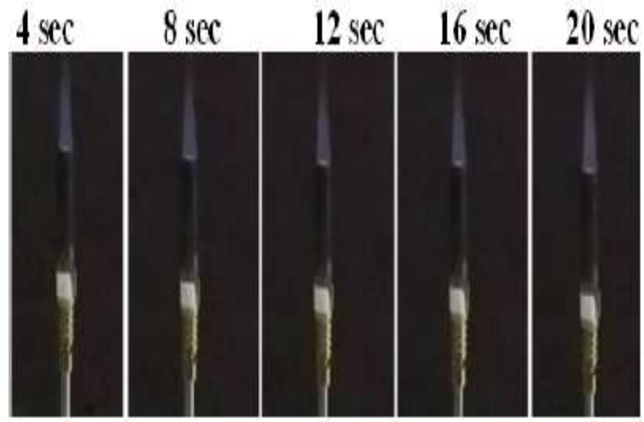

Fig.16: Only E2 closed case

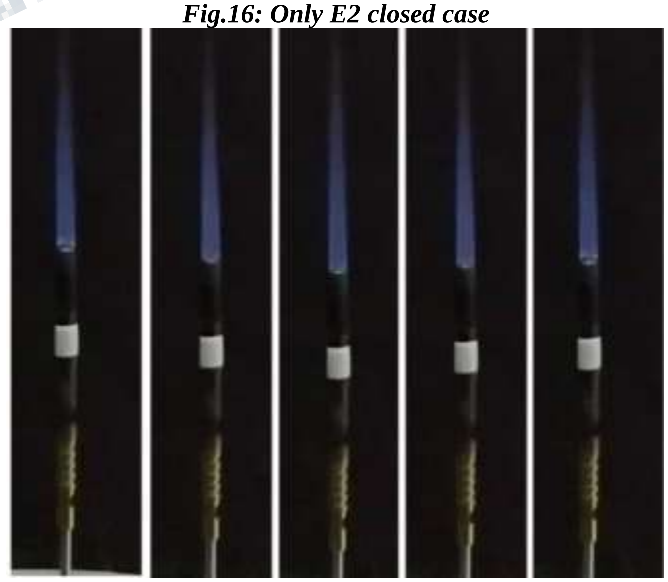

Fig.17: Only E1 closed case

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 3, Issue 3, March 2018

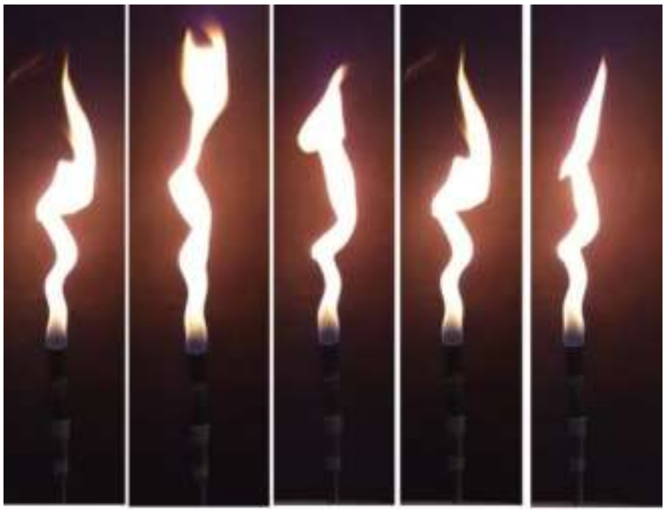

Fig.18: Only E1 open case

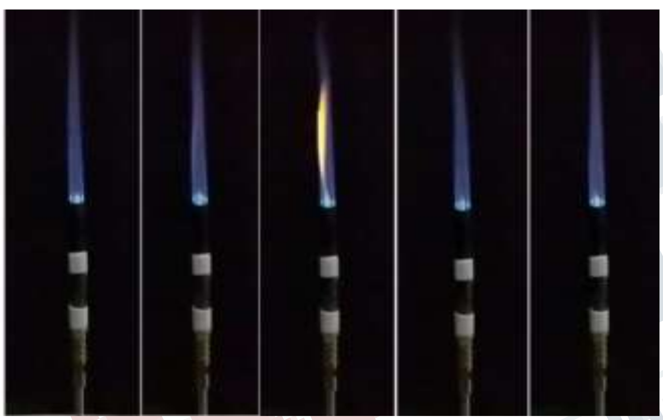

Fig.19: Only E3 open

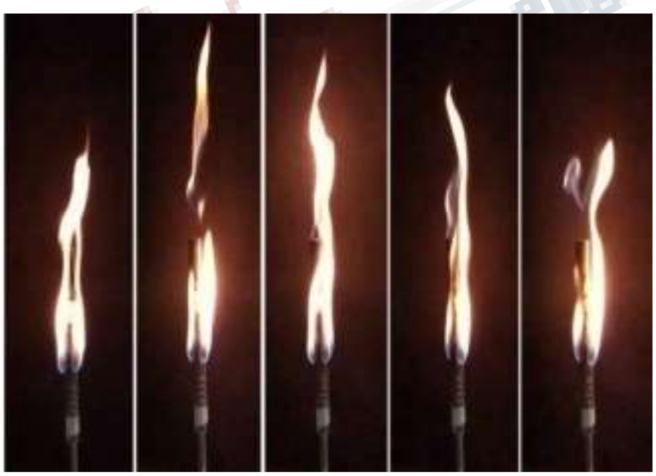

Fig.20: Only E2 open

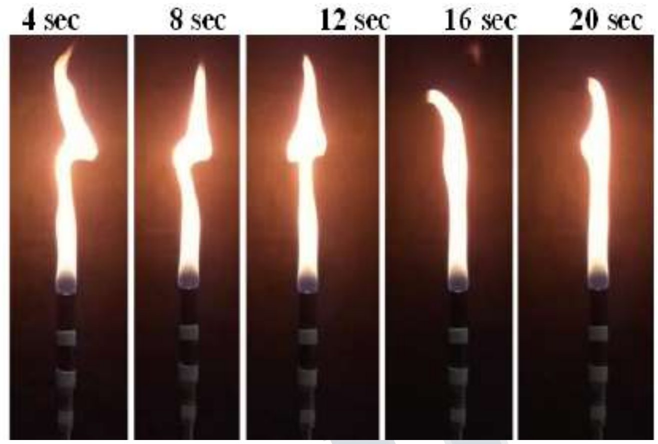

Fig.21: All holes closed

As shown in Fig. 14, all entrainment holes are open, in this case the fuel doesn‟t ignite when matchstick is bought closer to top of nozzle. This is because the fuel becomes too lean to ignite after entraining air from all three holes. This case represents blowoff limit. Whereas when the matchstick is bought closer to E3 it is found that it sucks the matchstick flame into it, thus characterizing high velocity flow. On the other hand when the matchstick is taken near E1, the matchstick flame is blown away from the nozzle, thus characterizing low velocity and high pressure of flow inside the nozzle. The reduction in velocity is caused due to aerodynamic interactions between flow inside nozzle and ambient atmosphere and also viscous friction between walls of nozzle and butane gas.

Following the categorization of configurations of SRV system, SRV-II defines only single set of holes opened cases. As per the representation in Fig. 15, only E3 is closed. This leads to the formation of small flamelets at E2 and taller flamelets emerging from E1 that finally merge with the bigger flame formed at the exit of the nozzle. The flamelets forming at E1 and E2 can be explained by phenomena called flashback, where the flame forms inside the tube. This happens because of the low velocity of butane and high quenching distance because of the presence of multiple holes. Only E2 set is closed in Fig. 16. It can be observed that a light blue flame with a very small height is formed. Compared to other cases where only one set of holes are closed this case has the lowest height. This can be explained by the escape of butane gas on the way to the exit nozzle. The air entrained through E3 reduces the velocity of the flow and by the time the gas reaches E1 the flow velocity would have decreased even further due to wall interactions and the pressure on walls due to butane gas increased more, therefore when the gas reaches E1 some of the gas escapes due to the

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International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 3, Issue 3, March 2018

pressure it exerts on the wall and the remaining reaches the nozzle exit and ignites to form flame. The final inference of SRV-II is shown in Fig. 17, enclosing only E1 set of holes. In this case the pre-mixed flame is more intense in terms of color with reference to the E2 closed case but less intense compared to the E3 open case. This trend holds well in case of flame height also. This observation can be again explained using the position of entrainment holes and their effect on increase in pressure energy which eventually leads to loss of butane gas to the atmosphere. In this case the loss of fuel is less compared to previous case. From these observations we can infer that better mixing of fuel and oxidizer due to entrainment occurs when the entrainment provision is placed where the flow has higher kinetic energy.

By the definition of SRV-III only 1 set of holes must be open which is shown in following listed figures. From Fig. 18, only E1 is kept open. We observe an unsteady diffusion flame that changes shape with time. The formation of a diffusion flame is caused due to lack of oxidizer pre-mixing which in turn forces the flame to diffuse oxygen from surroundings for combustion. The incomplete combustion leads to formation of unburnt combustion products called soot which is the visible yellow part of the flame. This can be explained by the presence of entrainment holes at end of the nozzle where the velocity of the flow is less and high pressure energy which causes some of the fuel to escape and the remaining fuel mixes with the little air that gets entrained into the nozzle and less distance for the flow mixing causes the formation of a diffusion flame. As shown in Fig. 19, enclosing E1 and E2 set of holes. It can be observed that the flame formed is a steady and pre-mixed flame that has the highest color intensity among premixed flames. This signifies complete combustion of fuel. In this case as the entrainment holes are placed at the beginning of the flow the low pressure created due to high kinetic energy of butane gas sucks in an adequate amount of air and the length of wall following the entrainment zone is long enough to allow proper mixing, which is also accompanied by stabilizing effect of swirler thus giving a complete combustion. Last case for SRV-III is depicted in Fig. 20, where only E2 is open and E3 and E1 are closed. Diffusion flames that are transient and flickering are formed. The small flames are formed at E2 and another flame is formed at the nozzle exit, both the flames interact periodically to combine into a single flame. In this case two zones of entrainment are present one at the beginning of the nozzle and the other at the end of the nozzle. This means the air entrained from E3 reduces flow velocity and decreases pressure and aerodynamic interaction at E1 causes further deceleration which causes flashback and formation of flame at E1.

One of the two extreme cases of experiment is given in Fig. 21, where all holes are closed. Again we observe an unsteady diffusion flame that is formed only at the nozzle exit. This can be explained by keeping in mind the fact that the nozzle doesn‟t entrain any air along the flow which leaves it to diffuse air from atmosphere to continue combustion. Thus we observe a tall diffusion flame that flickers.
Fig. 22 to Fig. 29 highlights the variation of flame structure with different configurations for medium mass flow rate of 2.4335 mg/s at time steps of 4 seconds from 0 to 20 seconds.

Fig.22: All open case

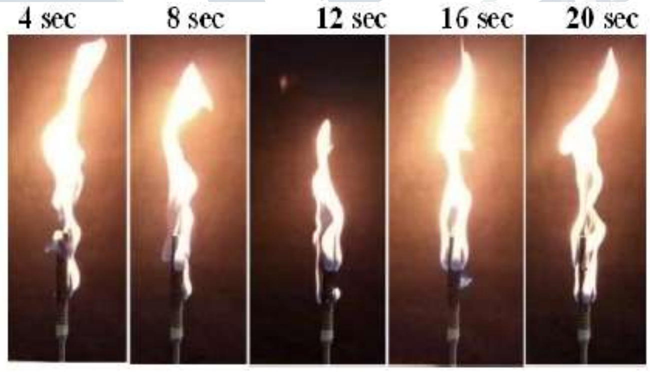

Fig.23: E3 closed case

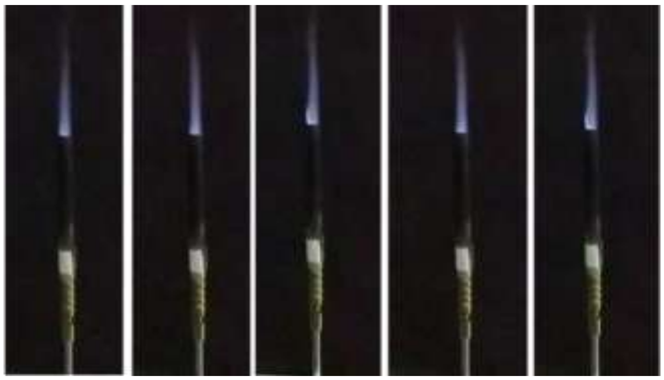

Fig.24: E2 closed case

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International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 3, Issue 3, March 2018

Fig.25: E1 closed case

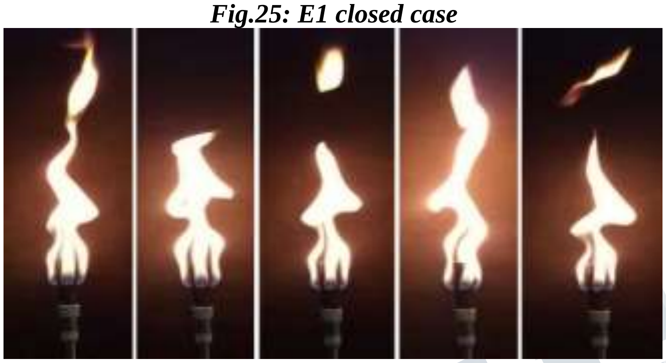


Fig.26: E1 open case

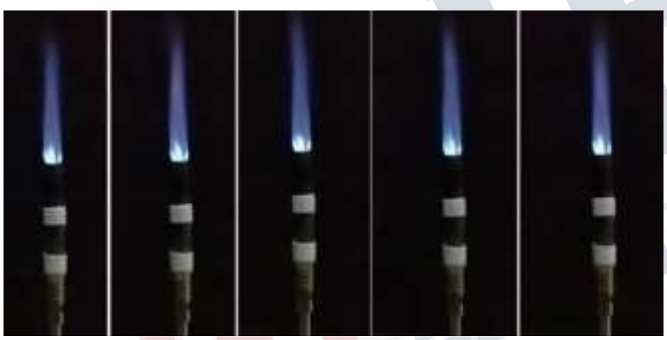


Fig.27: E3 open case

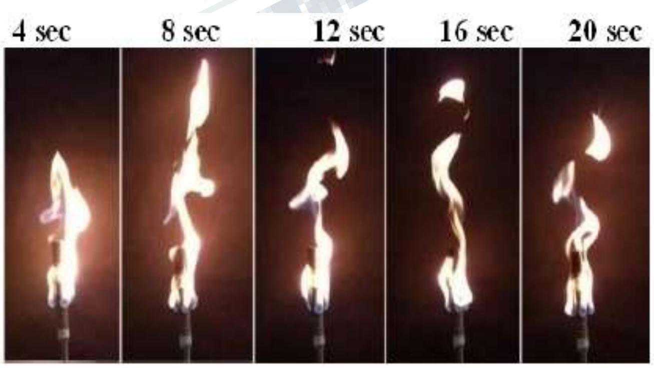


Fig.28: E2 open case

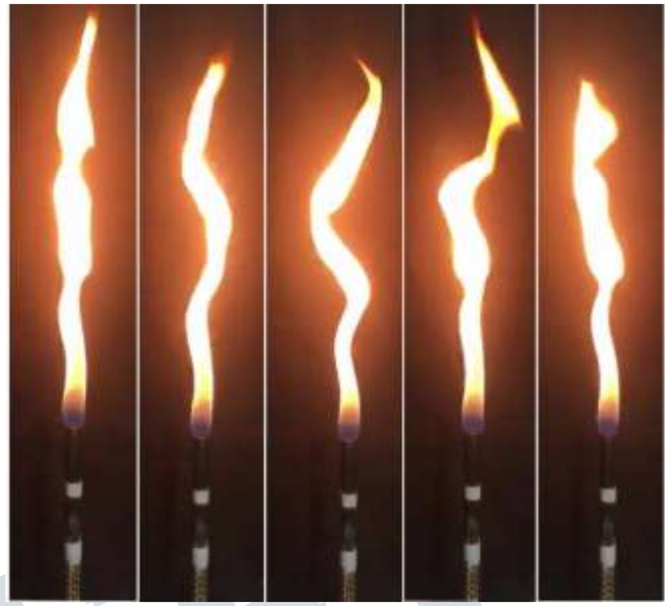


Fig.29: All closed case

Fig. 22 shows the case of all the entrainment zones opened we observe no flame to be formed. In fact when a lit matchstick is bought in front of the top of the nozzle exit it blow of the lit matchstick. This means that the air entrained from the 3 different entrainment holes have diluted the butane gas to an extent where it cannot attain ignition temperature. In short we can say that the three entrainment zones made the flammability limit lower than one thus making it unable to start or sustain combustion.

SRV-II is defined in following Fig. (23-25). In Fig. 23, the photos show variation of flame characteristics when E3 is closed. We can observe small flames emanating from E2, in the start we see flamelets formation only from two holes of the E2 but later it is observed that the flame stabilizes and interacts with flame from the nozzle top. The flame is observed to be a diffusion flame that is unsteady with respect to time. The formation of flame at interior of nozzle is because of flashback and formation of multiple flamelets in the mid of nozzle is due to increase in pressure energy and escaping of gas through holes. As presented in Fig. 24, it represents the case where only E2 is closed. We can observe from the photos that the flame formed is a premixed flame, but the flame is comparatively lower in height compared to other premixed flames of same mass flow rate and lower in color intensity as well. This observation can be explained by the phenomena where the fuel escapes from the entrainment zones that are at the end of the nozzle because of increase in pressure of the gas on the walls of the nozzle after aerodynamic interactions from air entrained from E1 and with viscous interactions with wall. Fig. 25 shows the case

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 3, Issue 3, March 2018

where only E1 is closed we observe a steady premixed flame that is conical in shape. From this observation we can infer that complete combustion is taking place in this configuration. By closing E1 entrainment zone that is present at the end of the nozzle we are preventing the escape of butane gas that was mixed with interaction from the air entrained through E2 and E3. Thus we observe a premixed flame.

SRV-III focuses the only effectiveness of single opened holes which are given in Fig (26-28). As shown in Fig. 26, where both E2 and E3 are closed we observe a four flames emanating from all the four holes of E1, and all the flames are diffusion flames and the extend along the wall of the nozzle to merge as one with the flame formed at the top of the nozzle. This phenomena is observed because the flow the entry of the orifice exits at a very high velocity and due to viscous interaction with the nozzle boundary it losses some of its kinetic energy and longer the duct more the loss happens and by the time the flow reaches E1 it possess very less kinetic energy and due to the pressure it exerts on the wall it tries to escape through the holes present and as it emerges from the entrainment holes it diffuses air from atmosphere and forms a diffusion flame. Some of the gas that is in the centerline of the nozzle doesn‟t interact with wall so it doesn‟t lose much velocity so that gas forms a diffusion flame just outside the nozzle exit. Enclosing the sets E1 and E2 the case is well shown in Fig. 27, the photos represent the case where only E3 is open and the air entrainment occurs where the velocity of butane gas is high which causes low pressure and sucks air into nozzle which mixes with the gas along duct passage and further interacts with swirler to form a stable premixed flame. From this we can infer that entrainment holes are the most effective when placed in the flow passage where the gas possesses maximum kinetic energy. Focusing on Fig. 28, where only E2 is open and E3 and E1 are closed. Diffusion flames that are transient and flickering are formed. The small flames are formed at E2 and another flame is formed at the nozzle exit, both the flames interact periodically to combine into a single flame. In this case two zones of entrainment are present one at the beginning of the nozzle and the other at the end of the nozzle. This means the air entrained from E3 reduces flow velocity and decreases pressure and aerodynamic interaction at E1 causes further deceleration which causes flashback and formation of flame at E1.

For the extreme case of total air-entrainment is obstructed Fig. 29 comes into picture, where all 12 holes are closed. Again we observe an unsteady diffusion flame that is formed only at the nozzle exit. This can be explained by keeping in mind the fact that the nozzle doesn‟t entrain any air along the flow which leaves it to diffuse air from atmosphere to continue combustion. Thus we observe a tall diffusion flame that flickers.

These case studies of various configurations for different mass flow rates depict beautiful behavior of flames. The possible reasons behind these transitional phenomena could be explained by stating the fundamental laws of nature i.e. buoyancy, diffusion, heat transfer, aerodynamics and conservation of energy. The governing physics lies in fuel which is forced fetching the sufficient air to cause a mixture for burning. In the whole experimentation the major parameter is “fuel flow speed while traversing through the nozzle”. By changing the location of set of holes opened for a combination of hole sets, the airflow impinging location to the fuel flow changed which created the pressure gradients relative to the surrounding and flow readjustments take place for other holes. Location of air-entrainment to fuel flow quantifies the composition of air-fuel mixture reaching the nozzle exit with losing flow velocity giving rise of sufficient pressure for combustion. The ignition takes place at the nozzle exit leads to flame formation and depending upon the oxygen diffused in fuel flow the flame tends to sustain by exposing it to more atmospheric oxygen by compensation of its height (and/or front area) via the systematic conversions of inter-energy between flame and corresponding flow just to not violet the law of net energy conservation and make the maximum possible rise in entropy change by the system. Results rise in unsteady flickering phenomenon occurs. For all the set of holes and combinations sur supply remains there, difference must be noted for two set of holes E1 and E2 being open because fuel supply is forced and continuous throughout. Therefore, the flame structures vary depending upon the availability, though the oxidize (air)is abundant in every case. Significantly the proportional heat comes from the top where manual ignition is done. It may lead to a different scenario of flame origination. So, entrainment alters the final fuel supply to the exit which leads to diverse flame structures because observation is done at the nozzle exit only. Before that, whatever response observed by the flame for any configurations are a consequence of first combustion that took place at the exit nozzle. The higher the fuel flow rate would be the higher the effects of air-entrainment would be. Since it shows unsteady phenomenon, the flame tends to gain steadiness and for a stabilized structure along with time. As time passes by the flame heats the metal walls of nozzle which eventually loses its heat sink potential and the resulting flame gains a stabilized structure by reduction in further heat lost to the metal which is shown clearly in Fig. 30. The orange bright color of flame is due to the influence of combustion of nozzle‟s metallic wall.

Fig. 30: The flame after sustaining 40 seconds.

Fig. 31 (a): Combustion Chamber

Fig. 31 (b): Burner Cans.

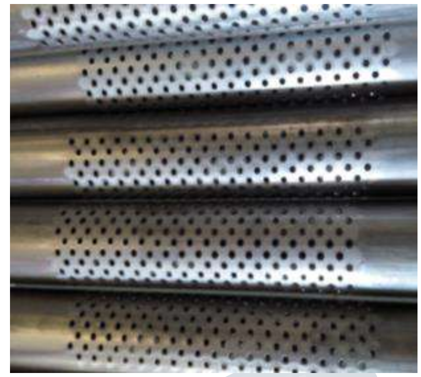
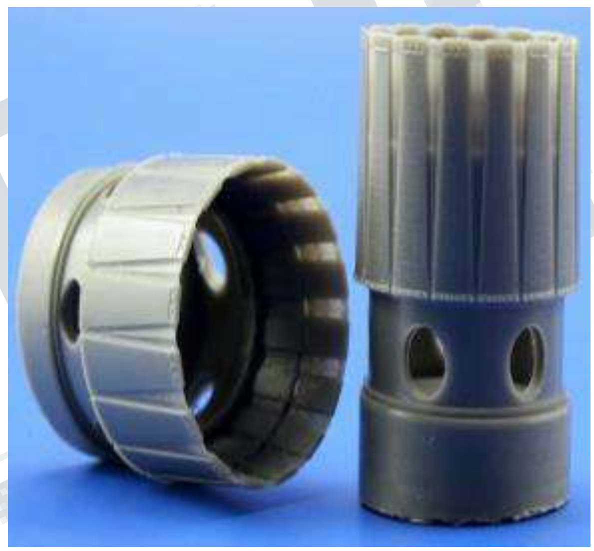


Fig. 31 (c): Perforated exhausts Fig.



31 (d): Nozzle exhausts.

Fig. 31 (e): Pool ring rims.

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Vol 3, Issue 3, March 2018

Fig. 31 (f): Tall infrastructures.

Fig. 31 (g): Bunsen burners.

The applications of the present study ranging from culinary stoves, automobile engines to sky-scrapers for efficient designs and enhanced fire safety factor (Fig. 30 (a- g)).

IV. CONCLUSION

A systematic experimentation was carried out for different mass flow rates and for different combinations of set of holes. To understand the flame behavior in response to the induced parametric variations viz. location of air-entrainment and combinations of air-entraining set of enclosures for a vertically upward nozzle case, the configurations were classified and by representing the phenomenon at periodic instances graphically comparative optimization of insight was done. The major observations of the study could be noted as:

(i) The air-entrainment enclosure location leading to premixed flame is stronger in the order of E1 < E2 < E3 for only one set of holes opened case in any fuel flow rate which is strongly inferred from SRV-II and SRV-III.
(ii) The diffusion flame strength as a function of air-entrainment can be stated in ascending order of enclosing only set E1, E2 and E3. Or vice versa for the premixed flame strength as a function of air-entrainment could be defined by opening only set of holes in ascending order of E1, E2 and E3.
(iii) The transition from premixed to diffusion flames could be observed displacing the air-entrainment location from E3 to E2 in only one set of holes opened configuration for a constant cross section circular area duct.
(iv) This study could be significantly effective for reducing fire hazards in combustion chambers due to the presence perforated liners, perforated exhausts and tall multi-windowed infrastructures.
(v) Understanding the behavior of flames as a function of varying locations of air-entrainment increase the scope for design enhancements of Bunsen burners, ring pool burners, exhausts, combustion chamber"s perforated liners, engines flame holder and good flame stabilization and enhancing fire safety for tall multi-windowed infrastructures.
(vi) This work can have significant effect on designing testing and validation of existing engines, their efficiency and identifications of issues also.

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