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CONTROL OF CASINGHEAD GAS FLARES FOR HARNESSING ENERGY

Anil Dubey [*], Abhijeet Kumar, Amit Kumar Singh, Nalinikanta Panda, Sameer Dubey

Department of Mechanical Engineering, GIET, Gunupur, Rayagada, Odisha, India

Department of Mechanical Engineering, Osmania University, Hyderabad, India

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ABSTRACT

In oil rigs associated gases or casinghead gases have to be burned as flares as a safety measure to reduce excessive strain on the refinery equipments. To harness the energy of these non-premixed combustion flames, they should be stabilized or controlled and this should be done without obstructing the flow of gases. Attempt was to analyze whether a cylindrical enclosure with a tapered inlet could keep the flame stabilized enough for effective convective heat transfer and flame area large enough for radiative heat transfer or not. Digital image processing in MATLAB with candle flames and CFD analysis in ANSYS FLUENT was performed with enclosures of different dimensions. Results generated show that it is possible to control the flame with proper choice of angle of taper and diameter of enclosure. Based on the findings from the results schematic of a device to extract energy from gas flares has been also presented.

KEYWORDS: Associated gases, Non-premixed combustion, Image processing; CFD analysis, Enclosure

INTRODUCTION

The natural gas which escapes the oil wells when they are drilled is called as Associated Gas or Casinghead Gas in oil and gas drilling terminology. Whenever an oil well is drilled, it is impossible to previously determine whether the well is going to produce too much of crude oil or too much of gas. As the gas along with oil is trapped in wells under very high pressures the gas escapes the well as soon as it is drilled. Usually it is not feasible to transport the gases for extracting energy, especially if they are in seas, far away from the shores. The gases do not have a definite composition and are a mixture of various gases such as methane, ethane, propane, pentane etc .In addition to these they may also contain water vapor, hydrogen sulphide (H_2S), carbon di-oxide and nitrogen. This raw natural gas with so many impurities cannot be used in engines without treatment. Further as they escape the well at such high pressures it is very difficult to control the gases or reinject them into the well. So generally there is no option other than releasing the gases to the atmosphere as a safety measure whenever there is excessive strain on the refinery equipments due to these high pressure gases. Methane is roughly 30 times stronger greenhouse gas than CO_2 (according to US EPA) and other impurities such as H_2S are poisonous, so they must be decomposed into less harmful products such as carbon dioxide, water and sulphur dioxide by combustion before they are released into the atmosphere. These burning gases appear as gas flares in the flaring stacks of oil rigs. In the situations of emergency there flares help to burn out excess gas. The flaring may continue for many days, months or years depending on the amount of gas a well has, without any utilization of the energy being released. Mostly it is very difficult to achieve complete combustion of the associated gases, thus carbon particles or soot is produced as a result. Continuous flaring for long time especially in the Nigerian Delta has made the environment inhabitable. [1]

Mohammad Reaza Rahimpoura and Seyyed Mohammad Jokar [2] have proposed three methods to recover flare gas instead of conventional gas burning in flare at the Farashband gas refinery. The proposed methods are:(1) Gas to liquid (GTL) production (2) Electricity generation with a gas turbine (3) Compression and injection into the refinery pipelines. To find the most suitable method, the refinery units that send gas to the flare as well as the required equipment for the three aforementioned methods were simulated by them. The results showed that for the 4.176 MMSCFD of gas flared from the Farashband gas refinery, the electricity production gives the highest rate of return (ROR), the lowest payback period, the highest annual profit and mild capital investment. Therefore, the electricity production is the superior method economically.

Complete combustion of toxic gases is possible whenever air and combustible gases mix in stochiometric ratio. This is indicated by low or no smoke production. Besides this Flame shape control is one of the most important aspects of combustion. Control of fuel flow rate is not always feasible for a combustion phenomenon. Many oil

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refineries discharge large volume of combustible waste gases as flare. In case of flares from a refinery it is almost impossible to control the rate at which flare gases are to be released, since flaring is provided for safe operation of other equipments. The energy of flare is a wasted because of lack of control on them. It is implied that we cannot control rate of release of the waste gases. Open air flaring makes the oxidizer supply to become uncontrolled. The oxidizer supply from the environment is not sufficient to achieve a complete combustion. This is reason for black smoke during flaring. A wandering flame lowers the efficiency of heat transfer. If heat is transferred by radiation then a small flame may reduce flame efficiency. So a method that keeps flame shape big enough for higher radiation heat transfer and controlled enough for convection heat transfer is indispensible for high efficiency of heat transfer.

The attempt is to devise a method to control the flame parameters i.e area without obstructing its flow and utilize it for proposing a device which could harness energy from gas flares. The device should also satisfy the other requirements of an efficient flaring system such as no soot formation (complete combustion), enhanced turbulence for proper mixing of the gas with oxygen as the flame is non-premixed, isolation of flame from other disturbances like cross winds which may cause flame egression into the flare stack, existence of enough draught for aspiration of atmospheric air into the combustion zone (for which air assisted flares use fans), proper dispersion of thermal plume.

Visualization methods have been used to study combustion flames in laboratories. Shimoda [3] reported a combustion diagnostic system where the radiation energy and temperature profiles were quantitatively identified from flame images. Huang [4] set up a flame-flicker monitoring system, where the flicker of a gaseous flame was quantified by computing the oscillation of the radiant intensity of individual pixels within the luminous region of flame images. The flicker of a flame is an important physical parameter associated with the characteristics of a combustion process. This paper presented an instrumentation system developed for on-line continuous flicker measurements of combustion flames. The system comprised a high-speed CCD camera, a frame grabber and associated image processing software. The flicker signal was obtained by processing the radiation intensity of individual pixels within the luminous region of a flame image. Power spectral density analysis was performed to obtain the frequency components of the flicker signal. The quantitative flicker of a flame is defined in terms of weighted spectral components in the frequency domain and this definition has been proven to be well suited to quantification of the flickering characteristics of a flame. A tungsten lamp driven by a frequency-varying power supply was employed to calibrate the measurement system. The calibration results showed that the system was capable of measuring the flicker of an unknown light source with a relative error no greater than 3%. Lu [5] designed and evaluated an instrument system for monitoring, characterization, and evaluation of flames in a utility boiler. Geometrical and luminous parameters of the flame were determined from the images. However, few of the above studies used turbulent non premixed flames as objects.

Many researchers studied candle flame to understand a wide range of combustion phenomena. Carleton and Weinberg [6] had examined effect of electric field on flame deflection. Chan and T'ien [7] performed experimental work to study the spontaneous flame oscillation phenomena. Buckmaster and Peters [8] and Maxworthy[9] have both studied stability and flickering phenomena for diffusion flames. An experimental investigation to study the behavior of candle flames in high gravitational field has been reported by Arai and Amagai [10]. A research was conducted by Dillon and Anthony [11] on candles. The candles were burned experimentally under controlled laboratory conditions in order to measure the mass burning rate, regression rate, flame height, and heat flux. Dietrich and Ross with Shu and T'ien [12] studied candle flames in non buoyant (typically zero gravity condition) atmosphere. This paper addresses the behavior of a candle flame in a long-duration, quiescent microgravity environment both on the Space Shuttle and the Mir Orbiting Station (OS). As a flickering Flame is less efficient and is hazardous because it may induce temperatures too high than that of design temperatures. And even the most experienced operator will have difficulty in judging the enclosure configurations for high energy yielding and stable flame. In this situation, a monitoring system based on image analysis can become very helpful. In this experiment also, commercially available candle is used as the study object. To analyze the color images, a feature extraction based on multivariate image analysis (MIA) [13] techniques was developed. Further analysis of the image features can be performed using partial least squares (PLS) to help understand the relationship between the feature variables and the process variables, and to predict the performance of the flame. David Castiñeira, Blake C. Rawlings, and Thomas F. Edgar [14] have shown that how Multivariate image analysis (MIA), which is based on principal component analysis (PCA) and projection to latent structures (PLS), can be applied to flare combustion systems in order to predict their resulting combustion efficiencies, as a function of the crosswind velocity, using simulated results, and as a function of steam or air flow rates, using experimental tests of a full-size flare. The results show that a multivariate regression model based on flare color images can be used to predict the flare performance over a range of operating conditions for steam-assisted flares. Therefore, simple two-dimensional color images of industrial flares may be a fast, accurate, and inexpensive approach for online monitoring of these industrial combustion systems. This would allow for developing effective flare control and mitigation strategies.

In this experiment also the ability of an enclosure to control the flame has been examined by conducting tests with many enclosures of different diameters and angles of cone of the truncated conical entry.

Any device to tap the energy from flares would require a heat exchanger to transfer the energy to working fluid. If cylindrical enclosures are used then many literatures show that helical coiled heat exchangers would be the best choice.

It has been widely reported in literature that heat transfer rates in helical coils are higher as compared to those in straight tubes. These heat exchangers have compact structure and high heat transfer coefficients. Helical geometry enables handling of high temperatures and extreme temperature differentials without high induced stresses or costly expansion joints. D.G. Prabhanjan, G.S.V. Raghavan and T.J. Rennie [15] showed that use of a helical coil heat exchanger increased the heat transfer coefficient compared to a similar dimensioned straight tube heat exchanger. Both heat exchangers had higher heat transfer coefficients when the bath temperature was increased, most probably due to increased buoyancy effects. Flow rate did not affect the heat transfer coefficient, most likely from the fact that the flow was turbulent and increasing the flow rate does not greatly change the wall effects. Temperature rise of the fluid was found to be effected by coil geometry and by the flow rate. N. Jamshi, et. al.[16] have shown that the higher coil diameter, coil pitch and mass flow rate in shell and tube can enhance the heat transfer rate in helical heat exchangers and shell side flow rate, coil diameter, tube side flow rate and coil pitch are the most important design parameters in coiled heat exchangers. So it would be better to use helical coil heat exchangers from geometrical consideration as well as effectiveness of heat transfer, as a helical heat exchanger could be easily accommodated around the cylindrical enclosures. It will be in contact with the metal enclosure thus ensuring that the temperature of enclosure does not exceed the design temperature and at the same time it could expose the working fluid to the temperature desired to change its phase.

MATERIALS AND METHODS

1. System setup

1.1 The flame monitoring system

The flame monitoring system is shown in figure 1. The commercially available candles were used in this study. There may be a great change in the composition of wax but the candles with minimal composition transition from the same lot were selected for analysis. A digital color camera (CCD camera) was used to feed input to processing modules. The resulting images were RGB (Red-green-blue) color images, with a specific size. A favorable image sampling frequency was set by considering the processing time.

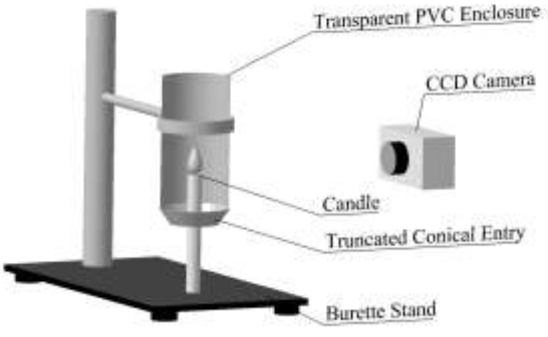

Fig 1 Experimental Setup

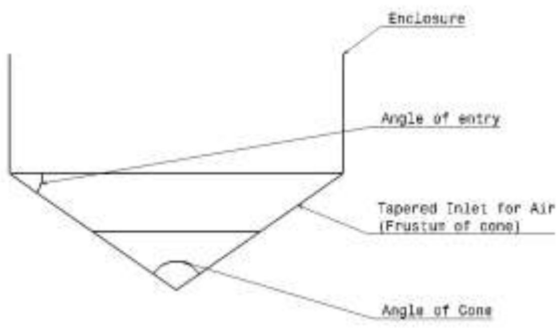

Fig 2 Relation between angle of cone and angle of entry

1.2 Apparatus

Transparent PVC enclosure with tapered inlet in the form of truncated cone was used in the present study. Figure 1 shows the schematic of experimental setup developed, which consists of a flexible mechanism for varying the enclosure height, digital camera connected to computer system and candle flame. The semicircular clamps allow use of various enclosure diameters. The taper angle at the inlet could be also changed by attaching frustums of different cones made with thin cardboard sheets. Top of enclosure is always open and the bottom of the enclosure has a tapered entrance in the form of a truncated cone. Since during the experiment the height of candle will be varied significantly, a new term is introduced as provided in equation 1.

$$\%\ \text{candle enclosed} = \frac{(Height\ of\ candle - Enclosure\ height\ from\ base)}{Height\ of\ candle} \quad (1)$$

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$$Angle\ of\ entry = 90 - \frac{Angle\ of\ cone}{2} \quad (2)$$

So, for a frustum of cone of *angle of cone* 135 degrees the *angle of entry* would be 22.5 degrees. This could be understood from figure 2. Henceforth the term 'angle of entry' would be used to differentiate tapered portions of different enclosures.

2. *Extracting features from flame images*

Every flame image is an RGB color image, in which the color of each pixel is characterized by the numerical values (normally integers from 0 to 255) of its R, G and B channels. A color image can then be expressed as a multivariate image composed of three channels of R, G and B. In this work, a practical method based on MIA techniques [13] is developed to extract feature variables from rapidly time varying flame images. Without considering the spatial coordinates of pixels, we can unfold the image matrix and express it as a two way matrix as in (3).

$$\underline{I}_{N_{row}\times N_{col}\times 3} \xrightarrow{\text{unfolds}} I_{N\times 3} = \begin{bmatrix} c_{1,r} & c_{1,g} & c_{1,b} \\ \vdots & \vdots & \vdots \\ c_{i,r} & c_{i,g} & c_{i,b} \\ \vdots & \vdots & \vdots \\ c_{N,r} & c_{N,g} & c_{N,b} \end{bmatrix} = \begin{bmatrix} C_1 \\ \vdots \\ C_i \\ \vdots \\ C_N \end{bmatrix} \quad (3)$$

Table1 Symbol Table

SYMBOL	QUANTITY
$\underline{I}_{N_{row}\times N_{col}\times 3}$	3-way Image Matrix
$I_{N\times 3}$	2-way unfolded Matrix
$S_{k,1}$	Total Intensity of kth Image stored in a column matrix.
C_i	i^{th} Row vector of I
$c_{i,j}$	intensity values of the j^{th} channel for pixel i .(j=1,2,3)
I_{Norm}	Normalized Intensity matrix for n number of images.
I_{Fluct}	Value of Normalized Intensity above and below Mean Intensity.

Where $I_{Nrow\times Ncol\times 3}$ is the three way image data array with image size $N_{row} \times N_{col}$ .I is the unfolded $N \times 3$ two-way image matrix, where $N = N_{row} \times N_{col}$. N is the number of pixels in every image. $c_{i,r}, c_{i,g}, c_{i,b} (i = 1,2,3 \dots N)$ are the intensity values of the R, B and G channels for pixel *i*. $C_i (i = 1,2,3 \dots N)$ is the i^{th} row vector of I, which represents the color values of i^{th} pixel. Whole vector elements of I matrix can be summed up along rows and columns to obtain the total intensity (4).

$$S_{k,1} = \sum_{i=1}^{N} \sum_{j=1}^{3} C_{ij} \quad (4)$$

Since the total intensity $S_{k,i}$ of a single image would be very large, to limit these values in a range of {-1, 1} normalization can applied for each image total intensity value using (5). This yields a column matrix I_{Norm} with as much elements as the no of image samples into which the video of burning candle inside an enclosure of given dimensions has been split into.

$$I_{Norm} = \left(\frac{S_{k,1} - S_{min}}{S_{max} - S_{min}}\right) \quad (k = 1 \dots N) \quad (5)$$

An intensity fluctuation matrix (6) can be calculated for each image in the image sequence and values can be plotted in time domain. Each intensity fluctuation value bears a one to one correspondence to a particular image in sequence.

$$I_{Fluct} = I_{Norm} - mean(I_{Norm}) \quad (6)$$

If the intensity fluctuation matrix in time domain is fluctuating too much producing a large no of peaks (40 or more) in each image sequence this may be most likely due to noise which crept in during experimentation. To obtain a smoother curve for data analysis an averaging low pass filter can be used. The filter oversees sharp fluctuations. The filtered image area under the curve can be found taking into consideration the polarity of fluctuation.

The flame area for each setup of enclosure can be obtained and plotted against the angle of entry. Each plot can approximated to a linear plot using partial least square technique. Thus the behavior of the flame with variation of angle of entry and diameter of enclosure can be studied by the above method. Similarly the numbers of peaks represent the fluctuation of the flame. Number of peaks could be also plotted against the angle of entry to determine the parameters of enclosure for which the flame is most stable.

3. Analysis in Ansys Fluent

Candle flames are laminar diffusion flames but the gas flares are turbulent flames resulting from a non-premixed combustion. The results from digital image processing could show when the flames would be most stable and when the flame area would be maximum. The result required further validation with turbulent flames. So to check whether the results obtained for laminar flames through image processing are also true for turbulent flames or not, a 2D analysis of enclosures in ANSYS FLUENT was also performed. The geometry of enclosure used for analysis has been shown in figure 3.

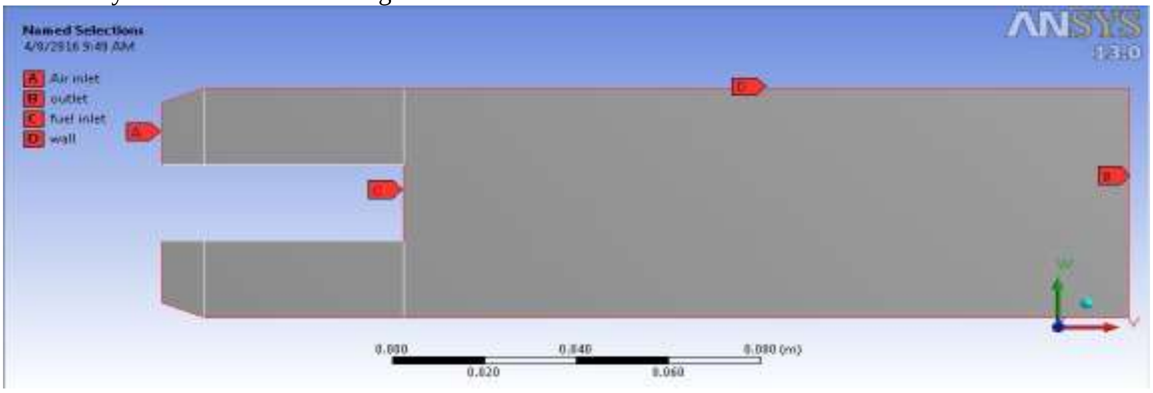

Fig 3 Geometry of enclosure for 2D analysis with the named selections.

In this analysis incompressible flow was assumed as the device would always operate under atmospheric pressures. As there was no swirl component a 2D planar space was selected for analysis. Energy equations were enabled and P1 radiation model was chosen as it works with minimum CPU demand. Standard k-ε model was used to model turbulence. Non-premixed combustion case was chosen to model the problem.

Creating the PDF (Probability Density Function) table is important to model the thermochemistry involved in the combustion process. This accounts for the interaction of turbulence and chemistry and the ensuing combustion of fuel. To create the table, mass fraction or mole fraction of various species that constitute the fuel stream should be previously known along with the adiabatic flame temperature and fuel stream rich flammability limit. ANSYS FLUENT interpolates the PDF during the solution of the non-premixed combustion model. Associated gases contain methane in largest percentage by volume. The composition of flare gas assumed in this case has been shown in table 2. For combustion cases, a value larger than 10% – 50% of the stoichiometric mixture fraction can be used for the rich flammability limit of the fuel stream.

Table 2 Species mole fractions in fuel stream (flare gas)

SPECIES	MOLE FRACTION
CH_4	0.965
N_2	0.013
C_2H_6	0.017
C_3H_8	0.001
C_4H_{10}	0.001
CO_2	0.003

3.1 Boundary Conditions

As the velocity at the air inlet and the outlet were unknown, pressure inlet boundary condition was applied to both of them. To model turbulence, Turbulence Intensity and Hydraulic Diameter condition was chosen at all the inlets and the outlet. The velocity of flare gases escaping the stack could be as high as 600 ft/sec [17] or approximately 182 m/sec. So an inlet velocity of 150 m/sec was chosen to be the inlet velocity for the fuel stream.

The material chosen for the enclosure was aluminum because it is lightweight as compared to other alternatives available. It has a melting point of 660.3 °C. So a constant wall temperature boundary condition with wall temperature of 500 K, which is well below its melting point, was chosen as boundary condition for the enclosure walls. This condition is also in agreement with the arrangement of helical coiled heat exchanger around the enclosure to transfer the heat released during the combustion process to the working fluid. In that case by suitably adjusting the mass flow rate of working fluid, the enclosure could be assumed to have a constant wall temperature.

RESULTS AND DISCUSSION

1. Time Domain Plots

The experiment was carried out in a closed dark room at night so that the videos captured from the cameras are exposed to a minimum level of noise from external light sources and any disturbance in atmospheric air. It was necessary to have a dark background in the image as the concern was only intensity of flame. This ensured that every pixel represents a non zero value corresponding to intensity of flame or zero, corresponding to the black portions in the background. Further to reduce any reflection of flame from the PVC enclosures, the rear portion of enclosure was covered with thin lampblack coated cardboard sheets. Lampblack is an excellent absorber of radiation. Its reflectivity is less than 1% [18] for wavelengths falling in the visual spectrum and reflects some ultraviolet radiations only, to which the CCD camera was insensitive. The experiment was carried out with candles of 2cm diameter. Videos were captured for 5cm, 5.5cm and 6cm enclosure diameters for 5%, 25%, 50% and 100% of candle enclosed each with angle of entry varying from 22.5° to 67.5° in the steps of 22.5°. From a 1 minute video an interval of 13.4 seconds was selected based on visual observation, in which abnormal fluctuations were least and the frames corresponding to that time period were analyzed.

Time domain normalized intensity plots were obtained for each enclosure, filtered to get the weighed area of curve and the no of peaks for the unfiltered curve was also determined simultaneously (figure 3). The flame could be characterized on two bases (1) Total flame weighed area is proportional to energy of a flickering flame. (2) Number of peaks is proportional to number of flicker in flame.

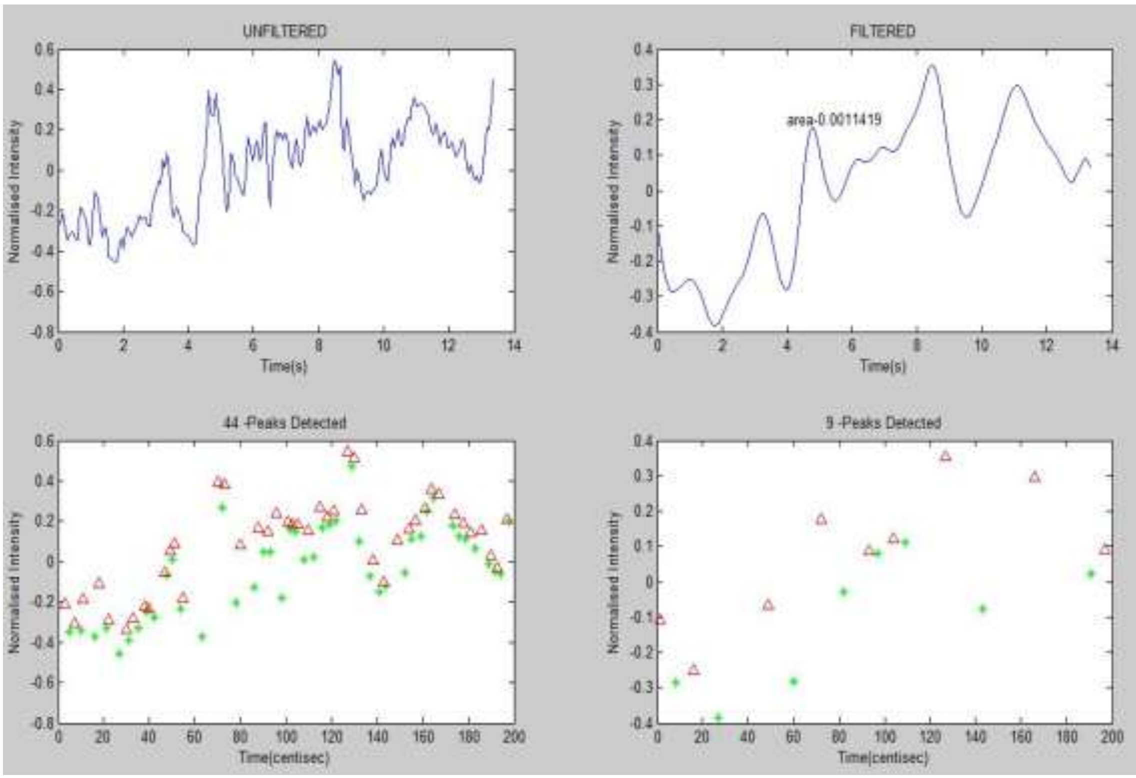

Fig 4 Unfiltered and filtered normalized intensity curves with peak detection for each curve for 5cm enclosure diameter, 22.5° angle of entry and 5% candle enclosed.

2. Determination of wall heat transfer rate from analysis in Ansys Fluent

Simulation in Ansys Fluent was performed for 6cm enclosure diameter with fuel being discharged at 25% of height from the tapered portion and angles increasing from 22.5° to 67.5° in the steps of 22.5°. Contour plots for velocity was also obtained for all the cases. Contour plot for velocity magnitude with 45° angle of entry has been shown in figure 7.

The heat transferred to the wall which has to be maintained at constant temperature of 500 K was calculated through simulation in Ansys Fluent. The data is displayed in table 3. The maximum velocity of combustion products at outlet and air at air inlet have been displayed in table 4 and table 5 respectively. These data are approximate as they were obtained by observation from contour plots for velocity.

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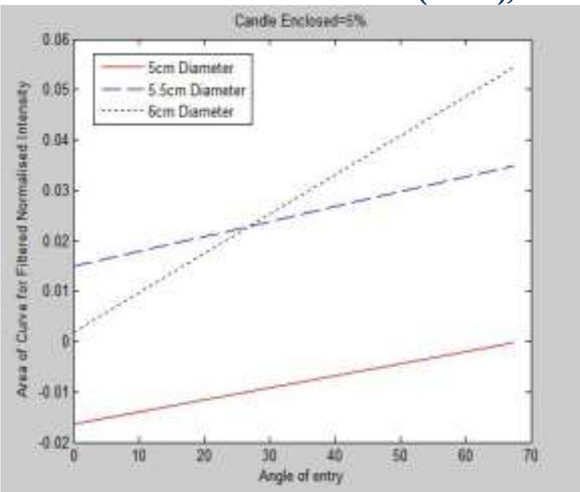

Fig 5 Area of curve for filtered normalized intensity versus angle of entry for 5cm enclosure diameter and 5% candle enclosed.

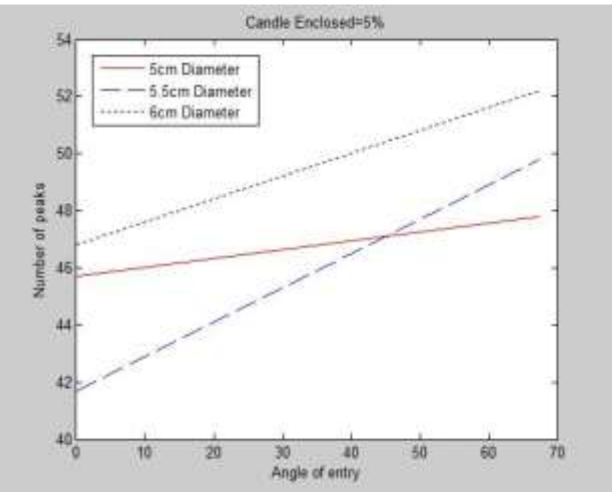

Fig 6 Number of peaks versus angle of entry for 5cm enclosure diameter and 5% candle enclosed.

Table 3 Heat transfer rate through wall for 6cm enclosure diameter.

Angle of entry	Wall Heat Transfer Rate (W)
0°	60.525
22.5°	167.187
45°	264.840
67.5°	359.610

Table 4 Maximum Velocity at enclosure outlet for 6cm enclosure diameter.

Angle of Entry	Velocity (m/sec)
0°	634
22.5°	640
45°	659
67.5°	667

Table 5 Maximum velocity at air inlet for 6 cm enclosure diameter.

Angle of entry	Velocity(m/sec)
0°	254
22.5°	256

45°	264
67.5°	200

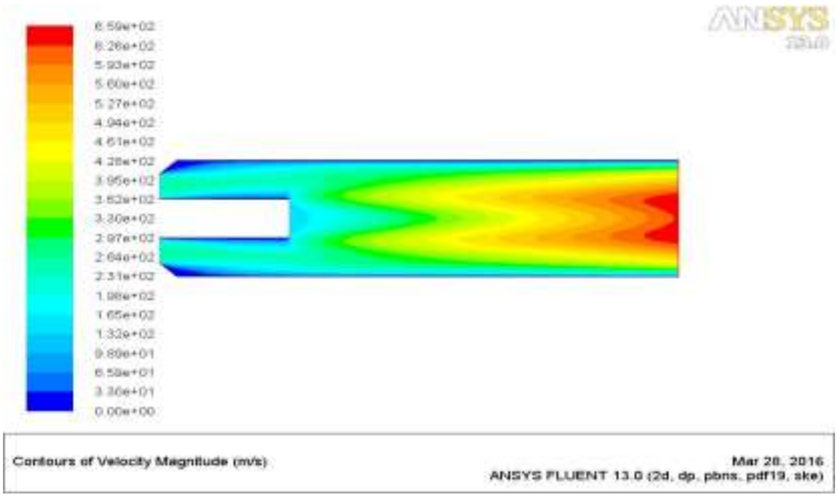

Fig 7 Contours of velocity magnitude for 6cm enclosure diameter, 45° angle of entry and fuel discharge at 25% of height of enclosure from the tapered portion.

3. Discussions

From the least square fitted plots of filtered normalized intensity versus angle of entry (figure 4) for each percentage height of candle enclosed, it was observed that the area of the flame goes on increasing with the angle of entry for a given percentage of candles enclosed for all the diameters. The normalized intensity curves are proportional to the weighed area of flame. Since all the images were obtained in a dark environment, so pixel intensity values of non-flame regions (dark regions) are zero. Pixels representing the flame are designated by a corresponding non zero pixel intensity. Positive flame intensity (area) indicates more flame area consequently high energy in flame. A negative area indicates that the flame area has shrunk as a result of oscillations and energy lowers.

From the plots of number of peaks versus angle of entry (figure 5) it was found that for smaller percentage of candle enclosed {0, 5} % and 100% candle enclosed the instability (flicker) of flame for all diameters increases with increase in angle of entry. As the flame has a tendency to become unstable at both the extremes some intermediate value may be chosen. A trade-off between the maximum energy condition and minimum instability condition could determine the best diameter for enclosure.

Analysis in Ansys Fluent shows that wall heat transfer goes on increasing as the angle of entry increases. This is in agreement with the result obtained from image processing technique. Larger is the flame area greater would be the heat transferred through radiation to the walls.

Further, the analysis from Ansys Fluent also shows that other requirements of an efficient flaring system could be also fulfilled by the enclosure.

(1) The maximum velocity of air entering into the enclosure as observed from velocity contour plots is around 264 m/s for 45° angle of entry. This ensures creation of turbulence for proper mixing of fuel with air necessary for complete combustion.

(2) It appears that, when the fuel escaping with such a high velocity is put inside an enclosure it somehow creates enough draught to draw air into the enclosure thus augmenting the oxygen supply which is essential for complete combustion of fuel. This will ensure that no soot is formed.

(3) An enclosure also isolates the flame from cross winds which cause egression of flares into the stack.

(4) The maximum velocity at the outlet as observed from velocity contour plots is near about 650 m/s in all the cases. Such a high velocity at the outlet ensures proper dispersion of thermal plume.

CONCLUSION

The experimental results and data obtained from simulation demonstrate that an enclosure of suitable dimensions can be used to control turbulent gas flares occurring in chemical and petroleum industries. This enables us to harness the energy of such flares. Moreover such enclosures could also ensure complete combustion of associated gases, inhibiting the production of sooty flames.

The schematic shown in figure 8 could be a possible design of a device to extract energy from the flares. It consists of an enclosure prepared from any material with adequate strength, good thermal conductivity and good resistance to corrosion. A helical coil heat exchanger could be fixed on the outer surface of enclosure through which working fluid will flow. This fluid will then pass through a prime mover and produce energy.

Fig 8 Schematic of a device to extract energy from gas flares.

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