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ORIGINAL ARTICLE

Investigation of Stability Limits of a Premixed Counter Flame

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ABSTRACT – The urgent need to improve premixed combustion processes in industrial furnaces and boilers is a major challenge; to power-increasing and reduces emissions. Many studies investigated the flame structure influences from the local extinctions perspective for different fuels. But, the stability limits for a premixed counter flame haven't been widely studied. In combustion operations, flame fronts are often spread in an irregular way. Therefore, the flame speed and temperature vary alongside the front of flame and rely upon the mixture composition asymmetry and the conditions of the local flow before the flame; especially this behaviour is evident in the double counter flames. The present research describes an analytical study of the stability limits of a premixed counter flame. This study is founded on experiments performed to identify the influence of changing the distance between the upper and lower burner edges on the stability limits at different equivalence ratio values; liquid petroleum gas (LPG) was used as fuel in experiments. The blow-off limit, disc flame limit, and double flame limit were investigated. The laminar counter flame model by using ANSYS 17.0 Premixed Flamelet Model (PFM) was used for simulating the counter flame of LPG and air mixture, under the influence of the distance between the burner edges. The outcomes experimental data were compared with the numerical and a good agreement was obtained. The experimental data and numerical analysis obtained manifested that the high stability for double flame, fuel-rich premixed flame operate over a narrow range of equivalence ratio (φ) from 0.43 to 1.41. The results elucidated that increasing the distance between the burner edges decreases the flame stability efficiency.

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Burner efficiency;
Blow-off

INTRODUCTION

In the past few years, improving premixed combustion operations in gas turbine and aircraft engines has become a significant challenge in order to reduce the NO_x emissions, providing a high mixing quality and low flame temperature. Moreover, the design of modern high-performance propulsion systems suffers from the major problem of combustion instability [1, 2]. Combustion instability generates an important issue concerning the self-sustained combustion oscillations in the combustion burners and igniters. The pressure fluctuations with an unstable rise in temperature are the cause of this closed-loop coupling. Furthermore, all these problems can induce unstable operations that resulted in the increased heat transfer at the combustion zone walls; finally, they may cause a whole blow-off [3, 4]. Also, many studies tested all the ways to determine the low typical frequency oscillations, which cause big mechanical vibrations in the system of combustion that may ultimately cause a blow-off [5, 6]. Combustion operation of the gas-air mixture is oxidation via a source of heat in the flow of mixture, and spreads comparatively to the flow into the unburned gas that consumes the reactants and leaves behind hot products [7]. In the applications of combustion, flames are often spread in an irregular and corrugated way and rarely in an ideal manner. Therefore, the flame speed and temperature and vary alongside the front of the flame and rely upon the mixture composition asymmetry, the heat loss, the spread of the different species that include the mixture, and the conditions of the local flow before the flame [8, 9]. The counter flame or the double opposed flame depends on the stabilisation of flames between the counter-flowing burners when all these burners deliver a premixed gaseous fuel and oxidiser mixture [10]. So, the flame front for both sides appeared at the stagnation limit, and this type of premixed flame will be visible [11-14].

In recent research, the flame quenching limit in a laminar flame is a subject that attracted consideration. A non-premixed flame being locally quenched; the edge of flame does exist at the reaction zones extremity, where the flame increasingly develops to incompletely premixed flames [15], as shown in Table 1. The rate of crucial strain to quench the incompletely premixed flames is affected via the incomplete premixing degree. For the laminar flames, the experimental and theoretical investigations [14, 15] utilising a counter flow pattern revealed that the incomplete fuel premixing to the air stream could raise the strain rate of quenching, while the air incomplete premixing to the fuel stream can reduce the crucial strain rate of quenching. In the high Reynolds no. turbulent flames, the process of quenching is highly intricate. In an experimental investigation of incompletely premixed flames [16], it was depicted that the air premixing to the fuel stream can reduce the system of flame stability, which is reliable with the laminar flame outcomes of [17, 18]. Nevertheless, a moderate air incomplete premixing to the fuel stream can also enhance the stability of combustion. Preceding investigations, at a specific state of premixing, have evinced that the stabilisation of flame in the disc is owing

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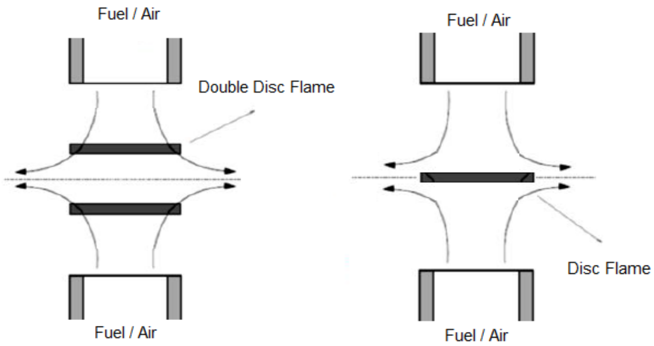
to the existence of double flame at the leading front of flame in the zone of recirculation, that created via the ambient air entrainment to the disc [19-24]. The fundamental physics behind this requires further investigation. The most problem of the inherent instability of flame is the hydrodynamic resulting from the expansion of burned gases, resulted from the heat that released through the process of combustion, which generates hydrodynamic factors to improve the flame front change [9, 11].

Table 1. Stabilisation positions of the counter burner flame.

<table>
<tr><th>Type</th><th>Reference</th><th></th></tr>
<tr><td>Premixed flame</td><td>Watson [15], Jassim [19], Yan [24]</td><td>
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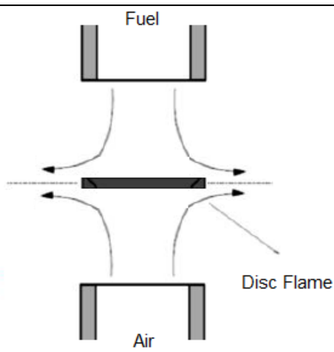
<tr><td>Diffusion flame</td><td>Kumaran [4]; Korusoy [7]</td><td>
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The literature review exhibited that numerous researchers have investigated the flame stability influences from the local extinctions perspective for different fuels. But, the effects of a distance between the burner's edges and nozzle burner diameter on the stability limits haven't been widely studied. In the outlook of the debated literature reviews and so as to address the identified literature gap, the present study experimentally investigates the stabilisation characteristics of counter premixed flame for different fuel/air mixtures and numerically analyse the counter flames structures at different conditions. For generating counter premixed flames from different mixtures, the laminar counter flame burner described in [25-30] is adopted.

EXPERIMENTAL SETUP

Combustor Set up and Diagnostics

The device in this research comprises a counter burner system and an optical system. Via this counter burner, a mushroom-shaped tented flame was arranged; the fuel and airflow rates were measured. Recording the mushroom-shaped tented flame front images needed for this investigation and was achieved via the optical system. Figure 1 depicts the components of the device. The counter burner system includes two counter copper tubes at 30 mm diameter, with each one has an end edge of 15 mm diameter. These burners were fixed by a vertical frame made of steel, while changing the distance between the burner's edges can be done. In this type of combustion process, the LPG and air were premixed before reaching the edge burner. To prevent the interference of the ambient air near the burner edge in the combustion process, the combustion region was surrounded with a nitrogen container (a transparent polycarbonate container was used; it was filled by the nitrogen gas during the experiments). Four gas flow meters were used to measure the flow rates for LPG and air, with metered individually (± 1.1% accuracy) during the experiments. The calibration of such reactant flow meters at the mass flow controllers exit was conducted utilising a RITTER Drum type (enable a measuring accuracy of ± 0.2% at a standard flow rate and approximately ± 0.5% over the whole measuring range). Air and LPG were fed to the combustor zone at the ambient conditions of 1 atm and 303 K. A wide range of equivalent ratios has been tested, where the flow rates of both gas and air were controlled to obtain the volumetric mixing ratios.

The optical system comprises a laser source (He-Ne) having low power of 0.21 mWatt, a wavelength of 713 nm, and a set of lenses. A digital camera setup, Phantom VEO 440 with 100~180 fps speed, was used in the experiments. Images were acquired at a resolution of 1280 × 720 dpi. The camera was located on a stationary base in the test rig front at an angle of 90º for the laser path. Also, the optical alignment alongside the section of the test rig was inspected and verified. Images for the counter flame stability limits with high contrast have been obtained by changing the distance between the burner's edges at 30, 50, and 70 mm, respectively. The counter burners are considered the most complex and difficult ones in terms of flame stability, but they give a high accuracy in the results. The basic principle of raising the flame stability efficiency of counter burners is to increase the aerodynamic and to create vorticity at the surface of the stagnation zone. For that, these three distances were used to compare the experimental data in order to improve accuracy. The front of the counter flame of LPG-air for a broad range of equivalence ratios (0.43 < φ < 1.41) at blow-off, disc flame as well as double flame limits were tested.

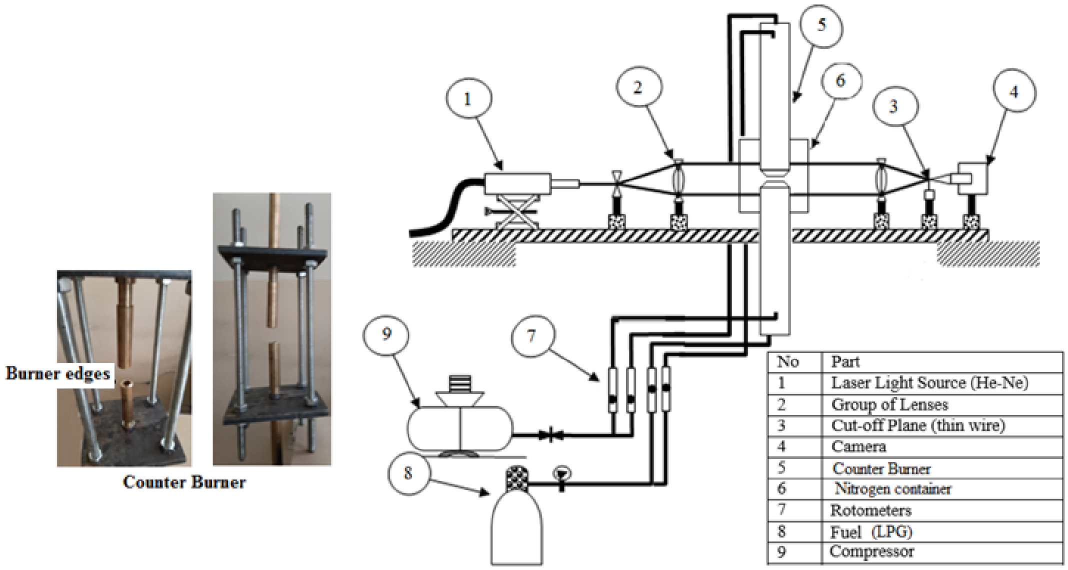


Figure 1. Experimental procedures and optical system.

Digital Image Processing

The technique of image processing has been broadly utilised in the investigation of a premixed laminar flame. The principal aim of this method is the flame boundaries detection, especially from the flames' edges which aren't visibly noticeable, thus causing it hard for identifying the edges of the flames by a simple technique of detection due to the low contrast ratio for these boundaries. Thus, it's too essential to implement digital image processing techniques for the raw images prior to analysing them. In order to process the image processed efficiently, a MATLAB software program was evolved and utilised for extracting the information from the registered images. This program includes two stages; the identification of a flame front; and the flame parameters verification. The schematic of image processing employed in this investigation is revealed in Figure 2. In the first stage, an image subtraction was utilised for reducing the background noise. Thus, a calibration image was obtained without combustion; it was subtracted from every image for providing the flame front image with a decreased background noise. In the second stage, every image was transformed into a binary one utilising a threshold of about (0.8-0.85). The output image alternates the whole pixels in the input image with a luminance more than a threshold with a value of 1 (White) and alternates the whole other pixels with a value of 0 (Black), where it was possible to suppress the light structures linked to the image. In the third stage, certain morphological functions were utilised for improving the image quality and the shape of the flame front. Eventually, the images with the flame front were arranged for quantitative analysis, like the measurement of the diameter of the disc flame. Depending upon the limited critical theory, the speed drop, g (1/sec) from measuring the unburned gases flow rate at blow-off, disc flame, and the double flame limits is given as [31, 32]:

$$g = \frac{8V_o}{D_t} \tag{1}$$

where, V_o is the unburned gas velocity (m/sec), and D_t is the burner edge diameter (mm).

For each case, 100 images of subsequent data were used to study the flame stability analyses, which are more than enough for a convergence study to be conducted on this particular data set. The data are read in first with the first 5 binary frames, and then the first 50, until 100, is reached. All these data sets are treated independently, and the statistics are compared to determine whether the stability limit statistics converge at 100 image sets or not. The stability limit was adopted to determine the extent of the case of the counter flame from the burner edge. The lean blow off limit is assessed by reducing the LPG flow rate while keeping the airflow rate constant. Flame stability efficiency was calculated by statistic representing the parameters (Re-δ) (Re: Reynolds number, δ: LPG mass fraction) for all cases.

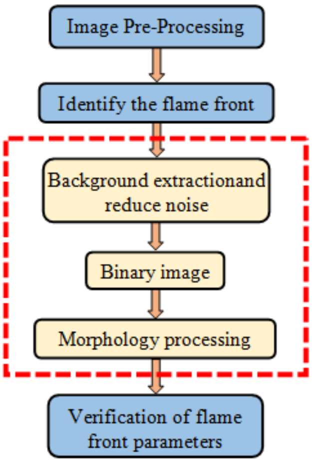


Figure 2. Flowchart of the digital image processing algorithm.

Analysis of Uncertainty

The analysis of uncertainty was conducted upon the experimental data for evaluating the uncertainties in measurements. In each measurement, the entire uncertainty can be found via the combination of the measuring accuracy and the instrument sensitivity. The addition of individual errors at the same time, nevertheless, can cause a worse state of uncertainty value. The components of error are improbable to be at their greatest value and similar polarity simultaneously. A highly realistic technique is to utilise the root-sum-of-squares approach by taking the square root of the individual errors summation [33].

$$\varepsilon_{\text{total}} = \sqrt{(\varepsilon_{\text{sensor}})^2 + (\varepsilon_{\text{instrument}})^2} \tag{2}$$

$$\text{Minimum and maximum uncertainty } (\%) = 100 \times \left(\frac{\varepsilon_{\text{total}}}{\text{Minimum and maximum reading}}\right) \tag{3}$$

where, ε_{total} is the total uncertainty. The percentage of uncertainty to the minimum and maximum values of the registered data was computed from the flow rate of air, fuel flow rate, and flame temperature. Table 2 depicts the percentage error of the uncertainty of the experimentally measured values.

Table 2. The percentage error of uncertainty to the minimum and maximum values of the registered data.

Parameter	Min. for the registered value	Max. for the registered value	Min. and max. (%) error of uncertainty
Airflow rate	42 SLPM	97 SLPM	0.44 - 0.40%
Fuel flow rate	11 SLPM	32 SLPM	0.19 - 0.13%

COMPUTATIONAL MODELLING

Methods of Numerical analysis are an efficacious tool for representing mechanical problems and analysing the physical phenomena for engineering uses. In this work, commercial computational fluid dynamics (CFD) software (ANSYS 17.0) Fluent Premixed Flamelet Module with pre-processing was used to model and simulate the stationary flame, double counter vertical burners. There're some steps conducted for performing the simulations. This simulation is interested in the dynamics of double counter flame through double vertical burner according to the research objectives.

Premixed Double Counter Flame

A three-dimensional model of the premixed fuel gas-air vertical counter burners was prepared in ANSYS software. A CFD model was used to study the stability limits for the premixed double counter flame burners, blow-off, disc flame, and double flame front at changing different parameters: dynamical premixed fuel gas/airflow and the distance between the double counter burner's edges. The highly significant parameters of simulations are manifested in Table 3. The CFD model has been established at several assumptions;

i. Unsteady 1D laminar flame in the external zone.
ii. Unburned gases flow of fuel/gas mixture in the internal zone, it's assumed that the fuel gas and air are blended together consistently, that the ratio of fuel gas to air is of unity order, and the phenomena of evaporation can be ignored.
iii. There's no reaction between fuel gas and air before the combustion process, and
iv. It is assumed that both gases (fuel gas and air) are treated as two interacting continua, and their densities remain constant.

Table 3. Important parameters of the simulation model.

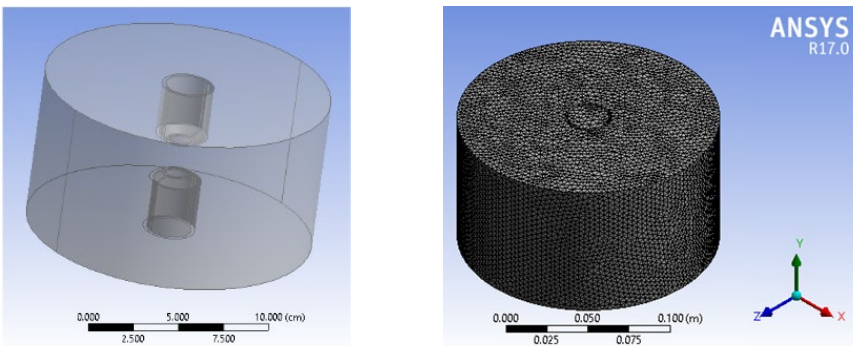
Parameter		Value
Internal zone diameter		30 mm
burner edge diameter		15 mm
External zone diameter		150 mm
Fuel	LPG	Propane 70% w/w
		n-Butane 17.5% w/w
		Isobutane 12.5% w/w
Inlet boundary conditions	Air	Fuel
Density	1.184 kg/m^3	0.884 kg/m^3
Axial velocity	0.7 -1.1 m/s	0.03-0.12 m/s
Temperature (K)	303 K	303K

The first step in the numerical simulation is the preparation of a computational domain. The dimensions of the premixed double counter geometry is acquired from the experimental setup as given in Table 4. The geometric model of the fuel gas-air burners is displayed in Figure 3. These burners are designed for the production of a premixed stationary counter flame. The burner edge is 15 mm while the fuel gas-air mixture is flowing through the top and bottom cross-sectional area of the burner's edges. There are three schemes with different distances between the burners (at 30, 50, and 70 mm).

Table 4. Nodes and elements for double counter burners.

Distance between burner edges, H	Scheme properties	
	Nodes	Elements
Scheme-30 mm	88893	491334
Scheme-50 mm	95678	556789
Scheme-70 mm	103428	678431

The significant step in the computational model is the creation of the computational grid that comprises computational cells. Governing equations are resolved in the computational cells. The flow of fuel gas-air and the field domain of combustion were meshed by tetrahedral elements utilising unstructured meshing that was chosen due to the intricate geometry. The recommended method for eliminating the mesh size effect is to look for the mesh autonomous solution that has been tracked. The optimal size of the grid was chosen, where the solution isn't influenced by the size of grid. For one of these cases, the number of elements was 556789. Study of the mesh refinement has been achieved for developing outcomes throughout increasing the used cells number. Results have appeared that the increase of cell number to 632222 and 789555 possesses no influence upon them. Consequently, 556789 number of elements was chosen to be the active number of elements that can be utilised in the simulation. Figure 3 illustrates the 3D meshed geometrical model of a double counter burner. The highly precise and comparable outcomes for flame front between burners edges; stability limits (blow-off, disc flame, and double flame front) were determined via the scheme of fine meshing. Therefore, the fine mesh was chosen for performing the simulations and the outcome explanation. The nodes and elements of the fine mesh for all schemes represented in Table 4.



(a) Geometric of numerical region (b) Geometrical mesh of burner

Figure 3. Computational domain prepared of three schemes of premixed gas fuel-air counter burner processing.

Premixed Flamelet Models Theory

Whereas the merely possible configuration for the premixed flamelets in one dimension is the opposed flow, one-dimensional steady can possess some configurations. These comprise unstrained non-adiabatic burner-stabilised and the unstrained adiabatic easily spreading. The equations of the one-dimensional adiabatic premixed flame can be converted from the physical space into the reaction progress space [25-31]. Neglecting the different diffusions, these equations are:

$$\rho \frac{\partial Y_k}{\partial t} + \frac{\partial Y_k}{\partial c}\omega_c \doteq \rho X_c \frac{\partial^2 Y_k}{\partial c^2} + \dot{\omega}_k \tag{4}$$

$$\rho \frac{\partial T}{\partial t} + \frac{\partial T}{\partial c}\omega_c \doteq \rho X_c \frac{\partial^2 T}{\partial c^2} - \frac{1}{c_p}\sum_k h_k \dot{\omega}_k \left(\frac{\partial c_p}{\partial c} + \sum_k c_p . k \frac{\partial Y_k}{\partial c}\right)\frac{\partial T}{\partial c} \tag{5}$$

where, Y_k is the kth species mass fraction [-], T is temperature (K), ρ is density of fluid (kg/m^3), t is time (sec), $\dot{\omega}k$ is the rate of the kth species mass reaction (kg/sec), hk is the entire enthalpy (J), and cpk is the kth species specific heat at a fixed pressure (J/kg.K). The rate of scalar-dissipation, Xc [-] in Eq. (4) and Eq. (5) is defined as:

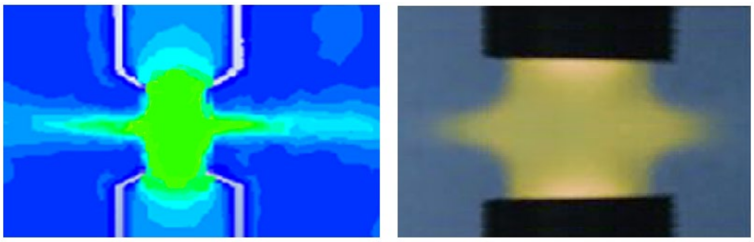
$$X_c = \frac{\gamma}{\rho c_p}|\nabla c|^2 \tag{6}$$

where, γ is thermal conductivity (W/m.K). Notice that the Xc changes with c, and it's an input to the set of equation. The values of the input parameters, which are the fuel gas-air flow velocities and the A/F percentage values, to the premixed flamelet cases, were determined from the measured data of mixture from the experimental test. The experimental factors being measured at the entry of the counter burner of all modeller's schemes and modeller for the fuel gas-air mixtures, as depicted in Table 2. After that, the numerical simulation was also performed for similar experimental factors. The numerical simulation of all modellers was successfully conducted via the outcomes in comparison with the experimental measurements. An additional assessment was carried out via implementing substantial values of similar parameters for studying the influence of raising the air-fuel gas ratio and the combustion models types on the stabilisation limits. Moreover, changing the vertical distance between the burner edges was performed by using three values (of 30, 50 and 70 mm), and the increased air-fuel gas ratio of the entry parameter was represented by a new evaluation variable. The said parameters were regarded as an inlet to the computational fluid dynamics simulations, whilst the parameters of output were associated with the distribution of the volume fraction of the flame front as well as the velocity of the unburned gas.

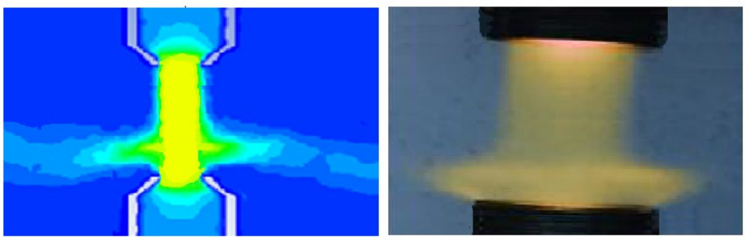
RESULTS AND DISCUSSION

Sensitivity Analysis on Flame Front Position

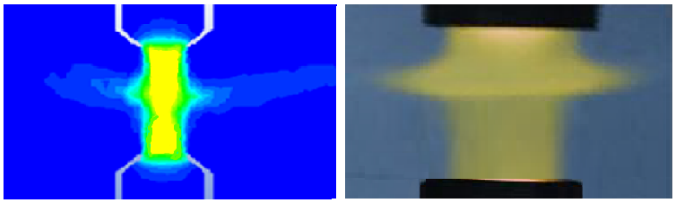
For understanding the influence of various distances between the burner edges on the flame front position and stabilisation limits, numerical simulations were conducted for three various cases. Within the first case, three-dimensional simulations were performed by taking the distance between edges, H= 30 mm, into account, while the initial condition was achieved at an equivalence ratio of 1.0, and the results of the burned gases volume fraction manifested a disc flame at the mid of the distance between the burner edges, as demonstrated in Figure 4(a). The results evinced that increasing the distance between the edges of burner at H= 50 mm and H=70 mm causes the fluctuation of the disc flame soon to the upper edge and the lower edge of burner, as revealed in two cases in Figures 4(b) and 4(c).



(a) disc flame at H=30 mm



(b) disc flame at H=50 mm



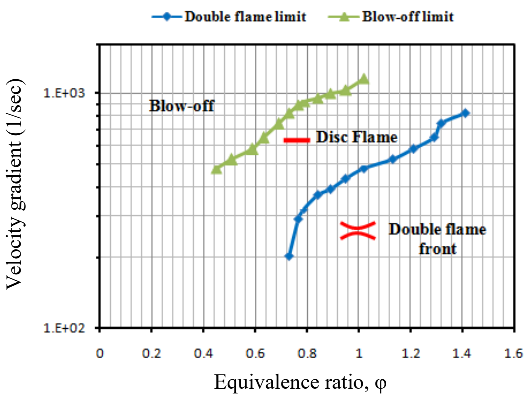
Numerical
Burned gases volume fraction

Experimental

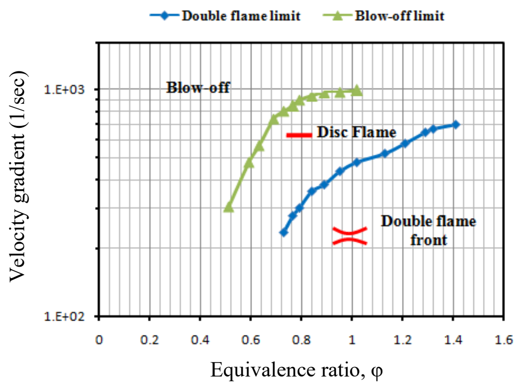
(c) disc flame at H=70 mm

Figure 4. The burned gas volume fraction contours and the experimental images of the LPG disc flame.

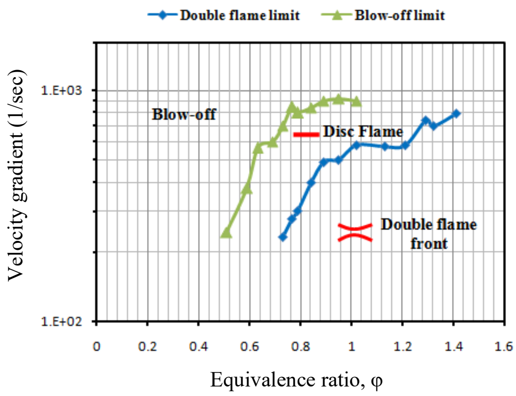
Figure 5 elucidates the change of the stability limits with the equivalence ratio. Within the experiments, a mean velocity, V_o, of gas throughout the burner edge being taken, and a premixed flame being stabilised upon the burner. There are three main limits of operation of the counter burner: blow-off, double flame, and disc flame as depicted in Figure 5, in terms of the flow rate of air and fuel from the edge of burner. In addition to the homogeneous mixture, the flow angle of the mixture and the largest area of vortex and mixing give complete combustion of the reactors. This leads to an increase in the velocity of reaction and diffusion due to the increased heat transfer between the reactors, and therefore it increases the temperature of the mixture. Furthermore, the results exhibited that increasing the distance between the burner edges caused an increase of blow-off and the double flame limits at the expense of decreasing the disc flame limit.



(a) H=30 mm



(b) H=50 mm



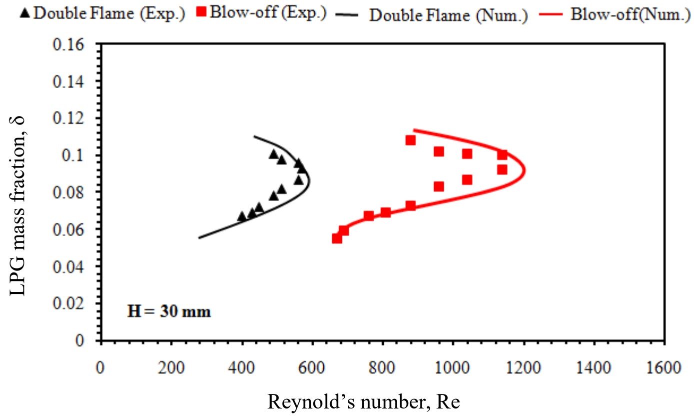
(c) H=70 mm

Figure 5. Change of the stability limits with the equivalence ratio.

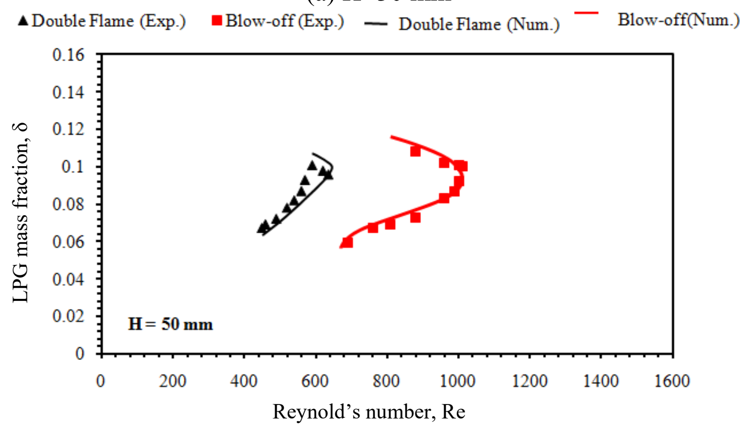
Flame Stability Efficiency

Experiments and numerical analysis have shown, increasing the distance between the counter burner edges reduces the area of disc flame front within the limits of the parameters (Re-δ) (Re: Reynolds number, δ: LPG mass fraction), as shown in Figure 6. The area within the double-disc flame limit and the blow-off limit curves displayed in Figure 6 is observed via A_D and A_B, correspondingly. The total of stabilisation for disc fame, A_T, is characterised as the discrepancy between the area of blow-off and the area of double disc ($A_T = A_B - A_D$) upon the (Re-δ) curves. The flame stabilisation efficiency (η) of the counter burner was defined as the following equation.

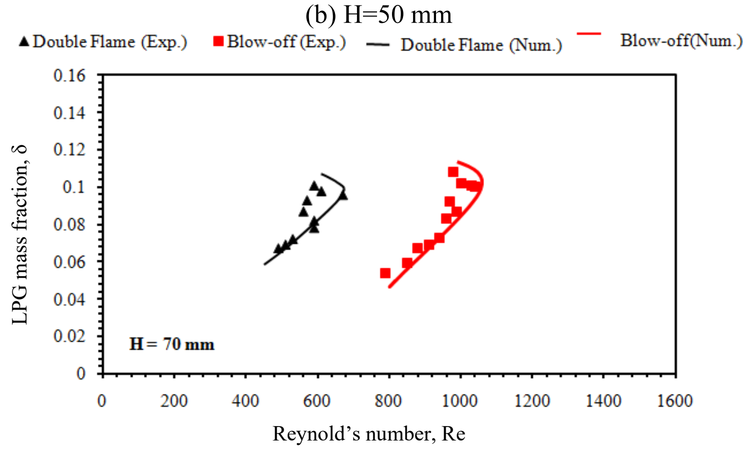
$$\eta = 1 - \frac{A_D}{A_B} = \frac{A_T}{A_B} \tag{7}$$



(a) H=30 mm



(b) H=50 mm



(c) H=70 mm

Figure 6. Flame blow-off and double flame stabilisation contours for the LPG-Air premixed flames at different distances between burner edges.

The flame stabilisation efficiency for the counter burner can be decreased by increasing the distance between the counter burner edges; in other words, the stabilisation efficiency decreased by decreasing the disc flame area or reverse. The experimental and numerical results for the flame stabilisation efficiency are presented in Table 5.

Table 5. Comparison of the experimental and numerical results for the flame stabilisation efficiency

Distance between burner edges, H (mm)	Flame stabilisation efficiency (%)	
	Experimental	Numerical
30	83.41	86.33
50	76.23	77.98
70	67.92	68.44

CONCLUSION

Several experimental and numerical investigations have been employed to consider various stability limits for counter flames, giving information upon the interaction between the dynamic processes of fluid and the chemical reactions occurring in the burner: The dynamic instabilities of fluid can activate the whole flame extermination, where a re-ignition of flame would be anticipated regarding the diagrams of stability. The present research characterises an analytical study of the stability limits of a premixed counter flame. This work is founded upon experiments that were conducted to identify the influence of changing the distance between the upper and lower burner edges on the stability limits at different values of equivalence ratio (air-gas mixing). The blow-off limit, disc flame limit, and double flame limit were investigated. The laminar counter flame model by using ANSYS 17.0 Premixed Flamelet Model (PFM) was used for simulating the counter flame of LPG and air mixture under the influence of the distance between the burner edges. The outcomes experimental data were compared with the numerical, and a good agreement was obtained. From the analysis of the results, the drawn conclusions are as follows:

i. The experimental data and numerical analysis showed that the high-stability for a double flame, fuel-rich premixed flame operates over a narrow range of equivalence ratios, φ, from 0.43 to 1.41.
ii. The results appeared that increasing the distance between the burner edges decreases the flame stability efficiency.
iii. Comparing the CFD simulation results and the experimental measurements of changing the flame stability efficiency with the separation distance from the burner edges evinced a good agreement. The mean percentage of the difference between the experimental measurement and the CFD simulation for distances of 30, 50, and 70 mm is 3.2%, 1.7%, and 1.54%, respectively.

It's strongly recommended to envisage the laminar flames within a counter burner with a high flow pattern. Further studies could continue to elucidating the exact physical basis for the observed correction of the stability laminar counter flame. All of the tests presented in this work were for atmospheric flames. If the industrial furnace applications are to be targeted, future work must consider the elevated pressures and temperatures.

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