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FULL PAPER

Predicting relationship among hydrogen flame length, flame ports, and volume flow for efficient burner design: an experimentally validated theoretical approach

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A total shift from fossil fuel based economy to green hydrogen based economy requires major technological upgrades and theoretical understanding. Hydrogen is a difficult fuel and unlike other fossil fuels, its flame characteristics differ in terms of flame speed, flashback, length, heat transfer, visibility, etc. In this study, a theoretical approach has been presented to estimate flame length in relation to orifice size, number of orifices, and volume flow rate of hydrogen. The theoretical approach is based on velocity and volume flow changes with reference to orifice size. The approach has been validated experimentally using various volume flow rates and orifice sizes. It has been observed that flame length has a permanent direct relation (increase in mass flow increases flame length) with flow rates. However, the flame length increases with an increase in orifice size (by keeping the flow rate constant) to a certain orifice size, and then starts decreasing. Further increase in orifice size results in flashback. It has been estimated that the flashback occurs when the velocity of hydrogen falls below a certain value i.e. 10 m/s. Moreover, gas velocities, higher than optimum due to very small orifice size prevent ignition to occur at all.

KEYWORDS

Burner design; clean combustion; hydrogen; modeling; renewable.

Introduction

The unprecedented climatic events and the devastating consequences in turns of flash floods, sudden rise and drop in temperatures, unexpected and extreme weathers throughout the globe warrant swift, and decisive push towards reduction in greenhouse gas (GHG) emissions associated with human activities and fossil fuels [1,2]. Renewable energy sources such as solar, wind, and hydropower, etc. have been considered as potential replacement for fossil fuels however, the main challenges are their intermittent nature and cost. The importance of storage assets in this regards have been greatly emphasized and hydrogen as energy carrier has been realized as one of the major asset due to its ease in integration with primary energy mix and current infrastructure [3].

Hydrogen when burn produces only water as by product, which idealize its use in combustion applications. Hydrogen has the potential to replace natural gas and liquid petroleum in combustion applications, however, due to its different combustion characteristics, the current infrastructure requires minor to medium modifications [4]. Hydrogen due to its low molecular weight and associated thermal to mass diffusion ratio (Lewis number) cannot be burned using same burners for natural gas. The Lewis number for lean hydrogen and air flame is approximately 0.3, whereas it is around 1 for natural gas and air mixture. Another property which effect the flame stability is the space speed which is approximately 6 times more than natural gas at stoichiometric mixture ratios. Moreover, the quenching distance for hydrogen flame is much smaller compared to the other hydrocarbon based flames which requires more careful design of the flame ports. Other related challenges are: (1) high risk of flashbacks at higher volumetric follow rates and (2) high burning temperatures associated with hydrogen flame. The flame temperature of hydrogen is around 280 C. All these challenges require deep investigation of flame characteristics as well as experimental data [5,6].

A recent study investigated the effect of flame velocity, flame port orifice diameter as well as flame port length. The simulated study reported that all the parameters such as fuel to air ratio, flame port thickness, flame port orifice size, and flame burning velocity needs to be optimized to avoid flashback. The study further concluded that the leaner mixture enhances the flame speed which causes the flashback limit velocities to scale less well with the adiabatic unstretched flame speed. Moreover, increase in slit width tend to increase the risk of flashback at constant flow rate. Furthermore, the study concluded that the slit thickness tend to reduce the flame port temperature and, in turn, reduce the risk of flashback [7]. Another study investigated the use of pure hydrogen as fuel for gas turbine. The study highlighted that the flame speed of premix fuel is of utmost importance to design proper burner to avoid flashbacks. To overcome this issue, fuel flow velocity needs to be optimized and adjusted based on the number of flame ports and combustor design [8]. The blending of hydrogen with other hydrocarbons have been also suggested to lower the laminar velocity of flame. The study concluded that hydrogen enrichment with heavier hydrocarbons such as propane leads to lower velocities compared to methane [9]. A recent study investigated the relationship among hydrogen pressure, orifice size, and flame length to assess the risk of accidental hydrogen leaks and fire. The study concluded that the flame length is highly dependent on orifice size and pressure. At hydrogen pressure of 82 MPa and 7.16 mm orifice size, the maximum diffusion distance was approximately 53.50 m [10,11]. Another study investigated the effect of nozzle geometry on the hydrogen flame length. The diameter of the spouting nozzle downstream has been varied from the choked nozzle upstream. The study concluded that the complex geometry of nozzle (i.e. two component nozzle) increases the flame length compared to single nozzle. The study further concluded that the effect of spouting upstream nozzle is pronounced for lower mass flow rates and tend to vanish for higher mass flow rates [12]. Another study concluded that the coaxial mixing of air with hydrogen rich fuel increases the pre-mixing, however, tend to reduce the flame length [13]. In another study, the flashback event has been investigated for low swirl injectors. The study suggested that flashback is related to distance between flame and nozzle which, in trun, is dependent on pressure and bulk velocity [14]. A numerical investigation on efficiency of hydrogen combustion has been performed. The study suggested the use of slits on both sides of bluff body of micro-combustor for uniform temperature distribution [15].

In this study, a systematic experimental study has been performed to investigate the effect of flow rate and orifice size on the flame length. A mathematical approach has also been presented based on HySafer model to predict the flame length in relation to flow rate and orifice size. The novelty of this study was to present an initial estimation of designing multi-orifice burner for premix hydrogen and oxygen fuel. This approach will allow the burner designer to theoretically calculate the orifice size, number of flame ports, and estimated flame length.

Materials and methods

Theoretical model

The methodology has been developed based on the stoichiometric ratio of hydrogen and oxygen mixture at atmospheric pressure and temperatures. The orifice shape remained circular (drilled hole). A copper tube of 10 mm outer diameter and 9 mm inner diameter has been used to create holes of various sizes using a hand drill.

First, the density of hydrogen and oxygen mixture (stoichiometric ratio) has been calculated using Equation (1).

$$density\ of\ gas\ mixture\ \left(\frac{kg}{m^3}\right) = (density\ of\ H_2\ x\ 0.67) + (density\ of\ O_2\ x\ 0.33) \qquad (1)$$

In the second step, the velocity of gas mixture was calculated against fixed parameters of orifice size and give gas mixture flow in liters per minute as presented in Equation (2):

$$Vao\ \left(\frac{m}{s}\right) = \frac{\left\{\frac{\left(\frac{flow\ rate\ (lpm)}{60\ (unit\ conversion)}\right)}{1000\ (unit\ conversion)}\right\}}{\frac{\pi\left(\frac{orifice\ diameter}{2}\right)^2}{1000000\ (unit\ conversion)}} \qquad (2)$$

Where, Vao is the velocity of gas mixture at the outlet of orifice.

The third step includes the calculations of mass flow rate of gas mixture in orifice. This factor has been calculated using Equation (3) by keeping orifice size and gas mixture flow rate constant.

$$Mo\frac{g}{s} = \{density\ of\ gas\ mixture\ x\ 1000\ (unit\ conversion)\}\ x$$
$$orifice\ area\ (m^2)x\ velocity\ of\ gas\ mixture\ in\ used\ pipe\ \left(\frac{m}{s}\right) \qquad (3)$$

Where, Mo in g/s is the mass flow rate of gas mixture from the orifice To further ease the calculations, the Mo has been converted to volume flow rate in liters/hr using unit conversion approach as described in Equation (4):

$$Vio\ \left(\frac{l}{hr}\right) = \frac{mass\ flow\ in\ orifice(\frac{g}{s})}{60\ (unit\ conversion)}\ x\ 3600\ (unit\ conversion) \qquad (4)$$

Where, *Vio* is the volume flow rate of gas mixture in orifice.

The flame length has been calculated using the HySAFER model as given in Equation (5) [16,17].

$$flame\ length\ (in) = \{54\ (m_{noz}\ x\ d_{noz})^{0.312}\}x\ 39.3701\ (unit\ conversion) \qquad (5)$$

Where, m_{noz} is the mass flow rate of gas mixture in orifice and d_{noz} is the diameter of the orifice.

Proposed method

Starting from fixing the value of flow rate in LPM, the initial step is to find out the orifice area which should give the gas velocities equal or more than 10 m/s. This area will be considered as the maximum area being provided for stable flame. However, it is not advisable and/or practical to drill only one hole of the calculated area. The next step is to choose the diameter of the flame port or orifice of jet. It is advisable to choose orifice size between 0.4-1.1 to avoid unstable flame. After choosing the jet orifice size, the area of the orifice needs to be calculated. In the third step, divide the maximum allowable area (previously calculated) to the area of selected orifice. This will provide you with the number of allowable flame ports/jet orifices for the chosen flow rate. In the final stage, calculate the volume flow rate for single flame port/orifice and using HySAFER model, the flame length can be calculated.

Materials and equipment

A copper pipe of 10mm outer and 9mm inner diameter has been used as burner pipe. Tungsten carbide micro drill bits have been employed to drill desired holes using manual micro drill. A digital AliCat HHO flow meter has been used to measure flow of gas mixture. A self-made electrolyzer apparatus connected with DC power supply has been used to controllably provide gas mixture (0.5l pm, 0.8l pm, and 1l pm). A H150 electrolyzer apparatus has been used to provide 1.5l pm gas mixture and for 3l pm, two H150 electrolyzer apparatuses have been connected with pipe using T joints.

Results and discussion

Figure 1a and b displays relationship between orifice size, velocity, and flame length, respectively, at various flow rates. In general, the velocity tends to decrease with increase in orifice size; however, a high reduction in velocities have been calculated at higher flow rates and the decreasing trend tend to stream line after 1.5 mm orifice size for all the flow rates under study (Figure 1a). On the other hands, the predicted model (Hysafer) suggests that the flame length increases with increase in both the orifice size and the orifice size (Figure 1b).

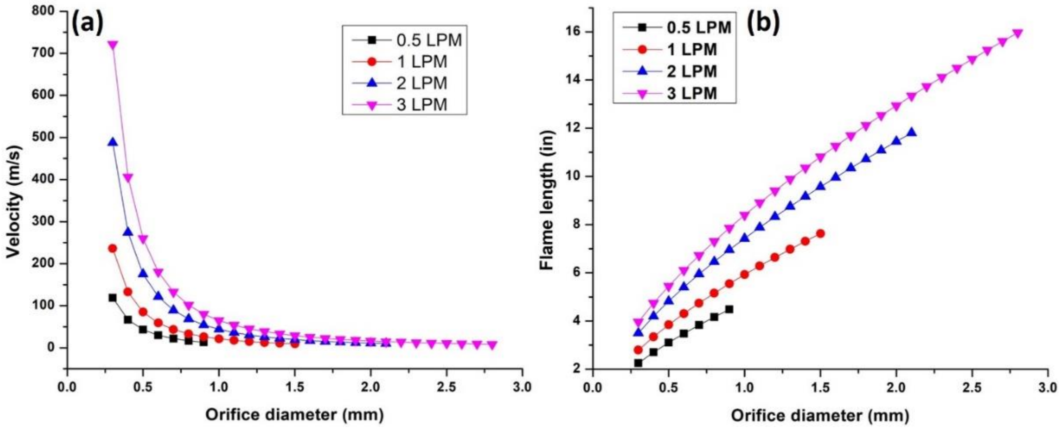

FIGURE 1 Relationship of orifice size with (a) fuel velocity and (b) flame length at various fuel flow rates

A series of experiments have been conducted to measure the flame length in relation to volume flow rate of pre-mixed hydrogen and oxygen along with orifice size.

Figure 2(a-q) shows the behavior of flame length with respect to volume flow rate and orifice size and detailed parameters have been presented in Table 1. In general, the flame length increases with increase in flame port orifice size at constant volume flow rate which is in-line with HySAFER model [18]; however, after a certain point, the flame length decreases, which may be associated with broadening of flame and lower velocities. Right after the reduction in flame length, the flashback phenomenon has been observed. In case of 0.5lpm flow rate of pre-mix fuel, the flame length increases from 0.3 mm to 0.7 mm orifice size. The flame length started reducing at 0.8mm orifice size and at 0.9 mm orifice size of flame port, flashback occurred (calculated flow velocity was 13.2 m/s and flame port thickness was 1.2 mm). At 1 lpm flow rate of pre-mix fuel, the maximum flame length has been observed for 0.9 mm orifice size and flashback occurred at 1.2 mm orifice size of flame port (calculated flow velocity was 14.7 m/s and flame port thickness was 1.2 mm). At 2lpm flow rate of pre-mix fuel, the maximum flame length has been observed for 1.1 mm orifice size and flashback occurred at 1.5 mm orifice size of flame port (calculated flow velocity was 19.4 m/s and flame port thickness was 1.2 mm). In case of 3l pm flow rate, the maximum flame length has been observed for 1.6mm orifice size of flame port and flashback occurred at 1.8mm orifice size (calculated flow velocity was 20.0 m/s and flame port thickness was 1.2 mm). Further increase in flow rate did not create a stable flame after 1.8 mm orifice size. The volume flow rate has been further increased to even 5 lpm; however, flashback occurred at 1.8mm orifice size of flame port. It has been inferred that 1.8mm orifice size is too large and should be considered as the maximum limit for the flame port with regards to stochiometric mixture of hydrogen and oxygen flowing at ambient pressure and temperature. Other reasons may include smaller flame port thickness and in appropriate orifice size of flame port thickness ratio [19]. It is worth mentioning here that the flashbacks always occurred when the fuel flow has been stopped except for 0.3 mm and 0.4 mm orifice sizes where the velocity was maximum compared to the other orifice sizes at constant fuel flow rate. To avoid the flashback occurrence, a high flow of compressed air has been used which extinguish the flame and the fuel flow has been stopped after that.

Figure 3 demonstrates the predicted and experimental flame length in relation to orifice size and volumetric flow rate. The prediction of HySafer model shows linear increase in flame length in relation to orifice size however, experimental data suggested linear relation still the flame length reached to the maximum and tend to decrease after certain orifice size. Furthermore, the predicted data does not show any limit for flashback. However, a close relation has been observed for predicted and experimental maximum flame length. The experimental flame length for 0.5 lpm flow rate and 0.6 mm orifice size was measured to be 3.37 inches, whereas, the predicted flame length for same conditions was calculated to be 3.47 inches (2.88% reducetion). In case of 1 lpm flow rate, the maximum measured flame length was 5.68 inches at 0.9 mm orifice size, and calculated flame length as same conditions was calculated to be 5.54 (2.46% increase). In case of 2 lmp flow rate, the maximum flame length was measured to be 8.20 inches at 1.1 mm orifice size, and the calculated value at same conditions was 7.88 inches (4.06% increase). Furthermore, in case of 3 lmp, the maximum measured flame length was 11.10 inches at 1.6 mm orifice size, whereas, the calculated flame length for same conditions was 11.25 inches (1.35% reduction). The observed deviation between predicted model and experimental data at maximum flame length conditions range between 1-4%.

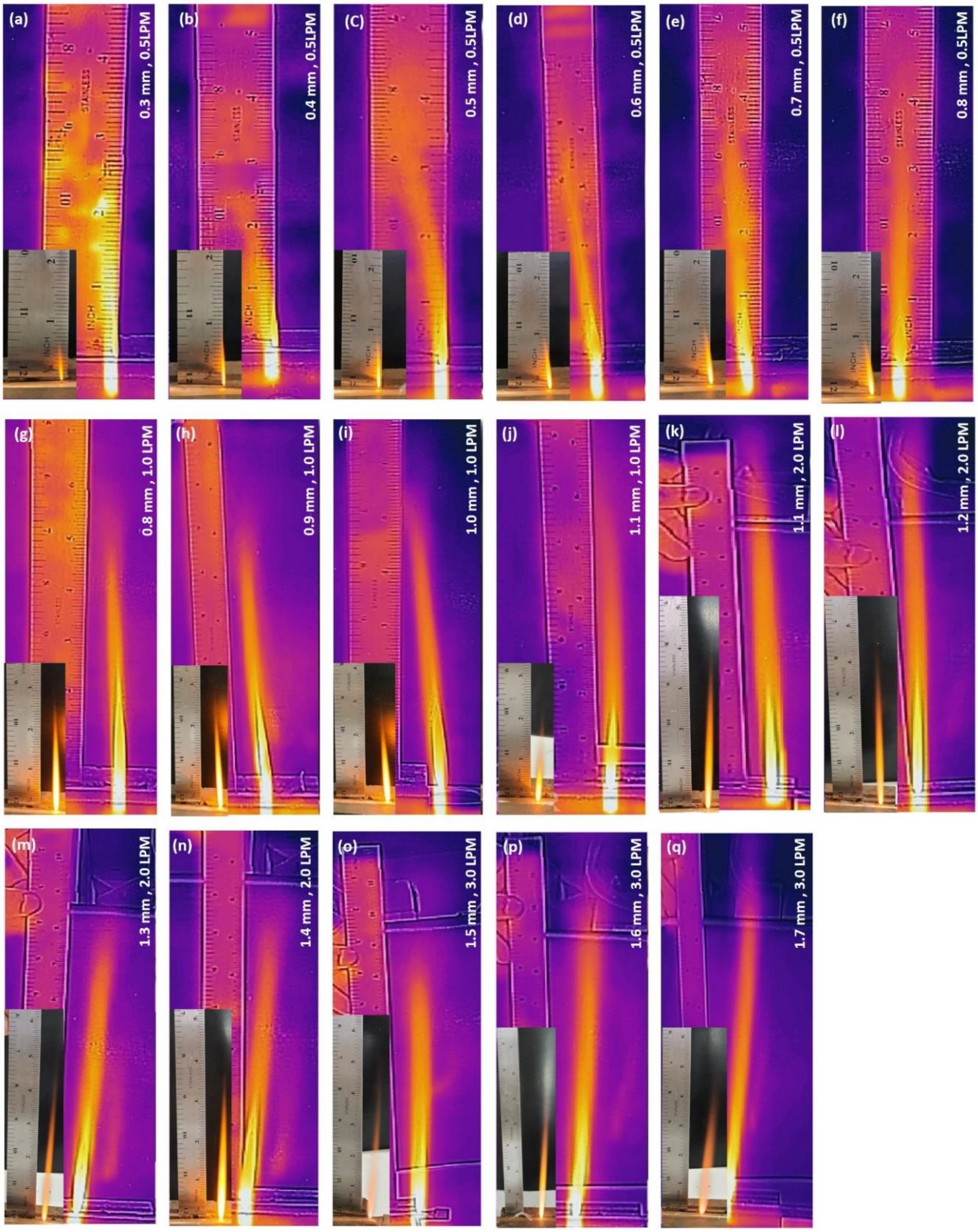

FIGURE 2 Experimental observations of flame length at various volume flow rates and orifice sizes of flame port (a-f) 0.5lpm volume flow rate, 0.3-0.8 mm orifice size, (g-j) 1.0 lpm volume flow rate, 0.8-1.1 mm orifice size, (k-n) 2.0 lpm volume flow rate, 1.1-1.4 mm orifice size, (o-q) 3.0 lpm volume flow rate, 1.5-1.7 mm orifice size

TABLE 1 Summary of measurements of flame length relative to volume flow rate of pre-mix fuel and orifice diameter of flame port

Sr. No	Orifice size (mm)	Length visible flame (in'div)					Length detected through FLIR (in'div)				
Flow rates (lpm)		0.5	1	2	3	5	0.5	1	2	3	5
1	0.3**	0'11					1'8				
2	0.4**	0'14					2'2				
3	0.5	1'0	2'9				3'0				
4	0.6	1'2	3'0				3;6				
5	0.7	1	3'1				3'8				
6	0.8	0'15	2'15				3'0	5'0			
7	0.9	FB*	2'12				FB*	5'11			
8	1.0		2'10					5'0			
9	1.1		2'4	4'7				5'0	8'4		
10	1.2		FB*	4'13				FB*	8'0		
11	1.3			5'5					7'8		
12	1.4			4'0					7'0		
13	1.5			FB*	6'8				FB*	10'4	
14	1.6				8'					11'2	
15	1.7				6'					9'8	
16	1.8				FB*	FB*				FB*	FB*

FB*: flash back.
**: no flash back has been observed for any flow rate after gas flow stopped.

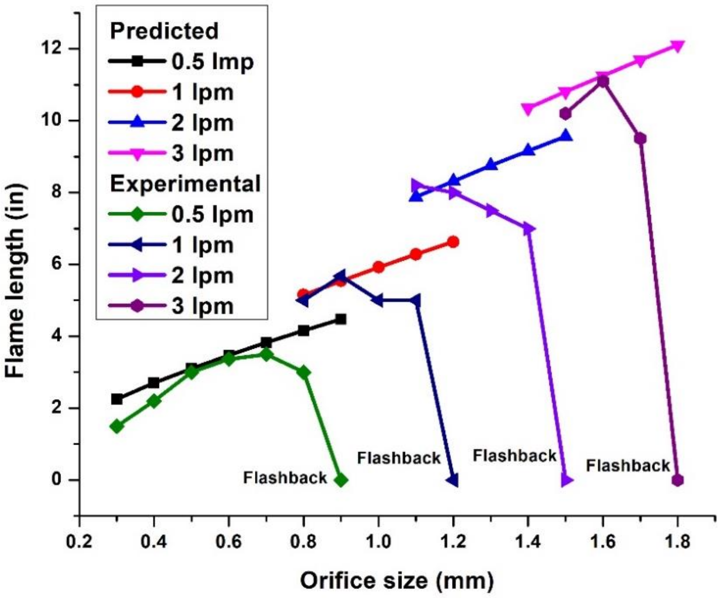

FIGURE 3 Comparison of predicted and experimental flame length relative to orifice size at different volumetric flow rates

The fuel flow (volumetric flow)-to-orifice size (f/o) ratio has been calculated at flashback to further understand the behavior of hydrogen burning and flame characteristics. Table 2 presents the f/o ratio. The difference between f/o ratios for 0.5-1 lpm, 1-2l pm, and 2-3 lpm was calculated to be 0.284, 0.519, and 0.336, respectively. It has been observed that at higher flow rates and increased orifice size, the difference between f/o ratio started decreasing after initial observed increase. This reduction in ratio difference suggests the approaching of limit for large diameter flame port.

TABLE 2 Fuel flow to orifice size ratio

Sr. No	Volume flow (lpm)	Orifice size right before flashback (mm)	f/o ratio
1.	0.5	0.8	0.625
2	1	1.1	0.909
3	2	1.4	1.428
4	3	1.7	1.764

Based on the experimental observations and calculations, the limit for the model for maximum orifice size has been suggested to be not more than 1.7 mm for any flow rate of pre-mixture of hydrogen and oxygen injected at atmospheric pressures. In the subsequent section, the multi flame port burners have been calculated and tested to validate the real-life application of the predictive model.

Applicability of model to design burners:

To estimate the optimum number of flame ports for a fixed volume flow and orifice size, first the volume flow rate of pre-mixed fuel has been fixed to 3 lpm. Various diameters of orifice have been tried (an excel sheet has been prepared for calculations) to reach to the lowest fuel velocity of 10 m/s (the velocities higher than 9.5 m/s-10 m/s would create stable flame in the case of stoichiometric mixture of hydrogen and oxygen flowing at atmospheric pressures). This practice would provide the maximum usable area which may be way more than 1.8 mm limit of flame ports. In our case where author fix the volume flow rate of 3 lpm, the maximum area of orifice near 10 m/s velocity was 4.5216x10^{-6} m^2 (2.4 mm diameter). By dividing the maximum area with the selected orifice size for flame port (in our case, we selected 0.6mm flame port size) would provide maximum number of flame ports that can be created i.e., 15. To reconfirm the number of flame ports for stable flame, the velocity of fuel for each flame port should be more than 10 m/s. this can be confirmed by dividing the volume flow rate with number of flame ports, i.e. 0.20 lpm. Using 0.2 lpm volume flow rate and 0.6 mm diameter flame port, the resultant velocity is 11.75 m/s, which is more than required velocity for stable flame. However, the maximum number of flame ports would result in minimum flame length i.e. in this case the flame length will be 2.6 inches (FLIR flame length). For our hypothetical application, authors limit the number of flame ports to 5. By dividing the volume flow rate to selected number of ports would give us the maximum flow rate for each flame port, i.e. 0.60 lmp, 3527 m/s fuel velocity at flame port and 3.67 inches flame length. Figure 4(a) shows the burner with 5 flame ports running at 3 lpm volume flow rate of fuel. The measured thermal signatures for each flame port are roughly within the range of 3.5-3.7 inches which validate our model for hydrogen based burner design. In another example, authors use 3lpm with 12 flame ports of 0.5 mm. The calculated flame length for 12 flame ports was 2.49inches and the experimental flame length as shown in Figure 4(b) is approximately 2.5 inches which is well in agreement with the predicted data.

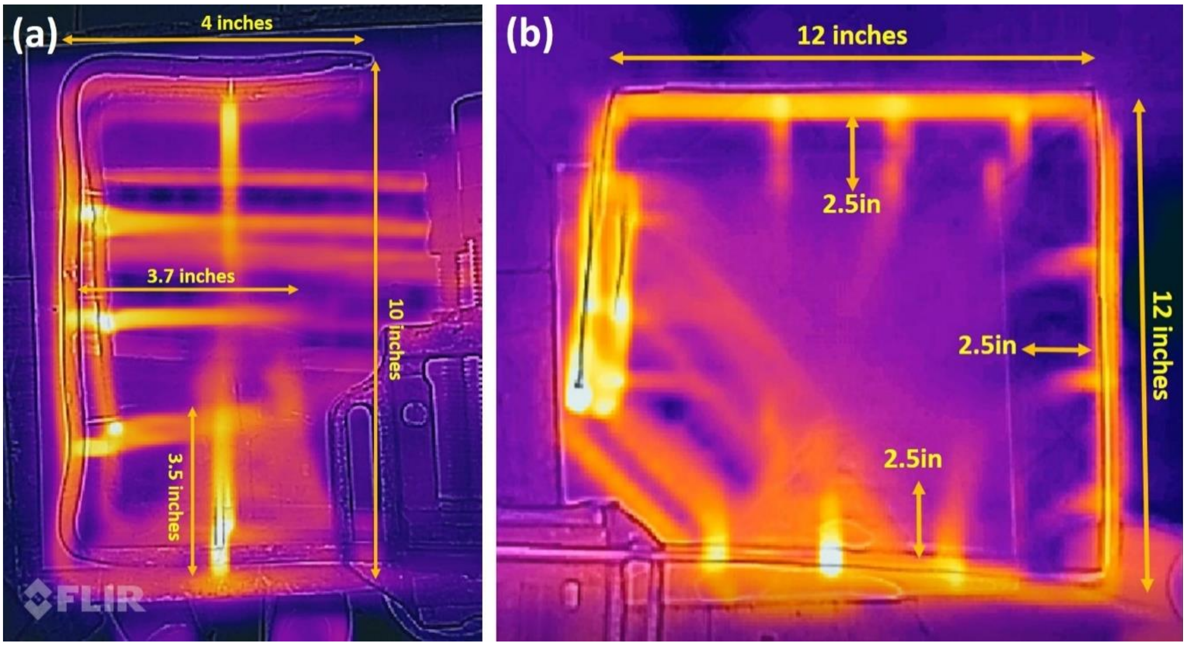

FIGURE 4 FLIR images of designed burners for 3 lpm flow rate (a) burner with 5 flame ports of 0.6 mm diameter and (b) burner with 12 flame ports of 0.5 mm diameter

Conclusion

In this study, a theoretical model based on HySafer model has been developed to design the multi-jet burner for pure premixed hydrogen and oxygen fuel at stoichiometric ratio and ambient pressures. The model has been experimentally validated through series of experiments by varying flow rates and orifice size. Finally, multi-jet burner design has been experimentally validated. It has been observed that the Hysafer model overestimate the flame lengths and the trend of flame length with flow rate and orifice size is linear upward. However, it has been experimentally proven that the trend among orifice size and flame length at constant flow rate is not linear. The flame length increases first, reached to maximum, and starts to decrease. This is due to lower fuel velocities which, in turn, leads to flashbacks. It is worth mentioning here that the model is valid for multi-orifice burner designs for pure hydrogen at ambient pressures and orifice size 1.8 mm has been thought to be the limit. The future work may include increased orifice size with much higher flow rates and increased pressures.

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Conflict of Interest

The authors declare that there is no conflict of interest.

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