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EFFECT OF HYDROGEN ENRICHMENT ON IMPINGING HEAT TRANSFER OF LPG-FIRED INVERSE DIFFUSION FLAME

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ABSTRACT

Experiments were conducted to study the influence of hydrogen enrichment on heating performance of LPG-fired inverse diffusion flame. Structure of the open flame was first measured to provide a basis for comparison. Heating performance of the inverse diffusion flame burning mixed LPG/hydrogen fuel at various hydrogen fractions was then studied by measuring the heat transfer from the flame to an impingement plate. Heat flux transfer from various points arranged at different burner-to-plate distance (H/d_{air}) and radial distance from stagnation points (r) were measured. The mixed LPG/hydrogen fuel for experimental investigation contained hydrogen fraction ranged from 0% to 50%. The Air jet Reynolds number, which dominates the hydrodynamic characteristics of the impinging inverse diffusion flame, was ranged from 2000 to 4000 in the study. The overall equivalence ratio of the air/fuel mixture was ranged from 1 to 2.2, in order to cover the fuel-lean and fuel-rich conditions. Effect of the non-dimensional burner-to-plate distance (H/d_{air}) on the heat transfer performance was also reported.

NOMENCLATURE

$\%H_2$	[%]	*Volumetric percentage of hydrogen in the fuel mixture*
Re_{air}	[-]	Reynolds number of air jet
$\emptyset$	[-]	Overall equivalence ratio
H	[mm]	Nozzle-to-plate distance
d	[mm]	Diameter of air jet nozzle
q	[KW/m^2]	Heat flux density
r	[mm]	Radial distance from stagnation point

INTRODUCTION

Impinging flame jet has many important applications such as heating or drying materials, annealing material, shaping glass, and drying paper. [1,2] By impinging the flame jet directly to a surface, people can enhance the convective heat transfer from flame to the surface greatly[3]. And the enhanced heat transfer can reduce the processing time and cost, which are very important requirement of heating process[4].

To seek the optimum heating method, researchers have investigated impinging flame jets of different flame types with various surface conditions. Dong et al. studied the heating performance of impinging premixed flame burning butane. [2] They found that the heating performance of impinging flame was affected by Reynolds number and equivalence ratio of the jet, and by the nozzle-plate distance. Similarly, Hou and Ko [5] investigated the flame structure, temperature, and thermal efficiency of an impinged laminar premixed flame burning methane. And they found that the heating height has great effect on thermal efficiency of impinging flame. Hsieh and Lin [6] studied the stability of impinging premixed flame. Tuttle et al. compared the heat transfer between premixed flame and diffusion flame. [4] Ng et al. [7] studied the heat flux distribution of impinging inverse diffusion flame (IDF) on plate. Kwok et al. [1] focused on the effect of burner shape on heating performances of impinging premixed flame. Dong et al. [8] analyzed the effect of flame jet arrangement on heat transfer of impinging flame. Agrawal et al. [9] simulated the heat flux distribution of turbulent flame on an inclined plate. Chander and Ray [10] measured the heating performance of laminar methane flame impinging to a cylindrical surface.

Inverse diffusion flame (IDF), studied by many researchers [11-14], has been classified as a partially premixed flame. With separated air jet and fuel jet, IDF combines the features of both premixed flame and diffusion flame, and has the advantages of high flame temperature, high flexibility, wide stable range, and low emission. Tuttle et al. [4] claimed that premixed flames yield higher heat flux than diffusion flames do. And experiment done by Dong et al. [15] shows that impinging IDF was found to produce even higher heat transfer rate than the premixed flame does due to the strong mixing of fuel and air in the flame neck of IDF. The superior heating performance of impinging IDF make it necessary to pay more attention to enhancing the heat transfer characteristics of IDF, and to making IDF an applicable heating solution for industry.

As a widely used gas fuel, Liquefied petroleum gas (LPG) gains it reputation with high heating value and low emission rate. Although the combustion of LPG produces relative less emission comparing with other gaseous fuels, the emission of CO/ CO2 is inevitable due to the chemical structure of LPG. Hydrogen, however, is an extremely clean fuel with no carbon component. It is reasonable to guess that the mixture of LPG and hydrogen would be an optimum gas, which has good heating performance, wide flammability range, low emission rate, and acceptable price. And the combination of LPG-H_2 mixture with IDF burner may be a flexible starting point for application of IDF in large scale.

Before applying LPG-H_2 IDF widely, it is necessary to comprehensively study the combustion characteristics of this flame, which includes flame stability, flame laminar burning velocity, heating performance, combustion emission, and safety issue. This paper presents a part of the project, and aims to study the effect of hydrogen addition on heat flux distribution of impinging LPG IDF.

EXPERIMENT SETUP AND METHOD

A special designed IDF burner is applied in this paper for research. The detailed structure and size of the burner was explained in previous research done by Miao et al..[16]

In this study, the IDF burner was fixed on a 3-D positioner under the impinging plate, as showed in Figure 1. The impinging plate is a rectangular copper plate with size of 200mm*200mm*8mm, and is supported by a stainless steel frame. A small ceramic heat flux transducer (Vatell HFM-6 microsensor) was installed in the center of the plate on the impinged side. The effective size of the heat flux transducer is 2mm*2mm*0.08mm coated with zynolyte. During experiment, the copper impinging plate and heat flux transducer were fixed, and the burning was moved vertically and horizontally to allow heat flux transducer collect heat flux data inside the flame. The collected heat flux data were amplified, and then were recorded by an IOtech data acquisitor. To ensure data accuracy, a cooling water jacket was install on the impinging plate to cool down the plate. A refrigerator was used to circulate the water and control water temperature. To prevent the water vapor producted in combustion from condensing on the plate, the temperature of cooling water was set as 40 degree Celsius.[4]

The fuels used in this study were liquefied petroleum gas (LPG) and H_2, within which LPG was the main fuel, and H_2 was auxiliary fuel. The LPG studied in this project is mixture of butane (70% (vol)) and propane (30% (vol)). The hydrogen purity is 98%. The air is compressed atmosphere air.

The heat flux along centerline (z direction) and radial direction (x direction) of LPG-H_2 IDF with various H_2 percentages were measured. For heat flux along the centerline, the variables include nozzle-to-plate distance (H) (can also be presented as unitless value H/d), Re_{air}, equivalence ratio, and %H_2. The range of H was from 10mm to 210mm. For some flames with short flame length, the tested H range deducted accordingly. The range of Re_{air} was from 2000 to 4000, in which the flame is stable [17], and the flame length is suitable for impingement. According to result obtained by Dong et al. [18] the maximum heat flux point and stagnation point appeared when $\emptyset \geq 1.4$. This phenomenon may because the high velocity center air entrains some ambient air into the flame during combustion, hence actual flame $\emptyset$ larger than the calculated $\emptyset$. Therefore, in this study, the tested $\emptyset$ was started from stoichiometric flame ($\emptyset = 1$) to fuel rich flame ($\emptyset = 2.2$). For heat flux distribution on the radial direction of the flame, there are variables: H, Re_{air}, $\emptyset$, and %H_2. In this project, the H was fixed at the value, at which the heat flux is highest along the centerline. And Re_{air} is fixed at 4000. Equivalence ratio varies from 1 to 2.2. Tested %H_2 varied from 0% to 40%.

The length of open flame measured in this study is the luminous flame height, which was obtained with the help of a digital camera.

The calculation process of Reynolds number, equivalence ratio, and hydrogen percentage can be found in the work of Miao et al. [17].

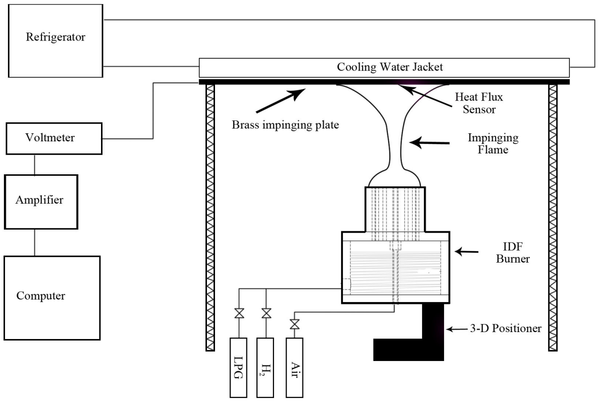

Figure 1 Experiment setup

RESULT AND DISCUSSION

This paper mainly focuses on the heat flux distribution of LPG-H_2 IDF. To identify the range of stagnation points to be measured, flame lengths of LPG-H_2 IDF under various conditions were measured before test. The effects of H_2, Reynolds number, and Equivalence ratio on heat flux distribution along centerline and radial directions were then tested within the range of flame length.

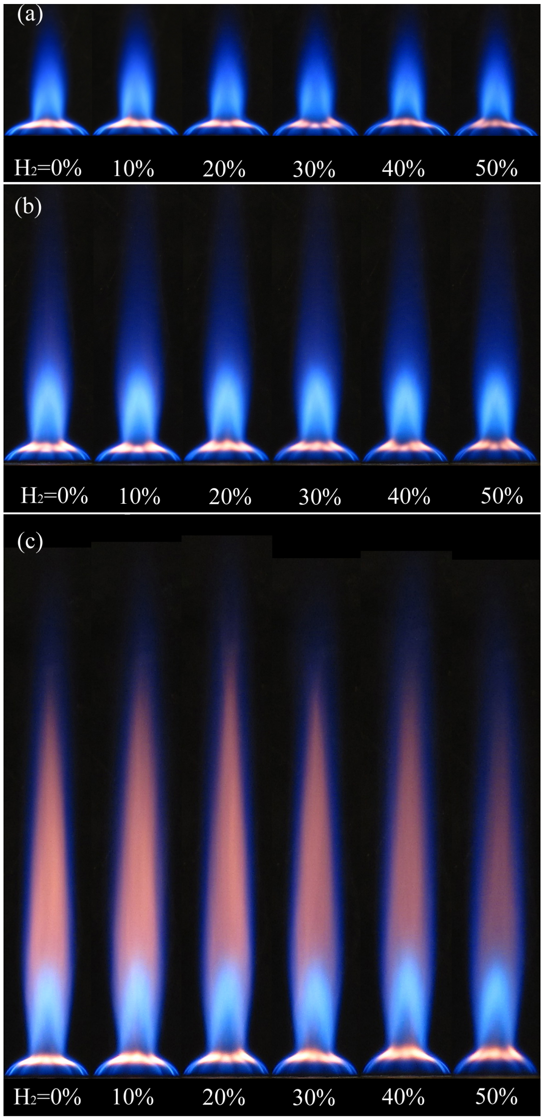

Figure 2 LPG-H$_2$ IDF with various %H$_2$ (a) Re$_{air}$=2000, $\emptyset = 1.0$, (b) Re$_{air}$=2000, $\emptyset = 1.4$, (c) Re$_{air}$=2000, $\emptyset = 2.0$

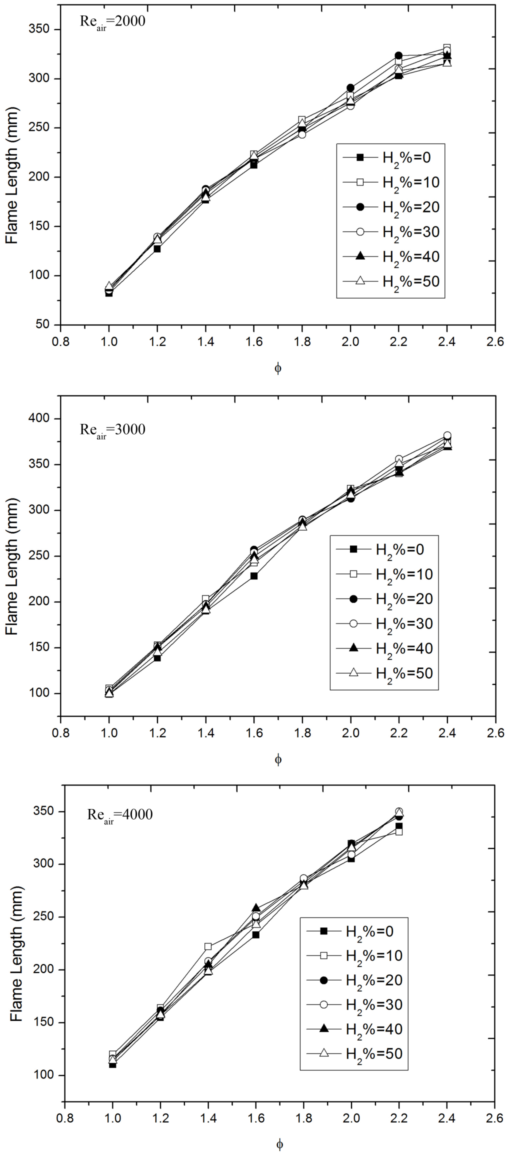

Figure 3 Flame Length of LPG-H$_2$ IDF under various conditions

1. Flame structure and flame length

Figure 2 shows the flame structure of LPG IDF with various %H$_2$. LPG-H$_2$ IDFs have adjustable flame length, which is also called flame torch. By varying the equivalence ratio, people and various flame lengths for different purpose.

Figure 3 shows the luminous flame lengths of LPG-H$_2$ IDF. It can be found that in the range of $\emptyset = 1.0 - 2.4$, flame lengths of LPG-H$_2$ IDF increase with overall equivalence ratio. For Re$_{air}$=3000 and Re$_{air}$=4000, the relationship between $\emptyset$ and flame length is almost linear. The proportional relationship between $\emptyset$ and flame length was also observed by Dong et al.[18] for butane IDF flame with Re$_{air}$=8000. This phenomenon can be explained that in IDF when Re$_{air}$ is fixed, flow rate of fuel jet increases with $\emptyset$. Therefore, larger the $\emptyset$ is, faster the fuel jet velocity, hence longer flame length.

Effect of Re$_{air}$ on flame length is not consistent for different $\emptyset$. For $\emptyset = 1.0 - 1.4$, increase of Re$_{air}$ results in increase of flame length. For $\emptyset = 1.6 - 1.8$, flame length also raises with Re$_{air}$, but the increase between flame length under Re$_{air}$=3000 and Re$_{air}$=4000 is not obvious. For $\emptyset = 2.0 - 2.2$, the highest flame length is obtained when Re$_{air}$ is equal to 3000.

Hydrogen addition does not have significant effect on luminous flame length of LPG as it shown in Figure 2. Actually, with hydrogen addition, the value of fuel flow rate was increased to keep the equivalence ratio fixed. (This is because H$_2$ has relative low stoichiometric air/fuel ratio comparing with LPG) Therefore it is reasonable to suppose that the flame would be more diffusive and would have longer flame length with H$_2$ addition. While, hydrogen has very high flame speed, therefore it is also possible that the flame length may reduce with H_2 addition. The result shows the flame lengths do not change steadily with %H_2. Flame length increases with %H_2 first when %H_2 is less than 20%, and then the length drops gradually with increase of %H_2. The variation of flame length may be explained that: when %H_2 is less than 20%, the mass ratio of H_2 in LPG-H_2 fuel is very low, therefore the effect of %H_2 on flame speed is not significant. Within this %H_2 range, fuel flow rate dominate the length of flame, hence higher flame length with %H_2 addition. When %H_2 is higher than 20%, the increase of flame speed due to %H_2 becomes significant. The effect of high flame speed overrides the effect of high flow rate and results in short flame length. Since for both ranges (%H_2<20% and %H_2>20%), there are two opposite mechanisms working behind, the change of flame length is not significant. It is also noteworthy that in fuel-rich condition, the deviation between flame lengths of various %H_2 is more obvious than that in fuel-lean condition. This could be explained that for fuel-lean condition, both LPG and H_2 have relative low flame speed, and the difference between flame speeds of LPG and H_2 are not as large as that under fuel-rich condition.

Experiment result shows that for LPG-H_2 IDF, the flame length various within the range of 75mm to 370mm under Re_{air}=2000-4000, $\emptyset = 1.0 - 2.2$, and % H_2=0-50.

2. Stagnation point heat flux

Figure 4 Impinging LPG-H_2 IDF

Effect of H_2

In this study, the impinging plate was cooled with water jacket with constant temperature of 40 degree Celsius. And the impinging plate is in black. Therefore, the heat flux concerned in this study is mainly due to convection and radiation. The heat flux distribution along the centreline of flame is an important datum, which can help determine the effective range of H/d for further investigation. [7]

Figure 5 - Figure 7 show the stagnation point heat flux of LPG-H_2 IDF with various %H_2 at various equivalence ratios. It can be found that effect of H_2 on heat flux distribution along the centreline of flame is not significant, especially for $\emptyset = 1.4$. At $\emptyset = 1.0$, H_2 addition slightly decreases the peak stagnation point (Point A) heat flux of LPG IDF, and the decreasing effect is substantial when %$H_2 \geq 40$%. At $\emptyset = 1.4$, LPG-H_2 IDF and LPG IDF have almost the same heat flux value along the centreline. It can be seen from Figure 6 that the only notable heat flux change due to H_2 addition happens at Point B, which is just before the dropping of heat flux. At $\emptyset = 2.0$, effect of H_2 becomes remarkable. The heat flux value increases with %H_2 for almost all H/d. And the 50%H_2 enrichment leads to 20% incensement of the peak heat flux value. This phenomenon may be because although H_2 has very high weight heating value (120 MJ/kg), its volumetric heating value is very low, which is only 9.89 MJ/m^3, comparing with that of LPG, which is 101.23 MJ/m^3. Since the hydrogen percentage was calculated by volume in this study, the actual heating value of the fuel mixture decreases with %H_2. But it is also necessary to consider about the stoichiometric air/fuel ratios of H_2 and LPG, which are 28.8 and 2.4 respectively. It means that with H_2 addition, the flue rate should be increase to keep the overall equivalence ratio unchanged. When $\emptyset < 1.4$, the balance between increased flow rate and decrease volumetric heating value, makes the effect of H_2 addition on flame temperature not notable; while, when $\emptyset > 1.4$, the flow rate increase much faster than the decrease of volumetric heating value, hence higher heat flux with H_2 addition.

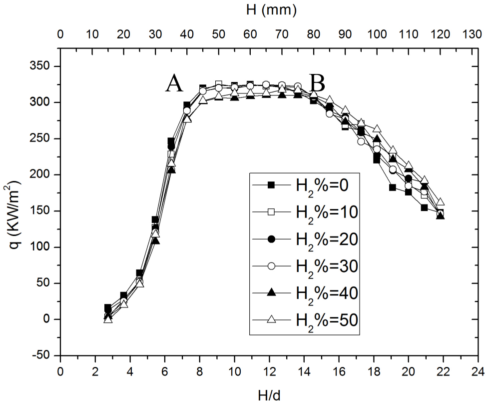

Figure 5 Stagnation point heat flux of impinging IDF with varied %H_2 under Re_{air}=4000 and $\emptyset = 1.0$.

There are two high heat flux points can be observed along the centerline for both stoichiometric and rich mixtures. The first one is the first peak (Point A in Figure 5- Figure 7), and is located near to the tip of inner core of flame. The second one is marked as Point B, and is located near to the middle of outer core of the flame. Although the trends of heat flux against H/d are different under different $\emptyset$, the double-peak trend can be identified. Point A and Point B define the high heat flux region along the centreline of flame. For convenience, the distance between Point A and Point B is also called as Major Heating Length in this study.

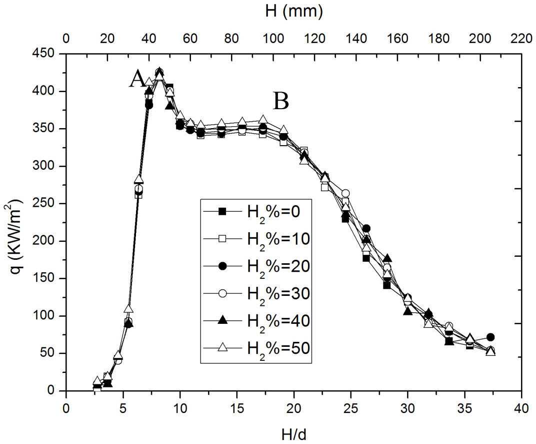

Figure 6 Stagnation point heat flux of impinging IDF with varied %H$_2$ under Re$_{air}$=4000 and $\emptyset = 1.4$.

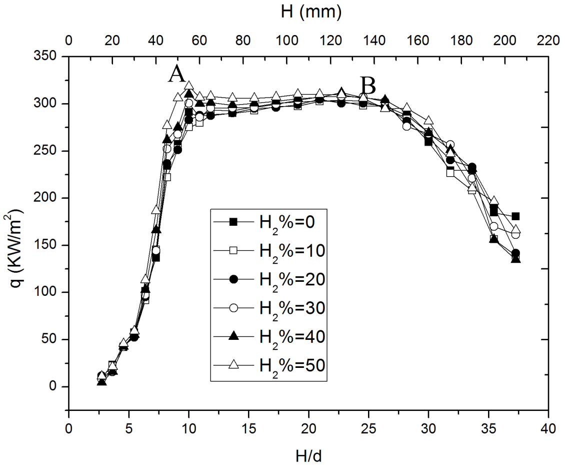

Figure 7 Stagnation point heat flux of impinging IDF with varied %H$_2$ under Re$_{air}$=4000 and $\emptyset = 2.0$.

As it mentioned before, 50%H$_2$ addition decreased the heat flux at Point A at $\emptyset = 1.0$. But it should be noticed that the heat flux values between LPG IDF and 50%LPG-50%H$_2$ IDF are almost same at Point B. This phenomenon may indicate that LPG and H$_2$ are not fully mixed during combustion, and these two fuels may be burned at different locations along the flame due to their physical and chemical nature.

Effect of Equivalence Ratio

Although many researchers have reported the effect of equivalence ratio on stagnation point heat flux of IDF, [7,15,19], there is few literature provides the heat flux data for H/d≥ 20. Since the second heat flux peak mentioned in previous session is usually located at H/d$\geq$ 20, it is necessary to study effect of $\emptyset$ in a wider range of H/d.

It can be found from Figure 8 and Figure 9 that compared with H$_2$ addition, $\emptyset$ seems to have more remarkable influence on heat flux distribution. For $\emptyset = 1.0$, the flame is short, and the heat flux increases with H/d first, and then reaches its highest value at H/d=9. After that the heat flux keeps at the high value for about 10 mm, and then decreases steadily with H/d.

For $1.2 \leq \emptyset \leq 1.6$, an impressive peak appears at around H/d=7.5. The heat flux value at the peak is much higher than the maximum heat flux of flame at $\emptyset = 1.0$ and $\emptyset \geq 1.8$. Dong et al. [2] pointed out that IDF at $\emptyset = 1.0$ is in fact fuel lean, while the flame gets closer to stoichiometric at $\emptyset = 1.2$. The high velocity of centre air jet entrains the fuel jets together with surrounding air into the flame. Therefore, the calculated equivalence ratio may be lower than the actual equivalence ratio inside the flame. For the burner used in this study, the highest heat flux peak was obtained at $\emptyset = 1.4$ for both LPG IDF and LPG-H$_2$ IDF. This result may indicate that for the IDF burner with this specific dimension, the stoichiometric flame requires a calculated equivalence ratio near to 1.4. Although the peak heat fluxes of IDFs at $1.2 \leq \emptyset \leq 1.6$ are significantly higher than those of other IDFs, the high heat fluxes do not keep for a long distance, but drop suddenly to a value about 350KW/m^2, which, however, is still higher than the maximum heat fluxes of other IDFs. The heat flux keeps at the value of 350KW/m^2 for about 40 mm, and then drops steadily to zero. It may suggest that LPG IDF and LPG-H$_2$ IDF at $1.2 \leq \emptyset \leq 1.6$ have the feature of super high temperature point and medium Major Heating Length. And this kind of flame may be suitable for industry required local high temperature.

For $\emptyset \geq 1.8$, the peak heat flux value reduces with the increase of $\emptyset$, and the peak heat flux point gradually disappears. But the Major Heating Length for these IDFs widens with the increase of $\emptyset$.

$\emptyset$ determines the main trend of heat flux along the centreline of flame. By changing $\emptyset$, people can get different peak heat flux value, and various Major Heating Length. But the locations of two high heat flux point (Point A and Point B) do not significantly change with $\emptyset$. This pheromone is also found in LPG-H$_2$ IDF.

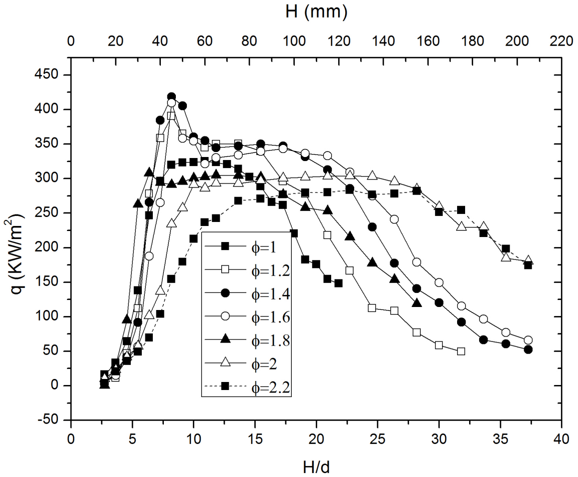

Figure 8 Stagnation point heat flux of impinging LPG IDF with varied $\emptyset$ at Re$_{air}$=4000

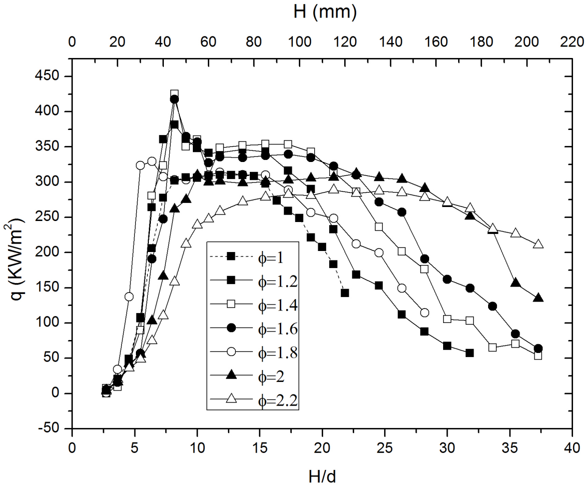

Figure 9 Stagnation point heat flux of impinging 60%LPG-40%H_2 IDF with varied $\emptyset$ at Re_{air}=4000

Effect of Re_{air}

Figure 10- Figure 11 show the effect of Re_{air} on centreline heat flux distribution of LPG IDF and LPG-H_2 IDF. Since the highest heat flux is found with $\emptyset = 1.4$, the data of this part were collect under the condition of $\emptyset = 1.4$. It can be found from the data that both the value and location of the peak heat flux point raise with Re_{air} in the range of Re_{air}=2000-4000. The curves of heat flux shown in Figure 10 and Figure 11 seem to be shifted to right with the increase of Re_{air}. When H/d is less than 8, the heat flux decreases with the increase of Re_{air}, and the phenomenon is adverse when H/d is larger then 8. Similar result is found for LPG-H_2 IDF. For a fixed $\emptyset$, the increase of Re_{air} indicates the increase of both air jet velocity and fuel jet velocity. With higher air/fuel velocity, the flame has higher momentum, and the high velocity species require longer length for complete reaction, hence higher peak heat flux point. Although with the fixed $\emptyset$, the fuel jet velocity increases proportional with air jet velocity, the difference between velocities of air/fuel jets is not constant. The difference increases with Re_{air}, and leads to higher pressure difference between air and fuel jets, hence more intensive mixing. The intensive mixing may be the reason of higher peak heat flux value under higher Re_{air}.

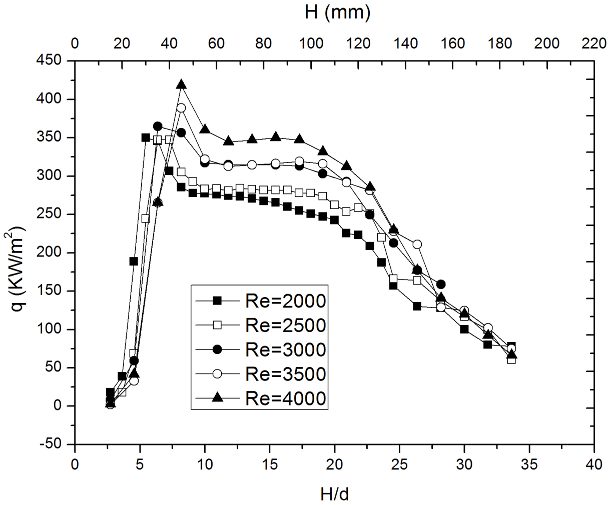

Figure 10 Stagnation point heat flux of impinging LPG IDF with varied Re_{air} at $\emptyset = 1.4$.

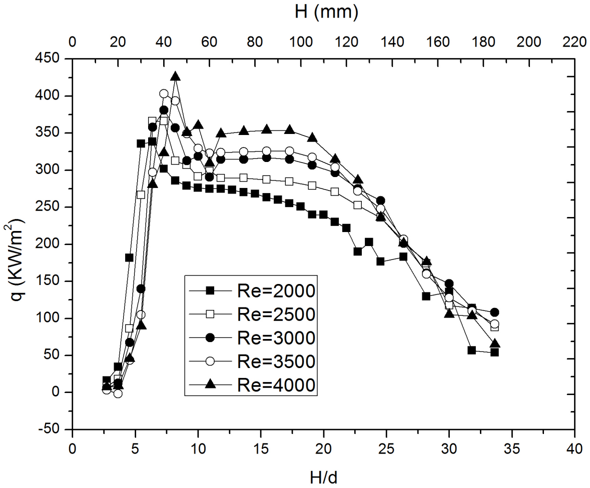

Figure 11 Stagnation point heat flux of impinging 60%LPG-40%H_2 IDF with varied Re_{air} at $\emptyset = 1.4$.

3. Radial heat flux distribution

Figure 12 and Figure 13 show the radial heat flux distribution of LPG IDF and LPG-H_2 IDF under stoichiometric and fuel rich condition. For each condition, the H/d was chosen to ensure that the peak heat flux point along the centerline just touches the impinging plate. According to experiment result obtain in previous session, H/d=8 was chosen for $\emptyset = 1.0$, and H/d=10 was chosen for $\emptyset = 2.0$.

It can be found by comparing Figure 12 with Figure 13 that hydrogen addition can increase the radial heat flux of LPG IDF, but the effect is more notable for rich mixture. For stoichiometric condition, 80%LPG-20%H_2 shows the best heating performance. While, for fuel-rich condition, the radial heat flux increases with H_2 addition.

The effect of H_2 on radial heat flux distribution of LPG IDF is only notable within the area of which $15\ mm \leq r \leq 40\ mm$. When r is outside this region, there is no obvious difference between heat fluxes of the flames.

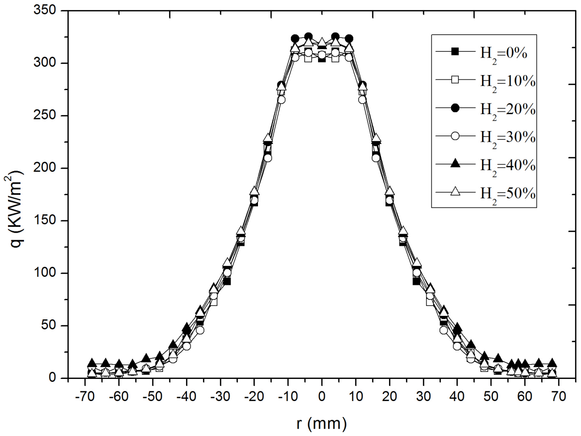

Figure 12 Radial heat flux of impinging IDF with varied %H_2 with Re_{air}=4000, $\emptyset = 1.0$, and H/d=8.

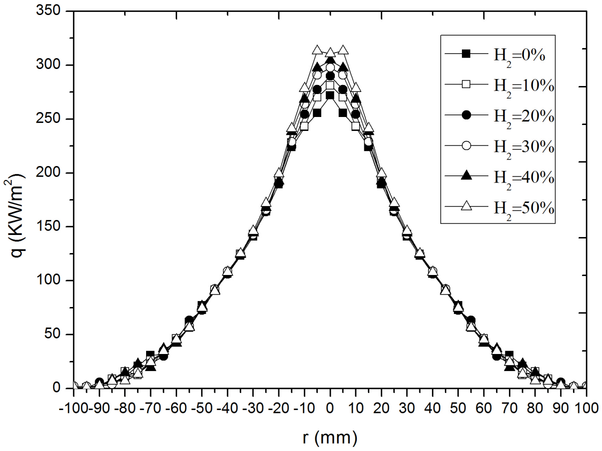

Figure 13 Radial heat flux of impinging IDF with varied %H_2 with Re_{air}=4000, $\emptyset = 2.0$, and H/d=10.

CONCLUSION

This paper studies the effect of H_2 addition on heat flux distribution of LPG IDF. Heat flux distribution along centerline and radial direction were measured. The influences of Re_{air} and overall equivalence ratio on heat flux distribution were also analyzed for both LPG IDF and LPG-H_2 IDF. The following conclusion can be drawn:

1. The effect of H_2 addition on heat flux distribution of LPG IDF is not significant, especially for stoichiometric mixture. For IDFs at $\emptyset = 2.0$, the peak heat flux value along centerline of flame increases with H_2 addition. The peak heat flux of 50%LPG-50%H_2 IDF is 20% higher than that of LPG IDF.

2. The overall equivalence ratio of air/fuel mixture significant affects the trend of heat flux distribution against H/d, but does not change the location of peak heat flux point. For all equivalence ratios, there are two peak points can be found along the flame centerline. For Re_{air}=4000, the highest heat flux is obtained when $\emptyset = 1.4$. The effect of equivalence ratio on heat flux distribution of LPG-H_2 IDF is similar with that on heat flux distribution of LPG IDF.

3. Re_{air} influences both value and location of peak heat flux along the flame centerline. The peak value of heat flux increases with Re_{air} in the range of Re_{air}=2000-4000.

4. H_2 addition can increase radial heat flux distribution of LPG IDF, especially for fuel-rich mixture. The affected radius are $r \leq 15mm$ and $r \geq 40mm$.

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