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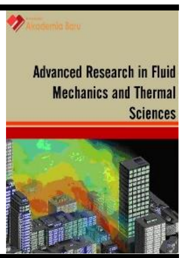

Effect of Pulsating Flame Jet on Flow and Heat Transfer Characteristics

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ABSTRACT

This research aims to study the effect of pulsating frequency on flame structure and heat transfer characteristics of premixed flame from a pipe nozzle. The LPG and air were used as gas fuel and oxidizer. The equivalence ratios (ϕ) were evaluated at 0.8, 1.0, and 1.2 under a constant Reynolds number Re = 500. The effect of nozzle-to-impingement surface distance ratio was investigated at H = 2D to 10D, here D is the nozzle diameter at 12 mm. The frequency of pulsating (f) was varied from f = 0 to 10 Hz using a solenoid valve. The flame structures of free flame jet and the impinging flame jet were recorded with a digital camera. The average heat flux on impingement surface was measured with water cooling plate and evaluated from the heat balance of the cooling water. The results show that the pulsating of flame jet become having gap on flame and the mushroom appear at the end of flame. The size of mushroom structure becomes larger when increasing the frequency. While the non-pulsating jet did not appear in this structure. Pulsating flame jet can increase the overall average heat flux on the impingement surface up to about 12% for case of ϕ = 1.2 and H = 2D and f = 10 Hz. when compared to case of f = 0 Hz.

Keywords:
Premixed flame jet; pulsating frequency; heat transfer enhancement; flame structure; impinging jet

1. Introduction

Impinging flame jet is a force convection method for the heating surface at high temperature by using the combustion flame. This is recognized as a highly effective technique for rapid heating. It has advantage of high heat transfer rate, especially in the flame impingement area. Usually, the impinging flame jet has been used widely in the metal and glass industry that requires high temperatures such as melting metal, heating metal material in a preheat furnace before fabrication and also for the glass-forming process, etc. Flame impinging jet can reduce the heating time [1-4],

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reducing emissions from combustion [5,6] and saving energy compared to conventional methods of heating by the infrared gas burner [7-9].

Generally, the flame jet can be divided into 2 types which are premixed flame jet and diffusion flame jet. The premixed flame jet is the fuel and oxidizer mixed before combustion outside the nozzle. The diffusion flame jet is the jet that the mixing and combustion process occurring outside the nozzle. Most of the flame jet used in various industries are premixed flame jet since the premixed flame jet gives the higher heating efficiency and higher flame temperature than the diffusion flame jet Including can reduce the pollution caused by incomplete combustion.

The pulsating jet is one of the ways to enhance the heat transfer rate on the impingement surface due to high mixing with ambient, large eddy flow around jet and disturbance on thermal boundary layer. There are many researchers from the past [10-13] investigated the effect of pulsating on the impinging jet. Mladin and Zumbrunnen [10] studied the nonlinear dynamics of hydrodynamic and thermal boundary layers within stagnation region to imposed temporal variations in both the freestream velocity and heat flux on the impingement surface. They reported that interactions between variations in the incident flow velocity and surface heating lead to very complex behavior in the thermal boundary layer. This also effects on temperature and Nusselt number responses on impingement surface. The flow structures and heat transfer due to pulsations of impinging jet was also investigated by Mladin and Zumbrunnen [11,12], who performed at the Reynolds number (Re) in range from 1,000 to 11,000, pulsating frequencies up to 82 Hz and pulsating amplitude at the nozzle exit up to 50 % of the mean flow velocity. They found that heat transfer increases by up to 12% in impingement region and by about 80% at far downstream on the surface.

Several investigators studied the heat transfer characteristics of a premixed butane-air [13,14], biogas-hydrogen [15], and methane-air [16,17] flame jet impinging on a flat plate. Dong *et al.,* [13] and Kwok *et al.,* [14] carried out the shape and the heat transfer characteristics of an array of three laminar premixed butane/air slot flame jets impinging on a horizontal water-cooled flat plate at the Reynolds number (Re) of 800 to 1,200. They reported that the area-averaged heat flux of the multiple slot flame jets was higher than the multiple round flame jets arranged at the same geometric configuration. Then, Wei *et al.,* [15] performed to study the heat transfer characteristics of a laminar premixed biogas-hydrogen flame jet impinging on a flat plate. They considered the effects of the distance between the nozzle and the impingement plate H = 5-30 mm, the Reynolds number Re = 600, 800, 1000 and the equivalence ratio ϕ = 0.8-1.4. They concluded that the increased velocity of unburnt gas can effectively enhance the local heat flux and the whole heat transfer rate through the stronger forced convection and more energy input. Fujisawa *et al.,* [16] and Kuntikana *et al.,* [17] investigated heat transfer characteristics of premixed methane-air flame jet impinging on a flat surface at Re = 400-1,200, ϕ = 0.8-1.5, and burner to plate distance ratio (*H/D*) of 2-6. They found that stoichiometric mixture (ϕ = 1.0) provided optimum heat transfer rate and lower *H/D* gave maximum effectiveness for impinging premixed cone flames.

Recently, Yousefi-Asli *et al.,* [18] studied temperature and heat transfer distributions of a slot burner methane/air flame impinging on a curved surface. They explained that reducing the distance between the burner exit and impingement surface increased the heat flux and the equivalence ratio was the most effective parameter on the maximum flame temperature. Beygi-Khosroshahi *et al.,* [19] investigated heat transfer characteristics of partially premixed methane-air impinging flame jet using Mach-Zehnder interferometry. They found that partially premixed impinging flame has higher maximum temperature about 4.5–6% than premixed flame. Besides, the average heat transfer enhancement by partial premixing was up to 10.2–13.5%. Kiani *et al.,* [20] examined the flame structure and temperature field of landfill gas in impinging slot burners. They evaluated at Reynolds number Re =70-150, equivalence ratio ϕ = 0.8-2.5 and jet-to-impingement surface distance *H/D* =

3.84-9.6. They concluded that the maximum flame temperature increased about 27% by changing the equivalence ratio from ϕ = 2.5 to 1.0. Hsu *et al.,* [21] studied flow and heat transfer characteristics of a pulsed jet impinging on a flat plate varying at the frequency in range of 20 to 200 Hz. They explained that the convective heat transfer was enhanced by increasing the convective velocity of the vortex ring and fluctuation intensity.

As aforementioned above, the earlier investigations focused mostly on the effect of impingement distance and equivalence ratios on flow and heat transfer characteristics of the impinging flame jet. The flow behavior and heat transfer characteristics of pulsating flame jet are rarely reported.

For case of pulsating flame jet, the premixed flame can help for more complete combustion due to strong mixing. And the temperature on the impingement surface can be controlled effectively when compare to non-pulsating flame jet. Ay and Ying-Chieh [22] conducted enhancements of impinging flame by varying the pulsation frequency in range of 0 to 20 Hz. They reported that pulsating flame developed faster than the continuous impinging flame and gave the optimized pulsating frequencies were near 9 to 11 Hz from the Re = 170 to 283.

In this study, not only for the heat transfer rate, the flame structure was also investigated for premixed pulsating flame jet. The distance from pipe nozzle exit-to-impingement surface was varied from 2 to 10. And the frequency of pulsation (*f*) were respectively varied from 0 to 10 Hz using a solenoid valve. The equivalence ratios (ϕ) was also considered at ϕ = 0.8, 1.0 and 1.2 under the Reynolds number Re = 500.

2. Experimental Setup and Procedures

2.1 Experimental Model and Parameters

Figure 1 shows the details of a pipe nozzle with impingement plate and a flame pulsating generation system used in this study. The pipe nozzle has inner diameter of D =12 mm and connected with a brass fitting with tube to the solenoid valve. The pipe nozzle was steel pipe having length at 12.5D.

For experimental parameters, the pipe nozzle exit-to-impingement distance was investigated at H = 2D, 4D, 6D, 8D and 10D. The LPG and air were applied as gas fuel and oxidizer combusting the premixed flame. The LPG gas was a mixture of 70% propane and 30% butane. The fuel-air mixing ratio was studied at equivalence ratios of ϕ = 0.8, 1.0 and 1.2, which ϕ = 0.8 for fuel-lean combustion, φ = 1.0 for stoichiometric combustion and φ = 1.2 for fuel-rich combustion. All experiments were carried out at constant Reynolds number Re = 500 based on the mean velocity of the mixture. To generate the pulsating flame jet, the solenoid valve controlled by PLC controller was used to create the pulsating flow of the LPG-air mixture. The pulsating frequency in this study was considered in range of 0 to 10 Hz. Besides, the essential parameters examined in this study were concluded in Table 1.

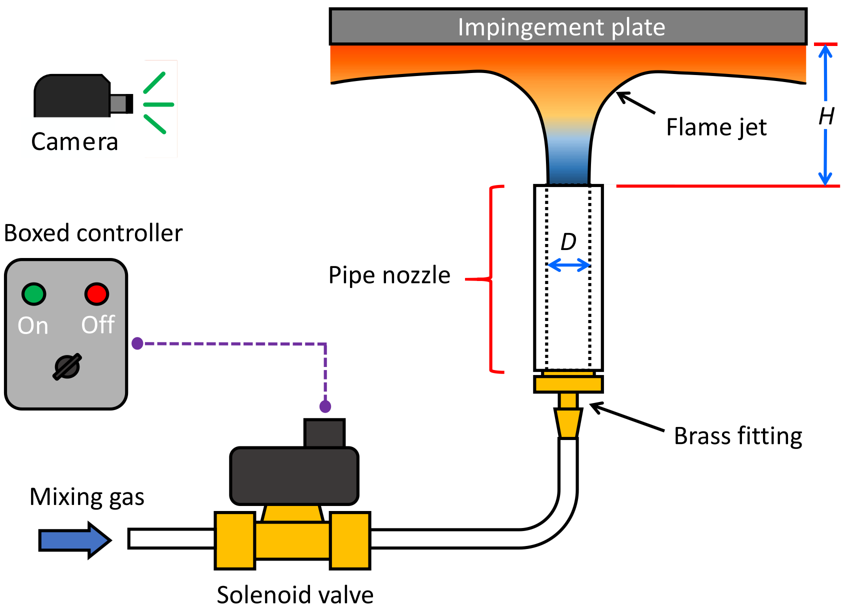

Fig. 1. Details of a pipe nozzle with impingement plate and a flame pulsating generation system used in this study

Table 1
Parameter for this experiment

Parameter and symbol	Values
Diameter of a piping nozzle, *D*	12 mm
Pipe exit-to-impingement distance, *H/D*	2, 4, 6, 8 and 10
Frequency of pulsating, *f*	0, 5, 7 and 10 Hz
Equivalent ratio, ϕ	0.8, 1.0 and 1.2
Reynolds number of gas mixture, Re	500

2.2 Experimental Setup

Figure 2 demonstrates the schematic diagram of the experimental setup in this study. The experimental setup was composed of two main parts, viz., part of pulsating flame jet generator, and part of heat transfer measurement.

For part of pulsating flame jet generator, the LPG gas was supplied from LPG tank. The LPG gas was controlled by a pressure control valve installed on the LPG tank. Then, LPG flowed through the valve and calibrated rotameter to control the flow rate and measure the pressure via a pressure transducer before entering the mixing chamber. Whereas, the air was supplied from the compressor. Then air passed through a pressure regulator with humidity filter, valve, pressure transducer and rotameter. Then, both measured air and LPG were mixed in a mixing chamber installed with some steel balls (having diameter of 3 mm) of about 3/4 of the entire volume of the mixing chamber. The small steel balls were used to mix air and LPG and to prevent flashback during the tests. After that, the gas mixture then passed through the solenoid valve to generate pulsating flow by opening and closing of the solenoid valve. The pulsating frequency was controlled with the PLC controller connected to solenoid valve. For all test, the pressure gage was less than 0.25 kPa before entering the mixing chamber.

For part of heat transfer measurement, the impingement plate consisted of cylindrical water chamber and insulator plate. The cylindrical water chamber was made of stainless steel of 75 mm in diameter and 25 mm in height. The cylindrical water chamber was mounted in cement insulator with square shape of 20 mm x 20 mm and a thickness of 25 mm. The flame jet impinged on the surface of cylindrical water chamber. The flame impingement surface was cooling by circulating the cooling water into the water chamber. And the heat transfer rate from flame impinging jet was evaluated from the heat transfer rate to water. During the measurement, the cooling water was circulated in close loop measured the flow rate with a rotameter and control temperature with heater and cooler. The cooling water was controlled at 40°C at the inlet of the water cooling chamber to avoid condensation on the flame impingement surface. For average heat transfer measurement, the digital data logger (midi LOGGER GL840) was used to measure the temperature of water inlet and outlet from the water chamber. After all of temperatures reached the steady-state, the water temperature at the inlet and outlet of water chamber was recorded for 5 min and then averaged for measured 300 temperature data.

In this study, the flame structure of free jet and impinging jet was recorded with a digital camera. The snapshot photo was taken for some timings of pulsating flame.

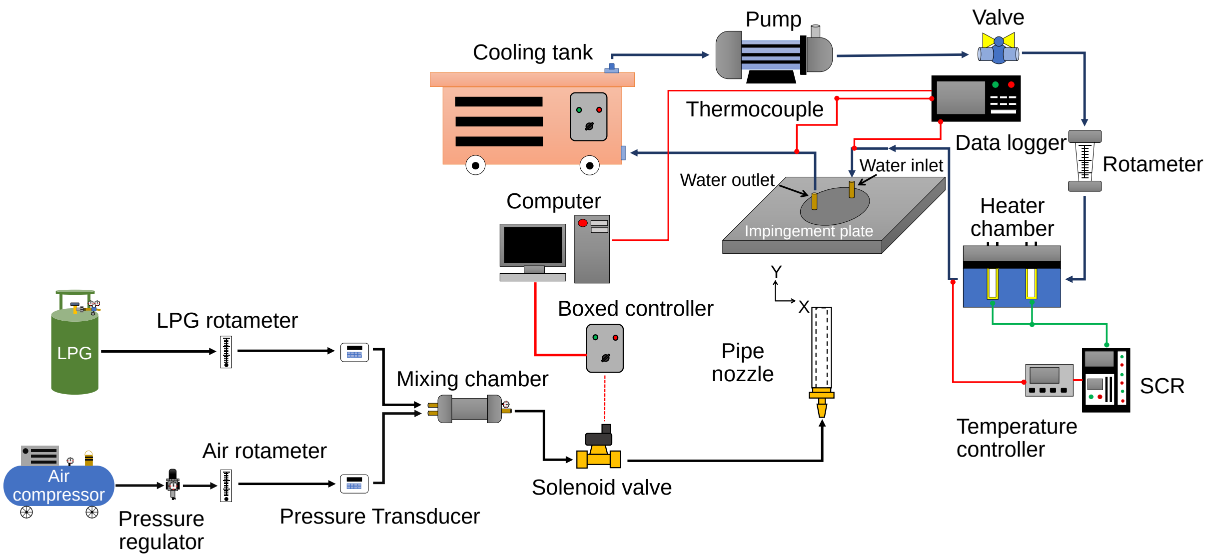

Fig. 2. Schematic diagram of the experiment setup

3. Data Reduction

All measurements of the pulsating flame jet were carried out at the Reynolds number of Re = 500 based on the mean velocity (V_m) calculated from flow rate of LPG-air mixture as follow,

$$Re = \frac{\rho_m V_m D}{\mu_m} \tag{1}$$

$$\mu_m = \frac{\sum \mu_j X_j \sqrt{M_j}}{\sum X_j \sqrt{M_j}} \tag{2}$$

$$\rho_m = \sum y_j \rho_j \tag{3}$$

where ρ_m is the density of mixture between LPG and air, μ_m is the viscosity of mixture gases, X_j, and M_j are respective the mole fraction and the molar mass of each component j. y_j, is mass fraction of each component j.

The evaluation of the equivalence ratio (ϕ) can calculated by

$$\phi = \frac{\text{actual fuel / air ratio}}{\text{stoichiometric fuel / air ratio}} \tag{4}$$

The average heat flux from a pulsating flame jet can analyze from Eq. (5).

$$\dot{q} = \frac{\dot{m} C_p \Delta T}{A} \tag{5}$$

where $\dot{m}$ is the mass flow rate of water, c_p is the specific heat of water, ΔT is the different water temperature between inlet and outlet, and A is the heat transfer area.

The uncertainty in this experiment were analyzed according to Moffat [22]. The maximum uncertainty of the Reynolds number (Re) and the equivalence ratio (ϕ), and heat flux ($\dot{q}$) was 4.3%, 4.8%, and 5%, respectively.

4. Results and Discussion

4.1 Pulsating Flame Structure

4.1.1 Free flame structure

Figure 3, 4 and 5 show snapshot photos of pulsating free flame jet under different frequencies at ϕ = 0.8, 1.0 and 1.2, respectively under Re = 500.

For case of ϕ = 0.8, it was found that the free flame at a frequency (*f*) = 0 Hz mostly appeared the blue flame shade at the end of a pipe exit and occurred the orange flame shade at the flame tip. However, both the blue and orange flame were significantly separated due to the pulsating frequency (*f*), especially at the timing step of t_4 and t_5. Generally, the physical flame structure of the flame tip with frequency looked like a mushroom. In this time series, the flame length gradually increased according to the timing step (t), which showed the shortest at t_1 and showed the longest at t_5. These phenomena were depended on the pulsating frequency. Besides, the results showed that the highest length of flame jet appeared at the frequency of 5 Hz when compared with other frequencies. And timing step at t_4 and t_5 for case of *f* = 5 Hz showed only the orange flame.

For case of ϕ = 1.0, the results showed that the end of flame jet become orange color with larger area than the case of equivalence ratio ϕ = 0.8 due to non completed combustion. In the case of pulsating flame jet mostly area become blue flame jet while the flame tip appeared the orange flame which looked like the mushroom shape. Because the surrounding air was induced to mix with the flame jet flow. When increasing the pulsating frequency to at *f* = 10 Hz, the flame jet flow was completely separated from the burner exit at t_2 to t_5, especially.

For case of ϕ = 1.2, It was obvious that the flame jet structure at *f* = 0 Hz has smaller region of blue flame and mostly appeared orange flame when compared with the equivalence ratio (ϕ) of 0.8 and 1.0. The orange flame occurred from the flame tip to the middle flame. The flame jet flowed continuously. When the frequency of pulsating increases, the flame will be clearly separated. This result was similar to the previous equivalence ratio cases. The pulsating flame near the pipe exit has mostly blue flame. For the timing step at t_2, the flame structure was similar to the mushroom shape that the near exit nozzle region has largely blue and the end of this flame flow spreads widely and has mostly orange for all pulsating jet cases. The pulsating flame jet structure cases is a time-varying. The results showed that the flame flow was significantly separated by about 2 to 3 parts of jet flow, which depended on the pulsating frequency.

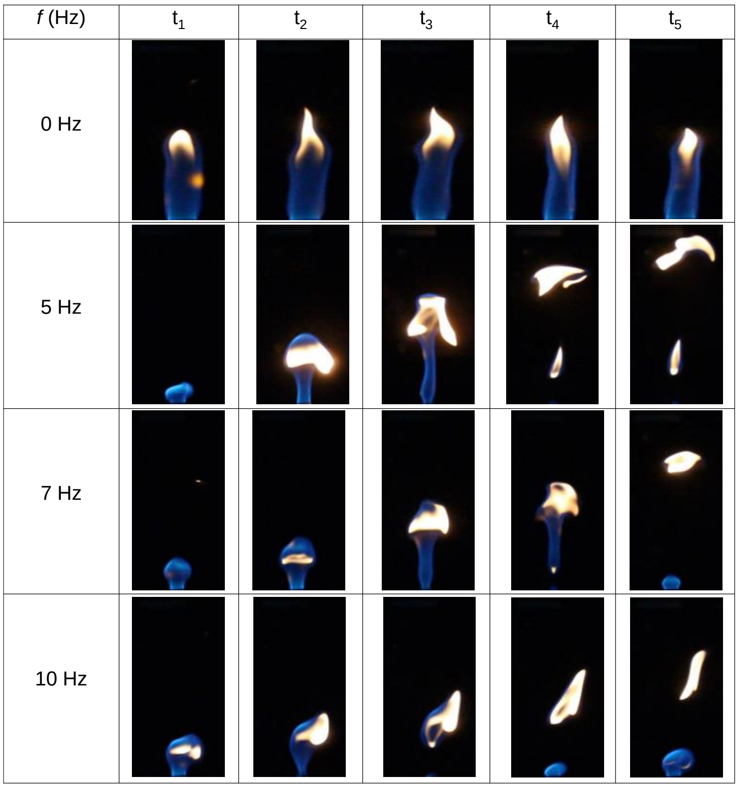

Fig. 3. Snapshot photos of pulsating free flame jet under different frequencies at ϕ = 0.8, and Re = 500

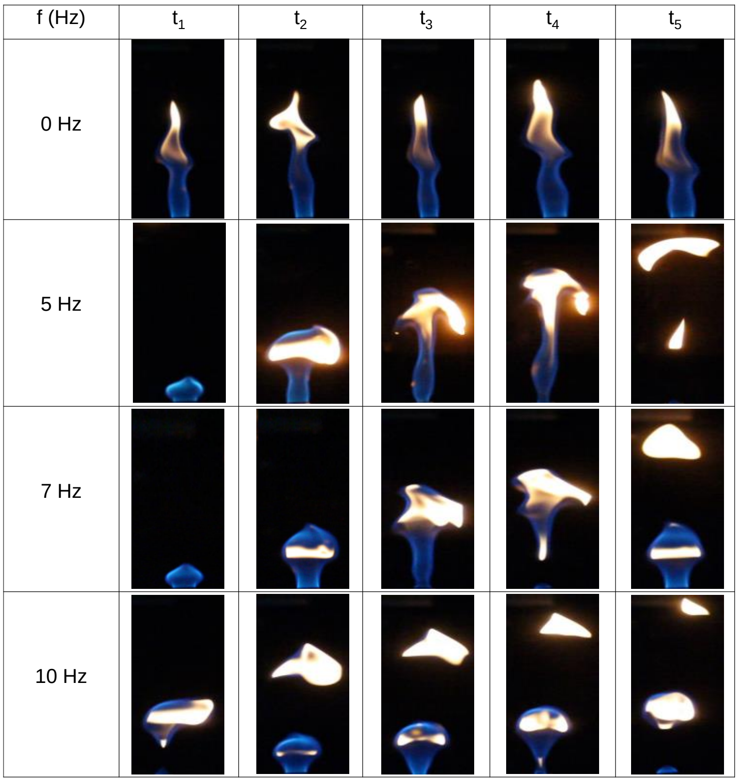

Fig. 4. Snapshot photos of pulsating free flame jet under different frequencies at ϕ = 1.0, and Re = 500

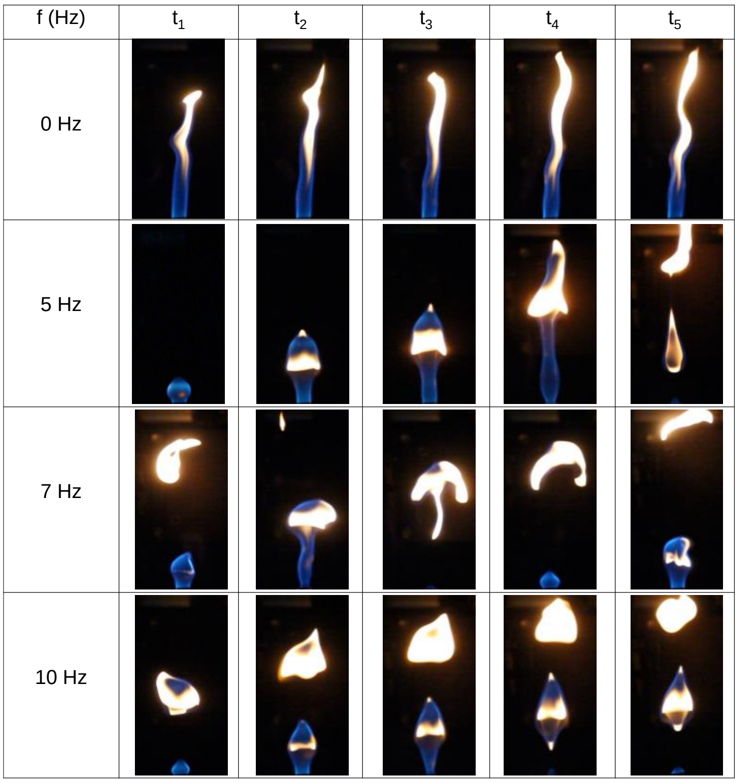

Fig. 5. Snapshot photos of pulsating free flame jet under different frequencies at ϕ = 1.2, and Re = 500

4.1.2 Impinging flame structure

Figure 6, 7 and 8 demonstrate snapshot photos of pulsating impinging flame jet under different frequencies for different impingement distances at ϕ = 0.8, 1.0 and 1.2, respectively under Re = 500. Each figure also compared the effect of impingement distance at H/D= 2, 4, 6, 8 and 10.

For case of ϕ = 0.8, it was found that the impinging flame jet for case of *f* = 0 Hz impinged continuously on the impingement surface, while the flame does not attach on the impingement plate for case of *H/D* = 10. The flame jet becomes mostly the blue color, except in the case of *H/D* = 8 appeared the orange color. For cases with pulsating frequencies, the pulsating impinging flame jet more spread due to the mushroom shape at the flame tip. This also leads to the flame can cover on the impingement surface with larger area. The length of the impinging flame jet decreases when *H/D* increases. The flame jet still appeared the blue color, except the flame jet for case at *f* = 7 Hz and *H/D* = 8 appeared the orange color only.

For case of ϕ = 1.0, the results showed that at *f* = 0 Hz, the flame has more cover on the impingement surface and the flame has mostly blue flame color, except for case of *H/D* = 8 and 10 showed the orange color. However, when impingement distance *H/D* increased, the pulsating flames still have flames covering the impingement surface when compared with non-pulsating (*f* = 0 Hz). Because the flame combusted completely before impinging to the impingement surface.

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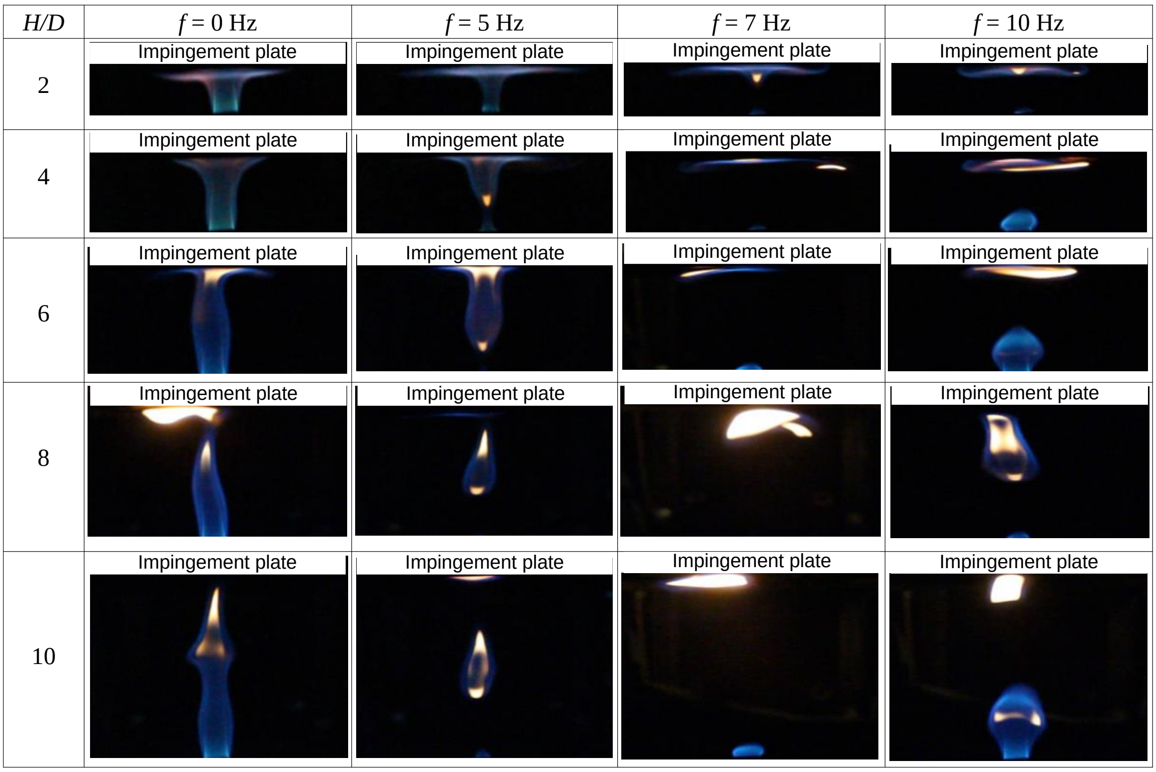

Fig. 6. Snapshot photos of pulsating impinging flame jet under different frequencies for different impingement distances at ϕ = 0.8, and Re = 500

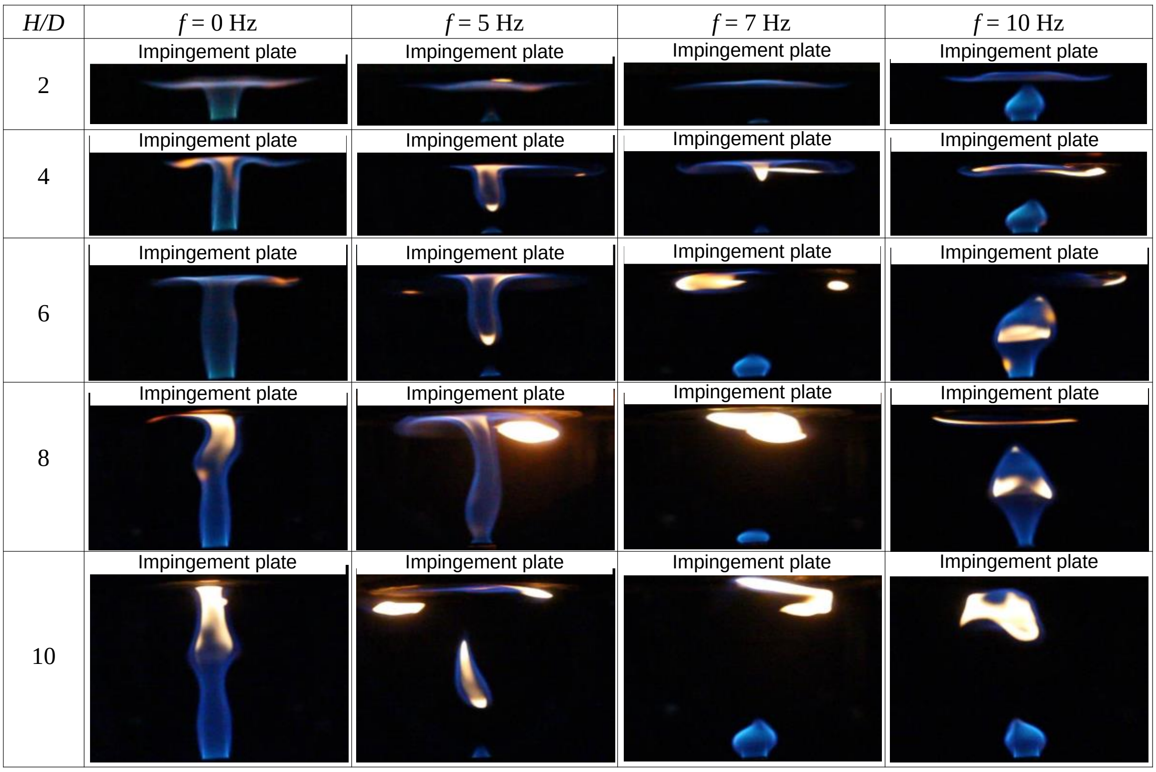

Fig. 7. Snapshot photos of pulsating impinging flame jet under different frequencies for different impingement distances at ϕ = 1.0, and Re = 500

For case of ϕ = 1.2, the flame has increasingly covered the impingement surface and has mostly orange color compared to the equivalence ratio of ϕ = 0.8 and 1.0. For all impingement distance *H/D*,

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the flame at f = 0 Hz impinged continuously on the impingement surface while the pulsating flame jet has decreasingly covered the impingement surface as increasing the impingement distance. However, the flame structure did not change, because the combustion was already completed. When the impingement distance *H/D* increases, the flame has mostly orange color and has decreasingly covered area on the impingement surface. However, it gains a larger impingement area when compared with non-pulsating flame. Furthermore, the flame still separated partly when the pulsating frequency and impingement distance *H/D* increased.

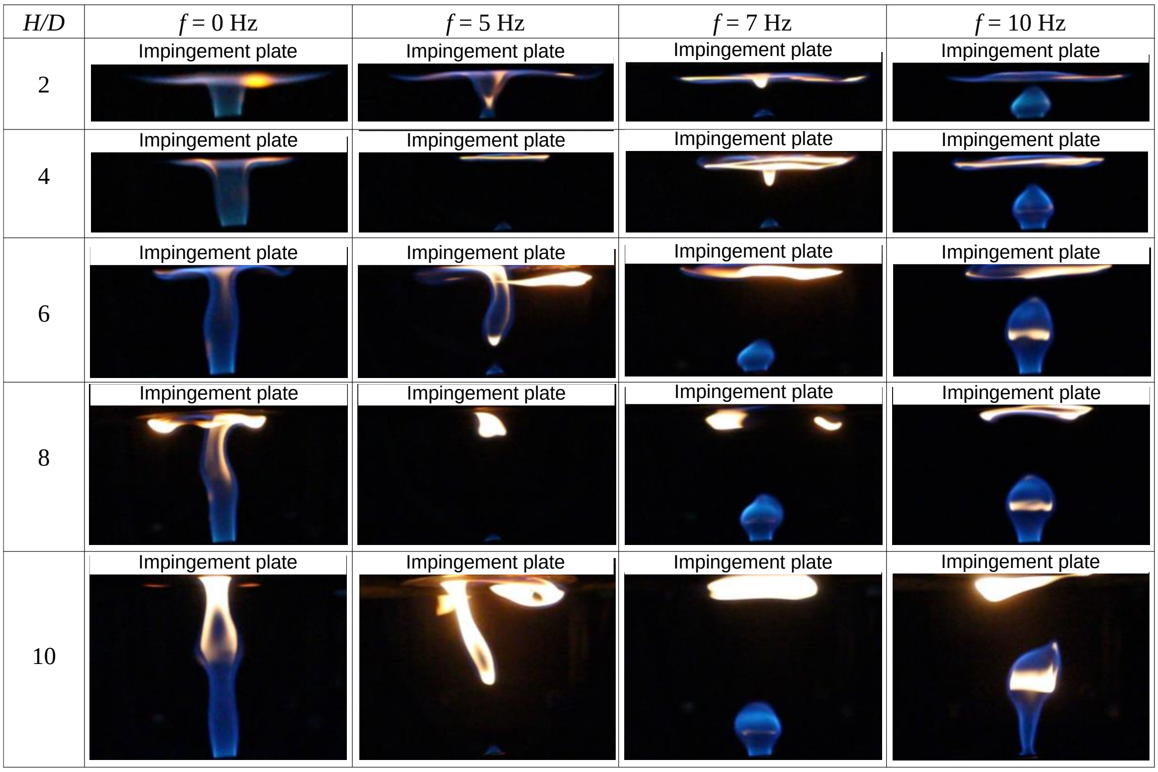
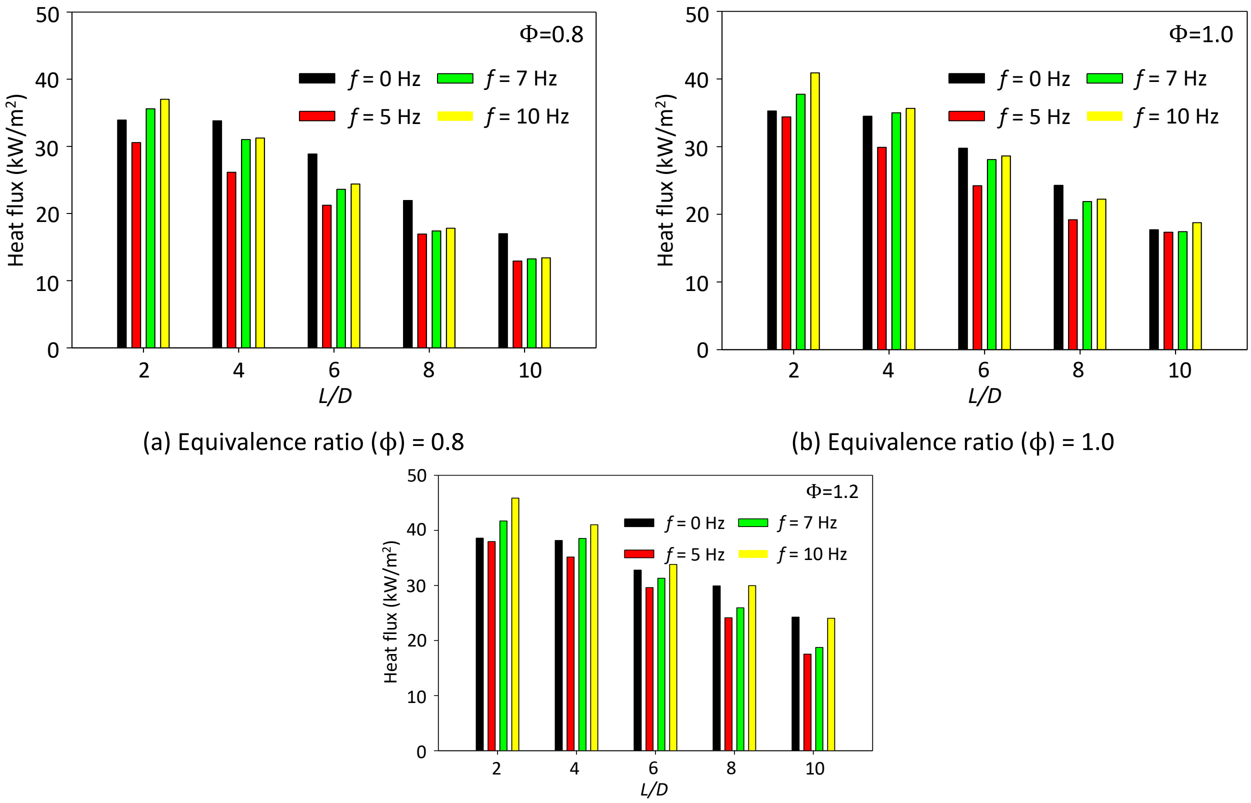


Fig. 8. Snapshot photos of pulsating impinging flame jet under different frequencies for different impingement distances at ϕ = 1.2, and Re = 500

4.2 Average Heat Flux

Figure 9. Illustrates the overall average heat flux of pulsating impinging flame jet for different impingement distances under different frequencies at Re = 500. The overall average heat flux was compared at equivalence ratio ϕ= 0.8, 1.0 and 1.2.

For impingement distance *H/D* = 2, it provided the highest average heat flux on impingement surfaces for all equivalence ratio because the impinging flame covered the widest area on the surface when compared to the other distance *H/D* cases. When the impingement distance *H/D* increased, the average heat flux on the surface decreased because the area of impinged flame covered on the surface decreased. In addition, it was found that the average heat flux on an impingement surface for case of *H/D* = 2, f = 10 Hz., and ϕ = 1.2 provided the highest by about 12% when compared with case of non-pulsating f = 0 Hz. This is due to the flame covering on impingement surface and the thermal boundary layer was destroyed by the pulsating effect. Whereas, the average heat flux rate on the surface for case of *H/D* = 10, f = 5 Hz., and ϕ = 0.8 achieved the lowest around 9% compared to case of non-pulsating f = 0 Hz. This may due to the flame jet cannot attach on the surface.



(a) Equivalence ratio (ϕ) = 0.8

(b) Equivalence ratio (ϕ) = 1.0

(c) Equivalence ratio (ϕ) = 1.2

Fig. 9. Comparison of overall average heat flux of pulsating impinging flame jet for different impingement distances under different frequencies at Re = 500

5. Conclusions

The main purpose of this research was to study the effect of pulsating frequency on flame structure and heat transfer characteristics of premixed flame jet from a pipe nozzle. The main study parameter consisted of equivalence ratios between LPG and air ϕ at 0.8, 1.0 and 1.2 and pulsating frequency (*f*) in range of 0 to 10 Hz. The Reynolds number was fixed at Re = 500 for all cases. Main experimental results can be concluded as follows

i. The flow structure of the free flame jet without pulsation (*f* = 0 Hz.) was combusted continuously and gained blue color flame mostly while appeared the orange color only at the flame tip. On the other hand, the structure of the free flame jet with pulsating frequencies (*f* = 5, 7, and 10 Hz.) was combusted and change structure according to the pulsation. Both the blue and orange flame color were separated. The flame structure shows the mushroom shape at the tip of flame, which the size of the structure increased with the pulsating frequency.
ii. The flow structure of the impinging flame jet without pulsation (*f* = 0 Hz.) was combusted continuously and then impinged on the impingement surface. The color of flame jet showed mostly blue color for all impingement distance *H/D*, except for case of *H/D* = 8 and 10 appeared the orange flame color. For case with pulsating frequency (*f* = 5, 7, and 10 Hz.), structures of the impinging flame jet can reach the impingement surface when increasing the impingement distance *H/D*. The flame can cover on the impingement surface when compared with non-pulsating (f = 0 Hz). The effect of pulsation can be observed for the flame on the impingement surface

iii. The overall average heat flux for case of *H/D* = 2, *f* = 10 Hz., and ϕ = 1.2 gave the highest value of about 12% when compared with case of non-pulsating *f* = 0 Hz. This is due to the flame covering on impingement surface and thermal boundary layer was also destroyed by the pulsating effect.

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