Comparison of Jet Diffusion Flame Characteristics and Flame Temperature of Dimethyl Ether (DME) and Liquefied Petroleum Gas (LPG)

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Abstract. Dimethyl Ether (DME) is currently considered as alternative to be used as energy source. Its similar physical properties with LPG made it possible to be used in household gas stove using same apparatus. Concern comes on its combustion properties regarding its lower calorific value than LPG. This research aimed to investigate the jet diffusion flame characteristics of DME compare to LPG in terms of flame height and lift-off flame, with correlation being made with fuel flow rate and burner hole diameter. The flame temperature is also measured on the same experiments. The results show that DME produce lower flame height than LPG. The flame height produced by both fuels were independent to burner hole diameter. The transitional regime in term of Reynold number is differ significantly between DME and LPG where DME reach the transitional regime at lower Re. The flame temperature of DME at nozzle tip and dark zone is higher than LPG.

1. Introduction

Dimethyl Ether (DME) is investigated intensively around the world as its similarity properties with Liquefied Petroleum gas (LPG) made it possible to substitute LPG [1]. DME can be made from various feedstock such as coal, natural gas, biomass, and from crude oil. All of these are attractive alternative energy sources. Many research were conducted to investigate the conversion process of renewable source to produce DME. A wind-based electrolytic hydrogen and CO₂ captured from ethanol fermentation process are among the newest renewable feedstock to produce DME [2]. The biomass that can be vary in a wide range based on local vegetation is also a very attractive source for DME. Rice straw bio-DME is studied in Thailand [3], black-liquor gasification to produce DME already established in Sweden [4], and a two-stage gasification concept is proposed to utilize low-grade residual biomass from agriculture and forestry to produce wide range of synthetic fuels including DME [5].

The use of DME as alternative fuel to substitute current fuels especially crude oil derivatives also becomes interesting topics among researcher. One of the most widely studied are the characteristics of Jet Diffusion Flame (JDF) of DME. The study of this field is very useful on the application of DME for gas fuels for domestic gas stoves, kilns and burners [6]. The JDFs of DME is investigated analytically by proposing a prediction model for Flame Length (L_f) and Width (W_f) and verify the result by sets of experiment [7]. The prediction model of flame length and flame width is very useful for the requirement of burner design and operation condition. The theory of predicting the flame dimension model can be looked back through on the paper of Hottel and Hawthorne [8]. A relation of the nozzle diameter,
molecular diffusivity, time of flow from nozzle to tip, mol ratio of air and fuel are developed empirically to predict flame length. Another approach to predict flame dimension is made by Kang et al [6] and [7] by analysing the flame structure and combine it with the flow field with mass and momentum conservation. Wang et al also study the flame dimension in term of flame radiant fraction and flame volume under sub atmospheric condition and found there is relationship between flame volume and ambient pressure [9].

On the JDFs, flame lift-off (LO) also considered an important parameter. On designing burner, the lift off height is an important parameter to keep flame stable [10]. The mechanism of lift off flame is studied by An et al [11] by elucidating the transition mechanism between attached and lifted swirl flames. Other approach was made by investigate the role of chemical kinetics in turbulent lifted jet flames using multi-flamelet generated manifold approach [12].

One of the drawbacks on DME combustion is higher NOx emission, Kim et al observed this finding in Compression Ignition (CI) engine [13]. The NOx emission is expected to be higher than other gases because DME has higher adiabatic flame temperature. A study by Kang et al [14] investigate the mechanism of NOx formation in DME flame under moderate or intense low-oxygen dilution (MILD). Under MILD condition, the NOx formation of DME combustion happened by NNH and N2O pathways, it differ from the traditional DME jet diffusion flame.

This study is aimed to investigate the JDFs characteristics in terms of flame height (FH) of DME compare to LPG in correlation with fuel nozzle diameter (DF) and fuel volumetric flow rate (Qf) using the correlation build by Hottel & Hawthorne [8] and Kang et al [6] for the baseline. In relation with factors affecting the flame height, temperature of the flames also measured to give the analytical reasoning in constructing the flame height equation. All of the experiments conducted in diffusional combustion using a cylindrical burner which can be replaced of its upper part to change the fuel nozzle diameter, DF.

2. Experimental Set Up

2.1 Materials
The DME used in this experiments is the high purity DME with purity of 99.8% produced by PT Bumi Tangerang Gas Industry in Banten. LPG used in this experiments is bought from PT PERTAMINA (persero) which has the composition of 60% m/m N-Propane and 40% m/m N-Butane. The physical properties of DME and LPG presented in Table 1.

| Physical Properties | Unit | DME   | LPG   |
|---------------------|------|-------|-------|
| Gas Density (ρG) @1atm, 25°C | kg/m³ | 1.92  | 2.08  |
| Dynamic Viscosity (μG) @1atm, 25°C | kg/m.s | 9.1.10^-6 | 7.85.10^-6 |
| Saturated Pressure (Ps) | MPa | 0.61  | 0.63  |
| Specific Heat (Cp) | kJ/kg.K | 1.43  | 1.73  |
| Auto Ignition Temp. | K | 508   | 717   |
| Adiabatic Flame Temp. | K | 2293  | 2263  |
| LHV | MJ/kg | 28.8  | 46.1  |

2.2 Diffusion Flame Experiment Set Up
The experiments were performed in Combustion Laboratory of Research and Development Centre for Oil and Gas Technology “LEMIGAS”. A working table equipped with fitted cylindrical burner, supporting bar for assembling the ruler, a line of stainless pipeline for delivering the fuel from gas cylinder into burner and the measuring instrument is used to conduct the jet diffusion flame experiments. This apparatus is designed to be used in atmospheric pressure without any closure to simulate the jet diffusion flame in an external combustion burner such as domestic gas stove.
The experimental schematic is shown in Figure 1.

![Experimental set up for jet diffusion flame measurement](image)

**Figure 1.** Experimental set up for jet diffusion flame measurement

The cylindrical burner used in this experiment is divided into two (2) parts; the burner barrel and burner head. Both parts are connected using screw connection. The burner head can be replaced to get the variation of fuel nozzle diameter, because the fuel nozzle is placed on the center top of burner head. Figure 2 shows us the design of cylindrical burner used.

![Schematics of cylindrical burner](image)

**Figure 2.** Schematics of cylindrical burner

Data of the $F_H$ is measured for each fuels by using direct measurement by a stainless ruler fitted right beside the burner, with 0 scale is fitted align with fuel nozzle position. We use 6 variations of fuel nozzle diameter; 2.5 mm, 3 mm, 3.5 mm, 4 mm, 4.5 mm, and 5 mm. For each fuel nozzle diameter, we measured the $F_H$ at variation of fuel flow rate which measured using rotameter type flowmeter. Each measurement is taken 3 times after the flames stabilized at approximately 2 minutes after changing the fuel flow rate. The data that is used for calculation is the means of the repeated value.

Temperature measurement is performed using K-type thermocouple which coupled with APPA 51 data logger to convert the physical data into digital data series. The data processing is done using APPA 50 Virtual DTM. Measurement of temperature were appointed on 2 points, $T_1$ which located right on the center of fuel nozzle and $T_2$ which located on the center of dark zone. $T_2$ position depends on the fuel and $Q_f$, so it can be moved along the Y axis by the change of both variable. Each measurement is taken for 1 minute where the data is recorded each second on data logger. The presented data is the mean of the recorded data in 1 position.
3. Result & Discussions

Comparison of the \( F_H \) as the result of change on \( Q_f \) is made between DME and LPG in Figure 3. We may observe that the change of \( Q_f \) only affect the \( F_H \) in the laminar regime (LR) area where the fuel jet velocity is quite low. Another finding is that the change of fuel nozzle diameter \( (D_f) \) do not affect the \( F_H \), or we can say that the \( F_H \) is independent to \( D_f \). These phenomenon happen for both DME and LPG flames, and this is inline with the finding of Hottel & Hawthorne [8].

![Figure 3. \( F_H \) of DME and LPG at various \( Q_f \)](image)

The interesting finding is the significant different of \( F_H \) between DME and LPG. On a paper based on research by Kang et al [6], it is said that the Fluid Regime (FR) that is classified into Laminar regime (LR), Transitional Regime (TR) and the Fully Turbulent Regime (FTR) between DME and LPG is similar. The similarity FR of DME and LPG is inline in this research, from Figure 3 we can observe that both DME and LPG curves for various \( D_f \) developed same pattern. The difference comes when we observe the \( F_H \) of DME is significantly lower than that of LPG, this is differ with Kang’s finding where the \( F_H \) of DME is similar with LPG.

One way to analyse the difference is use the \( Re \) number that is a dimensionless number to characterize FR since the \( Re \) is an indicator of the change in the mass transferring patterns, where in laminar is controlled by molecular collision, and in turbulent is significantly intensified by Eddy mixing. \( Re \) is defined as a ratio of momentum to shear stress inside the fluids. Equation (1) gives the formula of \( Re \).

\[
Re = \frac{ud}{v} = \frac{\rho u}{\mu}
\]  

(1)

On equation (1), \( \rho \) is the fuel density, \( D_f \) is the fuel nozzle diameter, \( u \) is fuel jet velocity, \( v \) is kinematic viscosity of fuel and \( \mu \) is molecular viscosity \( \left( v = \mu/\rho \right) \). Here we use the \( Re \) to analyze FR in the TR, since in this regime the flow pattern showing critical change from the LR to FTR and it is good acceptance to analyze since there is difference approach to solve the LR and the FTR.

Figure 4 shows us that the TR limit in term of \( Re \) between DME and LPG is quite different and shows that along with the increasing \( D_f \), the difference is getting higher. In typical manner, the transitional regime from laminar to turbulent range in Reynold number of 2300-4000 [6], but in this study, the Reynold number at TR higher than the typical. This happen because DME and LPG has high adiabatic flame temperature \( (T_{ad}) \) as listed in Table 1. As we notice that molecular viscosity \( \mu \) is approximately proportional to \( T \), consequently the DME and LPG has higher transitional \( Re \) number. The differences of behavior of \( Re \) to \( D_f \) from this study to the finding of Kang where find that the transitional regime of
DME and LPG is similar might come to the differences in the experimental set up. Kang et al provide co-flow using air that surrounded the fuel stream in steady velocity, while in this study only fuel stream injected from fuel nozzle. By injecting air co-flow right inside the fuel stream, the flow pattern of the fuel will be changed and this also affected the temperature of the unburned fuel.

![Graph showing comparison of the Transitional Regime of DME to LPG under different $D_f$](image)

**Figure 4.** Comparison of the Transitional Regime of DME to LPG under different $D_f$ (LTL ; Lower Transitional Limit, UTL; Upper Transitional Limit)

Analyzing the effect of temperature to the flow pattern of flames is also important. In this study, we measured the temperature of the DME and LPG flames to help us verify that the behaviour of Jet Diffusion Flame of DME is comparable to that of LPG because the temperature is not differ significantly. In Figure 5 the comparison of flames temperature between DME and LPG is shown.

![Graph showing temperature measurement at nozzle tip and dark zone of flame of DME and LPG](image)

**Figure 5.** Temperature measurement at nozzle tip and dark zone of flame of DME and LPG
The temperature at nozzle tip position between DME and LPG is similar, it shows us that in term of the heat dissipation from the combustible gas is not affecting the temperature at the bottom part of flame. In the dark zone point, the flame of DME shows higher temperature than LPG. Dark zone area is the part of the flame where no Oxygen can enter, so only the fuel itself that being pyrolized and the temperature is depend on the properties of the fuel. Table 1 verify this result, where adiabatic flame temperature of DME is higher than the LPG.

4. Conclusion
The correlation between fuel volumetric flow rate, fuel nozzle diameter and the jet diffusion flame characteristic in term of flame height is compared for DME and LPG flame. The experiment is performed in diffusional combustion with only fuel is injected from the fuel nozzle and contacted to the surrounding air at atmospheric condition. Six (6) fuel nozzle diameter (2.5 mm, 3 mm, 3.5 mm, 4.0 mm, 4.5 mm, 5.0 mm) are used and the fuel volumetric flow rate is varied to get the FR ranging from LR, TR and FTR. From the presented result, we can draw the following conclusion:

1. The $F_H$ of DME is lower than LPG for all $Q_f$ and $D_f$ variation. The analysis using $Re$ to construct the flame regime shows that the transitional regime of DME is reached at lower $Re$ number than LPG.
2. The flame temperature of DME at the point of nozzle tip and dark zone is higher than LPG. The heat dissipation effect is not seen on the nozzle tip for both DME and LPG.

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