International Journal of Technology 11(2) 400-410 (2020)
Received February 2020 / Revised February 2020 / Accepted April 2020

International Journal of Technology

http://ijtech.eng.ui.ac.id

Experimental Comparison of Working Region, Flame Stability, and Flame Height of LPG, DME, and DME-mixed LPG in an Atmospheric Diffusion Cylindrical Burner

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Abstract. This study investigates the possibility of substituting liquid petroleum gas (LPG) with dimethyl ether (DME) by considering the procedures of burner design in terms of working region, flame stability, and flame height. An experiment was designed using a cylindrical burner worked in atmospheric pressure by means of diffusion combustion. Comparisons of the working region, flame stability, and flame height were made between LPG, DME, and DME-mixed LPG with DME compositions of 10%, 20%, 30%, 40%, and 50% w/w. The results show that, based on flame stability in terms of lift off (LO) and blow out (BO), the u_f working region for DME is 67.8% lower than that of LPG, while the burning load (BL) working region for DME is 79.7% lower than LPG. Using the obtained u_f working region, the average F_H of DME is 31.4% lower than LPG. Blends of LPG and DME improve the working region and F_H of DME.

Keywords: Dimethyl ether; Flame height; Flame stability; Liquefied petroleum gas; Working region

1. Introduction

Liquefied petroleum gas (LPG) has been used as the main source of energy, especially for the household sector in Indonesia, since 2008, when the government's mega project of kerosene conversion to LPG began (Budya and Arofat, 2011). Currently, the demand for LPG can be divided into three sectors as shown in Figure 1 (MEMR, 2018).

Facing this situation, the option of using alternative energy is a good choice in order to reduce dependency on imported LPG. Dimethyl ether (DME) is emerging as an alternative fuel for LPG since it has similar properties that make it possible to be handled and distributed using the same facilities for LPG (Makoś et al., 2019), even though when using DME in LPG facilities, it should be considered to be careful on seals made of rubber-based materials (Saputra et al., 2016). Modification such as deproteinized natural rubber with acrylonitrile and styrene monomer is investigated to overcome the compatibility issue on rubber-based materials (Sari et al., 2020). Referring to Figure 1, the possibility of DME being used for household purposes is the main objective of this study. As DME will be used as a

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doi: 10.14716/ijtech.v11i2.3914

substitute for LPG in household stoves or burners, it would be more convenient to evaluate the operation parameters of current stoves or burners by comparing between DME and LPG.

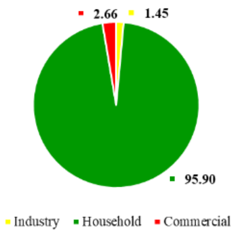

Figure 1 LPG demand by sector in Indonesia in 2018

Basically, the design procedure for domestic gas cooking devices and general burners such as boilers is similar. The design process steps are as follows (Couto et al., 2004): [1] power assessment; [2] choosing the working region based on heat input (watt/m^2) and flame stability; [3] calculation of fuel mass flow rate; [4] verification of flame size limits in terms of flame height; [5] design reliability check in terms of actual power and burner efficiency; and [6] pre-mixing pipe design. Some papers have investigated the design procedure steps for domestic gas burners separately. In relation to the investigation of DME as an LPG alternative, step [5] has already been done in a study comparing current stove power and efficiency using LPG and blends of LPG and DME (Anggarani et al., 2014). A comparison of flame size (as in step [4]) between LPG and DME was done in a co-flow type burner (Kang et al., 2015). Another study investigated the power produced by LPG compared to natural gas in a small industrial furnace (Zhou et al., 2016).

In this study, the burner design procedure in steps [2], [3], and [4] will be taken into account by comparing the parameters resulted experimentally in each step between LPG, DME, and blends of LPG and DME, or so-called "DME-mixed LPG." This study aims to experimentally compare the working region based on heat input, flame stability including the calculation of fuel mass flow rate, and flame height of LPG, DME, and DME-mixed LPG in various compositions. As current stoves cannot be used directly with DME (Anggarani et al., 2014), we designed a cylindrical burner for diffusion combustion in atmospheric pressure, which becomes the originality of this study.

2. Methods

The fuels tested in this study are LPG, DME, and DME-mixed LPG with varying DME compositions of 10%, 20%, 30%, 40%, and 50% by weight. The composition of DME from 10% to 50% was chosen due to the consideration that the scheme to substitute LPG in current gas stoves will use blends or DME-mixed LPG, with DME composition not exceeding the LPG composition. This composition variation is also in line with the study performed by the Combustion Laboratory of the Research and Development Centre for Oil and Gas Technology, LEMIGAS (Marchionna et al., 2008; Anggarani et el., 2014). The blending of LPG and DME was done using a gas-blending facility at LEMIGAS. Comparisons of flame height (F_H) and flame stability were done experimentally using a cylindrical-type burner working in atmospheric pressure.

2.1. Materials

The LPG used in this experiment was obtained from the market. LPG marketed in Indonesia for household purposes consists of propane (C_3H_8) and butane (C_4H_{10}) in a composition of both gases being regulated at a minimum of 97.5% v/v (Aisyah et al., 2015). DME was obtained from the sole commercial plant in the area of Tangerang district. The process for blending LPG and DME was performed using the blending method depicted in Figure 2.

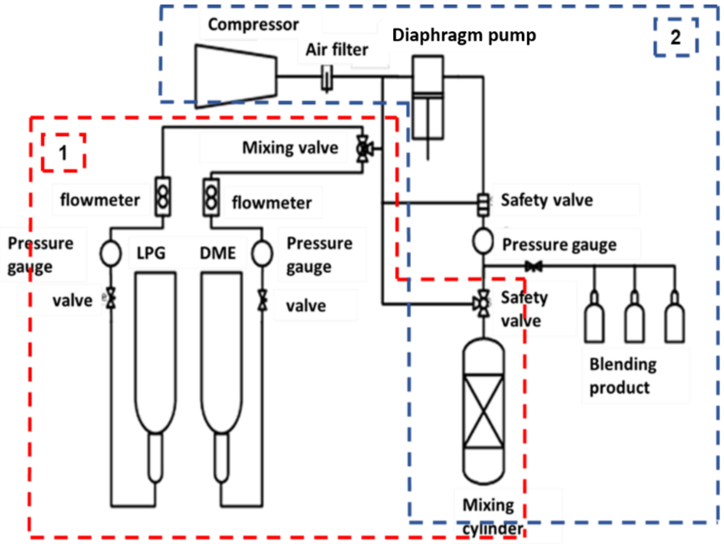

Figure 2 DME and LPG blending scheme

Blending is performed in two stages as marked by red line [1] and blue line [2]. Stage [1] is transferring LPG and DME in liquid phase from up sided down cylinder into separated vacuum mixing cylinder by utilize pressure difference only. This process is done alternately start from LPG first as it has lower density than DME. Transfer process were done based on weight percentage, as directly performed by putting the mixing cylinder on a scale. Stage [2] is started when both gases are completely transferred. The diaphragm pump is utilized to circulate the mixed gas to obtain good blending process and finally the mixed gas is transfer to blending product cylinder. Other study performing blending process between LPG and DME was done by Lee (Lee et al., 2015) which use direct method, where DME and LPG blended directly before utilized, no mixing cylinder needed in their method. The properties of LPG, DME and DME mixed LPG are shown in Table 1.

Table 1 Properties of LPG, DME, and DME-mixed LPG

Characteristics	LPG	DME	DME-mixed LPG				
			10%	20%	30%	40%	50%
Specific gravity, @60/60 ^{o}F	0.537	0.74	0.547	0.560	0.570	0.584	0.598
Vapor pressure, @100 ^{o}F (psig)	100	110	102	103	104	105	107
Weathering test @36 ^{o}F (%vol.)	99.4	99.95	99.5	99.6	99.6	99.7	99.7
Copper strip corrosion	1b	1a	1b	1b	1b	1b	1b
Total sulphur (grains/100 cuft)	2.21	1.13	1.89	1.75	1.61	1.55	1.43
Water content	-	-	-	-	-	-	-
Composition							
C2 (% vol.)	0.16	-	0.15	0.11	0.09	0,08	0,06
C3 & C4 (% vol.)	99.4	-	88.17	76.9	67.35	57,11	46,97
C5 + (heavier) (%vol.)	0.45	-	0.27	0.26	0.33	0,25	0,13
DME (% vol.)		99.96	11.41	22.73	32.23	42.56	52.84

From Table 1 we can observe that the blending process successfully mixed the DME and LPG, as can be seen from the composition of DME that is tested using gas chromatography (in % vol.) and which showed good agreement with the specified weight percentage for each blending.

2.2. *Experimental Setup*

The experiments were performed at LEMIGAS. A working table was equipped with the fitted cylindrical burner, a supporting bar for assembling the ruler, a line of stainless-steel pipeline for delivering the fuel from the gas cylinder into the burner, and the rotating flow meter used to conduct the jet-diffusion flame experiments. This apparatus was designed to be used in atmospheric pressure without any closure to simulate the jet-diffusion flame in an external combustion burner such as a domestic gas stove. The experimental setup is shown in Figure 3, while Figure 4 shows the cylindrical burner design.

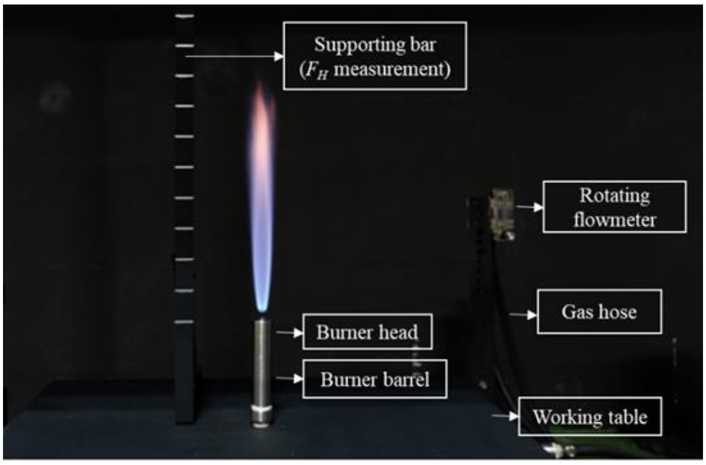

Figure 3 Experimental setup for atmospheric diffusion flame

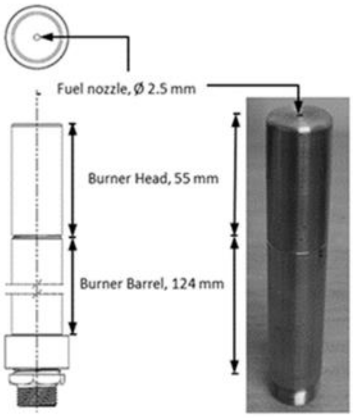

Figure 4 Cylindrical burner design

The cylindrical burner used in this experiment is divided into burner head and burner barrel, as can be seen in Figure 4. Both parts come from the same stainless-steel cylinder, so they share a similar inner diameter and were connected using a screw connector. The burner head has closed ends which are perforated by a certain diameter in order to function as a fuel nozzle. The fuel nozzle used in this experiment has a diameter of 2.5 mm. Through this fuel nozzle, the fuel is injected into the combustion zone at a certain fuel-jetting velocity (u_f, m/s) which is regulated by the opening of the flow meter. Using a spark-ignition device, the jetting fuel ignites to start the combustion and produces a jet-diffusion flame.

2.3. *Working Region, Flame Height, and Flame-stability Measurement*

Working region and flame stability are generally determined using a Fuidge diagram (Turns, 2000) which requires the theoretical air-to-fuel ratio (AFR) or equivalence ratio (ER) measurements to be plotted against the heat input by considering the phenomenon of the yellow-tip flame and lifting flame as the limitation for stability zone. Since this experiment was conducted in diffusion combustion, no measurement of the AFR was performed. Instead, we used the plotting of fuel-jetting velocity (u_f, m/s) versus DME composition in the fuel and heat input by considering the phenomenon of flame lift off (LO) and flame blow out (BO) as the limitation for stability zone. The following equations are used to calculate the u_f, the heat input known as the burning load (BL), and the DME fraction in the fuel consecutively:

$$u_f = \frac{\dot{Q}_f}{A_f} \tag{1}$$

where $\dot{Q}_f$ is the fuel volumetric flow rate in units of m^3/s as measured by the rotating flow meter and A_f is the fuel nozzle surface area in units of m^2.

In this study, heat input or burning load (BL) is a calculation of the total heat energy contained by the flow of fuel that is injected through a certain surface area (in this study, the nozzle injector; Caturwati, 2010). BL is calculated using the following equation:

$$BL = \frac{\dot{m}_f x LHV}{A_f} \tag{2}$$

where $\dot{m}_f$ is the fuel mass flow rate in units of kg/s, lower heating value (LHV) is the fuel lower heating value in units of MJ/kg, and A_f is the fuel nozzle surface area in units of m^2. BL is in units of kW/m^2. BL and the heat-release rate (HRR) share the same units, which is kW/m^2, but HRR is required to be tested using a cone calorimeter and can be used to compare combustion characteristics of some fuels, as shown by Numberi et al. (2017).

The DME composition which is notated by the DME fraction or X_{DME} is calculated as follows:

$$X_{DME} = \frac{m_{DME}}{m_{DME}+m_{LPG}} \tag{3}$$

where m_{DME} is the measured weight of DME in units of kg and m_{LPG} is the measured weight of LPG in units of kg.

The F_H measurement is done by measuring the visible flame length as described in Figure 5, which includes the measurement of the length of flame lift off (X_f).

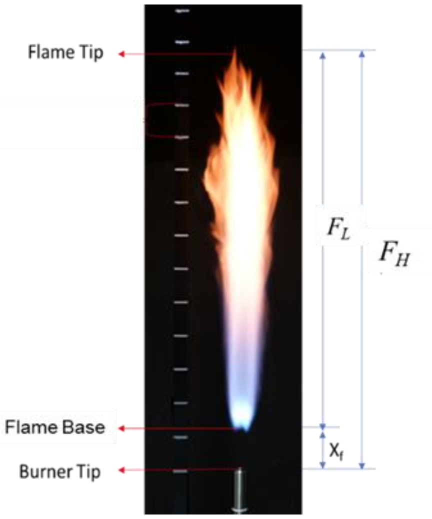

Figure 5 Schematic of F_H measurement

The measurement of F_H and X_f, as shown in Figure 5, combines the manual method of using a reading on a stainless-steel ruler marked by a silver sign as a scale placed right beside the flame zone, and a reading of digital photos of the visible flame that is produced, using Adobe Photoshop to get an accurate result. The use of a visible flame to measure F_H and X_f is in accordance with Cruz and Alexander (2019).

3. Results and Discussion

3.1. *Working Region and Flame Stability*

Working region and flame stability are determined using the phenomenon of flame LO and BO. LO happens when, in a certain u_f, the flame starts to lift above the burner rim.

Further increasing the fuel-jet velocity moves the flame into the downstream, finding a new position to stabilize. Knowing the fuel-jet velocity at which LO happens is important (Wu, 2010). BO is the phenomenon when high fuel-jet velocity results in an extinguished flame. Both results of LO and BO are presented in Figure 6.

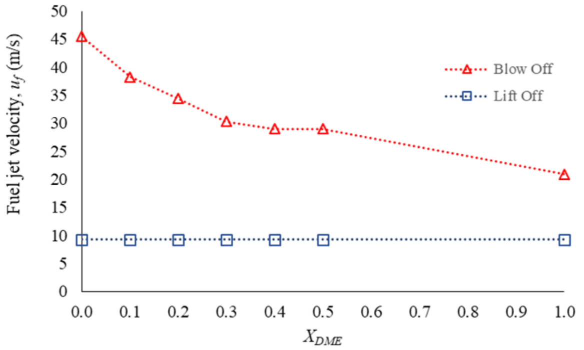

Figure 6 Blow out and lift off jet velocity of the tested fuels (at d_{nozzle} = 2.5 mm)

In Figure 6 it can be observed that, between the tested fuels represented by the DME fraction (X_{DME}), LO is reached at the same u_f, at approximately 9.3 m/s. The result also shows that the highest u_f for BO occurrence happens at X_{DME} = 0, which belongs to LPG, and the u_f for BO gets lower with an increase of X_{DME}, with the lowest reached at X_{DME} = 1. This result relates closely with the burning velocity for each tested fuel. The lowest u_f for BO, which belongs to DME, means that the burning velocity for DME is lower than LPG in the same condition. BO happens when the fuel concentration becomes too rich or too lean and hence its burning velocity can no longer counterbalance the fuel-jet velocity. Based on the experiment done by Kalghatgi (1981), the burner-exit velocity at which BO happened is a function of burning velocity and distance along the burner axis where the mean fuel concentration falls to the stoichiometric level. Fuel concentration here belongs to fuel mass fraction at the burner exit.

The working region can be obtained in terms of u_f range between the starting of LO to the point where BO happened for each tested fuel. This means that, for the burner-design process, we may consider working on an appropriate range of u_f which differs for each fuel. The widest range belongs to LPG, with a u_f range from 9.3 m/s to 45.5 m/s. The shortest range is for DME, from 9.3 m/s to 20.9 m/s. From this result, a burner for DME should be designed to work at a lower fuel-jet velocity than current burners designed for LPG.

As seen in Figure 6, blending of DME into LPG can improve the gap of the working region between LPG and DME. Replacement or substitution of LPG by DME in current burners cannot be done directly because DME will reach BO at a lower u_f, but by using X_{DME} = 0.1 we can obtain a closer working region to LPG in the range of 9.3 m/s to 38.3 m/s, or 19.9% lower than that of LPG. Table 2 presents the difference in working region magnitude in terms of u_f between DME, DME-mixed LPG, and LPG.

The magnitude of the fuels' working regions and their difference to LPG, as described in Table 2, clearly suggest to us that, by using the same burner (in this experiment represented by the same burner with a nozzle diameter of 2.5 mm), replacing LPG with DME directly drops the working region in terms of u_f by up to 67.8%. This explains the experiments performed by Anggarani et al. (2014) which compared only LPG and blends of LPG-DME (up to 50% DME) without pure DME in existing gas stoves marketed in Indonesia. Using DME directly in current household stoves or burners which are designed for LPG will produce shorter working regions of u_f that cause premature BO.

Table 2 Working region of the tested fuels based on u_f

Fuels	(a) $u_{f\text{-LO}}$ (m/s)	(b) $u_{f\text{-BO}}$ (m/s)	Working region magnitude = b–a	Difference to LPG (%)
LPG	9.3	45.5	36.2	-
DME mixed LPG (10%)	9.3	38.3	29.0	19.9
DME mixed LPG (20%)	9.3	34.4	25.1	30.5
DME mixed LPG (30%)	9.3	30.3	21.0	41.8
DME mixed LPG (40%)	9.3	29.0	19.7	45.6
DME mixed LPG (50%)	9.3	29.0	19.7	45.6
DME	9.3	20.9	11.6	67.8

Working region can also be described using burning load (BL), which is sometimes called heat input and is calculated using Equation 2. The use of BL directly relates to the burner or stove efficiency when using cooking appliances. The amount of total heat produced by combustible fuel per total fuel-jetting surface area will be used to heat some amount of cooking loads. Correlating the BL with flame stability can give us the working region, as in the previous step. Figure 7 describes the working region based on BL.

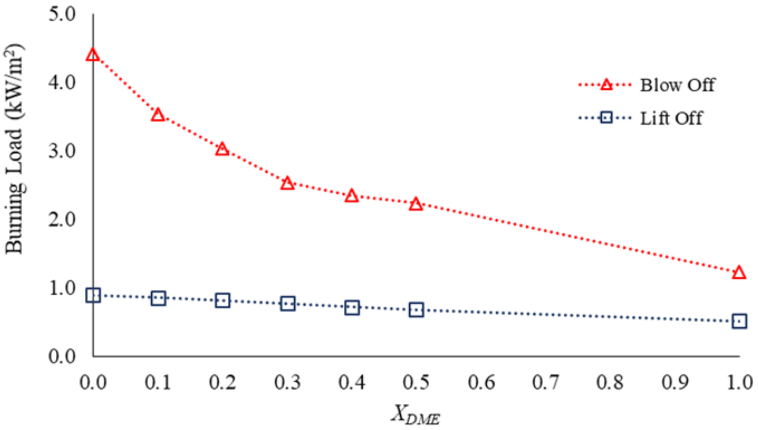

Figure 7 Blow out and lift off burning load of the tested fuels (at d_{nozzle} = 2.5 mm)

The working region represented by BL at the two limiting cases of LO and BO in Figure 7 generates a similar pattern to the working region represented by u_f in Figure 6. The decreasing trend of BL happens for both LO and BO, differing to the result of Figure 6 where LO was reached at the same u_f for all tested fuels. The decreasing BL at BO shows a steeper pattern than that of u_f because, for the BL calculation, there are two parameters decreasing with the increase of X_{DME}: mass flow rate and LHV. The difference of working region magnitude in terms of BL is presented in Table 3.

Table 3 Working region of the tested fuels based on BL

Fuels	(a) BL $_{\text{-LO}}$ (kW/m^2)	(b) BL $_{\text{-BO}}$ (kW/m^2)	Working region magnitude = b–a	Difference to LPG (%)
LPG	0.9	4.42	3.52	-
DME mixed LPG (10%)	0.86	3.54	2.68	23.9
DME mixed LPG (20%)	0.82	3.03	2.22	37.1
DME mixed LPG (30%)	0.78	2.54	1.77	49.9
DME mixed LPG (40%)	0.72	2.35	1.63	53.7
DME mixed LPG (50%)	0.68	2.24	1.55	55.9
DME	0.51	1.23	0.72	79.7

The working region between DME and blends of DME-LPG represented by BL shows a higher difference with LPG than that represented by u_f. The working region of DME drops to 79.7% lower than LPG in terms of BL. This huge difference is improved with the blends of DME into LPG; the closest working region belongs to DME-mixed LPG (10%), with a difference to LPG of 23.9%. Improving burners to get a wider span of working region can be done for DME and even for DME-mixed LPG. As the BL calculation depends on fuel mass flow rate and fuel-jetting surface area, a higher BL can be achieved by making the fuel-jetting surface smaller. This needs to be proved experimentally since flame stability is also considered.

3.2. *Flame Height*

Comparison between DME and DME-mixed LPG with LPG in terms of flame height (F_H) and flame LO length (X_f) is performed in the cylindrical burner with a fuel nozzle diameter of 2.5 mm. The guidance or schematic to measure F_H and X_f is shown in Figure 5. Figure 8 describes the F_H and X_f of the tested fuels.

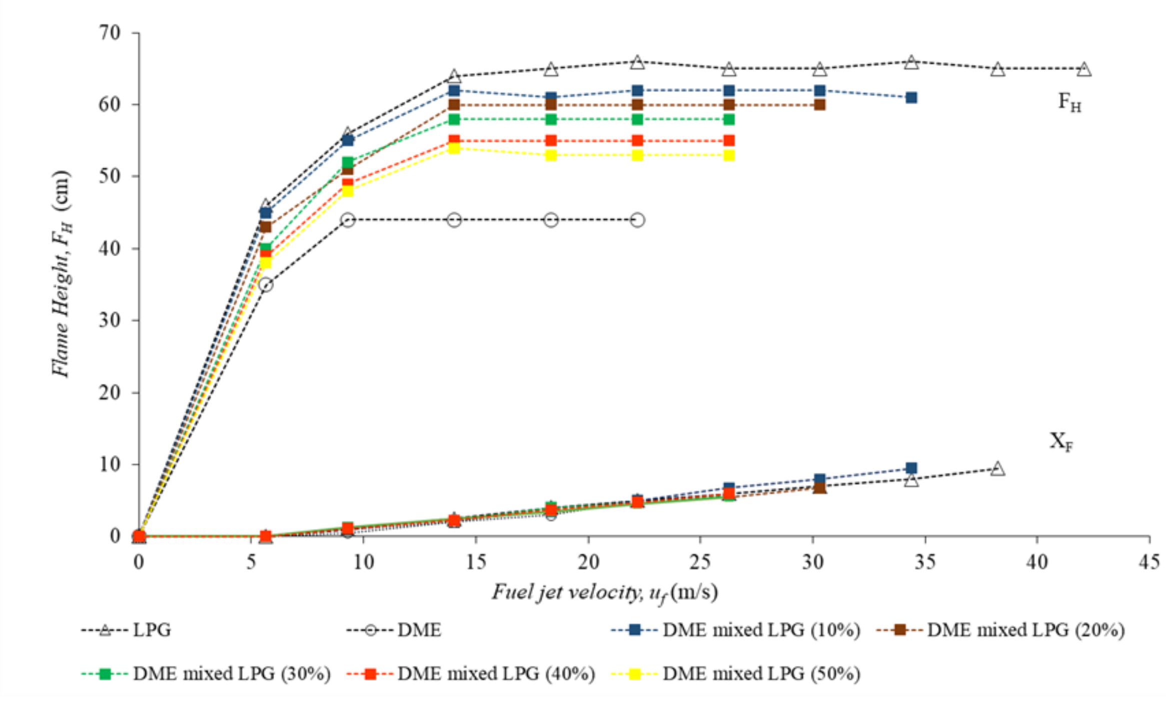

Figure 8 F_H and X_f of the tested fuels (at d_{nozzle} = 2.5 mm)

Figure 8 shows us that, when using a cylindrical burner with a fuel nozzle diameter of 2.5 mm worked in atmospheric pressure by means of diffusion combustion, the F_H of DME and LPG differ significantly, especially in transition and the turbulent flame regime. DME produced shorter F_H than LPG at the same u_f. Blending of DME into LPG can improve the F_H closer to that of LPG, decreasing with the addition of DME. In contrary, the length of flame LO for all tested fuels shows similar results.

All fuels generated flames that started to lift at the same u_f (9.3 m/s). The result presented in Figure 8 is in line with the study on the effect of u_f to F_H conducted by Hottel and Hawthorne (1948), where F_H increased linearly with increasing u_f and, after reaching maximum height, further u_f increases did not affect the F_H but changed the flame appearance from laminar to turbulent. The result in Figure 8 also proves that the blending process is performed properly, as shown by the flame characteristic of blending products that lie between two gas constituents, LPG and DME, with the trends exactly corresponding to the DME content in the blends.

In cooking appliances, F_H is important in order to design an optimum supporting rod in a gas stove so that the heat from the flames can be evenly distributed without too much loss to the surrounding air. According to the working region obtained in section 3.1, the average F_H for each tested fuel can be calculated at the suitable working range. Table 4 lists the average F_H for each fuel at the correlated working range.

Table 4 Average F_H at the corresponding working region

Fuels	u_f working region (m/s)	Average F_H (cm)	Difference to LPG (%)
LPG	9.3–45.5	64.1	–
DME mixed LPG (10%)	9.3–38.3	60.7	5.3
DME mixed LPG (20%)	9.3–34.4	58.5	8.8
DME mixed LPG (30%)	9.3–30.3	56.8	11.4
DME mixed LPG (40%)	9.3–29.0	53.8	16.1
DME mixed LPG (50%)	9.3–29.0	52.2	18.6
DME	9.3–20.9	44.0	31.4

The F_H between DME and LPG differs significantly by 31.4%. This difference can be improved by the blends of LPG and DME; DME-mixed LPG (10%) is only different by 5.3% to the flame height of LPG.

4. Conclusions

An experimental study was conducted in atmospheric pressure using a cylindrical burner worked by means of diffusion combustion to compare the working region, flame stability, and flame height of LPG, DME, and DME-mixed LPG with various compositions of DME. The results showed that, based on flame stability in terms of LO and BO, the u_f working region for DME was 67.8% lower than that of LPG, while the BL working region for DME was 79.7% lower than LPG. Using the obtained u_f working region, the average F_H of DME was 31.4% lower than LPG. The gap of the working region and F_H between LPG and DME can be improved by blending DME into LPG. The results of the working region and F_H between LPG, DME, and DME-mixed LPG imply the necessity to design dedicated burners if DME is to be used as a fuel for any purpose. The other option is using blends of DME and LPG at an optimum composition to meet the requirements of current burners.

Acknowledgements

This study is a part of the research conducted for the completion of the doctoral degree program which is funded by a scholarship provided by the Ministry of Energy and Mining Resources of the Republic of Indonesia through SK Menteri ESDM No. 7282 K/69/SJN/2016.

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