Thermal Efficiency and Pollutant Emissions of Domestic Cooking Burners Using DME-LPG Blends as Fuel

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Abstract

Traditional liquefied petroleum gas (LPG) is blended with Di-methyl-ether (DME) as substitution for conventional household cooking fuel. Effect of DME-LPG blend composition on performance of domestic cooking burner was investigated. Two types of the nationwide burner, conventional burner (CB) and porous radiant burner (PRB) were tested. DME was blended up to 30% weight in LPG, in which, the stabilized flames can be established without any burner modification, except for PRB, at 30%DME, the lifted flame was observed. It was found that a small amount of DME blended with LPG enhances significantly combustion efficiency. For the CB, a zero emission of CO gas was detected at 20% weight of DME in DME-LPG blend at constant fuel supply pressure. However, increasing DME decreases thermal efficiency. By mean of increasing oxygenate compound, flame length decreased, hence, the impinging flames is more diluted by a surrounding. In case of the PRB, there are no significant differences in thermal efficiency with the increase of DME less than 20%. On the other hand, at higher than 20%DME, thermal efficiency significantly decreases due to a decrease in radiation efficiency. The combustion zone moves downstream and the premixed flames stabilize at the upper surface of the porous media.

Keywords*:* DME-LPG blends, alternative fuel, cooking burner, thermal efficiency, pollutants emission.

1. Introduction

Energy efficient and environmentally friendly appliance has recently attracted much attention with the growing concerns of global warming. Clean cooking is the main issue to reduce indoor air pollutant, which also impacts human health. In Thailand, liquefied petroleum gas (LPG) is a conventional fuel used for household and industrial cooking. Light hydrocarbon compound, mainly propane and butane are composed, thus, preferable blue flames can be produced. Unfortunately, the total LPG consumption in the country is increasing year-by-year due to the increasing use in petrochemical industry and automobile as fuel in SI engines [1]. Thus, the gap between LPG production and consumption is continued growing. As mean for sustainable energy since LPG is the petroleum based fuel, seeking for alternative fuel as substitution for conventional household cooking fuel is needed for long-term energy conservation and environmental concerns.

Di-methyl-ether (DME) is a prospective fuel because it has similar physical properties to LPG [2] and it can be produced from many feedstocks, i.e. natural gas, coal, and biomass. Because DME is a simple oxygenate compound, it is quite easy to be burned without generating soot under any condition. However, heat content per unit mass is much lower compared with that of LPG [2]. Therefore, the optimum composition of DME-LPG blend is needed to enhance combustion efficiency (low CO emission) and to achieve high thermal efficiency for using without any modification of the existing LPG cooking burner. In Japan, it was found that the household cooking stoves designed to burn city gas (mostly methane) can be used to burn DME with only adjustment of the air damper [3]. In china, DME-LPG mixtures (up to 30%DME) were already used widely in household [4]. However, burners' performances have not been revealed yet.

This work, effect of DME-LPG blend composition on burner's performances in terms of thermal efficiency and pollutant emission (CO and NO_x) were investigated. Two types of the domestic cooking burner, which are the most popular used in the household sector, were selected for these testes.

2. Methodology

2.1 Test burners and facilities

Two nationwide cooking burners of the low-pressure type were selected. They were classified based on configuration of the burner heads as a radial flow or a conventional burner (CB) and a porous radiant burner (PRB). Each burner is composed of an outer ring and an inner ring burner heads for adjusting the turndown ratio.

DME mass fraction was varied from 0% to 30% in the Blended fuel. The conventional LPG was initially composed of propane and butane at 42% and 58% by mass, respectively. The liquid-phase blended fuel was evaporated by a vaporizer before being supplied to the burner for ensuring the uniformity of mixed gas composition and pressure. The gaseous fuel was supplied to the burners at the pressure less than 5.0 kPa, which corresponds to the typical heating rate in the range of 2 to 5 kW.

2.2. Performance testes

Fig.1 shows a schematic diagram of the burner's performance test. Thermal efficiency and pollutants (CO and NO_x) emission of different DME-LPG blend composition were measured. The fuel supply pressure (p) was fixed to be constant at 30 mbar in order to reflect the normal operation in household with no adjustment of the gas pressure regulator. Therefore, the firing rate was automatically decreased with an increased in DME mass fraction. European standards [5, 6] were used as the guideline for the testing procedures.

2.2.1 Thermal efficiency test

Aluminum pans with diameter of the bottom surfaces of 240 mm and 260 mm were filled with 4.9 and 6.1 kg of water, which were corresponded to the nominal firing rate of PRB and CB, respectively, as specified by the standards [5, 6]. The temperature of the water was measured at the center of its volume, using a K-type thermocouple, fixed by a correctly adjusted stopper through the lid (not shown). The burner was extinguished as soon as the water temperature increased by 70°C. Then, the water was considered to be sufficiently heated for the purpose of conducting the tests. The pan was then replaced by another standard pan containing the same quantity of water at the same initial temperature (T_1). The same procedure was repeated. The gas consumption and maximum water temperature (T_2) were measured and recorded. Thermal efficiency (η_{th}) was given by:

$$\eta_{th} = \frac{M \times C_P \times (T_2 - T_1)}{V_C \times H} \times 100 \quad (1)$$

Where C_p is specific heat at constant pressure of water, H is low heating value of gas fuel.

$$V_C = V_{mes} \times \frac{p_a + p - p_w}{1{,}013.25} \times \frac{288.15}{273.15 + T_g} \quad (2)$$

V_{mes} is a volume of gas measured. p_a is atmospheric pressure and p_w is partial pressure of water vapor in gas. T_g is gas temperature at the point of measurement of input thermal power.

2.2.2 Measurements of pollutant emission

The standard hood was used for this test to collect all exhaust gases to the analyzer with the minimizing of dilution effects (Fig.1). The pan was filled with water and was covered by a hood for collecting the exhaust gases separately from the generated steam, which was vented through the vertical channels integrated into the hood. The exhaust gases were then sampled by a probe connected to an emission analyzer at the hood exit. Emission analysis was carried out by using the Messtechnik Eheim model Visit01L, which is a portable emission analyzer designed specifically for quasi-continuous measurement. The measuring ranges of the analyzer were 0-10,000 ppm for CO and 0 - 4,000 ppm for NO with the measuring accuracy of about ±5, ±4 ppm (from the measured value), respectively and the resolution of 1 ppm. Repeated measurement showed an uncertainty of about 10% for the species concentrations. Combustion was checked within 15 minutes after ignition, and the concentrations of CO, NO and CO_2 were measured. To achieve adequate accuracy, dilution by ambient air should have been arranged so that the CO_2 content in the sample of the products of combustion was at least 2%. This could be done by adjusting an opening area of the restrictor installed at the hood exit.

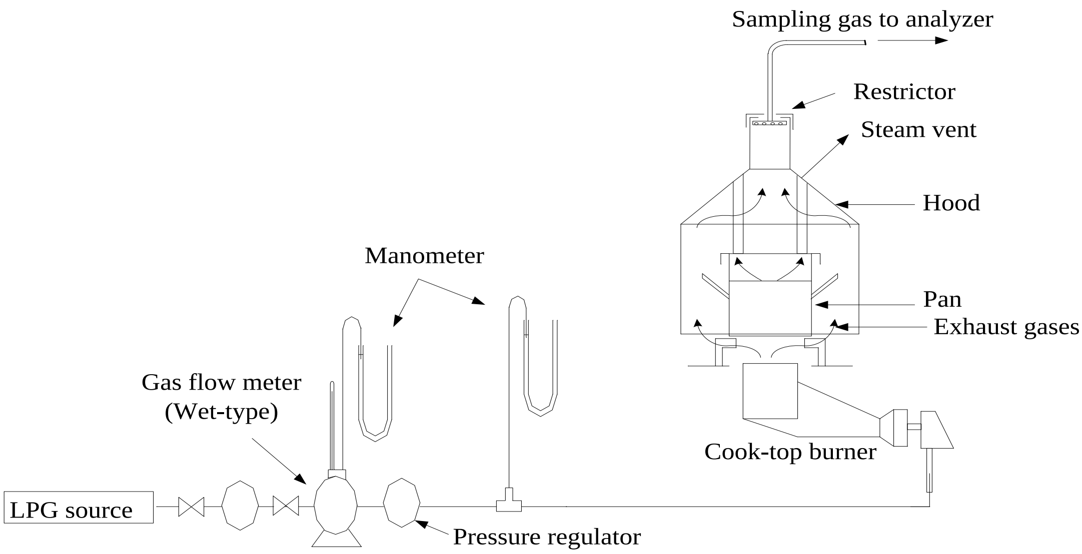


Fig. 1 Schematic diagram of burner's performance testes.

3. Results and discussion

3.1 Flame ignition and appearance

Ignition and appearance of blended fuel flame were also investigated. These tests are needed for testing the ability to safely use of this blended fuel in the LPG cooking burner without majority modification. Because DME is an oxygenate compound, in which, the auto-ignition temperature is lower than that of LPG, a high-pressure cooking burner named as KB10 burner was introduced for these observations. This burner is generally used in industrial cooking and heating with high degree of caution.

As shown in Fig. 2, the flames were ignited at firing rate of 26.5 kW, nominal heat input. A typical partially premixed flame (PP flame) of LPG-air mixture is presented in Fig.2a as a bluish-green flame. The same type of flame for the DME-LPG blends at 20%DME and 30%DME are shown in Fig.2b and Fig.2c, respectively. It is shown that the blended fuel can be ignited and the stabilized flames can be established at these blend compositions. The appearance of blended fuel flames look almost the same as that of the conventional premixed LPG-air flame, i.e. they are bluish-green in color at the flame base and violet at flame tip.

In contrast to PP flame, appearance of a yellow flame tip is observed for a non-premixed flame (NP flame), where a primary air adjustor at the entrance of mixing tube is completely closed (Fig.2d). At 30%DME, however, the bright green flames are stabilized at the base. Event though a primary air entrainment was completely blocked, the flame characteristic looks different from that of diffusion flame. Rather, this shows the apperance as fuel-rich premixed combustion is taking place. It is owing to being an oxygenate compound, adding DME will enhance ignition and combustion, and hence, the premixed-like flame can be stabilized.

Effect of firing rate on the appearance of the KB10 flames was visualized at 20%DME blend (see Fig.3). As can be seen, wide range of firing rate can be applied to ignite for a well-stabilized flame. At low firing rate, i.e. 15 kW, low gas-pressure was supplied; therefore, momentum of fuel jet is relatively low to entrain a sufficient amount of surrounding air for completely combustion. Thus, region of yellow flame tip is observed, however mainly bluish-green flame still be achieved. Increasing firing rate, yellow flame tip disappears; preferable blue flame as representative of the higher flame temperature is produced at even higher firing rate of 22.6 kW and 26.5 kW (see Fig.3c and Fig.3d, respectively).

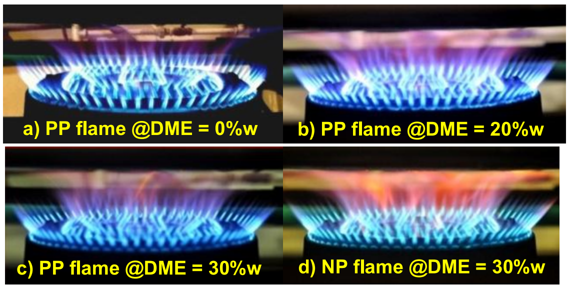


Fig. 2 Photographs of KB10 flames at firing rate of 26.5 kW.

Fig. 3 Effect of firing rate on appearance of KB10 flames at 20% DME.

3.2 Performances of low-pressure cooking burners.

3.2.1 Flame appearances

Corresponding flames of the tested low-pressure CB and PRB burners are shown and compared for different mass fraction of DME, respectively, in Fig. 4 to Fig.6.

Fig.4 and Fig.5 illustrate the photographs of free flames and impinging flames of the CB, respectively at fixed fuel supply pressure of 30 mbar. In the CB, the slot ports of both the outer ring and the inner ring are constructed in a radial direction. Therefore, most of the area of flame flows out in a radial direction and impinges a pan's bottom at an oblique angle. As shown in the figures, increasing DME will decrease the flame length. For the impinging flames (Fig.5), it is clarifying that distance between the flame tip and pan bottom surface increases with increase in DME. The shortening in the flame length is not only caused by a reduction in firing rate (Fig.7), but it might be also due to the increase of flame speed with increase in DME, as found by Lee et al. [7]. Moreover, the yellow tip on the flames at the inner ring burner is also reduced. Combustion enhancement due to the increasing of oxidizer (which is compounded in the DME molecules), may occur. Note that a shorter flame length of the impinging flame as compared with that of free flame is due to the heat recirculation occurring under the pan's bottom surface [8].

The PRB (Fig.6) provides a reaction zone positioned inside and slightly downstream near the upper surface of the ceramic plate. The heat is mainly radiated from the ceramic plate, i.e. radiation is the dominant form of heat transfer in this burner. A typical appearance or a preferable PRB flame is as appeared in Fig.6a, where a conventional LPG (0%DME) was supplied as a fuel. The combustion zones are uniformly distributed; radiant-red color appears entirely a cross-section of the ceramic surface.

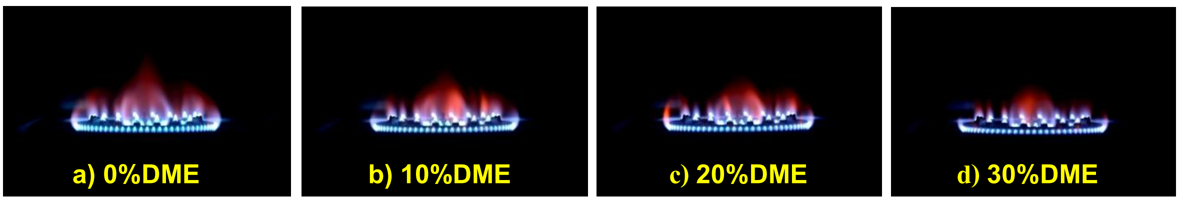


Fig. 4 Effect of DME on CB free flames at fuel supply pressure of 30 mbar.

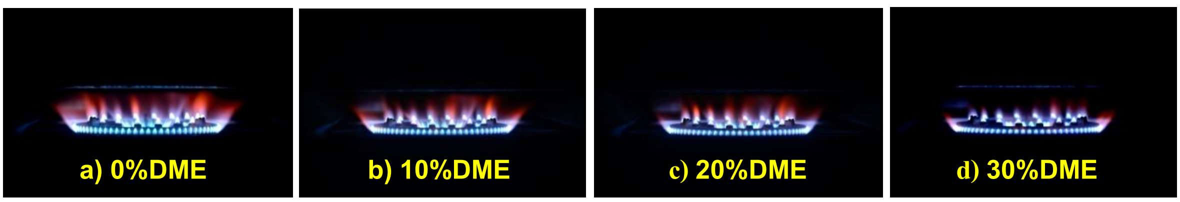


Fig. 5 Effect of DME on CB impinging flames at fuel supply pressure of 30 mbar.

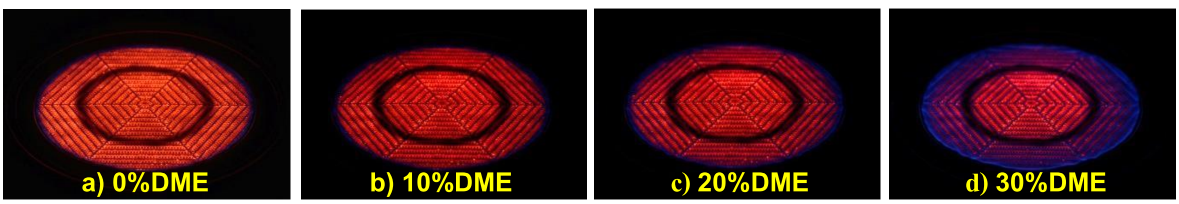


Fig. 6 Effect of DME on PRB flames at fuel supply pressure of 30 mbar.

It is shown that the porous media absorbs a sufficient heat of the combustion, which is generated inside the pore. And then, it emits infrared rays, i.e. thermal radiation to the surrounding. Increasing DME decreases radiant red color, i.e. it becomes darker on the surface. At high DME concentration, a decrease in heat input (i.e. with increase in DME) could be attributed to the effect of reduction in heat input overcomes the effect of increase in oxidizer on the combustion within PRB. In other words, the rate of heat loss is higher than the rate of heat generation, and thus, the combustion zone moves downstream and it is going to lift-off, especially at 30%DME (Fig.6d). Therefore, temperature of the porous media might decrease considerably; it may, in turn, decreases radiation efficiency. The remainder unburnt fuel is continually burnt up with inducing surrounding air and stabilized near the upper surface of the ceramic plate (porous media). Premixed flame layer (dark-bluish flame region) is appearing around circumference at the upper surface of PRB (Fig.6c and Fig.6d).

3.2.2 Thermal efficiency

At fixed fuel supply pressure of 30 mbar, negative effect of DME on thermal efficiency of both CB and PRB is received, i.e. thermal efficiency decreases with increase in DME, (Fig.7). For the CB, increasing DME, thermal efficiency decreases gradually. It might be due to the decrease of flame length (Fig.4 and Fig.5) that causes flame dilution before impinging with the pan surface. With linear fitting, every 5%DME adding will decrease about 1% (i.e. 0.5% point) of thermal efficiency with respect to the baseline value as use of the conventional LPG, e.g. η = 48.0%, 47.5%, and 47.0% for using 0%DME, 5%DME, and 10%DME, respectively.

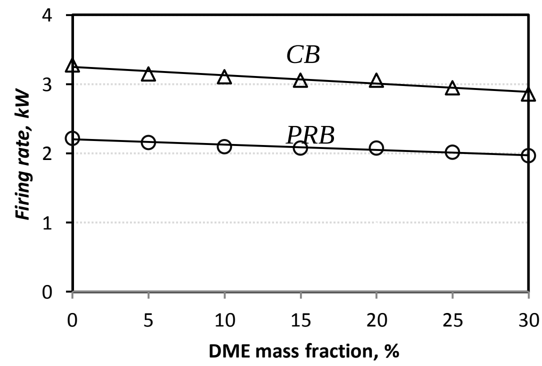


Fig. 7 Firing rate of CB and PRB at p = 30 mbar.

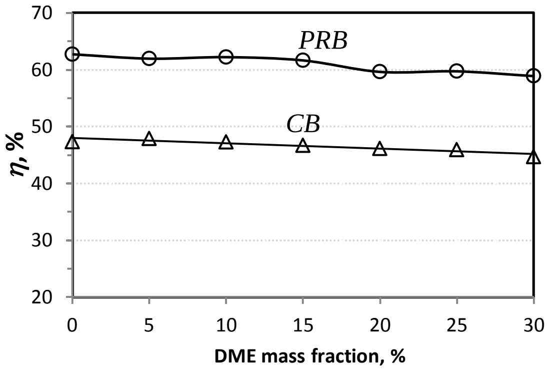
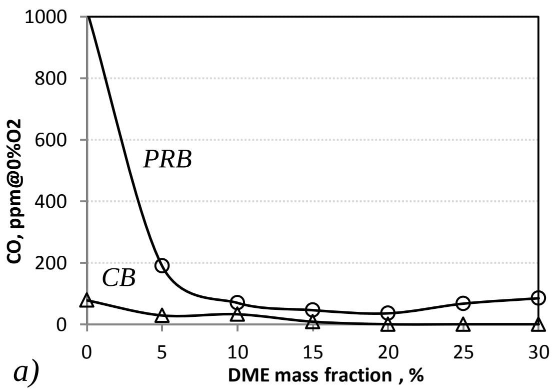


Fig. 8 Effect of DME on thermal efficiency of CB and PRB at p = 30 mbar.



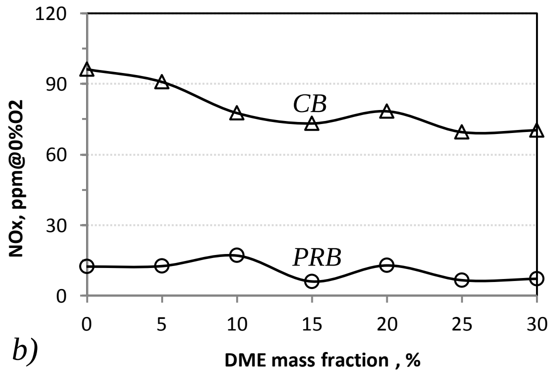


Fig. 9 Effect of DME on a) CO and b) NO_x emission of CB and PRB at p = 30 mbar.

For the PRB, effect of DME concentration on thermal efficiency is not a linear relationship. There is no significantly difference in thermal efficiency with increasing DME less than 20% in the blend, e.g. thermal efficiency is reducing from 62.7% to 61.6% (i.e. reducing less than 2%) as increasing DME from 0%DME to 15%DME. A slightly decrease in thermal efficiency might be due to the combustion is enhanced by increasing oxygenate compound, even though the firing rate is decreased. In contrast, increasing DME to higher than 20%DME will significantly decrease thermal efficiency. At 25%DME and 30%DME, thermal efficiency decreases to about 59.7% and 58.9%, respectively, i.e. decreasing higher than 5% with respect to the pure LPG. As can be observed from the PRB flame images (Fig.6), increasing DME will decreases radiant-red color, especially at relatively high DME concentration (i.e. at 30%DME). Thus, radiation efficiency of the ceramic plate will decrease, in turn, thermal efficiency decreases considerably.

3.2.3 CO and NO_x emissions

Fig.9a, increasing DME decreases CO emission of both CB and PRB. Especially for the PRB, CO emission is reduced from over 1,000 ppm to be less than 200 ppm at 5%DME substituted for LPG. As was described previously, the increase of DME will increase oxidizer in the mixture, and thus, the flame is more premixed-like flame characteristic, i.e. lower CO emission. Moreover for the CB flame, not only being more premixed-like flame that cause CO reduction, but it is also owing to a decrease in quenching effect (i.e. owing to decrease in the impingement velocity). Thus, a zero CO emission is found for the CB flame at 20%DME and the larger. However, for PRB, increasing DME larger than 20% will increase CO emission. As explained earlier that at relatively high DME concentration, the effect of reduction of heat input overcomes the effect of increase in oxygenate compound, thus, it seems as overall combustion temperature decreases. Thus, the flame lifts off, hence, CO increases.

NO_x emission of the CB decreases with increase in DME. There are two possibility reasons for NO_x reduction. NO_x formation might be decreased due to a reduction of the overall flame temperature by dilution effect and decrease in firing rate. The second possibility is due to a reduction of prompt NO_x, because the mixture is leaner when DME is increased in the blended fuel.

NO_x emission of the PRB is generally low compared with the others (Fig.9b), which is the advantage of combustion within porous media where uniform distribution of combustion is achieved. Thus, there is no peak temperature, which is the cause of thermal NO_x formation.

As considering in term of combustion efficiency, DME improves combustion, i.e. both CO and NO_x emission are reduced. However, as both thermal efficiency and pollutants emission are considered, it was found that the addition of DME in LPG should be less than 20%, in which, it is effective to reduce both CO and NO_x while the thermal efficiency of the two burners not significantly decreased. These results quite agree well with the results of previous studies carried out by Marchionna et al. in 2008 [9]. They said that the optimal volume concentration of DME in LPG mixtures was found to be between 15 and 20% as considering many of combustion parameter such as CO and NO_x emissions, Wobbe index and thermal input.

4. Conclusion

Effect of DME-LPG blend composition on performances of the two nationwide cooking burners (i.e. CB and PRB) was investigated. The following conclusions can be drawn from the studied results.

4.1. The blending of DME into LPG up to 30% by mass can be used in the LPG cooking burner. However, care should be taken when PRB is used because flame lift-off might occur at high DME concentration.

4.2. Blending DME with LPG will improve combustion efficiency of the burners because it can reduce the emission of CO and NO_x. However, at fixed fuel supply pressure, increasing mass fraction of DME will decrease thermal efficiency.

4.3. The optimum blend composition is 20%DME in DME-LPG blends.

5. Acknowledgement

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