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Research Article

Combustion Characteristics of Liquefied Petroleum Gas with Ammonia addition on Slot Burner

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Abstract:
This research focused on Liquefied Petroleum Gas combustion with ammonia (NH_3) non-premixed flame on a slot burner which combustion characteristics were investigated for decrease of carbon dioxide (CO_2). LPG combustion with flow variation of NH_3, (LPG: NH_3) was experimentally applied on slot burner to study flame shape, OH intensity, flame temperature, emission of NO_x, CO and exhaust gas temperature. As the results, the flame color became blue-yellow due to NH_2 radical from NH_3 added in LPG combustion. Moreover, NH_3 addition in LPG affected the combustion characteristics such as burning velocity, flame appearance, flame stability, flame temperature, NO_x and CO emissions. This research was clarified that NH_3 could be applied with LPG combustion and the lower burning velocity, blow off flame, unstable flame, lower flame temperature, higher NO_x, lower CO and CO_2 were achieved at less 60% of NH_3 addition.

Keywords: *Flame Shape, NH_3 combustion, LPG, Emission, Flame temperature*

1. Introduction

Ammonia (NH_3) is carbon-free, and it can reduce greenhouse gas emissions (GHG). NH_3 is derived from environmentally friendly and sustainable sources which ammonia's elevated hydrogen concentration renders it an outstanding fuel for combustion. Recently, the development of NH_3 was reviewed as a renewable energy carrier [1]. However, the amount of nitrogen in ammonia influenced on increase of NO_x emissions. In addition, NH_3 exhibits feature such as a low burning velocity, poor heating value, and a long ignition period. Investigating the establishment of a steady flame during NH_3 combustion is a complex research endeavor [2]. The recent study showed the influence mechanism of ammonia mixing on NO formation characteristics of pulverized coal combustion and N oxidation in ammonia-N/coal-N [3]. The results showed that the NO_x emission was influenced by fuel oxidation, NH_3/char, temperature and NH_3 blending ratio. In the past, the NH_3 combustion from the fundamentals to the applications was studied. Nevertheless, the modeling nitrogen chemistry in combustion was also studied to apply for NH_3 blended combustion [4]. The updates in the NO_x and De-NO_x pathways, NH_i recombination reactions and H_2NO chemistry including towards utilizing NH_3 in gas turbines and industrial applications with various NO mitigation strategies were reviewed [5]. However, the direct combustion of NH_3 may provide difficulties due to its unfavorable combustion properties. The combination of NH_3 and hydrocarbon is preferable for combustion compared to the utilization of pure NH_3 for combustion. Mixing NH_3 with hydrocarbons could enhance the combustion process, resulting in a higher level of efficiency compared to NH_3 combustion. This strategy also aids in reducing problems related to NH_3 combustion, such as prolonged ignition time and low heating value. The increased NO_x emission from ammonia combustion has received attention for further development by investigating the combustion system using the technique of flue gas recirculation (FGR) and the combustion instability of CH_4-NH_3 combustion [6]. The result demonstrates that FGR lowers CO emissions but raises NO_x emissions in fuel-rich environments.

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There is a qualitative agreement between the NO emissions derived from the chemical reactor network simulation and the experimental results. The results indicate that the impact of FGR on the formation of NO is mostly influenced by fundamental reactions involving HNO and NH_i radicals. NO_x emission investigations have received much attention for ammonia studies, including studies in high combustion efficiency burners such as porous material burners [7]. The results indicate that NO_x emissions reach their highest levels when the NH_3 molar fraction in the fuel mixture is approximately 0.5 for NH_3/CH_4 mixtures. The CO emission data suggests complete burning of the CH_4, but the presence of unburned NH_3 in the flue gas implies incomplete oxidation of the CH_4. Nevertheless, the quantity of ammonia injected is not the one determining factor for NO_x emissions. The emission of NO_x is influenced by the conditions of combustion, including lean, rich, and stoichiometric mixture [8]. However, incomplete combustion under lean combustion can increase the emission of NO while simultaneously decreasing the emission of NH_3. The NO_x generation was investigated. The lowering of OH, causes the NO_x to decrease as high as ammonia (70% by volume). The high quantities of OH radicals encourage the oxidation of NH_2 and NH radicals, which produces NO_x.[9] Moreover, the NH_3 combustion and emission in practical applications such as fundamental complexities of NH_3combustion, crucial for its practical and industrial implementation in various types of equipment were studied [10]. As the previous study, the combustion of NH_3 combined with CH_4 was conducted to compare the higher heating value [11]. Besides of methane, ammonia could apply with other fuels, such as propane and ethane to enhance the flame stability and broaden the flammability range [12]. Thermal generation in Thailand involves the utilization of many forms of gas, including natural gas and LPG. Specifically, LPG is frequently utilized in both the food sector and families as a cost-effective source of energy. However, the prior investigations had not been carried out regarding the combustion of liquefied petroleum gas (LPG) combined with ammonia. Thus, it is important to study both the fuel and burner to enhance flame stability during ammonia combustion. Multiple cutting-edge burner designs have been created to facilitate the concurrent combustion of ammonia. The double swirl burner is an axial burner type used to examine flame stability when co-combusting with ammonia [13]. Methane was positioned along the periphery of the burner's outer tube, while the inner tube was employed to deliver ammonia fuel. Despite being often employed in premixed combustion, axial burners are prone to the occurrence of flashback flame. Nevertheless, the issue of flashback flame can be efficiently reduced by employing non-premixed combustion for secure combustion. An investigation was conducted on the flame properties of ammonia combustion using an axial burner [14]. The results revealed that the flame exhibited an orange color, which was considered undesirable and associated with low temperatures. Further improvements were necessary to attain optimal combustion. The previous study of LPG combustion on slot burner was the one of LPG applications for industrial sectors such as food and metal industries. The porous bluff-body slot burner (PBSB) was a non-premixed combustion device that was designed to generate combustion akin to premixed combustion and a diffusion flame [15]. Furthermore, the Y-shape nozzle slot burner (YNSB) has been found to enhance the flame temperature more than the PBSB. This model could improve the combustion properties compared to the PBSB [16]. In addition, the slot burner ensures a consistent and even dispersion of heat across the whole length of the burner. The crossflow slot burner (CFSB) is a modified version of the PBSB that achieves a flame characterized by premixed combustion and lacks a diffusion flame [17]. To study the ammonia addition on LPG combustion, this study focuses investigation of the characteristics of LPG blended with ammonia non-premixed flame on a CFSB burner, with potential applications for industrial sector to reduce combustion emissions.

2. Experimental Setup and Method

The crossflow slot burner (CFSB) consists of two fuel slots positioned on the left and right sides of the burner. The two fuel slots contain crossflow plates, each with a single fuel slot in the center of the burner. These plates have 16 circular holes, each with a diameter of 2 mm, as depicted in Figure 2. The cylindrical bluff body is produced by optimizing the material's streamlined shape. The component is located centrally within the air slot and plays an important part in the recirculation of air. It results in the increased fuel mixing with the air. This study examines the composition of simulated Liquefied Petroleum Gas (LPG), which is comprised of 70% Propane (C_3H_8) and 30% Butane (C_4H_{10}) with 99.5% purity of both gases. It is important to maintain this composition under all conditions. The addition of ammonia (NH_3) with 99.5% purity replaced LPG based on its volume proportion. Therefore, the combustion equation of LPG can be described by Equation (1), while the combustion equation of NH_3 may be described by Equation (2). The ammonia volume fraction (X_{NH3}) can be determined from the NH_3 flow rate (Q_{NH_3}), the sum of the NH_3 and LPG flow rates ($Q_{LPG}+Q_{NH_3}$) and LPG flow rate determined by sum of 70% C_3H_8 and 30%C_4H_{10} flow rates ($Q_{LPG} = 0.7Q_{LPG}+0.3Q_{LPG}$).

The equivalence ratio (ϕ) is the variation between the actual fuel-air ratio $(F/A)_{actual}$ by volume and the stoichiometric fuel-air ratio $(F/A)_{stoic}$, as described in Equation (3). The firing rate (*F.R.*) is the rate at which fuel is inputted, calculated using the low heating value (*LHV*) and the mass flow rate of the fuel ($\dot{m}$) as indicated in Equation (4). The thermal properties of ammonia and LPG as shown in Table 1. Figure 1. (b) illustrates the experimental setup used to investigate the LPG and NH_3 combustion flames on a non-premixed slot burner. The process starts by separating the fuel gas into liquefied petroleum gas (LPG) and ammonia (NH_3). Subsequently, the gas is routed through a digital mass flow controller to precisely determine the flow rate. It then combines with the fuel in a mixing chamber before reaching the burner. Meanwhile, a digital flow controller (Azbil, F4Q Model) regulates the airflow from the compressor, determining a specific rate of flow that combines and ignites the fuel and air at the burner head. The exhaust gas analyzer (Testo 330) detected the CO emission after the fuel and air ignited, the thermocouple (Type B) measured the flame temperature, the digital camera (Nikon-D7100) captured the flame characteristics, and the OH camera (LaVision, Imager M-lite 2M CMOS Camera, Image intensifier module: IRO X) recorded the OH emission. Table 2 presents the experimental condition of LPG-NH_3 flame.

$$(1-X_{NH_3})[(0.7C_3H_8+0.3C_4H_{10})+5.45(O_2+3.76N_2)]\rightarrow(1-X_{NH_3})[3.3CO_2+4.3H_2O+20.49N_2] \quad (1)$$

$$X_{NH_3}[NH_3+0.75(O_2+3.76N_2)]\rightarrow X_{NH_3}[1.5H_2O+3.32N_2] \quad (2)$$

$$X_{NH_3}=\frac{Q_{NH_3}}{Q_{LPG}+Q_{NH_3}} \quad (3)$$

$$\Phi=\frac{(F/A)_{Actual}}{(F/A)_{Stoi}} \quad (4)$$

$$(F/A)_{Actual}=(\rho_{Fuel}Q_{Fuel})/(\rho_{Air}Q_{Air}) \quad (5)$$

$$FR=\dot{m}\times LHV \quad (6)$$

Table 1: Thermal properties of ammonia, propane, and butane [18, 19].

Fuel	NH_3	LPG	
		C_3H_8	C_4H_{10}
Boiling temperature at 1 atm (°C)	−33.4	−42.1	−0.4
Lower heating value, LHV (MJ/kg)	18.6	46.4	45.8
Adiabatic flame temperature (°C)	1800	1967	1970
Maximum laminar burning velocity (m/s)	0.07	0.43	0.39
Minimum auto ignition temperature (°C)	650	455	405
Density at 25°C (kg/m3)	0.769	1.796	2.400

Table 2: The experimental conditions of LPG-ammonia combustion.

X_{NH3} (Volume%)	Q_{LPG} (L/min)	Q_{NH3} (L/min)	Q_{Air} (L/min)	Φ	$(F/A)_{Stoi}$	FR (kW)
0	0.75	0.00	20.00	1.00	0.06442	1.19
10	0.67	0.08	20.00	0.91	0.06594	1.09
20	0.60	0.15	20.00	0.82	0.06777	0.99
30	0.52	0.23	20.00	0.74	0.07003	0.89
40	0.45	0.30	20.00	0.65	0.07288	0.78
50	0.37	0.38	20.00	0.56	0.07660	0.68
60	0.30	0.45	20.00	0.48	0.08165	0.58

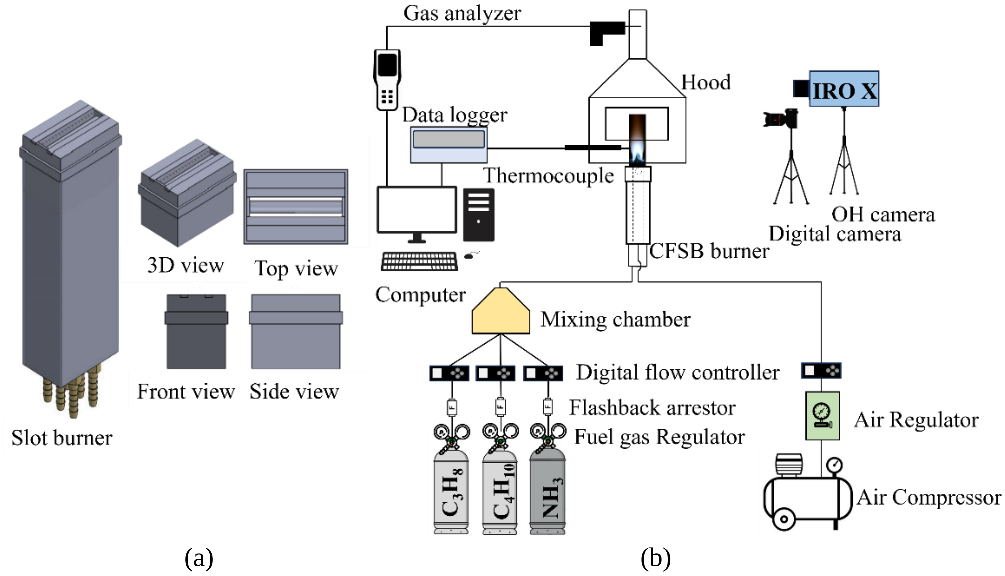

Fig. 1. (a) Geometry of crossflow slot burner (CFSB), and (b) the schematic of experimental setup

3. Result and discussion

The investigation into the combustion characteristics of ammonia addition to liquefied petroleum gas non-premixed flame aims to decrease the fossil fuel (hydrocarbon fuel) and carbon dioxide emission in gas burners. The results show the analysis of flame stability, temperature, and CO and NO_x emissions for a wide range of LPG-NH_3 blends.

3.1 Effect of X_{NH3} to equivalence ratio

The total flow rate at 20.75 L/min consists of 20 L/min of air flow rate and 0.75 L/min of fuel flow rate were set as the flow rate condition on CFSB, which is the stoichiometry condition and can produce the stability flame on the CFSB burner. Following Equation (2), the increasing ammonia volume percentage in fuel affects the equivalence ratio because ammonia requires less oxygen to react than LPG as shown in Table 2. The $(F/A)_{stoi}$ is increasing with high ammonia. It means the air consumption for ammonia combustion reaction dosing is reduced, resulting in excess air and a low equivalence ratio (lean combustion). Thus, Figure 2 shows the effect of X_{NH3} on the equivalence ratio, with the increasing ammonia effect decreasing the equivalence ratio. Ammonia addition is maximum at 60% by volume at 0.48 of equivalence ratio is refers to the short-range flammability limit on this operation.

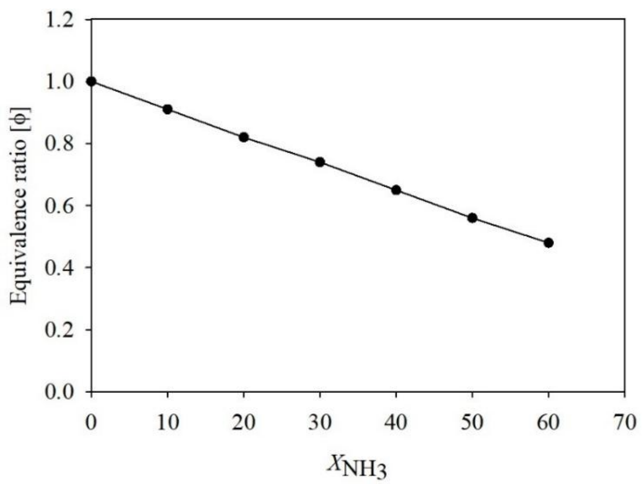

Fig. 2. Relations between variation of X_{NH3} and equivalence ratios.

3.2 Flame Shape

Figure 3 shows the flame shape of LPG-ammonia flames on a non-premixed combustion CFSB burner for various ammonia volume fractions (0 to 60%). There are two images in the picture: an image from the side view that shows the long side of the burner, and an image from the front view that shows the wide side of the burner. The LPG flame (0% ammonia) shows a strong blue flame at stoichiometry conditions and becomes a light yellow-orange color on top of the flame as the ammonia fraction increases. The intensity of the yellow-orange flame intensifies as the ammonia fraction increases, as indicated by the NH_2 ammonia spectrum [14]. The increasing of the ammonia fraction results in a slight decrease in the flame. This flame reduction is primarily due to the equivalence ratio that comes into play in the lean condition.

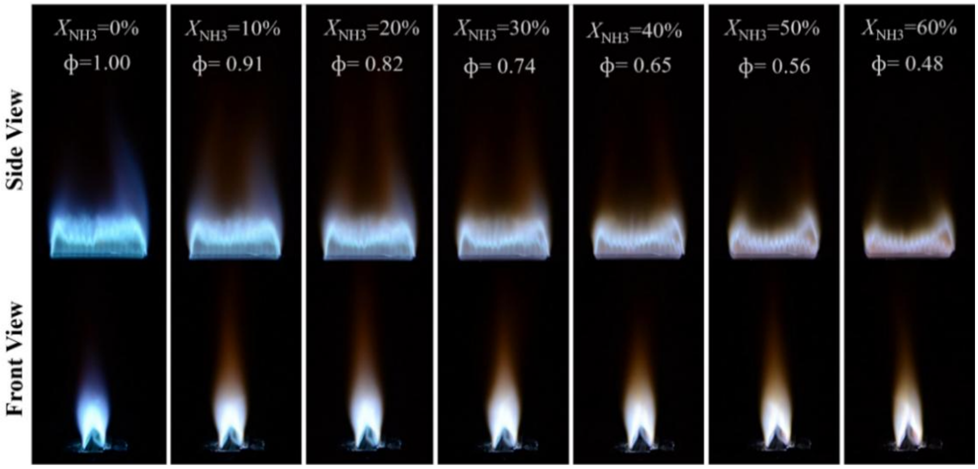

Fig. 3. Flame shape of LPG-NH_3 flames on non-premixed CFSB burner between 0 to 60% by ammonia volume fraction.

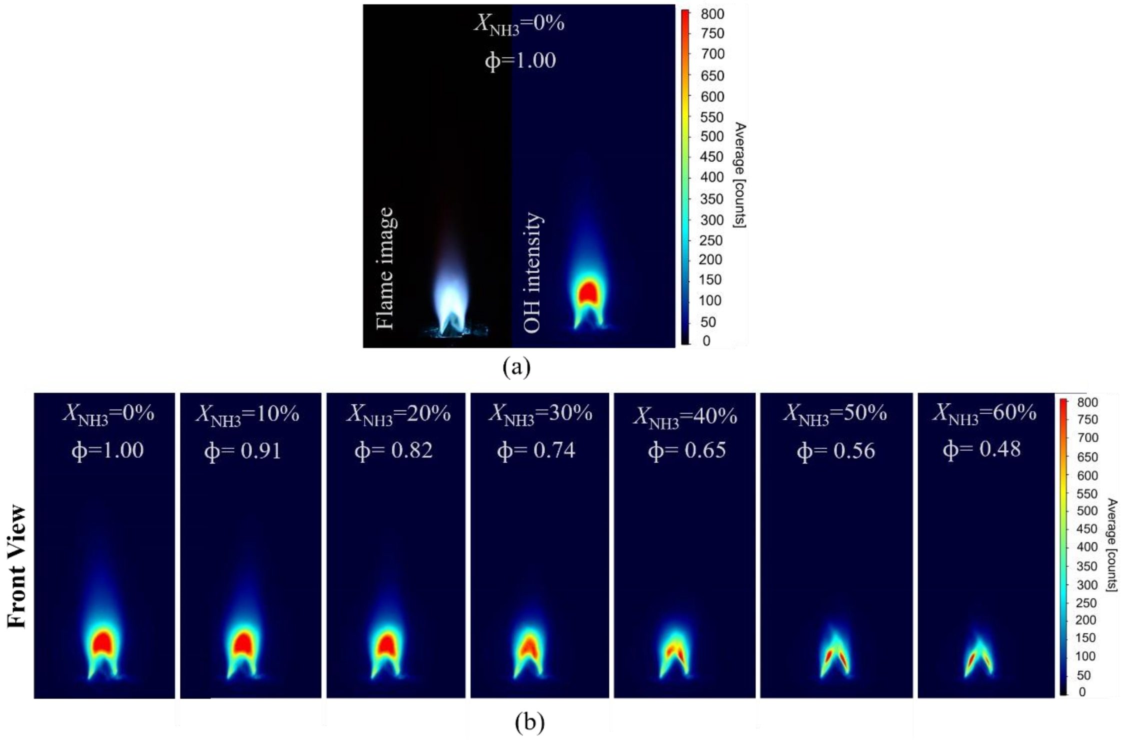

Fig. 4. (a) Flame image vs OH intensity, and (b) OH intensity of LPG-NH_3 flames on non-premixed CFSB burner between 0 to 60% by ammonia volume fraction.

3.3 OH emission

Figure 4 shows the OH emission of the LPG-ammonia flame on a non-premixed combustion CFSB burner. The front view of the image clearly illustrates the physical air-fuel feeding of the CFSB burner. The shape of the OH image is approximately the same as the flame image in Figure 4 (a). The OH image is the highest intensity in the red zone at the center of the flame as shown in Figure 4 (b). This section refers to the LPG-NH_3 combustion reaction zone. As the ammonia fraction increases, the LPG flame shows a wider and narrower red zone. The narrow red zone is clearly visible from 30% of the ammonia fraction onwards. Lean conditions primarily affect the small red zone, leading to an increase in the ammonia fraction.

3.4 Flame Temperature

Figure 5 shows the flame temperature measured from 6 cm above the burner. This position is almost a reaction zone, leading to the maximum flame temperature. The LPG flame at 0% ammonia fraction shows the highest temperature at 1,205.3 °C. The flame temperature was decreasing until 642.6 °C at 60% of the ammonia fraction. This reduction in flame temperature arises from the equivalence ratio effect and the low adiabatic flame temperature of ammonia.

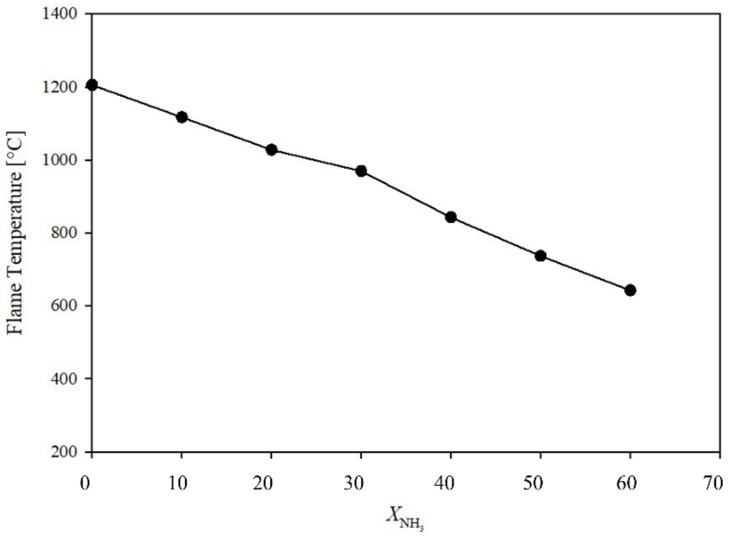

Fig. 5. Flame temperature of LPG-NH_3 flames on CFSB between 0 to 60% by ammonia volume fraction.

3.5 Exhuast Gas Emission

Figure 6 is a three-axis graph that shows the CO and NO_x emissions from LPG-ammonia flames on a non-premixed CFSB burner. The graph shows the emissions for ammonia volumes ranging from 0% to 60%. The graph displays the CO concentration on the right axis. The LPG flame at 0% of the ammonia fraction had a lower CO concentration of 3.91 ppm (at ϕ=1.00) before slightly increasing to more than 40% of the ammonia fraction and reaching the maximum value of 67.6 ppm (at ϕ=0.48). This attribute by incomplete combustion in lean conditions, where oxygen remains from excess air in the reaction. When ammonia increased, the CO concentration was small due to the low hydrocarbon content. The left-axis graph displayed the NO_x concentration. The LPG flame at 0% of the ammonia fraction produced the lowest NO_x concentration at 3 ppm (at ϕ=1.00) and dramatically increased when the ammonia fraction increased from 10% to 40% as the maximum NO_x concentration (177.9 ppm) and decreased after 50% of the ammonia fraction onwards. The increasing NO_x concentration in the earliest stage was attributed to the prompt NO_x caused by the increasing nitrogen in ammonia, as well as some effects from the thermal NO_x pathway, which still produced a high flame temperature. The decrease in NO_x after 40% of the ammonia fraction is due to the involvement of OH radicals in the reaction; combustion generated a high concentration of OH radicals, which promote the oxidation of NH and NH_2 molecules [9, 20]. As a result, the small OH concentrations in the higher ammonia fraction produced a low NO_x concentration. Moreover, the lower temperature in the high ammonia fraction led to the interception of thermal NO_x. However, the addition of ammonia clearly reduces the CO concentration. Figure 7 shows

CO_2 decreases with an increasing ammonia fraction, however CO_2 was not observed at 40% of the ammonia fraction. This phenomenon clearly illustrates how replacing ammonia in LPG leads to a decrease in CO_2 levels as the decrease of main carbon content of hydrocarbons.

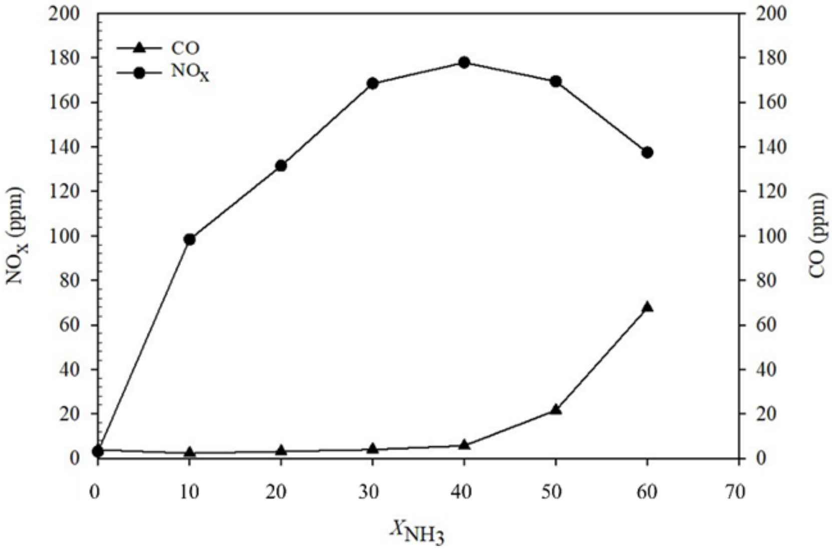

Fig. 6. CO and NO_x emission of LPG-NH_3 flames on non-premixed CFSB between 0 to 60% by ammonia volume fraction.

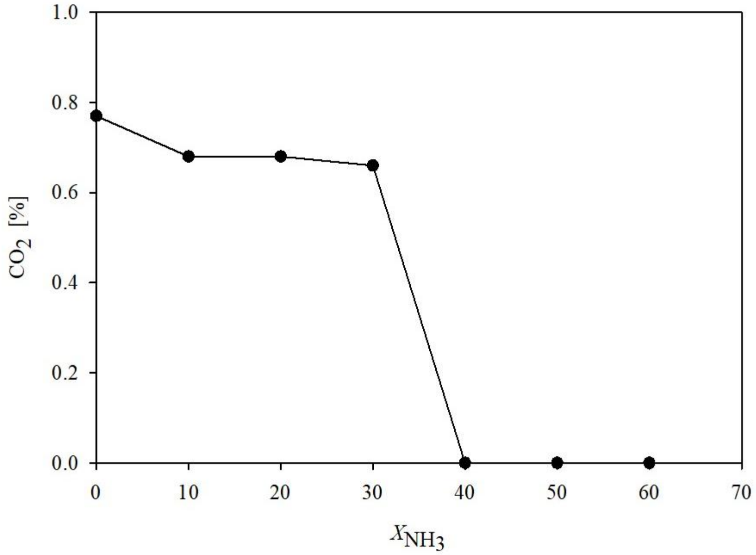

Fig. 7. CO_2 emission of LPG-NH_3 flames on non-premixed CFSB between 0 to 60% by ammonia volume fraction

4. Conclusion

Investigation of the characteristics of LPG combustion when combined with ammonia. The addition of ammonia between 0 % (Pure LPG) and up to 60% ammonia, the main conclusions from this study are as follows: Less 60% of NH_3 blended with LPG combustion and flammability limit was applicable. The flame colour became blue-yellow due to NH_2 radical from NH_3 added in LPG combustion. The OH intensity will gradually decrease with the addition of ammonia due to the decrease of equivalence ratio. Moreover, NH_3 addition could enhance the reduction of CO and CO_2 whereas low burning velocity, shorten flammability limit, lower flame temperature and higher NO_x were observed.

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