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Research Article

Numerical Study of LPG Combustion Affected by Y-Shaped Nozzle Mounted on Slot Burner

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Abstract:
This research is to study the LPG combustion affected by Y-shaped nozzle mounted on slot burner. The Y-shaped nozzle is a burner outlet which controls the air and fuel flow on the slot burner. In order to increase temperature by improvement of the mixing between air and fuel over the burner, the Y-shaped nozzle mounted on the slot burner was designed and investigated by numerical method. This study focused on main parameters as 15, 30, and 45 degrees of air circulating cavity angle with/without air strengthening hole by numerical simulation model at equivalence ratio Φ =1.0 and 2.0 kW of firing rate. As the result, more 423.15 K (11.0%) of maximum flame temperature was increased with Y-shaped nozzle slot burner mounted with 45 degrees of air circulating cavity angle and added air strengthening hole. This study shows the enhancement of LPG flame temperature influenced by the Y-shaped nozzle mounted on the slot burner due to the improvement of mixing flow.

Keywords: *Y-Shaped nozzle, Slot burner, Flame temperature, Air circulating cavity, Air strengthening, Non-premixed combustion*

1. Introduction

According to the Thailand Energy Consumption Statistics report during March - September 2021 by the Energy Policy and Planning Office, Ministry of Energy, liquefied petroleum gas (LPG) usage increased by 8.1 percent from 2020. LPG consumption increased by 45% in the petrochemical sector and 11% in the industrial sector. In the household sector, despite a decrease in consumption from the previous year, it still accounts for the second largest [1]. Most of the LPG is derived from crude oil refining and natural gas separation processes, with a composition of two liquefied hydrocarbon gases: 70% propane (C_3H_8) and 30% butane (C_4H_{10}). LPG is colorless, odorless, weighs more than air, and therefore has low buoyancy and easy ignition, resulting in high heat values and an adiabatic flame temperature [2].

In industry, LPG is commonly used in premixed combustion. As the flammability of LPG, the higher possibility of flashback flame is found on premixed combustion compared to non-premixed combustion [3]. Therefore, non-premixed combustion has a safety advantage because the air and fuel channels are clearly separated, but the fuel and air do not mix well, resulting in incomplete combustion and producing a more diffusion flame than premixed combustion [4, 5]. In this research, non-premixed combustion was studied on a slot burner, a burner used in industries that require constant heat, such as the food industry, glass melting, and steel industry. The distinctive feature of slot burner was designed for suitable length which affected high heat transfer rate per unit area or heat flux [6].

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The non-premixed combustion on the slot burner used several techniques for improving the mixing flow. One of the techniques used in the slot burner is the bluff body on the air central of the burner, which can improve mixing flow in terms of inducing more turbulence and enhancing air velocity [7]. Significantly, they obtained the high flame temperature by applying porous media on the bluff body slot burner. The bluff body shape significantly affected in the case of spiral bluff body shape by the characteristic of spiral shape that occurred fluctuation flow around the bluff body. In particular, the bluff body could enhance the airflow direction and mixing between fuel and air. Moreover, the fuel flow passing through the porous media can enhance the heat radiation and achieve a high temperature [8].

The flame temperature of the combustion on the PBSB is still far from the adiabatic temperature of LPG combustion which is high around 2,253.15 K. This problem is due to the lack of air and fuel mix, which is a heat loss to the environment. Therefore, this research is to study and develop further from the prototype PBSB to increase the combustion temperature of LPG to be closer to the Adiabatic temperature. The VGSB simulation model improved from PBSB with vortex generator (VG) showed the wider flame temperature distribution without VG [9]. Many techniques were designed to support the slot burner, and one technique that enhances the flame stability is the concentric flow technique slot burner. In addition, they are using the Truncated Rectangular Pyramid nozzle on the Wolf hard-Parker slot burner outlet. These techniques obtain flame stability because the nozzle can increase air circulation, allowing air and fuel to mix better, resulting in a more stable flame [10, 11].

Furthermore, there was the research that supports the Shuttlecock-like conical burner by air hole channel techniques occurred, which is the air hole effect to better flame characteristics than general conical burner due to some air flowing through the burner hole together with the air flowing above the burner area, causing the air inside and outside to curl together led to achieved higher reaction concentration and high temperatures having better distribution [12].

Therefore, this research focuses on the design of burner outlets in various shapes to support the use of PBSB to improve the combustion temperature of LPG on the Porous-Bluff Body Slot Burner (PBSB). To achieve higher LPG combustion flame temperatures, the numerical simulation method of ANSYS Fluent 2021R2 was applied to study the characteristics of air-fuel flow and of LPG flame temperature at Φ =1.0. The influence of air circulating cavity angle and air strengthening hole of the Y-shape nozzle applied on PBSB affected the LPG flame temperature is investigated. This study aims to improve the combustion characteristics and flame temperature of LPG flame, particularly for applications in the industrial sector.

2. Numerical Model

2.1 Simulation Domain and Boundary Conditions

The Numerical simulation was studied by the ANSYS Fluent 2021R2 program to create a fluid domain model using the cavity function on a solid model of the prototype PBSB burner. The fluid domain model determined the fluid inlet, fluid outlet, and wall contact. The simulations in subsequent models, it is necessary to consider the size and number of meshes to ensure that the results studied and analyzed do not depend on changes in the size and number of meshes, also known as mesh independence studies. Once the appropriate mesh size was determined and then set up conditions, calculated the air and fuel velocity by balancing the Stoichiometric combustion equation of liquefied petroleum gas with a ratio of 70% propane (C_3H_8) and 30% butane (C_4H_{10}) at an equivalence ratio of 1 (Φ =1.0), air volumetric flow rate 20 l/min. As calculation results, the air velocity (V_a) is 0.6670 m/s, the fuel velocity (V_f) is 0.0536 m/s at 25°C, and the other variables were set as close as possible to the laboratory environment. The simulation domain of the slot burner includes three parts: two fuel inlets on the side of the burner, the air inlet in the center of the burner, and the outlet on the exit of the burner. The domain size of the slot burner is 58,000 mm^3 of one fuel inlet, 72,500 mm^3 of air inlet, and 1,038,800 mm^3 of outlet.

2.2 Numerical Method

The calculation and simulation result with the laboratory experiment result until the flame temperature difference was as close to the laboratory experiment as possible by using the number of statics mesh elements close to 500,000 with an element size of 0.02 mm. Thus, such conditions can be used in the simulation of the burner outlet for calculation on Langtry-Menter 4-equation Transitional SST Model in the viscous model, the discrete ordinates (DO) radiation model solves the radiative transfer equation (RTE) and operates in a non-premixed combustion model. This was calculated by specifying species in mole fraction of C_3H_8 and C_4H_{10} and using to inlet diffusion to calculate the non-premixed model [9].

2.3 The Geometry of the Burner

In this research, the design and development of the fuel and air outlet slot, called the Y-shape Nozzle, was designed to support on Porous-Bluff Body Slot Burner (PBSB). The PBSB consists of two fuel slots on the left and right of the burner. The air slot on the central burner exit at the top of the burner sets the bluff body in the middle, and both fuel exits set nickel foam in porosity 50 ppi and covered by the case to reduce the cross-section area of the fuel slot. The Y-shape nozzle was divided into two parts: the air circulating cavity and the addition of the air strengthening hole, as shown in Fig. 1. The study parameter of air circulating cavity angle was studied at 15°, 30°, and 45°, and the parameter of air strengthening hole was studied in the type of with no hole and type of with hole on the angle of Y-shape nozzle at fixed hydraulic dynamic 29 cm as same entire case. The detail of the parameter study, as shown in Table 1 and Fig. 2 consists of one case for the phototype of the slot burner that was PBSB and six cases for the Y-shape nozzle on the PBSB. The parametric case on PBSB with a Y-shape nozzle is referred to as YNSB.

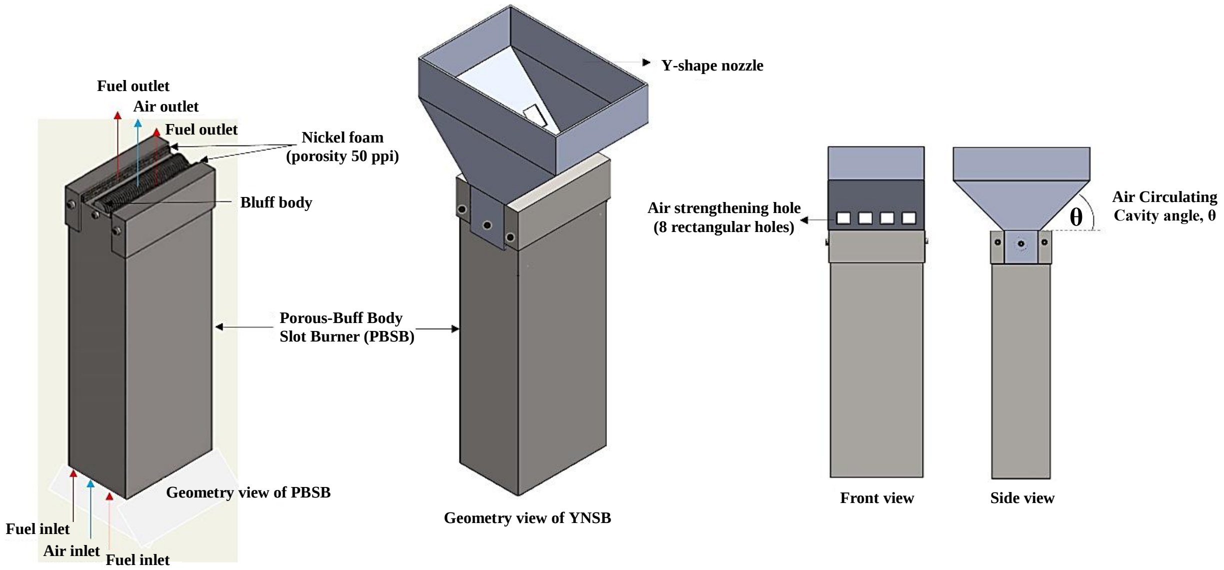

Fig. 1. PBSB with Y-shape nozzle on geometry view, front view, and side view.

Table 1: The parameter studied and 7 case studies in PBSB and YNSB

Case	**Detail of name case**	**Y-shape nozzle adding**	
		Air circulating cavity angle (degree, °)	**Air strengthening hole**
Case 1	PBSB	-	-
Case 2	15D-NH	15°	without hole
Case 3	15D-WH	15°	with hole
Case 4	30D-NH	30°	without hole
Case 5	30D-WH	30°	with hole
Case 6	45D-NH	45°	without hole
Case 7	45D-WH	45°	with hole

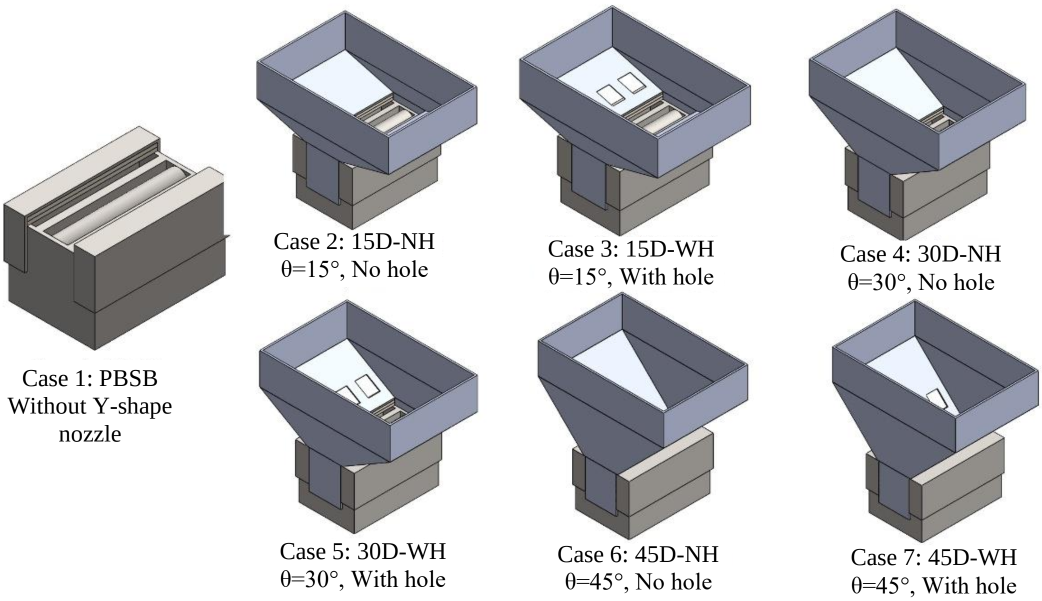

Fig. 2. PBSB and YNSB models.

3. Methodology

3.1 Stoichiometric Combustion Equation

The balancing of fuel-air chemical equations is fundamental to experiments because the quantities of fuel and air are used concerning the chemical equilibrium in the desired reaction. If there is enough oxygen, the hydrocarbon fuel can burn completely, so the carbon in the fuel is converted to carbon dioxide (CO_2), the hydrogen is converted to water, and the air still contains nitrogen. But when the product is at low temperatures, the nitrogen does not affect the reaction. A typical representation of complete combustion for hydrocarbon fuels and air can be shown as Equation (1).

$$C_aH_b+\left(a+\frac{b}{4}\right)(O_2+3.76N_2)\rightarrow aCO_2+\left(\frac{b}{2}\right)H_2O+3.76\left(a+\frac{b}{4}\right)N_2 \qquad (1)$$

3.2 Equivalence Ratio

The equivalence ratio is a unitless quantity commonly used in combustion that indicates how far the fuel-oxidizer mixture is from a theoretical value. If $\Phi < 1$ is a fuel–lean mixture, $\Phi > 1$ is a fuel–rich mixture, and $\Phi = 1$ means that it is stoichiometric as shown in Equation (2).

$$\Phi = \frac{(A/F)_{stoi}}{(A/F)_{actual}} \qquad (2)$$

3.3 Firing Rate

Firing rate is the input rate of fuel can be calculated from the mass flow rate and low heating value of the fuel as shown in Equation (3).

$$F.R. = \dot{m}_f \times LHV \qquad (3)$$

4. Results and Discussion

4.1 Maximum Flame Temperature Validation

The experimental flame temperature on PBSB was measured and collected in the laboratory. A maximum flame temperature of 1,256.15 K was achieved on the PBSB, located 6 cm from the head of the burner. The average maximum temperature obtained from the simulation was similar to the position of the burner geometry of the experiment PBSB was obtained at 1,515.85 K. As the characteristics of temperature distribution closed to experimental results as shown in Fig. 3. The validation between experiment and PBSB model was accepted with the maximum average temperature difference of 20.68 %, attributed to the significant losses to the surrounding in the actual experiment.

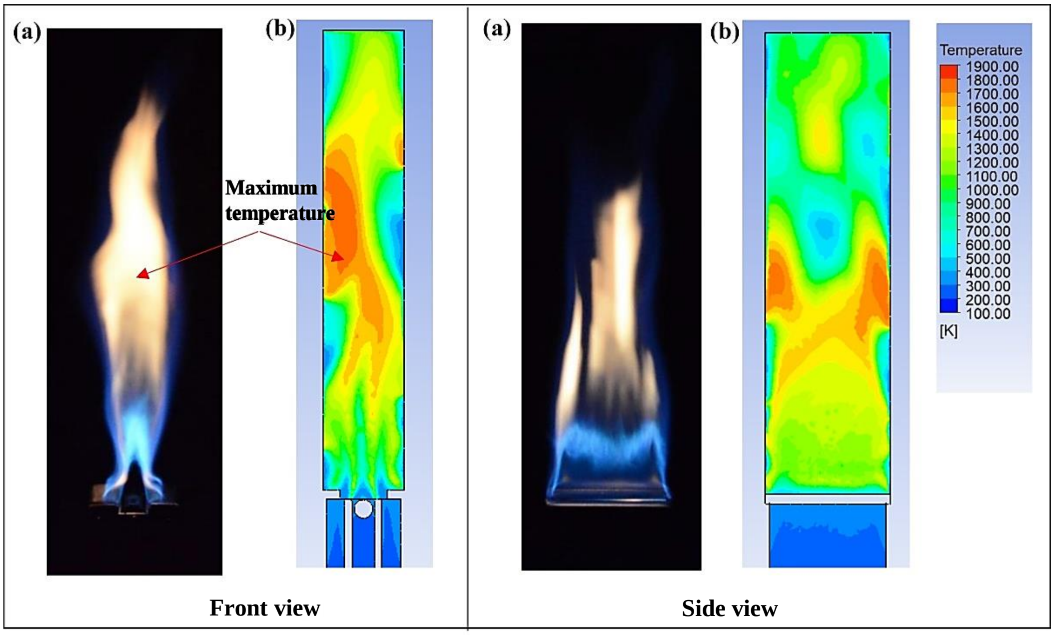

Fig. 3. Flame characteristics and temperature distribution of LPG combustion on PBSB burners on front view and side view (a) experiment result (b) simulation result.

4.2 Velocity Streamline

The velocity streamlines of LPG non-premixed combustion on Y-shape nozzle burner are shown in Fig. 4 for cases 1-7 that consist of the variation in air circulating cavity angle at 15°, 30°, and 45° with hole and without hole of air strengthening. The LPG gas combustion occurs at a stoichiometric or equivalence ratio equals 1.00 or 2.00 kW. The velocity streamlines were the difference between the PBSB model and YNSB model because the air and fuel fluctuation flow which non-smooth flow and sway flow on adding of Y-shape nozzle on slot burner model than the PBSB model are smooth flow in low flow velocity. The higher fluctuation streamlines on YNSB result in higher airflow velocity observe yellow line was increasing on adding Y-shape nozzle. The YNSB model at 15°, 30°, and 45° of air circulating cavity angle with a hole of air strengthening (case 3, case 5, case 7) observed the similarity of velocity streamline. In contrast, the YNSB without a hole of air strengthening appears to be similar. The several flows set of YNSB with the hole of air strengthening effect to great amount of airflow from air hole surrounding and the circulation airflow on open end the Y- shape. That induced the great air into the burning zone, especially in case 7. Meanwhile, the great circulation airflow occurs on YNSB without hole of air strengthening that the only way to induce the airflow from the surrounding.

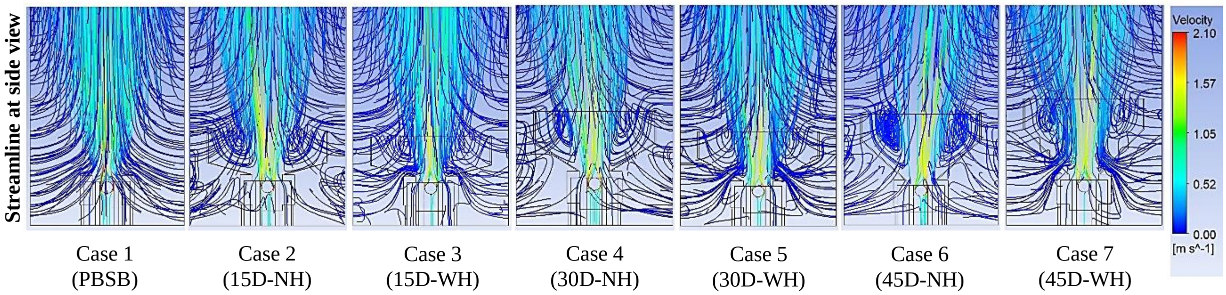

Fig. 4. The velocity streamline of LPG non-premixed combustion on Y-shape nozzle slot burner.

4.3 Flame temperature distribution

Figure 5 and Figure 6 show the temperature distribution on the front and side views of the YNSB model compared to the PBSB model. Although the temperature contour shape of PBSB was similar to that of the YNSB model, the intensity of temperature contour in the combustion zone (orange or red zone) differed. In case 3, case 5, and case 7, representing the effect of air circulating cavity angle with the hole of air strengthening at 15°, 30°, and 45°, respectively. The red intensity of temperature contour was observed on both views of YNSB that affected by the air hole induce air flow to enhance mixing fuel than without hole. The highest temperature contour (red zone) was clearly observed in the case of air circulating cavity angle at 45° with hole, followed by the next high-temperature distribution is 30° and 15°, respectively. Therefore, the angle of the air circulating cavity significantly affected the combustion temperature, and the wider the angle, the more open the outside air in the burner, leading to better mixing between air and fuel.

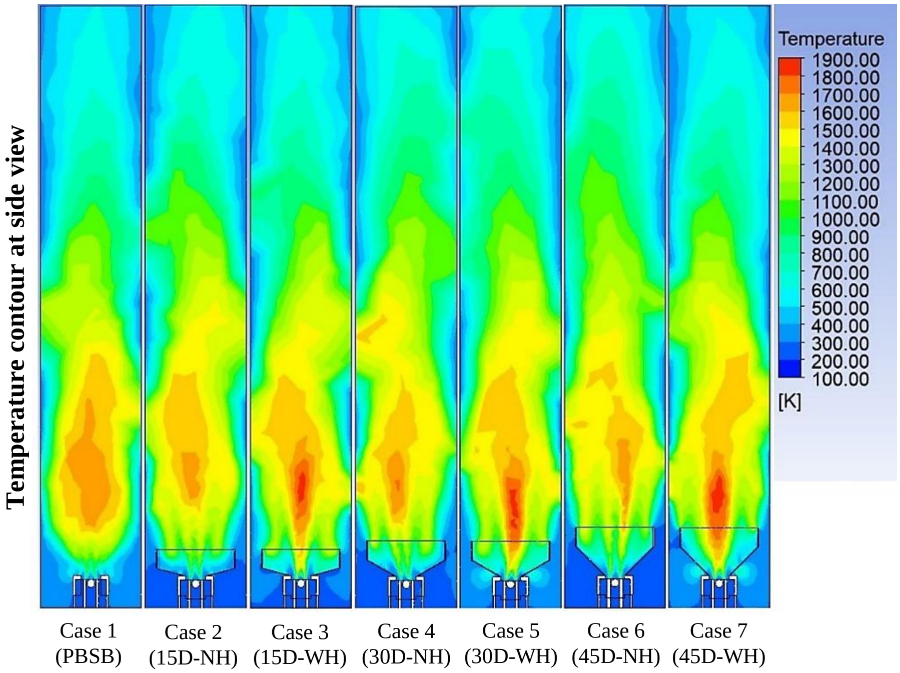

Fig. 5. Flame temperature distribution on front view of Y-shape nozzle burner.

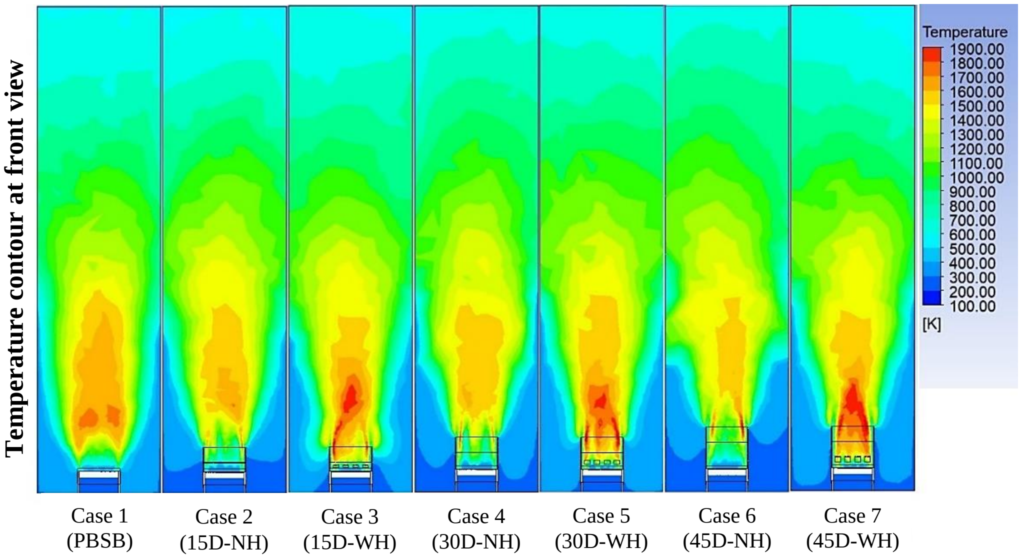

Fig. 6. Flame temperature distribution on side view of Y-shape nozzle burner.

4.4 Maximum Temperature

In addition to the velocity streamline and temperature contour, the maximum temperature is significant for combustion. Figure 7 shows the maximum temperature at 2 cm from the head of the burner, suitable for applying to another source. The similarity of the velocity streamline and temperature contour, the PBSB model obtained a lower maximum temperature than the YNSB model due to the devoid of air enhancement from the Y-shape nozzle. Meanwhile, in the case of YNSB, the highest maximum temperature was achieved at 15° and 45° of air circulating cavity angle with hole (case 3 and case 7) around 1,721.65 K and 1,722.81 K, respectively. In contrast, the angle of 30° with the hole was rather decreasing. Meanwhile, the YNSB without holes showed similarity across all angles of the air circulating cavity. However, the most significant effect of combustion temperature on the Y-shape nozzle slot burner was from the air strengthening hole due to the great air form air hole induct the air from surrounding to enhance the mixing air and fuel during the combustion.

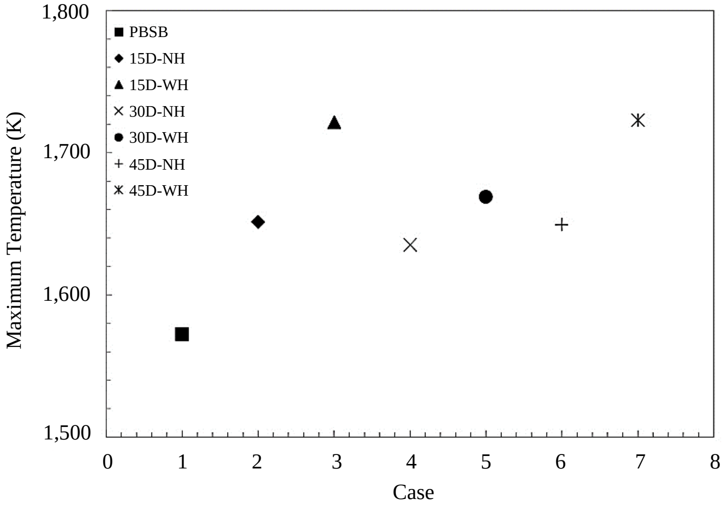

Fig. 7. Maximum temperature observed with variations of Y-shape nozzle on slot burner.

5. Conclusion

In this study of numerical simulation for non-premixed combustion of Y-shape nozzle mounted on slot burner with the effect of air circulating cavity angle and air strengthening hole studied for the LPG combustion at 70% of C_3H_8 and 30% of C_4H_{10}, the result were summarized as follows:

1. The temperature from the numerical model can approach the temperature from the experiment and predict the flame's shape is likely temperature contour.
2. The velocity streamline shows a clear difference in the case of PBSB and YBSB, especially in the case of YNSB with an air strengthening hole, where many inlets of airflow to burning were obtained.
3. The maximum temperature zone of 1,723.15 K was obtained in case of YNSB with air strengthening hole, in particular on 15°, and 45° of air circulating cavity with a hole. Although the flame temperature on YBSB could be improved compared to PBSB, however, it is lower than adiabatic flame temperature, of 2,200 K.

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Nomenclature

Φ	equivalence ratio
D	degree
F.R.	firing rate, kW
LHV	low heating value, kJ/kg
LPG	liquefied petroleum gas
$\dot{m}_a$	air mass flow rate, kg/s
$\dot{m}_f$	fuel mass flow rate, kg/s
NH	without hole
ppi	pores per inch
PBSB	porous bluff body slot burner
SB	slot burner
V_f	fuel velocity, m/s
V_a	air velocity, m/s
VG	vortex generator
VGSB	vortex generator slot burner
YNSB	Y-shape nozzle burner
WH	with hole

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