International Journal of Technology 12(1) 163-174 (2021)
Received February 2020 / Revised June 2020 / Accepted January 2021

International Journal of Technology

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

Construction of a Finned Heat Radiation Reflector for Improved Efficiency of Liquefied Petroleum Gas Stoves

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Abstract. The objective in this study was to construct a finned heat radiation reflector using a cut cone-shaped stainless steel plate. In addition, its efficiency was examined by the water boiling test by varying the fin rows and angles. Measurements were performed on reflectors with one, two and three rows of fins, which were compared with conventional stoves with and finless reflectors. Furthermore, fin angles of 5°, 10°, 15°, 20° and 25° were evaluated by the variation in the fin rows, and the most efficient configuration was investigated. Results revealed that finned reflectors increase the efficiency of liquefied petroleum gas stoves. The highest efficiency (60%) was obtained for the reflector with three finned rows and a fin angle of 10°. Compared with those of conventional reflectors and reflectors without fins, 7.87% and 4.47% increase in the efficiency was observed, respectively. Furthermore, the use of finned reflectors enhanced the area of complete combustion.

Keywords: Efficiency; Fin angle; Fin rows; Finned heat reflector; LPG stove

1. Introduction

Low efficiency of liquefied petroleum gas (LPG) stoves is attributed to the loss of heat from the flame, which occurs due to the high-temperature difference between the flame and its surroundings caused by the distance between the head burner and load (Abdurrachim et al., 2009; Gohil and Channiwala, 2011; Syahrial, 2012; Widodo, 2014; Widodo, 2015). Therefore, this loss needs to be minimized. On the basis of the results reported in previous studies, two methods can be employed to improve the efficiency of LPG stoves: construction engineering (Dongbin et al., 2007; Pantangi et al., 2011; Khan and Saxena, 2013; Muthukumar and Shyamkumar, 2013; Wu et al., 2014; Mishra et al., 2015; Mishra and Muthukumar, 2018) and combustion optimization (Abdurrachim et al., 2009; Gohil and Channiwala, 2011; Syahrial, 2012; Widodo, 2014; Widodo, 2015; Widodo, 2016; Sudarno and Fadelan, 2016; Fadelan and Sudarno, 2017). With respect to construction engineering, one approach involves the use of brass as a head burner material and that one with a flat face design for increasing the thermal efficiency by 4% and 10%, respectively (Pantangi et al., 2011; Khan and Saxena, 2013; Wu et al., 2014; Mishra et al., 2015; Mishra and Muthukumar, 2018).

Dongbin et al. (2007) have reported that the use of porous ceramics doped with

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doi: 10.14716/ijtech.v12i1.3958

rare-earth elements leads to the change in the fire colour from red to blue. In addition, CO and O_2 concentrations of blue gas decrease by 40.9% and 12.8%, respectively. On the basis of other research results, the use of porous radiant burners (PRBs) leads to a 10% increase in the efficiency, with the production of more stable fire (Muthukumar and Shyamkumar, 2013). The use of a two-layer PRB in the combustion process using silicon carbon (SiC) and in the pre-heating process using alumina leads to an almost uniform radial temperature distribution. The thermal efficiency increases from 45% to 58%, whereas CO and NO_x emissions significantly decrease (Pantangi et al., 2011; Wu et al., 2014; Mishra et al., 2015). Mishra and Muthukumar (2018) have employed the same method and reported a 10.1% increase in the thermal efficiency and a reduction in the CO and NO_x emissions in the range of 190–410 and 4.8–21.5 ppm, respectively.

Nevertheless, limited studies on the optimization of fire utilization are available. Widodo has reported that the addition of grid material between the burner and load increases the efficiency of LPG stoves. A high efficiency of 58.8% has been reported for a 5-mm-thick grid (Widodo, 2016). Moreover, the loading height of a gas stove affects the obtained efficiency. The optimal loading height is 4 mm, and the mass flow rate is 0.0125 L/s (Widodo, 2015). Previously, the element of embers of a nickel wire mounted between the burners and load leads to the increase in efficiency. The highest efficiency is reported for the element with a single layer of embers with a nickel diameter of 0.2 mm: The efficiency is enhanced by 8.32% in comparison with that of conventional LPG stoves (Sudarno and Fadelan, 2016; Fadelan and Sudarno, 2017). Furthermore, Syahrial has reported that the efficiency of biogas stoves increases by 5.6% by using perforated heat reflectors and a diameter of 10 mm (Syahrial, 2012). Abdurrachim et al. has reported that aluminium gas-flow collector tools increase the efficiency by 10% compared with that of conventional stoves (Abdurrachim et al., 2009). This result is in agreement with that reported by Gohil and Channiwala (2011). The use of a cover to close the combustion chamber leads to the enhanced efficiency of the gas stove. An efficiency of 66.27% is obtained at a power of 1.7849 kW. According to Widodo (2014), the use of ceramic as a reflector material on gas stoves leads to a 2.68% enhancement in productivity, from 43.88% to 46.56%.

Previous studies have concluded that the use of reflectors leads to the increase in the efficiency of LPG stoves. However, given that the reflection of radiation involves diffusion, the use of finless reflectors leads to the loss of heat to the environment (Incropera et al., 2006; Holman, 2010). Therefore, in this study, fins are added to minimize the heat loss, which cannot be controlled by finless reflectors. In this study, the objective is to determine the effect of finned heat reflectors on the efficiency increase and temperature distribution of LPG stoves.

2. Methods

2.1. Research Material Specifications

In this experiment, LPG was used because the flame stability and working region of LPG are greater than those of dimethyl ether (Anggarani et al., 2020). The experiment materials included a single-furnace LPG stove, SNI 7368-2001 or similar, an LPG tube SNI 1452 2011, PERTAMINA LPG for households (Aisyah et al., 2015), an aluminum pan, a stopwatch, a water thermometer (accuracy of ±0.5°C), digital scales (accuracy of ±0.1 g), a measuring cup, a data logger (type USB-4718, 8-ch Thermocouple Input USB Module), thermocouples (diameter of 1.6 mm and a maximum temperature of 1300°C), a flow metre (accuracy of ±0.01 g), water, and a finned reflector comprising stainless steel with a height of 30 mm and an angle of 22.5° was measured from the vertical axis (Sumadhijono, 2003). The width and height of the fin were 20 mm and 5 mm, respectively (Figure 1a).

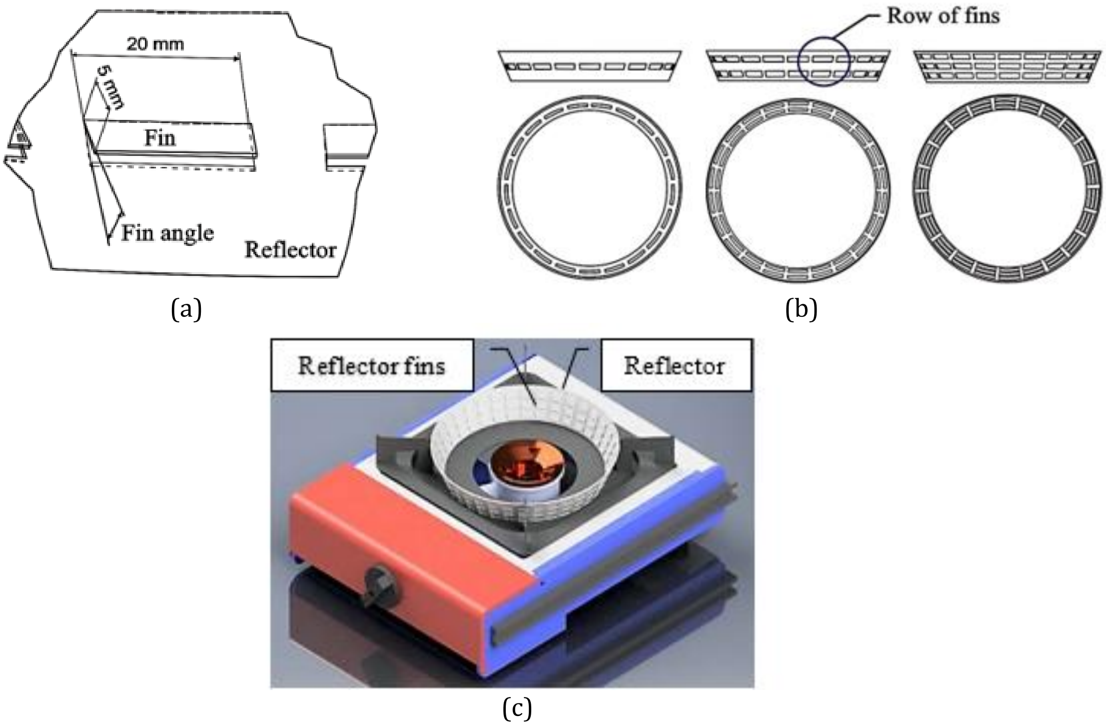

Figure 1 (a) Fin dimension; (b) finned reflector model; and (c) installation of the finned reflector on the LPG stove

The diameter of the aluminum pan was 220 mm, and its water mass was two-thirds the volume of the pan, which is 3625 g (World Bank, 1985; Panigrahy et al., 2016a; Sudarno and Fadelan, 2016; Fadelan and Sudarno, 2017; Sakthivadivel and Iniyan, 2017). Reflectors with one, two and three rows of fins were used (Figure 1b). For the best measurement results, the angles of the fins were varied at 5°, 10°, 15°, 20° and 25°. Figure 1c shows the installation of the finned reflector on the LPG stove.

2.2. Measurement Process

2.2.1. Efficiency measurement

The water boiling test (WBT) was employed to determine the efficiency of the stove. The measurement was started by placing the pan on a stove top after the stabilization of the fire for 5 min from the initial ignition. Blue flame was maintained under a constant LPG gas flow rate. The LPG consumption under each treatment was maintained constant, and on the basis of the measurements, the LPG consumption rate was 0.19 kg/h (0.05 g/s). This condition can be achieved due to the almost constant pressure of LPG inside the tube during the discharging process (Setiyo et al., 2017). To maintain a steady LPG flow, adjustments and controls were made on the regulator, flow meter and LPG gas valve openings on the stove. Water and ambient temperature data were recorded every 5 min until the water started to boil. Heating continued for 60 min. Subsequently, the mass used and the mass of lost steam were determined. This process was repeated eight times.

2.2.2. Measurement of fire temperature distribution

The temperature distribution was measured on a stove with load, such as a conventional one, and with the use of reflectors with and without fins.

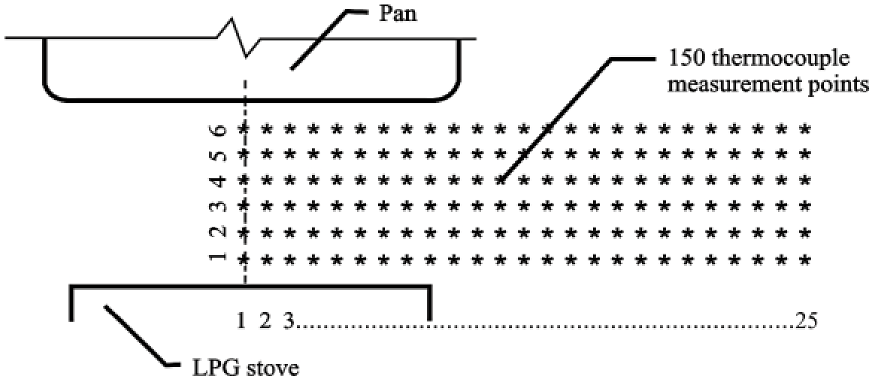

Figure 2 Installation determination position points

Measurement started from the point on the outer side using a six-channel thermocouple and shifted towards the axis at an interval of 5 mm until a total data of 6×25 points (150) were obtained (Figure 2). Data at each point were collected 25 times. The average temperature results were visualized to obtain the isothermal temperature distribution contour.

3. Results and Discussion

3.1. Efficiency Measurement

Stove efficiency measurements were conducted according to the Indian Standard 4246: 2002, which involved a WBT (EPA and PCIA., 2014; Panigrahy et al., 2016a; Panigrahy and Mishra, 2016b; Ziapour et al., 2016; Sakthivadivel and Iniyan, 2017). WBT was conducted by heating the water until it reached the boiling temperature, and the process continued up to 60 min. The stove efficiency was numerically calculated by the following equations (EPA and PCIA., 2014; Panigrahy et al., 2016a; Sakthivadivel and Iniyan, 2017):

$$\eta = \frac{\Delta E_{H_2O,heat} + \Delta E_{H_2O,evap}}{E_{released}} \quad (1)$$

$$\Delta E_{H_2O,heat} = m_w . C_{pw}(T_{wf} - T_{wi}) \quad (2)$$

$$\Delta E_{H_2O,heat} = C_{pw}(m_{wi} - m_p)(T_{wf} - T_{wi}) \quad (3)$$

$$\Delta E_{H_2O,evap} = m_u . H_u \quad (4)$$

$$E_{released} = m_f . E_{LPG} \quad (5)$$

$$\eta = \frac{\{(m_{wi} - m_p)C_{pw}(T_{wf} - T_{wi}) + m_u . H_u\}}{m_f . E_{LPG}} \quad (6)$$

where η (%) is the stove efficiency; $\Delta E_{H_2O,heat}$ (kJ) is the energy to heat the water; $\Delta E_{H_2O,evap}$ (kJ) is the energy to vaporize the water; $E_{released}$ (kJ) is the energy produced by the fuel; m_w (kg) is the water mass; Cp_w (kJ/kg K) is the specific heat capacity of water; Tw_f (K) and Tw_i (K) are the water temperatures before and after treatment, respectively, in Kelvin; m_{wi} (kg) is the initial mass of water and pan; m_p (kg) is the mass of the pan; m_u (kg) is the mass of steam after handling; H_u (2260 kJ/kg) is the latent heat of vaporization (EPA and PCIA., 2014) is the latent heat of vaporization; m_f (kg) is the mass of fuel used after treatment; and E_{LPG} (47100 kJ/kg) is the net calorific value of LPG (EPA and PCIA., 2014).

3.1.1. Measurement of distance between burners and loads

This measurement was conducted to determine the optimal load for the burner in conventional LPG stoves. Figure 3 shows the graph of the measurement results.

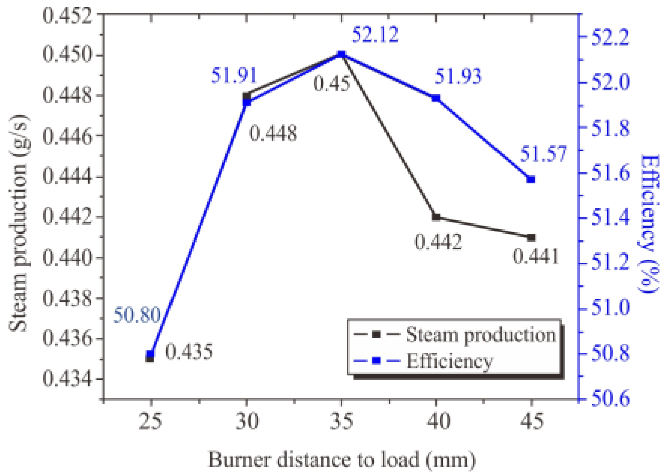

Figure 3 Graph of measurements results of the distance burner with a load in conventional LPG stoves

The distance between the burner with a load of 35 mm afforded the highest efficiency of 52.12%, because at that distance, an optimal balance occurred between the secondary air supply and fuel consumption. In addition, the balance made the process of mixing air and fuel more homogeneous. The optimal distance between the burner and load was used as a reference for measuring the efficiency and temperature distribution.

3.1.2. Measurements by the variation of fin rows in the reflector

On the basis of Figure 4a, steam production continuously increased with the increased addition of fin rows.

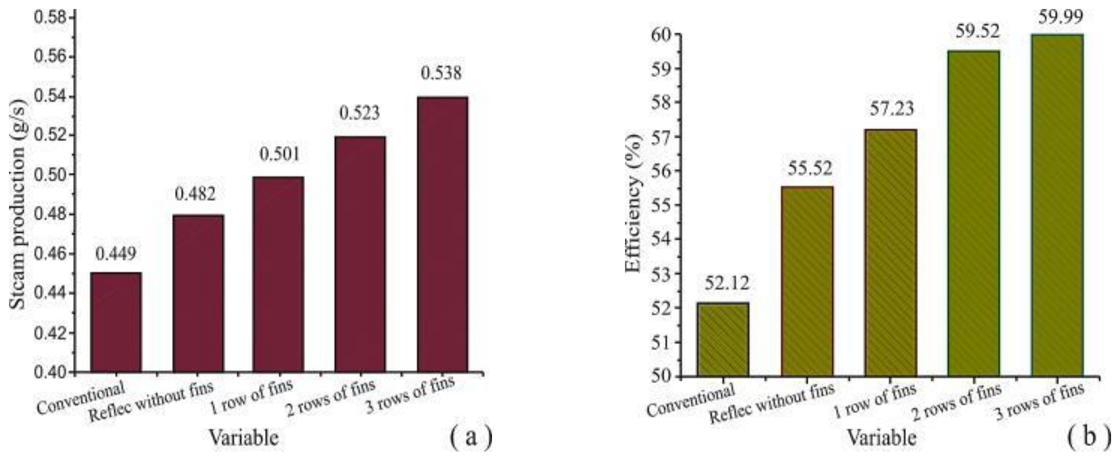

Figure 4 Measurement results for the variation of fin rows in the reflector: (a) steam production; and (b) efficiency

With the use of reflectors, the efficiency increased (Figure 4b), with the highest efficiency observed for three-row finned reflectors (Gohil and Channiwala, 2011). This condition leads to the increased area of complete combustion and intensifies the heat absorbed by the load, leading to increased steam production. Compared with stoves without-finned reflectors, in conventional stoves, a steam production increase of 0.033 g/s was observed, in addition to a 3.39% positive deviation in efficiency. This result was attributed to the use of finless reflectors, which capture and reflect heat loss to the environment (Gohil and Channiwala, 2011; Ziapour et al., 2016).

Compared with reflectors with one row of one fin, in finless reflectors, steam production increased by 0.019 g/s, which in turn improved the efficiency by 1.71%. Compared with reflectors with two rows, in one-row fin reflectors, the steam production significantly increased (0.022 g/s), thereby increasing the efficiency by 2.29%. The highest efficiency was observed for a three-row finned reflector, with a 7.87% and 4.47% increase compared with those in conventional stoves and reflectors without fins, respectively. In addition, the average measurement error was calculated to be 0.69%. Our results are in accordance with the radiation properties in with the radiation is reflected by a reflective surface (Incropera et al., 2006; Holman, 2010). As the material surface in this study is not perfectly smooth, heat radiation is diffusely reflected (Incropera et al., 2006; Holman, 2010). With the use of fins, radiation heat losses are captured and reflected more optimally. As a result of heat reflection, the unburned fuel steam in the chamber burns. With the enhancement in the process efficiency, complete combustion is improved, as well as the heat transferred to the load. In addition, the results obtained herein were in agreement with those reported previously: The use of reflectors can increase the efficiency of stoves (Abdurrachim et al., 2009; Gohil and Channiwala, 2011; Syahrial, 2012).

3.1.3. Measurements by variation of fin angle in the reflector

The inclination angle of reflectors affects their ability to collect and reflect radiation (Anggarani et al., 2020). In these experiments, the fin angle affected steam production (Figure 5). The total steam production was affected by heat from the combustion; the greater this is, the more efficient the process.

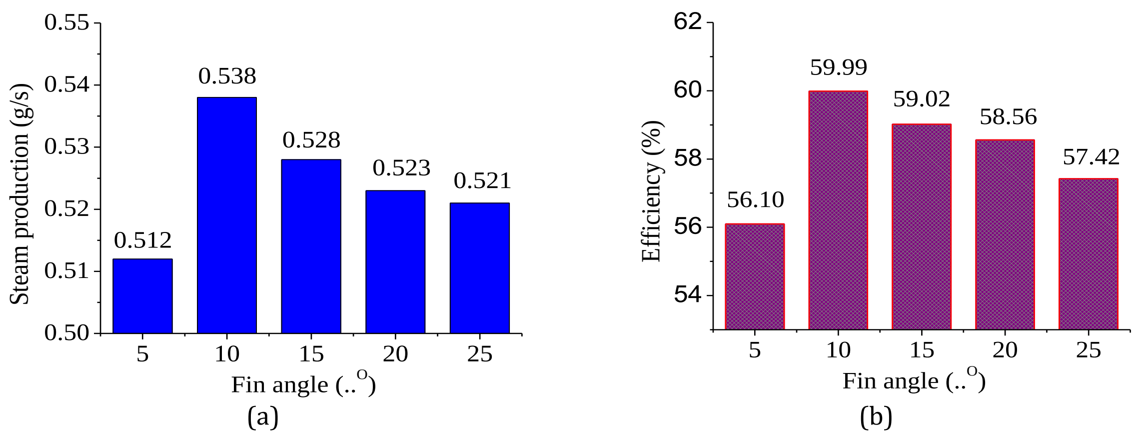

Figure 5 Measurement results for the variation of the fin angle in the reflector: (a) steam production and (b) efficiency

The highest steam production of 0.538 g/s was observed at a fin angle of 10°, while the lowest steam production of 0.512 g/s was observed at a fin angle of 5°. By the comparison of fin angles of 5°–10°, steam production increased by 0.026 g/s, from 0.512 to 0.538 g/s. Hence, the efficiency increases by 3.89% (from 56.10% to 59.99%). At a fin angle of 10°, the secondary air requirement for the combustion process was well fulfilled to complete the combustion. When complete combustion occurs, an increased amount of steam is produced via the increase in the heat area and temperature, which are related to efficiency improvement. In addition, the heat loss from the flame to the environment through the gap under the fins was minimal, thereby making the function of the reflector more optimal for thermal reflection. The highest efficiency of 59.99% was obtained in our experiment using a stove with three finned rows and an angle of 10°. This efficiency is 6.57% greater than that reported in the study by Syahrial, in which a perforated reflector with a diameter of 10 mm is used (Syahrial, 2012). This obtained efficiency is also better than that reported in the study by Widodo by 13.44%, in which ceramics is used as the reflector material (Widodo, 2014).

At fin angles of 10° to 15°, the production decreased by 0.010 g/s, from 0.538 to 0.528 g/s. This resulted in a 0.96% decrease in the efficiency, from 59.99% to 59.02%. This decrease was attributed to a fin angle of 15°, where the gap under the fins was extremely wide, indicative of the increase of heat loss to the environment and subsequently leading to the less optimal function of the reflector; hence, efficiency decreases. Similar alterations were observed at fin angles of 20° and 25°; the greater the fin gap, the higher the heat loss to the environment. At fin angles of 15° to 20°, steam production decreased by 0.005 g/s, from 0.528 to 0.523 g/s. This resulted in the slight decrease in the efficiency from 59.02% to 58.56%. The same result was observed at angles of 20° and 25°, with the 1.13% decrease in the efficiency, from 58.56% to 57.42%. In these measurements, an average error of 0.43% was obtained. A fin angle of 10° afforded the highest amount of steam, leading to the highest efficiency (Figure 5). This result was attributed to the angle at which the reflector functions optimally, as well as the adequate fulfillment of the secondary air, also referred to overfire air, requirements for the combustion process.

3.2. Measurement of LPG Stove Temperature Distribution

This measurement aimed to determine the effect of the installed finned heat reflector on the temperature distribution contour of isothermal fire. Matlab R2010a was employed to create visualization of the temperature distribution data. By utilizing this visualization, the effectiveness of the finned heat reflector can be concluded.

3.2.1. Fire temperature distribution by the variation of fin rows in the reflector

In this measurement, the stove was loaded, and finned heat reflectors were installed. Figure 6 shows the results of the fire temperature distribution.

The lowest and highest temperatures were 79°C and 1084°C, respectively (Figure 6a). In addition, conventional stoves exhibited a relatively low average hotness with relatively low temperature distribution areas. This result was related to the convection from the flame to the surrounding area, leading to a low production efficiency (Gohil and Channiwala, 2011). By using a finless reflector, the lowest recorded temperature was 78°C; this temperature is 1.2°C less than that observed in a conventional stove, and the highest temperature was 1107°C, which was 22.6°C greater than that observed in a conventional stove. From these figures, the areas of extreme temperatures greater than 1000°C and between 900°C and 1000°C were considerably wider than those observed in conventional stoves. This result is related to the capture of wasted heat by the reflector and subsequent reflection of the area of combustion and load (Widodo, 2018).

By using a single-row fin reflector, the lowest temperature was 78°C, corresponding to 0.2°C greater than that with a finless reflector, and the maximum temperature was 1115°C, or 7.5 °C higher than that with a finless reflector. The main difference was in the area with a high temperature greater than 1000°C and between 900°C and 1000°C, which was wider than that with the finless reflector. Compared to finless reflectors, in reflectors with fins, wasted heat can be captured. Moreover, the gap under the fins is beneficial for secondary air supply, maintaining a balance between air requirements and LPG consumption. With a two-row fin reflector, the lowest temperature was 77°C, corresponding to 1°C less than that with a single row, and the highest temperature was 1131°C, corresponding to 16 °C higher than that with a single row (Figure 6d).

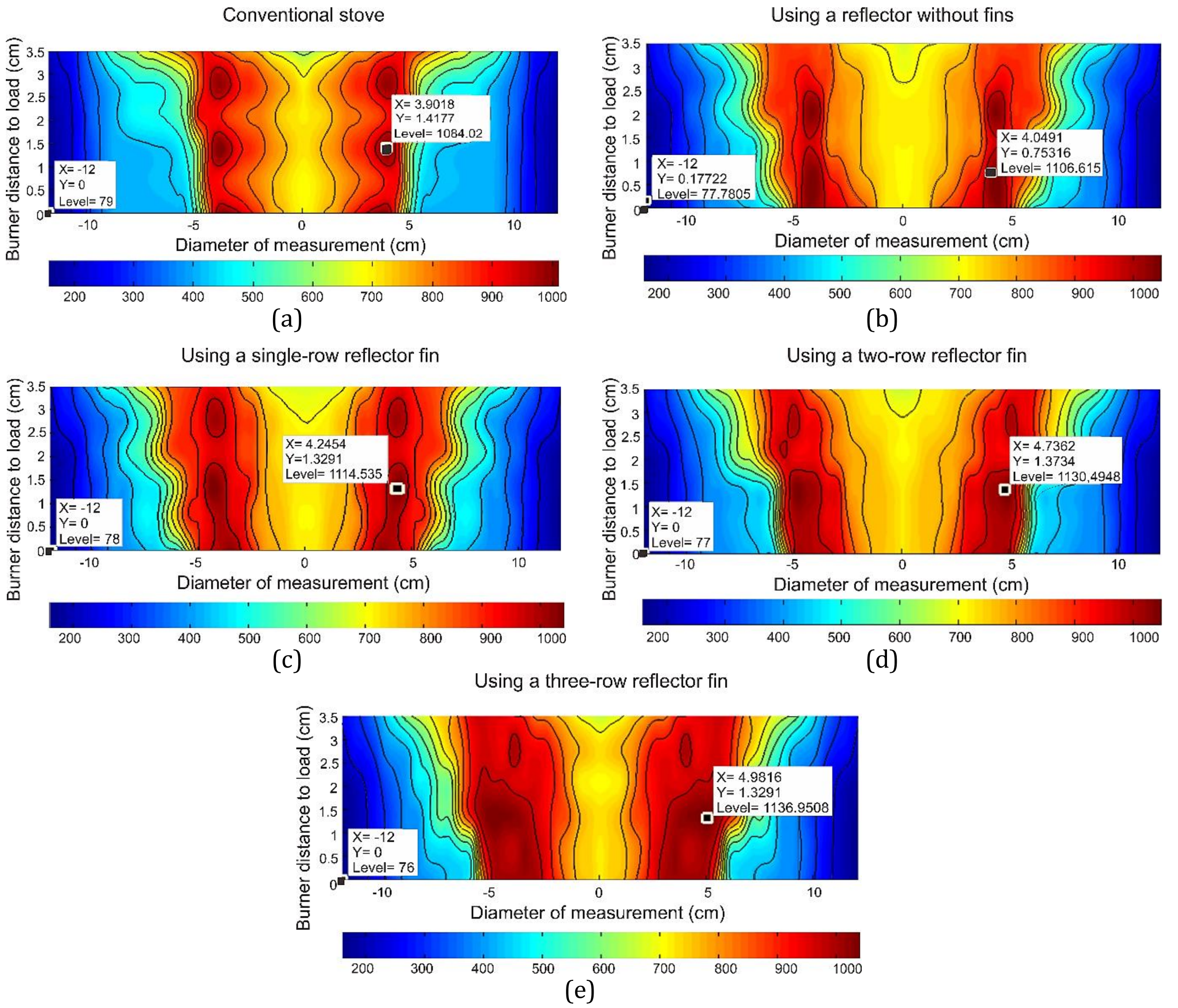

Figure 6 Temperature distribution of the LPG stove fire: (a) conventional; (b) using a finless reflector; (c) using a single-row reflector fin; (d) using a two-row reflector fin; and (e) using a three-row reflector fin

Furthermore, the area of high temperature greater than 1000°C and between 900°C and 1000°C was wider, whereas that between 800°C and 900°C was relatively less than that with one row of fins. These conditions were observed due to the increase in the function of the reflector, minimizing heat loss to the environment.

In the case of the three-row finned reflector, the lowest temperature was 76°C, corresponding to 1°C less than that of the two-row reflector, and the highest temperature was 1137°C, corresponding to 6.5°C higher. The most noticeable difference was observed in the area of high temperature greater than 1000°C. Between 900°C and 1000°C, it was considerably wider than that of the two-row fin reflector. The increase occurred due to more complete combustion, and the reflector function was optimal by the addition of the number of rows of fins.

3.2.2. Fire temperature distribution by the variation of fin angle in the reflector

On the basis of Figures 4b and 6e, compared to the other variations, the reflector with three rows of fins exhibited the highest efficiency and the largest area of high temperature. According to these results, a heat radiation reflector was selected with three rows of fins for the temperature distribution measurement by the variation in the fin angle on the reflector. Figure 7 shows the measurement results.

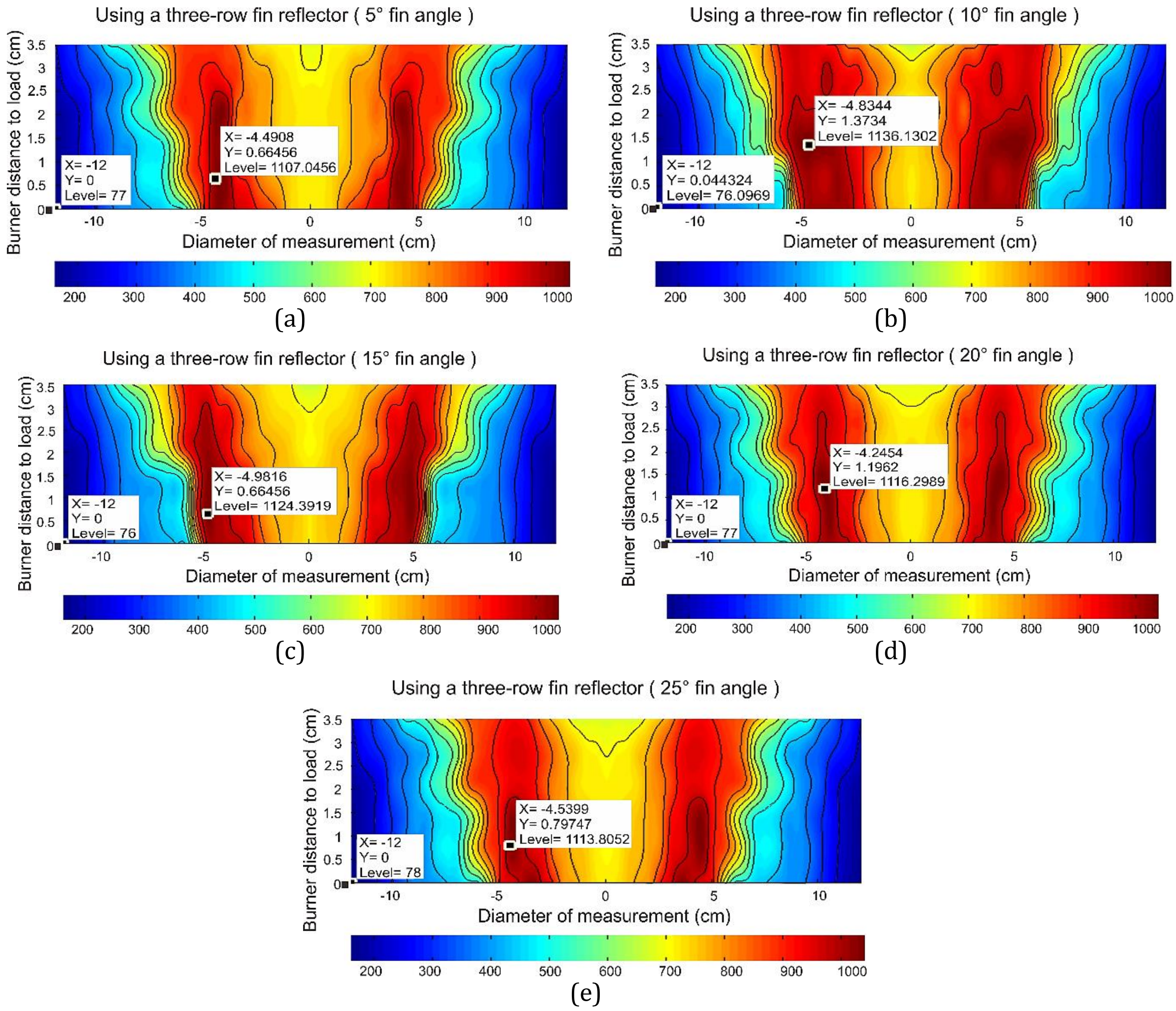

Figure 7 LPG stove temperature distribution using a reflector with three rows of fins at angles of: (a) 5°; (b) 10°; (c) 15°; (d) 20°; and (e) 25°

The lowest and highest temperatures were 77°C and 1107°C, respectively (Figure 7a). A fin angle of 5° produced an area of high temperature of greater than 1000°C, which was relatively small. However, at temperatures between 900°C and 1000°C, the area was quite wide, and the most extensive range was between 77°C and 900°C. As radiation reflection occurred by diffusion, with a fin angle of 5°C, substantial heat loss was still observed (Menghini et al., 2008).

The lowest temperature was 76°C, corresponding to 1°C lower, and the highest temperature was 1137°C, or 29.9°C greater than that with a fin angle of 5°. The main difference was observed in the high-temperature area of greater than 1000°C and between 900°C and 1000°C, which was considerably wider than that with a fin angle of 5°. The increase in the high-temperature area occurred due to complete combustion. The function of the reflector was increasingly optimal at a fin angle of 10°. Complete combustion was caused by the achievement of a secondary air supply flowing through the gap under the fins. The lowest temperature of 76°C was relatively similar with that of a fin angle of 10°, and the highest temperature was 1124°C, which was 11.7°C less than that with a fin angle of 10° (Figure 7c). In addition, the area of high temperature of greater than 1000°C and between 900 and 1000°C was less than that with a fin angle of 10°. The reflector was not optimal due to the large gap under the fins, and diffused heat radiation was lost to the surrounding area (Menghini et al., 2008; Gohil and Channiwala, 2011).

The lowest temperature was 77°C, which was 1°C higher, and the highest temperature was 1116°C, which was 8.1°C less than that with a fin angle of 15° (Figure 7d). Moreover, the area of high temperature of greater than 1000°C was smaller, but between 900°C and 1000°C, the area was slightly wider than that with an angle of 15°. The lowest temperature was 78°C, which was 1°C higher, and the highest temperature was 1114°C, which was 2.5°C less than that with a fin angle of 20°. In addition, the area of high temperature of greater than 1000°C was smaller, although between 800°C and 1000°C, it was relatively similar to that with a fin angle of 20°. The problem at fin angles of 20° and 25° was the same as those at a fin angle of 15°; the greater the angle of the fin, the lower the function of the reflector. The presence of large gaps under the fins makes heat loss into the environment even greater.

4. Conclusions

The use of finned heat radiation reflectors in LPG stoves positively affects efficiency. Reflectors with one row of fins exhibited an efficiency of 57.23%, representing 5.11% and 1.71% increase compared with those of conventional stoves and stoves with finless reflectors, respectively. However, reflectors with two rows of fins exhibited an efficiency of 59.52%, representing 7.40% and 4.00% increase in comparison with conventional stoves and stoves with finless reflectors, respectively. The highest efficiency (60%) was observed for the reflector with three rows of fins or 7.87% and 4.47% increase compared to conventional and finless stoves.This efficiency is greater than that reported in the study by Syahrial (by 6.57%) and by Widodo (by 13.44%), in which a perforated reflector with a diameter of 10 mm and ceramics as the reflector material are used, respectively. On the basis of the contour of the isothermal temperature distribution, the use of finned heat radiation reflectors increases the area of complete combustion, thereby increasing the heat absorption by the load and improving steam production; hence, efficiency is enhanced.

Acknowledgements

This study was supported by a Doctoral Research Grant from the Ministry for Research and Technology Higher Education of Indonesia, with contract No. 037/SP2H/LT/K7/KM/2018. The authors would like to thank Prof. Dr. Eng. Mikrajuddin Abdullah from the Bandung Institute of Technology, Indonesia; Rizal Arifin, M.Si., Ph.D. from the Muhammadiyah University of Ponorogo, Indonesia; and Dr. Muji Setiyo, S.T., M.T. from the Muhammadiyah University of Magelang, Indonesia.

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