POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)
URL: http://dergipark.org.tr/politeknik

Gaz çıkışı dikdörtgen kesitli ev tipi ocaklarda LPG'nin alev ve akış analizi

Flame and flow analysis of LPG in household cookers with rectangular ports

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To cite to this article: Sahın B., Doner N. and Ilbas M., "Flame and flow analysis of LPG in household cookers with rectangular ports", ***Journal of Polytechnic***, 27(3): 1121-1128, (2024).

Bu makaleye şu şekilde atıfta bulunabilirsiniz: Sahın B., Doner N. ve Ilbas M., "Flame and flow analysis of LPG in household cookers with rectangular ports", ***Politeknik Dergisi***, 27(3): 1121-1128, (2024).

Erişim linki (To link to this article): http://dergipark.org.tr/politeknik/archive

DOI: : 10.2339/politeknik.1246174

Flame and Flow Analysis of LPG in Housecold Cookers with Rectangular Ports

Highlight

- *Flame temperature*
- *Velocity*
- *Gas emission*
- *Flow regime*

Graphical Abstract

The cold flow and flame characteristics of LPG (mixing 70% butane and 30% propane) in a household stove are experimentally investigated. Temperatures in the horizontal, vertical, and diagonal directions are measured at points between the reference point and 3 cm.

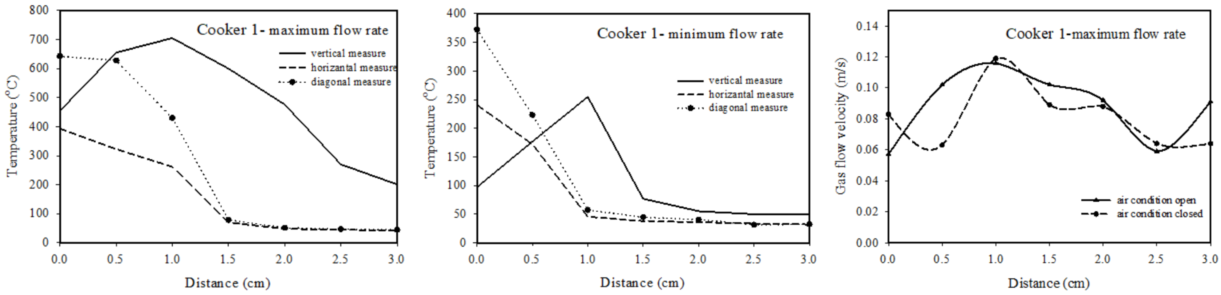

Figure. Temperatures in the horizontal, vertical, and diagonal directions

Aim

The household stove consists of cookers of different sizes with a rectangular geometry of gas outlet. Gas flow velocities for maximum and minimum flow rates are measured. In the largest furnace, gas emissions in the diagonal direction are also measured at maximum flow.

Design & Methodology

12 kg LPG tank, household cooker and used a thermocouple for temperature measurement, an anemometer for velocity and a NOVAplus emission device for gas emission were used in experiements.

Originality

Our study differs in terms of the LPG mixture having different values and the use of cooker with rectangular geometry outlet port and the measurement of gas emissions.

Findings

Based on the mixture of LPG (70% butane and 30% propane), the flow regimes are calculated and turbulent flow regime is observed at maximum flow for Cooker 1 and laminar flow regimes are observed in both flow conditions for Cooker 2 and Cooker 3.

Conclusion

The temperatures in the vertical direction at maximum flow rate for all cookers are significantly difference from the temperature in the horizontal and diagonal directions. For all cookers, the maximum temperatures are measured at the reference point in the diagonal direction at minimum flow rate. For emission measurement, there is a sharp decrease in the CO and NOx in distance from 1.5 cm and the reference point.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.3

Flame and Flow Analysis of LPG in Household Cookers with Rectangular Ports

Bu çalışma 16. Uluslararası Yanma Sempozyumu 2022 konferansında sunulmuştur. / This study was presented at 16th International Combustion Symposium (8-11 September 2022) conference.)

Araştırma Makalesi / Research Article

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(Geliş/Received: 01.02.2023 ; Kabul/Accepted : 28.02.2023 ; Erken Görünüm/Early View : 19.04.2023)

ABSTRACT

The cold flow and flame characteristics of liquefied petroleum gas (LPG- mixing 70% butane and 30% propane) in a household stove are experimentally investigated. The household stove has three cookers with rectangular ports and different sizes. The flame temperature and gas flow velocity are measured at maximum and minimum flow rates under laboratory conditions. Temperatures in the horizontal, vertical, and diagonal directions are measured at a distance between the reference point and 3 cm. The temperatures between the maximum and minimum flow rates show significant differences for all cookers. Flame temperatures at the gas exit point are 620–710 °C at the maximum gas flow rate. On the largest cooker, the gas emissions in the diagonal direction at the maximum flow rate are also measured. The maximum value of CO emissions 7000 ppm is measured at the reference point. CO_2 emissions are 12% between the reference point and 1.5 cm and slightly decreasing to 11% at other points. NOx measurements (ppm) show a peak value of 180 ppm at the 0.5 cm point. Cooker 1 is in the turbulence regime at maximum flow rate, while the other cookers are in the laminar regime.

Keywords: LPG, flame temperature, gas flow velocity, emissions, household cookers

Gaz Çıkışı Dikdörtgen Kesitli Ev Tipi Ocaklarda LPG’nin Alev ve Akış Analizi

ÖZ

Bir ev tipi ocakta sıvılaştırılmış petrol gazının (%70 butan ve %30 propan karışımlı) soğuk akış ve alev karakteristikleri deneysel olarak incelenmiştir. Ev tipi ocak, gaz çıkışı dikdörtgen kesitli farklı büyüklüklerdeki ocaklardan oluşmaktadır. Maksimum ve minimum gaz akış debisinde, alev sıcaklığı ve gaz akış hızları laboratuvar şartlarında ölçülmüştür. Sıcaklıklar yatay, dikey ve diagonal doğrultularda ve referans noktası ile 3 cm arasındaki mesafelerde ölçülmüştür. Maksimum ve minimum debilerdeki sıcaklıklar, tüm ocaklarda önemli farklılıklar göstermiştir. Maksimum debide, gaz çıkış noktasındaki sıcaklıklar 620–710 °C arasındadır. En büyük ocakta, maksimum debide diagonal yönde gaz yayınımları da ölçülmüştür. CO’in maksimum değeri referans noktasında 7000 ppm olarak tespit edilmiştir. CO_2 yayınımı referans noktası ile 1.5 cm arasında %12 olup, diğer noktalarda yavaşça %11 e azalmaktadır. NOx ölçümleri 0.5 cm noktasında 180 ppm ile maksimum değeri göstermiştir. Ocak 1 maksimum debide türbülanslı akışa sahip iken, diğer ocaklar laminer akış rejimine sahiptirler.

Anahtar Kelimeler: LPG, alev sıcaklığı, gaz akış hızı, yayınımlar, ev tipi ocaklar.

1. INTRODUCTION

The burner of household cookers convert the potential energy of the pressurized fuel, which is in a gaseous state, into its kinetic energy. This turbulent, axially symmetrical round jet spreads out in the air. The gas flow out of the port becomes laminar or turbulent depending on the type of burner and/or port and the Reynolds number [1]. Household cookers are used in heating applications with multiple laminar and mixed flame jets. The most common and well-known models have a circular burner and multiple small ports around it. They produce low-velocity flame jets with a Reynolds number of 300–800 [2].

Liquefied petroleum gas (LPG) is preferable due to its low carbon emissions, higher heating value and efficiency, and environmental friendliness compared to other fuels [3]. It consists of hydrocarbons such as propane (C_3H_8), butane (C_4H_{10}), and their isomers or mixtures [4]. One of the first studies that investigated the combustion characteristics of LPG was performed by Ref. [5]. In this study, LPG (40% C_3H_8 and 60% C_4H_{10}) was used to experimentally investigate the effects of temperature on the thermal efficiency.

Dong et al. investigated the effects of heat transfer of LPG at varying flow rates as a function of changing the distance between the burner and the top plate in an experimental setup using 14 thermocouples [6]. In another study, Li et al. investigated the household stove both experimentally and statistically using LPG (70%

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C_4H_{10} and 30% C_3H_8 by volume) without mixing and mixed with air [7]. In this study, the equivalence ratio (ϕ) for fuel-enriched flames was taken as 1.4, 1.7, and 2. The Reynolds number was found to have a significant effect on both the thermal efficiency and CO emissions. The performance of different gases (landfill gas, methane, LNG) was studied and compared with the performance of LPG (mainly C_3H_8) in a household cooker [8]. The authors concluded that the flame of LPG has the highest gas velocity in the experimental studies at an equivalence ratio of 1.1.

In recent years, various studies have been conducted on the use of LPG in household cookers. For example, in 2014-2015, a study titled "Access to Clean Cooking Energy and Electricity-Survey of States (ACCESS)" was conducted in India on household cookers. This study surveyed household cookers and fuels in 8568 homes and 714 villages in 51 regions. It was found that LPG is used in houses in 22% of the relevant regions [9]. In addition, the use of LPG in household cookers is also important in terms of the relationship between parameters such as health, climate, pollution, reduction of greenhouse gas emissions, and protection of the health of local people and women [10]. In another project, the conversion of more than 50 million household cookers to LPG for kitchen use was carried out in Indonesia over a period of five years since 2007 [11]. As can be seen, LPG is used as fuel in household cookers by a very large population in the world.

Makmool et al. [12] studied in detail the effects of flame height and distance between the outlet ports and the plate in household cookers on heating using different monitoring systems. The use of LPG in household cookers by mixing with different fuels has also been studied. For example, LPG mixed with dimethyl ethane (DME) in different volumetric ratios [13] and mixed with air [14] (Zhen et al., 2014) was investigated in terms of the thermal efficiency, Reynolds number, and gas emissions. Kang et al. [15] performed experimental and theoretical analyses of the combustion characteristics of flame jets when three different fuels (dimethyl ether, methane, and LPG) are used in a household stove. Based on the results of this study, in the laminar regime, the flame height is proportional to the Reynolds number, while in the fully developed regime, the flame height remains constant. It has been determined that the flame width does not change much with the flame jet speed. They concluded that the flame velocity and Reynolds numbers of dimethyl flames are smaller than those of LPG flames. In a review study, Arya et al. [16] evaluated the domestic use, combustion characteristics, and properties of LPG and dimethyl ether (DME) fuels in India and found through numerical analysis that the LPG flame reaches 2000 K. Combustion of LPG at a pressure of 2.8 bar in common models of domestic stoves (butane/propane ratio of 40:60; 20:80, or 60:40) and emission particles were analysed by Shen et al. [17]. In these tests, the average thermal efficiency of the stoves was found to be 51 ± 6%.

Mishra and Muthukumar [18] conducted experimental studies to investigate the effects of burner diameter and size of exit port on the design of household stoves. The authors found that the thermal efficiency reached high values (72–75%) with a small burner diameter and larger exit ports. In another study, Kwok et al. [19] investigated the flame efficiency as a function of port geometry and concluded that flames achieve greater spacing and a more homogeneous heat transfer process for ports with rectangular cross-sections. Similarly, Boggavarapu and Ravikrishna [20] analysed the effect of design on the thermal efficiency of an LPG-fired domestic gas burner head under premixed combustion conditions using experimental and numerical methods. They found that the maximum velocity near the burner holes is 5.4 m/s and the temperature at the top of the inner and outer burner holes is above 2000 K under a fuel-air equivalence ratio of 1.4 using a 3-D numerical modelling. A similar study was conducted by Ref. [21] using turbulent combustion modelling with the ANSYS program for a cooker with rectangular geometry ports, and it was found that the thermal efficiency increased.

Wae-hayee et al. [22] investigated the effects of the distance between the nozzle and the top plate on the heat transfer of the household stove operated with a mixture of air and LPG where LPG is used as fuel. They found that the highest heat transfer occurs at the longest distance from the nozzle and is calculated according to the law of conservation of energy. From these studies, the use of LPG with different gas mixtures in household stoves is widespread worldwide and it is important to determine its combustion characteristics. In our study, the flame characteristics of LPG (70% C_4H_{10} + 30% C_3H_8) in household cookers of different sizes with rectangular ports were investigated in terms of flame temperatures, gas flow velocities, and gas emissions.

2. MATERIAL and METHOD

Experimental studies were conducted using a 12-kg LPG tank, a household stove, and three cookers of different sizes under laboratory conditions. The pressure of the LPG used in the study is between 2–3 bar and consists of a mixture of 70% C_4H_{10} and 30% C_3H_8. A thermocouple with a portable ceramic tip AZ 8855 K, J, T, R, S, E with an accuracy of 0.1% was used for temperature measurements. For the experiments on flame characteristics, the most widely used model of household stove in Turkiye was used (Figure 1 (a)). The burners in the cookers shown in Figure 1 (b) are the same and have a diameter of 1 cm. The outer diameter of the largest, medium, and smallest cooker is 8 cm, 7 cm, and 5 cm, respectively. In the numbered display, the numbers 1, 2, and 3 correspond to the largest, medium, and smallest cooker, respectively. The maximum gas flow rate of Cooker 1 was determined to be 0.6 L/min and the minimum gas flow rate was set at 0.25 L/min. The maximum flow rate of Cooker 2 was determined to be 0.25 L/min and the minimum flow rate was determined to be 0.1 L/min. Cooker 3 has a maximum flow rate of 0.2 L/min and a minimum flow rate of 0.1 L/min. Cooker 1 consists of 40 ports, Cooker 2 consists of 35 ports, and Cooker 3 consists of 23 ports. The flame characteristics of all cookers were measured between the reference point (0 cm) and a 3 cm distance, and the reference points are shown on the cookers in blue. The image of the temperature measurement of Cooker 1 are presented here specifically to illustrate the measurement and monitoring methods.

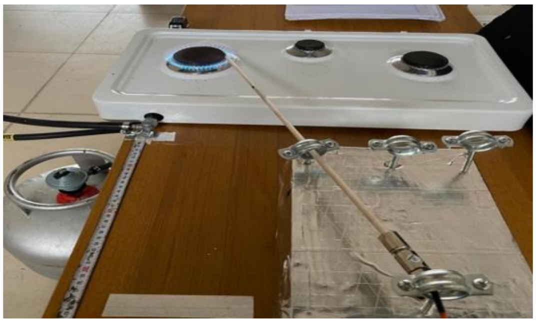


Figure 1. The Household Cooker Used In Our Study

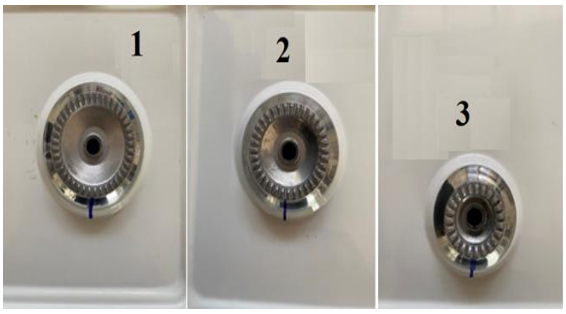


Figure 2. Cookers

Cooker 1: At the minimum and maximum gas flow rates, temperature measurements were taken from the reference point at 0.5 cm intervals for a measurement period of 10 min in the horizontal, vertical, and diagonal directions for all nodes. The image of the temperature measurement of Cooker 1 are presented here specifically to illustrate the measurement and monitoring methods. All measurements of Cooker 1 are shown in Figure 3.

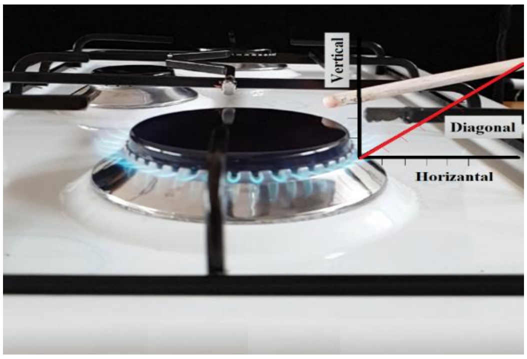


Figure 3. Measurements of LPG flame temperatures of

Cooker 1 for horizontal, vertical, and diagonal directions

3. FLOW REGIME

To determine the flow regime, the Reynolds number ($Re = vD/\mu$) and the gas viscosity should be calculated correctly. The viscosity of a gas mixture under a pressure of 1 atm can be calculated using Kay's rule according to Equation (1).

$$\mu_{gas} = \frac{\sum_{i=1}^{N} y_i \mu_i \sqrt{M_{gi}}}{\sum_{i=1}^{N} y_i \sqrt{M_i}} \tag{1}$$

where μ_{gas} is the dynamic viscosity of the gas mixture, y_i is the mole ratio of the ith gas component, μ_i is the viscosity of the ith gas component, M_{gi} is the molecular weight of the ith gas component, and N is the number of components in the gas mixture. The viscosity values of C_4H_{10} and propane gas as a function of temperature were obtained from Viscosity of hydrocarbon gases under pressure [23]. From the reference, the viscosities of C_4H_{10} and C_3H_8 at ~204.4 °C are measured as 0.0115 and 0.0135 cP, respectively. The molecular weights of the gases were assumed to be 58.12 for C_4H_{10} and 44.097 for C_3H_8.

The viscosity of gas as a function of temperature can be calculated using the Sutherland formula given in Equation (2).

$$\mu = \mu_o \frac{T_o + C}{T + C} \left(\frac{T}{T_o} \right)^{3/2} \tag{2}$$

where C is the Sutherland constant of the gas (K), T_0 is the reference temperature (K), μ_o is the viscosity of the gas at the reference temperature, and μ is the viscosity of the gas at temperature T. In our study, a constant of C of 270 K is assumed for butane and 150 K for propane.

4. RESULTS and DISCUSSION

The flame characteristics of LPG in a household stove were studied under laboratory conditions. The flame temperatures of all cookers were measured in the horizontal, vertical, and diagonal directions. In addition, the cold flow gas velocities of all cookers were measured in the diagonal direction for both flow rates. The gas velocities of all cookers at the burners were also measured for two cases: open and closed ventilation. The experimental measurements were repeated several times and confirmed. Measurements of NOx, CO (ppm), and CO_2 (%) from Cooker 1 were taken in the diagonal direction for gas emission control.

Figure 3 shows measurements of the flame temperatures of Cooker 1, Cooker 2, and Cooker 3 in all directions. The measured temperatures of the cookers are presented in Figure 4. It can be seen from Figure 4 that the temperatures are higher at maximum flow than at minimum flow for all cookers.

At the maximum flow rates for all cookers, temperatures in the vertical direction were significantly different than the temperatures in the horizontal and diagonal directions. The measured maximum temperatures of Cooker 1, Cooker 2, and Cooker 3 are ~705 °C , ~619 °C , and ~656 °C, respectively, in the vertical direction at this flow rate. The temperatures in the horizontal and diagonal directions were almost the same in the measurement points after 1.5 cm. Also, at the maximum flow rate, the temperature measurement in the vertical direction slowly decrease at distances after 1.5 cm. It is assumed that for the same flow rate, the change in velocities in the vertical direction between 0 and 3 cm is due to the flame width. In the study of Ref. [20], it was also reported that in the three-dimensional analysis of the velocities and temperatures of the conventional gas burner head, the maximum distributions are mainly in the vertical direction.

At minimum flow, the highest temperatures were reached at the reference points in the diagonal direction for all cookers. Again, at the same flow rate, a large change in horizontal and diagonal temperatures was observed in the range of 0–1 cm, while these trends were stable at 1–3 cm intervals. The maximum temperature for Cooker 1, Cooker 2, and Cooker 3 is ~373 °C, 276 °C, and 451 °C, respectively, in the diagonal direction at minimum flow. The temperatures in the vertical direction were measured as maximum values in the range of 0 to 1 cm, unlike the measured values in other directions at the same flow rate. That is, the maximum temperatures were not at the reference point but in the range of 0.5–1 cm above the exit point. The maximum temperature in the vertical direction is ~250 °C at 1 cm for Cooker 1, ~160 °C at the reference point for Cooker 2, and ~390 °C at 0.5 cm for Cooker 3 [24]. In addition, flame temperatures at the reference point decrease dramatically at minimum flow rates as one moves horizontally and diagonally away from the gas outlet. Flame temperatures were found to be about 50 °C at distances greater than 1 cm from the gas outlet.

From the studies in the literature, it appears that the gas flow velocity has a significant effect on the combustion characteristics. For this reason, gas flow velocity measurements were evaluated for open and closed ventilation cases in the laboratory for cold flow over a measurement period of 1.5 min. A Geratech brand velocity measurement device with 1% accuracy was used. Figure 5 shows the flow velocities for all cookers of the household stove.

As can seen from Figure 5, the gas velocity of Cooker 1 reached the highest value of 0.12 m/s at 1 cm, both with the ventilation open and closed at maximum flow.

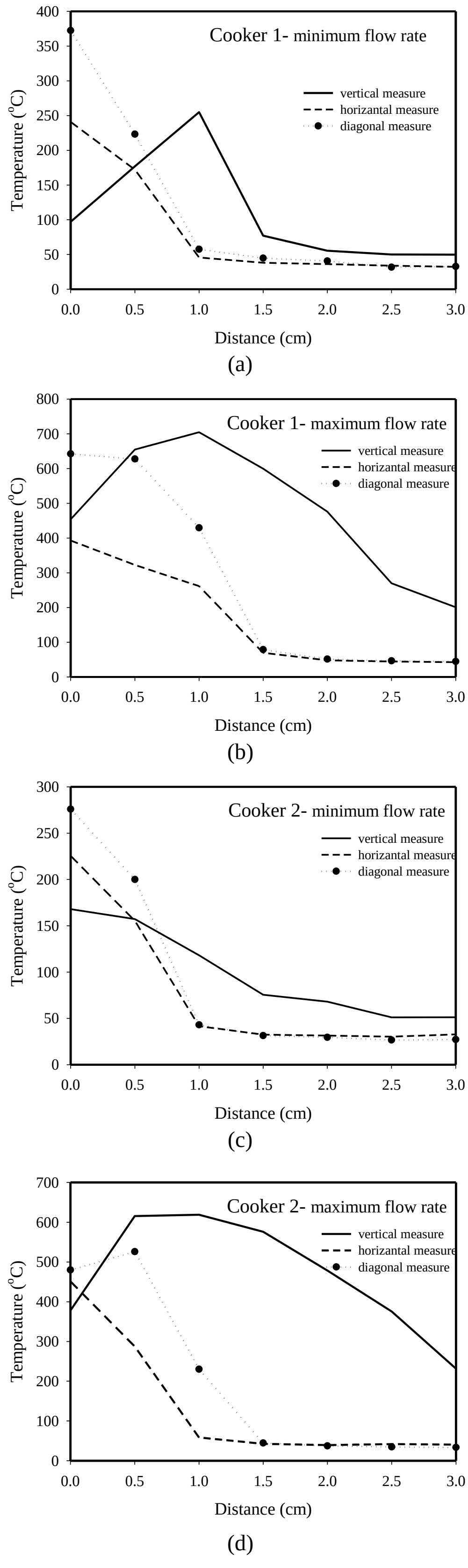
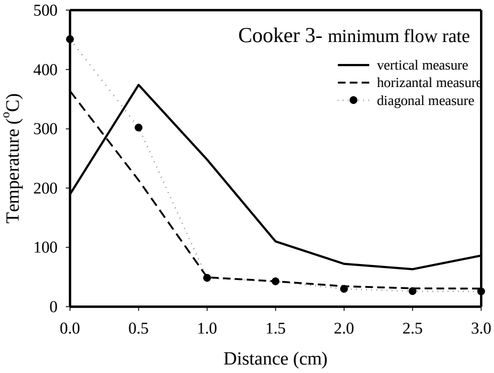


Figure 4. The flame temperatures of the household stove: Cooker 1 for (a) minimum and (b) maximum flow; Cooker 2 for (c) minimum and (d) maximum flow; Cooker 3 for (e) minimum and (f) maximum flow.



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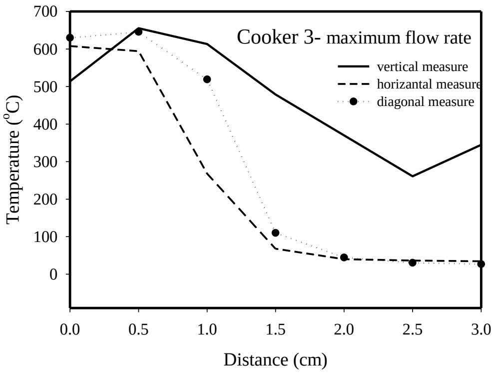
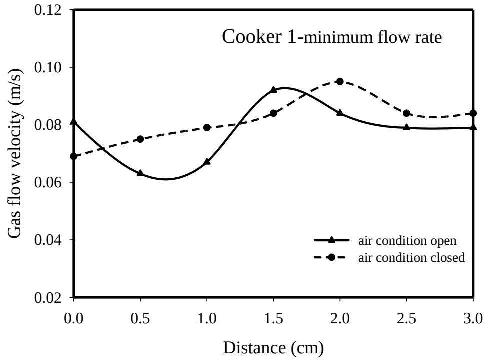


(f)

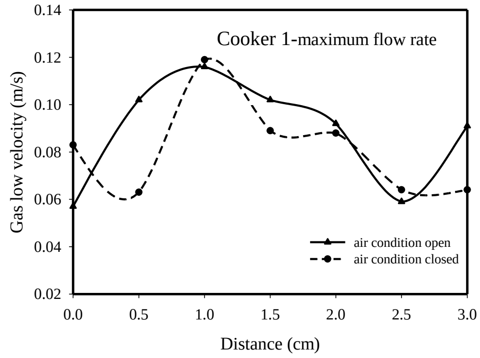
Figure 4 (continue). The flame temperatures of the household stove: Cooker 1 for (a) minimum and (b) maximum flow; Cooker 2 for (c) minimum and (d) maximum flow; Cooker 3 for (e) minimum and (f) maximum flow

At maximum flow, the gas flow velocity of Cooker 3 changes with wave motion and the values range from ~0.08 to ~0.1 m/s in the range of 0 and 1.5 cm, while the value approaches zero at distances after 2 cm. The flow velocity in the minimum flow of the same cooker decreases linearly from 0.09 to 0.07 m/s for the open vent case. Although our study is similar to the studies of Refs. [6] and [7] on LPG, it differs in terms of the shape of the cooker ports, flow rate, and gas pressure.

From Figure 5, for Cooker 1 and Cooker 2, the minimum flow rate of the open and closed vents are parallel to each other and the values are in the range from ~0.06 to ~0.09 m/s. The trend of Cooker 1 at the minimum flow rate in the case of closed ventilation is stable and the value range is ~0.08 to ~0.09 m/s. The trend of the same cooker with the ventilation open and the same flow conditions is significantly different.



(a)



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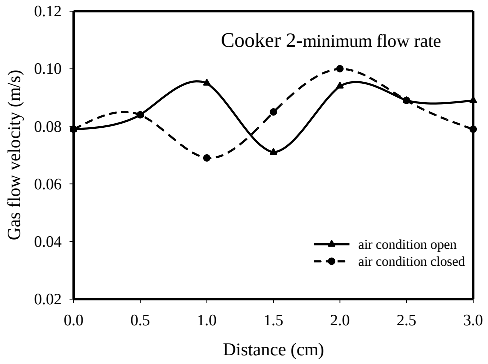

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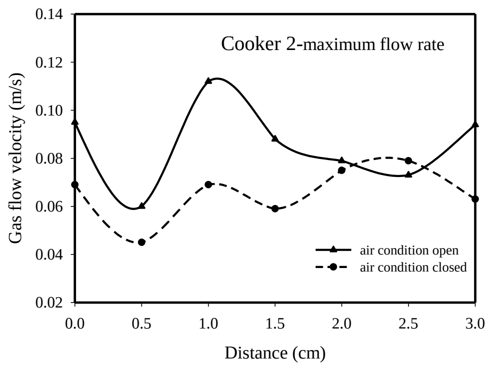
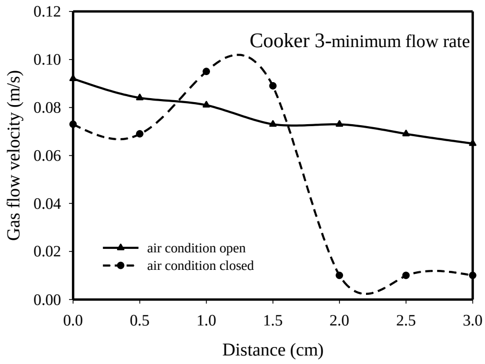


(d)

Figure 5. The gas flow velocities of the household cookers: Cooker 1 for (a) minimum and (b) maximum flow; Cooker 2 for (c) minimum and (d) maximum flow; Cooker 3 for (e) minimum and (f) maximum flow



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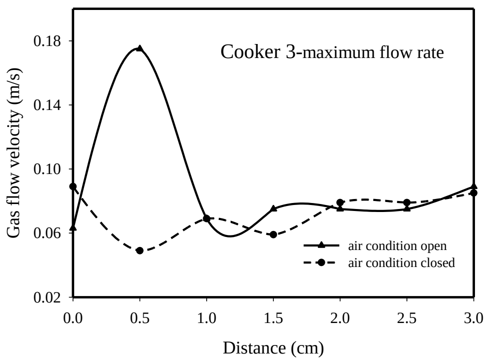
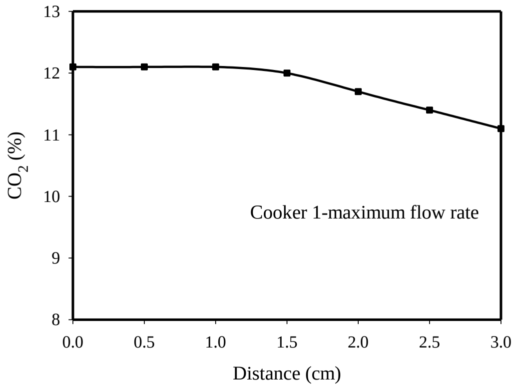


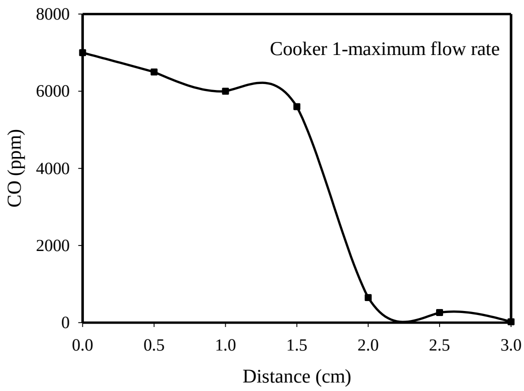
(f)

Figure 5 (continue). The gas flow velocities of the household cookers: Cooker 1 for (a) minimum and (b) maximum flow; Cooker 2 for (c) minimum and (d) maximum flow; Cooker 3 for (e) minimum and (f) maximum flow

It was found that the velocity of NOx formation increases with increasing temperature during combustion [25]. It is important to measure the emission values of gaseous NOx and other combustion products because they are important for human health. Emission measurements were made with the NOVAplus instrument in the diagonal direction at maximum flow in Cooker 1 over a measurement period of 1.5 min. The accuracy of the instrument is ± 10 ppm for CO, 5% for CO_2, and ± 5 ppm for NOx. The emission values are shown in Figure 6. According to these results, CO_2 emission was 12% between the reference point and 1.5 cm, and it was found to decrease to 11% for measurements between 1.5 cm and 3 cm. The maximum value of CO emissions (ppm) measured at the reference point was 7000 ppm. It then decreased linearly in the range of 0–1 cm, reaching 6000 ppm, and then suddenly decreased at a distance after 1.5 cm. For NOx measurements (ppm), a maximum value of 180 ppm was recorded at the 0.5 cm point. The NOx value tended to decrease after 0.5 cm, similar to the curve of CO (ppm) after the 2 cm point and approached zero.



(a)



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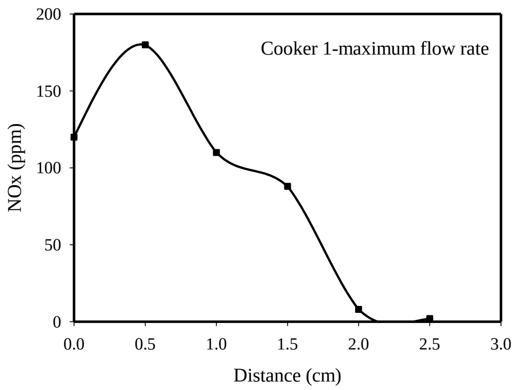

(c)

Figure 6. The (a) CO_2, (b) CO and (c) NOx emissions of Cooker 1.

The burner gas velocity measurements of all cookers are shown in Figure 7. At the minimum flow rate measurements for Cooker 1, the gas velocity was found to be 0.924 m/s with the vent open and 1.015 m/s with the vent closed. At the maximum gas flow rate, the gas velocity was 2.834 m/s with the ventilation on and 2.915 m/s with the ventilation off. From Table 1, it can be seen that the variation of the cooker gas flow velocities with the ventilation open and closed is evident for the maximum flow rate.

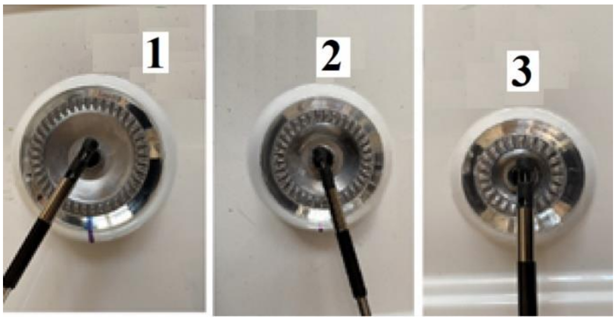

Figure 7. Measurements of gas velocities in the cookers

Table 1. The flow velocity measurements.

	Flow rate	Gas velocity (m/s)	
		Vent open	Vent closed
Cooker 1	min	0.924	1.015
	max	2.834	2.915
Cooker 2	min	1.22	1.18
	max	2.04	2.25
Cooker 3	min	0.78	1.105
	max	1.7	2.42

The viscosity of LPG was calculated using Kay's rule by Eq. (1) for temperatures above 200 °C with μ_{gas}= 0.012 cP=0.012×10^{-3} Pa.s. The Reynolds number at the gas exit point with a gas flow rate of 2.95 m/s was calculated to be *Re* = 2458.33. Because the flow in the circular tubes is laminar when *Re* is smaller than 2300, the flow regime was determined to be turbulent at the maximum gas flow velocity of Cooker 1. When the same cooker was evaluated by the minimum gas flow rate, the Reynolds number was calculated to be *Re* = 845.83, and it is in the laminar regime. Because of 70% of LPG is C_4H_{10} in our study, the viscosity of the used LPG was calculated from the butane using the Sutherland formula. Based on the gas temperatures in the vertical direction, it was found that laminar flow exists due to *Re* < 2300.

5. CONCLUSIONS

The flame temperature and cold flow characteristics of LPG in household cookers with rectangular geometry ports under laboratory conditions were studied. The fuel was LPG, which is a mixture of 70% C_4H_{10} and 30% C_3H_8. We can draw the following conclusions from the results of these experimental and numerical studies:

1) Temperatures at maximum flow rates are higher than those at minimum flow.

2) Temperatures in the vertical direction at maximum flow rates are significantly different than temperatures in the horizontal and diagonal directions for all cookers.

3) At the minimum flow rate, the highest temperatures in the diagonal direction were reached at the reference point for all cookers.

4) At open vent and maximum flow rate conditions, the maximum gas flow velocities were 0.12 m/s for Cooker 1 and Cooker 2 and 0.18 m/s for Cooker 3 near the reference points. The gas flow velocity at the minimum flow rate of Cooker 3 was influenced by the open and closed ventilation. Because gas velocities are high at maximum flow rates, the flame temperatures achieved also reach high values.

5) Cooker 1 exhibits a turbulent regime only at the maximum flow rate; the other cookers are in the laminar flow regime.

6) The CO and NOx measurements of Cooker 1 decrease rapidly after a distance of 1.5 cm from the reference point.

DECLARATION OF ETHICAL STANDARDS

The authors declare that there is no conflict of interest.

AUTHORS' CONTRIBUTIONS

Berkay ŞAHİN: Performed the experiments and analyse the results.

Nimeti DÖNER: Writing and editing**,** Analyse the results.

Mustafa İLBAŞ : Analyse the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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