ABSTRACT
The design of a preheating chamber for a safe flow of liquefied petroleum gas (LPG) or liquid fuel in a pressurized burner is investigated. In developing economies with an incessant scarcity of cooking gas, adulterated fuel is more a scarce commodity than a scary cause of fire accident to lives and household properties. Back-flow tendencies in conventional burners, associated with inevitable loss of pressure, mechanical wears, and seal leakages, are eliminated by the application of the concept of “sudden expansion,” while the fuel tends to flow back through the line at the downstream of the preheating chamber. Experimental setup of a novel feeding of liquid fuel from the overhead tank of the proposed design is compared with the performance of conventional burners. Pulsation due to back-flow tendencies of liquid fuel is calibrated for different heights (h) of burners, between the range of 46 mm and 60 mm. It is anticipated that the proposed design of burners will provide an effective flow of liquid fuel if uniquely characterized, using efficient treatment of the back-flow tendencies. Also, the proposed sudden expansion technology is capable of reducing the risk of an irritating exposure to adulterated fuel.

Nomenclature

\( a, \beta = \) regression coefficients for the head loss
\( A_1, A_2 = \) cross-sectional areas of the sudden expansion chamber (m²)
\( C_p = \) constant pressure specific heat capacity (J/(kg K))
\( D_1, D_2 = \) schematic dimension of the sudden expansion chamber (m)
\( d, D = \) dimension of the sudden expansion chamber (m)
\( F = \) fluid force (N)
\( g = \) gravitational acceleration in (m/s²)
\( h = \) height of the burner in (m)
\( h_{fg} = \) latent heat (J/kg)
\( h_l = \) head loss (m)
\( K = \) Loss coefficient
\( Q = \) volumetric flow rate (m³/s)
\( p = \) pressure (Pa)
\( P_1, P_2 = \) fluid pressure in the sudden expansion chamber (Pa)
\( Re = \) Reynolds number
\( q = \) heat transfer rate per unit area in W/m²²
\( T = \) Temperature (K)
\( t = \) Time (second)
\( v = \) velocity (m/s)
\( V_1, V_2 = \) velocities of fluid across the sudden expansion chamber (m/s)
\( \rho = \) density (kg/m³)

I. Introduction

The scarcity of liquid fuel for domestic combustion processes in household appliances is driving the uncontrollable practice of fuel adulteration by vendors in the Nigerian energy market. Whenever scarcity of liquid fuel impacts the preparation of food and resuscitation or fueling of human internal organs, environmental pollution and problems with engine performance cease to be the primary concern of the practice of fuel adulteration. Therefore, the management of fuel adulteration focuses on the development of burners with a safe combustion mechanism. With back-flow tendencies from the combustion chamber of most conventional cooking appliances, the danger of fire accident, among other precarious catastrophes such as carbon monoxide pollution, represents an increasing concern for local designers of household cooking appliances. The design of the preheating chamber is often recommended (for the pressurized liquid fuel burners) for enhanced atomization and proper evaporation of the liquid fuel. Due to an increased surface area of the liquid fuel, complete combustion of the atomized fuel is enhanced with the possibility of a reduced emission. Pereira recently investigated the concept of atomization and combustion of liquid. It was established that atomization has the advantage of limiting pollutants emission.

Preheating of liquid fuel contributes significantly to the process of a flameless combustion. While the attention of most researchers is focused on the stoichiometry of the combustion, after the preheating of liquid fuel, little attention has
been devoted to the mechanism that supplies fuel to the preheating chamber. Pressurized liquid fuel burners are generally operated either through mechanical pressurization or through the gravitational feeding of the fuel. The formal approach requires the use of a hermetically sealed tank, with certain accessories such as a small hand pump and pressure relief valve for effective operation, whereas liquid flow in the latter approach is driven by gravitational force. The use of the gravitational method appears relatively common, due to its small reservoir feature. Most fuel tanks are raised slightly above the level of the burner.

The fuel tank supplies liquid fuel under gravity to the burner, where it is vaporized before combustion. The operation of a gravity-fed stove is similar to the process of combustion in a traditional Primus stove. The burner is turned on in order to initiate the passage of a small amount of fuel into the burner. Meanwhile, the collection of the liquid fuel enables the priming of the pan. The burner is then turned off, while the fuel is ignited primarily for the purpose of preheating the burner. When the fuel in the pan is almost gone, the burner is turned back on. Then the fuel flows into the burner for vaporization with fuel injection for continuous burning.3–8 Moh2 constructed a portable kerosene pressure cooker with used materials and also overcame the sooty flame problem of conventional cook stoves. Busman et al.7 presented the design of a high-power kerosene stove, leading to cogent empirical expressions for burner dimensions. However, the transport mechanism of the liquid fuel to the preheating chamber and the possible impacts of the use of adulterated fuel were not considered. Elijah et al.9 carried out a comprehensive and comparative analysis of the transport of liquid fuel. It was reported that adulterated fuel leads to poor performance of pressurized burners with lower flame temperature, low heating rate, and a decrease in the thermal efficiency. Notwithstanding, limited attention has been devoted to the problem of back-flow tendencies in these pressurized burners.

Other problems, including pressure loss, mechanical wear, and seal leakages, pose a great challenge to users of pressurized burners. Among other possibilities, the gravitational method that appears devoid of these problems represents a better option. However, the pulsation problem is prevalent as a result of back-flow, caused by the built-up pressure in the preheating chamber. According to Kim,10 a check valve could be used to stop back-flow.11,12 However, this approach requires an appreciable force to open the valve for upstream flow, with the penalty of a loss in the pressure head. This article proposes the elimination of the back-flow tendencies by constructing a specially designed chamber, coupled with the design of a suitable sudden enlargement in the flow line.

The swirling of the back-flow, due to the introduction of sudden enlargement, causes a reduction in the kinetic energy until it tends to zero at the entrance of the burner. The sudden expansion phenomenon was proposed by Shickikha et al.13 using head loss analysis in pipe system components. It was reported that the combination of the head loss in the sudden expansion and the coefficient of the loss represent a function of the expansion (diameter) ratio. Previously, Oliveira et al.14 had noted that the drop in the pressure coefficient indicates that the local loss coefficient largely differs from the standard expressions found in reference books and manuals. This discrepancy increases with decreasing Reynolds number \(Re\). Mirianda et al.15 investigated the effect of shear thinning \(n\) and Reynolds number \(Re\) on the local loss coefficient \(C_l\) and deduced that at low Reynolds numbers, \(C_l\) varied inversely with \(Re\). Edwards et al.16 also investigated head losses in pipe fittings at low Reynolds numbers and concluded that in the laminar region, the loss coefficient is inversely proportional to \(Re\). But at higher \(Re\), a rapid transition is observed in a region where the loss coefficient approaches a constant.

Although the proposed recommendation toward the prevention of back-flow tendencies is anticipated for adoption by the Standard Organization of Nigeria, energy efficiency ratings of home appliances appear to be the main concern of the local regulatory agency in Nigeria. For example, the technical committee for air conditioners and heat pumps of the Standards Organization of Nigeria (SON) for the development and review of these standards have recently adopted the maiden standards, including the NIS ISO 5151 (non-ducted air conditioners and heat pumps – testing and rating for performance), NIS ISO 16345 (water-cooling towers – testing and rating of thermal performance), NIS ISO 15042 (multiple split-system air conditioners and air-to-air heat pumps – testing and rating for performance), NIS ISO 16358-1 (air-cooled air conditioners and air-to-air heat pumps – testing and calculation methods for seasonal performance factors, Part 1: cooling seasonal performance factors), NIS ISO 16358-2 (air-cooled air conditioners and air-to-air heat pumps – testing and calculation methods for seasonal performance factors, Part 2: heating seasonal performance factors), and NIS ISO 16358-3 (air-cooled air conditioners and air-to-air heat pumps – testing and calculation methods for seasonal performance factors, Part 3: annual performance factors). However, it is possible to update the relevant standard with the test and operational procedure for the production of locally fabricated burners, based on the consumption profile of the different blends of available fuel.

This article presents a novel design of a pressurized burner based on a practical application of the sudden expansion phenomenon, where the pulsation effect is considerably reduced, apparently with flow stabilization. Based on the application of this sudden expansion, prevention of head loss and back-flow tendencies in cooking appliances are anticipated. Section 2 presents the detailed experimental setup with the description of the various elements, including the burner, preheating chamber, sudden expansion chamber, and fuel tank. The effects of the integration of sudden expansion and variation in the heights of the burner are discussed in section 3, including the performance of the burner under different environmental conditions, thermal efficiency, and the liquid fuel consumption. Thereafter, the comparative advantage of the proposed design is demonstrated with a properly validated thermal efficiency test.

II. Experimental setup

The experimental setup intends to investigate back-flow tendencies. The setup is composed of two types of burners (a typical burner is shown in Figure 1), including the conventional burner (burner 1) and the proposed burner (burner 2), which are connected in parallel. Other elements within the setup include the fuel
filter (corrugated paper type), gate valve for controlling the flow, two isolation valves, and a calibrated rotameter with a measurement range between 0 and 90 ml/min. The fluid from the tank is filtered before moving through the valves (a gate valve appears the rotameter and a set of isolation valve is positioned immediately after the rotameter), before feeding the burner. Unlike the rotameter that was used by Catapan et al.\textsuperscript{17} to investigate non-uniform velocity profile mechanism for flame stabilization in the porous radial burner, a new type of rotameter is used in the proposed design, which has a higher range because of a high flow rate. The fuel supply system is driven by gravitational force with an overhead fuel tank at a capacity of 4 liters.

2.1 Environmental boundary effects

In order to simulate both the indoor and outdoor cooking, the same experiment is sequentially performed under two conditions (indoor and outdoor). The indoor experiment is conducted under a room temperature condition and a well-lighted space for an accurate reading of the rotameter. Also, the air in the test room is enclosed and free from natural draughts, which is capable of affecting the performance of burners. Burner 1 is isolated by a means of an isolation valve; while Burner 2 is preheated by an external source (methylated spirit). The flow control valve is then turned on in order to allow the flow of liquid fuel (kerosene) to the preheated Burner 2. The liquid fuel absorbed the heat in the preheating chamber through vaporization. The vapor is forced out of the jet, where it mixes with air and is burned with premixed flame.\textsuperscript{4} This process is allowed to stabilize for 10 minutes before the reading from the rotameter is taken. Thereafter, the whole procedure of vaporization is repeated for Burner 1, while Burner 2 is isolated. Also, the entire experimental setup procedure is repeated under the outdoor condition, and the readings are recorded. The rotameter provided the readings for flow rate as well as pulsation rate. The experimental uncertainties in flow rate are observed to be 5\%, based on an error propagation analysis.\textsuperscript{18} An equal classification of these errors, under both random and systematic errors, is considered. This consideration is based particularly on the visibility constraints in the reading of the calibration fractions on the rotameter and the pulsation leakages from the operation of the isolation valves. Propagation analysis of the combination of these errors is usually aimed at distributing the measured values of repeated experiment, using different parameters, such as maximum error, probable error, average deviation, and standard deviation.\textsuperscript{19}

Considering the validation of negligible experimental uncertainties, analysis of data for thermal efficiency and fuel consumption performances of the proposed burner under the indoor environment appears reasonable. Pulsation in combustion is readily pronounced during the operation of most conventional burners. However, an improvement is probable with the use of the sudden expansion feature in the proposed design. By varying the parameters of dimension in order to optimize the effects of sudden expansion, it is observed that back-flow tendencies reduce as the height (h) of the burner increases. Thereafter, further optimization with the use of linear regression enables the characterization of the effects with respect to the heights of the burner. Considering the transport of liquid fuel along the pipe, it is a well-known phenomenon that the minimum pressure loss takes place when the length to diameter ratio L/D approaches one.\textsuperscript{20} A parametric evaluation of the optimal L/D for the proposed design is beyond the scope of this study.

The mechanical pressurization method consists of a hermetically sealed tank equipped with accessories such as a small hand pump, a pressure relief valve, and an opening for refueling. The hand pump introduces the pressure force that drives the fuel from the tank into the burner along the sudden expansion mechanism. The fuel is pressurized in order to enable flow into the burner, unlike the proposed setup where the fuel flows is fed under the gravitational force. Meanwhile, the gravitational method addresses the problem of intermittent pumping, which represents a significant drawback of the mechanical method.\textsuperscript{21} Moreover, the exclusion of intermittent pumping of the mechanical pressurization method, compared to the proposed gravity-fed setup, appears to clearly pronounce the effects of the application of sudden expansion to the operation of the new design.

2.2 Thermal efficiency performance

Thermal efficiency test provides the optimum value of h. The thermal efficiency of a burner is defined as the ratio of heat actually utilized to the heat theoretically produced by complete combustion of a given quantity of fuel (which is based on the net calorific value of the fuel).\textsuperscript{22, 8} At room condition, maintained at between 25\(^\circ\)C from 30\(^\circ\)C, the burner is fitted on a stove stand and lighted to burn for a period of 10 minutes at a working pressure of 100 KN/m\(^2\) to 200 KN/m\(^2\), during which a flame is obtained. Under the prevailing room condition, the 10-minute period is considerably suitable for a steady-state consideration of the thermal efficiency experiment. Then a vessel containing water is placed on the stove, where pressure is readjusted until a stable blue flame is obtained.\textsuperscript{23} Likewise, the stove is operated at the maximum blue flame height for two periods of approximately 2 hours each, during which it was observed for any abnormal performance or leakage.
2.3 Fuel consumption performance

The fuel consumption performance of the different fuel samples is studied by filling the fuel tank with the kerosene fuel up to three-fourths of its capacity. The stove is lighted and brought up to working pressure of 140 KN/m² within 5 minutes. After burning for 5 minutes, the lighted stove is weighed first and then filled with the required amount of water, and the initial temperature of water is kept within ± 2°C from the actual room temperature. The fuel container is connected to a pressure gauge and filled to nearly three-fourths of its capacity. The stove is lighted and brought up to working pressure of 140 KN/m². After burning the stove for 5 minutes, the weight of the stove is noted after the water in the container is drained. The difference in the initial and final weight of the burning stoves gave the kerosene consumption rate in grams per hour. A cylindrical flat-bottomed aluminum pan is provided with an aluminum lid with two holes, one for inserting the cork for holding a thermometer and the other for the stirrer (made of aluminum wire). The pan alone with the aluminum wire alone is weighed first and then filled with the required amount of water, and the initial temperature of water is kept within ± 2°C from the actual room temperature. The fuel container is connected to a pressure gauge and filled to nearly three-fourths of the capacity. The burner is lighted at an average working pressure of 140 KN/m². After burning the stove for 5 minutes, the weight of the stove, time, and initial temperature of the water in the pan are recorded. The pan is covered with a lid fitted with a thermometer inserted into the cork in such a way that the bulb of the thermometer immersed to half the depth of the water in the vessel. It is observed that the blended fuel (adulterated fuel) gives lower thermal efficiency between 40% and 50%. The observation is consistent with the results obtained by Nagruti and Gopal.

III. Head loss modeling

The back-flow phenomenon, which is caused by a built-up pressure in the preheating chamber, needs to be checked in order to ensure effective flow of the liquid fuel for complete combustion. A sudden expansion is introduced along the pipe flow line, as illustrated in Figure 2.

3.1 Sudden expansion

The sudden enlargement causes the flow to swirl as shown in Figure 2, and all the kinetic energies tend to zero. The mathematical model for the system is based on the principle of Bernoulli. Assuming a pipe with a varying cross-sectional area and diameter (i.e., A₁ and A₂) represent the dimension for the area, while D₁ and D₂ represent the dimension for the diameter), when the fluid suddenly flows back from the smaller pipe and enters the wider part of the pipe, there is a sudden deceleration of the fluid being unable to move in sharp corners. It interacts with the boundary at the enlargement, thereby generating eddy currents. Since these eddies dissipate a large amount of fluid energy, expansion losses occur and the tendency for further flow is destroyed. Hence, from the law of conservation of mass:

$$\sum F = \rho Q (V_2 - V_1)$$

(1)

Since the flow in this section is incompressible:

$$A_1 V_1 = A_2 V_2 = Q$$

(2)

leading to

$$P_1 A_2 - P_2 A_2 = \rho Q (V_2 - V_1)$$

(3)

where ρ, A, and V are the fluid density, cross-sectional area of the pipe, and speed of the fluid, respectively. From the equation, we find that

$$\frac{P_1 - P_2}{\rho g} = \frac{V_2}{g} (V_2 - V_1)$$

(4)

Applying Bernoulli’s equation and ignoring friction losses but including the head loss at the expansion hₜ

$$h_L = \left( \frac{P_1 - P_2}{\rho g} \right) + \frac{V_1^2 - V_2^2}{2g}$$

(5)

Using Eqs. 4 and 5, it implies that

$$h_L = \frac{(V_1 - V_2)^2}{2g}$$

(6)

The loss is a function of the square velocity. And since exit flow from a pipe into a large reservoir is similar to a sudden expansion with V₂ = 0, the loss now becomes

$$h_L = \frac{V_1^2}{2g}$$

(7)

Considering the equations of continuity, momentum, energy, and stagnation pressure, the theoretical head loss (Eq. 7) is modified as

$$h_L = K \frac{V_1^2}{2g}$$

(8)

where K is loss coefficient (K ≤ 1) and equal to \(1 - \frac{D_1^2}{D_2^2}\). For the effective flow of the liquid fuel, hₜ must be increased. It implies that the value of K must tend toward 1 while minimizing the ratio \(D_1^2/D_2^2\) (see Figure 3).

3.2 Height of the burner

Besides the influence of the ratio of the diameters for the sudden expansion chamber (based on the theoretical model in Eq. 8), the correlation of the height of the burner on head loss is investigated, using a linear regression analysis of the experimental data and a hypothesized relationship

$$h_L = a + \beta h$$

(9)

where

Figure 2. Schematic of the Proposed Burner, Showing the Sudden Expansion Section.
\[ \alpha = \text{constant head loss at zero value of } h; \quad \text{and} \quad \beta = \text{effect on the head loss for every unit increase in } h \]

### 3.3 Adulterated fuel

Different procedures for the prediction of the quality of fuel and to discriminate between different adulterated fuel samples include calibration of the density values, distillation temperature, Fourier transform infrared analyses, and chromatographic separation. Since the focus here is the management of adulterated fuel, rather than the prediction of the quality of fuel, four different samples of kerosene and diesel blends (B5, B10, B15, and B20) are tested using the same burner (see Figure 1). In order to measure their back-flow tendencies, the pulsation rates of these samples recorded.

### IV. Discussions of results

Figure 4 shows the variation of the head loss at different heights of burner. Minimum head loss per mm of $0.45 \times 10^{-5}$ is observed at the lowest height of burner position during the experiment. The head loss increases non-linearly with the height of the burner, apparently showing that the performance of the burner depends on many other flow phenomena beyond the position of the burner nozzle from the supply tank. The values of \( \alpha \) and \( \beta \) that minimize the function (see Eq. 9) are obtained as \( 0.197 \times 10^{-5} \) and \( 6.96 \times 10^{-5} \), respectively, using simple regression of the experimental data.

Figure 5 shows the variation of thermal efficiency at different heights of burner. Minimum efficiency of 51% is observed at a minimum burner height of 50.0 mm. This trend appeared to increase linearly with the maximum value of 54.8% at the height of 54.0 mm, after which it is dropped non-linearly to 52.5% at the height of 60.0 mm. Invariably, the optimum height of burner that produces the maximum thermal efficiency is about 54.0 mm.

Table 1 gives the standard dimensions of the different type of burners. When compared with \( h = 53 \text{ mm} \) at a nozzle diameter of 0.35 mm obtained by Busman et al., the proposed design becomes \( h = 59.7 \text{ mm} \). By substitution into the regression model (Eq. 9), it implies that the experimental value of \( h_L = 0.569 \times 10^{-5} \text{ m} \) is obtained. Comparing the values of \( h_L \) obtained from the model (see Eq. 10) and that of experimental, \( h_L = 0.45 \times 10^{-5} \text{ m} \) at an average flow velocity of 0.1 m/s, it implies that there is a percentage increase of

| Country | Name       | Nozzle diam. (mm) | Burner (mm) | D (mm) |
|---------|------------|-------------------|-------------|--------|
| Indonesia | Zeppelin  | 0.30              | 61          | 38.5   |
|          | Penguin    | 0.60              | 74          | 47.0   |
|          | Butterfly  | 0.65              | 100         | 60.0   |
|          | Bee & Butterfly | 0.75      | 114         | 69.5   |
|          | Champion   | 0.80              | 117         | 69.5   |
| India   | Naaz de Lux| 0.35              | 53          | 38.0   |
|          | Super JH   | 0.40              | 71          | 43.4   |
|          |            | 0.45              | 71          | 43.4   |
26.4% in $h_L$. This corroborates the submission of Oliveira and Pinho\textsuperscript{14, 29} that the local loss coefficient differs by a large amount from the standard expressions found in textbooks and manuals. The flow field in this case is asymmetric since the expansion ratio $D/d$ is greater than 1.5 in this work.\textsuperscript{30, 31}

$$hL = K. \frac{V_1^2}{2g}$$

where $D_1 = 5mm, D_2 = 20mm$; and hence $K = 0.8789$.

Figure 6 compares the pulsation rate of the two burner designs, indicating the number of pulses within a specified period of time in minutes. It is observed that the number of pulses that represent back-flow tendencies increase sharply from 39 to 128 within 4 minutes for the existing burner. Meanwhile, relatively few pulses of 5 were observed within 4 minutes in the case of the proposed burner design. It implies that a considerable reduction in back-flow is achieved with proposed burner. Also, a significant reduction in the pulsation slope appears to reduce the risk of fire accident with the possible use of adulterated liquid fuel. Figure 7 compares the pulsation rate for the different fuel samples. Interestingly, the blends with the higher percentage of diesel have lower rates of pulsation, apparently because adulterated fuel produces lesser heat.

V. Conclusions

An experimental study of back-flow tendencies in pressurized burners is presented. The sudden expansion technology was proposed as a management tool if incorporated in the design of preheating chamber of pressurized burners. Also, the thermal efficiencies at different dimensions of the burners were investigated in order to obtain the optimum size for better performance. Back-flow tendencies were considerably reduced when the sudden expansion phenomenon was used with the coefficient of head loss approaching 1. The head loss to back-flow increases with higher values of $h$. The optimum value of $h$ being 54.00 mm for the standard burner corresponds to about the nozzle diameter of 0.35 mm. Comparing the back-flow tendencies of the different samples of adulterated fuel, it was observed that the blends with the higher percentage of diesel have lower rates of pulsation. However, the sudden expansion significant reduces combustion pulsation, while the burner produces smooth and effective combustion.

Acknowledgments

The authors are grateful for the assistance of the associates of the Energhx Research Group, University of Lagos.

Conflicts of Interest

The authors declare no conflict of interest.

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