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# COMPARATIVE STUDY ON THE PERFORMANCE OF A SWIRL-TYPE BURNER CAP FOR DOMESTIC GAS GEYSERS

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## Abstract

*Enhancing combustion efficiency in domestic gas geysers is essential for reducing fuel consumption and pollutant emissions. This study presents a comparative experimental investigation of a conventional swirl burner cap and a newly designed perforated 45° swirl-type burner cap for residential gas geysers. The modified burner cap was developed using a combined CAD-based design, sand casting, and CNC machining approach to ensure manufacturability and geometric precision. Performance evaluation was conducted on a domestic geyser test rig using real-time flue gas analysis and standardized combustion efficiency calculations. For the conventional swirl burner cap, the measured flue gas composition showed 8.40% $O_2$, 6.82% $CO_2$, and 0.0051% CO, with a stack temperature of 540.7 °C, resulting in a combustion efficiency of 68.41%. In contrast, the perforated swirl burner cap exhibited a significantly improved performance, with an average $O_2$ concentration of 11.80 ± 0.12%, reduced $CO_2$ concentration of 4.47 ± 0.40%, and CO emissions of 0.0045%. The stack temperature decreased substantially to 276.1 °C, indicating lower flue gas losses. Consequently, the modified burner achieved a higher average combustion efficiency of 82.03 ± 0.15%, representing an improvement of approximately 14% compared to the conventional design. The enhanced performance is attributed to improved air–fuel mixing and intensified turbulence generated by the hole-assisted swirl configuration. The results demonstrate that geometric modification of burner caps offers a simple, cost-effective solution for improving combustion efficiency and reducing emissions in domestic gas geysers. This study provides practical insights for the development of energy-efficient household heating appliances.*

## INTRODUCTION

Environmental pollution continues to be a critical concern, primarily due to the persistent dependence on fossil fuels, which account for roughly 80 % of the global energy supply [1]. Addressing this issue, while meeting rising energy demands under increasingly stringent environmental regulations, necessitates the development of cleaner and more sustainable combustion technologies [2]. One effective strategy is the transition toward gaseous fuels, which generally exhibit superior combustion properties and produce significantly lower pollutant emissions compared to solid or liquid fuels [3]. Nevertheless, relying solely on gaseous fuels introduces operational challenges; their distinct flame characteristics can complicate system stability and require greater flexibility in combustor design [4].

Reducing energy consumption has emerged as a pressing global concern due to the depletion of fossil fuel reserves, economic limitations, and escalating environmental challenges [5,6]. Among energy carriers, natural gas has experienced the fastest consumption growth. As a technically reliable and economically viable fuel, natural gas remains widely used worldwide. In 2024, global natural gas consumption rose by 2.8 % relative to 2023, representing an additional 115 billion cubic meters (bcm) and contributing to approximately 40 % of the increase in global energy demand, with the Asia-Pacific region accounting for nearly 45 % of this growth [7,8]. Despite its widespread adoption, natural gas is non-renewable and associated with considerable carbon emissions, prompting several countries to implement regulations aimed at mitigating greenhouse gas emissions, particularly $CO_2$.

In Pakistan, natural gas consumption has grown at an average annual rate of 7.8 % over the last decade. As of December 2023, daily consumption reached 3.662 Bcf/d, slightly lower than 3.696 Bcf/d in 2022. During the fiscal year 2024 (July-March), total gas utilization averaged 3207 MMCFD, comprising 2512 MMCFD from natural gas and 695 MMCFD from re-gasified liquefied natural gas (RLNG). The power sector remains the largest consumer, followed by the residential sector [9]. A significant portion of this residential demand stems from household appliances such as domestic geysers; improving their combustion efficiency can reduce energy costs while contributing to national energy security and lowering emissions.

Liquefied petroleum gas (LPG) has gained attention as a transitional fuel due to its availability, adaptability, and existing distribution infrastructure [10]. These attributes provide operational and logistical benefits that facilitate LPG integration into current industrial systems. In contrast, methane, although characterized by cleaner combustion and lower greenhouse gas emissions, faces challenges in storage, transportation, and mitigation of fugitive emissions [11,12]. LPG's ease of handling and deployment positions it as a practical alternative for minimizing environmental impact while ensuring energy supply reliability [13].

Previous research on LPG-based domestic burners has demonstrated that key factors influencing performance include burner geometry, air–fuel mixing, and flame stabilization [14,15][15–17][16]. For instance, confinement ratio, slot configuration, and primary aeration have significant effects on flame stability, heat transfer, and pollutant emissions [16] [17]. Optimizing these parameters is essential to achieving higher thermal efficiency and lower CO and NO emissions in domestic appliances.

Swirl-type burners are widely recognized for their ability to improve combustion efficiency by promoting better air–fuel mixing and stable flame formation [14] [18,19] [20]. Swirl-induced recirculation zones enhance flame retention, increase residence time, and facilitate uniform heat distribution within the combustion zone. Studies on swirl burners indicate that geometric modifications, such as the incorporation of slots or holes, can further improve combustion performance, reducing flue gas losses and emissions while maintaining operational stability [20] [21].

Domestic LPG burners operate on principles analogous to conventional Bunsen burners, where combustion efficiency is primarily determined by primary aeration and jet velocity [22] [17]. However, overall burner performance is also affected by specific design parameters, including slot angle, cap geometry, and flow dynamics [23]. Standardized evaluation protocols, such as the Water Boiling Test (WBT, Shell Foundation), are commonly employed to assess efficiency, highlighting the influence of testing methodology on measured performance [24].

Research on domestic gas burners has largely focused on three interrelated aspects: (i) burner geometry and structural design, (ii) swirl flows and turbulence effects, and (iii) combustion emissions and energy efficiency. A systematic understanding of these factors provides the basis for improving domestic geyser performance and motivates the present study on comparative performance evaluation of swirl-type burner caps.

### 1.1 Burner Geometry and Structural Design

Burner geometry is a primary factor affecting combustion efficiency, flame characteristics, and heat transfer. Domestic LPG burners operate on principles similar to conventional Bunsen burners [22], where efficiency is largely influenced by primary aeration, jet velocity [17], and burner head design [23].

Prior research indicates that nozzle configuration, burner head shape, and heat recirculation significantly impact thermal performance [23]. Porous recirculating burners with exhaust gas recirculation have been shown to enhance efficiency by reducing heat losses [25]. Structural modifications, such as annular inserts, spill trays, and adjustments in loading height, further improve heat transfer and efficiency [26] [27]. Material selection also affects performance; for example, brass burners have been observed to outperform cast iron designs by approximately 4% in thermal efficiency [28] [29]. Additionally, interactions between the vessel and burner, including pot size and integrated fins, can provide measurable gains in heat transfer [30] [31].

Recently, an experimental evaluation of burner cap designs for residential gas geysers compared circular, plate, and swirl burners under controlled laboratory conditions [32]. The swirl burner exhibited superior performance, achieving peak thermal and combustion efficiencies of 54.1% and 75.2%, respectively, at a 49° cap angle. This improvement was attributed to enhanced turbulence and superior air–fuel mixing, which reduced CO emissions to as low as 27 ppm. In contrast, the plate and circular burners demonstrated lower efficiencies, confirming the dominant influence of burner geometry on combustion behavior. These findings highlight swirl-induced turbulence as a critical design parameter for improving domestic geyser performance.

Despite these advancements, most studies have concentrated on flat, porous, or hole-patterned burners, with limited investigation into cap tilt or swirl angles above 40°, restricting understanding of higher-intensity turbulence effects.

### 1.2 Swirl Flows and Turbulence Effects

Swirl flows are an effective mechanism for enhancing air-fuel mixing and stabilizing flames. Research has shown that swirl motion improves both efficiency and emissions performance, though excessive swirl or elevated loading heights can reduce thermal efficiency due to higher atmospheric losses [33] [34,35]. Experimental comparisons of swirling strip-port burners with conventional designs demonstrate reductions in NOx formation under swirl conditions [36]. Increased swirl angles can enhance thermal performance but may also raise CO emissions if not carefully managed [36] [37].

Computational fluid dynamics (CFD) studies have provided further insights into swirl behavior. Turbulent combustion modeling in self-aerated burners highlights the importance of uniform premixing for stability, while flame position and turbulence intensity strongly influence efficiency [38] [39]. Optimal flame delivery angles are generally in the 30°-35° range, with higher swirl and inclination angles (up to 60° and 30°, respectively) showing additional efficiency gains, albeit at the cost of increased CO formation [40,41]. Nevertheless, systematic experimental investigations of swirl angles above 40° in residential appliances remain limited, primarily due to fabrication and design constraints.

Complementing domestic-scale research, a novel counter-rotating double-swirl burner was recently developed for diesel-LPG cofiring [42]. Cold-flow simulations confirmed that the premix chamber created strong central and outer recirculation zones essential for flame stability. At a liquid-to-gas energy ratio of 70/30, the burner achieved a maximum thermal efficiency of 51%, a 40% reduction in flame length, and a 95% reduction in CO emissions compared to pure diesel operation. Although this study targeted industrial-scale combustion, it clearly demonstrates how swirl-induced recirculation zones enhance mixing, stabilize flames, and improve efficiency, principles that directly support swirl optimization strategies for domestic geyser applications.

### 1.3 Emissions and Environmental Considerations

Combustion efficiency alone does not ensure environmentally responsible operation; emissions of CO, NOx, and $CO_2$ are equally important. Studies have shown that swirl burners significantly reduce CO emissions compared to conventional stoves [36] [35]. Structured baffle configurations in domestic gas geysers improve heat transfer, fuel-air mixing, and reduce gas consumption. For example, bladed frustums achieved high thermal efficiency (69.03%) but slightly reduced combustion efficiency, while other frustum designs balanced efficiency (67.07%) with reduced fuel use [43]. Optimized flow structures and porous inserts can simultaneously enhance thermal performance and mitigate pollutant formation [44] [45] [44] [46].

Inclined burner geometries and higher swirl angles can lower $CO_2$ and NOx emissions but often increase CO, reflecting the typical efficiency-emissions trade-off [40,41][47]. Studies incorporating hydrogen enrichment demonstrate extended lean burning limits and reduced CO formation [48]. Similarly, adjusting loading heights can decrease CO emissions while improving efficiency by approximately 20% [49]. Collectively, these findings indicate that emissions are strongly dependent on swirl intensity, geometric configuration, and air-fuel ratios. However, the effects of higher swirl angles on the simultaneous control of CO, $CO_2$, and NOx in residential appliances remain largely unexplored.

The recent domestic geyser burner study [32] further demonstrated that a 49° swirl cap produced the lowest emissions among tested configurations, particularly reducing unburned hydrocarbons and CO. This confirms that swirl geometry plays a decisive role in emission control for residential heating systems. Similarly, diesel-LPG cofiring in a double-swirl burner achieved ultra-low NOx levels while dramatically reducing CO emissions, although moderate increases in NO were observed due to elevated flame temperatures [42]. These results reinforce the strong coupling between swirl intensity, combustion temperature, and emission formation.

**Table 1. Summary of Studies on Burner Design and Performance**

| Study | Focus | Method | Findings | Limitation / Gap |
|---|---|---|---|---|
| 2023 [23] | Burner geometry | Experimental | Nozzle and head design strongly affect efficiency | No swirl analysis |
| 2002 [25] | Porous recirculating burner | Experimental | Heat recirculation improved efficiency | Not swirl-based |
| 2014 [33] | Swirl cap | Experimental | Swirl improved efficiency & reduced emissions | Swirl < 40° |
| 2018 [34,35,50] | Swirl configurations | Experimental | Counter-swirl reduced CO | Efficiency loss at high load |
| 2019 [36] | Swirl strip-port | Experimental | Significant NOx reduction | No tilt optimization |
| 2016 [39] and 2017 [38] | Self-aerated burners | CFD | Uniform mixing improved stability | No high-angle validation |
| 2013 and 2017 [40,41] | Port geometry | CFD | Optimum at 30°–35° | No strong swirl study |
| 2022 [47] | Angled burner holes | Experimental | >10% efficiency increase | Moderate angles only |
| 2025 [32] | Geyser burner caps | Experimental | 49° swirl gave 54.1% thermal, 75.2% combustion, CO=27 ppm | Lab-scale only |
| 2026 [42] | Double-swirl cofiring | CFD + Exp | 51% efficiency, 95% CO reduction | Industrial burner |
| 2022 [31] | Vessel-burner interaction | Experimental | Fins improved heat transfer | Vessel-focused |

From the literature summarized in Table 1, three major research gaps are evident. First, while burner hole patterns, inserts, and materials have been optimized, systematic investigation of swirl angles exceeding 40° remains scarce. Second, although swirl is widely recognized as a mixing enhancement mechanism, experimental validation in residential appliances is limited due to manufacturing challenges. Third, most studies emphasize CO reduction or thermal efficiency, with limited balanced evaluation of $CO_2$ and NOx under strong swirl regimes.

The recent domestic geyser study [32] confirms the importance of optimizing swirl angles, yet testing was conducted only under laboratory conditions with limited operational variability. Similarly, double-swirl cofiring research [42] demonstrated the benefits of recirculation zones but focused on industrial burners rather than household appliances.

Despite extensive research in industrial systems, few studies focus on swirl optimization for household gas geysers. Conventional domestic burners often lack geometric refinement, presenting an opportunity to enhance combustion efficiency while remaining compatible with existing appliances.

### 1.4 Novelty Statement

This investigation presents the design and experimental evaluation of a perforated 45° swirl-type burner cap for domestic gas geysers. A combined CAD-based design, sand casting, and CNC machining approach is employed to develop a manufacturable burner cap with controlled swirl features. The novelty lies in the hole-assisted swirl configuration that enhances air-fuel mixing while remaining fully compatible with existing geyser systems. A standardized experimental framework using real-time flue gas analysis is established for reliable performance comparison between conventional and modified burner caps.

## 2. Study approach

### 2.1. Burner Design and Fabrication

The burner cap was developed using a structured approach, as shown in Figure 1. The process involved CAD modeling of the burner geometry, followed by sand casting using cast iron. CNC machining was then applied to achieve accurate dimensions and slot features, resulting in the final finished burner cap ready for testing.

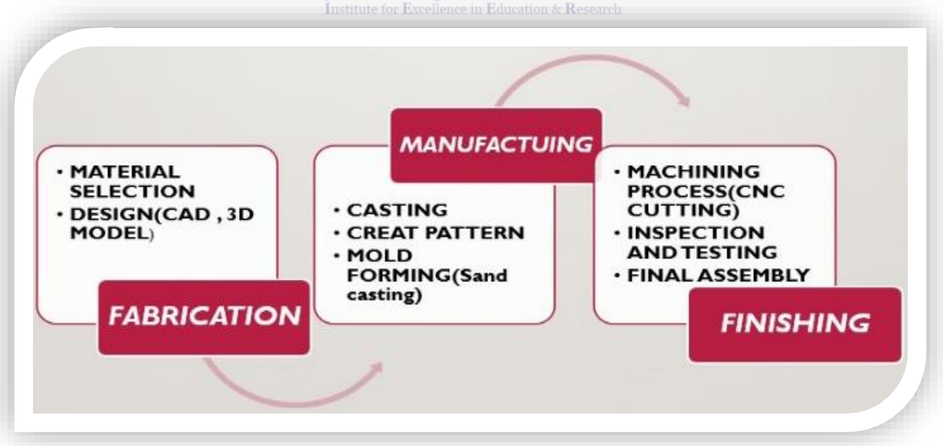

**Figure 1. Methodology of burner cap**

### 2.2 Burner Configuration

The burner configuration employed in this study is based on a conventional domestic water tank geyser system, modified to accommodate a swirl-type burner cap for performance evaluation. The existing burner assembly of the geyser was retained, while the conventional burner cap was replaced with a newly designed swirl burner cap to ensure a fair comparative assessment under identical operating conditions. The burner cap geometry was developed using CAD modeling to achieve precise dimensional control and repeatability, as illustrated in Figure 2, which presents the three-dimensional CAD design of the burner cap. A detailed cross-sectional view of the burner cap is shown in Figure 3, highlighting the internal geometry responsible for inducing swirl and promoting improved air-fuel mixing within the combustion zone. This configuration allows stable flame formation while maintaining compatibility with standard domestic geyser burner assemblies.

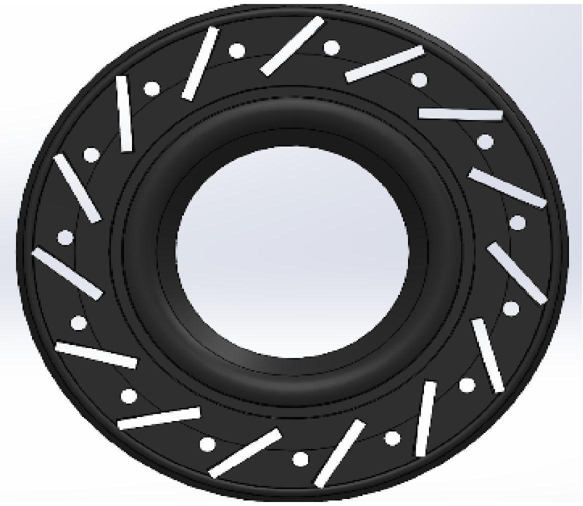

Figure 2. CAD Design of Burner Cap

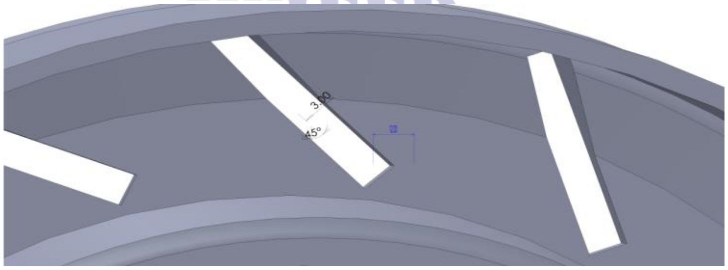

Figure 3. Burner cap cross-sectional view

### 2.3 Fabrication of Burner Cap

The swirl burner cap was manufactured using a sand-casting process with gray cast iron, selected for its high thermal stability, durability, and suitability for high-temperature combustion applications. Initially, a cast iron mold was prepared based on the finalized CAD design, and molten metal was poured into the sand mold to form the basic burner cap geometry. After solidification and cooling, the cast component was subjected to CNC machining to achieve accurate dimensions, uniform thickness, and precise formation of the swirl slots and holes. This post-casting machining ensured consistency and repeatability across the fabricated component. **Figure 4** shows the existing swirl burner cap without holes, while **Figure 5** presents the newly fabricated burner cap with holes used in the experimental study, highlighting the geometric modifications introduced to enhance air–fuel mixing and combustion performance.

Figure 4. Existing Swirl burner Cap without holes

Figure 5. Newly fabricated burner cap with holes

### 2.4 Experimental Setup

The experimental study was conducted using a domestic gas geyser test rig, modified to allow the installation of the fabricated swirl burner cap. The setup included precise instrumentation to monitor water temperature, gas flow, and combustion parameters. A flue gas analyzer, shown in Figure 7, was used to measure $O_2$, $CO_2$, CO, and other combustion gases in real time. Figure 6 provides an overview of the water tank geyser and the overall experimental methodology, ensuring controlled and reproducible testing conditions for all burner cap configurations.

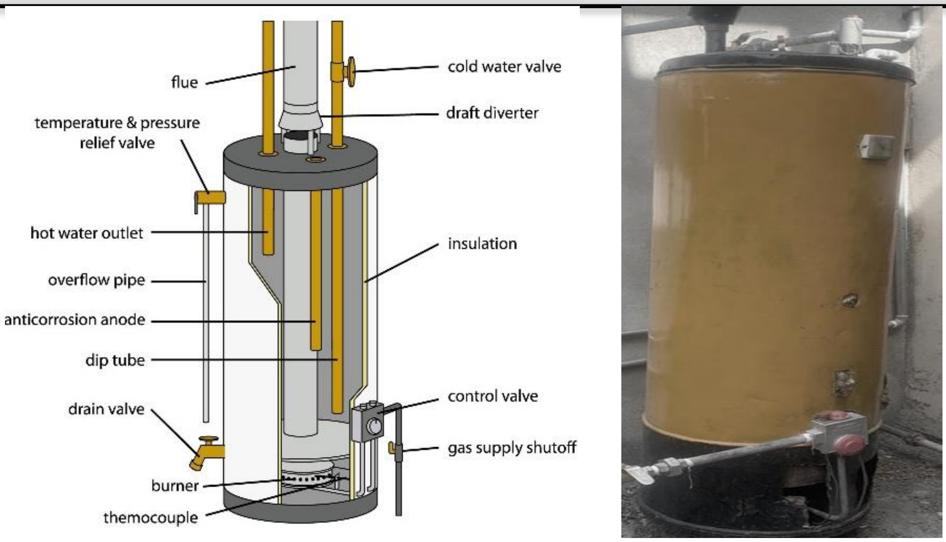

Figure 6. Water Tank Geyser

Figure 7. Flue gas analyzer

### 2.5 Measurement Parameters

The study measured flue gas concentrations ($O_2$, $CO_2$, CO, NO, $NO_2$, HC) and temperature parameters, including inlet ($T_i$), outlet ($T_f$), and temperature rise ($\Delta T$), along with ambient and stack temperatures. Temperature measurements were recorded using a K-type thermocouple, as shown in Figure 8.

Figure 8. K-type thermocouple

### 2.6 Combustion Efficiency Calculation

Combustion efficiency was evaluated using Eq. (1) for flue loss and Eq. (2) for efficiency, applying fuel-specific constants for accurate performance assessment.

$$q_A = (Ts - Ta) \times \left(\frac{A2}{(21-O2)} + B\right) \qquad (1)$$

$$Efficiency = 100 - q_A \qquad (2)$$

- $q_A$: flue loss
- Ts: flue gas temperature
- Ta: supply air temperature
- $O_2$: measured volumetric oxygen concentration (%)
- $A_2$ and B: fuel-dependent constants (values based on fuel composition, see Table 1)

Table 2. values of A2 and B

| **Fuel type** | **A2** | **B** |
|---|---|---|
| Natural Gas | 0.66 | 0.009 |
| Fuel Oil | 0.68 | 0.007 |
| Town Gas | 0.63 | 0.011 |
| Cooking oven gas | 0.60 | 0.011 |
| LPG | 0.63 | 0.008 |

## 3. Results

### 3.1 Combustion Characteristics of 45° Swirl Burner

The combustion characteristics of the 45° swirl burner were evaluated by analyzing the flue gas composition, stack temperature, and excess air ratio. For the existing swirl burner cap without holes, as presented in Table 2, the measured $O_2$ concentration was 8.40%, CO at 0.0051%, $CO_2$ at 6.82%, NO at 0.0042%, $NO_2$ at 0.00031%, and HC at 0.035%. The stack temperature (Ts) was recorded at 540.7°C, and the ambient temperature (Ta) was 26°C. Using the flue gas analysis, the calculated combustion efficiency was 68.41%. These results indicate moderate combustion with incomplete air–fuel mixing, typical of a conventional swirl cap without modifications.

**Table 3. Combustion Efficiency for Existing Swirl type burner without Holes**

| | | | |
|---|---|---|---|
| O2 | 8.40% | Γ | 13.696 |
| CO | 0.0051% | ɀ | 22.071 |
| NO | 0.0042% | ø | 82.985 |
| NO2 | 0.00031% | Mf | 109.71g |
| CO2 | 6.82% | Ma | 3029.907g |
| HC | 0.035% | FAR | 0.03621 |
| TS | 540.7°C | $q_A$ | 31.59 |
| Ta | 26°C | Efficiency | 68.41% |
| ɒ | 6.8569 | | |

In contrast, the newly fabricated burner cap with holes showed significant improvements, as summarized in Table 3. The average $O_2$ concentration increased to 11.80 ± 0.12%, while $CO_2$ decreased to 4.47 ± 0.40%, reflecting enhanced combustion completeness. CO levels averaged 45 ± 2.52 ppm, and the measured stack temperatures $(T_f)$ ranged around 276.1°C. The excess air ratio increased to 133%, demonstrating better air-fuel interaction. The flue gas measurements confirm that introducing holes into the swirl cap enhanced the mixing of gas and air, improved flame stability, and promoted more uniform heat distribution within the burner.

**Table 4. Data of the newly fabricated Cap with holes**

| Reading | $O_2$ (%) | $CO_2$ (%) | CO (ppm) | Loss (%) | Efficiency (%) | XAir (%) | Ra | Tf (°C) | Ti (°C) | ΔT (°C) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 11.72 | 4.9 | 43 | 19.45 | 81.9 | 136 | 0.000878 | 279.5 | 35.9 | 243.6 |
| 2 | 11.92 | 4.1 | 48 | 18.89 | 82.2 | 127 | 0.001171 | 269.4 | 35.6 | 233.8 |
| 3 | 11.71 | 4.4 | 45 | 19.46 | 82 | 136 | 0.001023 | 279.3 | 35.8 | 243.5 |
| Average ± SD | 11.80 ± 0.12 | 4.47 ± 0.40 | 45 ± 2.52 | 19.27 ± 0.32 | 82.03 ± 0.15 | 133 | 0.001024 | 276.1 | 35.8 | 240.3 |

### 3.2 Combustion Efficiency

The combustion efficiency, calculated using the flue gas method (Eq. 1 and Eq. 2), further highlights the performance difference between the two designs. The existing burner cap without holes achieved 68.41% efficiency, whereas the newly fabricated cap with holes reached an average efficiency of 82.03 ± 0.15%. This improvement of nearly 14% is

attributed to reduced flue gas losses, more complete oxidation of the fuel, and enhanced thermal transfer due to the swirl effect induced by the cap holes. The data also show that consistent performance was achieved across multiple trials, with low standard deviation, indicating high repeatability and reliability of the experimental setup.

Overall, the results clearly demonstrate that the 45° swirl burner cap with holes significantly improves combustion performance by increasing efficiency, optimizing flue gas composition, and ensuring better thermal management compared to the conventional design.

## 4. Conclusions

This study experimentally evaluated the performance of a newly designed perforated 45° swirl-type burner cap in comparison with a conventional swirl burner cap for domestic gas geysers. The investigation confirms that geometric modification through hole-assisted swirl generation significantly enhances combustion characteristics and overall system performance. The conventional burner cap exhibited a combustion efficiency of 68.41%, with flue gas parameters of 8.40% $O_2$, 6.82% $CO_2$, and 0.0051% CO, and a high stack temperature of 540.7 °C, indicating substantial heat loss. In contrast, the modified burner cap achieved a markedly higher average combustion efficiency of 82.03 ± 0.15%, representing an improvement of approximately 14%. The optimized design resulted in an increased $O_2$ concentration of 11.80 ± 0.12%, reduced $CO_2$ concentration of 4.47 ± 0.40%, and low CO emissions of 0.0045%. Additionally, the stack temperature decreased significantly to 276.1 °C, confirming reduced flue gas losses and improved thermal utilization.

The enhanced performance is attributed to improved air-fuel mixing and intensified turbulence generated by the perforated swirl configuration, which promotes more complete combustion and stable flame formation. The low standard deviation across repeated trials demonstrates excellent repeatability and reliability of the experimental framework. Overall, the proposed burner cap offers a simple, low-cost, and manufacturable solution for improving energy efficiency and emission performance in domestic gas geysers. The findings highlight the strong potential of swirl geometry optimization as an effective strategy for developing energy-efficient household heating systems and reducing environmental impact.

## REFERENCES

[1] Mądziel M. Investigating Real-world Emissions from Liquefied Petroleum Gas-fueled Vehicles: A Modeling Approach that Utilizes Portable Emissions Measurement Systems. The Open Transportation Journal 2025;19. https://doi.org/10.2174/0126671212367963241223053201.

[2] Unfccc. ADOPTION OF THE PARIS AGREEMENT - Paris Agreement text English n.d.

[3] Borelli D, Devia F, Schenone C, Silenzi F, Sollai F, Tagliafico LA. Assessing environmental benefits of the transition from standard fossil fuels to liquefied natural gas: The Sardinia Region case study. Energy for Sustainable Development 2023;73:205–17. https://doi.org/10.1016/J.ESD.2023.01.008.

[4] Haque MA, Nemitallah MA, Abdelhafez A, Mansir IB, Habib MA. Review of Fuel/Oxidizer-Flexible Combustion in Gas Turbines. Energy & Fuels 2020;34:10459–85. https://doi.org/10.1021/ACS.ENERGYFUELS.0C02097.

[5] Tayyeban E, Deymi-Dashtebayaz M, Gholizadeh M. Investigation of a new heat recovery system for simultaneously producing power, cooling, and distillate water. Energy 2021;229:120775. https://doi.org/10.1016/J.ENERGY.2021.120775.

[6] Rezapour M, Gholizadeh M. Analysis of methanol thermochemical reactor with volumetric solar heat flux based on Parabolic Trough Concentrator. Renew Energy 2021;180:1088–100. https://doi.org/10.1016/J.RENENE.2021.09.015.

[7] Energy Agency I. Gas Market Report, Q1-2025. 2025.

[8] Ye Z-H, Li Y-K, Yan Q. Global Natural Gas Consumption History and Energy Consumption Pattern. ESSE 2017 2017:241–6. https://doi.org/10.1515/9783110540048-025/PDF.

[9] 14_energy n.d.

[10] Elbaz AM, Moneib HA, Shebil KM, Roberts WL. Low NOX - LPG staged combustion double swirl flames. Renew Energy 2019;138:303–15. https://doi.org/10.1016/J.RENENE.2019.01.070.

[11] Abdelhameed E, Tashima H. An investigation on the behavior of the torch flame in the LBGE combustion process. International Exchange and Innovation Conference on Engineering and Sciences 2022:207–14. https://doi.org/10.5109/5909093.

[12] Khudhair R, Jung Y. Environmental and Economical Evaluation of Liquified Natural Gas Vehicles Promotion Program in The City of Baghdad. International Exchange and Innovation Conference on Engineering and Sciences 2022:31–7. https://doi.org/10.5109/5909059.

[13] Wang X, Zheng L, Wang J, Pan R, Shi Z, Zhang J, et al. Experimental study on the oxygen-enriched biogas explosion characteristics by co-firing propane in a duct. Process Safety and Environmental Protection 2022;166:133–42. https://doi.org/10.1016/J.PSEP.2022.08.009.

[14] Zhao Z, Liang Y, Zhong X, Song S, Guo B, Liu Z. Study on the effect of duct length and hydrogen on explosion characteristics of LPG/H2 blended clean fuel. Fuel 2024;365:131209. https://doi.org/10.1016/J.FUEL.2024.131209.

[15] Hasan KS, Al-fahham M, Al-wahid WAA, Khwayyir HH, Kareem AR, Hasan SS, et al. Experimental study on the combustion of gaseous based fuel (LPG) in a tangential swirl burner of a steam boiler. Journal of Thermal Engineering 2024;10:1226–40. https://doi.org/10.14744/thermal.0000863.

[16] Shehata M, Gad HM, Alshete MY, Shamso E, Ibrahim IA. Effect of confinement ratio on LPG diffusion flame characteristics. Fuel 2025;391:134809. https://doi.org/10.1016/J.FUEL.2025.134809.

[17] Elbe G von, Grumer J. Air Entrainment in Gas Burners. Ind Eng Chem 2002;40:1123–9. https://doi.org/10.1021/IE50462A027.

[18] Reddy VM, Mohapatra S, Alsulami R, Karmakar S, Dash SK. Experimental and Computational Investigation upon Combustion Characteristics of Liquid Fuel in a Novel Combustor with Hybrid Swirl and Recirculation Bowl. ACS Omega 2022;8:1523–33. https://doi.org/10.1021/ACSOMEGA.2C07028.

[19] Gupta AK. Effect of swirl and flow distribution on the spray flame characteristics. Proceedings of the Intersociety Energy Conversion Engineering Conference 2000;2:1300–5. https://doi.org/10.1109/IECEC.2000.870944.

[20] Zhang F, Heidarifatasmi H, Harth S, Zirwes T, Wang R, Fedoryk M, et al. Numerical evaluation of a novel double-concentric swirl burner for sulfur combustion. Renewable and Sustainable Energy Reviews 2020;133:110257. https://doi.org/10.1016/J.RSER.2020.110257.

[21] Adam AA, Abdulnaim AM, El-Kholy AE, Shahein MA, Moneib HA. Non-Premixed Cofiring of Two Fuel phases: Performance and Emissions Study for a New Air Staged Burner. International Exchange and Innovation Conference on Engineering and Sciences 2024;10:725–30. https://doi.org/10.5109/7323341.

[22] Jensen WB. The Origin of the Bunsen Burner. J Chem Educ 2005;82:518. https://doi.org/10.1021/ED082P518.

[23] Gao W, Hu Y, Yan R, Yan W, Yang M, Miao Q, et al. Comprehensive Review on Thermal Performance Enhancement of Domestic Gas Stoves. ACS Omega 2023;8:26663–84. https://doi.org/10.1021/ACSOMEGA.3C01628/ASSET/IMAGES/LARGE/AO3C01628_0022.JPEG.

[24] Arora P, Das P, Jain S, Kishore VVN. A laboratory based comparative study of Indian biomass cookstove testing protocol and Water Boiling Test. Energy for Sustainable Development 2014;21:81–8. https://doi.org/10.1016/J.ESD.2014.06.001.

[25] Jugjai S, Rungsimuntuchart N. High efficiency heat-recirculating domestic gas burners. Exp Therm Fluid Sci 2002;26:581–92. https://doi.org/10.1016/S0894-1777(02)00164-4.

[26] Das M, Ganguly R, Datta A, Verma MM, Bera AK. Performance improvement of a domestic liquefied petroleum gas cook stove using an extended spill-tray and an annular metal insert. J Therm Sci Eng Appl 2021;13. https://doi.org/10.1115/1.4047525/1084538.

[27] Wae-hayee M, Yeranee K, Suksuwan W, Nuntadusit C. Effect of burner-to-plate distance on heat transfer rate in a domestic stove using LPG. Case Studies in Thermal Engineering 2021;28:101418. https://doi.org/10.1016/J.CSITE.2021.101418.

[28] Surange JR, Patil NK, Rajput A. Performance Analysis of Burners used in LPGCooking Stove-A Review. Int J Innov Res Sci Eng Technol 2014.

[29] Wu CY, Chen KH, Yang SY. Experimental study of porous metal burners for domestic stove applications. Energy Convers Manag 2014;77:380–8. https://doi.org/10.1016/J.ENCONMAN.2013.10.002.

[30] Petro LM, Machunda R, Tumbo S, Kivevele T. Theoretical and Experimental Performance Analysis of a Novel Domestic Biogas Burner. Journal of Energy 2020;2020:8813254. https://doi.org/10.1155/2020/8813254.

[31] Wang J, Zhang W, Yang T, Yu Y, Liu C, Li B. Numerical and experimental investigation on heat transfer enhancement by adding fins on the pot in a domestic gas stove. Energy 2022;239:122439. https://doi.org/10.1016/J.ENERGY.2021.122439.

[32] Said F, Khan A, Khan Z, Sheraz M, Abbasi MZ, Tareen WUK, et al. Experimental evaluation of burner cap design on energy efficiency in residential gas geysers. Results in Engineering 2025;28:108166. https://doi.org/10.1016/J.RINENG.2025.108166.

[33] Zhen HS, Leung CW, Wong TT. Improvement of domestic cooking flames by utilizing swirling flows. Fuel 2014;119:153–6. https://doi.org/10.1016/J.FUEL.2013.11.025.

[34] Kotb A, Saad H. Case study for co and counter swirling domestic burners. Case Studies in Thermal Engineering 2018;11:98–104. https://doi.org/10.1016/J.CSITE.2018.01.004.

[35] Kotb A, Saad H. Case study for co and counter swirling domestic burners. Case Studies in Thermal Engineering 2018;11:98–104. https://doi.org/10.1016/J.CSITE.2018.01.004.

[36] Chen Z, Zhang Y, Qin C, Duan P. Combustion performance of domestic gas cookers with swirling strip-port and normal round-port on various natural gas compositions. Case Studies in Thermal Engineering 2019;13:100366. https://doi.org/10.1016/J.CSITE.2018.100366.

[37] Zhen HS, Leung CW, Wong TT. Improvement of domestic cooking flames by utilizing swirling flows. Fuel 2014;119:153–6. https://doi.org/10.1016/J.FUEL.2013.11.025.

[38] Özdemir B. Simulation of turbulent combustion in a self-aerated domestic gas oven. Appl Therm Eng 2017;113:160–9. https://doi.org/10.1016/J.APPLTHERMALENG.2016.10.205.

[39] Özdemir IB, Kantaş M. Investigation of partially-premixed combustion in a household cooker-top burner. Fuel Processing Technology 2016;151:107–16. https://doi.org/10.1016/J.FUPROC.2016.04.039.

[40] Hou SS, Chou CH. Parametric Study of High-Efficiency and Low-Emission Gas Burners. Advances in Materials Science and Engineering 2013;2013:154957. https://doi.org/10.1155/2013/154957.

[41] Özdemir IB. Use of Computational Combustion in the Development and Design of Energy-Efficient Household Cooker-Top Burners. Journal of Energy Resources Technology, Transactions of the ASME 2017;139. https://doi.org/10.1115/1.4035256/373399.

[42] Soliman KM, Mater EO, Moneib HA, Abdulnaim AM. Optimization of thermal and combustion performance for diesel-LPG cofiring in a novel double swirl burner. Fuel 2026;404:136258. https://doi.org/10.1016/J.FUEL.2025.136258.

[43] Said F, Khan A, Khan Z. ENHANCING THERMAL AND COMBUSTION PERFORMANCE OF GAS WATER TANK GEYSER THROUGH BAFFLE INTEGRATION. Spectrum of Engineering Sciences 2025;3:214–29. https://doi.org/10.5281/zenodo.15037922.

[44] Wichangarm M, Matthujak A, Sriveerakul T, Sucharitpwatskul S, Phongthanapanich S. Investigation on thermal efficiency of LPG cooking burner using computational fluid dynamics. Energy 2020;203:117849. https://doi.org/10.1016/J.ENERGY.2020.117849.

[45] Bidi M, Avval MS, Seminar MHN-E, 2007 undefined. A two-dimensional numerical study of combustion in porous media. ResearchgateNetM Bidi, M Saffar Avval, M Heyrani NobariEurotherm Seminar, 2007•researchgateNet n.d.

[46] Bibrzycki J, Poinsot T. Investigation of Laminar Flame Speed of CH4/N2/O2 and CH4/CO2/O2 Mixtures Using Reduced Chemical Kinetic Mechanisms 2010.

[47] Ahmadi AA, Rahbari A, Mohamadi M. Energy efficiency improvement and emission reduction potential of domestic gas burners through re-orientating the angle and position of burner holes: Experimental and numerical study. Thermal Science and Engineering Progress 2022;32:101232. https://doi.org/10.1016/J.TSEP.2022.101232.

[48] Zhao Y, McDonell V, Samuelsen S. Influence of hydrogen addition to pipeline natural gas on the combustion performance of a cooktop burner. Int J Hydrogen Energy 2019;44:12239–53. https://doi.org/10.1016/J.IJHYDENE.2019.03.100.

[49] Usman M, Ammar M, Ali M, Zafar M, Zeeshan M. Emissions and efficiency of an improved conventional liquefied petroleum gas cookstoves in Pakistan. Environ Dev Sustain 2023;25:5427–42. https://doi.org/10.1007/S10668-022-02273-Y/TABLES/1.

[50] Kotb A, Saad H. Case study for co and counter swirling domestic burners. Case Studies in Thermal Engineering 2018;11:98–104. https://doi.org/10.1016/J.CSITE.2018.01.004.