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Review

Comprehensive Review on Thermal Performance Enhancement of Domestic Gas Stoves

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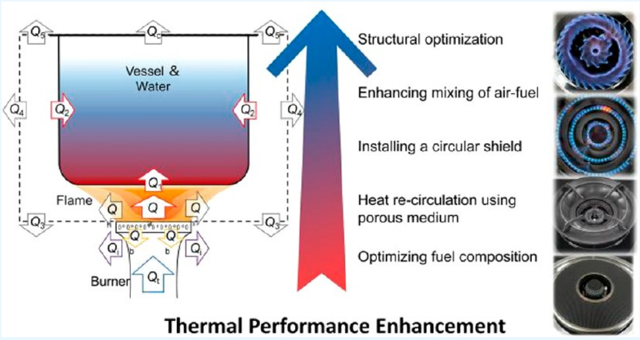
ABSTRACT: Cooking is a daily activity in every household, which consumes energy and produces pollution. Using clean gas fuels instead of traditional solid fuels will significantly reduce household air pollution. Although the use of clean-burning burners can reduce emissions, early domestic gas cookers had poor thermal performance. Currently, even small improvements in efficiency can result in significant energy savings due to the large number of domestic gas stoves in use. There has been a long history of research into the development of domestic gas stoves to improve performance and reduce energy consumption. Meanwhile, research into the use of hydrogen-enriched natural gas as a promising environmentally friendly fuel is increasing. In this paper, we perform a descriptive statistics and graphical visualization of network analysis by combining common databases with Bibliometrix. We also analyze the energy balance of domestic gas stoves and the influence of a single factor and multiple factors on stove performance. Then we provide a detailed overview of some research technologies in enhancing the thermal performance of gas stoves. We also discuss the research progress and application prospects for the use of hydrogen-enriched natural gas as a fuel in domestic gas stoves and identify areas for future research and issues that need attention.



1. INTRODUCTION

Cooking is an energy-consuming activity that almost every family does every day. More than 3 billion people in the world still rely primarily on solid fuels and poor-quality stoves for cooking.[1] If these solid fuels do not burn completely, pollutants such as SO_2, CO, NO_X, $PM_{2.5}$, and PM_{10} will be produced, which can lead to indoor air pollution and have adverse effects on human health.[2] Due to the disadvantages of solid fuels, cleaner fuels are used as an alternative to solid fuels for cooking. This helps to improve indoor air quality, public health, and energy consumption.[3−5] Domestic gas stoves are widely used as universal gas appliances because of their attractive appearance and ease of use.[6,7] They operate at low pressure and use natural gas (NG) or liquefied petroleum gas (LPG) as fuel for premixed combustion.[8] Thus, a small improvement in the thermal performance of the stove can also result in huge energy savings due to the large number of domestic gas stoves in use.[6,9−11] Consequently, it is significant to study how to raise the thermal performance of gas stoves for energy savings.

There has been much research into technology to enhance the thermal performance of gas stoves.[12−14] To achieve these goals, it is important to understand the fuel properties, structural design, and operating conditions of gas stoves.[15] The thermal performance of gas stoves is mainly influenced by combustion efficiency of the burner and heat transfer performance between the burner and the vessel.[16] The principle of the current thermal performance enhancement technology for domestic gas stoves is based on these two methods, such as improving structural optimization,[17,18] applying the swirl flow,[19] enhancing mixing of air−fuel,[16,20] reducing heat loss,[21] heat recirculation using porous medium,[22] optimizing fuel composition,[23] etc.

The structural optimization of stoves mainly includes the optimization of the burner, as well as the optimization of the nozzle and the ejector. With regard to the structural optimization of the burner, some researchers are currently studying the effect of the burner-port number and angle, burner-head size, and heating height on the combustion performance.[24−26] These optimizations will affect the mixing of flames and secondary air, as well as the combustion flow field.[27] In addition, the thermal performance of the burner can be maximized by optimizing the impingement flame. Some studies

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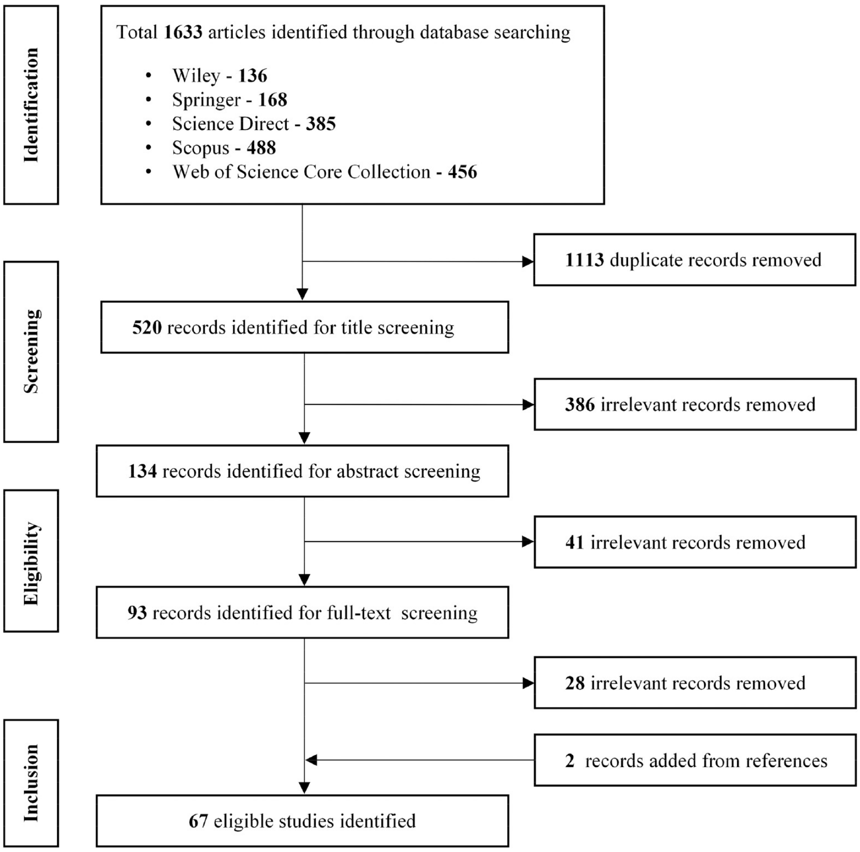


Figure 1. Flowchart of the systematic literature search procedure.

have shown that higher vortex angles result in higher tangential velocities and also allow more ambient air to be entrained into the burning jet, resulting in improved flame propagation.[28−30] As the combustion process is also influenced by the mixing effects of air and fuel, most studies are conducted through numerical simulations, which investigate jet characteristics to obtain a significant amount of entrained mass.[31,32] The shape and diameter of the nozzle, the nozzle position, and the ejector geometry are considered to be the main factors affecting the mixing effects of fuel and primary air.[33] In addition, the stove's thermal performance can also be effectively enhanced by installing a circular shield to reduce heat loss or by using a porous media burner (PMB) to achieve heat recirculation.[34] Most studies focus on the influence of the position and shape of the shield on the flue gas and the thermal efficiency of the burner.[21,35,36] This is because heat transfer can be enhanced by efficiently circulating the burned gases around the vessel and prolonging the heating time of the burned gases. Many studies have demonstrated porous radiant burners can effectively improve combustion performance and emissions. Due to the excess enthalpy in porous media, the thermal efficiency of porous radiation burners can reach 75%, compared to other traditional burners.[37] Many scholars have recently studied the influence of hydrogen-enriched natural gas (HENG) on the performance of domestic gas stoves, including flashback limits, flame characteristics, thermal efficiency, and emissions. Numerous studies have shown that current conventional domestic gas stoves are perfectly suited to 25% hydrogen addition without any modifications to the equipment infrastructure.[44] In addition, the use of HENG can effectively reduce CO emissions and even have a beneficial effect on thermal efficiency.[44−46]

However, there are no papers that provide a comprehensive summary and analysis of these techniques. In particular, a comprehensive review of recent studies on the influence of HENG on domestic gas stoves has not been available. In this paper, we have endeavored to summarize the technical work concerning the direction of efficiency improvement of domestic gas stoves. Descriptive statistics and graphical visualization of the network analysis are performed by combining popular databases with Bibliometrix. The energy balance of the domestic gas stove in use is described theoretically, and the influence of a single factor and multiple factors on stove performance is reported. Then we provide a detailed overview of some research technologies for enhancing the thermal performance of domestic gas stoves. We also discuss the research progress and application prospects of HENG on gas stoves and identify areas for future research and issues that need attention.

2. METHODOLOGY AND RESULTS

2.1. Methodology. A typical research methodology for systematic reviews is used in this paper, which was proposed by Tranfield et al.[47] and which follows a rigorous, replicable method that minimizes bias compared to traditional narrative reviews. This study searched for relevant articles published between January 2012 and May 2023 in common databases, including Web of Science (Core Collection), Scopus, Wiley, Springer, and Science Direct. To retrieve the documents and to include all studies in the field of thermal performance of domestic gas stoves, the following search string was constructed and entered into the above databases: (stove) OR (cooker) OR (cooktop)

Table 1. Trend of Advances in Thermal Performance Enhancement for Domestic Gas Stoves

year	authors	fuel	study focus	method
2012	Yang et al.[32]	CH_4	the effect of different nozzle structures on ejector performance	numerical
2013	Muthukumar and Shyamkumar[37]	LPG	a comparison of the performance differences between a novel porous radiant burner and a conventional burner	experimental
2013	Zhang et al.[50]	NG	effect of changes in natural gas composition on the stove's performance	experimental
2014	Zhen et al.[28]	LPG	developed and compared the performance of two different swirling burners	experimental
2014	Chen et al.[51]	PNG/LNG	flame stability of partially premixed combustion for PNG/LNG interchangeability	experimental
2014	Wu et al.[52]	CH_4	research on porous metal burners for domestic gas stoves	experimental
2014	Grima-Olmedo et al.[53]	biogas	comparison of the stove's thermal performance using landfill and digester biogas	experimental
2014	Boggavarapu et al.[21]	LPG/NG	improving the stove's thermal performance by installing a circular insert and a radiant sheet	experimental and numerical
2015	Mishra et al.[40]	LPG	performance of a double-layer PMB in the LPG cooker	experimental
2015	Keramiotis et al.[41]	NG	performance of a PMB using natural gas	experimental
2015	Iral and Amell[54]	NG	performance study of a domestic porous radiant burner at high altitude	experimental
2016	Zhang et al.[55]	NG	effect of variations in the natural gas component on the primary air coefficient for domestic gas stoves	experimental and analytical
2016	Özdemir and Kantaş[56]	CH_4	effect of operating conditions and design characteristics of a stove on the combustion performance	experimental and numerical
2016	Laphirattanakul et al.[39]	LPG	effect of porosity geometry on the stability of porous radiant burners	general
2016	Panigrahy et al.[57]	LPG	combustion performance of a domestic LPG cooker with PMB	experimental and numerical
2016	Fumey et al.[58]	H_2	development of a novel gas stove based on catalytic hydrogen combustion	experimental
2016	Zhen et al.[59]	CH_4/H_2	effect of air preheating on the visual, thermal, and emission characteristics of HENG	experimental and theoretical
2017	Laphirattanakul et al.[33]	LPG	effect of a central cone-shaped bluff-body on the combustion performance of a domestic gas burner	numerical
2018	Mishra and Muthukumar[60]	LPG	development of a self-aspirating LPG cooking stove with a two-layer porous radiant burner	experimental
2017	De Vries et al.[61]	HENG	interchangeability analysis for domestic appliances using HENG fuels	theoretical and analytical
2017	Zhou et al.[62]	NG	combustion performance of a domestic gas stove at different altitudes	experimental
2017	Silva et al.[63]	LPG	performance improvements in burners for small aspect ratio changes	experimental
2017	Özdemir[64]	CH_4	development and design of energy-efficient household burners	numerical
2017	Kuntikana and Prabhu[65]	LPG	jet characteristics of the methane−air premixed flame of a multiport burner	experimental
2018	Lin et al.[66]	NG	gas interchangeability of domestic fully premixed burners	experimental and theoretical
2018	Kotb and Saad[30]	LPG	combustion performance of co- and counterswirling burners	experimental
2018	Jones et al.[67]	HENG	theoretical analysis of flashback and blow-off for gas appliances with HENG	theoretical and analytical
2018	Chen et al.[68]	NG	lifted flame property and interchangeability of NG on partially premixed gas burners	experimental and theoretical
2018	Pradhan et al.[69]	LPG	performance analysis of a novel domestic porous radiant burner	experimental
2019	Kuntikana and Prabhu[70]	LPG	research on self-aspirating type radial flow burners with induced swirl	experimental and analytical
2019	Duan et al.[14]	NG	influence of natural gas constituents on emission of a gas stove	experimental
2019	Zhao et al.[71]	HENG	effect of HENG on the combustion performance of a domestic gas stove	experimental
2019	Zhong et al.[72]	LPG	study of the heating characteristics of a domestic gas stove using the infrared thermography methodology	experimental and theoretical
2019	Chen et al.[23]	NG	combustion performance of a domestic gas stove on various natural gas compositions	experimental
2020	Das et al.[25]	LPG	burning characteristics and overall performance of a gas cook stove burner at different parametric conditions	numerical
2020	Dey et al.[31]	LPG	design optimization of the ejector of a gas burner	numerical
2020	Yangaz et al.[73]	HENG	combustion performance of a premixed burner using HENG fuels	experimental
2020	Wichangarm et al.[35]	LPG	proposal of a new method for predicting the thermal efficiency of domestic LPG stoves	experimental and numerical
2020	Bakry et al.[74]	LPG	start-up performance of the double-layer media burners	experimental
2020	Altunin[75]	NG	improving the combustion performance of a domestic gas stove by installing a novel heat transfer enhancer	experimental
2020	Sutar et al.[76]	LPG	effect of pot design on the energy efficiency of domestic gas stoves	experimental
2021	Das et al.[36]	LPG	improve heat transfer of a gas stove by installing a spill tray or an annular insert	numerical
2021	Wae-hayee et al.[77]	LPG	effect of heating height on the heat transfer performance of domestic gas stoves	experimental
2021	Matthujak et al.[29]	LPG	improved thermal efficiency of domestic LPG stoves using swirling flames	numerical
2021	Deb et al.[38]	LPG	investigation on the applicability of a clustered porous radiant burner in small- and medium-scale applications	general
2021	Rojas et al.[78]	NG	improving the performance of domestic gas burners with structural design	experimental and analytical

Table 1. continued

year	authors	fuel	study focus	method
2021	Teotia et al.[79]	LPG	effect of porosity and heating height on combustion performance of a domestic LPG stove	experimental and analytical
2021	Laguillo et al.[80]	NG	CO emissions and temperature analysis during partial premixed methane flame combustion	experimental and numerical
2022	Leicher et al.[81]	CH_4	impact of HENG on domestic gas stoves	theoretical
2022	Ahmadi et al.[24]	NG	effect of burner head design on thermal efficiency and emissions of domestic gas stoves	experimental and numerical
2022	Deymi-Dashtebayaz et al.[82]	NG	effect of swirling at the outlet port on the combustion performance of the burner	numerical
2022	Soltanian et al.[42]	NG	assessing total thermal performance of PMB in domestic application	experimental and analytical
2022	Xie et al.[83]	HENG	impact of HENG on the flame stability of the burner	experimental and theoretical
2022	Sun et al.[84]	HENG	effect of HENG on the domestic stove performance	experimental and analytical
2022	Glanville et al.[44]	HENG	impact of HENG on NO_X emission and operational performance of a partially premixed burner	experimental
2022	Yitong et al.[85]	NG	CO emission projections for partially premixed gas stoves	experimental and analytical
2022	Hou et al.[86]	HENG	effect of hydrogen addition on the extinction dynamics of partially premixed methane air flames	numerical
2022	Wang et al.[6]	LPG	improved heat transfer by adding fins to the pan of a gas stove	experimental and numerical
2022	Yang et al.[87]	HENG	flame extinction of HENG premixed flames	experimental and theoretical
2022	Dinesh et al.[88]	NG	impingement heating characteristics of domestic gas burner flames under various operating parameters	experimental
2022	Du et al.[89]	HENG	combustion performance of swirl burners using HENG	experimental and numerical
2022	Devi et al.[90]	Biogas	influence of PM materials on the combustion performance of the PMB with biogas fuel	experimental
2023	Fang et al.[46]	HENG	combustion performance of three typical burners using HENG	experimental
2023	Usman et al.[91]	LPG	emissions and efficiency of improved LPG cook stoves	experimental
2023	Deymi-Dashtebayaz et al.[92]	NG	effect of parameters on the stove's performance	experimental and numerical
2023	Ozturk et al.[93]	HENG	the impact of using HENG on emissions and combustion performance	experimental
2023	Liu et al.[45]	HENG	investigation on the combustion characterization of HENG in domestic swirl stoves	experimental and numerical

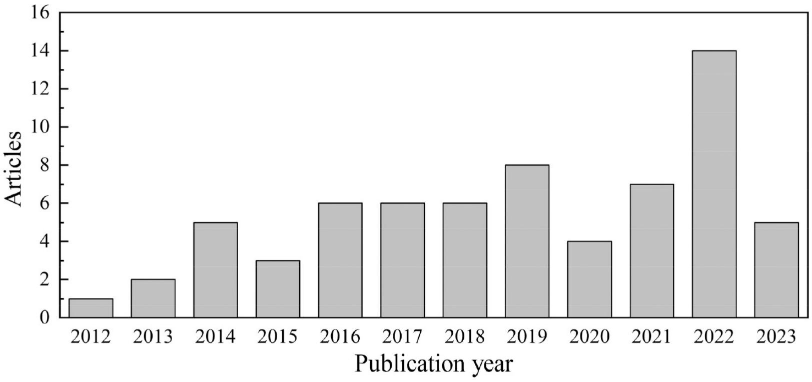


Figure 2. Annual articles publication from 2012 to 2023.

OR (burner) AND (domestic) AND (gas) NOT (biomass) NOT (electric) NOT (induction) NOT (solar). The keywords "cooker" and "cooktop" have been considered synonymous with the term "stove". Add the keywords "biomass", "solar", and "electric" to exclude some irrelevant literature, such as research on biomass stoves, solar cookers, induction cookers, and electric ranges. For the Web of Science, search terms were completed using the "Topic" option in the advanced search. For all other databases, the search terms were completed using the "Abstract" option.

All articles generated from the initial search were saved to Zotero, and then duplicates were removed. Next, the articles were further filtered by checking their titles and abstracts, and some irrelevant articles were removed. Then, the articles were identified for full text review. Finally, the reference lists and citations of the selected articles were checked to increase the accuracy of identifying relevant articles that were not visible in the database search.

Finally, the data obtained were used to perform descriptive analysis and thematic analysis in Bibliometrix.[48] For the descriptive analysis, the data were analyzed using descriptive statistics according to selected categories (e.g., journals covered, time frame, and geographical distribution). The thematic analysis focused on the main themes from the literature. The keyword analysis is used to draw an interconnected framework structure that reflects the interrelationships between different articles obtained. This allows for a quantitative analysis of the focus areas of the publications based on the keywords used.[49]

2.2. Results. Figure 1 describes the process for selecting articles. A total of 1633 articles were initially identified. 1113 duplicate articles were removed, and 520 articles were saved in Zotero. The titles and abstracts of all 520 articles were analyzed, and 427 articles were excluded because the research objectives did not match. This was followed by a thorough in-depth analysis of the full text of the identified 93 articles. Of these, 28 articles were removed because they did not meet the inclusion: conference papers, reviews, abstracts only, and irrelevant topics. After a manual search of the reference lists and citations of the identified articles, two additional articles were identified. Thus, 67 articles were included in our study, as presented in Table 1.

Figure 2 shows the annual scientific production from January 2012 to May 2023. The results show an overall upward trend in research on the thermal performance of gas stoves from 2012 to 2022, and the highest number of research studies was conducted in 2022 with 14. Currently (as of 1 May), there are five relevant articles published in 2023, so we predict that there will still be a high level of research interest this year. The main reason for this is that with the advancement of zero carbon plans around the world, there is now more and more research into HENG fuels and many countries have started HENG fuel projects.[94−96]

The journal, study regions, and fuels used in the gas stoves obtained from selected articles are presented in Table 2.

Table 2. Characteristics of the Selected Articles

characteristic	no. (%) of studies
journal (top 5)	
Energy	9 (13.4%)
Case Studies in Thermal Engineering	8 (11.9%)
Fuel	7 (10.4%)
Applied Thermal Engineering	6 (9.0%)
International Journal of Hydrogen Energy	4 (6.0%)
study region (top 5)	
China	23 (34.3%)
India	16 (23.9%)
Thailand	5 (7.5%)
Turkey	4 (6.0%)
Iran	4 (6.0%)
fuels used (top 5)	
LPG	24 (35.8%)
NG	19 (28.4%)
HENG	13 (19.4%)
CH_4	6 (9.0%)
biogas	2 (3.0%)

Currently, the "impact factor" is often used to evaluate the quality of papers, but it is not applicable to assess the quality of recently published papers due to the low number of citations.[49] It is considered acceptable to use the journal's quality in which the paper is published as an indication as to the potential impact of the paper when evaluating recently published work.[49] The results indicated that most of the selected articles were from the top journals in the field, such as *Energy* (13.4%, Q1, IF 8.857), *Case Studies in Thermal Engineering* (11.9%, Q1, IF 6.268), *Fuel* (10.4%, Q1, IF 8.035), and *Applied Thermal Engineering* (9.0%, Q1, IF 6.465). According to Bradford's Law, more than one-third of the articles are in the core zone, and more than one-third of the articles are in the middle zone. This indicates that the selected article has good publication quality and credibility.

Most of the selected articles were carried out in Asian, with China, India, and Thailand accounting for 34.3%, 24.9%, and 7.5% of the total, respectively. The fuels used in these articles are LPG, NG, and HENG, accounting for 35.8%, 28.4%, and 19.4%, respectively. In addition, 9.0% of the articles use CH_4 as a fuel; in fact these authors aim to replace NG with CH_4. So, considering these articles, then the amount of research on LPG fuels and NG fuels is about the same. In addition, there are significant differences in the fuel used for household gas stoves in different regions. Research from India and Thailand mostly uses LPG as the fuel, while research from China and European countries mostly uses NG as the fuel. Recently, HENG fuel has received increasing attention in many countries. The design, manufacture, and fuel selection of all gas cookers are typically designed and developed according to the location, environment, availability of materials, and energy sources.

The relationship between authors' countries, authors' keywords, and journals is summarized by a Sankey plot in Figure 3. The results showed that articles from India have the most research areas that focus not only on thermal efficiency or energy efficiency but also on emissions, and they prefer to use LPG fuels. Meanwhile, articles by scholars from India and Thailand are more interested in porous media combustion technology applied to gas cookers, and most of the articles on this technology are contributed by them. Articles from Thailand prefer to use CFD technology to optimize the structure of burners to improve thermal efficiency. The articles from China seem to focus more on the use of natural gas and HENG, so their research focuses on flame stability and interchangeability. Flame stability is significantly affected by variations in natural gas components. Most articles on thermal efficiency or energy efficiency research have been published in professional journals such as *Case Studies in Thermal Engineering*, *Journal of Thermal Science and Engineering Applications*, *Energy*, and *Applied Thermal Engineering*. There are many research directions covered in articles in *Case Studies in Thermal Engineering*, *Energy*, *Applied Thermal Engineering*, and *International Journal of Hydrogen Energy*.

Figure 4 visualizes the network of the authors' keywords. The scientific credibility of a literature review can be assessed by analyzing the authors' keywords in the publication.[49] The co-occurrence network provides a snapshot of the most important areas of research in the selected articles. The colors represent the clusters to which each word belongs. The node size reflects the importance of the selected article relative to the occurrence of the authors' keywords. The line depth joining two or more circles indicates the co-occurring pattern.[97] The co-occurrence network analyses are carried out using the R package *Bibliometrix*, and clustering is performed using the Louvain community detection algorithm. In addition, synonyms are merged, and isolated nodes are removed. A strong correlation between these selected articles is observed in Figure 4, and the main research objective is to enhance the thermal performance of gas stoves. Compared to NG and hydrogen, LPG has a strong correlation with thermal efficiency. However, there is a significant correlation between hydrogen and emissions. The main factors that affect the thermal performance include the structural design, operating parameters, fuel composition,

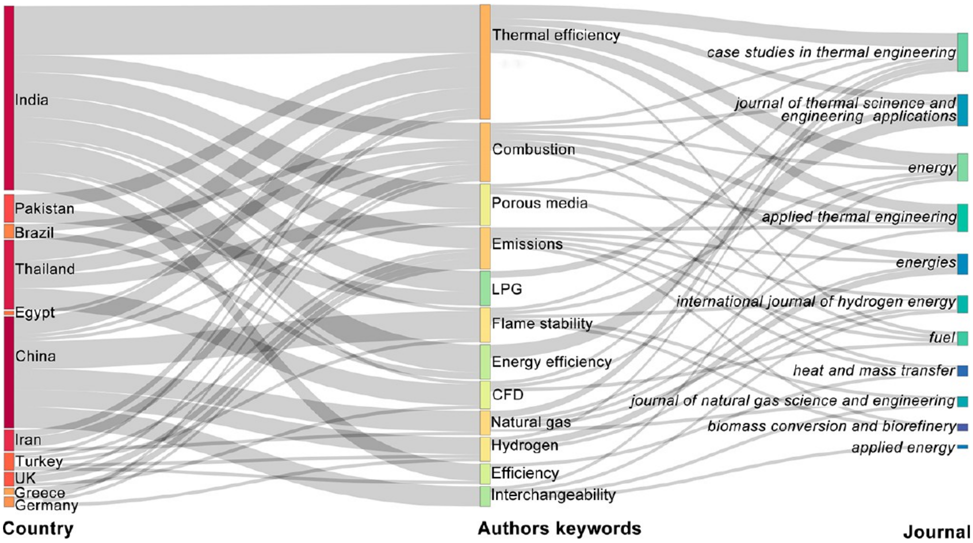


Figure 3. Relationship among authors' countries, authors' keywords, and journals.

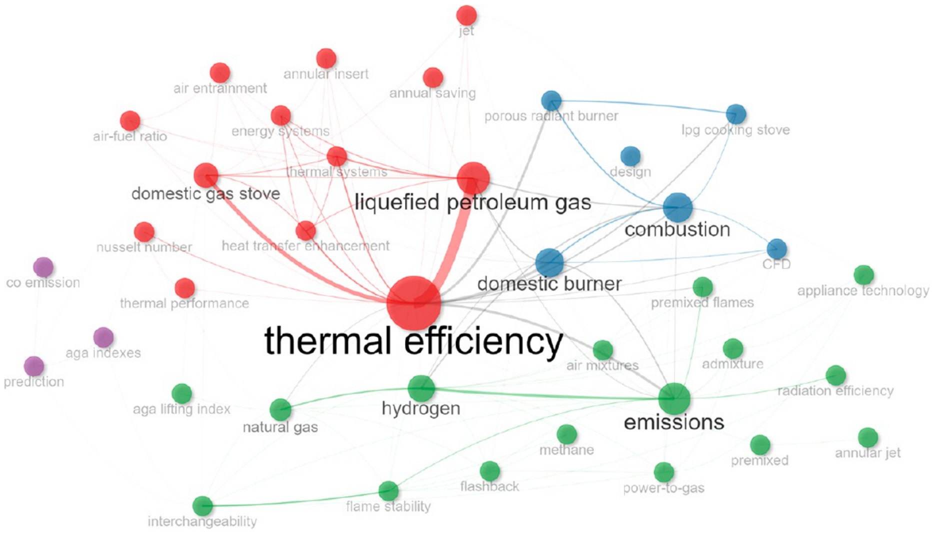


Figure 4. Co-occurrence network of authors' keywords.

burner type, annular inserts, etc. Based on this, a technical review is carried out.

3. ENERGY BALANCE AND INFLUENCING FACTORS ANALYSIS

3.1. Energy Balance Analysis. A diagram of the energy balance of the gas burner in operation is shown in Figure 5. First, the heat flow from fuel combustion accumulates at the bottom of the vessel.[31] Then, due to the impact of the flame jet, the hot gas flows toward the vessel periphery along its bottom. Heat transfer takes place directly from the flame to the bottom of the vessel. Next, due to the buoyancy effect, the heat flow turns 90° at the bottom edge of the vessel and then rises along the side of vessel. Heat transfer occurs in the combustion gases with the side walls of the vessel.[25]

Suppose a controlled volume contains the burner, the vessel, and the gas around the vessel. Then the system's energy balance in the control volume is

$$Q_t = Q_i + Q_b + Q_a + Q_h + Q_c \qquad (1)$$

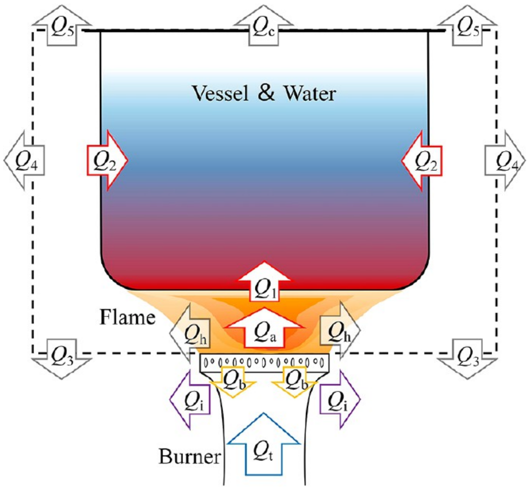


Figure 5. Energy balance diagram of the gas burner system.

where Q_t is total energy input to the system; Q_i is the energy loss due to chemically incomplete combustion; Q_b is the total energy absorption of the burner body; Q_a is the total energy absorption of the vessel; Q_h is the total energy loss in heat transfer; and Q_c is the total energy loss due to heat transfer from the vessel lid to the ambient air.

The total energy input to the burner system from fuel supplied which contains energy in chemical form is calculated as[98]

$$Q_t = m_f \times H_l \tag{2}$$

where m_f is the fuel consumption rate, kg/s; and H_l is the fuel's lower heating value, MJ/m^3.

The heat transfer between a solid surface and a gaseous medium can be expressed by the Newton−Richmann law.[99] So, the total energy absorption of the vessel is determined as follows:[100]

$$Q_a = (C_{p(\text{water})} \cdot m_{\text{water}} + C_{p(\text{vessel})} \cdot m_{\text{vessel}}) \cdot (T_{\text{in(water)}} - T_{\text{fin(water)}}) \tag{3}$$

where $C_{p(\text{water})}$ is the heat capacity of water, kJ/(kg·°C); $C_{p(\text{vessel})}$ is the heat capacity of the material of the vessel, kJ/(kg·°C); m_{water} is the mass of the water in the vessel, kg; m_{vessel} is the mass of the vessel itself, kg; and $T_{\text{in(water)}}$ and $T_{\text{fin(water)}}$ are the average initial and final temperatures of the water, respectively, °C.

$$Q_a = Q_1 + Q_2 \tag{4}$$

where Q_1 is the total energy absorption of the vessel through its bottom surface and Q_2 is the total energy absorption of the vessel through its lateral surface. For Q_1, the energy transfer from the support pan to the bottom of the vessel can be neglected because it is small. Q_1 is expressed using Newton's Law of Cooling:

$$Q_1 = Ah(\theta_{\text{flame}} - \theta_{\text{bottom}})t \tag{5}$$

where A is the area of the heat transfer surface, m^2; h is the heat transfer coefficient, W/(m^2·K); θ_{flame} and θ_{bottom} are the temperature of the flame and the bottom of the vessel, respectively, K; and t is the heating time, S.

Q_h is the total amount of energy loss in the heat transfer process, which could be written as

$$Q_h = Q_3 + Q_4 + Q_5 \tag{6}$$

Q_3 and Q_4 are the total energy losses due to heat radiation between the combustion flue gases and the environment,[100] which can be expressed by the Stefan−Boltzmann law:[101,102]

$$Q_3 = \varepsilon \cdot \sigma \cdot (T_{\text{bottom}}^4 - T_{\text{amb}}^4) \cdot A_{\text{bottom}} \tag{7}$$

$$Q_4 = \varepsilon \cdot \sigma \cdot (T_{\text{side}}^4 - T_{\text{amb}}^4) \cdot A_{\text{side}} \tag{8}$$

where ε is emissivity, between 0 and 1; σ is the Stefan constant, W/(m^2·K^4); T_{bottom} and T_{side} are the burned gas temperature at the bottom and side edge of the control volume, respectively, °C; T_{amb} is the ambient temperature, °C; and A_{bottom} and A_{side} are the area of the bottom and side surface of the control volume, m^2.

Q_5 is the heat loss of the flue gas leaving the upper edge of the control volume after heat transfer with the vessel sidewalls, which can be calculated as

$$Q_5 = m_{\text{gas}} \cdot C_{p(\text{gas})} \cdot (T_{\text{top}} - T_{\text{amb}}) \tag{9}$$

where m_{gas} is the flue gas flow rate, kg/s; $C_{p(\text{gas})}$ is the flue gas heat capacity, kJ/(kg·°C); and T_{top} is the flue gas temperature at the top of the control volume, °C.

Finally, the total thermal efficiency could be expressed as the ratio of the total energy absorbed by the vessel to the total energy input by the fuel, which can be calculated as

$$\eta = Q_a + Q_t \tag{10}$$

3.2. The Influence of a Single Factor. According to the formula above, the thermal efficiency η can be enhanced by increasing Q_a or decreasing Q_h. In general, the amount of heat absorbed by the vessel side is negligible since the heat transfer coefficient is lower at the vessel side than at the vessel bottom.[98] So, increasing Q_1 is a more effective and achievable way.

According to the formula 5, increasing A, h, and θ_{bottom} can increase Q_1. Some methods have proven effective, including the use of swirl burners (Figure 6) or multiring burners (Figure 7), increasing the hole numbers of the inner ring, the primary air coefficient, and the burner size. Increasing the hole numbers of the inner ring can enhance the thermal efficiency, but it can also increase emissions due to incomplete combustion which is caused by the insufficient amount of secondary air.[56] Using multiring burners or increasing the size of the burner may increase manufacturing costs. So, some researchers devote more effort to the structural optimization of the burner, like hole numbers, hole arrangement, hole angles, and nozzle shape, etc. In addition, reducing Q_h is a simpler and more effective way to improve thermal efficiency than increasing Q_a. Some methods have been demonstrated to achieve this, such as lowering the heating height, reducing the excess air coefficient, and installing

Figure 6. Swirl burner.

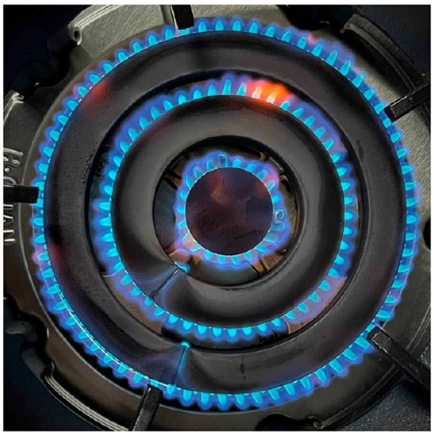


Figure 7. Multiring burner.

a wind shield, etc. However, these methods still tend to lead to high emissions, while putting more stringent requirements on the structural design of the burner and the optimization of operating parameters. Recently, the use of PMBs has proven to be a suitable method for domestic gas stoves due to its low emissions and high thermal efficiency.[37]

3.3. The Influence of Multiple Factors.

The stove's thermal performance may be influenced by multiple factors, as in the real world domestic gas stoves could be different from others in many aspects. Other factors (such as altitude,[54,62] fuel compositions,[103] ambient temperature, gas pressure,[104] the power of the range hood, etc.) can also have a different effect on the stove's thermal performance. These environmental factors and operating parameters will have an interaction effect on the stove's thermal performance with the structural parameters of the burner. The relationship between the different factors affecting thermal efficiency is shown in Figure 8. The double-headed arrow represents an interactive relationship between two factors. It can be seen that most factors have a joint effect on the thermal performance, but there is currently no investigation indicating that the nozzle structure interacts with other factors.

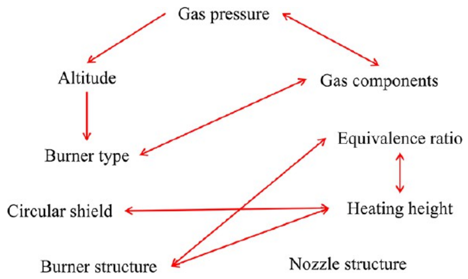


Figure 8. Relationship between the different factors affecting thermal efficiency.

In particular, at high altitudes and high latitudes, the ambient temperature, gas pressure, and oxygen content in the air are different from those in lowland areas, which has a complex effect on the gas stove's performance. The absolute pressure of the gas is observed to decrease at higher altitudes relative to lower altitudes due to the reduction in gas density.[62] Therefore, the heat input of the stove could decrease. The low oxygen content of the air at high altitudes leads to incomplete combustion. The incomplete combustion can cause higher CO emissions and more heat loss leading to a decrease of thermal efficiency.[105] But it also reduces flue gas temperatures and heat losses, resulting in an increase in thermal efficiency. Finally, the stove's thermal efficiency is higher at high altitudes than at low altitudes. Zhou et al.[62] concluded that the effect of heat input at high altitudes could be improved by increasing fuel pressure to promote complete combustion. However, there is currently no better way to solve the problem of high CO emissions at high-altitude areas. The higher excess air coefficient could meet the O_2 requirements for fuel combustion, but it increases the flue gas flow rate and thus heat loss, which can reduce thermal efficiency. Therefore, it is necessary to carefully consider the practical conditions when increasing the excess air coefficient for combustion in high-altitude areas.

At high altitudes, the porous radiant burner appears to have inferior combustion performance compared to the conventional burner of gas stoves, especially in terms of CO emissions. Iral and Amell[54] conducted a performance study using three different thicknesses of PMBs at 1550 m.a.s.l. The findings suggested that the PMB had difficulty achieving complete combustion at high altitudes due to the lack of sufficient primary and secondary air. CO emissions from all burners were approximately 2800 ppm, which is significantly higher than emissions from conventional burners. This is because the gas residence time in the first and second combustion zones is reduced due to its increased flow rate, leading to incomplete combustion. However, lower NO_X emissions were observed for all burners, which was considered to be due to the fact that the low-temperature gradient within the porous media combustion zone is not conducive to the generation of thermal NO_X.

The environmental characteristics of high altitudes (low oxygen concentration in the ambient air and high atmospheric pressure) are more likely to have a negative impact on the thermal efficiency of a PMB than a conventional burner. Increasing the air—fuel ratio will not have a meaningful effect on this, but increasing the fuel gas pressure will have a positive effect on its thermal efficiency.

However, under normal conditions, increasing the fuel gas pressure does not improve combustion. There is not much difference in the impact of fuel gas pressure on the thermal efficiency of burners installed with different annular inserts. Wichangarm et al.[35] investigated the influence of fuel pressure on the gas flow phenomena and the thermal efficiency of three different LPG burners by installing different insert wings on top of the burner ring. The results explain that increasing the LPG pressure could improve the turbulence intensity of the mixture flow and the amount of secondary air entrained by the flame, leading to higher heat flux and higher combustion temperature. However, increasing the LPG pressure could also decrease the thermal efficiency, as higher flow rates and turbulence intensities can reduce the heat transfer time of the hot air to the vessel. Overall, with the increase of gas pressure, all three types of burners showed a similar decrease. So, it is believed that the impact of fuel gas pressure and the installation of annular inserts on thermal efficiency is not related.

Dramatic fluctuations in gas compositions and gas pressure will affect the fuel's heating value and flow rate. This has a direct impact on heat input, flame length, flame stability, and flame speed and ultimately on thermal efficiency and emissions.[103] It was identified that when PNG and LNG fuels were interchanged in a partially premixed burner, the change in gas composition directly affected the combustion flame inner core height and flame speed.[51] Ko and Lin[103] claimed that it is inappropriate and hazardous to burn natural gas with various heating values in the same domestic gas stove, which may cause incomplete combustion, flashback, inadequate heat input, and low thermal efficiency. Therefore, some researchers have already conducted many studies in natural gas interchangeability and proposed some interchangeability indices to characterize the interchangeability of natural gas for avoiding dramatic fluctuations in gas compositions, such as Flash-Back Index, Yellow-Tip Index, Combustion Potential, Wobbe Index, Heating Values, etc.[68,106,107] However, those indices are not perfectly suitable for the gas interchangeability of all gas appliances.[108] This is because in the past, most domestic gas stoves used atmospheric burners, which are partially premixed burners. So in the past, fully premixed burners were not considered when determining the conventional gas interchangeability index.[66] Fully premixed burners are increasingly being used due to the development of the porous medium combustion with less emission and high thermal efficiency.[109] Currently some indices cannot be applied accurately to fully premixed burners due to the different combustion methods. So, it makes perfect sense to scientifically reset the interchangeable region of the gas based on all gas appliances.

In addition, the stove's thermal performance with different types and configurations of burners shows different behavior in response to the fluctuations of gas composition. The most obvious difference is the combustion under hydrogen addition conditions. It was found that as the proportion of hydrogen in the mixed fuel increased from 0% to 15%, the thermal efficiency of both typical burners and porous media burners increased. However, after the percentage of hydrogen exceeded 15%, the PMB thermal efficiency started to decrease.[46] Furthermore, for typical burners, no significant difference was observed in the thermal efficiency of the round-port burner and the swirling strip-port burner as the proportion of hydrogen in the mixed fuel increased. Based on the above discussion, it can be seen that PMBs are more demanding in terms of operating conditions, environmental conditions, and fuel composition.

The structure and operating parameters of the burner also have an interactive effect on the stove's thermal performance. However, the variation of heating height has a consistent effect on the thermal performance in a typical base burner (BB) and a swirl burner (SB). The thermal efficiency of both burners decreases with the heating height increases, and the degree of decrease is consistent. However, Hou and Ko[110] concluded that the heating height and the angle of the hole jointly affect the flame structure. However, at higher heating heights, the angle of the hole has little effect on the flame structure.

The equivalence ratio (Φ) shows different effects on the thermal efficiency for different burner structures. Kotb and Saad[30] found that there was not a significant difference in thermal efficiency between the BB and the SB at $1.0 < \Phi < 1.2$. When $\Phi < 1.0$ or $\Phi > 1.2$, the thermal efficiency of the BB decreases rapidly and the difference between the BB and the SB grows larger as Φ moves away from the 1.0−1.2. This is due to the high swirl intensity of the SB, which carries more atmospheric air, making it easier to completely burn and more adaptable to variations of Φ than the BB.

4. TECHNOLOGIES TO IMPROVE THERMAL EFFICIENCY

4.1. Structural Optimization of the Burner. The performance of gas stoves could be improved through different design modifications in the burner.[16] Some factors like the number of holes, the angle of the holes, the material and size of the burner head, and the heating height have a different impact on the performance of the gas stove.[110−114] Besides, applying the swirl flow has also been proven to be an effective method to improve thermal efficiency.

4.1.1. The Optimization of Hole Numbers and Angles. Increasing the number of holes in the inner ring can increase the burner's thermal efficiency. A very turbulent flow occurs under the vessel with complex vortex structures that interact with the jet flame.[56] An outer large vortex can be created by the interaction of the jet flame from the burner with the flame hitting the bottom of the vessel. Part of the flue gas can be reinvolved in the jet flame due to the effect of this outer large vortex. At the same time, the adjacent inner vortex is driven by the outer vortex, keeping the combustion gases below the bottom of the vessel. Thus, the combustion gases have more residence time in the inner vortex. Increasing the strength of the inner vortex will help to increase the thermal efficiency but may also lead to increased emissions. This is because the temperature of the inner vortex is lower than that of the outer vortex, and there is not enough oxidant to complete the reaction.[56]

Ahmadi et al.[24] reported the influence of various burner head configurations on the burner's thermal performance. Figure 9 shows nine different burner head designs. The results indicated that burner I has the highest thermal efficiency of 69.6% among all burners. This is due to the fact that the burner has been optimized by suitable structural optimization to increase the residence time of the combustion gases and optimize the temperature distribution of the flame, which results in improved heat transfer between the combustion gases and the vessel bottom. In addition, the jet flame from burner I can be mixed better with the ambient secondary air, which reduces the flue gas temperature leaving the vessel.

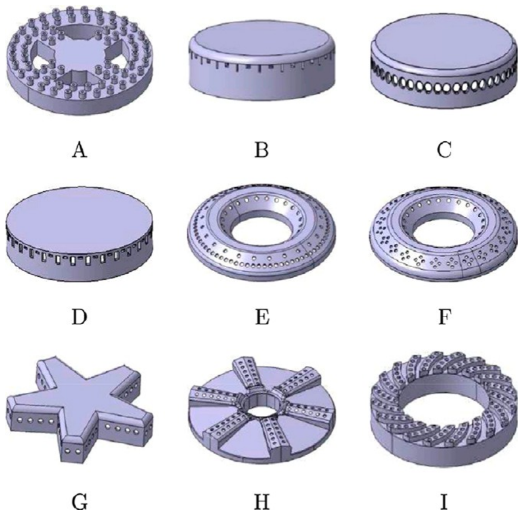


Figure 9. Nine different burner head designs examined in literature: (A) burner A; (B) burner B; (C) burner C; (D) burner D; (E) burner E; (F) burner F; (G) burner G; (H) burner H; (I) burner I. Reprinted with permission from ref 24. Copyright 2023 Elsevier.

Setting a bluff-body on the burner to stabilize the premixed flame is an efficient way to enhance mixing characteristics and improve flame stability, which has been applied in many engineering applications.[115−118] Tong et al.[119] investigated the effects of a central air jet on a burner with a 45° conical bluff-body. The experimental results show that the central air jet has both positive and negative effects on the burner. It reduces the temperature of the bluff-body surface but also makes the flame more susceptible to blow-off. Therefore, further research is needed to understand the flow structure and how the central jet and annular flame interact.

Burners made of different materials have different heat transfer properties, which can affect the combustion velocity of the exit gas. Although the burners made up of brass have a higher thermal efficiency than the iron-made burners, their economy is an important consideration for manufacturers.[120]

4.1.2. The Optimization of Heating Height. The purpose for studying the heating height is to achieve maximum combustion efficiency and lower pollutant emissions, as the temperature is highest when the core of the flame contacts the surface.[121] The effect of heating height on combustion performance and thermal efficiency of gas stoves was reported by Hou and Ko.[112] They found that the stove's thermal efficiency increased as the heating height increased in the early stages. As the heating height increased to a certain value, the stove's thermal efficiency began

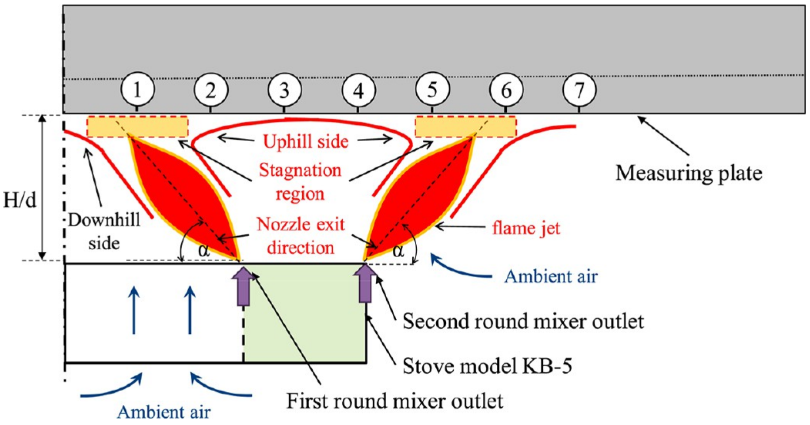


Figure 10. Effect of the injecting angle and the burner-to-plate distance on flame behavior. Reprinted with permission from ref 77. Copyright 2023 Elsevier.

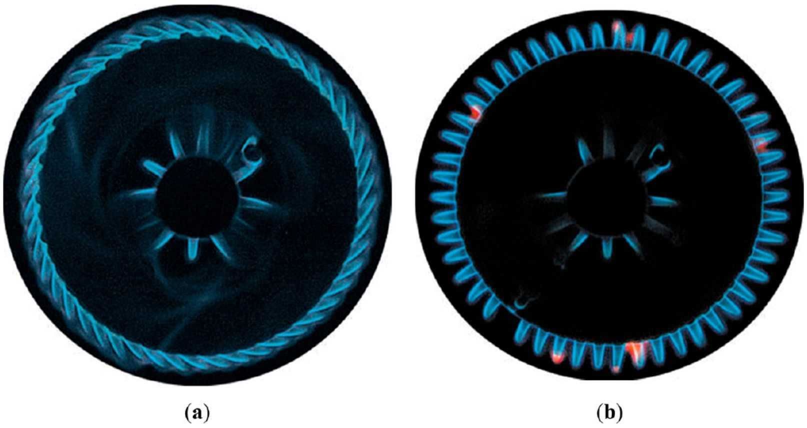


Figure 11. Top view of the different burners: (a) the swirling flame burner; (b) the nonswirling flame burner. Reprinted with permission from ref 123. Copyright 2023 Hindawi.

to decrease. The CH_4 concentration and jet velocity were key factors to determine the optimum heating height. It was found that the stove's thermal efficiency was maximum when the vessel bottom was slightly below the tip of the inner flame. Şener et al.[26] concluded that the vessel diameter and the heating height have a common effect on the stove's thermal performance and the emission values of unburned CO, NO, and HC. Increasing the vessel diameter and the heating height will reduce the average temperature at the vessel bottom and the stove's emissions.

The flame from the burner hits the vessel bottom over a short distance, resulting in inadequate mixing with the ambient air. In contrast, at a great distance, flames cannot reach the vessel bottom and are excessively mixed with the surrounding air.[122] Although this is not conducive to heating the bottom of the vessel, it is conducive to complete fuel combustion and reducing pollutant emissions.

It is meaningful to combine other parameters (e.g., oblique angle, air excess rate, and gas flow rate) and heating height to study the impact on combustion characteristics because these parameters together determine the flame structure. Hou and Ko[110] suggest that the oblique angle of the burner port and the heating height together influence the flame structure and play different roles in the process. The oblique angle plays the dominant role in the influence on the flame structure at lower heating heights but has a very small impact on the flame structure at higher heating heights. Wae-hayee et al.[77] conducted a further study on the influences of burner-to-plate distance (H/d) and LPG flow rate on the stove's thermal performance. Figure 10 shows the effect of the injecting angle and the burner-to-plate distance on flame behavior. The results demonstrated that to achieve the highest heat transfer rate, the value of H/d must be adjusted as the Re changes, in order to ensure that the flame core just reaches the vessel bottom. The total flame length reaching the bottom of vessel should be approximately 70% of its length, which could obtain the optimal results.

It can be concluded that the above studies are all aimed at obtaining the optimal heating height, so that the flame core can contact the vessel bottom resulting in the highest thermal efficiency, while maintaining pollutant emissions at low levels. However, it is difficult to achieve this goal through these methods. Sometimes it is necessary to reduce some thermal efficiency to meet pollutant emissions or to improve thermal efficiency while ignoring pollutant emissions.

4.1.3. Using of Swirling Burners. The swirl effect has widespread applications in household gas burners because the swirl effect can improve the stability of flame propagation and prolong the residence time of combustion gases. The swirl effect can also improve combustion strength because of the high shear stresses generated by its rotational moment.[120] Many factors can affect the swirling burner's thermal efficiency, such as the gas-flow rate, the primary air ratio, and the burner-port number and angle.

Deymi-Dashtebayaz et al.[82] reported the influence of different swirl angles of the output port on the heat performance. It was found that the highest flame temperatures and lowest emissions were obtained when the swirl angle for the burner output port was set to 20°. Figure 11 shows a swirling flame burner (a) and a nonswirling flame burner (b). Hou and Chou[123] concluded that the thermal efficiency of the swirling flame burner was higher than that of the nonswirling flame burner, and its thermal efficiency increased by at least 2% when the swirl angle changed from 0° to 56°. It can be concluded that the swirling flame enhances the mixing effect of hot gases with the ambient air through rotational flow motion and extends the residence time, greatly improving the heat transfer.

Matthujak et al.[29] investigated the effect of swirling flow on the thermal performance of domestic LPG stoves. It was found that the swirling flow increases the flame temperature, which increases the effective heat flow into the vessel and increases the heat transfer efficiency. The numerical simulation results are in agreement with the results of Hou and Chou.[123] The thermal efficiency of the swirling flame burner is increased by about 2.75% by modifying the typical burner. This is due to the high shear stresses generated by swirling flow, resulting in the following benefits: (1) enhanced air−fuel mixing effects; (2) increased flame residence time and flame area resulting in improved heat transfer; and (3) enhanced reaction owing to increased secondary air entrainment rates.

Kotb and Saad[30] compared the thermal performance and emissions of domestic burners with different swirling flow modes. They noticed the swirl burner extended the flame residence time and increased the heat transfer coefficient resulting in a good performance in thermal efficiency. Meanwhile, the coswirl burner has a wide operating range due to the intersection between jets. Typical swirling flow burners have been designed using ring slots or circular jets arranged at an angle around the burner circumference. Zhen et al.[28] proposed two new swirling flow burners that use two different methods to create a swirling flow. They found that both swirling flow burners had higher heating efficiency than the typical burner. The gas stove with swirl burner II has lower CO emissions and a wider operating range. However, this phenomenon was not observed with swirl burner I.

From all represented works, regarding structural optimization of the burner, some scholars currently focus on optimizing the number and angle of the holes, the arrangement of the holes, the size of the burner head, and the heating height in order to achieve the best combustion performance. These optimizations will affect the mixing of flames and secondary air, as well as the combustion flow field. In addition, the stove's thermal performance can be maximized by using a swirling burner due to an optimal impinging flame.

4.2. Enhancing the Mixing Effect of Air−Fuel.

The mixing effect of air−fuel can directly impact the air excess rate which is a key operating parameter in the gas−fuel combustion process. It can affect the flame temperature, flame stability, thermal performance, and pollutant formation.[81] The mixing effect of air and fuel depends mainly on the *Re*, the equivalence ratio, the design of the nozzle, the distance between the nozzle and the ejector, and the spacing between adjacent nozzles.[8] The distinction of nozzle structure has a direct effect on the air entrainment rate and the fuel flow rate, thus affecting the combustion and the heat load of the burner. Li et al.[8] examined the influences of the distance between the nozzle and the plate and the spacing between adjacent jets on the stove's thermal performances. As the distance between the nozzle and the plate increases, the stove's thermal efficiency at first reaches a maximum and then falls. Özdemir and Kantaş[56] considered that the size and position of the throat of the ejector determine its efficiency when the fuel jet is injected in the ejector. Rahman et al.[124] analyzed the influence of nozzle geometry on gas entrainment rate. Figure 12 shows two types of nozzles: (a) convergent nozzle and (b) straight-hole nozzle. It has been observed that nozzles with lower discharge coefficients produce a higher vacuum, resulting in a higher entrainment rate. Therefore, air entrainment can be improved by reducing the resistance of the air inlet line to allow more air to enter the burner.

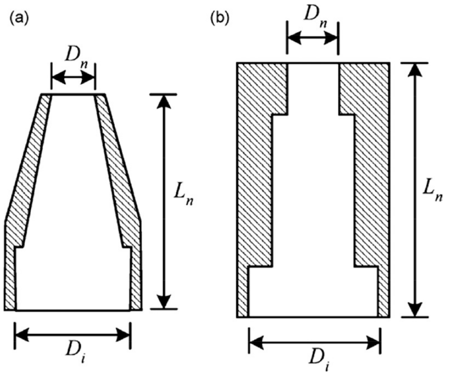


Figure 12. Nozzle types: (a) convergent nozzle; (b) straight-hole nozzle. Reprinted with permission from ref 124. Copyright 2023 Elsevier.

Yang et al.[32] compared the influence of differences in nozzle structure on entrainment behavior using CFD techniques. The cross-shaped nozzle was found to have better entrainment behavior compared to other nozzles. This nozzle allows strong interaction between the spanwise vortices and the streamwise vortices, resulting in enhanced mixing of the two combined streams. They suggested that a high level of mixing can increase the entrainment ratio by increasing outlet diameter and structural optimization. Laphirattanakul et al.[33] reported a way to improve the air entrainment rate by adding a needle rod in a circular nozzle. They compared the effect of the nozzle with a circular bluff-body and a conical bluff-body on the combustion performance of a premixed burner. Results indicated that the air entrainment of the nozzle with a conical bluff-body is 25% higher than that of the conventional circular nozzle, as well as a significant improvement in the visible flame color and length. This is because the jet through the bluff-body nozzle has a narrower cone shape resulting in greater penetration. The air entrainment in a confined duct was improved by deeper penetration of the jet, resulting in a significant reduction in the maximum Reynolds shearing stress upstream. However, Deymi-Dashtebayaz et al.[92] considered that the simple input nozzle has better performance compared to the conical nozzle due to the higher temperature volume that can be obtained. Figure 13 shows the temperature contour of the vessel bottom surface at different vessel height positions. In the condition of the simple input nozzle, the temperature domain at the vessel bottom is more uniform. For the conical nozzle, this increases the flow pressure, which leads to flame fluctuations and nonuniform flame temperature distribution.

From the above review, it can be seen that most researchers have concluded that the amount of mass entrained is largely

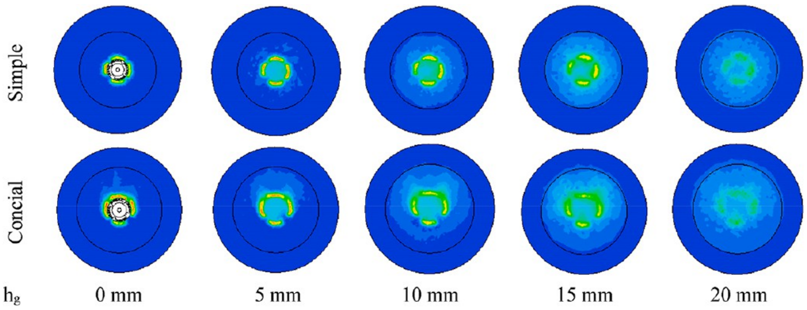


Figure 13. Temperature contour of the vessel bottom surface at different vessel height positions. Reprinted with permission from ref 92. Copyright 2023 Elsevier.

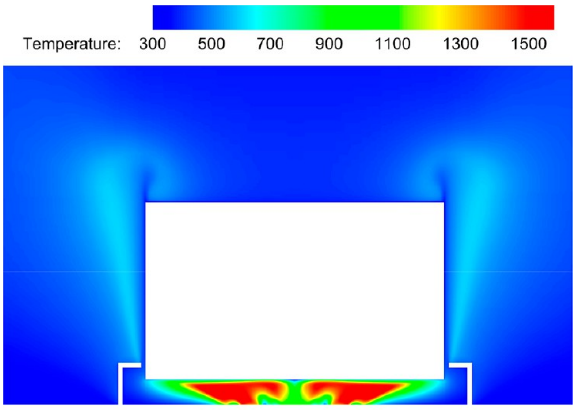
dependent on the jet characteristics. The primary air coefficient decreases as the nozzle diameter increases. It first decreases and then increases with increasing distance between nozzle and plate. Therefore, to achieve a larger primary air coefficient, it is necessary to select a smaller nozzle diameter and a suitable nozzle-to-plate distance. However, reducing the nozzle diameter will reduce the flow rate resulting in a lower heat load. In the process of designing the burner, machine-learning techniques may be a good way to solve the multiobjective optimization problem of requiring a suitable primary air coefficient while meeting the heat load requirements. This requires many experiments to obtain a large amount of training data. The use of CFD numerical simulation can save a lot of time, but it still requires some experiments to verify this result. Then some multiobjective evolutionary algorithms that have proven to be effective (Genetic Algorithm, Particle Swarm Optimization, and Evolutionary Algorithm, etc.) can be used to train these data to obtain the desired results.

4.3. Installation of a Circular Shield.

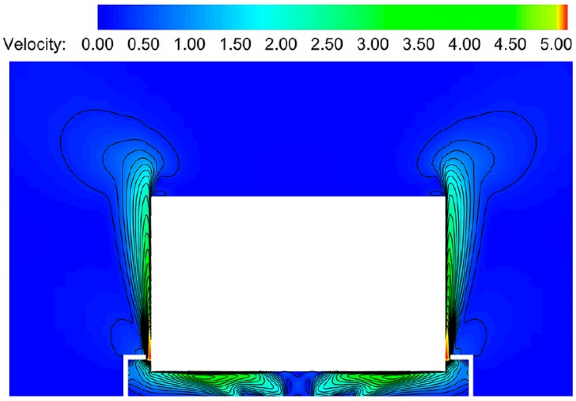
According to the previous energy balance analysis of the stove, Q_h is the total amount of energy loss in heat transfer, including Q_3, Q_4, and Q_5. The temperature of these hot combustion gases that are not used and escaped to the environment is between 950 and 1170 K.[21] Therefore, the stove's thermal performance can be enhanced by extending the residence time of high-temperature gas through efficient circulation of the flue gas around the vessel. Installing a radiation shield around the burner ring is considered an effective way to reduce flame heat loss and improve the thermal efficiency of gas stoves.[125] Figure 14 shows a gas stove burner with a circular shield.

Figure 14. Burner with a circular shield.

Some researchers concluded that the flame speed can be increased due to the installation of a circular shield. Wichangarm et al.[35] presented an energy-saving burner (EB) by installing an insert wing on top of the burner ring to form an extra chamber. Figure 15 shows the CFD simulation results of the EB. The results indicated this chamber can produce stronger turbulence intensity compared to other burners, resulting in more secondary air being rolled up into the flame to meet the reaction. This chamber can also reduce heat loss by separating and delaying the entry of entrained secondary air into the high-temperature flue gas to avoid lowering the temperature of the combustion gas. The study by Dwivedi et al.[126] shows the same conclusion. They found that the flame temperature increased by 19.30% from 1745 to 1910 K by using a flame shield burner. There is also a significant increase in average flame speed, from



(a) Temperature distribution on the burner system



(b) Velocity distribution on the burner system

Figure 15. CFD simulation results of the energy-saving cooking burner.

0.05 to 0.18 m/s. The overall results show that using a flame shield burner has better thermodynamic performance and economic benefits.

However, Boggavarapu et al.[21] considered that the shield reduced the velocity of the flue gases and increased the contact time between the hot flue gases and the vessel. In addition, the shield provides radiation heat transfer to the vessel bottom. The combined effect of the two ways leads to an increase in the stove's thermal performance. Hou and Chou[123] also found that adding a shield could create a semienclosed combustion flame, which helped to limit the dispersion of hot flue gas into the ambient air. This will improve the stove' thermal efficiency by 4%−5%.

The shield also guides the flue gas flow, forming a heat recirculation of hot gas in the space between the vessel and the circular shield.[36] Based on this, Gohil et al.[127] developed a novel shield for domestic gas burners. It was found that the thermal efficiency of a typical burner was increased from 66.27% to 74.07% by installing this shield. This is because this flame shield increases the hot gas residence time and reduces heat loss. Das et al.[36] also found that the stove's thermal efficiency could exceed 73.6% when the inset was installed in an optimum position below the vessel bottom.

At present, most studies focus on the influence of the position and shape of the shield on the flue gas and the stove's thermal performance. However, the material of the shield and the material of its coating can have a significant impact on performance improvement. In addition, the application of double-layer or hollow structure baffles to improve the heat barrier capacity and reduce heat loss is also an effective method.

4.4. Heat Recirculation Using a Porous Medium.

Porous medium combustion (PMC) is proven as an appropriate method to be used in gas stoves owing to lower emissions, high thermal efficiency, extension of the lean flammability, etc.[37,38] Figure 16 shows a typical porous radiant burner for domestic gas stoves. Due to the efficient heat transfer between the reaction gas and the porous medium (PM), a self-organized heat recuperation process is formed within the PM, which allows the PMC to significantly improve the thermal characteristics of the system.[128,129] A porous material means an inert material with a large number of connected voids where gases can easily flow through the internal pores.[129] Therefore, due to the large number of pores and internal surfaces of a PM, heat diffusion and heat transfer can be effectively enhanced. With the internal recirculation caused by heat transfer from fluid to solid and from solid to fluid, an internal method of energy recuperation is activated, resulting in excess enthalpy or super adiabatic combustion.[130] Excess enthalpy generated in the porous medium helps improve thermal efficiency and reduce emissions.[130−132]

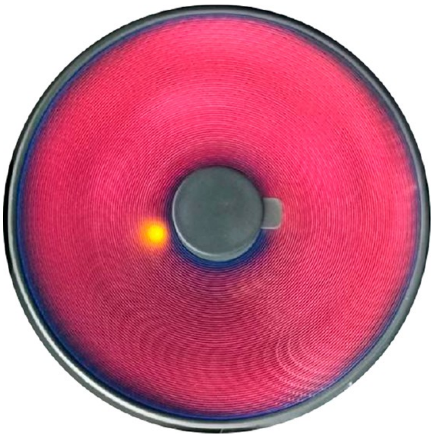


Figure 16. Typical porous radiant burner for domestic gas stoves.

The critical pore size of a PM determines whether the combustion position is inside the PM. Flame propagation will be prohibited when the pore size is smaller than its critical dimension. On the other hand, flame propagation can be allowed inside the PM when the pore size exceeds its critical dimension. Muthukumar and Shyamkumar[37] compared the differences in thermal performance and emissions between a conventional burner and a porous radiant burner (PRB) on a domestic stove and found that the thermal efficiency of the stove with a PRB can achieve 75% at 90% porosity. Meanwhile, the stove with a PRB has lower CO and NO_X emissions, and CO emissions would increase with decreasing PRB porosity and equivalence ratio. Soltanian et al.[42] evaluated the heat transfer process at the bottom and sides of the PRB to investigate its total thermal performance. They found that the bottom and side convection fractions dominate the heat transfer in the PRB with 58% and 28%, respectively. The contributions from surface and flame radiation were small, with 2% and 12%, respectively.

Figure 17 illustrates a schematic diagram of a two-region PRB. The two-region PRB has a wide spectrum of useful practical applications because they can stabilize the combustion wave within the PM.[39−41] The two-region PRB has a two-layer structure. The PM material in the upstream section has a low porosity and poor conductivity, which serves as the preheating zone since combustion cannot occur in this section and prevents flashback formation.[74] The PM material in the downstream section has a high porosity and good conductivity, which serves as the combustion zone to provide a place for fuel burning. When the fuel ignites at the surface of the combustion zone, it immediately propagates in an upstream direction and finally stabilizes after reaching the intersection of the preheating zone and the combustion zone.[74]

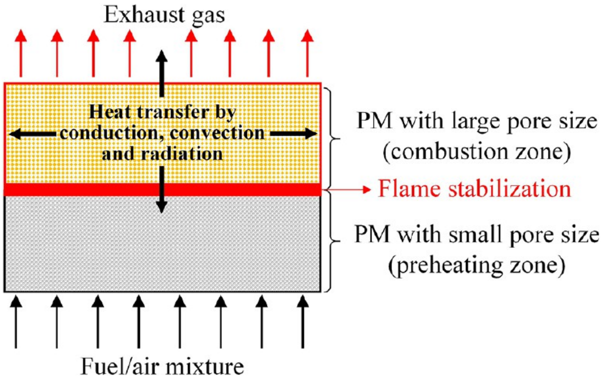


Figure 17. Schematic diagram of a two-region PRB.

The material of the two-region PRB can also have a significant effect on burner performance. Pantangi et al.[133] presented the effect of burner diameter and operating parameters on the performance of a two-region PRB on a domestic cooker. The preheating zone of the PRB consisted of a series of stacked 5 mm diameter Al_2O_3 balls. The combustion zone of the PRB consisted of a 90% porosity SiC foam. It was noticed that the

Table 3. Comparison of the Thermal Efficiency of the PRB with Different Designs

authors	ref	PM region	structure	thermal load/ kW	equivalence ratio	thermal efficiency/%
Muthukumar and Shyamkumar	37	two regions	Al_2O_3 (φ: 40%); SIC (φ: 90%)	1.30−1.70	0.50−0.70	71−75
Mishra et al.	40	two regions	Al_2O_3; SIC	5.00−10.00	0.56−0.70	42−58
Pantangi et al.	133	two regions	Al_2O_3 (Ø: 5 mm); SIC (φ: 90%)	0.80−2.00	0.30−0.70	50−68
Mishra and Muthukumar	60	two regions	Al_2O_3; SIC	1.00−3.00	0.56−0.70	63.0−75.1
Wu et al.	52	one region	bronze ball (Ø: 5 mm)	1.00−2.00	0.60−1.20	40−56
Muthukumar et al.	135	two regions	Al_2O_3 (φ: 40%); SIC (φ: 90%)	1.24−1.48	0.55−0.80	62−67
Deb and Muthukumar	43	two regions	Al_2O_3; SIC (cluster porous radiant burner)	12.60	0.70−0.85	49.0−59.2

thermal efficiency of the cooker with a two-region PRB is 4% higher than that of the conventional cooker.

However, when this two-region PRB is under low heat load, the fuel has difficulty igniting and burning at its downstream surface. Bakry et al.[74] conducted a systematic investigate to explore this phenomenon. It was found that the limiting excess air ratio (λ) led to abnormal combustion, which would result in two different combustion modes. Both combustion modes were unable to maintain normal combustion and resulted in flame extinction in the two-region PRB. The limiting excess air ratio depends only on the type of PM material.

Table 3 shows a comparison of the thermal efficiency of the PRB with different designs. Although the PRB shows promise for high performance, especially in terms of thermal performance and emissions, it needs to overcome several hurdles to become a more widely accepted device for domestic use. For example, the PMB has a lower heat load compared to the conventional burner, which results in longer heating times. The PMB must ensure a suitable gas flow rate to maintain submerged combustion so that the flame remains inside the porous media and avoids flame burning on the surface. This means that there are certain requirements for the heat load of the stove. If a higher heat load is required, the burner size needs to be increased. In addition, food residues clogging the surface pores of PMB are also something to be noted. Maintaining flame stability over a wide range of heat input and reducing thermal stress of the PM during long and repeated cyclic use are important issues to be addressed in the future.[134]

4.5. Use of Hydrogen-Enriched Natural Gas.

As a clean, zero-carbon energy source, hydrogen plays a key role in the global energy transition.[136] Hydrogen-enriched natural gas (HENG) is gaining more attention as a promising environmentally friendly fuel, as it will extend the application scenario of hydrogen energy. The properties of hydrogen and methane are summarized in Table 4. Hydrogen and natural gas (which mostly consists of methane) differ significantly in volumetric heating value,[81] with a high heating value of 12.5 and 37.8 MJ/m^3 respectively, but the difference in Wobbe index is not significant, at 48.5 and 51.9 MJ/m^3 respectively. This will allow hydrogen to replace some of the natural gas without a significant impact on the heat input to the gas appliance.[71] However, mixing hydrogen with natural gas could increase flame speed and affect the stability of the combustion process, which could lead to the destabilizing phenomena known as "blow-off" and "flashback".[137] The destabilizing phenomena of flames are shown in Figure 18. Many studies have been carried out to investigate combustion characteristics of HENG, including the combustion rate, the concentration limits of flame propagation, and the ignition delay.[84,87,89,138]

Table 4. Properties of Hydrogen and Methane

property		hydrogen	methane
relative density[71]		0.555	0.070
volumetric stoichiometric air requirement[83]	m^3/m^3	2.38	9.52
viscosity[71]	10^{-5} Pa·s	0.89	1.11
laminar flame speed[71]	m/s	2.1	0.4
low heating value[83]	MJ/m^3	10.2	34.0
high heating value[83]	MJ/m^3	12.5	37.8
ignition energy[71]	10^{-5} J	2	33
autoignition temperature[139]	°C	560	600
lower flammability limit[83]	vol%	4	5
higher flammability limit[83]	vol%	75	15
burning velocities[61]	cm/s	203.9	36.7
adiabatic flame temperatures[61]	K	2381	2226
Wobbe index	MJ/m^3	48.5	51.9

The Wobbe index is defined as the ratio of the high heating value of the gas to the square root of its relative density. This will directly affect the heat input to the gas appliance and is often used to evaluate gas interchangeability. Figure 19 illustrates the variation of Wobbe index and high heating value with different hydrogen additions. As the hydrogen addition ratio increases. The Wobbe index first decreases, reaching its lowest point at 80% hydrogen addition ratio, and then increases.

If the difference in the Wobbe index between the two types of gas does not exceed 5%−10%, they can be exchanged in gas application.[84] However, both the Wobbe index and the AGA multi-indices are not applicable to HENG when the hydrogen percentage exceeds 20%. Xie et al.[83] proposed a method that can analyze the flame stability region changes under different gas components, which is mainly based on the flashback and lifting limits of fuels. This method allows to divide the stable flame region of HENG according to the hydrogen percentage and the flame temperature and describe their relationship to flashback and lifting, which was a great help to adjust the gas appliances to use HENG fuel.

Flashback behavior of the flame determines the maximum ratio of hydrogen addition. The burning velocity can also be evaluated for changes in flashback tendency as the combined velocity of the burned flame and the unburned mixture directly affects the flame stability.[140] The variation of the burning velocity with different hydrogen additions and excess air coefficients is shown in Figure 20. The burning velocity varies slowly with increasing proportion of hydrogen until the proportion reaches 50%. There is a significant change in the

(a) (b)

Figure 18. Destabilizing phenomena of flame: (a) blow-off; (b) flashback.

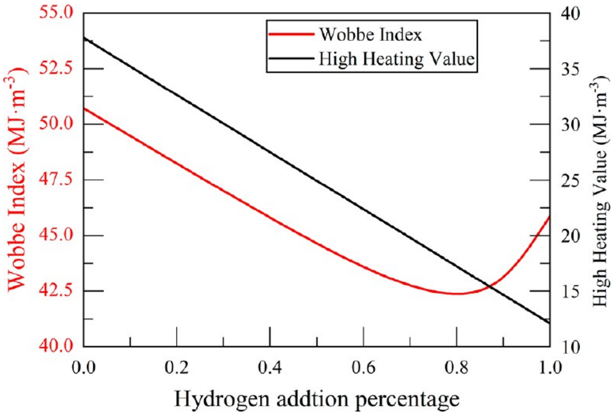


Figure 19. Change of Wobbe index and high heating value with different hydrogen additions.

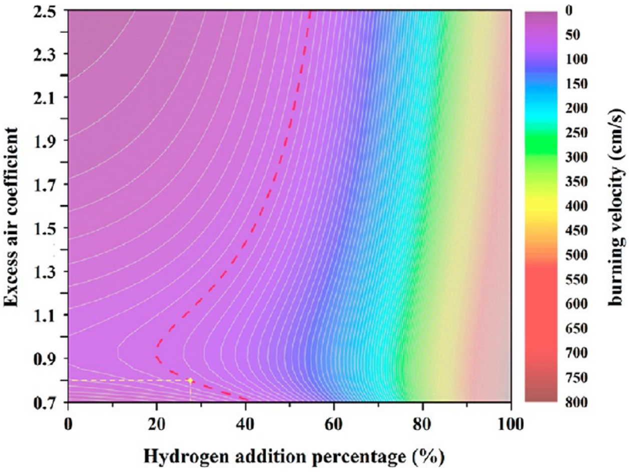


Figure 20. Change of burning velocity with different hydrogen addition and excess air coefficient. Reprinted with permission from ref 84. Copyright 2023 Elsevier.

burning velocity when the hydrogen percentage exceeds 50%. At different hydrogen percentages, the burning velocity showed a large variation at excess air coefficient between 0.7 and 1.0.[84] Therefore, the proportion of hydrogen addition must take into account the amount of the deviations between the actual and design values of the excess air coefficient for the different gas appliances in order to avoid accidents in the worst case.[84]

Schiro et al.[139] concluded that proper burner design is necessary to manage the HENG ignition to ensure that the velocity balance is satisfied at different application locations and operating conditions. When the velocity of flame propagation exceeds the jet velocity of the unburned mixture, it will cause the flame to propagate to the inside of the burner causing a flashback. As the proportion of H_2 addition increases, the density and volumetric heating values of HENG decrease. This means that a greater volume of HENG is required to achieve the same heat input. At the same time, this reduces the ratio between the theoretical air volume and the fuel volume. This means that less theoretical air is required to achieve complete combustion of the same volume of fuel. De Vries et al.[61] argued that the premixed burners suitable for the fuel-rich combustion conditions are sensitive to flashback, while the burners suitable for the fuel-lean combustion are relatively insensitive to flashback. The percentage limit for blending hydrogen into natural gas takes into account both the limitations of the Wobbe index and the effect on the flashback of the blended fuel. Figure 21 shows the flame from a typical round-port burner using HENG fuels with different hydrogen addition percentages. As the proportion of hydrogen increases, the inner cone is brighter than the outer flame, and the length of the inner cone gradually shortens, indicating a higher risk of flashback.[46] This is because of the higher propagation velocity of hydrogen flame than methane flame and the higher reactivity of hydrogen than methane. Burning gas close to the nozzle raises the burner temperature, which may hurt the burner.

Hydrogen enrichment can increase the tendency of laminar flames to a destabilizing phenomenon called “blow-out” or “blow-off”.[141] This destabilizing phenomenon depends on the velocity balance between the flame and the injected premixed gas, which determines the flame flow characteristics and the reaction times.[142,143] To establish a more general relationship between these two velocities at the jet beginning, Jones and Dunnill[144] provide a simplified semiempirical model that relates the critical energy density of the reactants to the premixed flow rate, the visible surface area, and the total power output of the critical stabilizing flame, which can predict blow-out behavior based on measurable input parameters. This can be useful for designing new burners or modifying existing gas applications. However, the model was generated with a single ring burner, and it was not always possible to apply it to other structural burners. Liu et al.[45] developed a simplified combustion mechanism for HENG fuels in a stove using the Sensitivity Analysis and Direct

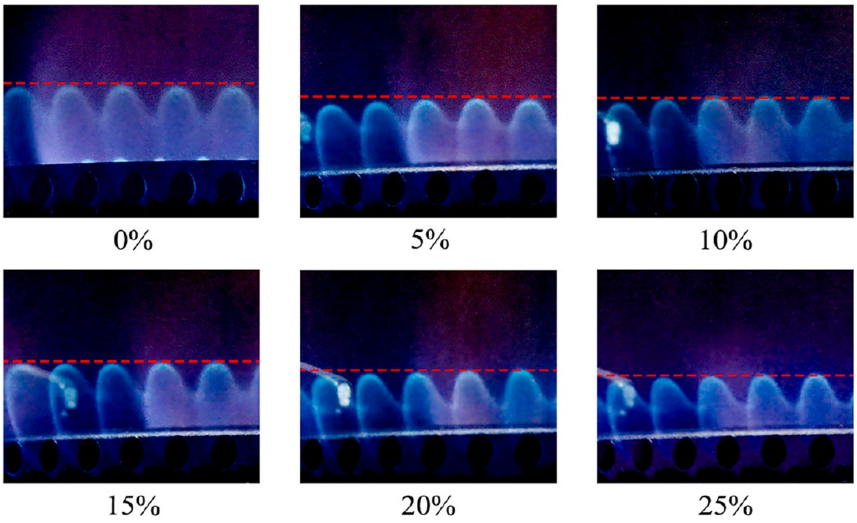


Figure 21. Flame from a typical round-port burner using HENG fuels with different hydrogen addition percentages. Reprinted with permission from ref 46. Copyright 2023 Elsevier.

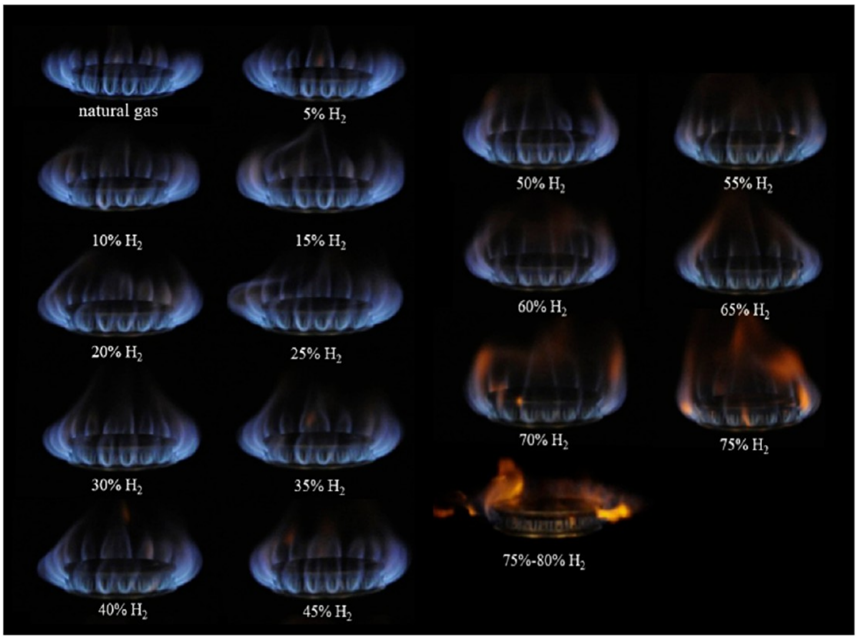


Figure 22. Burner flames characteristics with different H_2 addition percentages. Reprinted with permission from ref 71. Copyright 2023 Elsevier.

Relationship Graph. It reduces the number of chemical reactions by 82% compared to the conventional detailed mechanism (GRI-Mech 3.0). Moreover, the difference between the calculation of a detailed mechanism and a simplified mechanism is less than 1%. However, this study has only studied hydrogen concentrations up to 15%. The effects of other hydrogen mixing ratios on mixed fuel combustion have not been investigated.

Besides, some experimental studies have already been conducted to assess the thermal performance and emission characteristics of gas stoves using HENG fuels. Fang et al.[46] concluded that the different hydrogen addition percentages (0–25%) have different effects on the thermal efficiency of three types of burners (typical round-port burner, swirling strip-port burner, and radiant porous media burner). For the typical round-port burner and swirling strip-port burner, the average thermal efficiency increased by 0.82% and 1.18%, respectively. However, the thermal efficiency of porous media burners increases first and then decreases with the increase of hydrogen proportion. The reasons are considered as follows: (1) As the hydrogen proportion increases, the theoretical air volume decreases, and the actual primary air coefficient increases. This makes the air/fuel ratio close to the stoichiometric ratio, which accelerates the combustion reaction. Although the increase in the primary air coefficient does not contribute to the increase in the flue gas temperature, the increase in the mole fractions of H, O, and OH accelerates the combustion reaction and increases the flame temperature.[145,146] Conclusively, the temperature of the flue gas increases with the increase of flame temperature, increasing the convective temperature difference between the flue gas and the boiler, thereby improving the thermal efficiency of the burner.[147] (2) Increasing the hydrogen addition percentage will shorten the flame length, which will result in a weaker air entrainment effect of the flame.[23] (3) For the radiant porous media burner, the smaller-sized vessel was used in the experimental testing of porous media burners due to the lower thermal load of the burners. As the proportion of hydrogen increases, the water vapor content of the flue gas increases, resulting in more condensed water attaching to the vessel walls. Then, the condensed water falls onto the burner surface which decreases the temperature.

The effect of hydrogen addition percentages on the emission of different types of burners appears to be the same. The CO emissions of three types of burners decrease significantly with the increase of hydrogen addition percentages. This is mainly because the air coefficient increases with the hydrogen percentage increases, making the fuel/air ratio close to the equivalent ratio.[30] The flame length shortens, weakening the impact effect between the flame and the vessel bottom, leading to a sharp decrease in CO emissions. For NO_X emissions of different types of burners, this was observed to remain unchanged as the hydrogen proportion increased. Although increasing the hydrogen proportion will increase the flame temperature, leading to an increase in NO_X emissions, it will reduce the theoretical air volume and indirectly increase the actual primary air coefficient. This also reduces the CH_4 content of the fuel−air mixture which limits NO_X production.[46] Besides, this effect may also be triggered by the operating condition. The heating load of the burner decreases with more hydrogen addition. This allows the heat release to overcome the increase in flame temperature and result in a decrease. Because there is a significant difference between the open-burning situation and the ideal adiabatic situation, it is not appropriate to use the adiabatic flame temperature characteristics for open-air combustion analysis.[71]

Some projects have already been carried out to study the practical implementation of HENG within a main gas supply in Europe.[67,148−150] Domestic gas appliances proved to be compatible with HENG containing up to 20% H_2 in the NaturalHy project.[67] A low, fixed range of hydrogen addition percentage is not feasible for real future applications, and a larger, variable hydrogen percentage must be considered. Zhao et al.[71] studied the effect of hydrogen addition (0−80%) on the combustion and cooking performance in a cooktop burner. Figure 22 shows burner flames characteristics with different H_2 addition percentages. They concluded the hydrogen percentage could reach 55% considering the flashback limit under actual pot-heating conditions. It is mainly because of an obvious interaction between the flame tip and the vessel bottom, which increases the uncertainty and instability of the flame. In general, the study results demonstrate that domestic gas stoves can operate safely with up to 20% hydrogen addition. Jones et al.[67] concluded that HENG, in addition to suppressing blow-out and yellow-tipping behavior, does not significantly increase the risk of flashback during ignition for realistic burners. For the burner with a circular port less than 3.5 mm in diameter, flashback on extinguishing can be avoided unless the hydrogen percentage exceeds 34.7%. Thus, the hydrogen percentage can be further increased to 30% without any modifications to the equipment infrastructure.[44]

Based on the above review, it can be seen that current conventional domestic gas stoves are suitable for low hydrogen proportion (0−30% hydrogen). However, with the increase of hydrogen proportion, the instability phenomena of "blow-off" and "flashback" will occur. Therefore, when the hydrogen ratio is greater than 30%, a specific structural design for the specific gas source component is required to prevent this phenomenon. While hydrogen addition can reduce the heat load of the burner, there is no definite conclusion on the effect on thermal efficiency. Because a conventional gas burner should theoretically exhibit the best combustion under natural gas conditions, with the addition of hydrogen this best combustion will be destroyed. If this burner is designed with deviations and with the addition of hydrogen, this will have a different result.

5. SUMMARY AND OUTLOOK

Since domestic gas stoves are widely used in both developing and developed countries, it is very meaningful to investigate how to improve their thermal performance to save energy. The design of burners has been developed significantly through numerous theoretical analyses, tests, and simulations for optimization. As a result, the stove's thermal performance is significantly improved. This increase is the result of better heat transfer performance and less heat loss achieved by combining higher combustion gas temperatures, longer burned gas residence times, and optimized flow fields.

In this paper, we perform a descriptive statistics and graphical visualization of network analysis by combining common databases with the Bibliometrix and analyze the energy balance of the burner of a domestic gas stove and the influence of a single factor and multiple factors on stove performance, which will help researchers to understand how to improve the heat transfer performance and reduce heat loss in order to achieve the purpose of improving thermal efficiency. Then, the paper reviews the technological advancements in thermal performance enhancement for domestic gas stoves and analyzes the influence of various parameters on their thermal performance, like structural optimization of the burner and the nozzle, installation of a circular shield, and use of swirl burners or porous radiant burners. The paper also reviews the study of the effect of HENG on stove performance.

This paper has also identified some new development areas to which attention needs to be paid attention. Some advanced combustion methods, such as swirling combustion and porous medium combustion, are applied to domestic gas stoves to improve thermal efficiency, which may be an area requiring more research. The selection of porous materials, flame stability in a wide range of heat inputs, and thermal stress of porous matrix in long-term use need further study. Generally, reducing emissions while improving combustion efficiency is difficult, but using HENG as a fuel may be a solution. It will be a hot research topic in the future to prevent the instability phenomena of blow-off and flashback by redesigning the burner structure for HENG with different hydrogen proportions. Besides, using porous media combustion technology with HENG may be a good direction for technology development. However, this needs to avoid the possible flame movement to the porous medium surface due to the addition of hydrogen. For designers, optimizing the burner structure to balance the thermal efficiency and emissions of gas stoves, based on the consideration of the burner manufacturing cost and process, is still an area that needs to be further studied in the future. Machine-learning techniques may be a good way to perform the optimal design of domestic gas stoves. Some research focuses and gaps identified in this paper will help researchers to plan their future studies.

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Notes

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