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A Study on Combustion Temperature of a Rocket-Type Ceramic Burner Using CNG as Fuel by Computational Fluid Dynamics

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Abstract. This study aims to investigate the combustion temperature of a rocket-type ceramic burner when using Compressed Natural Gas (CNG) as a fuel instead of Liquefied Petroleum Gas (LPG) through Computational Fluid Dynamics (CFD) methods. The simulations were conducted using Fluent 2021 R2 with a 3D model, comparing the combustion temperature of CNG with LPG. The results reveal that as the heat input increases, both the flame length and maximum temperature rise. At 30.02 kW, the maximum temperatures obtained from LPG and CNG were 1396 and 1842 K, respectively. Moreover, the maximum temperatures from CNG were consistently higher than those from LPG at all heat inputs. This difference is attributed to the higher primary air intake from CNG, enhancing the effectiveness of premix combustion. Consequently, transitioning from LPG to CNG as a fuel for a rocket-type ceramic burner holds the potential for energy savings and reduced emission.

Keyword. Rocket-type ceramic burner, CNG, LPG, CFD

1. Introduction

In Thailand, the ceramic industry, receiving vital support and promotion from the government, operates across numerous production bases. The ceramic production process comprises three primary stages: soil preparation, product molding, and product firing. Within this process, 25% of the energy is sourced from electricity, while the remaining 75% is obtained from LPG, constituting 40% of the overall production cost [1]. LPG finds extensive utilization in ceramic burners, notably in prevalent rocket-type ceramic burners, which serve as primary burners in the ceramic manufacturing process, as illustrated in Fig. 1

After an initial assessment (Fig. 1), the components and operational mechanisms of these ceramic burners exhibit similarities to high-pressure gas burners or KB burners (Katsura burners). While KB burners have been extensively investigated through both

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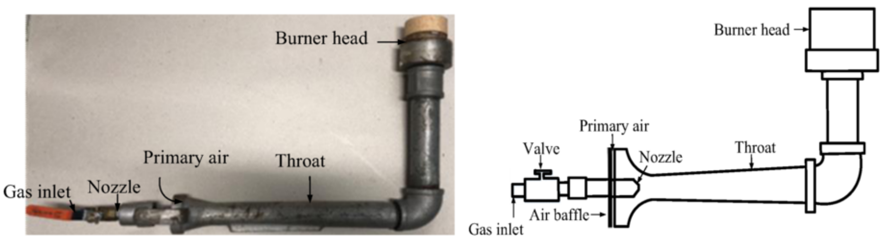
experimental and Computational Fluid Dynamics (CFD) approaches [2-7], the attention directed towards ceramic burners has been relatively constrained.In 2020, Wichangarm et al. [5] presented an innovative approach for predicting the thermal efficiency of an LPG energy saving burner (EB) using Computational Fluid Dynamics (CFD) data. The method involved correlating data from experimental measurements and numerical heat flux to estimate thermal efficiency. The resulting correlation equation demonstrated a difference of approximately ±2.41% when compared to experimental data. Additionally, two enhanced versions of the EB burner, namely EB-W and EB-WT, showcased predicted thermal efficiencies of 9.02% and 7.87%, respectively. These values exceeded the performance of the original EB burner and closely aligned with experimental results.

In 2023, Matthujak et al. [6] introduced the NB-5, an innovative LPG burner. They employed Computational Fluid Dynamics (CFD) techniques to assess and highlight its advantages compared to three existing Thai commercial burners—KB-5, S-5, and EB-5. The investigation focused on optimizing combustion temperature and flow velocity, resulting in a significant improvement in the net heat flux of the NB-5. Simulation outcomes revealed that the NB-5 achieved the highest average temperature of 929.35 K and a peak heat flux of 58.01 kW/m², directly translating into enhanced thermal efficiency. Experimental testing of the NB-5, guided by CFD results, demonstrated substantial improvements in thermal efficiency and notable reductions in CO and NOx emissions compared to the three commercial burners. Particularly noteworthy, when compared to the traditional KB-5 burner, the NB-5, EB-5, and S-5 burners exhibited average energy savings of 22.37%, 8.46%, and 1.69%, respectively.

In ongoing research, Boggavarapu et al. [7] are actively exploring the transition from LPG to alternative gaseous fuels, with a specific focus on piped natural gas (PNG), for KB burners. Employing a combination of experimental measurements and Computational Fluid Dynamics (CFD) techniques, the study incorporates a 3D steady-state model that integrates combustion and heat transfer functions. The CFD data provide insights into combustion phenomena and the transfer of heat from combustion products to the surrounding vessel, illustrating these processes through velocity vectors and temperature contours. Furthermore, the research proposes an innovative approach to enhance thermal efficiency by introducing circular sheets and inserts atop the burner head in the CFD model. According to the CFD results, the incorporation of circular sheets and inserts leads to notable improvements. Specifically, for the LPG model, a circular sheet and insert result in thermal efficiency increments of 1.5% and 4.9%, respectively. Meanwhile, the PNG model exhibits increments of 2.5% and 3.5%, respectively. Moreover, increasing the loading height to 24 cm results in a substantial 10% increment in thermal efficiency.



(a) Photo of burner (b) Schematic diagram

Figure 1. Rocket-type ceramic burner.

There have also been attempts to explore alternative fuels for ceramic burners through experimentation. In 2015, Puttapoun et al. [8] conducted experimental studies on the application of biomethane gas in a small ceramic kiln. The study utilized two types of ceramic burners, namely the rocket type and the shower type, and compared LPG and CBG (Compressed Biogas) burners in terms of efficiency, temperature, emissions, and the quality of ceramic products after the firing process. The experimental results revealed that using CBG as a direct replacement for LPG is not feasible without improving the nozzle for gas injection. However, enhancing the burner to accommodate CBG as fuel could lead to fuel cost savings of up to 30% compared to using LPG, with a payback period of 3.5 years. It's worth noting that no study using Computational Fluid Dynamics (CFD) has been reported yet.

Therefore, the focus of this paper is to investigate the combustion temperature of a rocket-type ceramic burner when substituting CNG for LPG, employing CFD techniques. This approach aims to complement and extend the understanding of fuel alternatives for ceramic burners, building upon the experimental findings reported by Puttapoun et al. [8].

2. Methodology

The simulation of the combustion behavior for the ceramic burner, utilizing a single model for the entire process, proved to be excessively large and time-consuming. To address this challenge, the simulation was bifurcated into two distinct parts: Part 1 focused on simulating the flow features inside the burner, while Part 2 addressed the simulation of combustion behavior outside the burner, as illustrated in Figure 2. This division allowed for a more efficient and manageable simulation process, facilitating a detailed examination of both the internal flow dynamics and the external combustion phenomena.

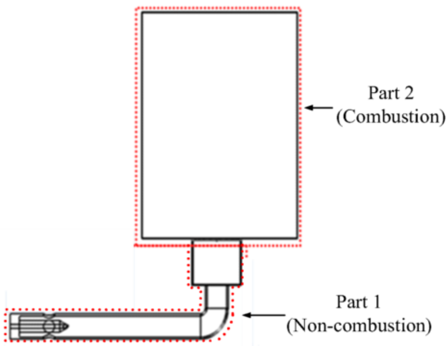


Figure 2. Simulation domain.

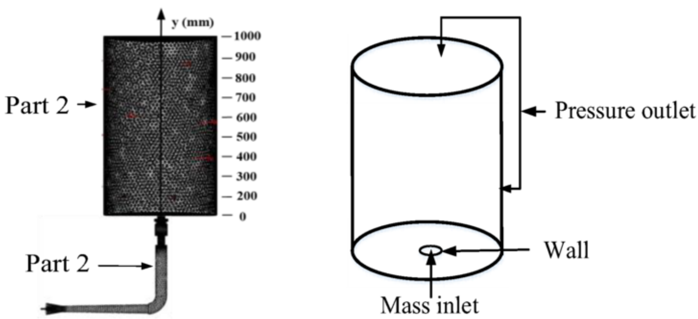
Table 1. Computational setup for Part 1 model

Boundary condition	Model
Inlet boundary condition	Air gauge pressure inlet = 0 pa CNG gauge pressure inlet = 4 psi
Outlet boundary condition	Pressure outlet (air gauge, pressure outlet = 0 pa)
Solver	Pressure base

Time	Steady state
Near-wall treatment method	Standard wall function
Turbulence model	RNG k-ε model
Other species transport	Species transport
LPG (C_3H_8 : C_4H_{10})	70 : 30
CNG (CH_4 : CO_2)	89 : 11

Table 2. Computational setup for Part 2 model.

Boundary condition	Model
Inlet boundary condition	Mass flow inlet (part 1) Mass fraction of (part 1)
Outlet boundary condition	Pressure outlet (air gauge, pressure outlet = 0 Pa)
Solver	Pressure base
Time	Steady state
Near-wall treatment method	Standard wall function
Turbulence model	RNG k- ε model
Radiation model	Discrete ordinates (DO) radiation model
Combustion model	Eddy dissipation model



(a) Mesh (b) Boundary condition at Part 2 model

Figure 3. Computational domain of Part 2 model.

In Part 1 of the simulation, the focus will be on studying the flow features inside the burner. The mass fraction of CH4, CO2, N2, and O2, along with the mass flow rate from Part 1 at the burner exit, will serve as the inlet data for the subsequent simulation in Part 2. The simulation for Part 1 will utilize a Tetrahedral Grid, and after examining an appropriate number of grids (Grid variation), it was determined that 1,413,770 elements constitute a suitable grid for accurate representation. This simulation will adopt a steady-state flow, and the computational conditions for Computational Fluid Dynamics (CFD) are detailed in Table 1.

In Part 2 of the simulation, both Tetrahedral and Square grids will be employed. After evaluating various grid options (Grid variation), it was determined that a grid with 1,402,330 elements, as illustrated in Figure 3(a), provides a suitable representation.

Regarding the boundary conditions for Part 2, the air surrounding the burner is specified as a pressure outlet, as depicted in Fig. 3(b). The burner walls are defined as walls, and the burner head is set as a mass flow inlet. The mass fraction values of CH4, CO2, N2, and O2, along with the mass flow rate, are derived from the CFD calculations of Part 1. The computational setup for Part 2 is detailed in Table 2.

3. Results and Discussion

Figure 4 provides a comparison of the primary air obtained from LPG and CNG at various heat inputs. The primary air naturally flows inside the nozzle due to the injection of both LPG and CNG, as illustrated in Fig. 1. The primary air obtained from the Part 1 model increased with the rising heat input for both fuels, as shown in Fig. 4. Heat input is defined as the product of the mass flow rate (kg/s) and the heating value of the fuel (kJ/kg). The mass flow rates of primary air obtained from CNG consistently surpassed those from LPG at all heat inputs. This disparity arises because the heating value of CNG is lower than that of LPG, leading to a higher mass flow rate for CNG. Consequently, the velocity of CNG is higher than that of LPG at the same heat input. This observation aligns with the theory of compressible fluid flow, where higher fuel velocity induces a greater primary air flow.

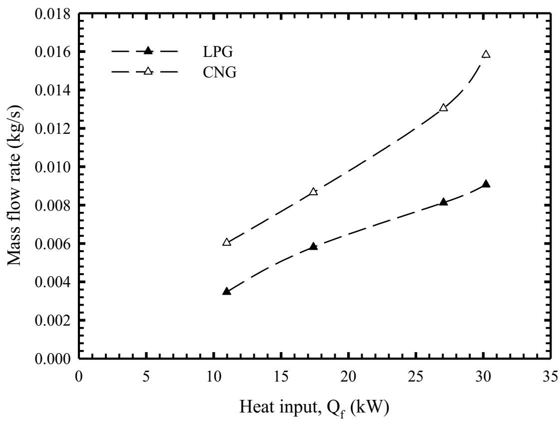
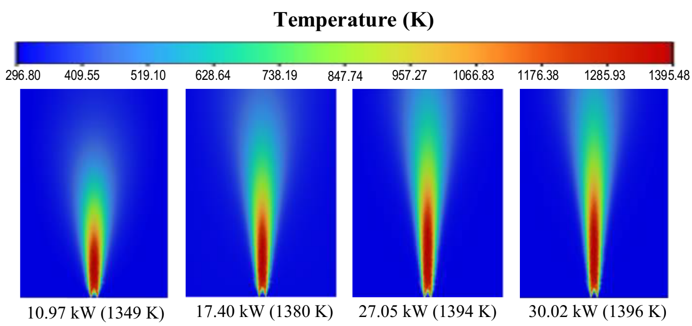
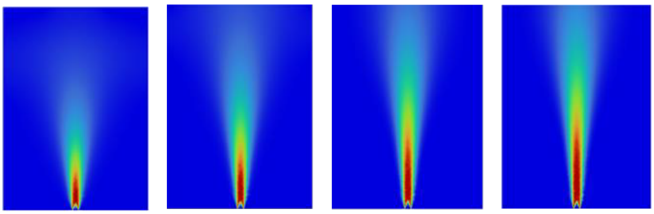


Figure 4. Comparison of primary air obtained from LPG and CNG at various heat inputs.



(a) LPG



(b) CNG

Figure 5. Effect of heat input obtained from LPG and CNG on the temperature contour at mid-plane of Part 2 model.

Figure 5 illustrates the effect of heat input on the temperature contour at the mid-plane of the Part 2 model for both LPG and CNG. The Computational Fluid Dynamics (CFD) results reveal a distinct flame structure, with the highest temperature concentrated inside the flame. Temperature gradually decreases with increasing distance from the core flame and the flame height. As anticipated, an increase in heat input leads to a rise in flame length and maximum temperature. For LPG, the maximum temperatures increased with higher heat inputs: 1349 K at 10.97 kW, 1380 K at 17.40 kW, 1394 K at 27.05 kW, and 1396 K at 30.02 kW. Similarly, for CNG, the corresponding maximum temperatures were higher: 1581 K at 10.97 kW, 1648 K at 17.40 kW, 1752 K at 27.05 kW, and 1842 K at 30.02 kW.Comparing the flame structures of LPG and CNG, it is evident that the flame of CNG is slimmer at all heat inputs. The consistently higher maximum temperatures obtained from CNG, as opposed to LPG at all heat inputs, are attributed to the more effective premix combustion achieved with CNG. This efficiency is attributed to the higher primary air intake from CNG, as illustrated in Fig. 4. It is widely acknowledged that premix combustion is more effective than diffusion combustion under the same conditions.

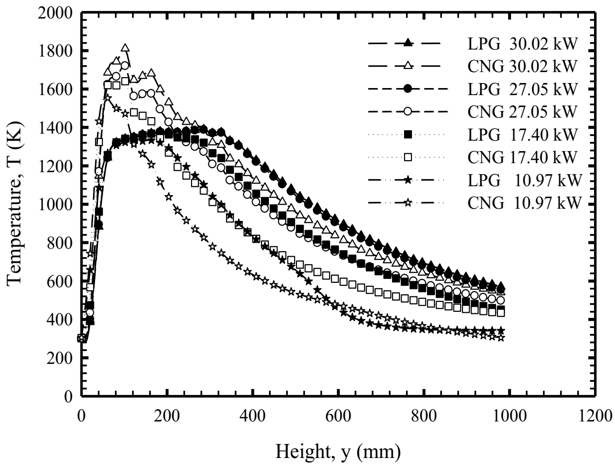


Figure 6. Comparison of combustion temperature obtained from LPG and CNG at the central of Part 2 model for various heat inputs.

Figure 6 presents a comparison of combustion temperatures obtained from LPG and CNG at the center of the Part 2 model for various heat inputs, as illustrated in Fig. 3. In both LPG and CNG, at all heat inputs, the temperature gradually decreases with increasing burner height, consistent with the observations in the temperature contour in Fig. 5. The maximum temperatures obtained from CNG consistently exceed those from LPG at all heat inputs. Specifically, the maximum temperature is observed near the burner exit at around 80-100 mm height for CNG and 280-300 mm height for LPG. This observation leads to the conclusion that the combustion process of CNG is significantly faster than that of LPG. This acceleration is attributed to the higher primary air intake observed in CNG, as shown in Fig. 4, making the premix combustion of CNG more effective than that of LPG. Meanwhile, the lower primary air intake in LPG requires more secondary air, resulting in a lengthened combustion process.

4. Concluding Remark

This paper investigates the combustion temperature of a rocket-type ceramic burner using CFD in a 3D model, specifically comparing the use of CNG with LPG. The developed model accurately captures the flame structure of rocket-type ceramic burners utilizing both fuels. The findings reveal that as the heat input increases, both flame length and maximum temperature rise. At 30.02 kW, maximum temperatures from LPG and CNG were 1396 K and 1842 K, respectively. Importantly, CNG consistently yielded higher maximum temperatures at all heat inputs, attributed to its elevated primary air intake, enhancing premix combustion effectiveness. This suggests that transitioning from LPG to CNG in rocket-type ceramic burners holds potential for energy savings and reduced emissions. Furthermore, the presented ceramic burner model can serve as a valuable tool for designing and optimizing burner efficiency, providing insights for adjusting and enhancing flow parameters in future applications.

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