

Article

Numerical Study on Ignition and Combustion Characteristics of Symmetric and Asymmetric U-Bend Catalytic Micro-Burners: A Comparison with the Straight-Channel Design

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Abstract

Geometric asymmetry in recirculating micro-burners remains underexplored in catalytic micro-combustion research, despite its potential to significantly influence ignition behavior. This numerical study investigates the ignition and combustion characteristics of four micro-channel catalytic burners with distinct geometric configurations, aiming to evaluate the role of asymmetry on combustion behavior. Burner 1 is a straight-channel design without heat recirculation. Burners 2–4 are U-bend recirculating configurations: Burner 2 with symmetric channel sizes, Burner 3 with a wider inlet channel, and Burner 4 with a narrower inlet channel. A two-dimensional computational fluid dynamics model with a one-step global propane oxidation mechanism and catalytic wall reactions is employed. The results show that Burner 1 exhibits the highest ignition temperature (555 K) and shortest ignition delay (28.5 s) due to its low thermal mass. Among U-bend burners, Burner 4 achieves the lowest ignition temperature (530 K) and the highest steady-state combustion temperature (1726 K), owing to reduced recirculation velocity and enhanced thermal feedback. Burner 2 shows moderate performance, while Burner 3 gives the weakest combustion intensity among recirculating designs. The heterogeneous reaction contribution is highest in Burner 1 (69.3%) and lowest in Burners 2 and 3 (~55%). Asymmetric channel sizing, particularly a narrow catalytic channel combined with a wide recirculation channel (Burner 4), significantly improves ignition and combustion performance under cold-start conditions.

Keywords: micro burners; catalytic combustion; geometric asymmetry; thermal recirculation; ignition temperature; numerical simulation



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1. Introduction

Over the past two decades, the rapid development of micro-electro-mechanical systems (MEMS) and portable electronic devices has driven increasing demand for compact, high-energy-density power sources. Traditional batteries often suffer from limited energy storage capacity and long recharging times, prompting researchers to explore alternative power generation technologies [1–4]. Among various candidates, micro-scale combustion-based power systems have emerged as a promising solution due to the high energy density of hydrocarbon fuels and the potential for efficient energy conversion in small-scale devices [5]. However, scaling down conventional burners to millimeter or sub-millimeter dimensions introduces significant challenges, primarily associated with increased heat loss

to the surroundings and reduced residence time for complete fuel conversion. These issues often lead to flame instability, incomplete combustion, and even flame extinction, which severely limit the practical application of micro-burners.

Catalytic combustion has proven to be a particularly effective flame stabilization strategy for micro-scale applications. By coating the channel walls with catalytically active materials such as platinum (Pt) or palladium (Pd), catalytic micro-burners can sustain stable reactions at lower temperatures and under fuel-lean conditions, where homogeneous gas-phase reactions would otherwise be quenched [6].

The extent of catalytic enhancement, however, depends critically on the catalyst activity. Numerical studies in both straight-channel and U-bend configurations identify a sensitive activity range, within which ignition temperature drops substantially [7]. Beyond this range, further increases in catalyst activity yield only modest improvements, indicating diminishing returns [8]. Comparative studies of multi-channel and posted catalytic inserts have shown that while both configurations can enhance surface area and mixing, they exhibit different stability characteristics: channel microreactors are more stable toward high-flow-rate blow-out, whereas post microreactors are significantly more stable at the lower flow-rate extinction limit, allowing operation under more fuel-lean mixtures [9]. The design of the catalytic layer itself has also been shown to significantly influence reactor performance. For instance, the distribution of catalyst within the combustion catalytic layer affects heat and mass transport characteristics, with gradient designs producing more uniform temperature distributions and higher fuel conversion rates [10].

In parallel with catalytic stabilization, thermal recirculation has been recognized as another powerful strategy to enhance combustion performance in micro-scale devices. The concept of excess enthalpy combustion utilizes heat exchange between hot combustion products and the incoming cold fresh mixture to preheat the reactants [5]. This thermal feedback mechanism effectively increases the sensible enthalpy of the reactants without additional energy input. In practice, thermal recirculation is commonly realized through U-bend or spiral channel geometries, where the inlet and outlet channels are placed adjacent to each other, allowing heat transfer through the common dividing wall [5]. The thermal management of such heat-recirculating configurations has been further explored in recent studies. For instance, differentiating the thermal conductivity between inner and outer walls has been shown to simultaneously improve extinction and blowout resistances, thereby enlarging the stable operating window [11]. Moreover, the combined effect of catalyst placement and wall conductivity reveals that optimal coating strategies depend on the input power level and the dominant instability mechanism [12].

Heat recirculating burners exhibit lower ignition temperatures compared to straight-channel designs. This advantage was clearly seen in U-bend catalytic microreactors at high inlet flow rates, which achieved a lower ignition temperature than their straight-channel counterparts [13]. Furthermore, a comparative study of U-bend and spiral micro-burners revealed that the U-bend configuration, which features counter-current heat exchange, is more stable over a wider range of operating conditions, whereas the spiral design achieves higher peak temperatures due to better internal heat recirculation and lower heat loss to the ambient [5]. Additionally, the number of U-bends in multi-bend microchannels also significantly affects thermal performance. A recent CFD-based study on catalytic hydrogen combustion revealed that increasing the U-bend number from 0 to 2 raises the average wall temperature by 18 K and hydrogen conversion by 0.9%, with a moderate pressure drop of 1651 Pa [14]. However, further increasing the bend number from 2 to 5 yields only marginal thermal gains while the pressure drop rises sharply to 7208 Pa, leading to the identification of $U = 2$ as the most balanced design through multi-objective optimization [14].

Effective utilization of both the input energy required for cold-start ignition and the output energy converted for power generation is essential for practical micro-burner systems. Ignition strategies for catalytic micro-burners have been systematically compared in [15]. Three startup modes—feed preheating above ignition temperature, resistive heating using electric power, and spatially distributed resistive heating—exhibit distinct ignition characteristics [15]. Promoting front-end ignition via local heating of the initial reactor section or feed preheating significantly reduces ignition time and emissions. Lower thermal conductivity materials show shorter ignition times for all startup modes, and an optimal startup strategy involves igniting the micro-burner at a low flow rate before increasing it [15]. The integration of micro-burners with energy harvesting devices was explored in [1], where CFD-based multiphysics models were developed to design microcombustor–thermoelectric coupled devices. In such systems, the efficiency of power generation depends on the trade-off between combustion stability and electrical efficiency, and the use of symmetric heat-recirculating reactors with water-cooled heat sinks has been proposed to address this trade-off [1].

Despite the demonstrated benefits of both catalytic walls and thermal recirculation, the interaction between geometric parameters and combustion behavior in recirculating catalytic micro-burners remains insufficiently understood. Specifically, most existing studies have focused on symmetric U-bend configurations, where the inlet and outlet channels possess identical cross-sectional dimensions. However, from a design perspective, the channel gap sizes on the inlet and outlet sides may not necessarily be equal. Introducing geometric asymmetry—i.e., making the inlet channel wider or narrower than the outlet channel—could alter the flow velocity distribution, residence time, and heat transfer efficiency within the recirculation zone, thereby affecting the overall combustion performance. To date, systematic investigations on the role of such geometric asymmetry in catalytic U-bend micro-burners are still lacking in the literature. The present study fills this gap by numerically investigating the ignition and combustion characteristics of four micro-channel catalytic burner configurations, comparing symmetric and asymmetric U-bend designs against the straight-channel baseline without any recirculation.

The remainder of this paper is organized as follows. Section 2 describes the geometric models, governing equations, numerical methods, and boundary conditions. Section 3 presents the results and discussion, including ignition temperature, ignition delay, steady-state temperature distributions, species profiles, and reaction contribution analysis. Finally, Section 4 summarizes the main conclusions and suggests directions for future work.

2. Results and Discussion

This numerical work simulates the ignition and combustion behavior of four micro-burners. Initially, steady-state simulations were performed to determine the minimum inlet gas temperature required for ignition, defined as the ignition temperature. Then, with the inlet temperature set at 10 K above the ignition temperature while keeping the mass flow rate unchanged, transient simulations were carried out to observe the dynamic ignition and combustion processes. The results are presented from two perspectives: temporal evolution and steady-state combustion characteristics.

2.1. Determination of Ignition Temperature

Figure 1 presents the maximum temperature as a function of inlet gas temperature for the four burners.

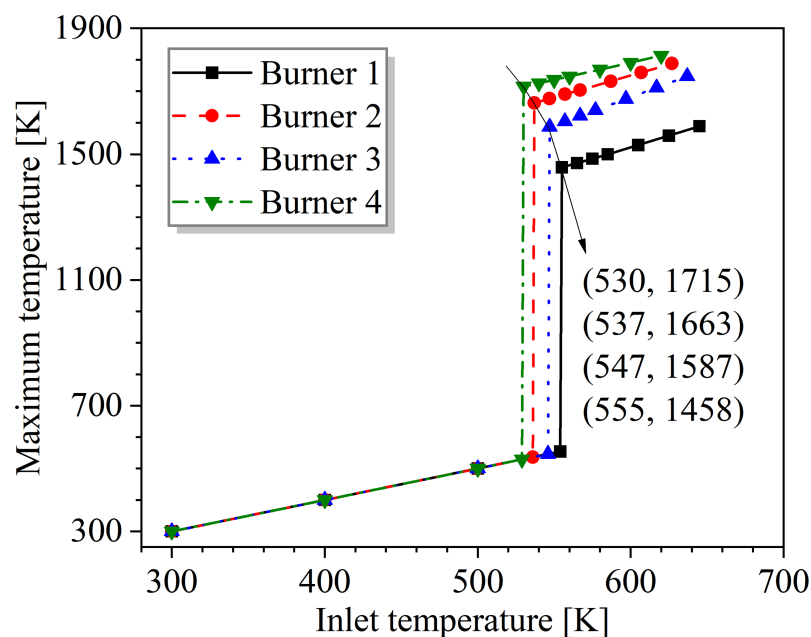


Figure 1. Maximum temperature as a function of inlet temperature.

For each burner, a critical temperature exists. Below this temperature, the maximum temperature remains nearly equal to the inlet temperature, indicating no ignition. At or above this critical temperature, the maximum temperature rises sharply above the inlet temperature, marking the onset of ignition. This critical temperature is defined as the ignition temperature. As summarized in Figure 1, Burner 1 yields the highest ignition temperature (555 K), followed by Burner 3 (547 K), Burner 2 (537 K), and Burner 4 (530 K). The high ignition temperature of Burner 1 is explained by its straight-channel geometry, which lacks any heat-recovery mechanism to preheat the incoming fresh mixture. In contrast, Burner 4 exhibits the lowest ignition temperature. This favorable behavior stems from its reduced catalytic channel gap size, which, under the same mass flow rate, leads to a higher flow velocity there. Meanwhile, the benefit of Burner 4 is the extended heat exchange duration resulting from the lower flow velocity in its recirculating channel, which enhances thermal recirculation efficiency and improves preheating of the fresh mixture. From a practical standpoint, a lower ignition temperature is highly desirable for portable micro-combustor devices, as it reduces the external energy input required for start-up and enhances system robustness under cold-start conditions. Additionally, for all burners, the maximum temperature increases monotonically with inlet temperature. This trend is physically consistent: a higher inlet temperature raises the sensible enthalpy of the reactants, meaning the incoming gas already carries more thermal energy. Meanwhile, the fuel flow rate—and hence the total heat release from combustion—remains fixed. Hence, the flame temperature is elevated, leading to a higher maximum temperature in the burner.

2.2. Comparison of Ignition Temperatures of the Catalytic Micro-Burners

Figure 2 compares the ignition temperature and the maximum temperature (obtained at an inlet temperature 10 K above the ignition temperature) for the four burners at a fixed inlet mass flow rate. Consistent with Figure 1, Burner 1—characterized by a straight-channel configuration without heat recovery—exhibits the highest ignition temperature. Among the remaining burners, Burner 4 has the smallest gap size in the catalytic channel and the largest gap size in the recirculating channel. This geometric feature results in the lowest flow velocity within the recirculating channel, which prolongs the residence time of hot products and thus improves heat transfer to the incoming fresh mixture. As

a result, Burner 4 achieves the lowest ignition temperature. Interestingly, the ranking of maximum temperature across the burners is inversely related to that of ignition temperature. Specifically, burners with lower ignition temperatures tend to yield higher maximum temperatures. Although Burner 3 operates with a higher inlet temperature—meaning it carries greater sensible heat and more initial thermal energy—its maximum temperature is still lower than those of Burners 2 and 4, both of which have lower inlet temperatures. This finding highlights that heat recovery plays a dominant role in combustion enhancement.

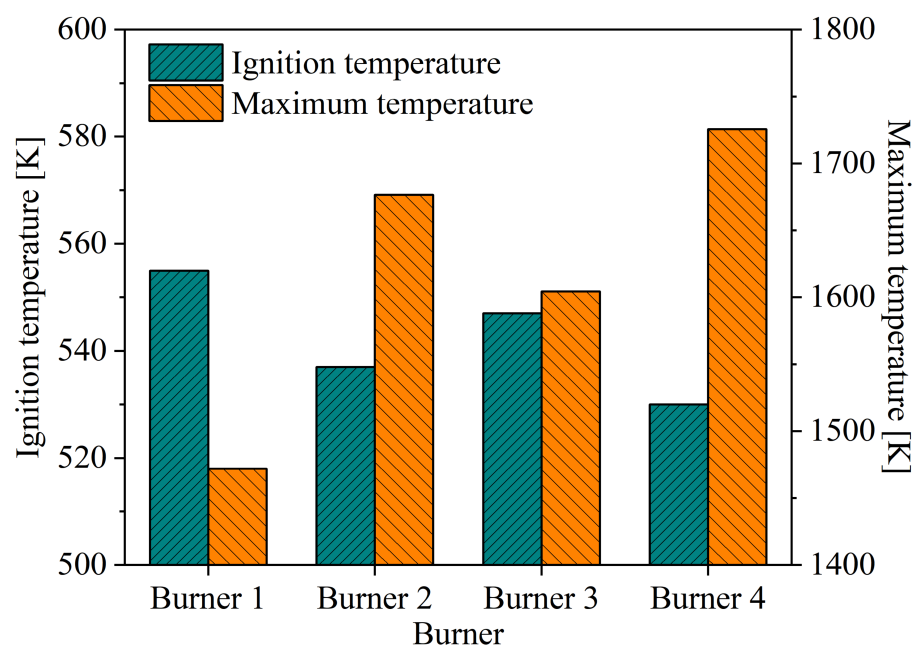


Figure 2. Ignition temperatures of catalytic micro-burners 1–4.

2.3. Comparison of Combustion Performances of the Catalytic Micro-Burners

Figure 3 compares the combustion performance of four micro-burners under identical inlet mass flow rates. Despite having the highest inlet temperature, Burner 1 exhibits the lowest peak temperature and a relatively downstream flame location, confirming that without thermal recirculation, combustion intensity remains limited. Among the U-bend burners, Burner 4 achieves the best performance: the highest peak temperature and the most upstream flame location, even though its inlet temperature is the lowest. This is attributed to its large recirculating channel, which reduces recirculation flow velocity. Lower recirculation velocity increases the residence time of hot combustion products within the recirculation zone, allowing more effective heat transfer to the incoming fresh mixture. Strong thermal feedback thus overcomes the disadvantages of low inlet temperature and high inlet velocity (due to the small inlet channel). Burner 3 shows the opposite trend. Although its inlet temperature is relatively high and its inlet velocity is low, its small recirculating channel forces recirculation flow to move faster. The shorter residence time limits heat transfer from hot products to fresh gas, resulting in weak thermal feedback. Consequently, Burner 3 has the lowest peak temperature among U-bend burners and the most downstream flame location. Burner 2 performs moderately, with a peak temperature of 1677 K and an intermediate flame location.

These results point to a clear design guideline for U-bend micro-burners: under fixed mass flow conditions, enlarging the recirculating channel cross-section to reduce recirculation velocity is an effective strategy to maximize thermal feedback and combustion intensity, which is directly relevant to enhancing power density in micro-combustor applications.

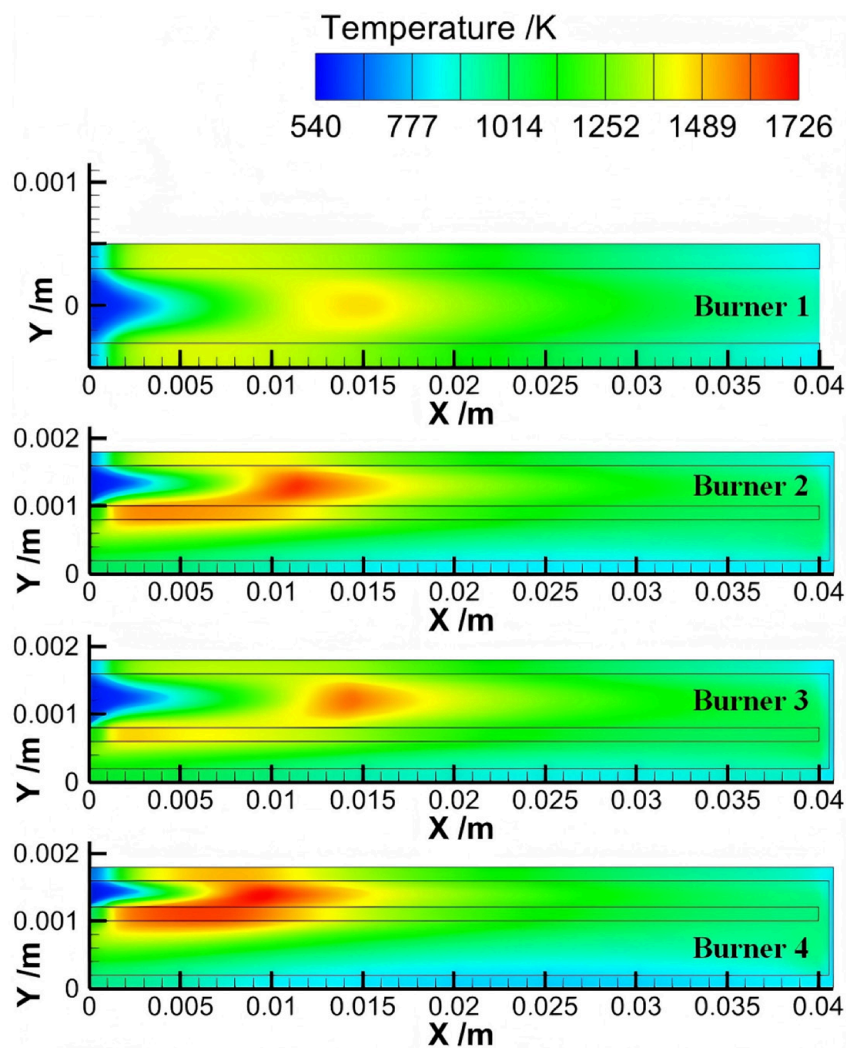


Figure 3. Temperature distributions of catalytic micro-burners 1–4 with inlet temperatures of 565 K, 547 K, 557 K, and 540 K, respectively.

2.4. Comparison of Species Mass Fraction Distributions of the Catalytic Micro-Burners

Figure 4 presents the steady-state mass fraction distributions of key species—namely propane, oxygen, carbon dioxide, and water—measured along the centreline of the burner. Data are shown for four different burner configurations. To begin with the CO_2 profiles provided in the figure, a clear differentiation emerges among the burners. All four burners exhibit similar trends, with CO_2 levels rising gradually and reaching a plateau at greater axial distances. In terms of the distance from the inlet where CO_2 begins to stabilize, Burner 2 shows a closer position, while Burner 4 exhibits the closest position among the four burners. For Burner 1 and Burner 3, the complete consumption of propane occurs farthest from the burner inlet, indicating a longer flame development zone. Conversely, Burner 2 and Burner 4 show reactant depletion much closer to the inlet, with Burner 4 having the shortest depletion distance of all four configurations. This order—Burner 4 being the most compact, followed by Burner 2, then Burners 1 and 3 being the most extended—is highly consistent with the primary combustion zone behavior reported earlier. Specifically, this trend directly mirrors the temperature distributions presented in Figure 3, where Burner 4 also exhibited the most rapid temperature rise near the inlet, while Burners 1 and 3 showed slower thermal development. Therefore, Figure 4 confirms that geometric differences among the burners lead to variations in the axial distance required for full species conversion.

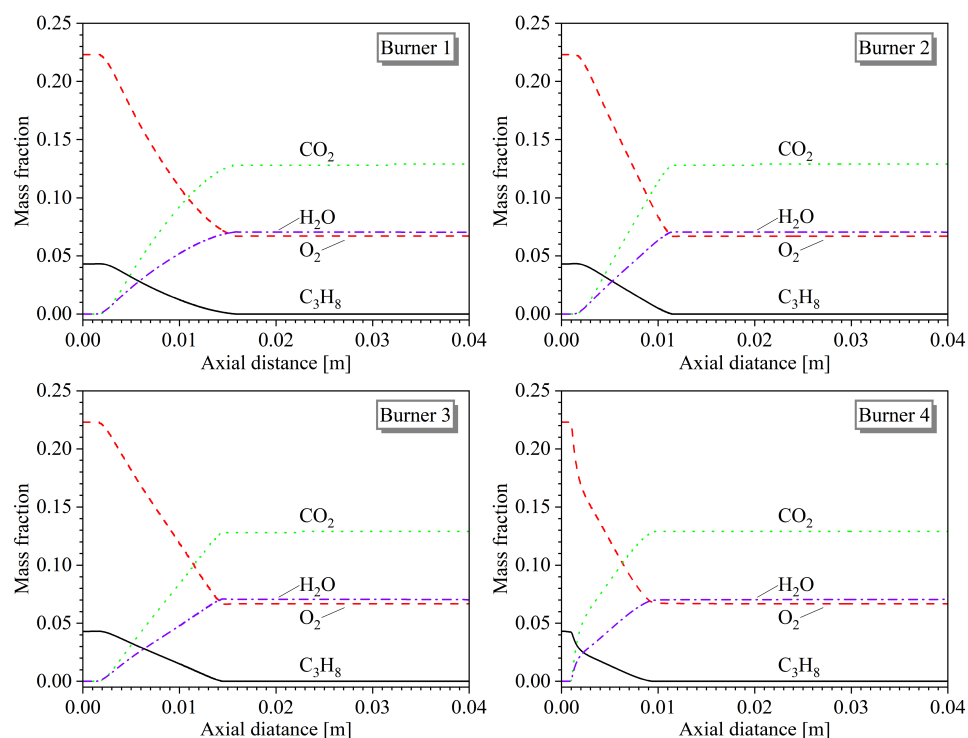


Figure 4. Species mass fraction distributions along the axial direction for catalytic micro-burners 1–4.

2.5. Comparison of Ignition Delay Times of the Catalytic Micro-Burners

Figure 5 shows the ignition delay times for the four burners under cold-start conditions (initial temperature 300 K). Here we define the ignition delay as the time required to reach 50% propane conversion at the micro-burner exit. Burner 1 has the shortest delay at 28.5 s, followed by Burner 3 (67.5 s) and Burner 4 (68.3 s), while Burner 2 has the longest at 72.2 s.

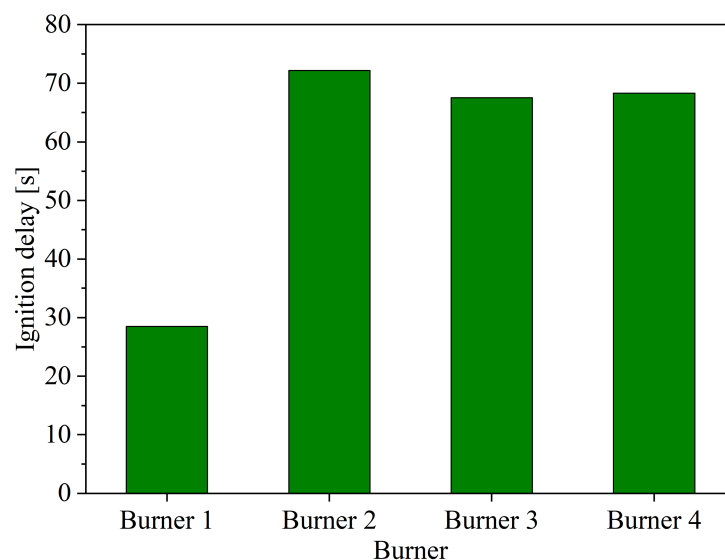


Figure 5. Ignition delay times of catalytic micro-burners 1–4.

However, it is important to note that the difference between Burners 2, 3, and 4 (approximately 4–5 s) is much smaller than the difference between Burner 1 and any U-bend burner (approximately 40 s). This indicates that the asymmetry pattern plays a negligible role in determining the ignition delay under cold-start conditions, compared to the presence or absence of a recirculation structure in the burner.

2.6. Comparison of HR and HTR Contributions of the Catalytic Micro-Burners

Figure 6 compares the heterogeneous reaction (HTR) contribution across the four burners, along with the corresponding homogeneous reaction (HR) contribution. Here, HTR contribution refers to the fraction of fuel consumed by catalytic reactions on the catalytic walls. For each burner, the HTR and HR contributions sum to 1, since all fuel consumed is either through catalytic reactions on the catalytic walls or through gas-phase reactions in the bulk flow.

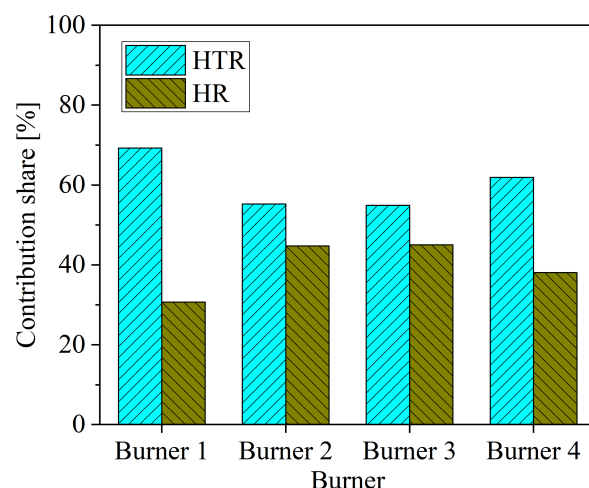


Figure 6. HTR and HR contributions of catalytic micro-burners 1–4.

Burner 1 exhibits the highest HTR contribution. The absence of any thermal recirculation structure keeps the temperature level low, thereby suppressing gas-phase reaction kinetics and directing most of the fuel toward oxidation on the catalytic walls. Burner 4 shows the second highest HTR at 61.9%. This burner features a small-gap catalytic channel. The narrow channel geometry physically restricts the development of gas-phase reactions, likely by reducing the volume available for homogeneous combustion. Thus, even though Burner 4 achieves the highest peak temperature, the geometric confinement favors catalytic over homogeneous consumption. Burners 2 and 3 have nearly identical HTR contributions at approximately 55%. Burner 3 has a larger catalytic channel gap size than Burner 2, which would be expected to promote gas-phase reactions. However, Burner 3 operates at a lower temperature level compared to Burner 2. The lower temperature inhibits homogeneous reaction rates, canceling out the geometric advantage. As a result, the two burners end up with similar partitioning between catalytic and gas-phase fuel consumption.

These observations highlight a key principle in catalytic micro-burner design: the balance between heterogeneous and homogeneous reactions is governed by both thermal conditions and geometric constraints.

3. Mathematical Model

3.1. Model Description

In the present study, four micro-channel catalytic burner configurations are numerically investigated to evaluate the role of geometric asymmetry on combustion behavior. Burner 1 is a straight-channel baseline configuration without any recirculation. Burner 2 is a symmetric U-bend (recirculating) configuration consisting of an inlet channel and an outlet channel of equal cross-sectional side length, allowing the fresh reactant mixture to be preheated by the hot exhaust gases via heat transfer through the dividing wall, representing a typical recirculating burner. Burner 3 is a U-bend recirculating burner where the inlet channel gap size is larger than that of the outlet channel. Burner 4 is a U-bend recirculating

burner where the inlet channel gap size is smaller than that of the outlet channel. The comparative analysis among these four burners centers on their ignition and combustion behaviors, with particular emphasis on key metrics: ignition temperature, ignition delay time, and steady-state combustion performance. The dimensions of the two-dimensional geometric models are provided in Figure 7. The four micro-burners feature the same channel length of 40 mm and wall thickness of 0.2 mm.

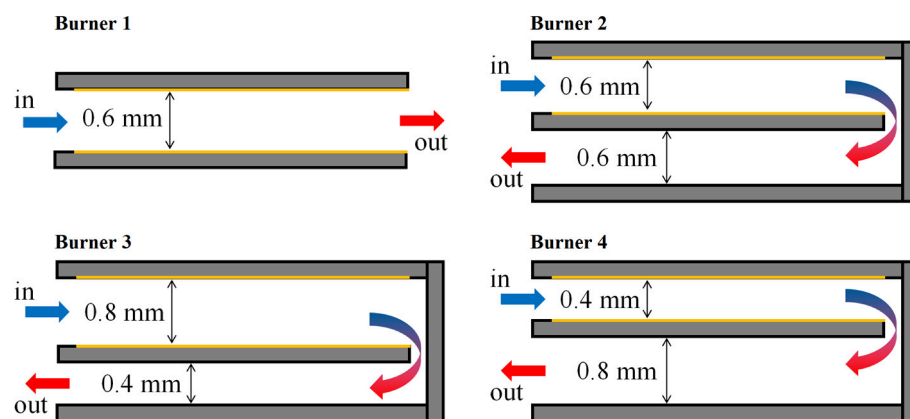


Figure 7. Two-dimensional geometric configurations of catalytic micro-burners 1–4.

Before presenting the governing equations, the following assumptions are made:

- (1) In view of the large width-to-height aspect ratio, the burners are modeled as two-dimensional domains in the present study;
- (2) The flow is laminar and incompressible;
- (3) The inlet velocity is taken as a uniform profile across the channel cross-section;
- (4) Body forces are negligible;
- (5) No internal heat sources other than chemical reactions are considered.

Based on the above assumptions, the governing equations for mass, momentum, species, and energy are expressed as follows.

Continuity equation

$$\frac{\partial \rho_g}{\partial t} + \nabla \cdot (\rho_g V) = 0 \quad (1)$$

where ρ_g represents the density of the gas mixture.

Momentum conservation equation

$$\frac{\partial (\rho_g V)}{\partial t} + \nabla \cdot (\rho_g VV) = -\nabla P + \nabla \cdot \mu \left[\left(\nabla V + (\nabla V)^T - \frac{2}{3} (\nabla \cdot V) I \right) \right] \quad (2)$$

where P denotes the pressure, and μ stands for the dynamic viscosity.

Gas energy conservation equation

$$\frac{\partial (\rho_g h_g)}{\partial t} + \nabla \cdot (\rho_g h_g V) = \nabla \cdot (\lambda_g \nabla T - \sum_i^{n_{\text{gpc}}} h_i J_i) + \sum_i^{n_{\text{gpc}}} h_i R_i^{\text{gas}} \quad (3)$$

where h_g denotes the gas enthalpy, λ_g represents the gas thermal conductivity, and J_i is the diffusion flux of the i -th component.

Solid energy conservation equation

$$\frac{\partial (\rho_s h_s)}{\partial t} = \nabla \cdot (\lambda_s \nabla T) \quad (4)$$

where h_s is the solid enthalpy, and λ_s denotes the solid thermal conductivity.

Species conservation equation

$$\frac{\partial(\rho_g Y_i)}{\partial t} + \nabla \cdot (\rho_g Y_i V + J_i) = R_i^{\text{gas}} \quad (5)$$

where Y_i is the mass fraction of the i -th component.

The global reaction equation governing propane oxidation can be written as follows:



The homogeneous reaction kinetics of propane are described by a one-step global mechanism [16]:

$$r_{\text{homo}} = 4.836 \times 10^9 e^{(-\frac{1.256 \times 10^8}{RT})} c_{\text{C}_3\text{H}_8}^{0.1} c_{\text{O}_2}^{1.65} \quad (7)$$

where c is the molar concentration.

The heterogeneous reaction kinetics of propane are governed by the following single-step reduced-order mechanism [17], which was derived from a systematic reduction of a detailed microkinetic model for small alkanes on Pt, with propane-specific parameters provided in the original study, and which has been successfully adopted and validated in several subsequent studies [5,9,13].

$$r_{\text{hete}} = \frac{\eta k_{\text{C}_3\text{H}_8}^{\text{ads}} X_{\text{C}_3\text{H}_8}}{\left(1 + \sqrt{\frac{k_{\text{O}_2}^{\text{ads}} X_{\text{O}_2}}{k_{\text{O}_2}^{\text{des}}}}\right)^2} \quad (8)$$

where k^{ads} and k^{des} represent the adsorption and desorption rate constants, respectively, and are computed by the following expressions:

$$k_i^{\text{ads}} = \frac{s_i P_{\text{tot}} e^{-E_{a,i}^{\text{ads}}/RT}}{\Gamma \sqrt{2\pi M_i RT}} \left(\frac{T}{T_{\text{ref}}}\right)^{\beta_i^{\text{ads}}} \quad (9)$$

$$k_i^{\text{des}} = A_i e^{-E_{a,i}^{\text{des}}/RT} \left(\frac{T}{T_{\text{ref}}}\right)^{\beta_i^{\text{des}}} \quad (10)$$

where s and A represent the sticking coefficient and the pre-exponential factor, respectively. The activation energy for the oxygen desorption is given by the following [18]:

$$E_{\text{O}_2}^{\text{des}} = 0.126T_r^4 - 1.849T_r^3 + 9.142T_r^2 - 13.253T_r + 23.903 \quad (11)$$

where $T_r = T/T_{\text{ref}}$ denotes the temperature ratio.

The specific values of the kinetic rate parameters for propane catalytic combustion are summarized in Table 1. The surface catalytic reaction mechanism is integrated with the ANSYS Fluent standard modules through a user-defined function (UDF).

Table 1. Specific values of the kinetic rate parameters for propane catalytic combustion.

Parameter	Value/Description
Catalyst material	Pt/Al ₂ O ₃
Active surface area factor	1.7
Site density	2.9×10^{-9} mol/cm ²
Sticking coefficient (C ₃ H ₈)	0.06
Sticking coefficient (O ₂)	0.0542
Temperature exponent (C ₃ H ₈ adsorption)	0.154

Table 1. *Cont.*

Parameter	Value/Description
Temperature exponent (O ₂ adsorption)	0.766
Activation energy (C ₃ H ₈ adsorption)	4 kcal/mol
Activation energy (O ₂ adsorption)	0 kcal/mol
Pre-exponential factor (O ₂ desorption)	8.41×10^{12}
Temperature exponent (O ₂ desorption)	−0.796

3.2. Meshing, Boundary Conditions, Physical Properties, and Solution Strategy

A structured quadrilateral mesh with a uniform edge length of 0.02 mm is employed for all configurations. Under this grid setting, the total cell counts for Burner 1 (straight channel), Burner 2 (symmetric U-bend), Burner 3 (wide inlet U-bend), and Burner 4 (narrow inlet U-bend) are 50,000, 183,600, 183,600, and 183,600, respectively. The adequacy of this mesh density is verified through a grid independence study. Using Burner 3 as the test case, the results obtained from the refined mesh (470,016 square elements with a side length of 0.0125 mm) were compared with those from the baseline mesh (183,600 square elements with a side length of 0.02 mm). With the refined mesh, ignition was observed at 547 K but not at 546 K, consistent with the baseline mesh, indicating a difference of less than 1 K in predicted ignition temperature. At an inlet temperature of 557 K, the refined mesh yielded a peak temperature of 1603.35 K and an HTR fraction of 55.01%, compared with 1604.28 K and 54.92% from the baseline mesh. These discrepancies are substantially smaller than the performance differences observed between burner configurations, confirming that the current grid resolution is sufficient.

The boundary conditions are specified as follows. At the inlet, a mass-flow inlet boundary condition is applied. The mass flow rate is fixed at the value obtained for a propane/air mixture at $\phi = 0.7$ under standard conditions, assuming an inlet velocity of 5 m/s and a catalytic channel gap of 0.6 mm. For burners with different catalytic channel gap sizes, the inlet velocity varies accordingly to maintain this constant mass flow rate, ensuring identical thermal power input across all cases. At the outlet, a pressure outlet boundary condition is set at one atmosphere. For the outer walls, a mixed thermal boundary condition combining convection and radiation is employed, with an ambient temperature of 300 K, a convective heat transfer coefficient of 15 W/(m²·K), and an emissivity of 0.5. The inner walls (fluid–solid interfaces) are subjected to no-slip conditions and are treated as thermally coupled.

The thermophysical properties of the materials are specified as follows. For the gas phase (propane/air mixture and combustion products), the gas mixture is treated as an ideal gas, and accordingly the density is computed using the ideal gas law. The specific heat capacity of each individual species is expressed as a fifth-order piecewise polynomial function of temperature, while the mixture-specific heat capacity is obtained via mixing law. The thermal conductivity and viscosity of each species are determined from kinetic theory, and those of the gas mixture are calculated using the mass-weighted mixing law. The mass diffusion coefficients are computed via the kinetic-theory formulation with Lennard–Jones parameters, combined with the mixture-averaged model for the diffusion fluxes. For the solid phase (channel wall), the density is 2800 kg/m³, the specific heat capacity is 900 J/(kg·K), and the thermal conductivity is 2 W/(m·K).

The governing equations are discretized and solved using a finite volume method implemented in ANSYS Fluent 14.0. The SIMPLE algorithm is utilized to handle the pressure–velocity coupling. A second-order upwind scheme is employed for the discretization of convective terms in the momentum, energy, and species transport equations. The time step size is set to 0.01 s. The adequacy of this value was verified through a time-step

sensitivity test on Burner 3 at an inlet temperature of 557 K, in which reducing the time step to 0.001 s changed the predicted ignition time by less than 0.1 s (both cases gave 67.5 s). The convergence criteria are set to 1×10^{-8} for the energy residual and to 1×10^{-4} for the continuity, momentum, and species residuals.

3.3. Model Validation

The reliability of the present model is assessed by comparing its predictions with the experimental measurements of Lu et al. [19] under typical operating conditions (inlet velocity of 0.3 m/s and equivalence ratio of 1.0).

As shown in Figure 8, the simulated axial wall temperature distribution closely follows the experimental profile, especially in capturing the position where the peak temperature appears. Quantitatively, the maximum absolute deviation, occurring near the outlet, is 27 K, yielding a relative error of about 3.1%. Such discrepancies are acceptable and can be mainly attributed to the use of a one-step global reaction mechanism, which tends to slightly overpredict the flame temperature, and the neglect of modeling the porous catalyst coating as a distinct layer. Overall, the low error level confirms that the present computational framework offers sufficient accuracy for the parametric studies conducted in this work.

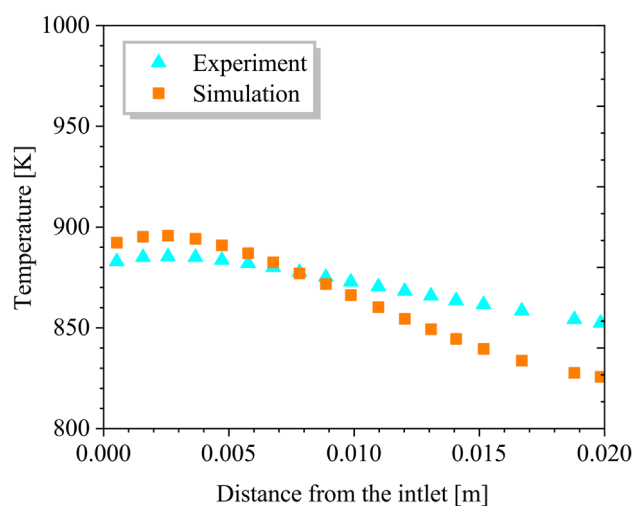


Figure 8. Comparison of the axial wall temperature distribution between simulation results and experimental data [19].

4. Conclusions

This numerical study compares four micro-channel catalytic burners to assess the impact of geometric asymmetry on ignition and combustion characteristics. The main conclusions are as follows.

1. Thermal recirculation significantly lowers ignition temperature compared to the straight-channel design. Among recirculating burners, Burner 4 achieves the lowest ignition temperature (530 K), outperforming the symmetric Burner 2 (537 K) and Burner 3 (547 K). This is attributed to reduced recirculation velocity and prolonged heat exchange.
2. Ignition delay is dominated by the total thermal mass of the burner. The straight-channel burner ignites fastest (28.5 s) due to minimal solid material. All U-bend burners require much longer delays (67.5–72.2 s), with asymmetry causing only minor differences (~4–5 s).
3. Steady-state combustion performance follows an opposite trend to ignition temperature. Burner 4 yields the highest peak temperature despite the lowest inlet temperature, while Burner 1 yields the lowest peak temperature. Effective thermal recirculation compensates for lower inlet sensible heat.

4. Regarding HTR contribution, Burner 1 exhibits the highest value (69.3%) due to its low temperature level suppressing gas-phase reactions. Burner 4 follows with 61.9%, where geometric confinement in the narrow catalytic channel limits homogeneous reaction space. Burners 2 and 3 show similar HTR contributions (55%), indicating a trade-off between thermal and geometric effects.

From a design perspective, a U-bend burner with a narrow catalytic channel and a wide recirculation channel provides the best overall performance for devices and applications requiring rapid start-up and high combustion temperatures. It should be noted that the present model adopts a one-step global reaction scheme for both gas-phase and catalytic surface reactions. This simplification does not resolve the detailed radical chemistry or the coupling between homogeneous and heterogeneous reactions through intermediate species, which may be important for accurately predicting ignition and extinction limits in catalytic micro-burners. Employing reduced or detailed kinetic mechanisms would help provide a more quantitative assessment of the observed trends. Future work should also focus on the development of experimental prototypes to validate the optimized asymmetric configuration of Burner 4 under realistic operating conditions, as well as parametric sweeps over a range of inlet velocities and equivalence ratios to assess its operational flexibility.

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References

1. Yedala, N.; Kaisare, N.S. Design of microcombustor–thermoelectric coupled device using a CFD-based multiphysics model for power generation. *React. Chem. Eng.* **2024**, *9*, 2135–2148. [\[CrossRef\]](#)
2. Karim, A.M.; Federici, J.A.; Vlachos, D.G. Portable power production from methanol in an integrated thermoelectric/microreactor system. *J. Power Sources* **2008**, *179*, 113–120. [\[CrossRef\]](#)
3. Lin, E.; Wilson, C.T.; Leroy, A.; El Fil, B. High energy density entrainment-based catalytic micro-combustor for portable devices. *Energy Convers. Manag.* **2023**, *285*, 117014. [\[CrossRef\]](#)
4. Chen, J.; Qin, X. Computational modelling of methanol autothermal reforming phenomena in microchannel reactors for hydrogen production. *Fuel* **2024**, *371*, 131887. [\[CrossRef\]](#)
5. Raghu, A.K.; Kaisare, N.S. Study of propane/air catalytic combustion in heat recirculating U-bend and spiral microcombustors. *J. Flow Chem.* **2021**, *11*, 345–355. [\[CrossRef\]](#)
6. Baigmohammadi, M.; Tabejamaat, S.; Zarvandi, J. Numerical study of the behavior of methane-hydrogen/air pre-mixed flame in a micro reactor equipped with catalytic segmented bluff body. *Energy* **2015**, *85*, 117–144. [\[CrossRef\]](#)
7. Wang, Z.; Wang, Z.; Miao, Z.; Ma, L.; Xu, W.; Li, Z.; Yang, Z.; Jiang, G. Propane ignition characteristics in a Pt-catalyzed microreactor for SOFC preheating: A numerical study of catalyst activity effects. *Batteries* **2025**, *11*, 390. [\[CrossRef\]](#)
8. Li, Z.; Yu, M.; Bi, J.; Yang, H.; Wang, X.; Wang, Z.; Wu, G.; Yang, Z. Effect of catalytic activity on ignition and combustion characteristics in a propane-fueled U-bend micro-reactor: Numerical modeling with catalyst coating as reactive wall. *Coatings* **2026**, *16*, 419. [\[CrossRef\]](#)
9. Regatte, V.R.; Kaisare, N.S. Propane combustion in non-adiabatic microreactors: 1. Comparison of channel and posted catalytic inserts. *Chem. Eng. Sci.* **2011**, *66*, 1123–1131. [\[CrossRef\]](#)

10. Kong, W.; Shen, Q.; Huang, N.; Yan, M.; Li, S. Effect of catalyst distribution in the combustion catalytic layer on heat and mass transport characteristics of the microchannel reactor. *Int. J. Numer. Methods Heat Fluid Flow* **2024**, *34*, 2539–2559. [[CrossRef](#)]
11. Di Sarli, V. The effect of differentiating the thermal conductivity between inner and outer walls on the stability of a U-bend catalytic heat-recirculating micro-combustor: A CFD study. *Appl. Sci.* **2021**, *11*, 5418. [[CrossRef](#)]
12. Kaisare, N.S.; Di Sarli, V. The effect of catalyst placement on the stability of a U-bend catalytic heat-recirculating micro-combustor: A Numerical Investigation. *Catalysts* **2021**, *11*, 1560. [[CrossRef](#)]
13. Yedala, N.; Kaisare, N.S. A CFD study of ignition of lean propane-air mixtures in a heat recirculating U-bend catalytic microreactor. *Chem. Eng. Res. Des.* **2021**, *173*, 15–26. [[CrossRef](#)]
14. Guo, S.; Hui, Y.; Qiu, Y.; Zhao, P.; Wang, M.; Bhattacharya, S.; Dai, B.; Yu, J. Thermal performance and mechanistic role of U-bend number in microchannel catalytic hydrogen combustion: A CFD-Based study. *Energy* **2026**, *352*, 140921. [[CrossRef](#)]
15. Kaisare, N.S.; Stefanidis, G.D.; Vlachos, D.G. Comparison of ignition strategies for catalytic microburners. *Proc. Combust. Inst.* **2009**, *32*, 3027–3034. [[CrossRef](#)]
16. Westbrook, C.K.; Dryer, F.L. Simplified reaction mechanisms for the oxidation of hydrocarbon fuels in flames. *Combust. Sci. Technol.* **1981**, *27*, 31–43. [[CrossRef](#)]
17. Deshmukh, S.R.; Vlachos, D.G. A reduced mechanism for methane and one-step rate expressions for fuel-lean catalytic combustion of small alkanes on noble metals. *Combust. Flame* **2007**, *149*, 366–383. [[CrossRef](#)]
18. Regatte, V.R.; Selle, G.; Kaisare, N.S. The role of homogeneous chemistry during ignition of propane combustion in Pt-catalyzed microburners. *Int. J. Spray Combust. Dyn.* **2012**, *4*, 155–174. [[CrossRef](#)]
19. Lu, Q.; Zhou, H.; Zhang, Y.; Gou, J.; Fan, B.; Jiang, C.; Yang, W.; Yuan, J.; Pan, J. Experimental and numerical investigations on hetero-/homogeneous combustion characteristics of C₃H₈/Air mixtures in the micro catalytic combustor. *Appl. Therm. Eng.* **2025**, *274*, 126638. [[CrossRef](#)]

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