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Microscale Combustion: Principles, Challenges, and Prospects of Microchannel Burners

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Abstract: Microscale combustion technology is a cutting-edge direction in the field of energy miniaturization and high efficiency, offering potential advantages such as high energy density, excellent integration, and superior combustion efficiency. As a core component enabling microscale combustion, microchannel burners demonstrate broad application prospects in areas like microenergy systems, micropropulsion, and portable thermoelectric conversion. This paper provides a systematic review of the fundamental working principles and structural characteristics of microchannel burners, with a focus on analyzing key challenges (e.g., flame stability, heat transfer losses, material limitations) and corresponding enhancement strategies (regenerative, catalytic, structural optimization). Additionally, it examines the current application status in fields such as miniature thermoelectric systems and micropropulsion, identifies existing research limitations, and outlines future development trends, aiming to provide references for in-depth research and engineering applications of microchannel combustion technology.

Keywords: Microscale Combustion; Flame Stability; Heat Loss; Micro Energy System.

1. Introduction

With the rapid development of Micro Electro Mechanical Systems (MEMS) technology, portable electronic devices, and micro spacecraft, the demand for efficient, compact, and long-range miniaturized power and energy supply systems is becoming increasingly urgent [1]. The energy density of traditional batteries is limited (usually below 1 MJ/kg), making it difficult to meet the increasing energy demand. Carbon hydrogen fuels exhibit significant advantages, with an energy density (approximately 45 MJ/kg) that is 1-2 orders of magnitude higher than lithium-ion batteries. Therefore, efficiently converting the chemical energy of fuel into usable energy (thermal energy, electrical energy, or thrust) through micro combustion devices has become a highly attractive solution. [2]

Micro porous burner usually refers to a combustion reaction device made of high-temperature resistant materials (such as quartz glass, ceramics, stainless steel, silicon-based materials, etc.), with internal flow channel characteristic dimensions in the microscale range [3]. Its basic structure mainly includes fuel/oxidant premix or supply inlet, microscale combustion reaction chamber (i.e. microchannel), and exhaust port. According to application requirements, there are various structural forms, which can be divided into single channel straight pipe type, multi-channel parallel type, reheating type, porous medium filling type, catalytic type, etc. [4]

The combustion process in microchannels follows the laws of conservation of mass, momentum, and energy, as well as chemical reaction kinetics, but its dominant mechanism changes due to scale effects [5]. Its working principle can be summarized as follows: pre mixed or non pre mixed combustible mixtures enter the microchannel, are ignited at a certain position, and form a propagating flame or a stationary reaction zone. Chemical energy is released through combustion reactions, most of which are converted into heat energy, heating the combustion products and walls. These thermal energies can be utilized in different ways: for example, heating the heat absorbing end of a thermoelectric module to generate electricity; Heating and propelling the working fluid to generate thrust; Or directly used as a miniature heat source. [6]

Micro combustion technology is the core link to achieve the above-mentioned micro energy conversion. As the core site for carrying microscale combustion reactions, the typical characteristic size (hydraulic diameter) of microchannel burners is in the sub millimeter to millimeter range. At such a small scale, the physical and chemical processes of combustion exhibit significantly different characteristics from conventional scales, such as a sharp increase in surface area to volume ratio leading to a significant increase in heat loss, enhanced quenching effect of free radicals on the wall, and the problem of matching the time/space scale of flow and reaction, making it a huge challenge to maintain stable, efficient, and complete combustion. Since the late 1990s, research on microchannel burners has gone through multiple stages, from exploring basic flame propagation and stabilization mechanisms, to developing active stability strategies, and finally to integrating specific application systems. It has become a cutting-edge interdisciplinary hotspot. This article aims to comprehensively review the research progress of microchannel burners and provide systematic references for subsequent research.

2. Core Challenges and Strategies to Enhance Stability

2.1. Main Challenges

2.1.1. Poor Flame Stability

The primary challenge faced by microscale combustion is insufficient flame stability. Due to the small size of the channel, its surface area to volume ratio (S/V) significantly increases, resulting in a much higher heat loss stall rate than the chemical reaction heat release rate, causing a sharp decrease in the temperature of the reaction zone and making it difficult to maintain the continuous progress of the chain reaction. The flame is easily quenched during propagation. There exists a critical "quenching diameter" (or "quenching distance"), and when the channel characteristic size is smaller than this value, the flame cannot sustain itself. In addition, the wall has strong adsorption and surface recombination effects on key active free radicals such as H, O, and OH, further weakening the gas-phase reaction kinetics and exacerbating flame instability.

2.1.2. Low Combustion Efficiency and Fuel Conversion Rate

Due to the extremely short gas residence time and significant heat loss, fuel is often not fully oxidized and is discharged from the combustion zone, resulting in incomplete combustion. This not only reduces energy release efficiency, but also leads to increased emissions of pollutants such as carbon monoxide (CO) and unburned hydrocarbons (UHC), seriously affecting the overall energy efficiency and environmental performance of the system.

2.1.3. Narrow Operating Range and Challenges in Material and Thermal Management

The stable operating window of micro burners is extremely limited, and their combustible equivalence ratio range and flow rate operating range are much narrower than macro burners, making them highly sensitive to fluctuations in operating conditions. At the same time, local high temperatures impose strict requirements on microfabrication materials, requiring excellent heat resistance, oxidation resistance, and long-term structural reliability. More complicated is that the thermal management objectives themselves have inherent contradictions: on the one hand, they need to minimize heat loss to maintain flame stability, and on the other hand, they need to efficiently dissipate heat to achieve energy recovery and utilization. This dual demand poses significant challenges to the design and integration of micro burners.

2.2. Flame Stability Enhancement Strategy

To address the core challenges faced by microscale combustion, such as poor stability, low efficiency, and narrow operating windows, researchers have proposed various innovative flame stabilization and performance enhancement strategies, mainly including the following categories:

2.2.1. External Heat Recovery

This is the most classic and efficient flame stabilization method. By integrating heat exchange structures on the combustion chamber wall or outside, the heat of downstream high-temperature combustion products is transferred to upstream unburned premixed gas, achieving effective preheating of the inlet gas. This strategy significantly compensates for the heat loss in the inlet section caused by high surface area/volume ratio (S/V), increases the initial temperature of the reactants, thereby broadening the flammability limit and reducing the quenching distance. Typical structures include U-shaped or Ω - shaped heat recovery channels, coaxial sleeve structures (such as "Swiss coil" structures), and wall integrated counter current heat transfer channels. Numerous studies have shown that well-designed regenerative systems can significantly enhance flame stability and improve overall combustion efficiency.

2.2.2. Inert Porous Medium Filling

Filling the microchannel with foam ceramics or porous media with high thermal conductivity and high emissivity, such as SiC, Al_2O_3, can improve the combustion performance in many ways: (a) The strong convection and radiation heat transfer between the solid skeleton and the gas makes the heat more evenly distributed in the flow channel, playing the role of internal "self preheating" and flame stabilization; (b) The porous structure disturbs the mainstream, enhances fuel oxidant mixing, induces local turbulence, and promotes reaction rate; (c) High temperature solid skeleton serves as a radiation source, compensating for wall heat loss through thermal radiation. In addition, the high thermal capacity of porous media helps to maintain local high temperature environments under transient conditions and enhance disturbance resistance.

2.2.3. Catalytic Combustion

Loading precious metals such as Pt and Pd or transition metal oxides (such as Co_3O_4, MnO_2) catalysts on the inner walls of microchannels can initiate surface catalytic reactions at lower temperatures, significantly reduce ignition thresholds, and decrease dependence on gas-phase radical chain reactions, effectively suppressing wall quenching effects. The heat released by catalytic reactions can preheat adjacent mixtures, thereby inducing or enhancing subsequent gas-phase combustion, forming a "catalytic gas-phase synergistic combustion" mechanism. This strategy is particularly critical for the stable combustion of high ignition point hydrocarbon fuels such as methane and propane at the microscale.

2.2.4. Structural Optimization and Flame Anchoring

By introducing geometric perturbation structures such as expansion cavities, grooves, blunt bodies, or micro flame stabilizers into the flow channel, a stable low-speed recirculation zone is formed behind them. The recirculation zone continuously delivers high-temperature combustion products and active free radicals (such as H, O, OH) to the root of the flame, acting as a local "ignition source" and "anchoring point" to firmly fix the flame in a specific position. This type of flame stabilization method based on fluid mechanics principles does not require additional energy input, has a simple structure, and has significant effects.

2.2.5. Rich Hydrogen Fuel or Online Fuel Reforming

By utilizing the excellent combustion characteristics of hydrogen gas (high flame speed, wide flammability limit, low flame energy), the combustion stability and quenching resistance of hydrocarbon fuels at the microscale are significantly improved through hydrogen doping. Another strategy is to implement online catalytic reforming: utilizing the heat released from partial fuel combustion, the remaining fuel is converted in situ into synthesis gas rich in H_2 and CO, which has better ignition and combustion performance, indirectly achieving efficient and stable combustion.

2.2.6. Material Selection and Thermal Management Optimization

In view of the dual challenges of heat loss and material tolerance, on the one hand, low thermal conductivity materials (such as quartz and zirconia ceramics) are used to manufacture the burner body, or high-performance thermal insulation layer (such as silica aerogel) is coated on the outside to minimize heat dissipation to the environment; On the other hand, for application scenarios that require efficient heat dissipation, such as micro thermoelectric or micro propulsion systems, the design concept of "zone thermal management" is adopted: the combustion core zone focuses on insulation to maintain the flame, while the energy extraction zone strengthens heat transfer through high thermal conductivity materials or micro rib structures, achieving the coordinated optimization of "combustion preservation" and "energy extraction".

3. Current Status of Research in Application Fields

3.1. Micro Thermoelectric Power Generation System

Micro thermoelectric power generation system is one of the most representative application directions of microchannel burners. The system usually consists of three parts: a micro burner, a thermoelectric conversion module (such as Bi_2Te_3based thermoelectric generator), and a radiator. The heat released by combustion maintains high temperature on the burner wall, while the radiator provides a low-temperature cold end. The temperature difference between the two drives the thermoelectric module to directly output DC electrical energy. The current research focuses on optimizing the structure of the burner (such as using a Swiss coil reheating channel) and system level integrated design, aiming to improve the uniformity of wall temperature distribution, enhance effective heat flux input, and minimize interface contact thermal resistance and overall heat loss. At present, the output power range of the laboratory prototype system ranges from milliwatts to tens of watts, and its overall energy conversion efficiency (i.e. the conversion efficiency of fuel chemical energy to electrical energy) is generally in the range of 1%-5%, with significant potential for improvement, especially in material matching, thermal management coordination, and combustion power generation coupling mechanisms, which urgently need to be further explored.

3.2. Micro Propulsion System

In the field of attitude control and orbit fine-tuning of micro nano satellites (such as CubeSat and Pinar satellites), micro thrusters based on micro channel burners have demonstrated unique advantages. This type of thruster is centered around a micro scale combustion chamber, which generates high-temperature and high-pressure gas through efficient mixing and stable combustion of fuel (such as methane, hydrogen) and oxidant (often oxygen or hydrogen peroxide catalytic decomposition products). The gas is then accelerated and sprayed out through a micro nozzle to generate controllable thrust. The key performance indicators include specific impulse, thrust accuracy, and propellant utilization efficiency. The research focuses on achieving reliable ignition, disturbance resistant stable combustion, rapid response, and highly integrated design at the microscale. The introduction of catalytic combustion technology and high heat-resistant materials such as silicon carbide and silicon nitride ceramics has effectively improved the reliability and service life of the system. Compared to cold air propulsion, this solution can provide a higher specific impulse ratio; Compared to electric propulsion systems, it has the advantages of simple structure, no need for high-voltage power supply, and fast response, and is expected to become an important technological path for future micro spacecraft propulsion.

3.3. Other Emerging Applications

In addition to the mainstream directions mentioned above, microchannel burners have also demonstrated potential applications in multiple cutting-edge fields: Portable miniature heat source: directly utilizing its high-density heat output to serve field individual heating devices, miniature chemical synthesis reactors, or on-site sample processing equipment; Flame ionization detector (FID) in micro analytical instruments: As the core component of gas chromatography or gas sensors, it relies on hydrogen/air micro flames that are small in size, low in power consumption, and highly stable. Micro burners are an ideal choice due to their strong controllability and low ignition energy consumption; Micro scale thermoacoustic energy conversion system: coupling the periodic heat release generated by micro combustion with a thermoacoustic resonant cavity to excite strong thermoacoustic oscillations, thereby driving acoustic power output or pulse tube refrigeration units, providing new ideas for micro refrigeration or energy recovery without moving parts.

4. Limitations and Future Prospects of Current Research

4.1. Current Limitations

The current microscale combustion technology still faces multiple challenges. In terms of basic theory, the assumption of continuous medium in the near wall region of microchannels may fail, and rarefied gas effects such as slip flow and temperature jump need to be introduced; Meanwhile, gas-phase free radical reactions are highly coupled with wall catalysis/quenching processes, and their complex mechanisms lack universal predictive models. At the engineering application level, the vast majority of research is still in the stage of single laboratory prototypes, making it difficult to achieve high reliability integration of micro burners with heat exchangers, thermoelectric modules, fuel supply and control systems in centimeter level packaging, and long-term (thousands of hours) operational stability has not been verified. In addition, due to the low ZT value of thermoelectric materials and the system's thermal management efficiency, the overall energy conversion efficiency is generally only 1%-5%; Moreover, existing work mainly focuses on gas fuels such as hydrogen and methane, and there is a significant lack of research on liquid fuels that are easier to store (such as methanol and butane) or actual reforming gases, which hinders the practical application process.

4.2. Future Prospects

Facing the future, it is urgent to promote breakthroughs in micro combustion technology from multiple dimensions. On the one hand, it is necessary to develop multi-scale and multi physics coupling simulation methods that integrate rarefied flow, surface chemistry, and radiative heat transfer, and combine machine learning to achieve intelligent collaborative optimization of burner structure, materials, and flow field; On the other hand, actively introducing high-performance composite materials (such as low thermal conductivity, self catalytic ceramics) and advanced manufacturing processes (such as ceramic 3D printing) to construct complex internal structures such as biomimetic fractal flow channels and three-dimensional regenerative networks, to enhance the synergistic performance of heat flow reaction. At the same time, energy utilization pathways should be expanded to explore hybrid energy supply systems composed of micro combustion, photovoltaics, and fuel cells, or to develop new thermoelectric materials (such as cobaltite and silicon germanium alloys) and micro power cycles (such as micro Rankine and micro Brayton cycles) that match high-temperature heat sources. More importantly, it is necessary to strengthen system level engineering research and development, focusing on practical issues such as rapid startup, dynamic response, intrinsic safety control, and integrated packaging of fuel storage, supply, and combustion. In addition, in-depth research should be conducted on the micro scale evaporation combustion coupling mechanism of liquid fuels and the feasibility of low pollution combustion modes such as MILD, in order to accelerate the transformation from "laboratory devices" to "reliable engineering products".

5. Conclusion

As a key bridge connecting high energy density fuels with miniaturized applications, micro porous burners have achieved fruitful results in flame stabilization mechanisms and various enhancement strategies after more than 20 years of research. The comprehensive application of technologies such as reheating, catalysis, porous media filling, and structural optimization has made stable and efficient combustion possible at the microscale, and has been successfully validated in prototype systems such as micro thermoelectric power generation and micro propulsion. However, the large-scale commercial application of this technology still faces multiple challenges such as fundamental theory, integrated processes, system efficiency, and long-term reliability. In the future, with the deepening of interdisciplinary integration, breakthroughs in new materials and manufacturing technologies, and the empowerment of intelligent design tools, micro porous combustion technology is expected to play an irreplaceable role in emerging fields such as portable power sources, distributed sensing networks, and micro aerospace power, opening a new chapter in micro energy systems.

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