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ORIGINAL RESEARCH ARTICLE

Design and performance analysis of hydrogen-fueled micro combustion chamber with focus on back pressure minimization

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ABSTRACT

The combustion chamber is a crucial component in power generation within a micro gas turbine. This paper prioritizes practical over theoretical considerations in designing an efficient, small-scale combustion chamber for micro gas turbine applications. The investigation covers the temperature profile within the combustion chamber, employing 19 reversible reactions and considering 9 different chemical species in reactive flow calculations. Preliminary experiments demonstrate hydrogen as a feasible fuel in a micro combustion chamber, generating approximately 1 kW of thermal power. Turbulence physics are assessed using the accurate k-Ɛ model. Findings indicate a reactant inlet temperature of 300 K and a primary zone temperature of 1750 K. This research suggests that minimizing the back pressure effect in a steady-state micro combustion chamber can improve turbine performance.

Keywords: fuel; micro combustion chamber; temperature, design

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1. Introduction

The miniaturization of equipment is increasing across a variety of industries, including biotechnology, information technology, the 22 automobile industry, biomedical engineering, aerospace, and military applications[1]. The rapid development of microsystems and micro-electro-mechanical systems (MEMS) has given momentum to miniaturization technology. The present power sources, however, restrict the applications of MEMS. Therefore, the need for power sources with high energy density and small volumes is important[2]. Such a concept is used to create microscale equipment, which has a huge and vital impact on people's lives and the flourishing of society[3]. A few Micro Power Generation Systems (MPGS) are being developed to fulfill the needs of MEMS[4]. Still, the microscale devices are powered by the small size of the batteries. However, the power supply is constrained for miniature and microscale devices due to the size of the batteries, which affects its durability as well as its reliability and power output[5,6]. Therefore, these devices urgently need micro energy or a power plant with high energy density, so that they can give full play to their advantages and further miniaturization and multifunction. However, the batteries commonly employed in micro electro mechanical systems have some problems, such as long charging times, large size, weight, and low energy density[7–9]. The MPGS is largely driven by the micro-combustion of hydrocarbon fuel in compact or restricted places, termed micro-combustors. Micro-combustion is an exothermic chemical reaction in which fuel and an oxidant react to produce heat and convert chemical species on a micro-scale. The use of micro combustors allows for greater flexibility, better control, higher efficiency, and finer precision. However, micro combustors have challenges such as a high heat loss ratio and minimal flame instability[10]. Therefore, many fascinating and important studies have been conducted to better understand and enhance the flame stability, combustion efficiency, and thermal performance of micro combustors.

Several researchers have carried out different studies on improving the performance of hydrogen/air combustion in micro-combustors for the operation of thermo-photo-voltaic power systems. Peng et al.[11] suggested a micro-combustor with a front cavity and compared its effectiveness in terms of flame stability and thermal performance to that of a micro-combustor without a front cavity. They reported that the front cavity enhances flame stability and boosts the energy conversion efficiency of the micro-combustor. Bagheri et al.[12] investigated the combustion properties of premixed hydrogen/air in a micro-combustor with various bluff body structures and intake velocities. They observed that the micro-combustor with a wall fin acting as a bluff body exhibits the maximum flame temperature and emission efficiency at an intake velocity of 10 m/s. Balakrishnan et al.[2] numerically evaluated the combustion performance of a micro-combustor with and without a rib at varied hydrogen mass flow rates. The results showed that the micro-combustor with a rib exhibits a greater outer wall temperature than the micro-combustor without a rib. E et al.[13] proposed a novel micro-combustor with a suction pipe, mixing pipe, diffuser pipe, and shrinkage pipe, as well as the combination of the cavity and backwards-facing step. The performance of the suggested micro-combustor was then numerically examined, and it was found that the backwards-facing step and cavity are beneficial for heat recirculation and flame stability.

The micro-combustor is also an integral part of the micro-gas turbine. The residence time in micro combustion is relatively short due to the small size of the combustion chamber, making it more difficult to control when paired with the overall complexity of the micro-gas turbine[14]. The low-pressure ratio of the turbine, the recuperated thermal cycle, the restricted temperature increase through the combustor, and the low temperature rise through the combustor because of the low-pressure ratio are all factors that affect the combustion process in a micro gas turbine[15]. Numerous researchers have carried out numerical and experimental investigations on micro-combustor for the application of micro-gas turbines. Cao and Xu[16] conducted a premixed combustion experiment of hydrogen gas and air in a stainless steel-based micro-annular combustor for the application of operating micro-gas turbines. They found that micro-scale combustion was stable with a 2 mm gap, operating effectively up to an excess air ratio of 4.5. However, the micro-combustor experienced significant heat loss, exceeding 70% of the total thermal power. Jiang et al.[17] examined the performance of a micro gas turbine combustor with a sintered porous chamber wall. They noticed that the heat loss ratio in the porous-walled combustor was substantially lower than in the traditional solid-walled combustor. Heat loss increases significantly with the surface area-to-volume ratio of the micro combustor, making it challenging to reach the required sufficiently thin combustor wall temperature of micro combustor. Moreover, when the combustion chamber size is reduced, the mixture's residence time decreases due to incomplete combustion occurring in the chamber. In a Planar micro combustor, cavities are included to minimize the issues[18–22].

Over the last few decades, combustion in miniature Swiss-roll combustors has been extensively studied for applicability to micro gas turbine plants. Wang et al.[23] proposed a miniature Swiss-roll combustor that has two inlets for counter flows of methane and air and two outlets for exhaust gas. Experimental studies revealed that the proposed combustor can operate at a very low fuel flow rate, making it appropriate for micro gas turbines. Li et al.[24] investigated non-premixed CH_4/air combustion in a micro Swiss-roll combustor experimentally and numerically. It was found that the maximum and average surface temperatures of the combustor cover vary non-monotonically with respect to the nominal equivalency ratio. Ma et al.[25] conducted a numerical analysis on a micro Swiss-roll combustor with a double chamber with the primary purpose of determining the effect of solid material on the premixed CH_4/air flame blow-off limit. The investigation showed that the copper micro-combustor achieved the lowest blow-off limit, while the stainless steel micro-combustor achieved the greatest blow-off limit.

According to the brief literature assessment, there have been several research studies in the area of micro-combustor design and performance evaluation. However, there has not been much research on the Swiss-roll combustor, particularly for the application of operating micro-gas turbines. Therefore, in this study, an experimental and numerical investigation of a Swiss-roll combustor is carried out. The goal of this study is to devise a method for determining the increase in the effectiveness of micro combustion systems caused by certain adjustments. In this study, a micro-combustion device was developed using a computational fluid dynamics (CFD) model. The novelty of this research resides in the fact that, in contrast to prior studies based on Swiss-roll combustors where the combustion of CH_4/air is studied, this research models the combustion of hydrogen as a fuel for the power demand of 1 kW.

2. Design of combustion chamber

The current paper describes the study of the micro combustion chamber's numerical analysis. **Figure 1** shows a top view and model of a Swiss-manufactured role micro combustion chamber. In order to design the combustion chamber, design constraints must be satisfied. The compressor and turbine work must be considered to determine the overall size. Combustion inlet requirements and compressor exit conditions depend on each other, which must be considered when designing a combustor. In order to design the combustion chamber for a 1 kW gas turbine engine, two considerations must be used. Major combustion chamber dimensions consider aerodynamics and chemical for the casing and liner design of Swiss role-type combustion chambers for small gas turbine applications. The commercial CFD package ANSYS CFX performs the CFD simulation for the intended chamber.

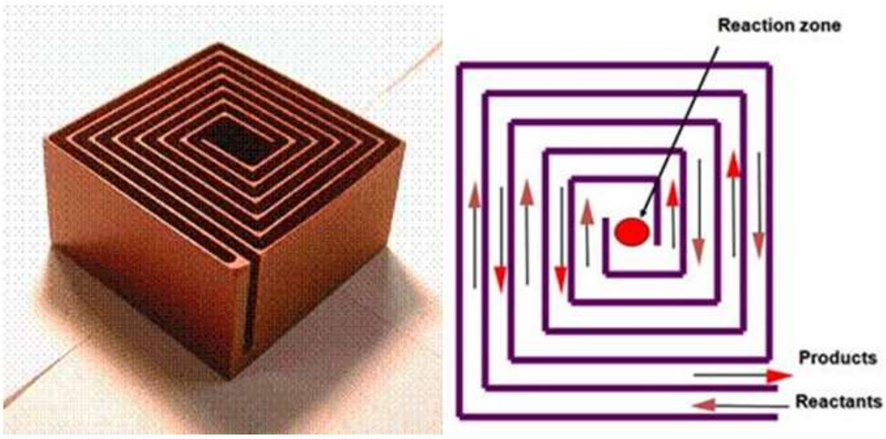


Figure 1. Swiss role combustor.

2.1. Casing area

2.1.1. Aerodynamic consideration

Aerodynamic processes heavily influence the design and performance of gas turbine combustion systems. When proper aerodynamics and fuel injection are considered, a trouble-free combustor with minimal modification is possible. Aerodynamics allows for thermodynamically perfect constant-pressure combustion. Combustion theory aims for this. The overall pressure loss and the combustion load determine the appropriate casing, A_{ref}.

Under these conditions, the overall pressure loss dictates the casing size, and A_{ref} is obtained as Equation (1):

$$A_{(ref)} = \left[\frac{R}{2}\left(\frac{\dot{m}_3\, T_3^{0.5}}{P_3}\right)^2 \frac{\Delta P_{3-4}}{q_{ref}}\left(\frac{\Delta P_{3-4}}{P_3}\right)^{-1}\right]^{0.5} \tag{1}$$

2.1.2. Chemical consideration

Chemical factors are to be considered to estimate the size of the chamber. It leads to achieving a high combustion efficiency. This efficiency is represented by the parameter (Θ), which is defined as Equation (2):

$$\theta = \frac{\left[P_3^{1.75} A_{ref} D_{ref}^{0.75} exp\left(\frac{T_3}{b}\right)\right]}{\dot{m}_A} \tag{2}$$

It is apparent from the varied forms that the reference area for the combustor has varying values. This isn't surprising, given that effective combustion necessitates more specific requirements than low-pressure loss.

Aerodynamic considerations govern the area for constant pressure combustion, while chemical considerations rule the area for improved combustion efficiency. Due to the very small size of the area evaluated using the combustion efficiency criteria, the resulting pressure loss is significant. The area is higher when it comes to aerodynamics. Lefebvre[26] studied the heat transfer process in gas turbine combustion chambers. Gas turbine combustion chambers (for which the length is proportional to the diameter of the flame tube) radiate significant amounts of heat to the wall. Therefore, he claims that an increase in chamber size leads to an increase in wall temperature.

2.1.3. Liner area

The most obvious benefit is that it reduces the speed and duration of residence within the liner, both of which are beneficial to ignition, stability, and combustion efficiency, among other things.

Increasing the liner diameter requires reducing the annulus. Increased annulus velocity reduces static pressure drop between liner holes. The pressure drops because the combustion products are injected quickly through the air jets into the liner. The dynamic pressure in the combustion zone (q_{pz}) is a good indicator of mixing performance. When k is equal to the most optimal value, the highest values of $\Delta p_L/q_{pz}$ are obtained. It can be shown in Equation (3):

$$\frac{\Delta P_L}{q_{pz}} = 1 + \frac{T_3}{T_{pz}}\frac{k^2}{m_p^2}\left\{\frac{\Delta P_{3-4}}{q_{ref}} - \frac{(1-m_{sn})^2 + \lambda[r^2(1-k)^2 - 1]}{(1-k)^2}\right\} \tag{3}$$

2.1.4. Length of liner

The length of the liner is directly proportional to the pattern factor and liner diameter. Equation (4) provides the approximate length:

$$L_L = D_L \left(A \frac{\Delta P_L}{q_{ref}} In \left(\frac{1}{1 - PF} \right) \right)^{-1} \quad (4)$$

2.1.5. Surface area and volume ratio

$$\text{Surface area of Combustor} = S = 2\pi(DL \times L_L) \quad (5)$$

$$\text{Volume of Combustor} = V = \left(\frac{\pi}{4} \times DL_2 \times L_L \right) \quad (6)$$

Equations (5) and (6) show that surface area and volume ratio (S/V) depend on liner diameter and length. In the swish role, the combustion chamber length of the reaction zone is 20 mm.

3. Design data

Actual cycle analysis of the regeneration cycle for the micro gas turbine engine by Saravanamutto et al.[27] and Pandya[28] provided the foundational data for the design of the combustion chamber. Listed in **Table 1** are the initial and fundamental data for the micro gasoline turbine.

Table 1. Initial data for cycle analysis.

Sr.	Parameters	Value
1	Net power output	1 kW
2	Compressor pressure ratio	1.5
3	Ambient condition	1.0132 bar; 300 K
4	Turbine inlet temperature	700 K
5	Specific heat of air	1.005 kJ/kg K
6	Specific heat of product of combustion	1.1228 kJ/kg K
7	Ratios of specific heat for air	1.4
8	Calorific value of hydrogen	120,000 kJ/kg

The combustion chamber is created in accordance with the guidelines laid forth by Kulshrestha and Channiwala[29], Mattingly et al.[30] and the methodology outlined in the previous section. **Table 2** provides information on the characteristics of the combustion chamber of a tiny gas turbine powered by hydrogen.

Table 2. Details of square Swiss role combustion chamber.

Chamber	Air fuel mixture		Reaction zone		
	No. of holes	Diameters of hole (mm)	Length (mm)	Width (mm)	Height (mm)
Square Swiss role	04	1	20	20	25

4. Numerical simulations

Small-scale combustion chambers will only be able to combust if a proper pre-mixture of gas is used properly. Hydrogen and compressed air enter both the pre-combustion chamber from the storage cylinder. Air intake holes, such as cooling slots for the sensitivity of flow recirculation, jet penetration and mixing, and discharge coefficients, must all be designed with aerodynamics in mind. Without the flow pattern analysis, the combustion chamber would be significantly impeded. CFD has made it possible to view its flow in any state. The same methodology is employed here. The commercial CFD package is known as Ansys CFX is used. CFX was utilized to perform CFD simulations on the combustion chamber, provide predictions on the centerline and wall temperature distributions, and even predict certain combustion phenomena. To inspect the combustion chamber, only one measurement is taken. The flow continues from the circulation slots, which lead to the primary zone and exit slots. It is a real-world duplicate experiment where known input gas pressures, temperatures, and velocities supply known amounts of various reactant gases to the system. Computational combustion researchers have used the k-Ɛ model, which portrays the physics of turbulence and hydrogen as a fuel, to describe the theory of computational combustion. Using the k-Ɛ model, the initiation of flow separation and the amount of flow separation are accurately predicted. Although single-step chemistry and reduced kinetics provide adequate prediction with limited computational power, few researchers have discovered this. The combustor temperature can be predicted by single-step chemistry, but the temperature of the hydrogen-air combination cannot. For this reason, a gas-phase reaction model for the combustion of hydrogen and air mixtures has been created, which includes 19 reversible elementary processes and 9 species. The changing wall boundary conditions and heat loss affect the expected flame structure and temperature. Pre-heat (outside the combustion chamber) all reactant gases. Unlike flow transport processes, which are slow compared to chemical reactions, the combustor is simulated using an eddy dissipation model. Molecular reactions immediately result in the formation of products after the combination of the reactants. **Table 3** provides a summary of the CFD model.

Table 3. CFD models.

1	Fluid model	Thermal energy
2	Turbulence model	k-ε
3	Combustion model	Eddy dissipation
4	Radiation model	Discrete transfer
5	Nitrogen	Constraint
6	Combustion reaction	Hydrogen air multi-step

The independent study on the three-dimensional grid was finished when it had 379,053 nodes and 1,948,796 elements are shown in **Figure 2**. The grid spacing that was decided to use for the CFD simulations was quite comparable to the Eulerian grid is shown in **Figure 2**. In order to achieve a higher level of precision, a high-resolution advection technique was selected because of the unstructured grid use.

For studying the temperature and velocity distribution of reactant and product in the micro combustion chamber in ANSYS R15 k-ε model is considered having hydrogen as a fuel, input the initial temperature is 300 K, and 1.5 bar pressure of mixture enters into the micro combustion chamber using **Figure 3** model.

Figure 4(a) shows the initial condition of the combustion process when the reactant gas enters the combustion chamber at 300 K and 1.5 bar pressure. The temperature remains the same at all places inside the chamber. After a microsecond of the entrance of the reactant gases, the variation in the temperature in the inlet passage of the primary zone and the primary zone is observed.

During the intake of the reactant into the chamber, there is no variation in the temperature. The temperature in the primary chamber is increasing by the velocity of reactants. In both figures, **Figure 4(b)** increase in the temperature from inlet to primary chamber than to exhaust can be seen.

In **Figure 4(c)**, in both cases, the temperature of a primary zone increases and near the inlet of the primary zone swirl effect is shown at low temperature with respect to the temperature of the primary zone. In **Figure 4(d)**, due to velocity, the reactants near the primary zone generate the swirl effect, which is helpful for the proper combustion of fuel, and temperature also increases up to 1250 K inside the primary zone. Because of the dissipative effect, there is an appreciable temperature increment at the corner during exhaust. The geometry of the chamber is one of the reasons for this variation.

In **Figure 4(e)**, a red circle in a primary zone indicates the time of spark ignition and combustion process in the primary zone. The temperature of flue gases in a primary zone is near about 1600 K. After combustion, the temperature of the exit passage also increases.

The pressure and temperature of the primary zone increase due to combustion. **Figure 4(f)** shows that the temperature inside the zone is rising to around 1710 K. The center of the primary zone, where the swirl effect is created, is the maximum combustion point. The combustion chamber experiences high pressure near the inlet of the reactants. Products flow out of the exit passage, where the temperature is also increased, and then decreases in temperature to the end of the exhaust.

After combustion inside the primary zone temperature is higher at the center. **Figure 4(g)** indicates no more changes in the inlet reactants' temperature due to steady state condition. Temperature does not change with respect to time after some seconds. The hot spot in the exhaust path at various places is seen in **Figure 4(g)**, which creates questions regarding the passage's geometry and flow distribution. The back pressure effect is also minimized.

The velocity streamlines analysis of the velocity flow of reactants and products can be used to estimate reaction and product flow. The mass flow rate of reactants enters the combustion chamber at speed higher than the velocity of the reactants entering. In **Figure 5**, the swirl effect present in the center of the primary zone is due to low velocity. As the products enter the primary combustion zone, velocity increases, but velocity falls once reaching the chamber. The effect the prototype experiences is achieved by using ANSYS simulation software. During the actual experimental work, the researcher seeks to identify fluid flow, temperature variation, heat losses etc.

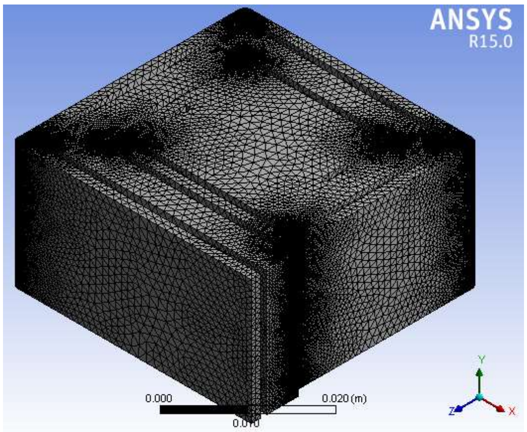


Figure 2. Mesh model of combustion chamber

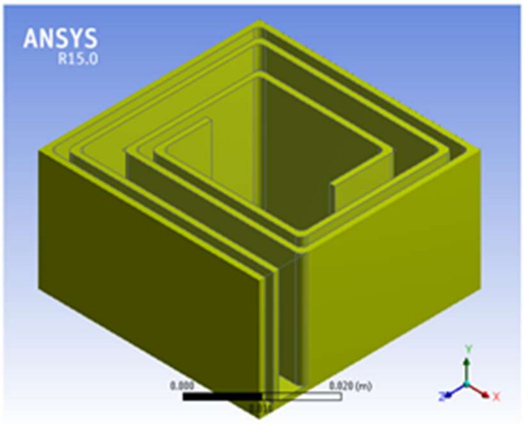


Figure 3. 3-D model of the combustion chamber.

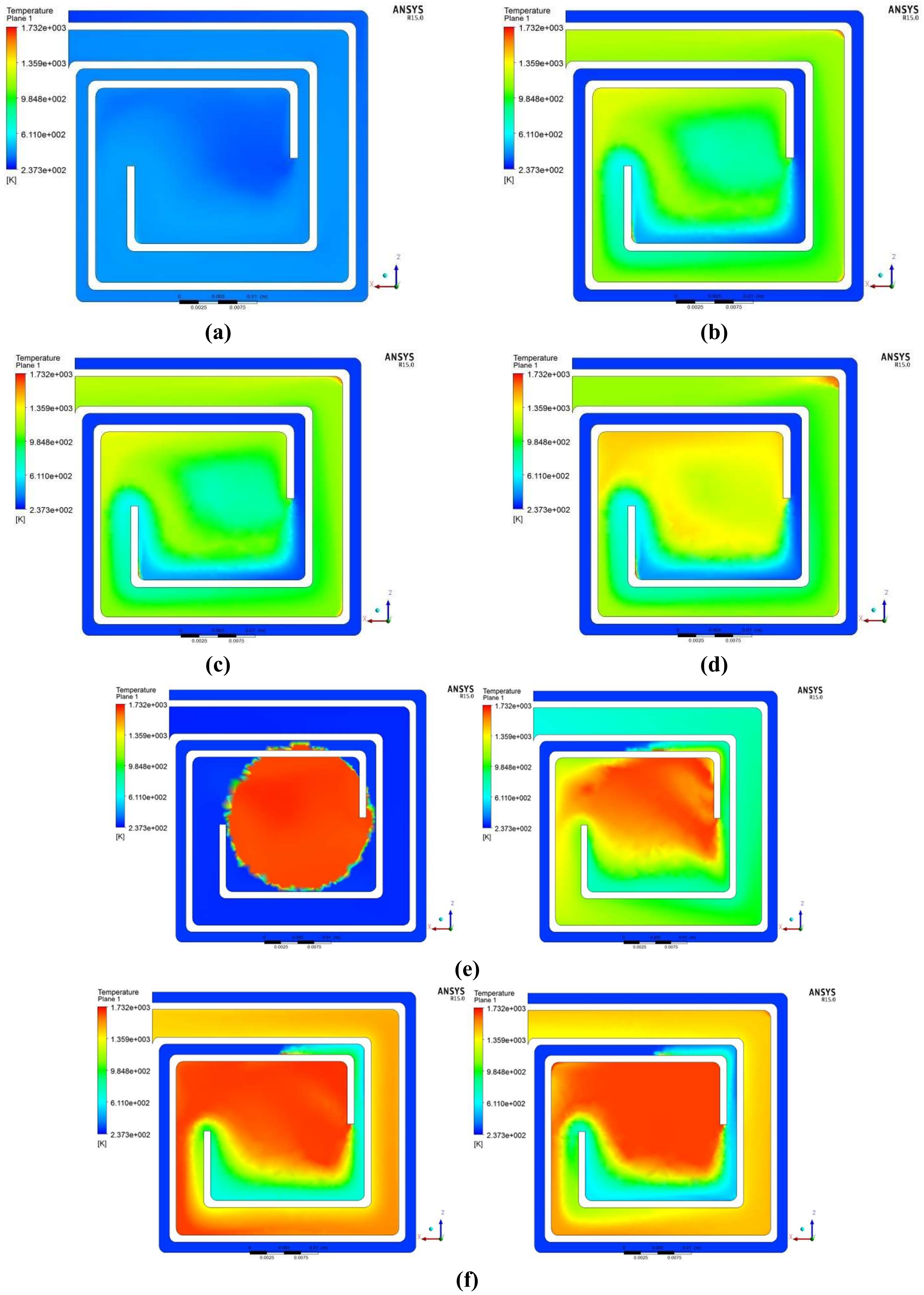
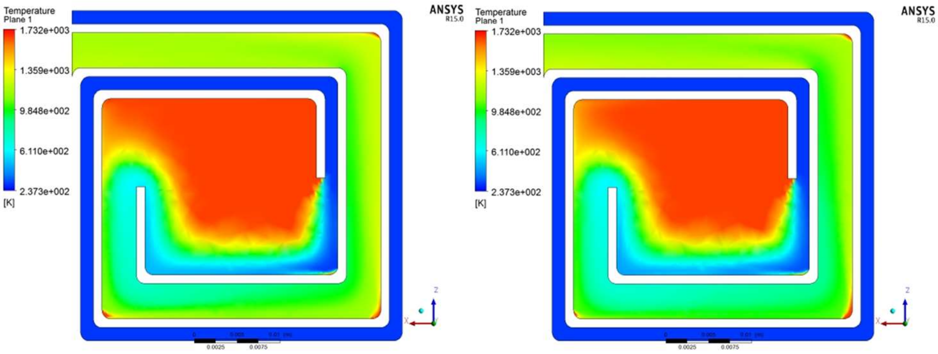


Figure 4. (*Continued*).



(g)

Figure 4. (a–g) Temperature distribution.

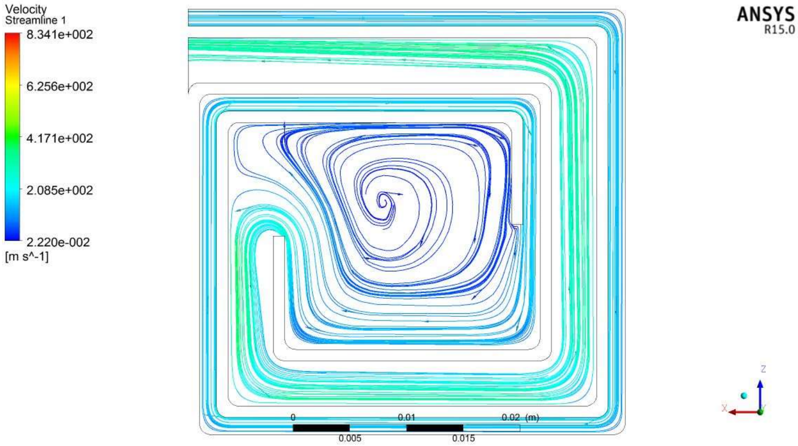


Figure 5. Velocity distribution.

5. Experimental investigations

The experimental setup was developed using micro-combustors which is shown in **Figure 6** and was numerically simulated. When the components of the pre-mixture are added to the reactants, they enter the micro-combustion chamber through four inlet holes are shown in **Figure 6**. Inject the igniter into the reaction zone to begin the combustion process. **Figure 7** shows the visualization of flame propagation, a glass cover is attached to one side of the micro combustion chamber. The experimental work has been successfully completed. The overall temperature of flames tends to decrease as the equivalence ratio increases. Selecting new micro-combustor chamber material and chamber size and reducing heat losses can be done through number-based analyses.

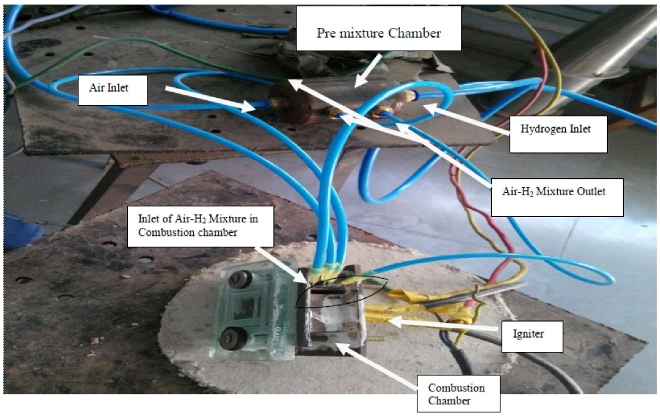


Figure 6. Experimental setup.

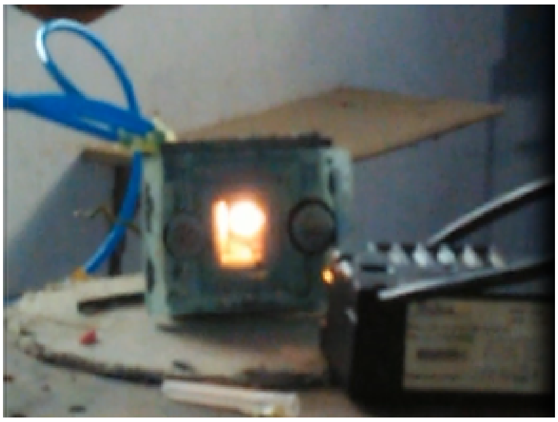


Figure 7. Experimental work

6. Conclusion

However, the narrow combustion chamber, large surface-to-volume ratio, high heat dissipation ratio, and backfire effects have brought great challenges to the combustion stability, limit, operating range, thermal efficiency, and power output of the micro combustor. This paper offers a new way to build micro gas turbines based on a thorough numerical and experimental study of the temperature profile in a combustion chamber with hydrogen fuel, reducing the backfire effect and improving the combustion efficiency. In the estimates for reactive flow, there were 19 reversible reactions and 9 different chemical species. Simulations of the system using ANSYS CFX showed that hydrogen could be a good fuel for the mini combustor in early tests. Using the ANSYS simulation software, a successful virtual prototype was made. When paired with experimental methods, this prototype gives important information about fluid flow, temperature changes, and heat loss, which helps to reduce these problems significantly. One important result of this study is that the back pressure effect in the micro combustion chamber with hydrogen fuel is greatly reduced once steady-state conditions are reached. This opens the door for future improvements in micro gas turbine technology efficiency.

Author contributions

Conceptualization, RS and DK; methodology, VC; software, MK; formal analysis, FS; resources, CS; data curation, PS; writing—original draft preparation, RS and DK; writing—RS and DK; Visualization, AO; supervision, AK; All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

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