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Modelling and Simulation of Micro Gas Turbine Performance and Exhaust Gaseous

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ABSTRACT

Numerical simulation of cold flow and explosion in a Capstone C30 micro gas turbine is simulated using OpenFOAM. This study is aimed to investigate the combustion of non-premixed methane/air inside a micro gas turbine. The combustion characteristic inside a micro gas turbine with 100% methane is assumed for the fuel is studied with a three-dimensional model of micro gas turbine. The velocity of the flow increases significantly in the explosion simulation where the combustion of non-premixed methane/air mixture is initialised. The temperature in the micro gas turbine increased to 2400K at the downstream of inlets and reduces to 1500K at the combustion zone. High concentration of CO and CO_2 is in the main reaction zone. The fraction of water vapours and hydroxyl on the other hand is lower compared to other species.

1. Introduction

Power generation is the process of producing electricity through main energy sources such as coal, natural gas, hydro and more. Power is generated through a turbine where a driving force for the turbine is generated from processes of extracting energy from energy sources. There are different types of turbines varying in function, speed and size depending on the demand of power output. Various studies on the performance analysis of ideal open cycle gas turbine system have been widely studied over decades.

Numerical analysis on the performance optimisation of the irreversible open regenerator Brayton-cycle is investigated by Chen *et al.,* [1] with a physical model of the cycle based on the ideal gas law. A thermodynamic analysis of a simple open cycle gas turbine is used to investigate the effects of compressor inlet temperature (CIT), compressor pressure ratio and turbine inlet temperature (TIT) on the performance parameters of ideal open cycle gas turbine. Kurt *et al.,* [2] concluded that the CIT, TIT and pressure ratio are the parameters that have the most significant effects on the net power output, the thermal efficiency and the fuel consumption of open cycle gas turbine system. The

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thermal efficiency and the net power output increase with the increasing TIT and PR and decreasing CIT. The fuel consumption is inversely proportional to CIT and PR, while directly proportional to TIT. Torres [3] investigates the effect of the ideal gas model with different heat capacities evaluation method and analyses the performance of open cycle gas turbines. Torres [4] conducts an extension study to optimize the Specific Fuel Consumption (SFC) of the open simple cycle gas turbine with the ideal gas model shown in Figure 1.

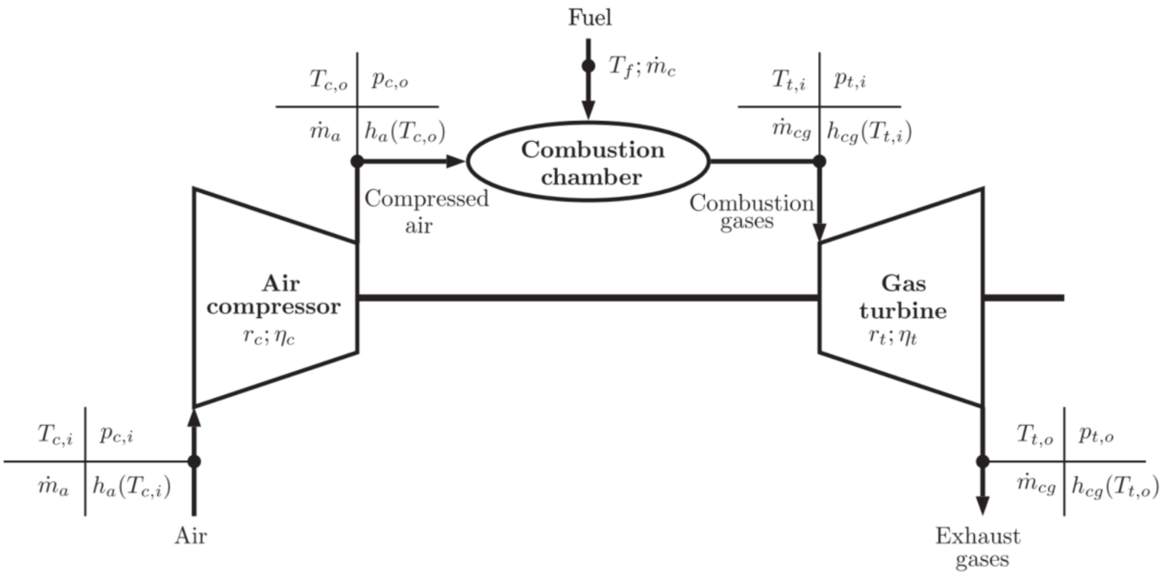


Fig. 1. Schematic representation of the simple cycle of the single-shaft gas turbine [4]

The application of turbine type in a small-scale distributed system is widely known as micro gas turbine. The micro gas turbine is well established due to the extreme total effectiveness and flexibility which provides an economic success and ideal usage. The micro gas turbine is operating on a basic operation of a Brayton cycle with a compressor, combustor, turbine, and generator. The operation of the cycle starts with a compressor where the air is drawn in and compressed. The compressed air is then channelled to the combustor where the air and fuel is mixed. The air-fuel mixture is ignited through spark ignition and the combusted gas is transferred to the turbine. The combusted gases transferred the energy to the rotor blades of the turbine by rotating it and thus power is generated by the generator. Micro gas turbine is well known as it can utilise gaseous [5] or liquid mineral fuels [6] or biofuel [7] for combustion to generate power. However, various scientific and technological issues need to be addressed due to variety of the energy sources and the corresponding large variation in fuel properties [8,9]. A review on next generation fuels can be found in [19].

Numerical analysis on the performance of the combustion characteristics and the emission of the nitrogen oxides (NO_x) in the micro gas turbine has been widely study. NO_x is formed in the combustor of micro gas turbines due to the oxidation of atmospheric nitrogen present in the combustion air and conversion of nitrogen present in the fuel. The chemical mechanism of the formation of NO_x can be divided into four type which is Zeldovich mechanism [10], prompt or Fenimore mechanism [11], fuel-bound nitrogen mechanism [12] and nitrous oxide mechanism [13]. Omendra [14] conducted numerical simulation to investigate theoretical value of temperature produced in the gas turbine combustor using MATLAB. In the study, the maximum flame temperature is limited to 1355K to avoid NO_x formation where NOx is formed at 1500K. A numerical study on the modifications or redesigns of a micro gas turbine combustor is modelled to address the cooling issue inside a compact combustor [15].

Another important factor that affects the combustion performance is the swirling of the flow in the chamber to enhance the mixing of the fuel and air before combustion. This explains the high pitching sound during the actual micro gas turbine. Recently, 3D RANS simulations are conducted with varies model to investigate the capability of difference model in capturing the main flow features of swirl-stabilized isothermal turbulent flow inside a burner. Tariq *et al.,* [21] reported k - ε and the Transition-SST model able to capture the prominent flow features. Similar studies have been conducted by Radwan *et al.,* [22] who used standard and realizable k - ε, standard k-ω and Reynolds stress model with 2D axisymmetric domains while De Meester *et al.,* [23] used non-linear k-ϵ model by comparing the general flow patterns with experimental data.

The actual performance of a C30 micro gas turbine on the effect of varies composition of syngas is limited. The results of the current study will be the preliminary result (known as a reference case) for the future study on the effect of composition of syngas on the performance of a C30 micro gas turbine. The purpose of this study is to investigate the combustion of non-premixed methane/air inside a micro gas turbine (Capstone C30) where thermodynamic model of Capstone C30 micro gas turbine can be found at [16]. This is to determine the combustion characteristic inside a micro gas turbine with 100% methane is assumed for the fuel. The analysis of simulation will be presented in section 3.

2. Numerical Methodology

2.1 Governing Equation

The simulations were carried out using OpenFOAM [17] with the reactingFoam solver [18] with the k - ε turbulence model. An assessment of turbulence modelling study with a pico hydro turbine to determine a suitable turbulent model can be found in [20]. ReactingFoam is a transient solver where it is used to simulate compressible and laminar or turbulent reactive system. A GRI-Mech 3.0 mechanism is used to model combustion where it contains 325 reactions and 53 species. The reaction set and species properties is defined and reported in chemkin file format. In this study, *reactingFoam* is used to investigate combustion with chemical reactions in a micro gas turbine. The density is solved using the ideal gas equation in Eq. (4). The governing equations employed in the study take the form

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \tag{1}$$

$$\frac{\partial (\rho \boldsymbol{u})}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}\boldsymbol{u}) = -\nabla p + \nabla \cdot \tau \tag{2}$$

$$\tau = \mu[(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T) - \frac{2}{3}\nabla \cdot \boldsymbol{u} I \tag{3}$$

$$\frac{\partial (\rho Y_i)}{\partial t} + \nabla \cdot (\rho \boldsymbol{u} Y_i) = \nabla \mu_{eff} \nabla Y_i + \dot{R}_\iota \tag{4}$$

$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho \boldsymbol{u} h) = \frac{\partial \rho \boldsymbol{K}}{\partial \boldsymbol{t}} + \nabla \cdot (\rho \boldsymbol{u} K) - \frac{\partial \rho}{\partial t} = \nabla \alpha_{eff} \nabla h + \dot{R}_{heat} \tag{5}$$

$$\rho = \frac{p}{RT} \tag{6}$$

where ρ is density, ***u*** is the velocity vector, and p is pressure. μ is the dynamic viscosity of the fluid mixture and μ_{eff} is the effective dynamic viscosity which is calculated based on the turbulence model. Y_i is the mass fraction of the *i*-th species and R_i is the production rate of the same species due to reactions. The energy equation is solved for internal enthalpy, h, in which K, α_{eff} , and R_{heat} are the kinematic energy, effective thermal diffusivity, and heat generation due to reactions.

2.2 Parametric Study

Figure 2 shows the three-dimensional model of the micro gas turbine with the dimension of 1.8438m × 2.885m × 2.678m (Lx × Lz × Ly) respectively. The gas turbine can be divided into several section, air inlets, fuel inlets, main combustion zone and an exhaust. There is total of 3 air and fuel inlets where the diameter of air inlet, d_a = 0.127m and diameter of fuel inlet, d_f = 0.0867m with the mass flow rate of 0.516kg/s and 0.03kg/s. The exhaust has a diameter of 0.762m with pressureInletOutletVelocity boundary condition. No slip boundary condition is applied to all sides of the wall. There is a total of 1,028,434 of cells which is sufficient to resolve the flow field with reasonable accuracy.

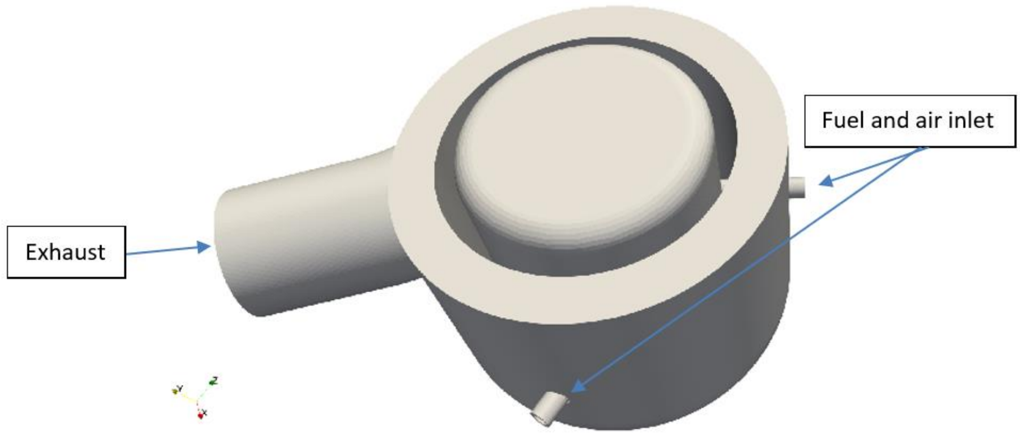


Fig. 2. Isometric view of the gas turbine model

Figure 3 shows the top and cross-section view of the micro gas turbine. All the inlet is located around the gas turbine. The cross-section of the inlet is shown in Figure 4 where the air enter from the outer layer of the inlet and the inner layer of the inlet represents the fuel inlet. Mixing of the fuel and air occurs prior to the entrance to the combustion zone which is located slightly downstream of fuel inlets. The exhaust gas will then be channelled through the centre core.

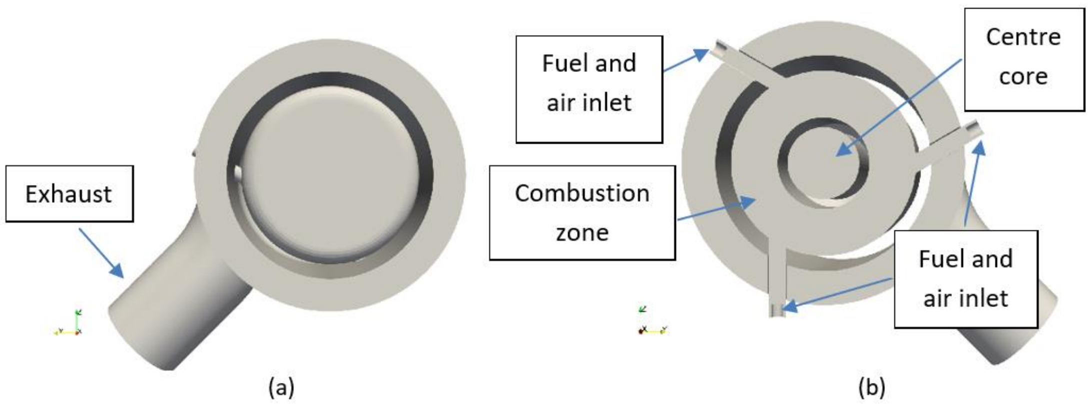


Fig. 3. (a) Top and (b) cross-section view of the gas turbine

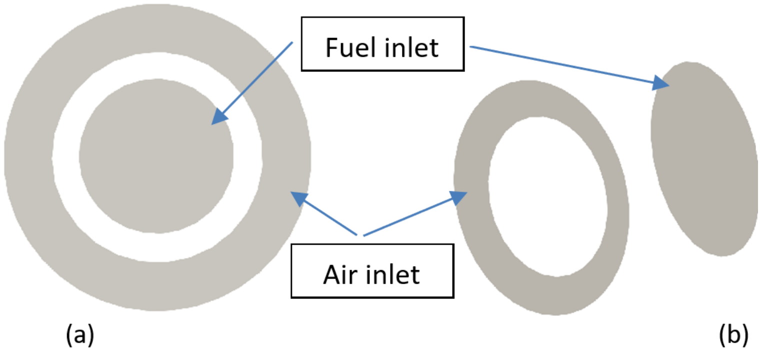


Fig. 4. (a) Front and (b) isometric view of the air and fuel inlet

The simulation is simulated with 100% natural gas and an ideal air-fuel ratio of 14.7:1, where every one gram of fuel, 14.7 grams of air is required the mixture to burn completely. The fuel inlet consists of 100% of methane, CH_4 and the air inlet consist of 23% of oxygen, O_2 and 77% of nitrogen, N_2 The boundary conditions used in the simulation is summarized in Table 1. The composition of natural gas is assumed to be pure methane to reduce the complexity and computational cost. The mass fraction of methane is set to be 1 and the mass fraction of oxygen and nitrogen is 0.23 and 0.77 respectively.

Table 1
Summary of boundary condition for the OpenFOAM simulation

Fuel inlet (kg/s)	0.003
Air inlet (kg/s)	0.516
Wall	No slip
Exhaust	PressureInletOutlet
T_{air} (K)	600
T_{fuel} (K)	400
k (m^2/s^2)	1
epsilon (m^2/s^2)	1
CH_4 [1]	1
O_2 [1]	0.23
N_2 [1]	0.77
H_2O [1]	0
CO_2 [1]	0

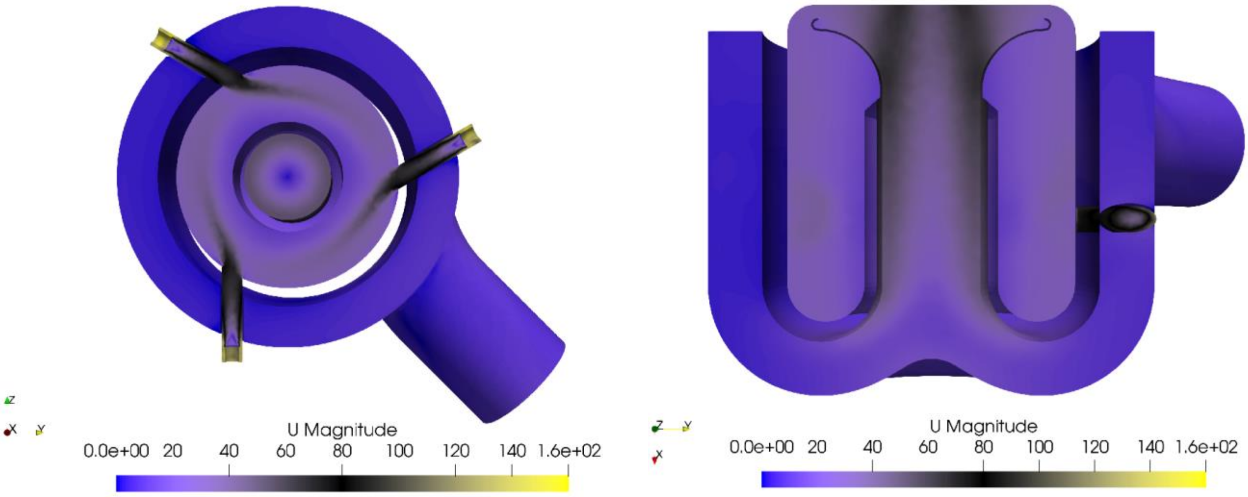
[1] Species mass fraction

3. Result and Discussion

The simulation is divided into two parts namely cold flow and explosion. In the cold flow case, the chemical reaction is turned off and this no reaction occurs. The purpose is to allow the flow field to develop before turning on the reaction. This is important to allow relaxation to the sets of governing equations need to be solved when chemical reaction is turned on. Once the flow is stable and developed, the reaction is turned on and fuel and air are allowed to react during ignition at a given time step.

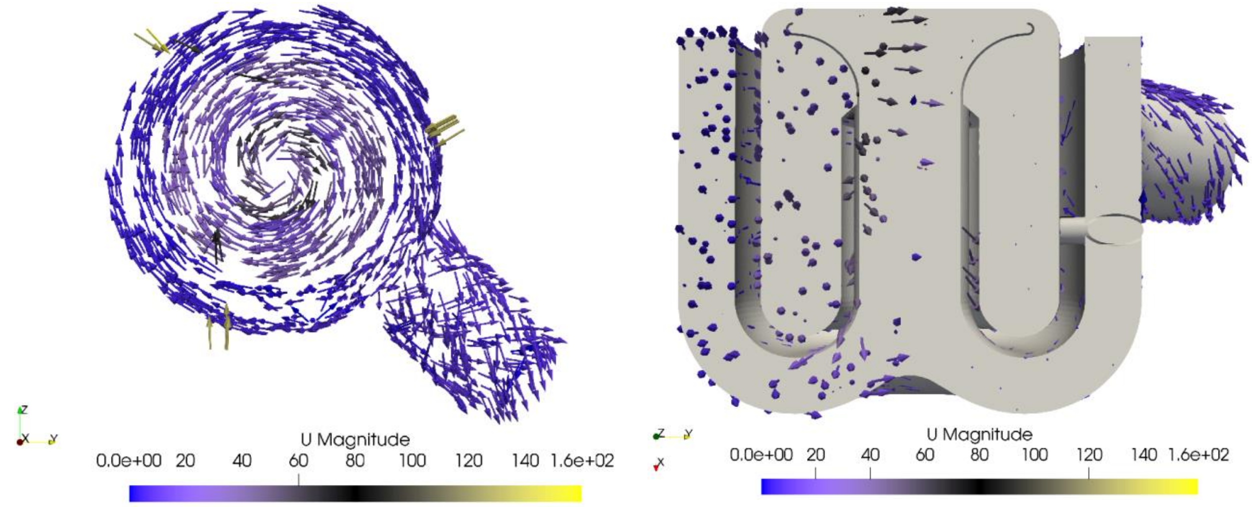
3.1 Cold Flow Simulation

In this section, the chemistry setting is turned off where no chemical reaction is occurred. The flow field in the gas turbine is discussed with the velocity and temperature contour. Figure 5(a) shows flow field in the micro gas turbine with top cross-sectional view. The maximum velocity is observed at air inlets and the flows begin to swirl in the combustion zone. The flows will then be channelled through the centre core shown in Figure 5(b). A significant difference in velocity can be observed at the annular regions between the wall separating the main combustion zone and exhaust duct due to relatively small cross-sectional area. Figure 6 shows the velocity streamlines in the micro gas turbine. Mixing of the fuel and air occurs prior to the entrance to the combustion zone which is located slightly downstream of fuel inlets. Swirl flow can be observed clearly in the Figure 6(a) where the flow is swirling in the combustion zone and then be channelled through the centre core. The flow is guided to the exhaust and flow out of the turbine.



(a) (b)

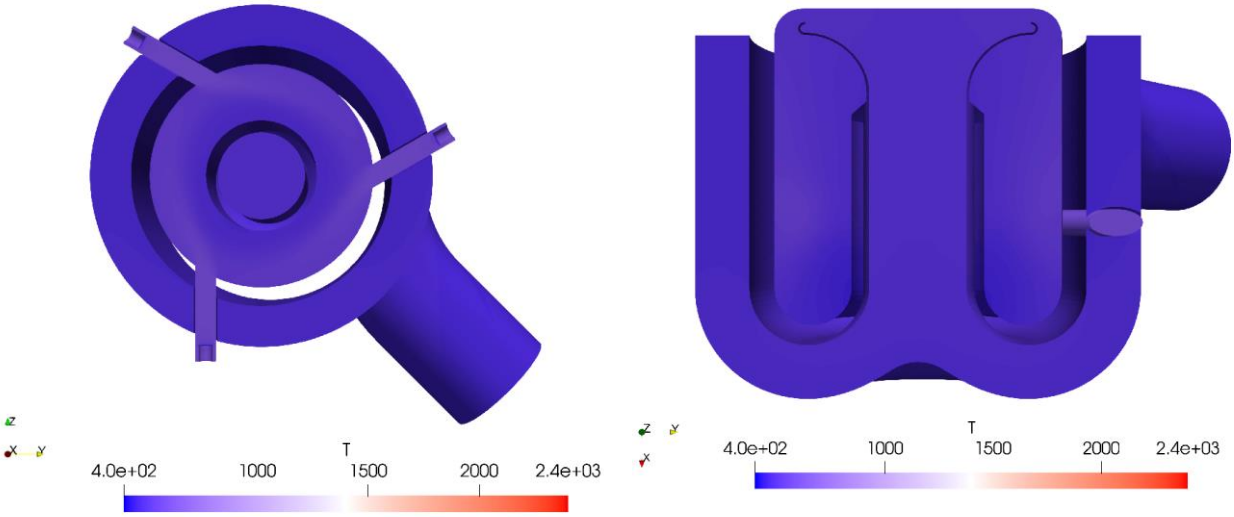
Fig. 5. Velocity contour of (a) top and (b) side cross-sectional view of the micro gas turbine before ignition



(a) (b)

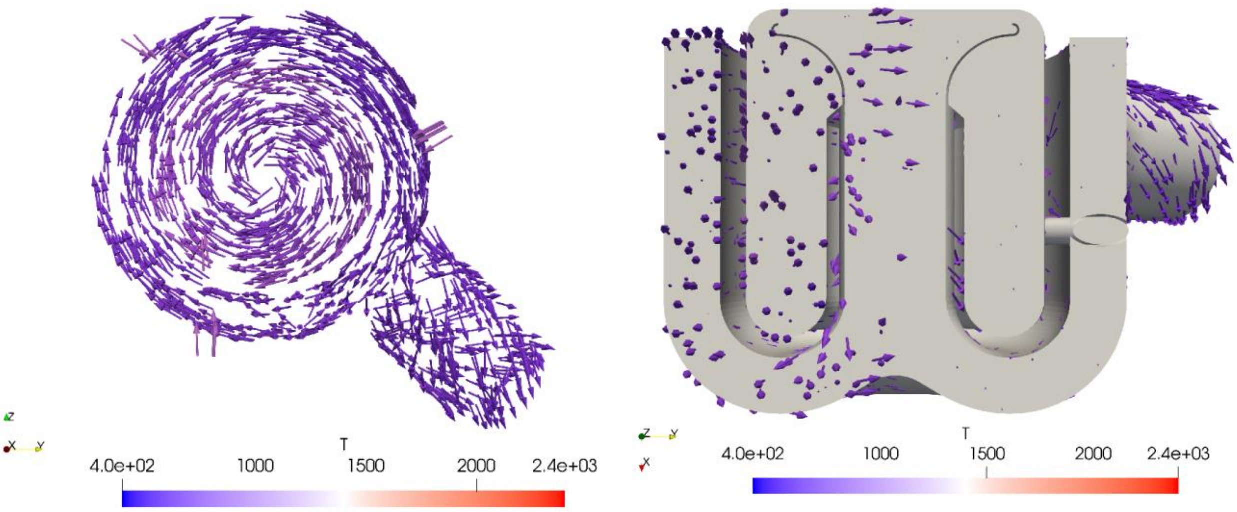
Fig. 6. Velocity streamlines of (a) top and (b) side cross-sectional view of the micro gas turbine before ignition

Figure 7 shows the temperature contour of the micro gas turbine. Air enters through the air inlet at a temperature of T_{air} = 600K and the temperature of methane is set to be T_{fuel} = 400K. The temperature contour with the velocity streamlines is shown in Figure 8. The temperature of the mixtures reaches to a steady state as it channelled to the centre core from the combustion zone.



(a) (b)

Fig. 7. Temperature contour of (a) top and (b) side cross-sectional view of the micro gas turbine before ignition



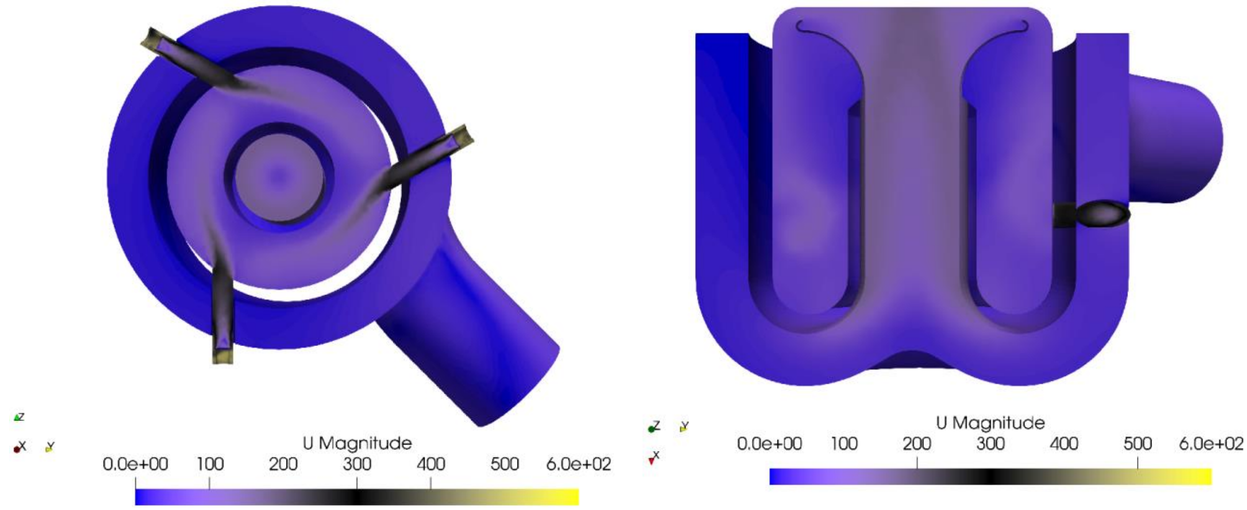
(a) (b)

Fig. 8. Velocity streamlines coloured by temperature of (a) top and (b) side cross-sectional view of the micro gas turbine before ignition

3.2 Explosion Simulation

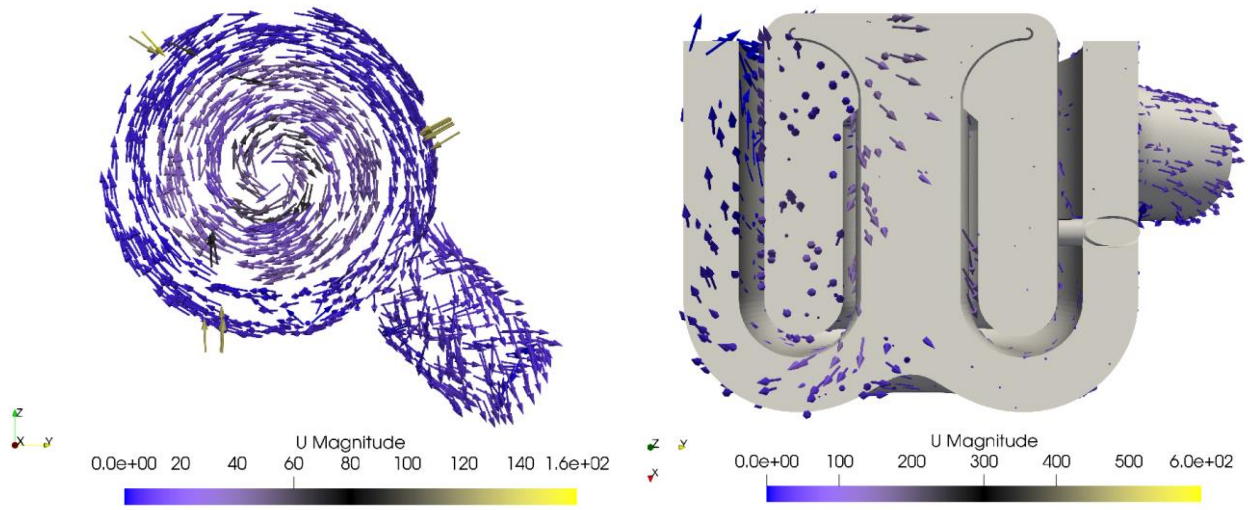
Combustion of the methane/air mixture with the distribution of the species will be discussed in this section. The simulation is stopped after the flow is developed in the micro gas turbine (refer Section 3.1). Combustion is initialised by setting the inlet air temperature to 1800K with chemistry setting is turned on. Combustion of the methane/air mixture can be indicated by an increase in temperature (see Figure 11).

Figure 9 shows the flow field in the micro gas turbine after the combustion is occurred. The magnitude of the velocity of flow in the combustion chamber increases rapidly from U = 60m/s to 200m/s. The magnitude of the velocity at the annular regions on the other hand increases from 100/s to 400 m/s and can be considered supersonic and this explains the high pitch sound during the operation of micro gas turbine. The velocity streamlines in the micro gas turbine during combustion (see Figure 10) does not differ significantly with the plot before ignition in Figure 5.



(a) (b)

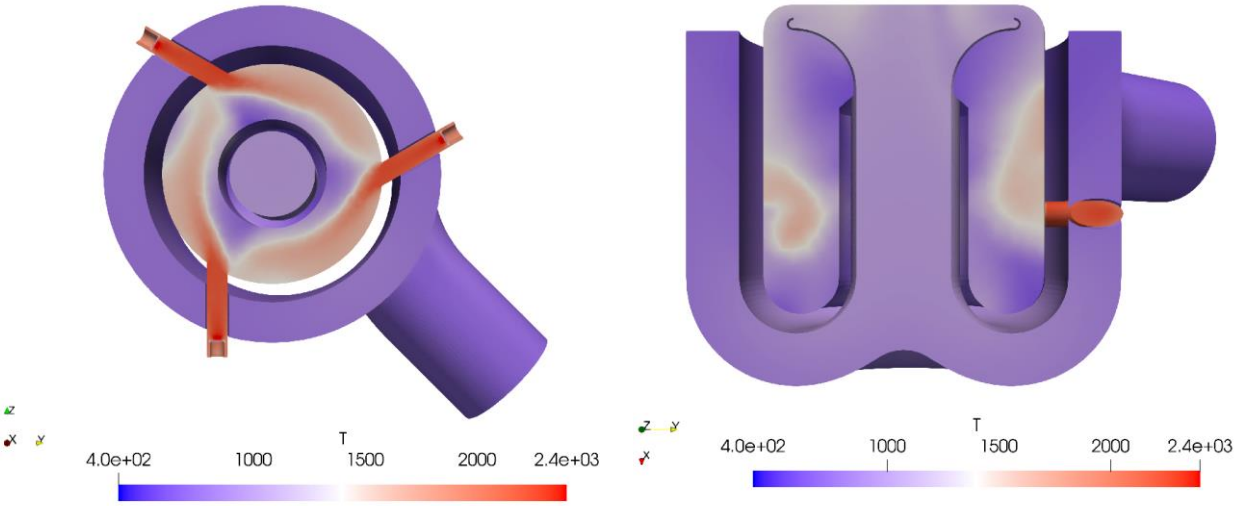
Fig. 9. Velocity contour of (a) top and (b) side cross-sectional view of the micro gas turbine after ignition



(a) (b)

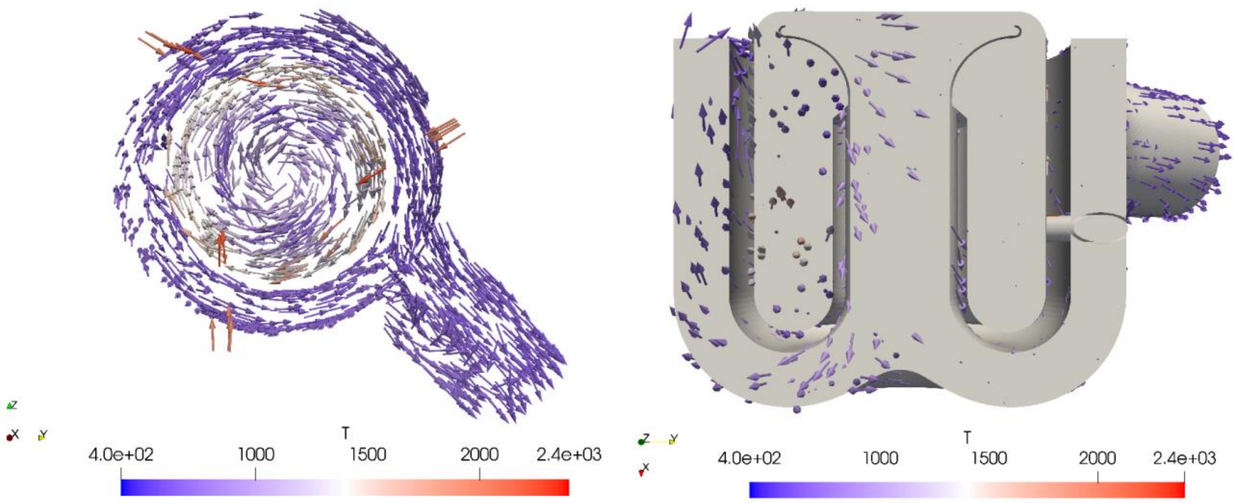
Fig. 10. Velocity streamlines coloured by temperature of (a) top and (b) side cross-sectional view of the micro gas turbine after ignition

Figure 11 shows the temperature contour of the micro gas turbine after combustion is occurred. The temperature of the inlet air is set to be 1800K to initiate combustion. The temperature rises to 2400K at the downstream of inlets in Figure 11 indicates combustion is started. The temperature then reduces to approximately 1500K as the combustion gas flow reaches the combustion zone. The temperature continues to decrease as the combustion gas flow downstream towards the exhaust as shown in Figure 12.



(a) (b)

Fig. 11. Temperature contour of (a) top and (b) side cross-sectional view of the micro gas turbine after ignition



(a) (b)

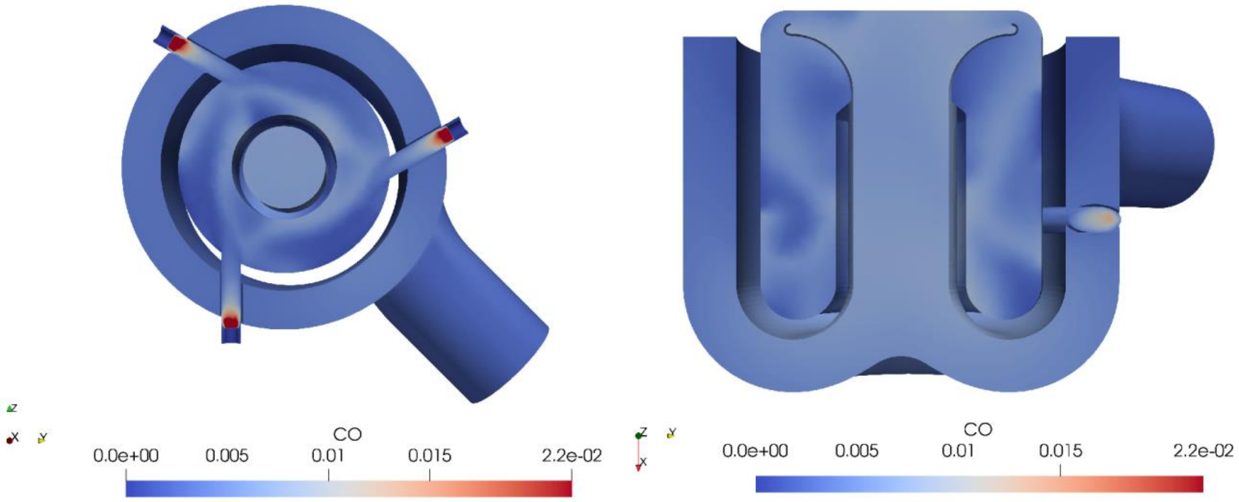
Fig. 12. Velocity streamlines coloured by temperature of (a) top and (b) side cross-sectional view of the micro gas turbine after ignition

3.3 Species Concentration

Species concentration is another vital factor that need to be considered in the investigation of combustion in micro gas turbine. In this section, the species concentration in the micro gas turbine after the combustion will be discussed. The species that are investigated in this study are carbon monoxide (CO), carbon dioxide (CO_2), water vapour (H_2O) and hydroxyl (OH).

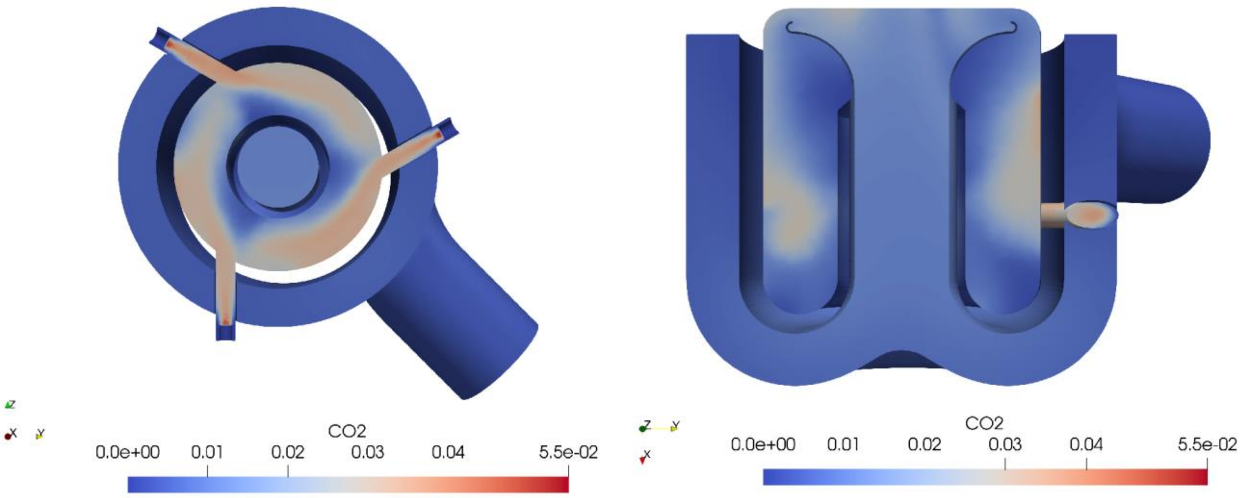
The mass fraction of CO is shown in the Figure 13. The mass fraction of CO is very minimal in the downstream of the combustion chamber. The highest concentration can be observed in the main combustion zone. The concentration of CO reduces downstream of the burner towards the turbine exit. The concentration of CO_2 is the highest in the downstream of the combustion chamber where the combustion of the methane/air mixture occurs and most of the hydrocarbon molecules is converted to CO_2. The concentration of CO2 reduces as the combustion gas flows towards the turbine exit as shown in Figure 13.

The concentration of water vapour is shown in the Figure 15. The distribution of water vapour is very high in the main combustion zone. However, the fraction of water vapour is lower as compared to other species such as CO_2. The concentration level of water vapour decreases as combustion gas exit the turbine. The fraction of the hydroxyl (OH) is very small compares to other species and is shown in Figure 16. The hydroxyl is formed in the downstream of the inlets where methane is mixing with air and combust.



(a) (b)

Fig. 13. Mass fraction of CO of (a) top and (b) side cross-sectional view of the micro gas turbine after ignition



(a) (b)

Fig. 14. Mass fraction of CO_2 of (a) top and (b) side cross-sectional view of the micro gas turbine after ignition

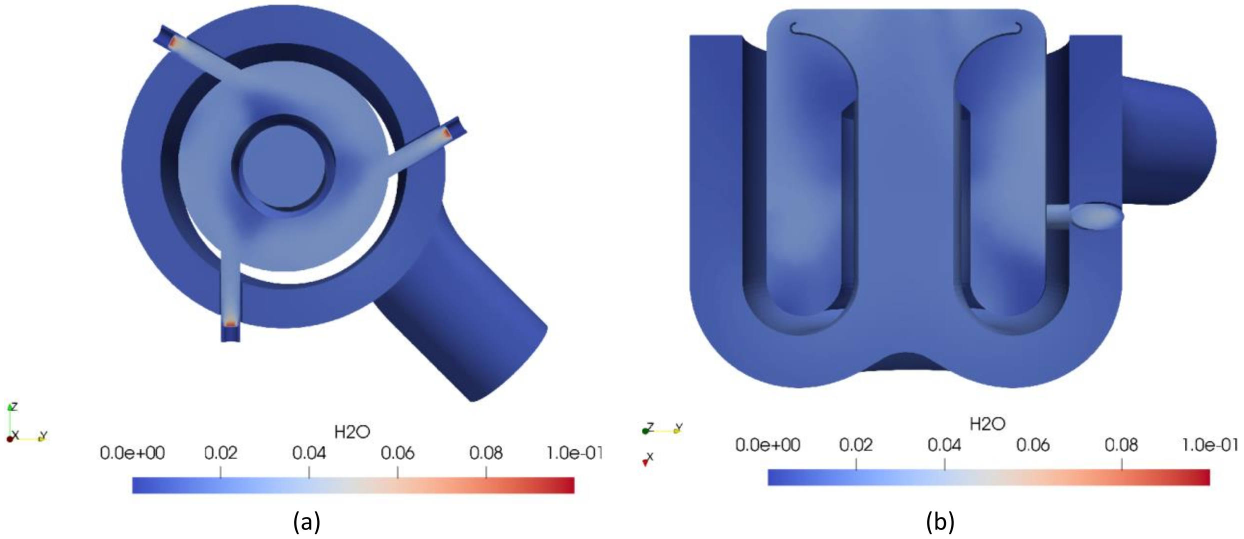


Fig. 15. Mass fraction of H_2O of (a) top and (b) side cross-sectional view of the micro gas turbine after ignition

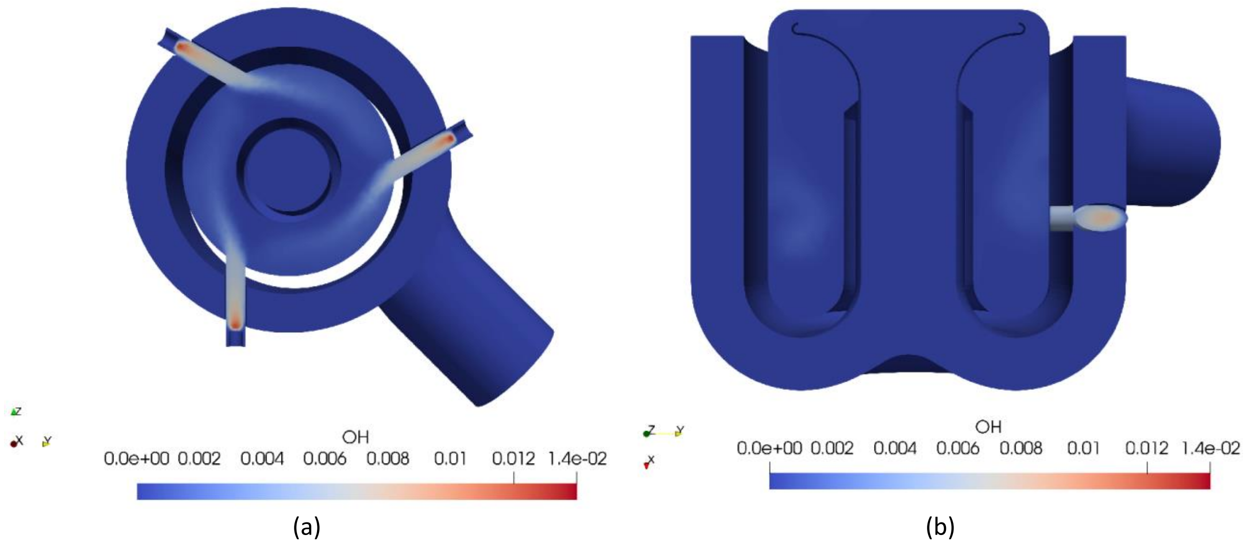


Fig. 16. Mass fraction of OH of (a) top and (b) side cross-sectional view of the micro gas turbine after ignition

4. Conclusion

Numerical simulation of combustion in a micro gas turbine is simulated to investigate the combustion characteristic of non-premixed methane/air mixture inside a micro gas turbine using OpenFOAM. A significant difference in velocity is observe at the annulus between main combustion zone wall due to small cross-sectional area in the cold flow simulation. The velocity of the flow increases significantly in the explosion simulation where the combustion is initialised. Species concentration in the micro gas turbine is discussed where high concentration of CO and CO_2 is in the main reaction zone. The fraction of water vapours and hydroxyl is lower compared to other species.

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