

An Optimization-Based Approach for the Development of a Combustion Chamber for Residential Micro Gas-Turbine Applications

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In the field of micro gas turbine, attention must be paid on the design of the combustion chamber to reduce NO_x formation without compromising combustion efficiency. To this goal flameless combustion represents an appealing solution. The present work aims at the design and optimization of a combustion chamber for a micro gas-turbine, operating in flameless combustion regime. The feasibility of such system is analysed with numerical simulations, using CFD-tools. Among the several configurations under investigations, it is possible to identify one that guarantees the maximum combustion efficiency, the minimum pressure losses as well as the minimum overall dimension.

1. Introduction

Micro Combined Heat and Power generation (μ -CHP), or micro-cogeneration, is an alternative to conventional methods of producing heat and electricity separately. Nowadays the challenge is the development of micro gas turbines with improved efficiency and reduced pollutants emission. In the field of micro gas turbine, attention must be paid on the design of the combustion chamber to reduce NO_x formation without compromising combustion efficiency. To this goal flameless combustion represents an appealing solution.

Wunning and Wunning (1997) showed that flameless is able to provide high combustion efficiency with low NO_x (even with very high air preheating) and soot emissions. The increasing interest in flameless combustion is also motivated by its large fuel flexibility, representing a promising technology for low-calorific value fuels, high-calorific industrial wastes as well as in presence of hydrogen. Flameless combustion needs the reactants to be preheated above their self-ignition temperature and enough inert combustion products to be entrained in the reaction region, in order to dilute the flame. As a result, the system is characterized by a more uniform temperature field than in traditional non-premixed combustion systems, and by the absence of high temperature peaks. As a consequence, NO_x formation is suppressed as well as soot formation, due to the lean conditions, low temperatures and the large CO₂ concentration in the exhausts.

Moreover, as reported by Duwig et al. (2008) flameless combustion is very stable and noiseless so it could be potentially suited for gas-turbine applications where conventional operations may lead to significant thermo-acoustic instabilities ("humming") and stresses. A review of the literature about gas-turbine applications is reported by Arghode et al. (2012). In particular, Luckerath et al. (2008) demonstrated for the first time that a flameless combustor (FLOX[®]) could successfully operate at the high pressures typical of a gas-turbine. More recently Arghode and Gupta (2011a,b) investigated different designs of flameless combustors for gas-turbine applications.

Flameless regime appears to be still worthy of further investigations and attention. In particular, the fundamental mechanism of the interaction between turbulent mixing and chemical kinetics needs to be elucidated. With respect to conventional flames, turbulence levels are enhanced (due to the high momentum of the gases), thus mixing timescales are reduced; on the contrary chemical timescales are increased due to

dilution of the reactants, as described by Galletti et al. (2007). In flameless combustion, the Damköhler number approaches unity, implying that both mixing and chemical kinetics should be taken into account when modelling such a regime, resulting in a very challenging problem. An approach to overcome this problem is suggested by Kanniche (2009), who post-treated 3D simple chemistry calculations to generate a 0D chemical reactor network, which includes detailed chemistry.

More encouraging results in literature on the modelling of such flames have been obtained using the Eddy Dissipation Concept (EDC) model by Magnussen (1981), coupled with detailed chemical mechanism. A review of the existing literature may be found in Fortunato et al. (2014).

The present work focuses on the design and the optimization of the combustion chamber for a micro gas-turbine operating in flameless combustion regime, using CFD-tools.

2. Methodology

The commercial code Ansys 14.5 was used to perform the study on the combustor. Numerical calculations were run with the standard k- ϵ model. In a first stage the EDC model coupled with a global kinetic mechanism was considered, in order to save CPU time. In a second stage of the study a skeletal kinetic mechanism, namely the KEE58, was used.

The design is carried on with the objective of increasing the recirculation rate k_R , a key factor in flameless combustion regime, as reported by Wunning and Wunning (1997), who defined the recirculation rate as showed in Eq(1):

$$k_R = \frac{\dot{m}_e}{\dot{m}_f + \dot{m}_a} \quad (1)$$

where \dot{m}_e is the net mass flow rate of recirculated flue gas, whereas \dot{m}_f and \dot{m}_a are the fuel and air mass flow rates, respectively.

According to Cardoso (2011) to increase k_R , it is necessary to increase the chamber-to-nozzle(s) area ratio. Therefore the key parameters in the design of the combustion chamber are the combustion chamber section and the air and fuel inlet sections. In order to choose the best value for each parameter, Factorial Design is performed, following Pavelic and Saxena (1969). In this case, it was chosen to consider 3 different levels for each of the 3 variables under investigation. 27 (3^3) have been examined.

Since the combustion chamber is supposed to be part of a micro gas-turbine, inlet temperature as well as air and fuel mass flows are fixed a priori and they cannot be subjected to any change. The inlet temperature is related to the operating condition of the heat exchanger, while the outlet temperature is chosen based on the optimal inlet condition of the gas turbine. The mass flows are chosen in order to guarantee a certain thermic input.

Once the first design was performed, the obtained configuration was the subject of an optimization study. The main goal of this optimization study it is to determine the optimal geometrical parameters of the combustion chamber in order to:

- Minimize NO_x emissions,
- Minimize pressure losses,
- Maximize homogeneity of temperature at the outlet,
- Maximize combustion efficiency.

The optimization consists in a Design of Experiments (DoE) and a Response Surface.

With the DoE, output parameters are calculated for the different geometries, obtained changing the input parameters. The DoE was performed with the Optimal Space Filling algorithm, which fills the design space efficiently with as small number of points as possible while keeping the discrepancy as low as possible.

The main geometrical parameters of interest are:

- The radius of the fuel inlet that would impact the fuel inlet velocity;
- The distance between the inner and outer radii of the air inlet so that the air inlet velocity can vary,
- The wall distance between the air inlet and the outlet to see the influence of the position of the outlet along the wall,
- The distance between the outlet and the upper wall of the chamber and the length of the chamber to see the influence of the change in radius of the chamber (note that the change in radius of the chamber is also influenced by the other parameters)
- The length of the combustion chamber to determine its influence on the pressure losses.

Once the output parameters are calculated, the relationship between the latters and the input parameters, namely the Response Surface, is calculated thanks to meta-modelling algorithms. In this case the Kriging algorithm was used. It consists in an optimal interpolation technique based on regression against observed z

values of surrounding data points, considering weights derived from covariance function or semivariogram. More details about those techniques may be found on the Ansys Workbench User Guide (2010).

3. Results

3.1 Design of the combustion chamber

As mentioned before, this combustion chamber is part of a micro gas-turbine. Therefore some parameters, such as inlet temperature as well as the mass flow rates, are fixed a priori and they are not subject to any change. Moreover, it was chosen to consider a cylindrical geometry to better integrate the combustion chamber with the heat exchanger and the other parts of the micro gas-turbine.

The fuel considered for this combustion chamber is methane.

The values for the combustion chamber section and the air and fuel inlet sections are the result of the Factorial Design performed as explained in the previous section. The values of each variable that led to the highest value of k_R are: diameter of the chamber 0.130 m, air inlet velocity 200 m/s and fuel inlet velocity 15 m/s. The length of the combustion chamber, for this configuration is 0.310 m. In order to avoid the flame blow-out, due to the high velocity of the jets issuing in the combustion chamber, the exhaust gases outlet is placed on the same side of the inlets and it has an annular geometry. The recirculation rate k_R it has been estimated at 1.42, which is in agreement with what observed by Galletti et al (2007), for a self-recuperative FLOX® burner. The flow field inside such combustion chamber is shown in Figure 1.

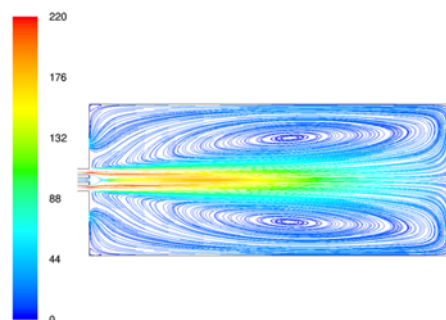


Figure 1: Velocity [m/s] distribution.

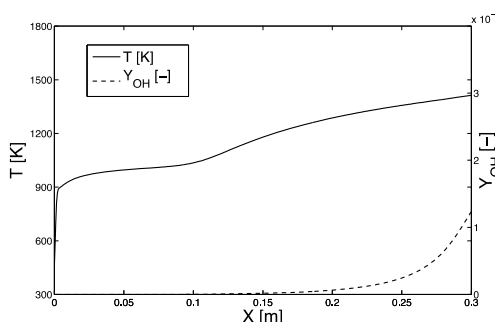


Figure 2: Temperature [K] and OH mass fraction [-] along the chamber axis.

It can be seen that a well-established recirculation zone is present in the combustion chamber.

In order to achieve a better understanding of the phenomena inside the combustion chamber, a numerical simulation with a skeletal kinetic mechanism (namely KEE58) was also carried on. Among the several chemical species considered in this mechanism, attention was focused on the radical OH. When combustion occurs, the radical OH shows where exactly the reaction is taking place. Figure 2 shows the temperature and the OH mass fraction along the axis of the combustion chamber. The temperature is uniform with a very low increase in temperature. Those are all characteristics of the flameless combustion regime.

As far as the radical OH is concerned, its mass fraction increases towards the end of the chamber, meaning that combustion is actually taking place in diluted conditions and not when the two jets first mix.

3.2 First Optimization Study

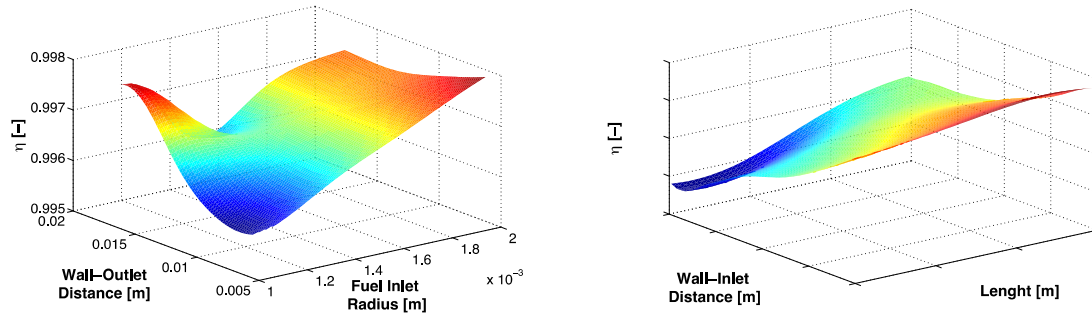
The first design of the combustion chamber provided for the output parameters, discussed in Section 2, the values reported in Table 1.

Table 1: Output parameters values for the first design

Outlet temperature, K	1325
Temperature Homogeneity, %	99.96
NO _x concentration, ppm	≅ 0
Combustion efficiency, %	99.7
Pressure losses, %	6.1

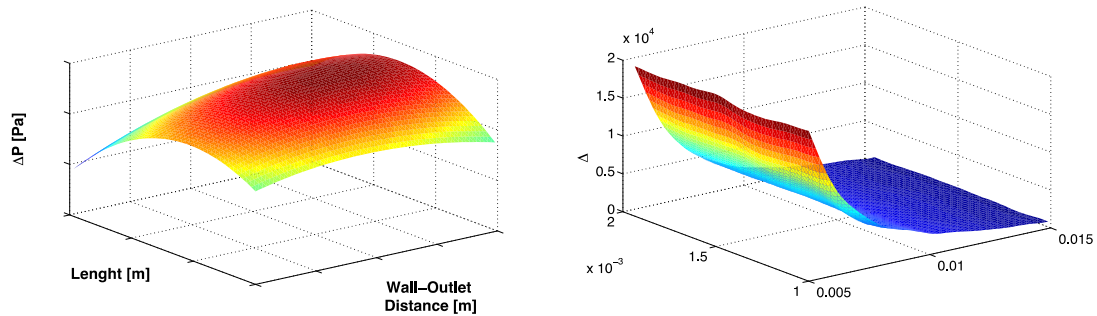
The objective of the optimization study is reducing the outlet temperature and the pressure losses and increase the combustion efficiency.

The relationship between the output parameters, calculated with the DoE, and the input parameters is calculated with the Kriging algorithm in the Response Surfaces, as described in Section 2. Figure 3a and 3b show how the combustion efficiency is affected by the different input parameters. It can be noticed that the combustion efficiency is higher when the length and the diameter of the combustion chamber are higher.



(a) (b)
Figure 3: Effect on the combustion efficiency of: (a) the fuel inlet radius and chamber radius and (b) the length and the radius of the chamber.

Figure 4a and 4b report the effect of the different input parameter on the pressure losses. In this case, the lower value for the pressure losses is achieved reducing the air inlet section and the length of the chamber.



(a) (b)
Figure 4: Effect on the pressure losses of: (a) the length and the radius of the chamber and (b) the fuel inlet and the air inlet radii.

Figure 3 and 4 also show that different combinations of the input parameters generates geometrical configurations that satisfy the required criteria. In particular ten different configuration matched the required criteria. The values for the output parameters obtained with those configurations are reported in Table 2.

Among those configurations, a further selection was made comparing the improvement on the first design of the chamber. Three configurations were selected (points 2, 8 and 9 in Table 1). Point 2 permits to increase the combustion efficiency and reducing the pressure losses. Points 8 and 9 highly reduce the outlet temperature inside the chamber, which is very interesting for the downstream turbine. They also reduce largely the pressure losses. Among those three points, point 2 is characterized by the minimal overall dimension, a fundamental parameter since this combustion chamber is part of a micro-gas turbine.

The optimization study finally led to a combustion chamber with a diameter of 0.102 m, air inlet velocity 74 m/s and fuel inlet velocity 24 m/s. This combustion chamber is characterized by a combustion efficiency of 99.8 %, pressure losses of 0.95 % and NO_x emissions close to 0 ppm.

Table 2: Values of the outlet parameters for the ten selected configurations

	T_{out} , K	η_{comb} , %	ΔP , %
			1.23
1	1342	99.7	
2	1326	99.8	0.95
3	1329	99.7	3.62
4	1325	99.6	0.97
5	1311	99.5	0.62
6	1241	99.7	3.86
7	1284	99.7	1.96
8	1206	99.7	1.36
9	1211	99.6	0.85
10	1323	99.6	1.07

3.3 Second Optimization Study

To better integrate such combustion chamber in the micro gas-turbine it was chosen to analyse and optimize a slightly different configuration, characterized by having the exhaust gases outlet placed on the opposite side of the inlets, close to the side wall of the chamber. The flow field inside this new configuration is shown in Figure 4.

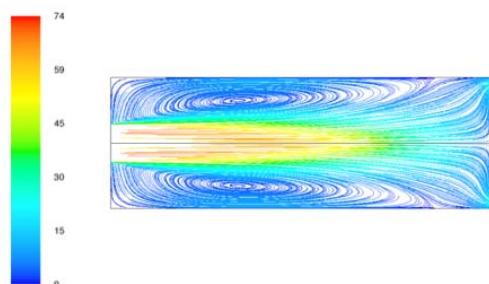


Figure 4: Velocity [m/s] distribution

The parameters under investigation in this second optimization study were:

- The length of the combustion chamber;
- The air inlet inner radius;
- The distance between the outlet and the side wall.

The output parameters are the same discussed in the previous sections, and are reported in Table 3.

Table 3: Values of the outlet parameters for the ten selected configuration

	T_{out} , K	η_{comb} , %	ΔP , %
			0.61
1	1310	71.7	
2	1230	26.8	0.20
3	1337	96.6	0.27
4	1292	42.0	0.29
5	1324	97.1	0.75
6	1332	95.8	0.24
7	1336	93.3	0.40
8	1288	61.8	0.19
9	1258	40.4	0.31
10	1297	51.6	0.47

Unfortunately, none of the configurations analysed satisfies the required criteria.

Therefore it was chosen to implement in the micro gas-turbine the combustion chamber obtained from the first optimization study.

4. Conclusions

In the field of micro gas turbine, attention must be paid on the design of the combustion chamber to reduce NO_x formation without compromising combustion efficiency. To this goal flameless combustion represents an appealing solution. The present work aimed at the design of a combustion chamber for a micro gas turbine, operating in flameless combustion regime. The feasibility of such system was analysed with numerical simulations, using CFD-tools. The configuration that gave the most satisfactory results was the cylindrical one, with the outlet on the same side of the inlets. This configuration was then the subject of an optimization study. Ten geometrical configurations were found, from which three were retained by comparing the improvement on the first design of the chamber. One of these points permits to increase the combustion efficiency and reducing the pressure losses. The two others highly reduce the maximum temperature inside the chamber, which is very interesting for the downstream turbine. They also reduce largely the pressure losses. Among those three points the first was chosen because of the minimal overall dimension, a fundamental parameter since this combustion chamber is part of a micro-gas turbine.

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