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DESIGN AND NUMERICAL INVESTIGATIONS OF AN AFTERBURNER SYSTEM USING METHANE-HYDROGEN BLENDS

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Abstract: The gas turbine industry strongly committed to develop gas turbines operating with 100% hydrogen till 2030, such fully supporting the transformation of the European natural gas grid into a renewable-based energy system by overcoming technical challenges and ensuring that this transformation takes place swiftly. By extending the fuel capabilities of gas turbines to hydrogen, their role can become predominant in the energy transition period but also in long-term energy strategies. In combined cycle configuration (CCGT), gas turbines are already the cleanest form of thermal power generation. For the same amount of electricity generated, gas turbines running on natural gas emit 50% less CO_2 emissions than coal-fired power plants. Mixing renewable gas (e.g., green hydrogen, biogas) with natural gas enables further reduction in net CO_2 emissions. In this paper pure hydrogen and blends of hydrogen methane will be studied as fuel in order to predict the behavior of afterburner system with a new designed geometry.

Key words: Afterburner, Numerical Simulation, Hydrogen Mixtures, Renewable gas, Combustion.

1. INTRODUCTION

Changes in fuel composition, particularly the addition of hydrogen to hydrocarbon fuels, affect both the chemical and physical processes occurring in flames. These changes influence flame stability, acoustics, pollutant emissions, combustor efficiency. Few of these issues are clearly understood. Studies in the literature related to the use of hydrogen as both the primary fuel and a fuel additive have been directed toward the effects of small amounts of hydrogen addition on hydrocarbon flame stability and pollutant formation under fuel-lean conditions Relevant studies regarding internal combustion engines demonstrate the advantages of using as fuel hydrogen blended with natural gas on exhaust emissions [1] and on extending the lean engine operating limits [2, 3]. Early results in large-scale gas turbine combustors also indicate advantages to hydrogen addition. [4] carried out a study on the effect of hydrogen addition in aircraft gas turbines. Up to 15% hydrogen addition to JP-5 or JP-6 produced leaner blowout limits and corresponding reductions in NOx (less than 10 ppm @ 15% O_2) while maintaining acceptable CO and HC emissions levels. In [5] experiment premixed hydrogen with propane (up to 5% of the total fuel flow) to show that H_2 addition extended the premixed lean flammability limits and improved combustion efficiency. One of the priority investment areas of the National Recovery and Resilience Plan (PNNR) is hydrogen production. Considering this increased interest, within the Combustion Chamber Laboratory of INCD Turbomotoare COMOTI, researches were carried out regarding the combustion of H_2/CH_4 mixtures. In Romania, has been preoccupation for using cogeneration groups with gas turbines conducted by INCDT COMOTI Bucharest who installed in 2007 two PAES cogeneration groups each of 2000 kW at SC Termica SA from Botoşani for combined electrical power and hot water production for urban use [6]. INCDT COMOTI also completed two cogeneration groups each with electrical power of 1750 kW equipped with ST18 – Pratt & Whitney gas turbines for the Cogeneration Plant 2xST18 – Suplacu de Barcau for combined electrical power and overheated steam, needed for oil extraction and production [6]. The development of advanced combustion capabilities for gaseous hydrogen and hydrogen blended hydrocarbon fuels in gas turbine applications is an area of much current interest. The technical solution starts (Figure1 and 2) from the patent no. RO128845B1/2016[7], where the first author approached this subject in his Ph.D. theses. The first stage of afterburner fuelled with natural gas was manufactured and tested with success using a mass flow of CH_4 of 0.002 kg/s. From this research resulted the following publications presented in references [8- 15]. This paper is a continuation of previous work. The main purposes of this paper are as follows: first is to design an

afterburner system and second is to perform a series of numerical simulations using ANSYS CFX software tools in order to predict the behaviour of afterburner system using new designed geometry. Blends of hydrogen methane ($60\%H_2+40\%CH_4$,$80\%H_2+20CH_4$) and pure hydrogen will be tested in order to evaluate the flame stability. The testing rig is composed from afterburner system designed, and manufactured at INCDT – COMOTI and placed behind a gas turbine engine [15]. Computational domain reproduces the test rig arrangement in order to obtain accurate results [15]. Based on the obtained results, geometries (fuel injectors and flameholder) will be selected for additive manufacturing and testing.

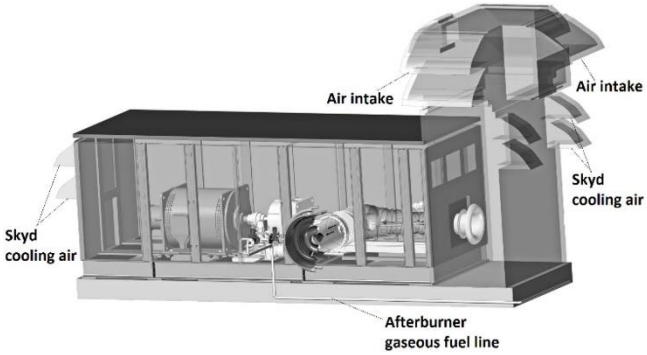


Fig. 1. General Assembly, [7]

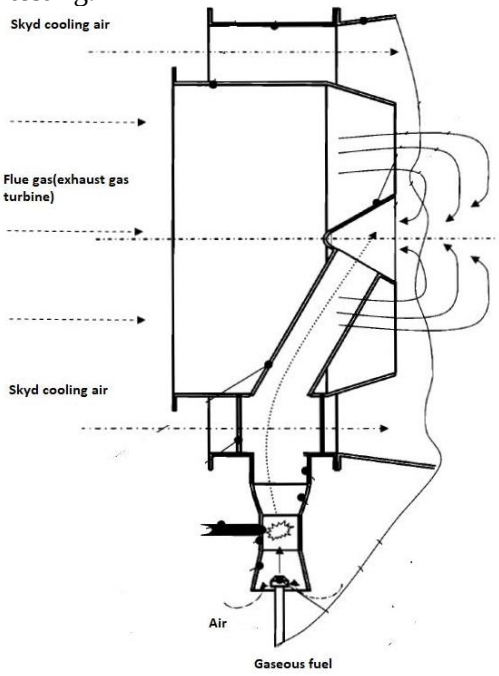


Fig.2. First stage of the afterburner, [7]

2. ESTIMATION OF FUEL MASS FLOWS FOR MIXTURES OF HYDROGEN WITH METHANE GAS ($60\%H_2+40\%CH_4$, $80\%H_2+20\%CH_4$) AND FOR PURE HYDROGEN ($100\%H_2$)

The natural approach would be to aim for the same performance when replacing the fuel with another, therefore the method chosen will be: keeping the thermal power constant, using equation (1). This approach is detailed in following papers [16,17,18]:

$$P = \dot{m}_c \cdot H_i \tag{1}$$

where: P – thermal power [kW], $\dot{m}_c$ – fuel mixture mass flow rate [kg/s] and Hi – lower calorific value of the fuel mixture [kJ/kg], Table 1. Air mass flow is same for all numerical simulation variants: m_{air} = 0.49 kg/s (given by the Garret micromotor) and thermal power kept constant P=100 kW.

Table 1. Fuel mass flows calculated according to thermal power

Fuel(volumetric%)	mc(kg/s)	H_i[kJ/kg]	P(kW)	Mass Fraction (%)
$100\%CH_4$	0.002	50000	100	H_2=0 CH_4=1
$60\%H_2+40\%CH_4$	0.001637921	61.053	100	H_2=0.157895 CH_4=0.842105
$80\%H_2+20\%CH_4$	0.001363643	73.333	100	H_2=0.33 CH_4=0.67
$100\%H_2$	0.000826644	120.000	100	H_2=1 CH_4=0

3. GEOMETRY OF THE FLAME HOLDER AND NUMERICAL SIMULATION SETUP

The geometry of the computational domain has been created using 3D design software CATIA. A 3D steady RANS numerical simulation has been performed using Ansys CFX.

3.1. The prototype (version 1)

In order to obtain the final design for the flameholder, the first step is to simulate the combustion using the new fuel (mixtures of hydrogen with methane gas and pure hydrogen) on the initial version of afterburner design for natural gas.

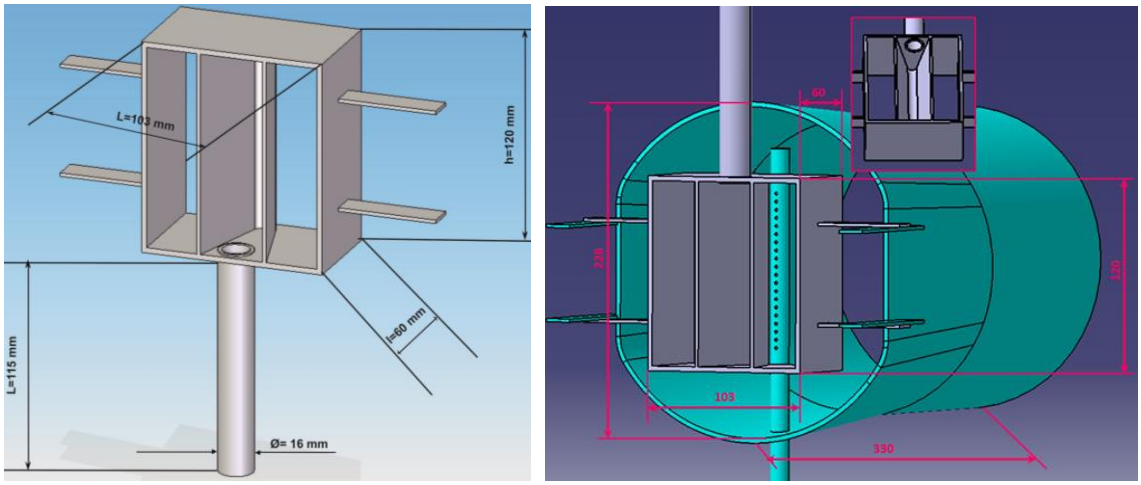


Fig. 3. Version 1 - Flameholder

The afterburner system, shown in Fig.3, has the next global dimensions: length of the afterburner system is 330 mm; height of the casing is 228 mm and the width is 168 mm. The fuel injector contains 20 equally spaced holes of 2 mm in diameter [8,11,15]. The flame stabilizer assembly includes the actual, "V" - shaped flame stabilizer. Other detail about geometry can be found in [8-15].

3.2. The prototype (version 2)

The casing and the stabilizer housing remained unchanged. The essential modification of the flameholder consists in the application of two convex walls at the edge of the flame stabilizer to form a fuel injector. Within the created enclosure, 20 fuel holes with Ø2 mm diameters (10 on each side) were applied. Also were provided with walls placed on the sides of the flame stabilizer on which 15 holes with Ø2 mm were applied for the direction of the gas flow and additional cooling. Two version were created for “V” flameholder for 45° and 60° angle.

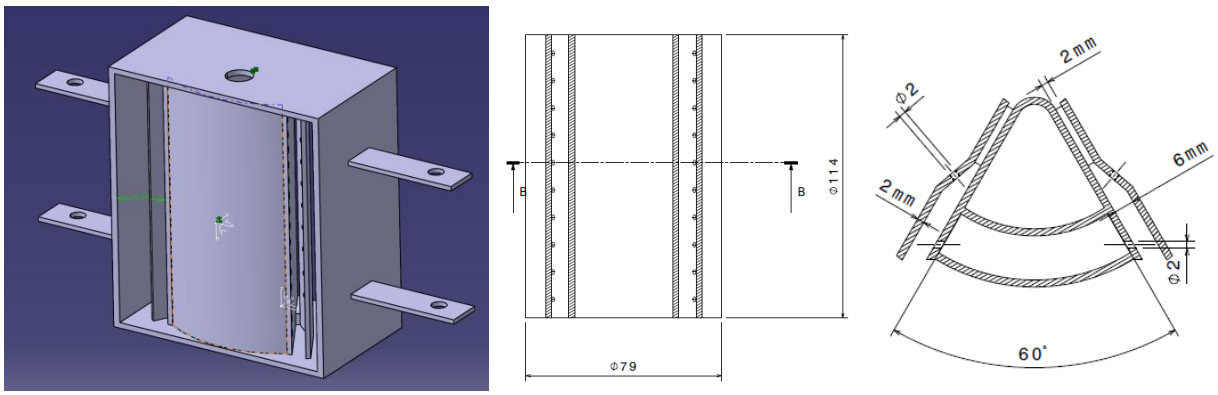


Fig. 4. Version 2 - Flameholder

3.3. The prototype (version 3)

The casing and the stabilizer housing remained unchanged. The essential modification consists in the application of a concave walls at the edge of the flame stabilizer to form a fuel injector. Within the created enclosure, 20 fuel holes with diameters of Ø2 mm were applied. Unlike the previous version, the arrangement of the holes is as follows: There are 5 holes on each side (left and right) and 10 fuel holes (left and right) were also provided on the front side of the concave wall. As well were provided with walls placed on the sides of the flame stabilizer on which 15 holes Ø2 mm were applied for the direction of the gas flow and additional cooling. The role of the walls placed on the sides of the flame stabilizer is to direct the flow of combustion gases, namely

a constant mass flow of 0.49kg/s, provided by the turbo engine (Garret) around the V geometry of the flame stabilizer. The provided flow channel simultaneously allows the blending of combustion gases with fuel and at same time cooling of the flameholder wall due to the increase speed of the flow. Two version were created for "V" flameholder with 45° and 60° angle.

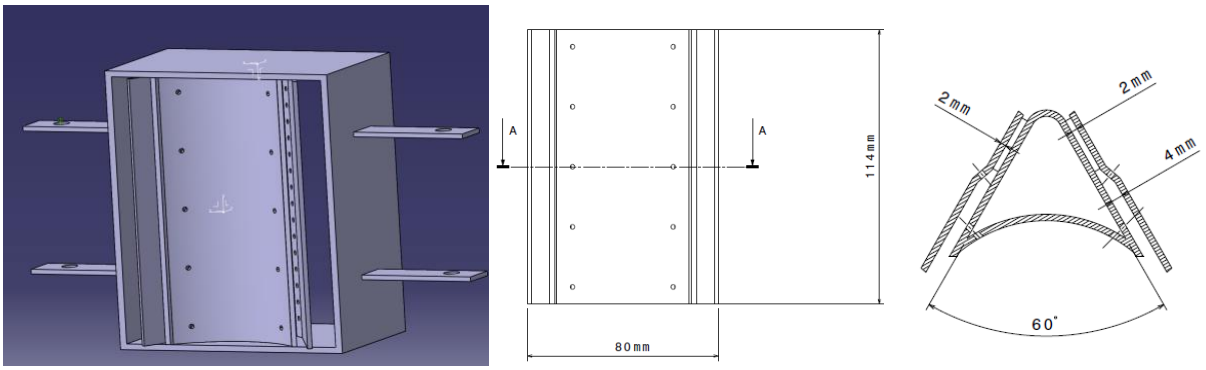


Fig. 5. Version 3 Flameholder

3.4. Boundary conditions

For the numerical application, the RANS technique will be used, this requiring smaller computing resources. The RNG k-ε turbulence model and the EDM combustion model have been chosen. The RNG k-ε model is considered the standard turbulence model used in industrial applications. It proved to be numerically stable and robust. The EDM combustion model was developed to be used in a wide range of reactive turbulent flows, both for premixed and diffusive flames. This model is widely used in industrial applications due to its simplicity and robustness, as well as due to the efficiency with which it predicts the behaviour of flames, [19-21]. The boundary condition is presented in Table 2.

Table 2. Boundary conditions

Location	Boundary conditions
Inlet Air	Subsonic, V=30m/s, Temperature static =550K
Inlet Fuel	Mass Flow= [Table 1], Temperature static=300K
Wall	Boundary type: Wall; Heat Transfer: Adiabatic; Mass and Momentum: No Slip Wall
Atmosphere	Boundary type: Opening, Flow Regime: Subsonic, Relative pressure=0[Pa], Temperature=300K
Pressure reference	101325 Pa
Turbulence model	RNG k-Epsilon
Combustion model	Eddy Dissipation

The discretization of the computational domain was performed using the ICEM CFD program. The mesh types generated for computational grids were unstructured. The calculation domain is presented in Figure 6. The atmospheric pressure of 101.325 Pa has been set as reference pressure.

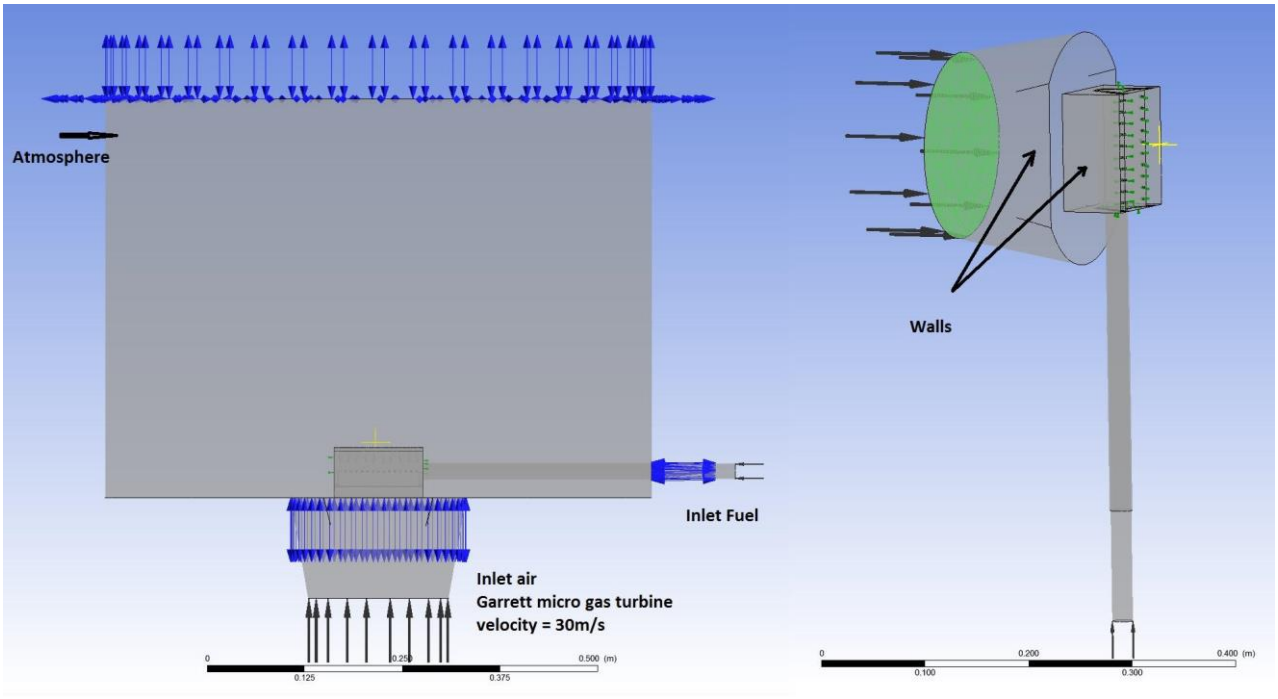


Fig. 6. Boundary conditions

4. RESULTS AND DISCUSSION

4.1. The prototype (version 1)

The fuel burns in the vicinity of the injection holes. The flame surrounds the stabilizer producing, as can be seen, high temperatures (Figure 7) on the walls of the flameholder. For this reason, this solution it was abandoned

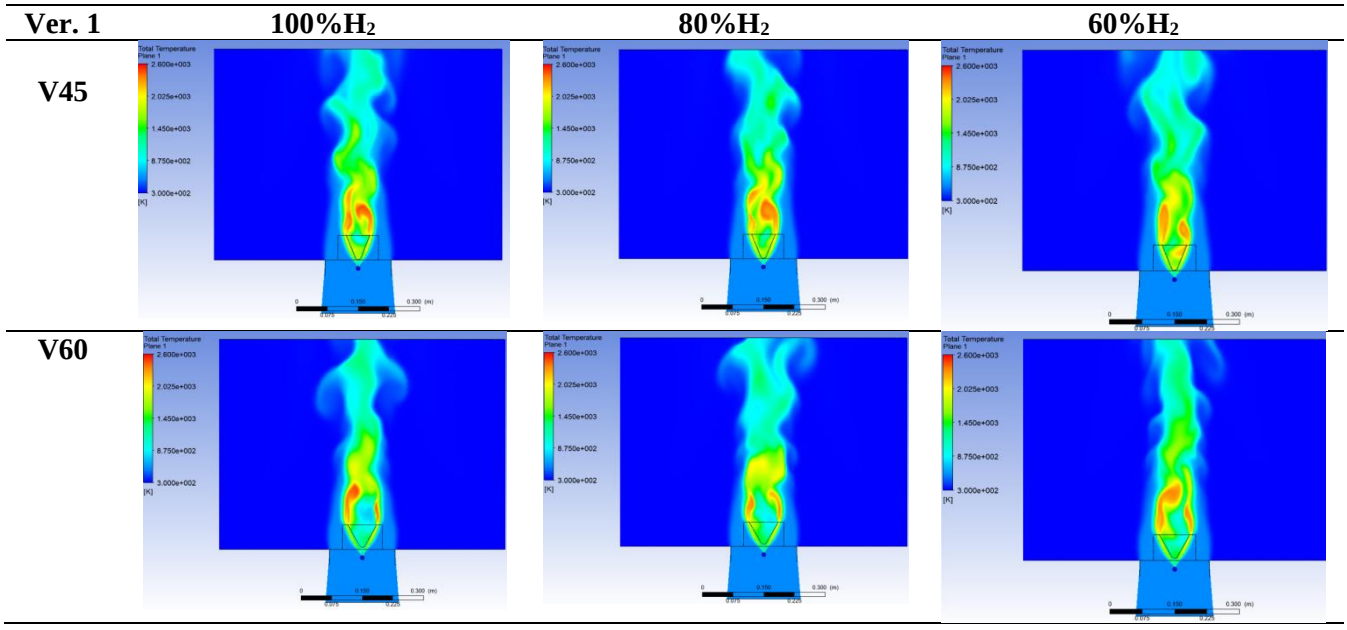


Fig. 7. Total temperature on prototype

4.2. The prototype (version 2)

The temperature in the recirculation zone, varies in a range from 2000k to 2600 K, as this point out there is burned gas. In this case, the flame sticks (Figure 8) to the convex wall, continuously exposing the convex wall to hight thermal stress. For this reason, this solution was also abandoned.

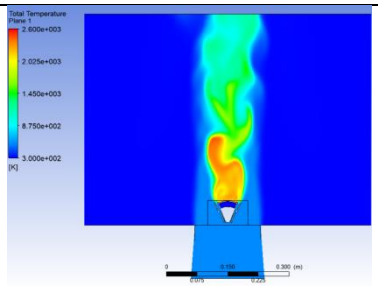
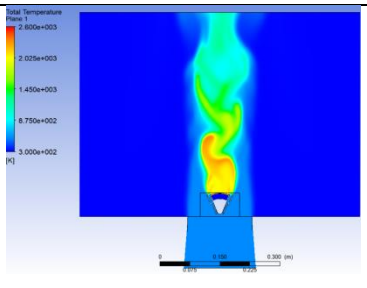
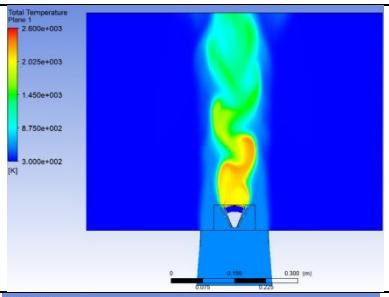
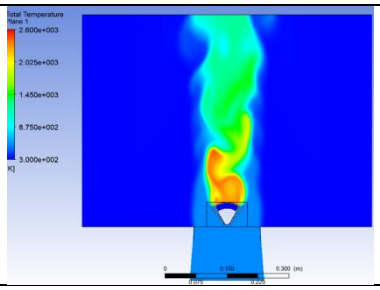
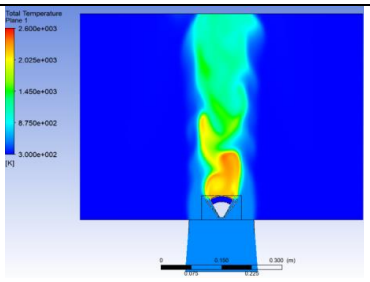
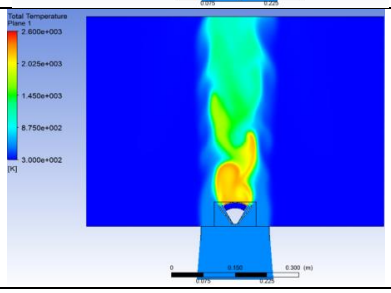
Ver. 2	100%H_2	80%H_2	60%H_2
V45			
V60			

Fig. 8. Total temperature on version 2 design

4.3. The prototype (version 3)

Comparing recirculation zones (Figure 9) for the 45° flameholder is observed that increase of hydrogen percentage leads to a decrease in average burning temperature. On the other hand, the length of the flame increases. For the 60° flameholder, numerical simulation shows an intensification of combustion which leads to an increase in temperature near the trailing edge of the flameholder. The intensity of combustion is improved due to the perforated holes from flameholder's side walls such that the velocity of mixture (fuel and combustion gases) is accelerated. The fuel disperses in shear layer so the temperature gradually increases in all area.

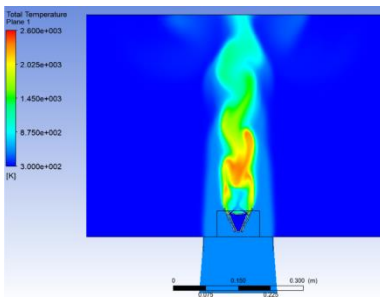
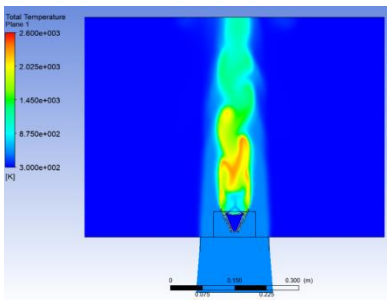
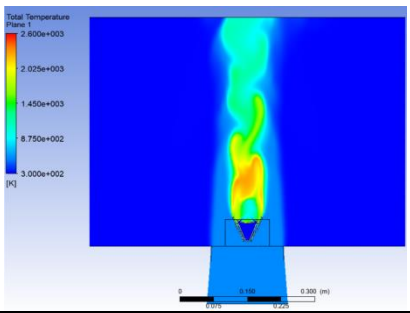
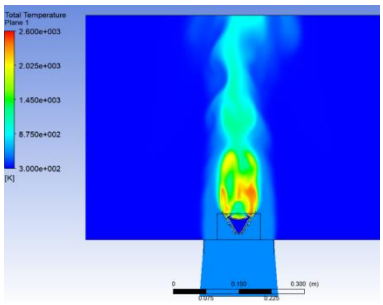
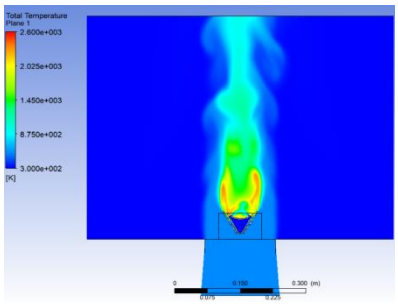
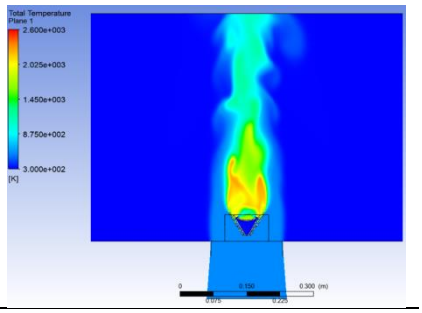
Ver. 3	100%H_2	80%H_2	60%H_2
V45			
V60			

Fig. 9. Total temperature on vesion 3 design

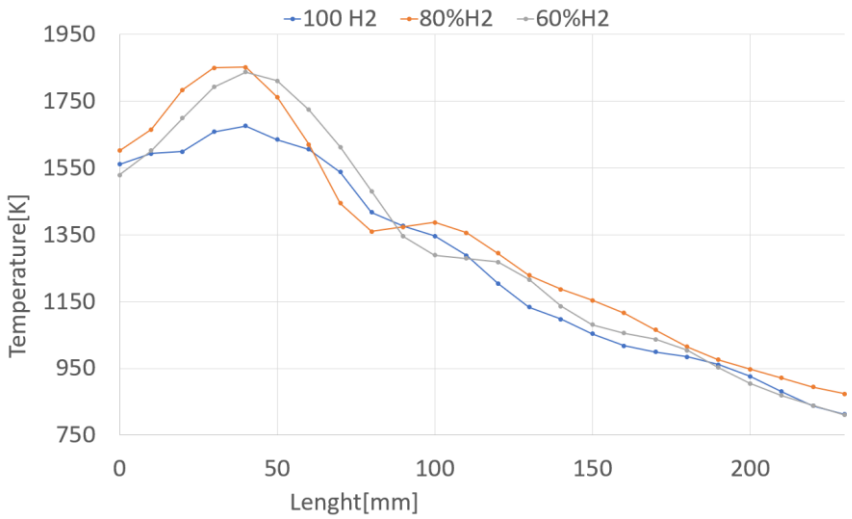


Fig.10. Mean axial temperature for V60(Version 3)

In Figure 10 is presented the mean temperature along the longitudinal axis. Starting from the edge of the flameholder as point 0 mm, from 10 to 10 mm, 25 circular planes with diamneter of 110 mm have been created. On every plane an average total temperature has been calculated. In figure 10, the blue line which indicates the mean axial teamperature for 100% H_2 used as fuel, shows a lower maximum temperature in the first 50 mm from the injection ports compared to the 80% and 60% H_2 mixtures with metane. Theoreticaly this is due the fact that pure hydrogen does not produce radicals such as the methylidyne radical (CH) and diatomic carbon (C_2), like the combustion of the mixtures of hydrogen with metane. Those species are responsible for the raise of temperature in the proximity of the injector where the flame anchoring mechanism occurs. Up to 70 mm can be seen the temperature differences between the fuels used. One of the explanations can be related to the fact that the reaction mechanism for mixtures is more complex, considering the formation of CO and CO_2. After 70 mm the temperatures are close because the thermal power is kept constant.

5. CONCLUSIONS

The main goal of this work was, using RANS numerical simulation, to provide more information about the reactive flow in the new designed afterburner which uses mixtures of hydrogen with methane gas and pure hydrogen as fuel, in order to allow its optimization. The observed discrepancies being most likely related to the known limitations of the RANS approach and of the Eddy Dissipation combustion model with simplified chemistry. This is a work in progress related to first stage of this study. The used geometry was developed using previous experimental work. However, these are just preliminary results, and more post processing still needs to be performed. Further research using different fuel orifice diametres needs to be performed. The next step for the flame holders approached in Version 3 is to validate the numerical results through experiments. If there are significant differences between them, the numerical simulations will be repeated.

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