Numerical investigation on combustion and NO$_x$ emissions of a CH$_4$ / kerosene afterburner

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Abstract. Cogeneration groups equipped with gas turbines usually operate with natural gas. The new requirements regarding the flexibility of functioning both with conventional and alternative fuels have led to the development of new solutions. An afterburning installation facilities, on the one hand, the combustion of fuels which can not normally be used in gas turbines, and on the other hand, allows a rapid adaptation of the cogeneration group to the user's variable thermal energy requirements. In some cases, an afterburning installation may contribute to the reduction of NOx emissions. It also increases the group's adaptability to changing environmental conditions, especially during the summer. Having in mind these tendencies and starting from the data collected from the 2xST 18 – Suplacu de Barcau cogeneration plant, this paper presents a numerical analysis of an afterburner in order to switch from natural gas to natural gas / kerosene functioning, with minimal modifications to the existing solution. A 3D steady RANS numerical integration of the Navier-Stokes equations has been carried out using the commercial software ANSYS CFX. For future research work, it will be taken into consideration the use of more complex reaction mechanisms and the variation of the spray angle will be considered. Also, in order to validate the CFD results a combustion experiments campaign will be conducted.

1 Introduction

Cogeneration groups equipped with modern gas turbines have to meet the requirements regarding the flexibility of functioning both with conventional and alternative fuels. Also, the pollutant emissions, have to be kept at a low level, even in partial load operation conditions.

The high oxygen content in the exhaust gases coming from the gas turbine, around 11-16 % vol. [1], can be used in the combustion of an additional amount of fuel (afterburning).

Afterburning is generally used on supersonic military aircrafts at take-off or during combat [2].

The utilization of an afterburning installation on cogeneration groups equipped with gas turbines increases the flexibility regarding of the used fuel and allows a rapid adaptation to the user's variable thermal agent requirements [3].

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The control of the combustion process and of the afferent pollutants emissions, while complying with increasingly restrictive legislative requirements, remains one of the main challenges of designing a combustion system. In the field of cogeneration groups with gas turbines, combustion process modelling inside the afterburner becomes an integral part of the entire group design.

In the scientific literature, afterburning numerical modelling addresses, besides pollutant emissions reduction issues, aspects related to efficiency gains, compensation of environmental parameters variations, impact on the recovery boiler, optimization of flow conditions etc.

Sullivan-Lewis [4] analyzes several afterburner geometrical configurations regarding the functioning with low NO_x and CO emissions, at a given fuel/air ratio and the geometry's influence on the combustion stability. Ganjehkaviri [5] has conducted a study on the impact of introducing an afterburner into a combined cycle power plant. Elmegaard et al. [6] studied the possibility of using a polycarbonate afterburning installation - functioning on natural gas / biogas or pyrolysis gas - to increase the efficiency of a power plant with indirect combustion gas turbine. Mehrabani et al. [7] proposed using an afterburning installation to compensate for the environmental parameters variation and to increase the efficiency of combined cycle power groups. Backlund [8] shows that parallel flow burners lead to: larger steam flows, a high efficiency of the gas turbine power plant, an efficient use of the oxygen from the exhaust gases coming from the gas turbine, a larger range of operating regimes, low NO_x and CO emissions. Ahamed [9] analyzes various methods to improve the blending of fuel with exhaust gases from a turbo-engine, as well as the impact on the recovery boiler. Shi [10] optimizes the velocity and temperature fields upstream and downstream of the afterburner using numerical modelling. To determine the performance of an afterburner, Lezsovits et al. [11] used the commercial software ANSYS CFX 5.6.

The construction of the 2xST 18 - Suplacu de Barcau cogeneration plant, which has an afterburner installation functioning on natural gas with multiple parallel flows, led to researches regarding performance improvement. The afterburner was designed to function using as oxidant exhaust gases from a turbo-engine. However, in emergency cases (when there is a problem with the turbo-engine), it can also function with pure air as oxidant, air delivered by a fan.

Similar to the afterburner in the 2xST 18 cogeneration plant, a test bench for a 3-modules afterburner with a single gas supply ramp has been built in INCDT COMOTI [12] (Figure 1 a)).

Each afterburner module is composed of a deflector and 3 fuel nozzles. The central fuel nozzle, with a diameter of 6 mm, is the primary one. The other two are secondary ones with a role in flame propagation from one module to another. The deflector is fixed to the fuel ramp by the means of the 2 secondary fuel nozzles. The deflector (Figure 1 b)) is composed of a horizontal swirler plate and two vertical plates with the role of limiting the flame.

This configuration of the afterburner module insures a good mixing of the fuel (natural gas) with the oxidizer (exhaust gases from the turbo-engine / pure air). It insures the cooling of the area surrounding the afterburner, the stabilization of the flame front and leads to obtaining higher temperatures downstream, with low pollutants levels.
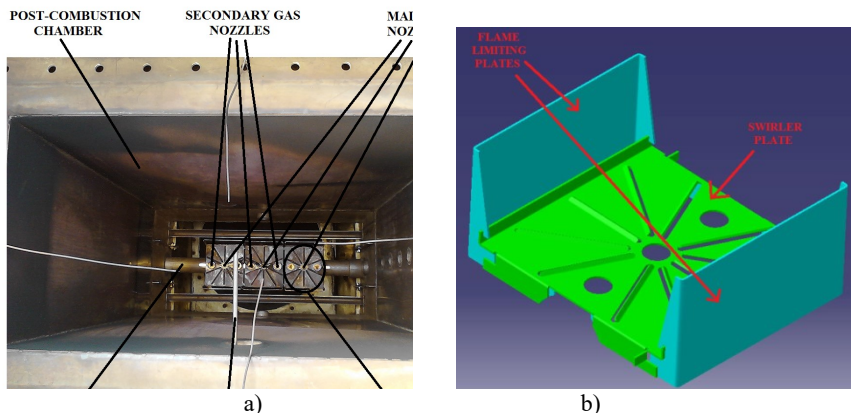
Fig. 1: a) The 3-modules afterburner in COMOTI; b) the deflector

The test bench has the possibility of testing the afterburner using as oxidant either exhaust gases coming from a turbo-engine or pure air (Figure 2).

The test bench is mainly composed of: a TA2 turbo-engine running on natural gas (this is a TV2-117A turbo-engine converted by researchers from COMOTI to function with natural gas instead of kerosene), positioned horizontally, the afterburner and afterburning chamber positioned vertically in the turbo-engines exhaust chimney. The exhaust gases temperature and composition are monitored at a height of 1895 mm from the afterburner.
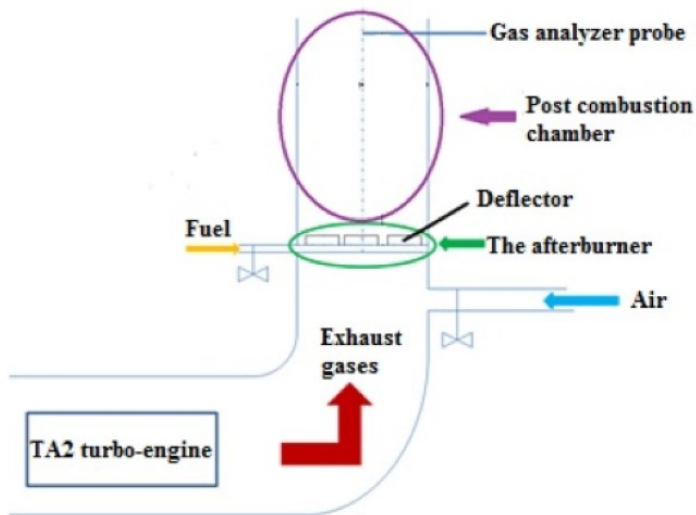

Fig. 2 Median longitudinal plan section through the afterburner test bench in COMOTI

In the context of the shown tendencies, the article presents a numerical analysis regarding changing the afterburner functioning on natural gas to functioning on natural gas/ kerosene, with minimal modifications to the existing solution.

2 Numerical simulations

2.1 Geometry

The proposed solution consists of modifying the central module of the afterburner presented in Figure 1 in order to function on kerosene, the adjacent natural gas modules remaining unchanged.

To better understand the implications of the proposed solution, there have been conducted first numerical simulations with natural gas as fuel and exhaust gases/ pure air as oxidant, for the configuration presented in Figures 1-3.
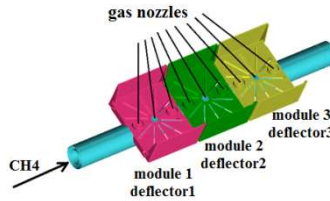

Fig. 3 Afterburner modules configuration

Based on the results obtained from the numerical simulations on natural gas, there have been proposed an afterburner configuration functioning on kerosene. The central natural gas nozzle corresponding to the central module has been replaced with a liquid fuel atomizer. The atomizer exit nozzle diameter is of 0.85 mm. The other natural gas nozzles are blocked.

2.2 Computational domain and mesh

In Figure 4 a)-b) is presented the computational domain. For this domain an unstructured computational grid of 7.678.803 tetrahedral elements and 1.341.681 nodes has been created using ICEM CFD.

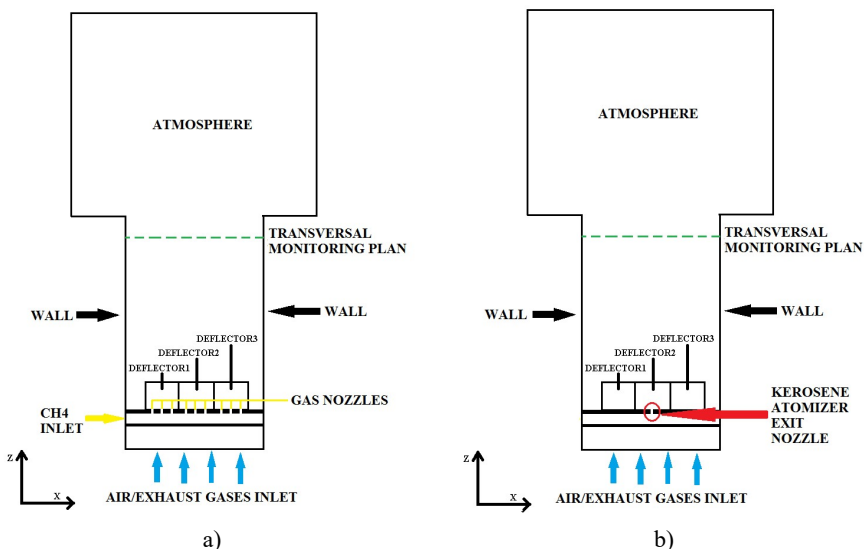a)   b)

Fig. 4 Computational domain, on the median longitudinal plan of the afterburner: a) afterburner functioning on methane gas; b) afterburner functioning on kerosene

2.3 CFD settings

A three-dimensional steady RANS numerical integration of the Navier-Stokes equations has been carried out using the commercial software ANSYS CFX.

In the numerical simulations it has been considered that the natural gas is composed only of methane gas (CH_4).

The methane gas mass flow corresponding to one module has been chosen in accordance with the design parameters of the afterburner from the 2xST 18 cogeneration plant, functioning on natural gas [12]. It has been considered that the total fuel mass flow is equally distributed to each module.

The composition of the exhaust gases, coming from the TA2 turbo-engine, used as oxidant is presented in Table 1.

Table 1. Exhaust gas composition

	Mass fraction
CO_2	0.0465
H_2O	0.0418
O_2	0.1623
N_2	0.7494

The kerosene mass flow, for the afterburner functioning with exhaust gases coming from the turbo-engine, was calculated according to relation (1) [13]:

$$\dot{m}_{kerosene} = \dot{m}_{methane\_gas} \cdot \frac{q_{methane\_gas}}{q_{kerosene}} \qquad (1)$$

where: $\dot{m}_{kerosene}$ - kerosene mass flow (kg/s), $\dot{m}_{methane\_gas}$ - methane gas mass flow (kg/s), $q_{methane\_gas}$ - natural gas lower heat value [14], $q_{kerosene}$ - kerosene gas lower heat value [15].

The kerosene mass flow, when the afterburner functions on fresh air (emergency regime), was calculated taking into account the maximum allowed thermal power for an afterburner module (350 kW) and the lower calorific value of kerosene [15].

In practice, the measurement of the flue gas temperature is performed in the centre of the afterburner chamber, on the monitoring plane positioned at 1895 mm above the burner, using the gas analyzer's integrated temperature probe. The flue gas reference temperature, resulting from the cogeneration plant design data, is 1043 K [12]. Preliminary experiments on natural gas, performed in COMOTI (Fig. 5) [16], showed a strongly turbulent flame. Thus in the numerical simulations the average temperature of the flue gases on the monitoring plane was compared with the reference temperature of 1043 K.

The fuel mass flow being thus set, the oxidant mass flow has been determined by varying it until an average temperature on the monitoring plan of 1043K, with an error of ± 1%, has been obtained.

Fig. 5 Flame structure during the preliminary experiments on the 3 modules afterburner functioning on natural gas

In Table 2 are presented the boundary conditions for the considered cases.

Table 2. Boundary conditions

Fuel	Fuel mass flow [kg/s]	Fuel temp. [K]	Oxidant	Oxidant mass flow [kg/s]	Oxidant temp. [K]
CH4	0.006	293	Exhaust gases	0.813	797
CH4	0.014	293	Air	0.65	293
Kerosene	0.007	293	Exhaust gases	0.9	797
Kerosene	0.008	293	Air	0.23	293

The outlet has been considered of opening type, setting the pressure to be the atmospheric one.

In these numerical simulations an Eddy Dissipation combustion Model (EDM) and a k-ε turbulence model have been used. The combustion model was based on a two steps methane-air reaction mechanism, respectively a two steps kerosene-air reaction mechanism, both imported from the ANSYS library [17]. Also, both used reaction mechanisms take into consideration the formation of thermal NO and prompt NO.

In the case of functioning with kerosene, the fuel was uniformly injected into the atmosphere through the atomizer exit nozzle, under a total spray cone angle of 45°. The initial fuel droplets diameter was set at 0.1 mm. The break-up of the fuel droplets into smaller droplets was simulated using the CAB second break-up model from the ANSYS library. To simulate the transformation of the Jet A (kerosene) droplets into Jet A vapours a Liquid Evaporation Model from the ANSYS library was used.

3 Results and discussions

In Fig. 6 a)-b) and 7 a)-b) are presented the temperature field, respectively the NO mass fraction field on the afterburning chamber's median longitudinal plan.
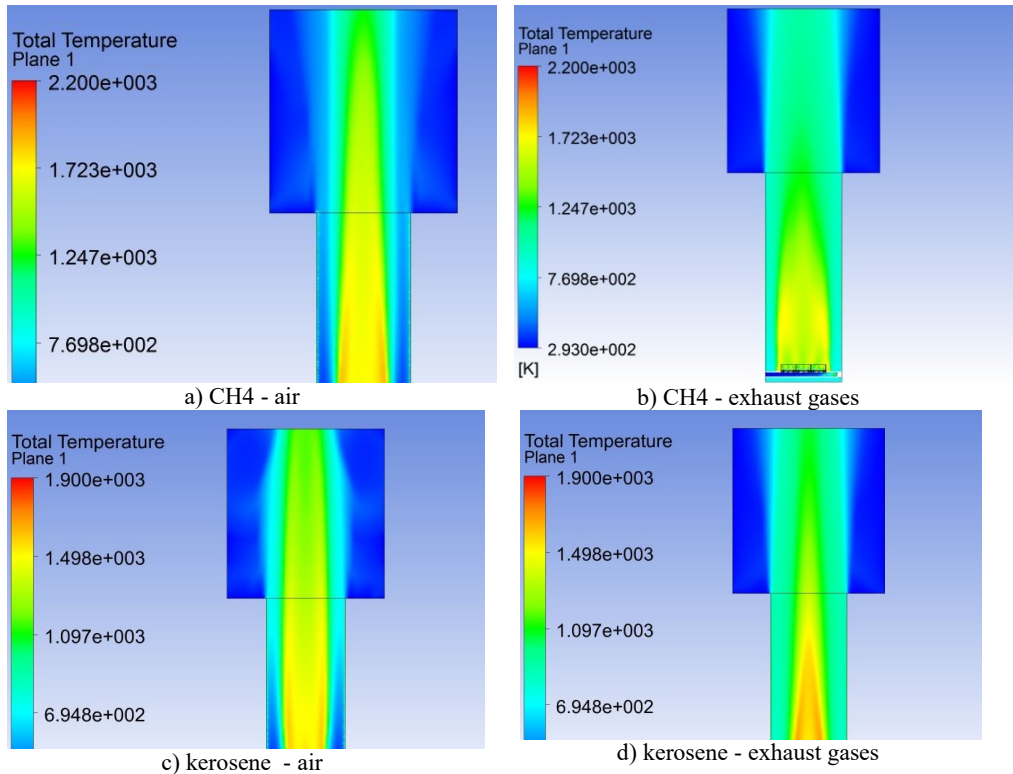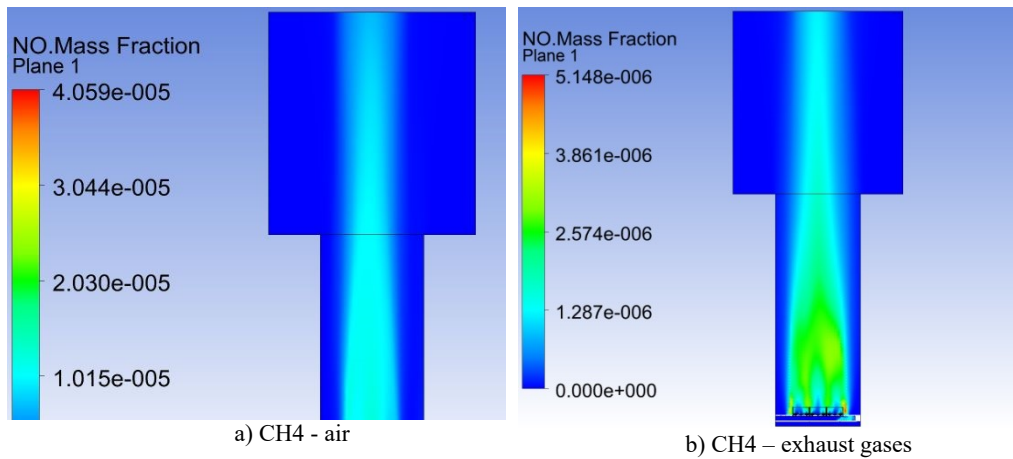
a) CH4 - air

b) CH4 - exhaust gases

c) kerosene - air

d) kerosene - exhaust gases

Fig. 6 The temperature field on the median longitudinal plan

a) CH4 - air

b) CH4 – exhaust gases

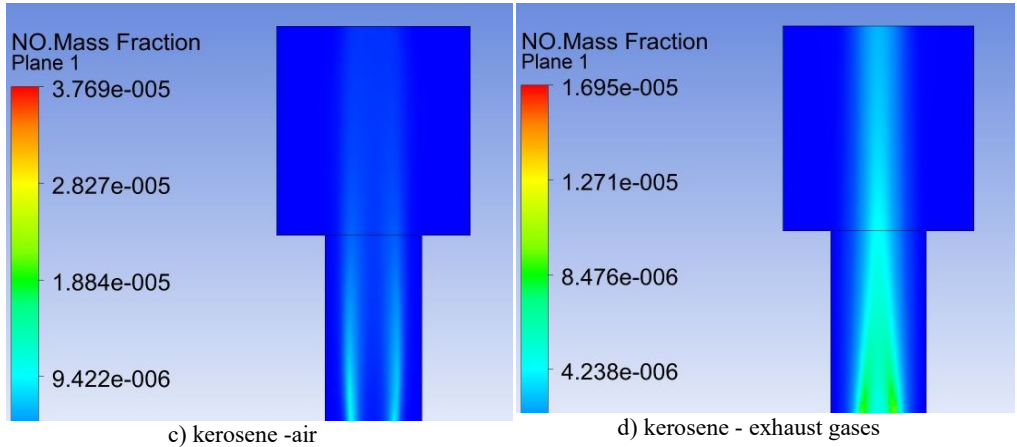c) kerosene -air   d) kerosene - exhaust gases

Fig. 7 The NO mass fraction field on the median longitudinal plan

The trend followed by the NO mass fraction in the exhaust gases is consistent with the behaviour of the exhaust gases temperature. The NO concentration increasing with the rise of the temperature. The NO concentration is higher when fresh air is used as oxidant, both when CH_4 was used as fuel, as well as when kerosene was used as fuel. The high exhaust gases temperature favours the dissociation of the nitrogen molecules, which leads to the formation of nitrogen oxides [18].

In Fig. 8 and 9 are presented the temperature and NO mass fraction variations, along the central axis of the afterburner combustion chamber.
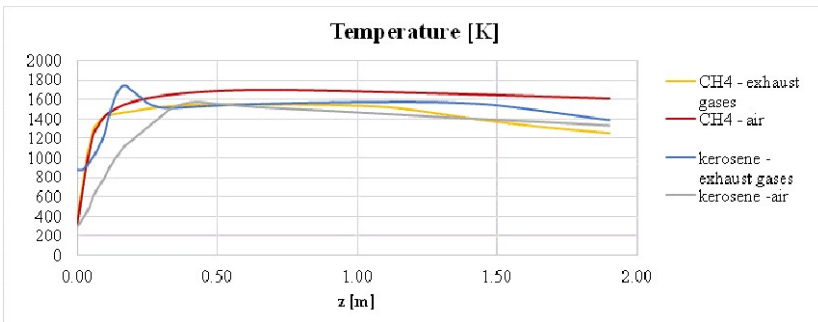

Fig. 8 Temperature variation along the symmetry longitudinal axis
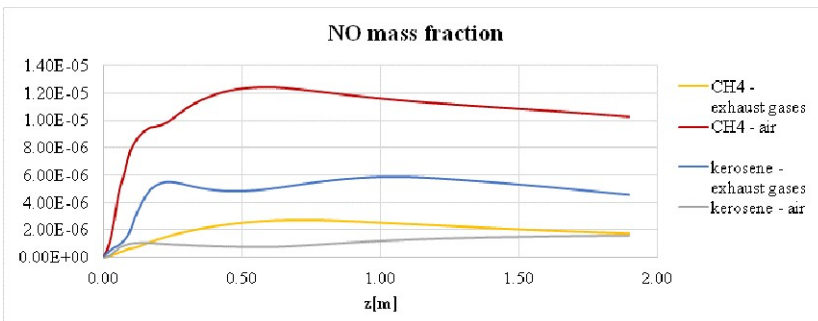

Fig. 9 NO mass fraction variation along the symmetry longitudinal axis

As was expected the NO mass fraction increases with the temperature rise. The NOx emissions are significantly higher in the functioning regime CH_4 - air compared with the functioning regime CH_4 - exhaust gases. This confirms that the afterburner has been optimized to function in CH_4 - exhaust gases regime.

In Fig. 10 and 11 present the temperature variation on the transversal axis on the monitoring plan (positioned at 1895 mm from the afterburner).
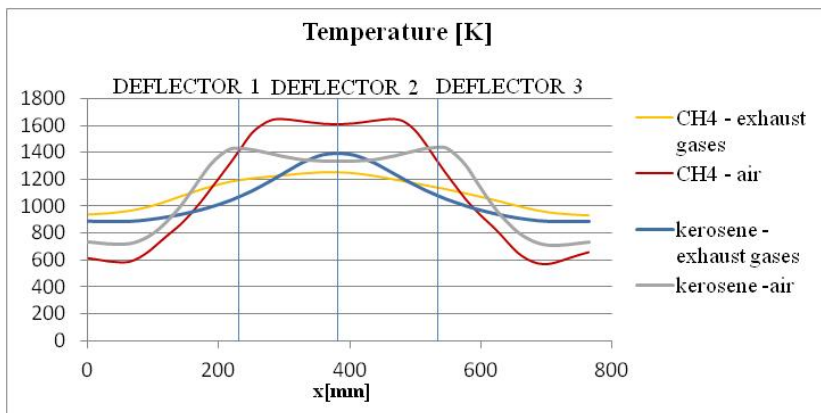

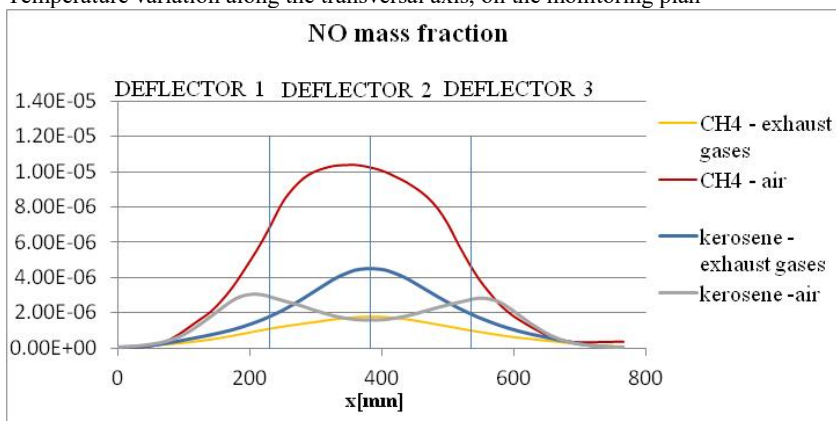Fig. 10 Temperature variation along the transversal axis, on the monitoring plan

Fig. 11 NO mass fraction variation along the transversal axis, on the monitoring plan

Fig. 10 and 11 reconfirm the normal dependence between the NO emissions and the gases temperature. The lowest NO emissions are obtained for the functioning regime CH_4-exhaust gases. This is consistent with the fact that the afterburner was designed to function optimally in this regime. The highest NO_x emissions are obtained when operating on CH_4 - air, as emergency regime. This is observed also in the results presented in Fig. 9.

Regarding the functioning on kerosene, further numerical investigations are necessary in order to optimize the afterburner. Interestingly, NOx emissions values, when functioning on kerosene - air, are comparable to the values obtained for functioning on CH_4-exhaust gases from the turbo-engine.

In Table 3 are presented the averaged temperature values obtained through numerical simulations, on the monitoring plan where the gas analyser probe is positioned (see Fig. 2).

Table 3. Averaged temperature on the monitoring plan

Fuel	Fuel mass flow [kg/s]	Oxidant	Oxidant mass flow [kg/s]	Temp. [K]	Temp. error [%]
CH4	0.006	Exhaust gases	0.813	1042	0.095
CH4	0.014	Air	0.65	1033	0.958
kerosene	0.007	Exhaust gases	0.9	1039	0.383
kerosene	0.008	Air	0.23	1034	0.862

From the results in Table 3, it can be seen that, for the considered numerical simulation conditions, an error under 1 % for the average temperature on the monitoring plan has been obtained.

4 Conclusions

In order to study the possibility of switching the afterburner from functioning on gaseous fuel to liquid fuel (kerosene) functioning, a CFD analysis has been carried out. During all numerical simulations, it has been intended that the average temperature on the monitoring plan to be 1043 K ± 1%.

The numerical modelling, confirmed that the constructive afterburner solution has been optimized for functioning on gaseous fuel with exhaust gases from the turbo-engine, the lowest NO_x emissions been obtained for this functioning regime.

Theoretical data and preliminary experiments have highlighted the turbulent structure of the flame, imprinted by the afterburner's modules' swirls, and the flame stability in the range of the analyzed CH_4 mass flow (0.006 - 0.014 kg/s). In the case of functioning on kerosene, the flame stability and the low NOx emissions will have to be confirmed through experiments. The transition to kerosene functioning will be based on an original technical solution, which will be the subject of a patent application.

For future research work it will be taken into consideration the possibility of the afterburner functioning simultaneous with CH_4 and kerosene. Also, the use of more complex reaction mechanisms and the variation of the spray angle will be considered. In order to validate the CFD results, in parallel with the numerical simulations the combustion experiments campaign will be continued.

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