

Applied Modelling for Bio- and Lean Gas Fired Micro Gas Turbines

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Summary

This contribution presents the outcome of applied computational fluid dynamics (CFD) for analysis of combustion technologies to find an efficient firing mode for use of bio and low calorific gaseous fuels in micro gas turbine combustors. The combustion technologies considered are based on the new concepts of flameless oxidation (FLOX[®]) and continued staged air (COSTAIR). Both concepts ensure through high flue gas recirculation extremely low NO_x emission and full burn-out when burning natural gas. To optimise these concepts to burn low calorific gaseous fuels with a broad range of fuel compositions manifold numerical simulations have been carried out at Gaswärme-Institut e.V. Essen using the CFD code FLUENT version 6. The results achieved showed the influence of the fuel compositions on the flow behaviour inside the combustion chamber, reaction zone, flame structure and pollutant emission expected. Through the comparison of different burner geometries and their numerical results optimal burner designs were proposed and experimentally tested on a test rig for pressurised conditions of micro gas turbine combustors. The calculated results confirmed the experimental trends for the combustion behaviour and proved the usefulness of applied modelling approach.

1. Introduction

Based on the intensified preservation of resources and sustained climate and environment protection, the utilisation of combustible gases with low calorific values is increasingly gaining significance. Especially decentralised gas sources of low calorific value geographically scattered because of their origins such as biogases from fermentation systems, landfills and mines and also product gases of biomass pyrolysis and biomass gasification and waste gases from production processes containing hydrocarbons must be increasingly integrated in the conversion of energy under the terms of sustainable development [2 –5].

With this expected increasing use of bio and lean gases the output of gas turbines for power generation are projected to considerably increase in short future term [1]. Unfortunately, at present there is no combustion systems available to efficiently operate with multiple lean fuel compositions in gas turbine combustors. Today's burners used are based on the premixed combustion principle and still suffer from the changing fuel quality, which caused insufficient flame stability, combustion fluctuations and high pollutant emissions [2, 5, 6]. Additionally, such burners fail to

operate for combustible bio and lean gases with low caloric values (LCV up to 2,5 kWh/m³) which are available in large quantities in Europe [4, 7].

Due to this fact new combustion technology is needed which can efficiently utilise multiple gaseous fuel qualities. In this context the application of numerical simulation turned out to be a useful means to gain first estimation about the combustion system design and expected results. Although extensive CFD research work has been published on the field of natural gas application, there are only few papers dealing with lean and alternative gaseous fuels. One example of a CFD study to optimise a burner fired with a product gas containing high amounts of NH₃ is given in [11]. Results achieved there reproduced the experimentally observed trends and provided NO_x reduction by almost 40% through adjusting the design parameters. This confirmed the usability of CFD numerical simulation to find optimal burner configurations.

In the framework of an German funded project, new combustion systems derived from the diffusion combustion concepts of flameless oxidation (FLOX[®]) and continued staged air (COSTAIR) have been developed for use of low grade gaseous fuels in micro gas turbine combustors. The first stage in the development methodology covered detailed CFD numerical simulations to discover the burner combustion behaviour under the conditions of micro gas turbine. In the following a short explanation of the burner concepts and the CFD optimisation procedure used will be explained, the modelling mechanisms and operating conditions will be presented and results achieved will be evaluated and validated by experimental data.

2. Burner Concepts

The combustion principle of flameless oxidation (FLOX[®]), developed by the company WS Wärmeprozessstechnik GmbH, is based on high internal flue gas recirculation rates, which leads to a diluted combustion. The high recirculation ratio is realised by the high momentum of the preheated air jets entering the combustion chamber (see Figure 1), thus a controlled flameless oxidation without pulsation and with complete burn-out is achieved. Due to the high recirculation ratio, the maximum reaction temperature in FLOX[®] operation mode is below 1500°C, thus reducing NO_x formation considerably.

The COSTAIR combustion concept uses the principle of continued staged air to suppress the NO_x formation. Figure 2 illustrates schematically its design. It consists of a coaxial tube; the combustion air flows through the inner tube and the fuel through the outer cylinder ring. The combustion air is continually distributed into the combustion chamber by means of an air distributor with numerous openings on its contour. The fuel enters the combustion chamber by means of several jets arranged around the air distributor. The COSTAIR burner has the advantages of operating in full diffusion mode or in partially premixed mode. In both cases it is essential for the COSTAIR principle that only combustion air flows through the air distributor.

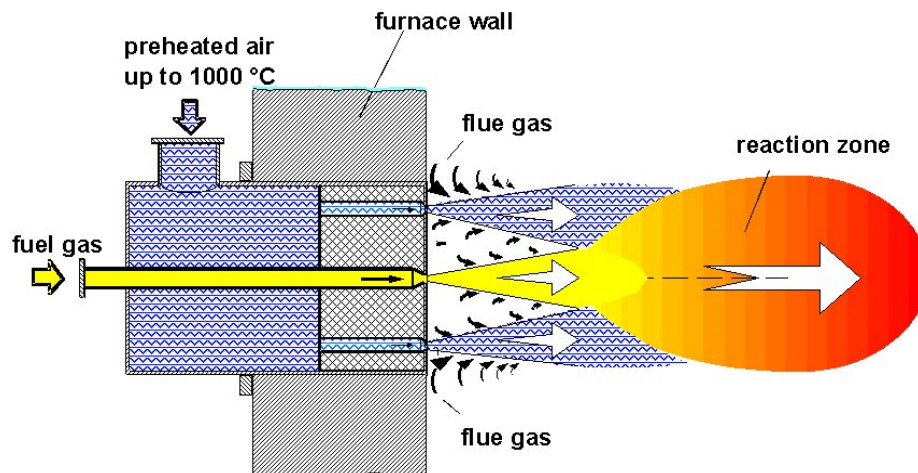


Figure 1. FLOX® combustion concept

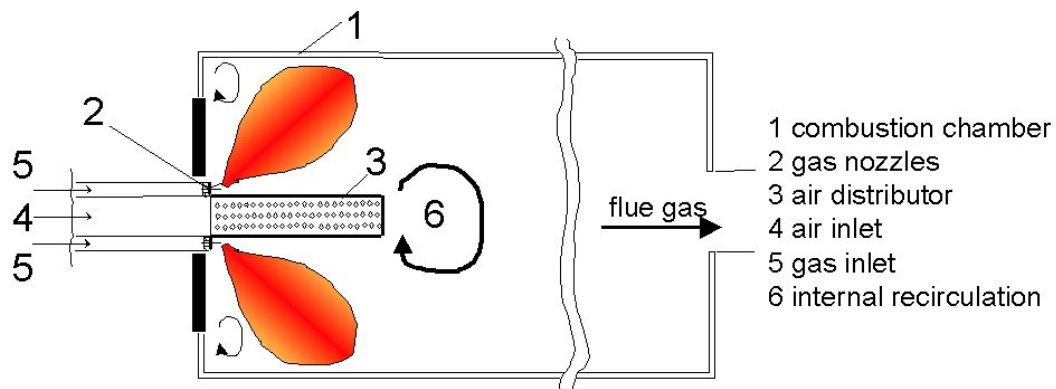


Figure 2. COSTAIR combustion concept

3. Optimisation Procedure

To find the optimal burner designs suitable for efficient burning of lean gaseous fuel with broad qualities and compositions the following optimisation procedure has been used:

- Step 1: Definition of basis burner configurations and combustion chamber geometry and set-up the operating conditions and fuel compositions.
- Step 2: Selection of mathematical models appropriate for combustion concepts and carrying out of detailed numerical investigations at atmospheric conditions.
- Step 3: Determination of optimal burner designs regarding combustion behaviour as for flow and temperature distributions, recirculation and reaction zone size, NO_x and CO emission levels.
- Step 4: Modelling of the combustion behaviour for the selected optimal burner designs under pressurised conditions.
- Step 5: Comparison of calculated results against measured data and final conclusions.

Burner Configurations and Combustion Chamber Geometry

Based on detailed numerical and experimental investigations made on the FLOX[®] and COSTAIR burners for use in gas turbine combustors fired with natural gas [10] the multi single nozzles FLOX[®] burner illustrated in Figure 3 and the COSTAIR burner illustrated in Figure 4 have been selected as the basis configurations to start the CFD optimisation for low calorific gaseous fuels.

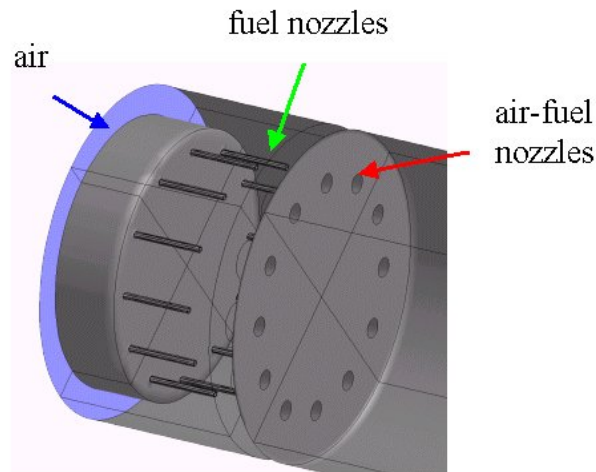


Figure 3. Basis FLOX[®] burner configuration

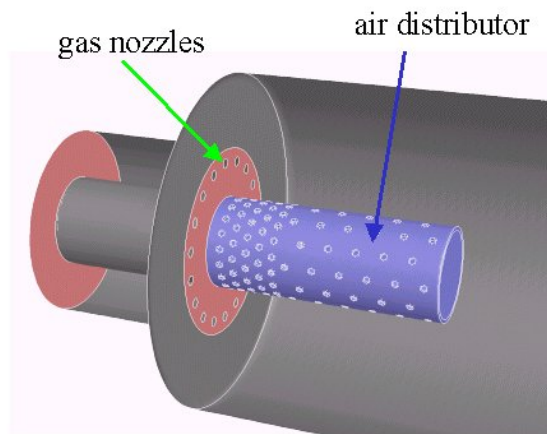


Figure 4. Basis COSTAIR burner configuration

A cylindrical combustion chamber of 100 mm in diameter and 300 - 500 mm in length has been proposed for the numerical investigations. This geometry corresponds to the combustor geometry of micro gas turbines.

4. Operating Conditions and Fuel Compositions

To meet the operating parameters for micro gas turbine combustors the following operating conditions have been set:

- burner load:	25 – 35 kW/bar
- air ratio:	2 - 3
- fuel inlet temperature:	20°C
- air inlet temperature:	420 - 550°C
- wall temperature:	850°C
- specific heat density:	15 MW/m ³
- combustion chamber pressure:	atmospheric and 3 bar absolute
- pressure drop:	< 5 %

As fuels several mixtures of CH₄/N₂ and CH₄/N₂/CO/H₂ with low calorific heat value (LHV up to 2,5 kWh/m³) have been defined, so that the features for bio and lean gaseous fuels can be produced.

5. Mathematical Models

In the frame of an EU project [9] GWI investigated the use of the different reaction models implemented in FLUENT to predict the combustion behaviour of the FLOX[®] and COSTAIR burner in gas turbine combustors fired with natural gas. Simulation results achieved have been validated by comparisons with measured data. Figures 5 and 6 show exemplary this comparison for the temperature profiles. To optimise the FLOX[®] burner concerning the pollutant emission behaviour in the exhaust gas the pdf equilibrium model is more effective than the other reaction models. But for detailed investigations in the reaction zone to examine the backgrounds of the function mode of the flameless oxidation the EDC model is necessary, as shown in figure 5. While hot spots are predicted in the premixing duct and in the combustion chamber by the pdf-equilibrium model those hot spots disappeared by the EDC model. These behaviour is more realistic for the practical application of the FLOX[®] burner.

Regarding the COSTAIR combustion system results confirmed that the partial premixed model based on pdf-equilibrium mechanism is suitable, calculated results predicted sufficient the measurement data, as shown in Figure 6.

Based on these results the following mathematical models to carry out the numerical simulations for use low calorific gaseous fuels in micro gas turbines have been applied:

- for turbulence: k-ε-turbulence-model
- for reaction: pdf equilibrium model (for FLOX[®]),
partial premixed equilibrium model (for COSTAIR)
- for radiation: Discrete-Ordinates-model

The models for the thermal and prompt NO formation based on the ZELDOVIC and FENIMORE mechanism have been used for the calculation of NO in FLUENT.

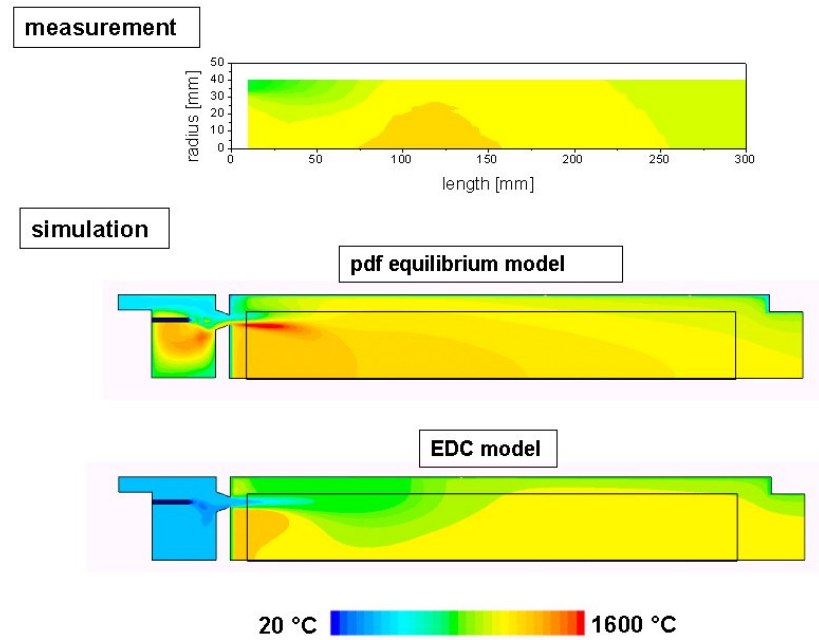


Figure 5. Validation of combustion models for the FLOX[®] burner by comparison of calculated results by measured data for natural gas

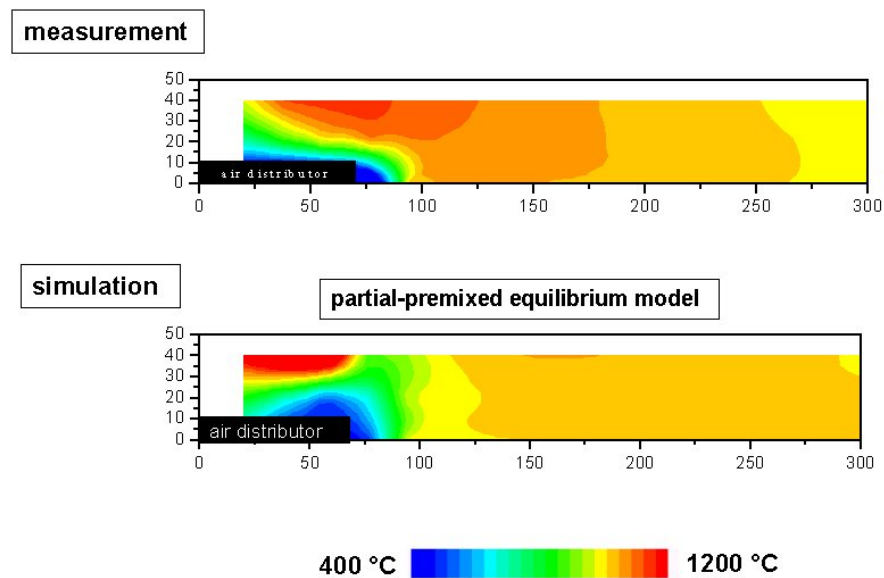


Figure 6. Validation of combustion model for the COSTAIR burner by comparison of calculated results by measured data for natural gas

6. Numerical Simulation Results

a) Under Atmospheric Conditions

To obtain the initial values for the numerical simulation with low calorific gases the scale-up criteria included in [12 - 14] have been applied on the optimised burner designs illustrated in figures 3 and 4 to transfer the geometry from the design for natural gas to a design for low calorific gas [7, 16]. First numerical simulations have been carried out under atmospheric pressure using the initial values for burner configurations calculated by the scale-up criteria. As a fuel several CH_4/N_2 and $\text{CH}_4/\text{N}_2/\text{CO}/\text{H}_2$ gaseous fuel mixtures were defined.

Extensive simulation activities studying the influence of parametric variations have been done to optimise the burner configurations for low calorific gaseous fuels. Results achieved are explained exemplarily by the following graphs. Figure 7 represents the calculated temperature profiles of the FLOX[®] burner using lean gas mixture. This simulation has been made to optimise the distance between fuel and gas nozzles in the premixing duct. Figure 8 shows similar temperature profiles for a the same gas mixture burned by the COSTAIR burner to optimise the air distributor geometries. Figure 9 and 10 represent the combustion behaviour of both burners when firing different gas mixtures by the same burner design.

As seen on the Figures 7 – 10 while similar temperature profiles are produced by the same burner design, changing the geometry of burner leads to different combustion behaviour, even for the same gas mixture.

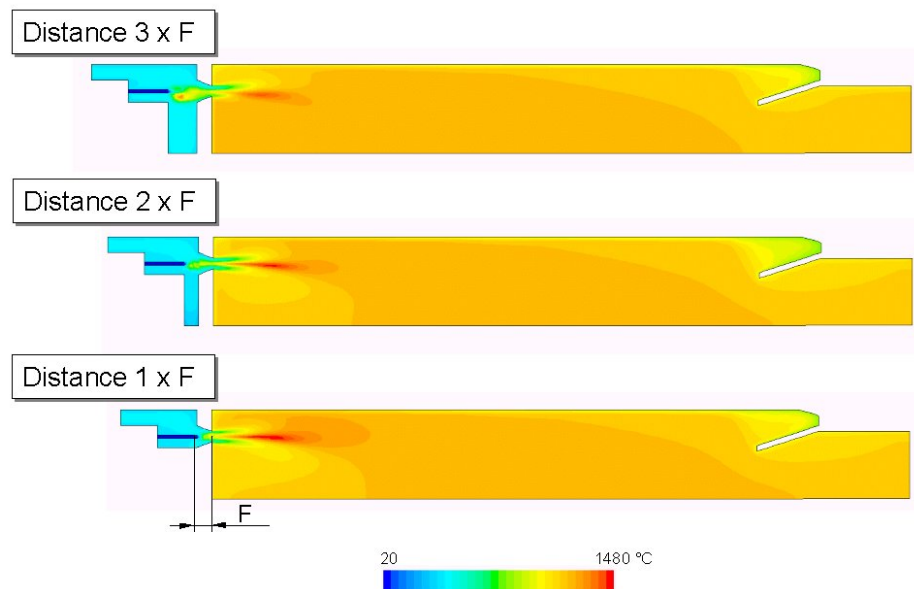


Figure 7. Calculated temperature profiles for the lean gas mixture 5% CH_4 ; 10% CO ; 30% H_2 ; 55% N_2 fired with the FLOX[®] burner at an air to fuel ratio $\lambda=2,5$ and air temperature $T_{\text{air}} = 500^\circ\text{C}$ for different distances “F” between fuel and air nozzles

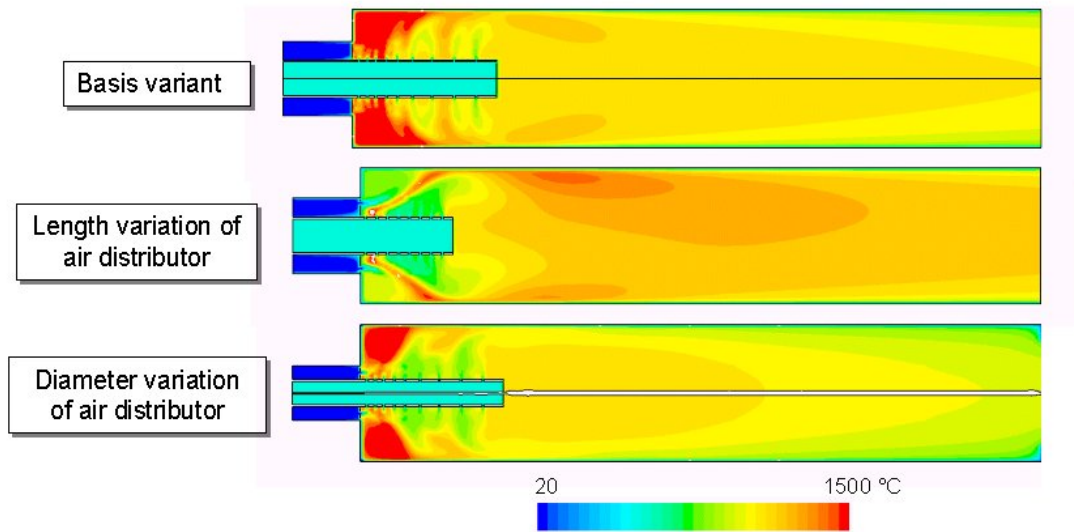


Figure 8. Calculated temperature profiles for the lean gas mixture 5% CH₄; 10%CO; 30% H₂; 55% N₂ fired with the COSTAIR burner at an air to fuel ratio $\lambda=2,5$ and air temperature $T_{\text{air}} = 500^{\circ}\text{C}$ for different geometries of the air distributor

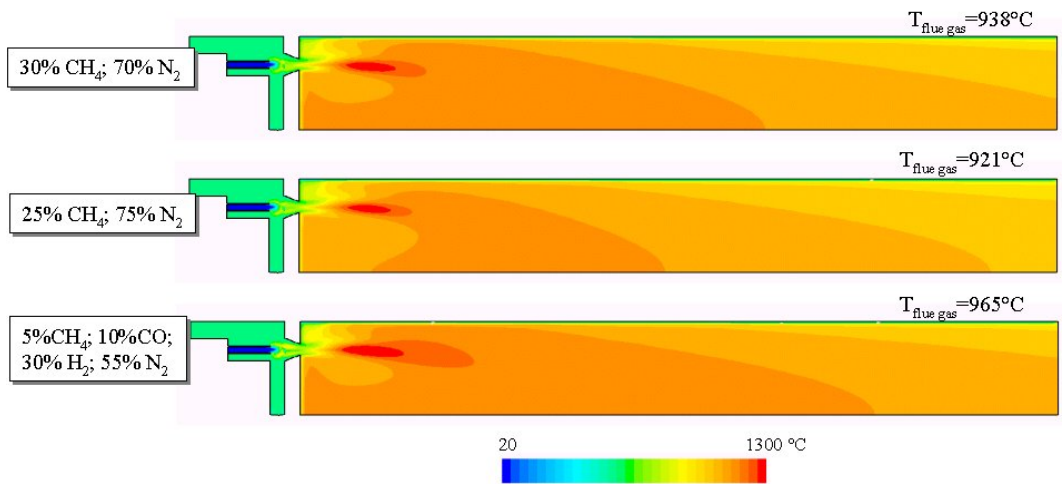


Figure 9. Temperature profiles for different lean gas mixtures fired with the FLOX[®] burner at an air to fuel ratio $\lambda=2,5$ and air temperature $T_{\text{air}} = 500^{\circ}\text{C}$

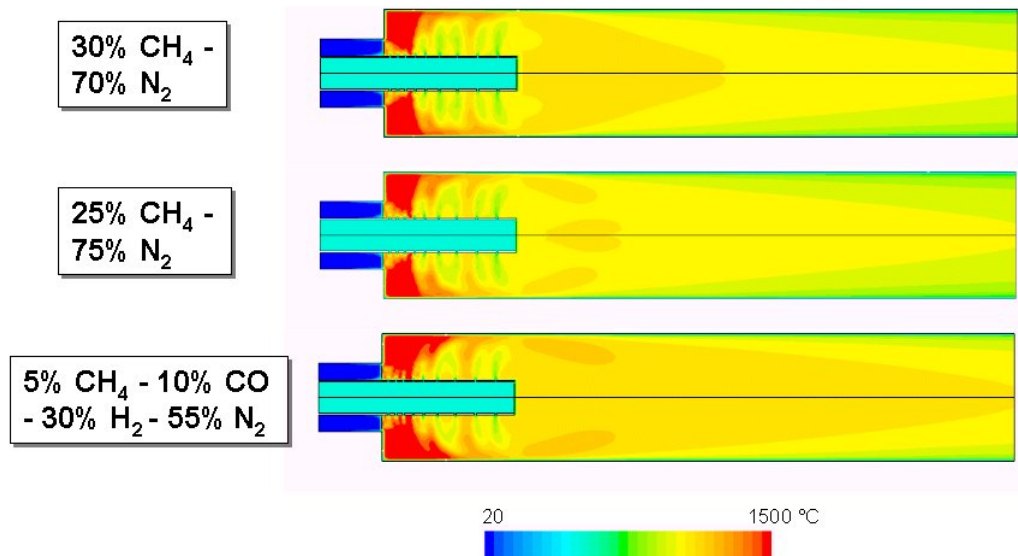


Figure 10. Temperature profiles for different lean gas mixtures fired with the COSTAIR burner at an air to fuel ratio $\lambda=2,5$ and air temperature $T_{\text{air}} = 500^{\circ}\text{C}$

Based on simulation results achieved and through the parametric study and the comparison with measured data optimal burner designs for FLOX[®] and COSTAIR have been found. These optimal design leads in case of the FLOX[®] burner to evenly temperature profiles through the whole combustion chamber (see Figures 7 and 9). This is caused by the strongly recirculation zone of this combustion mode. The experimentally measured NO_x and CO emission values for the optimised burner design were lower than 10 ppm at 15 vol.-% O_2 in the flue gas.

Regarding the optimal COSTAIR burner configuration obtained locally higher temperature values appear in a short area around the air distributor, where mixture of air and fuel ignites. In the rest of combustion chamber the temperature distribution profiles are regular (see Figures 8 and 10). Calculated NO_x - and CO emission values are despite this temperature peaks lower than 10 ppm.

b) Under Pressurised Conditions

Pressurised numerical simulations at 3 bar absolute have been made on the same optimal burner configurations found under atmospheric pressure. The combustion behaviour of the burners was studied for the low caloric gas mixture with 25 vol.-% CH_4 and 75 vol.-% N_2 at an air temperature $T_{\text{air}} = 500^{\circ}\text{C}$ and an air to fuel ratio $\lambda = 2$. Figures 11 and 12 show the temperature distributions for both burners, FLOX[®] and COSTAIR, at a pressure of 1 and 3 bar for the gas mixture mentioned. The comparison of these distributions shows similar combustion behaviour for the FLOX[®] burner at 1 and 3 bar and to slightly differences in the combustion behaviour of the COSTAIR burner (higher values at 3 bar around the air distributor). This is also confirmed by the sizes of the recirculation zones caused at the pressures 1 and 3 bar as shown in Figure 13. While the higher pressure seems not to exert an effect on

the recirculation zone at the FLOX[®] burner, a minor change in the form and size of this zone can be observed at the COSTAIR burner. Additionally, the flow distributions (not presented here) generated under atmospheric and pressurised conditions are similar for the FLOX[®] burner and a little bit different for the COSTAIR burner.

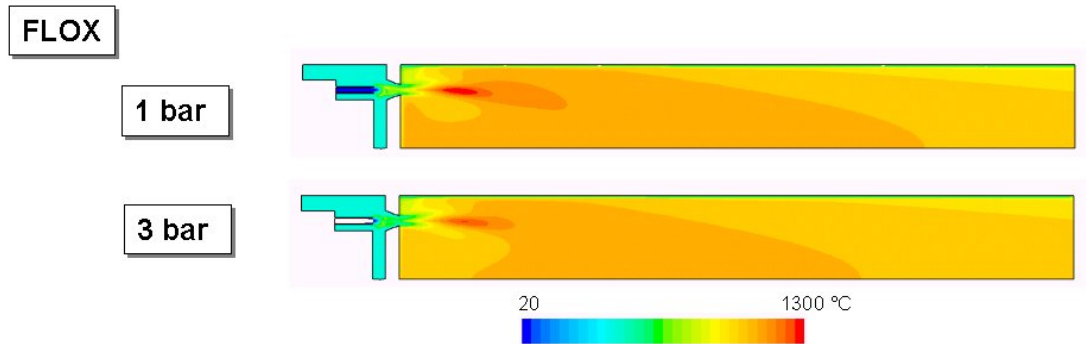


Figure 11. Calculated temperature distribution for the FLOX[®] at 1 and 3 bar

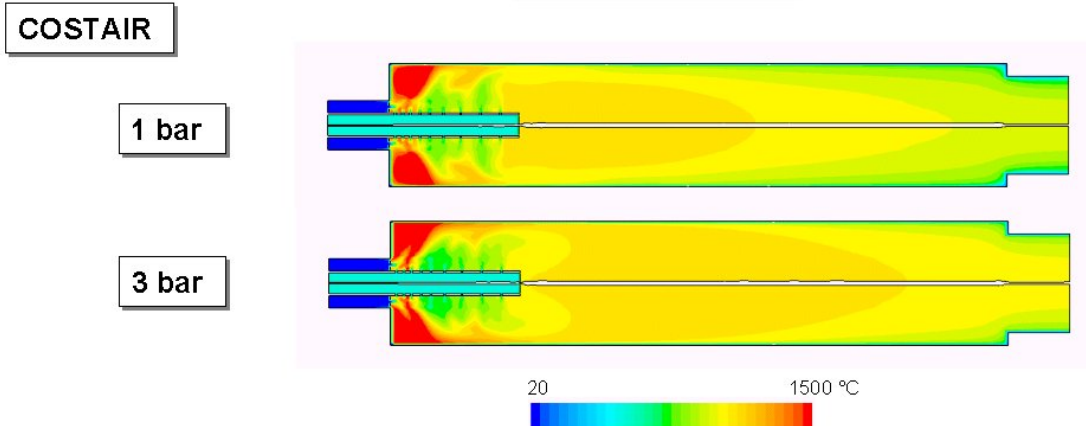


Figure 12. Calculated temperature distribution for the COSTAIR at 1 and 3 bar

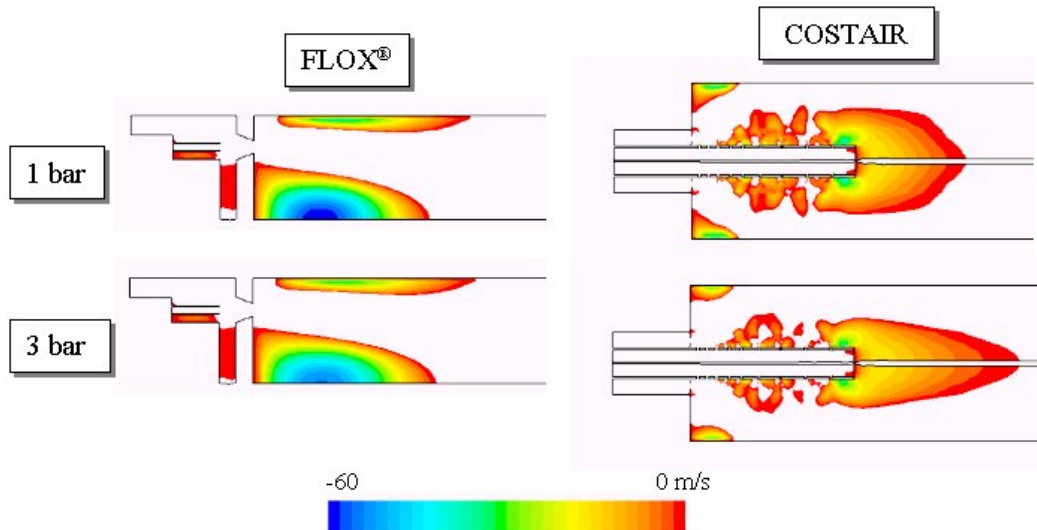


Figure 13. Calculated recirculation zones for FLOX[®] and COSTAIR at 1 and 3 bar

The calculated NO and CO emission values for the found optimal burner designs are given in table 1.

	FLOX		COSTAIR	
	CO	NO	CO	NO
1bar	0	0	0	0,02
3bar	0	0	0	0,24

Table 1. Calculated NO and CO emission values at 1 and 3 bar in ppm at 15 vol.-% O₂

7. Comparison of Calculated and Measured Results

To confirm calculated results against measured data of the optimised burner design comparisons have been made for the mixture CH₄/N₂ at the same operating conditions. First comparison is presented in table 2 showing the NO and CO emission values when firing the mentioned mixture at atmospheric pressure. It is obviously that tendency and level of results of experiment and calculation agree well with each other. Similar conclusions can be obtained by the comparison made in table 3 for the same gas mixture but at pressurised conditions.

FLOX [®] (T _{air} = 420 °C, λ=2)				
	30% CH ₄ / 70% N ₂		25% CH ₄ / 75% N ₂	
	CO	NO	CO	NO
Measurement	4,83	0	5,52	0
Calculation	0	0	0	0
COSTAIR (T _{air} = 500 °C, λ=2,5)				
Measurement	2,9	6,75	3,3	3,55
Calculation	0	0,27	0	0,09

Table 2. Comparison of calculated and measured CO and NO emission values for the mixture CH₄/N₂ at atmospheric pressure in ppm at 15 vol.-% O₂

	30% CH ₄ / 70% N ₂	
FLOX [®]	CO	NO _x
Measurement	0,9	1,27
Calculation	0	0 (only NO calculated)
COSTAIR		
Measurement	1	3,43
Calculation	0	0,24 (only NO calculated)

Table 2. Comparison of calculated and measured CO and NO_x (NO and NO₂) emission values for the mixture CH₄/N₂ at p = 3 bar, T_{air} = 500 °C, λ = 2 in ppm at 15 vol.-% O₂

8. Conclusion

Generally, the applied CFD calculations predict well the level for NO_x and CO emissions for lean gas mixtures using the combustion systems FLOX[®] and COSTAIR. This conclusion is valid for globally evaluation of the combustion behaviour, e.g. for analysis of the flue gas. For detailed information about combustion process inside the combustion chamber, specially for the flameless combustion mode [15], other modelling approach as the eddy-dissipation concept included in FLUENT could be more appropriate, as proved by actual CFD investigation at GWI.

9. Acknowledgement

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