14th World Congress on Computational Mechanics (WCCM)
ECCOMAS Congress 2020
11–15 January 2021, Paris, France

ENHANCEMENT OF THE MIXING EFFICIENCY FOR A STEAM BOILER PREMIX CHANNEL WITH A SURROGATE BASED OPTIMIZATION

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Key Words: CFD, Steam Boilers, Ansys Fluent, Dakota, Multi-Objective-Genetic-Algorithm (MOGA), Kriging, Nitrogen Oxides (NO_x)

Abstract Global warming and the ever-increasing pollutants in the atmosphere force many governments to limit emissions. The use of methane as a fuel is widespread in the boiler industry, due to the low pollutant levels in its exhaust gas products. Nevertheless, in the combustion process, nitrogen and oxygen bind giving rise to a series of molecular compounds called NO_x, which are considered pollutants because they react in the atmosphere causing the production of acid rain and reducing the level of ozone [1]. The aim of this work is to improve the mixture quality between fresh air, methane and recirculated exhaust gases introduced within Ecovapor Boiler's Mixing-Channel and, as consequence, to increase the combustion quality and limit the pollution production. The geometry is parameterized within Ansys Space Claim CAD software [2], and gas mixture flow is computed with Ansys Fluent solver [3]. To achieve these goals an automated shape optimization is adopted, which couples the Ansys Workbench environment to Dakota software [4]. In particular, a multi-objective genetic algorithm (MOGA) [5] combined with the Kriging response surface method is used, while the geometries are evaluated by solving for a compressible mixture of non-reacting gases the steady-state Reynolds Average Navier-Stokes (RANS) equations coupled with the k-ε Realizable turbulence model [6].

1 INTRODUCTION

Since the first years in the $19th$ century, steam boilers have been extensively used as source of powerfor their ease of assembly, for the possible use of different fuels and a wide thermal powers modulation. Nowaday, the polluting emissions increase into the atmosphere, forced many governments to issue new laws, which reduced emissions in plants that produce energy from fossil sources. This obliged many Boiler's producers to improve their technology, reaching higher thermal efficiency and limiting their environmental impact. In the last years, many steam boilers have been equipped with burners that employ only methane as fuel, for lower emissions of carbon dioxide (CO_2) and nitrogen oxides (NO_x) during the combustion. A further improvement came by the large use of exhaust fumes (EGR) for NO_x reduction [1]. Following this approach, ICI Caldaie [7] designed a new type of steam boiler, called Ecovapor, which uses on the gas-side a methane-premixed burner with EGR. The mixture system is based on a mixing channel connected to a pneumatic gas valve that delivers methane according to the negative pressure measured downstream. After an accurate experimental test campaign, some mixing issues were noticed, that can be ascribed to the mixing system. However, a lack of information has been observed in literature regarding the “rules” for the design of boilers mixing channel. Nowadays, this issue can be overcome by the coupling of CFD and shape optimization algorithms, which represents a viable path toward a robust and fast design strategy [12, 13, 14, 15, 16, 17]. In fact, optimization techniques allow to drastically reduce the time required by the trial and error procedure traditionally employed by the designer, who has to produce only a tentative initial geometry.

In particular, in this work a shape optimization technique base on Multi-Object-Genetic-Algorithm (MOGA) [5] and a response surface method will be exploited to design a new mixing channel for Ecovapor.

2 ECOVAPOR MIXING SYSTEM

An experimental campaign has been realized at different thermal powers, in order to measure some flows thermo-physical properties. These data can be used to set correctly the boundary conditions (BCs) for CFD calculations and to validate CFD results.

2.1 Experimental measurements

The CFD analysis was led on the Ecovapor Boiler that can produce a maximum of 1000 kg/h of steam. The mixing channel design [7] consists of an air inlet surface in correspondence of the air filter, a gas pipe for the methane and an EGR window where exhaust fumes are collected from the back of the boiler. The three gases are mixed and move downstream foreword to the combustion head. The experimental campaign was conducted for the minimum, medium and maximum thermal power. Thermocouples, pressure devices and flow-meters were positioned on the mixing system to acquire the data, which are repoirted in Tabs. 1, 2 and 3.

Table 1: Measured quantities at 30.6% of the maximum thermal power

Variables	Volumetric Flow	Temp.	Static Press.	e	NO_X	Volume Fraction		
Unit	$[m^3/h]$	$[^\circ C]$	*[Pa]*	*[/]*	$[mg/kWh]$	$\%CO_2$	$\%O_2$	$\%CH_4$
CH4 Inlet	23.5	27.7	-230	/	/	/	/	100.0
Air Inlet	/	26.8	/	/	/	/	21.0	/
EGR Inlet	/	70	-160	33	80	8.9	5.3	/
Outlet	/	40	-190	/	/	0.9	18.5	6.4

Table 2: Measured quantities at 61.0% of the maximum thermal power

Variables	Volumetric Flow	Temp.	Static Press.	e	NO_X	Volume Fraction		
Unit	$[m^3/h]$	$[^\circ C]$	*[Pa]*	*[/]*	$[mg/kWh]$	$\%CO_2$	$\%O_2$	$\%CH_4$
CH4 Inlet	47.4	31	-730	/	/	/	/	100.0
Air Inlet	/	26	/	/	/	/	21.0	/
EGR Inlet	/	97	-580	25	80	9.4	4.2	/
Outlet	/	39.3	-700	/	/	1.1	18.2	6.4

Table 3: Measured quantities at 95.6% of the maximum thermal power

Variables	Volumetric Flow	Temp.	Static Press.	e	NO_X	Volume Fraction		
Unit	$[m^3/h]$	$[°C]$	*[Pa]*	*[/]*	$[mg/kWh]$	$\%CO_2$	$\%O_2$	$\%CH_4$
CH4 Inlet	73.5	28	-1600	/	/	/	/	100.0
Air Inlet	/	25.7	/	/	/	/	21.0	/
EGR Inlet	/	103	-1320	24	83	9.5	4.1	/
Outlet	/	33	-1720	/	/	0.7	18.9	6.6

2.2 Models setup and boundary conditions

The fluid-dynamic simulations were performed with Ansys Workbench program [8], a software which contains many different tools for CAD, Mesh and CFD solvers. The flow is modeled with steady state RANS equations for compressible flows, coupled with two equations Realizable $k-\varepsilon$ turbulence model [6] and with equations of non-reacting species [9]. In addition, for each chemical species of the mixture, the viscosity has been calculated with the Sutherland [10] model. Momentum, energy, turbulence and species equations were discretized with a second order upwind scheme, while the gradient is discretized with a least-square method. Mass flow rates, temperatures and the chemical compositions were imposed at inlet surfaces, while measured static pressures were set on the outlet surfaces. These values were obtained by experimental data and correlations. In particular, starting from energy balance equation, it was possible to calculate the $\dot{m}_{CH_4}$:

$$\dot{m}_{ch4} = \frac{\dot{m}_{vap}\Delta h}{\theta_{th}K_i}, \tag{1}$$

where the thermal efficiency θ_{th} is computed by Siegert formulation [11]. Thanks to the literature stoichiometric balance equations, the air mass flow rate can be obtained by:

$$\dot{m}_{air} = (1+e)\dot{m}_{CH4}(17.12), \tag{2}$$

while the Exhaust-Gas-Recirculation mass flow has been estimated as 10% of the total mass that flows in the mixing channel:

$$\dot{m}_{egr} = \frac{1}{9}(\dot{m}_{CH_4} + \dot{m}_{EGR}). \tag{3}$$

The total mass flow can be calculated by the sum of Eqs. (1), (2) and (3). Starting by previous equations, the complete boundary conditions for minimum, medium and maximum thermal powers are available. Finally, the channel's mixing quality has been estimated with the standard deviation of methane mass fraction on the outlet surface, defined as:

$$\sigma_{CH_4} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(X_{i(CH_4)} - \overline{X}_{CH_4}\right)^2}, \tag{4}$$

and monitoring the value of the area averaged total pressure:

$$\overline{p_{tot}} = \frac{1}{A}\int p_{tot}dA. \tag{5}$$

2.3 Ecovapor channel results

During the experimental data campaign on the Ecovapor 1000 boiler, unusual flames detachment and high NO_x production have been monitored. In fact, different chemical compositions have been measured at different positions in the lower side of the mixing channel, confirming a bad mixing quality. This issue has been confirmed also by CFD simulations, as shown in Fig. 1.

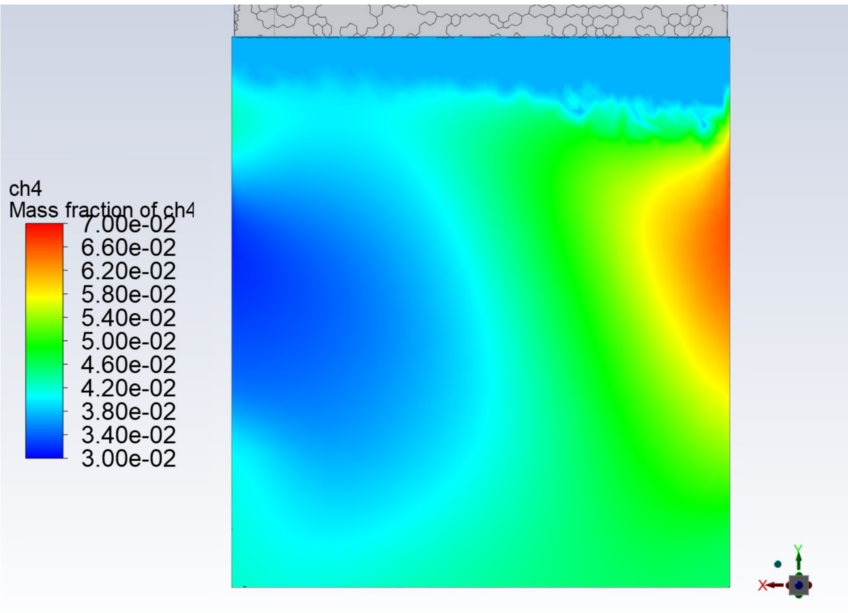


Figure 1: Standard deviation of methane mass fraction on the Outlet-surface at 61.0% of the maximum thermal power

3 NEW MIXING CHANNEL

As shown in the previous Section, Ecovapor is characterized by a poor mixing quality. However, the mixing of the mixture relies only on the flow turbulence generating along the vertical channel. As a consequence, this design can not be affected by a shape optimization approach, and, therefore, a new design of a mixing channel (see Fig. 2) was created and a complete fluid-dynamic campaign was performed to assess its performance. The shape of the inlet section is unchanged, while a throat has been arranged in the middle of the channel with aerodynamics profiles to increase the mixing quality. Moreover, in the lower part of the channel the walls have been modeled to better convey the mixture flow towards the burner (the outlet section).

3.1 CFD setup

For all thermal powers, the methane and EGR mass flow rates were imposed on the corresponding inlet surfaces (values are the same of the previous simulation), while the expected total mass flow rate, calculated by the sum of Eqs. (1), (2) and (3) has been imposed on the outlet surface. Total pressure equivalent to environment pressure was set on the air inlet surface.

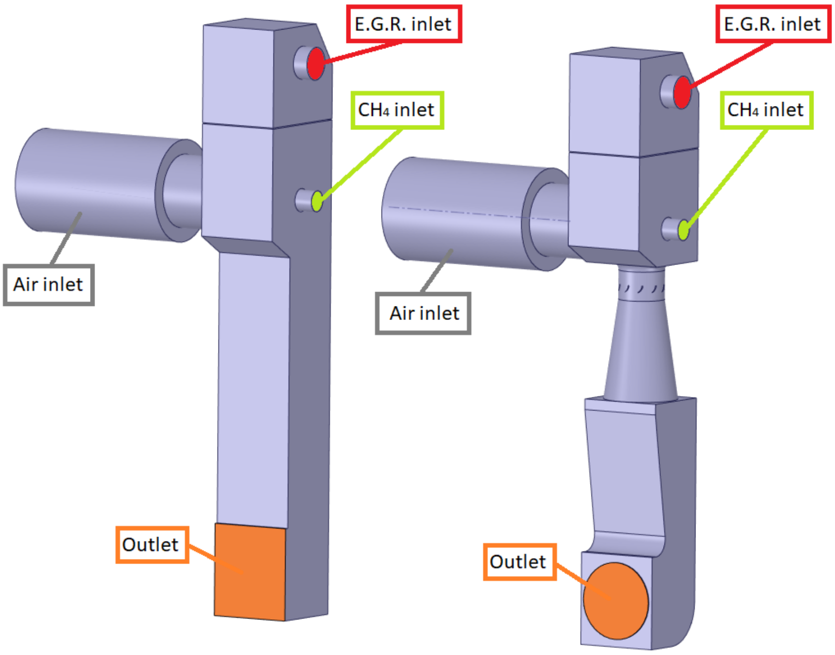


Figure 2: Old and New mixing channel comparison

3.2 Simulation results

The new mixing channel shows a better mixing quality for all thermal powers, as depicted in Fig. 3 and summarized in Tab. 4, where the σ_{CH_4} values at the outflow sections are reported.

Table 4: Channels Mixing-quality comparison in terms of σ_{CH_4}

σ_{CH_4}	Unit	$Pow.20\%$	$Pow.50\%$	$Pow.100\%$
$Old-Channel$	$/$	0.00408	0.00556	0.00599
$New-Channel$	$/$	0.00142	0.00131	0.00147

At the same time, higher total pressure values were verified (as reported in Tab. 5), compared to the previous channel, with a real risk of not reaching the maximum boiler's thermal power.

Table 5: Channels Outlet-Total-Pressure comparison

P_{TOT}	Unit	$Pow.20\%$	$Pow.50\%$	$Pow.100\%$
$Old-Channel$	Pa	-172	-638	-1391
$New-Channel$	Pa	-255	-1384	-3048

4 SHAPE OPTIMIZATION OF THE NEW CHANNEL

In order to reduce the new channel pressure losses, keeping the good mixing quality, a shape optimization approach based on Multi Object Genetic Algorithm (MOGA) was applied. Initially, seven design param-

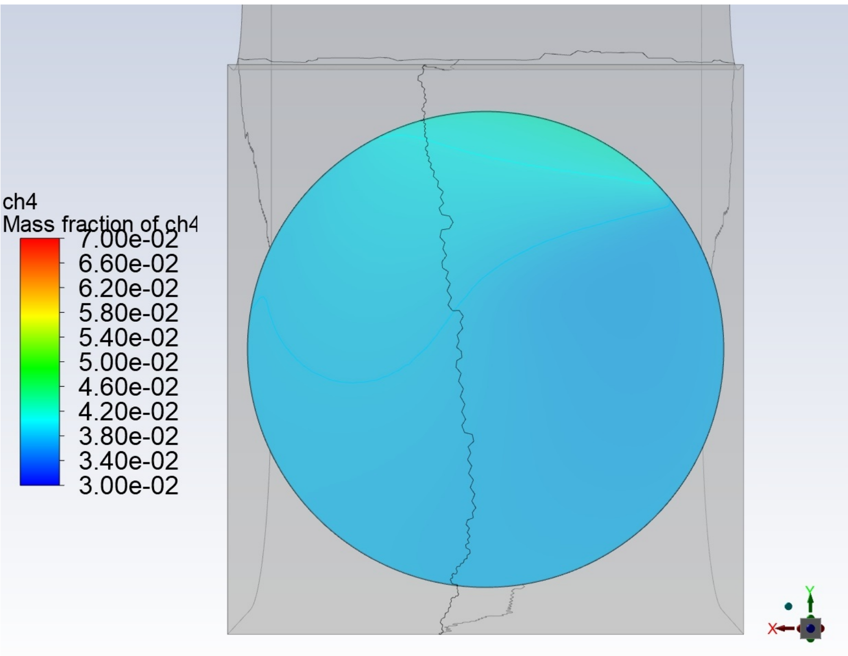


Figure 3: Standard deviation of methane mass fraction on the New Mixing Channel Outlet-surface at 61.0% of the maximum thermal power

eters and two objective functions were chosen. Successively, the Latin Hypercube method was applied to investigate the hyperspace solutions domain. Finally, the MOGA algorithm [5] has been applied to discover the parameters combination which leads to the best compromise in terms of good mixing quality and low pressure losses. The optimization process is driven by a script that couples the Workbench software [8] with the optimization library Dakota [4].

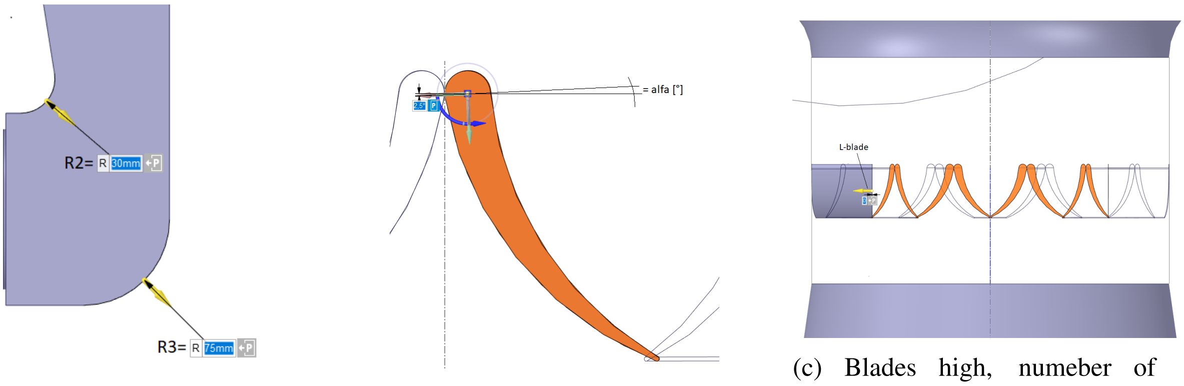
4.1 Design variables and objective functions

The variables of the parametrization are described in Fig. 4. Every variable has a specific range with constrains, while the objective functions that drive the optimization procedure are:

- f' = minimization of pressure losses (maximizing P_{TOT} on the outlet surface);
- f'' = maximization of mixing efficiency (monitoring σ_{CH_4} value).

4.2 Optimization loop

The optimization procedure is based on a response surface method coupled with the MOGA algorithm. Initially, a search method (LHS) has been applied to investigate the possible combinations between different parameters (orange points in Fig. 5). Successively, the Genetic Algorithm (GA) has been used to discover new generations of possible design variables, that better respect the objective functions. Best candidates are verified with CFD analysis. This loop can be applied several times until a stop criterion parameter, defined as Generational Distance (GD), is satisfied [18]. The solutions which belong to the true Pareto front have *GD* value close or equal to zero.



(a) radii curvatures (b) Attack angle (c) Blades high, numeber of blades, channel diameter

Figure 4: Parameterized variables

4.3 Fluid-dynamic BCs for the optimization process

Without experimental results for the optimized mixing channels, new BCs have been calculated in order to optimize the channel behaviour at 66% thermal power condition with the same procedure described in Section 2.1. The adopted BCs are reported in Tab. 6.

Table 6: BCs at 66% of the maximum thermal power

Sections	Mass Flow	Static Pressure	Temp.	Mass fraction			
Unit	*[kg/s]*	*[Pa]*	$[°C]$	%CH4	%CO2	%O2	%H2O
CH_4 Inlet	0.00949	/	25	100	/	/	/
Air Inlet	/	0	20	/	/	22.9	/
EGR Inlet	0.0235	/	140	/	12.34	4.31	10.1
Outlet	0.23502	/	/	/	/	/	/

5 RESULTS AND DISCUSSION

After seven loops, the GD parameters have reached a low and stable value and the optimization procedure was stopped. Between the different solutions on the Pareto Front, i.e. the sets of variables that better satisfy the objective functions, are the design variables that guarantee higher values for σ_{CH_4} and lower value for the Outlet-total-Pressure (indicated with the green point in Fig. 5).

The performance of the optimized channel design was verified with a CFD analysis for minimum, medium and maximum thermal powers (as shown in Tabs. 7, 8 and 9).

The results confirmed the good mixing quality and lower pressure losses respect to the previous non-optimized channel but, unfortunately, they were still with respect to the old Ecovapor mixing channel.

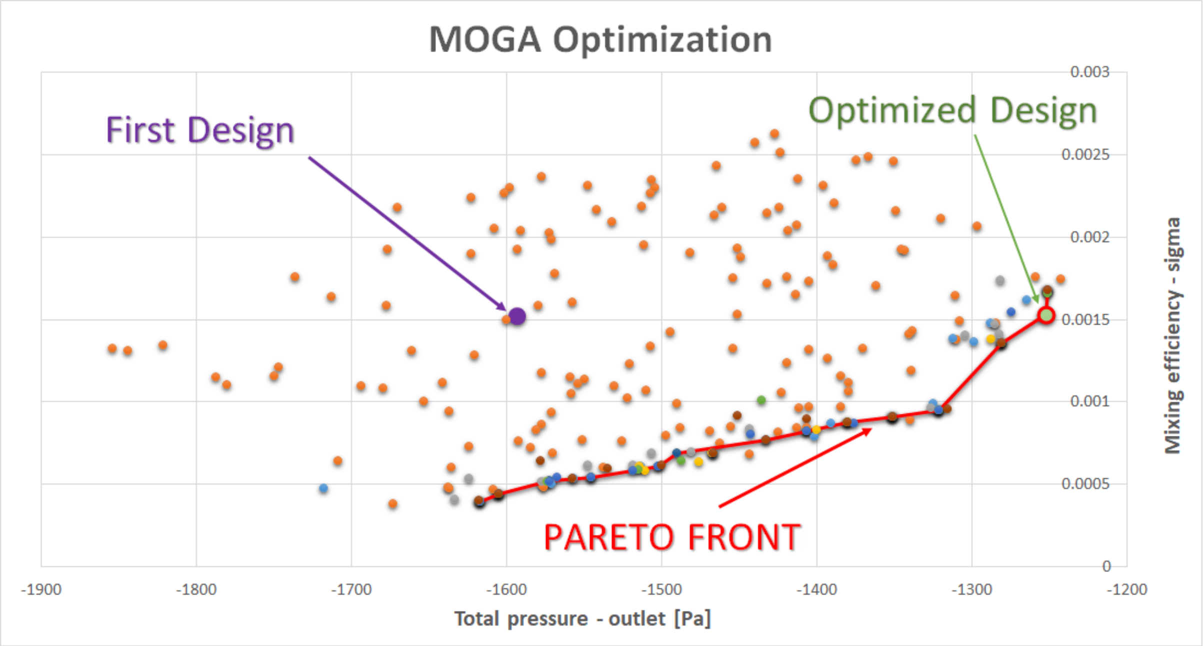


Figure 5: Pareto Front

Table 7: CFD results at 20% of the maximum thermal power

Sections	Mass Flow	Static Pressure	Temp.	Mass fraction			
Unit	*[kg/s]*	*[Pa]*	$[°C]$	% CO2	% O2	% H2O	% CH4
CH4 inlet	0.00288	-93.9	20.0	0.0	0.0	0.52	100.0
Air	0.06912	0	27.0	0.0	0.2308	0	0.0
EGR	0.00799	-78.5	60.0	12.34	4.31	10.1	0.0
Outlet	0.08001	-175.5	29.87	1.232	20.374	1.46	3.602

Table 8: CFD results at 50% of the maximum thermal power

Sections	Mass Flow	Static Pressure	Temp.	Mass fraction			
Unit	*[kg/s]*	*[Pa]*	$[°C]$	%CO2	%O2	%H2O	%CH4
CH4 inlet	0.00719	-460.2	20.0	0.0	0.0	0.52	100.0
Air	0.15298	0	27.0	0.0	0.2308	0	0.0
EGR	0.01789	-386.9	75	12.34	4.31	10.1	0.0
Outlet	0.17809	-864.1	31.3	1.234	20.27	1.457	4.035

6 CONCLUSIONS

An accurate experimental data campaign on Ecovapor Steam Boiler monitored some issues on the mixing channel in terms of bad mixture quality. Due to the system design (straight vertical channel) the shape

Table 9: CFD results at 100% of the maximum thermal power

Sections	Mass Flow	Static Pressure	Temp.	Mass fraction			
Unit	*[kg/s]*	*[Pa]*	$[^\circ C]$	%CO2	%O2	%H2O	%CH4
CH4 inlet	0.01438	-1858.5	20.0	0.0	0.0	0.52	100.0
Air	0.3067	-5.8	27.0	0.0	0.2308	0	0.0
EGR	0.0356	-1541.2	100.0	12.34	4.31	10.1	0.0
Outlet	0.3562	-3483.2	33.12	1.232	20.275	1.4565	4.03

optimization could not promote any benefit, and, therefore, a new mixing channel was designed and analyzed. Good mixing quality results were reached but, at the same time, too high pressure losses were verified. To overcome this problem, an optimization procedure based on a response surface Genetic Algorithm was applied. A new optimized mixing channel was obtained and CFD simulations confirmed the expected better performance in terms of mixing quality and pressure losses. The optimal geometry will be manufactured and tested directly on the steam boiler.

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