Journal of Physics: Conference Series

PAPER • OPEN ACCESS

CFD design of a novel device for temperature profile measurement in Waste-to-Energy plants

To cite this article: G. Grossi *et al* 2024 *J. Phys.: Conf. Ser.* **2685** 012011

CFD design of a novel device for temperature profile measurement in Waste-to-Energy plants

G. Grossi [1,*], F. Arpino [1], C. Canale [1], G. Cortellessa [1], G. Ficco [1], T. Lombardi [2]

[1] Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, Via G. Di Biasio 43, Cassino, 03043, FR, Italy
[2] HERAmbiente S.p.a, Via dell'Energia, Pozzilli, 86077, IS, Italy

* Corresponding author: giorgio.grossi@unicas.it

Abstract. Monitoring the flue gas temperature is a crucial issue for Waste-to-Energy (WtE) plants companies, since it is essential to preserve the materials in the post-combustion chamber, the energy efficiency of the plants as well as to control the emissions of pollutants. As of today, the temperature of flue gases in such plants is commonly monitored by means of thermocouples, infrared pyrometers or aspirated thermocouples. However, all these instruments show limitations in terms of accuracy and reliability inside post-combustion chambers. In this paper, the authors present the thermo-fluid dynamics design of a novel device aimed at mitigating the issues of existing technologies, realised by using the modern CFD techniques. Numerical analyses, performed with the open-source OpenFOAM code, allowed to find a suitable shape for the device and to give a first estimate of the measuring errors, which are of the order of 2% (~26 K at the typical working temperature of WtE plants' post-combustion chambers).

Keywords: Waste-to-Energy plants, combustion chamber, temperature profile, thermocouple, CFD analysis

1. Introduction

The temperature of flue gases in the post-combustion chamber of Waste-to-Energy (WtE) plants must be maintained within a narrow range of values, for environmental (i.e., to control the emissions of pollutant agents), structural (i.e., to ensure the preservation of materials properties) and energy efficiency reasons [1]. The minimum value is set by the Legislative Decree No. 152/2006 and its subsequent amendments and supplementations, prescribing that after the last injection of combustion air, the temperature of the gaseous combustion products must be kept above 850 °C for at least 2 seconds (1100 °C if hazardous wastes with a content of more than 1% of halogenated organic substances, expressed as chlorine, are incinerated). Such temperature, referred to as T_{2S}, is not directly measurable and is typically estimated by employing advanced CFD techniques or empirical and semi-empirical correlations based on temperature, volumetric flow rate and oxygen content continuously measured in the post-combustion chamber. Monitoring the flue gas temperature is essential also to ensure that it is not overly high, as an excessive rise in the combustion temperature leads to an increased production of nitrogen oxides, results in a decrease of the plant efficiency and could also compromise the structural integrity and functionality of the materials and components employed [1].

The temperature of flue gases in WtE plants is commonly monitored by means of thermocouples, infrared pyrometers or aspirated thermocouples (also referred to as suction pyrometers or high velocity thermocouples) [1–4]. The first two techniques showed limitations in strong radiative environments such as the one inside the post-combustion chambers of a WtE plant, both in terms of accuracy and reliability [1,2,5]. The latter, albeit exhibiting greater accuracy and overcoming most of the issues affecting the performances of the other instruments, still presents criticalities in its management and reliability [4]. In addition, none of these measurement techniques allows to obtain a temperature profile with a single immersion by simultaneously measuring the temperature at different depths. In fact, to measure temperature in multiple points of the combustion chamber, essential for validating the CFD codes employed to verify the plant operating conditions, the same instrument must be moved back and forth resulting in an uncertainty of the position and measurements in correspondence of potentially different operating conditions of the WtE plant. In fact, the properties and the conditions of the flue gases may vary significantly over time according to the composition of the waste being burned.

In this paper, the authors present the design of a novel device to measure the temperature of flue gases evolving in the post-combustion chamber of WtE plants, designed for the HERAmbiente S.p.a. plant in Pozzilli (Italy), aiming to mitigate the issues of existing temperature measuring approaches. The novel device relies on thermocouples as sensing elements, shielded from radiative heat fluxes. The rising motion of the fumes is exploited to take measurements at three points of the chamber and near the wall simultaneously. This work presents the preliminary results of the thermo-fluid dynamics design of the device, realised by means of transient CFD analyses. The developed numerical tool considers the effects of thermal radiation, essential to correctly estimate the errors of measurements taken inside post-combustion chambers, and of conjugate heat transfer between fluid and solid media.

2. Materials and methods

The concept of the novel device is sketched in Figure 1. It is 2 m long, 0.035 m wide (limited by the maximum opening available in the membrane walls of the Pozzilli plant) and 0.38 m high.

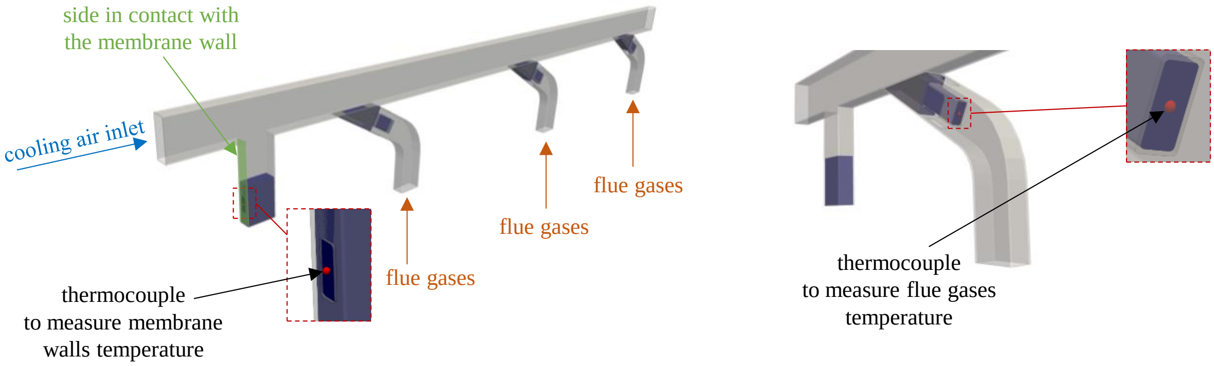


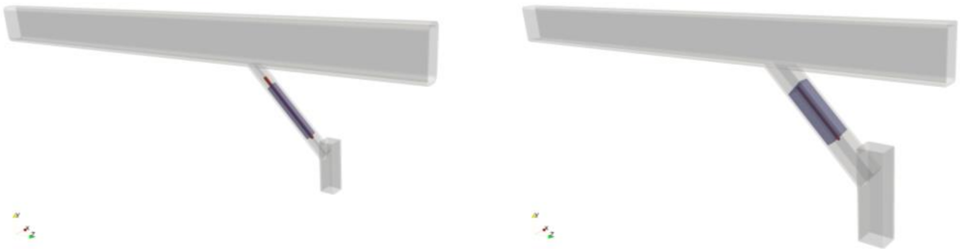
Figure 1. The novel measuring device.

It relies on the use of one thermocouple to measure the inner wall temperature and of three thermocouples to measure the temperature of flue gases flowing in the post-combustion chamber. Thanks to the designed shape, the framework itself shields the sensing elements from the radiative heat exchange between the sensors and the chamber walls. Cooling is provided by fresh air injected into the main duct and released in the flue gases stream; refractory cement (coloured blue in Figure 1) is employed to prevent contact between the hot gas stream and the thermocouples wirings. The piping is made of Inconel 625 alloy, whereas the refractory is made of a silicon carbide-based cement. More structural details of the device are shown in Figure 4. The solution here proposed has several advantages over the technologies currently existing on the market: (i) errors due to radiation are reduced thanks to the shape of the device; (ii) there is a clear reference for the position of the measurement points, since one side is in contact with the membrane wall and the relative distance between sensors is constant and known; (iii) temperature is measured at multiple points simultaneously, with a single immersion;

(iv) unlike suction pyrometers, cooling is provided by injecting air, not water, and flue gases are not drawn out of the post-combustion chamber; (v) the gas stream is not sped up (as it happens for suction pyrometers), conversely its natural vertical motion is exploited.

2.1. Steps in the thermo-fluid dynamics design of the novel device

The device shown in Figure 1 is the result of thermo-fluid dynamics analyses carried out on four different geometries, depicted in Figures 2-4. From first to fourth (i.e., the final) test, changes were made according to the results of CFD analyses, as described in Section 3. To save computational resources, at this stage of the design process a simplified geometry was analysed.



(a) first test (b) second test

Figure 2. (a) first and (b) second tests for the design of the novel device.

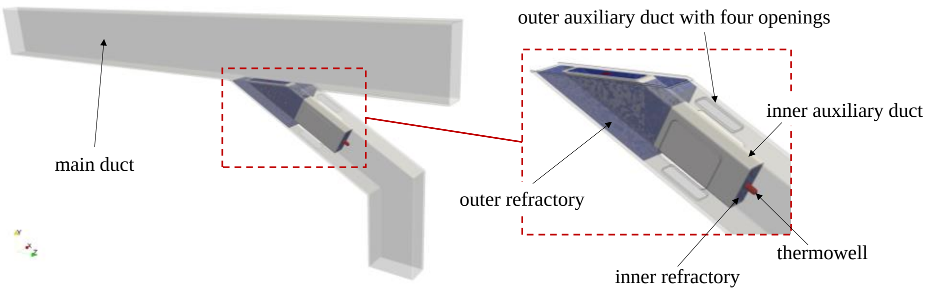


Figure 3. Third test for the design of the novel device.

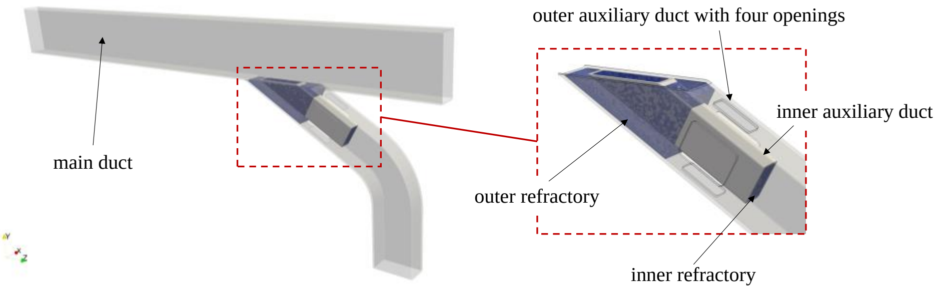


Figure 4. Fourth (and final) test for the design of the novel device.

The third and fourth geometries (Figure 3 and Figure 4) differ significantly from the initial concepts (Figure 2); an inner auxiliary duct brings the thermocouple and an outer auxiliary duct channels the flow, shields the thermocouple from radiation and allows the hot gases to flow out through four openings.

2.2. Numerical setup

Numerical investigations were performed employing the *chtMultiRegionFoam* solver available in the open-source OpenFOAM code, based on the finite volume formulation.
Velocity, pressure and temperature in the fluid region were predicted solving the mass, momentum and energy conservation equations under the assumption of three-dimensional, unsteady, turbulent and

compressible flow with ideal gas behaviour. The unsteady Reynolds-averaged Navier-Stokes (URANS) approach was selected for turbulence modelling, solving the Shear Stress Transport (SST) k–ω model [6,7] as recommended by Costa et al. [8]. Pressure-velocity coupling was solved with the PIMPLE algorithm [9], processing the overall transient phenomenon as consecutive steady-state time steps; a time step of 0.005 s was adopted and as requirement for time step convergence the scaled residuals were set $<10^{-3}$ for pressure and $<10^{-5}$ for other variables. The effects of thermal radiation were taken into account using the Finite Volume Discrete Ordinates Method (fvDOM) model [7,10], solving the radiative transfer equation (RTE) for 60 discrete solid angles and considering a non-scattering medium. Once all the directional radiation intensities I (W m^{-2} sr^{-1}) are known, it is possible to calculate the radiative heat fluxes at surfaces, q_r (W m^{-2}), as well as the radiative source term in the fluid energy conservation equation. As regards the solid domains, the only variable is temperature, and it is determined by solving the energy conservation equation under the assumption of constant thermophysical properties within the regions. For a comprehensive description of the governing partial differential equations, the reader is referred to the existing literature [6,7,10].

Figure 5 shows the computational domain for the fourth (i.e., the final) test case. Its set-up is identical to the one used for the other scenarios and is composed of multiple sub-regions: (i) a fluid one, with two inlets (one for the flue gases, coloured green, and one for the cooling air, coloured blue), an outlet section (coloured red) and walls (coloured grey); (ii) separate solid regions for the piping and for refractories (other concepts also include a solid region for the thermowell, as visible in Figure 2 and Figure 3).

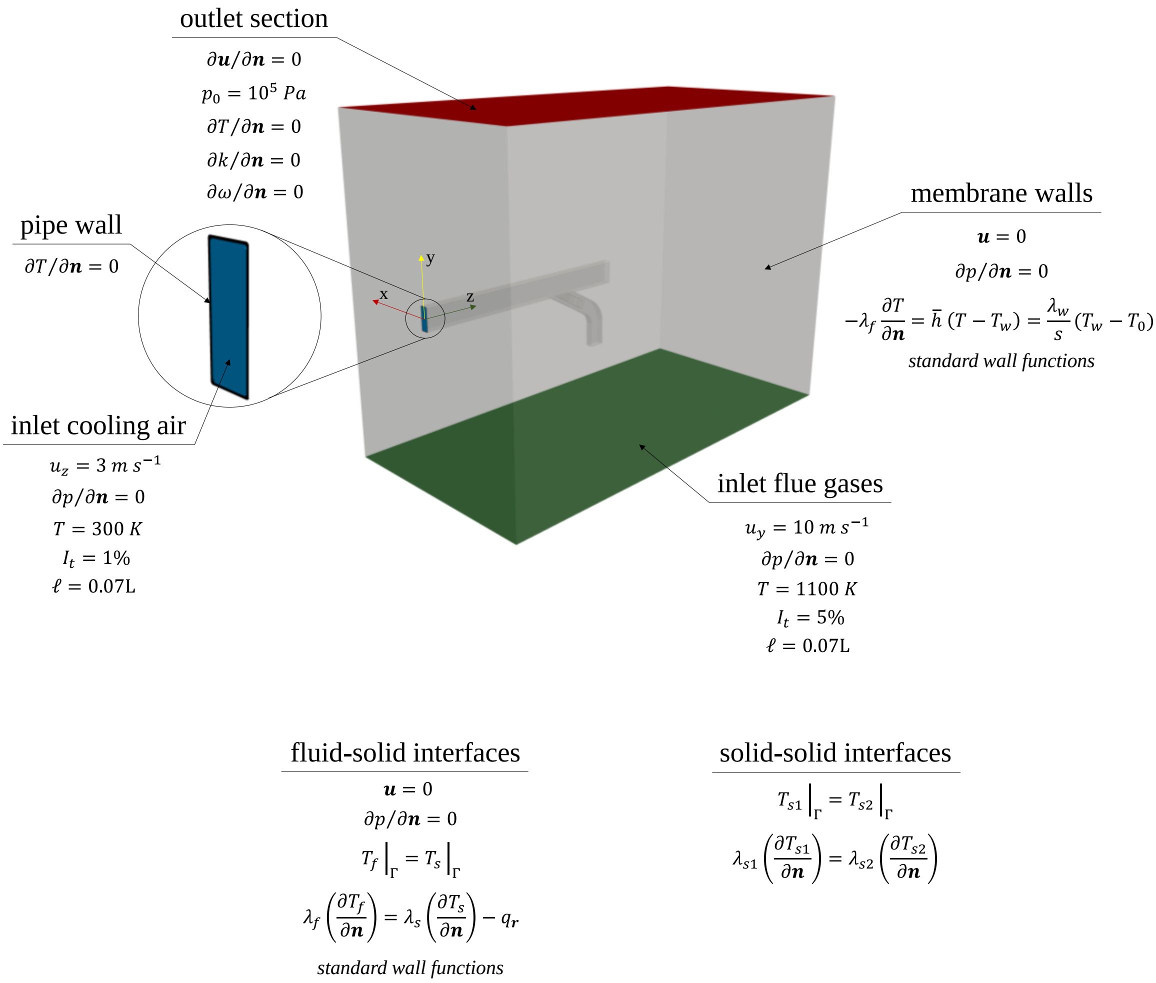


Figure 5. Computational domain and main boundary conditions employed for the simulation of the fourth geometry.

Figure 5 also presents the main boundary conditions set for numerical simulations. A velocity of 3 m s^{-1} was assumed for the cooling air whereas the velocity of flue gases (assumed to be air) was set equal to 10 m s^{-1} [1]. At the outlet section, the value of the total pressure p_0 is imposed. For turbulent quantities, the turbulence intensity I_t (%) and the turbulent mixing length ℓ (m) were specified. The latter was calculated as 7% of the characteristic length L (m), assumed equal to the width of the corresponding inlet section. For the resolution of temperature field, at the membrane walls heat transfer with the external environment is modelled: λ (W m^{-1} K^{-1}) is the thermal conductivity, $\bar{h} = 1.5 \text{ W m}^{-2} \text{ K}^{-1}$ the convection heat transfer coefficient, s (m) the wall thickness, T_W (K) the wall temperature and T_0 the temperature of saturated water at 40 bar (524.48 K). It should be remarked that the velocity and temperature values set at the inlet for the flue gases and the cooling air are preliminary values. These values are used to conduct simulations aimed at finding the best shape for the measuring device. Future investigations will replicate the actual conditions of the WtE plant and will involve a thorough analysis to determine the optimal velocity and temperature of the cooling water.

At the interface Γ between two regions (i.e., fluid-solid and solid-solid interfaces), the continuity of temperature and the balance of the heat fluxes are imposed. Finally, a grey-diffuse condition is provided for the radiation intensity [7,10], at all boundary patches.

The domain sketched in Figure 5, was meshed with an unstructured hexa-based grid, made up of 5,323,212 cells; the maximum non-orthogonality is equal to 56 and the maximum skewness is equal to 1.52. A detail of the grid, on the yz plane at x=0, is depicted in Figure 6. Grid sensitivity analysis, as well as the validation of the numerical model, will be performed in future studies.

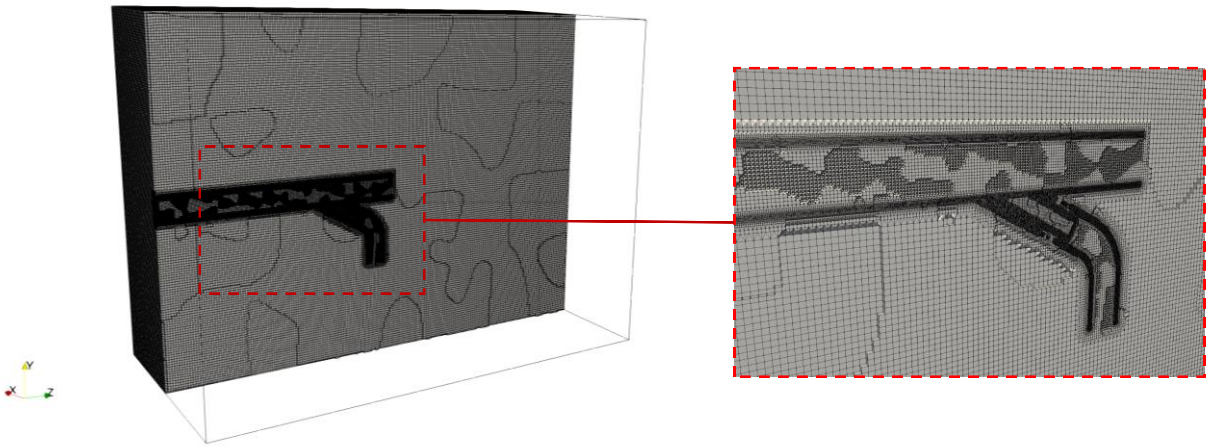


Figure 6. Detail of the computational grid employed for the simulation of the fourth geometry, on the yz plane at x=0.

3. Results and discussions

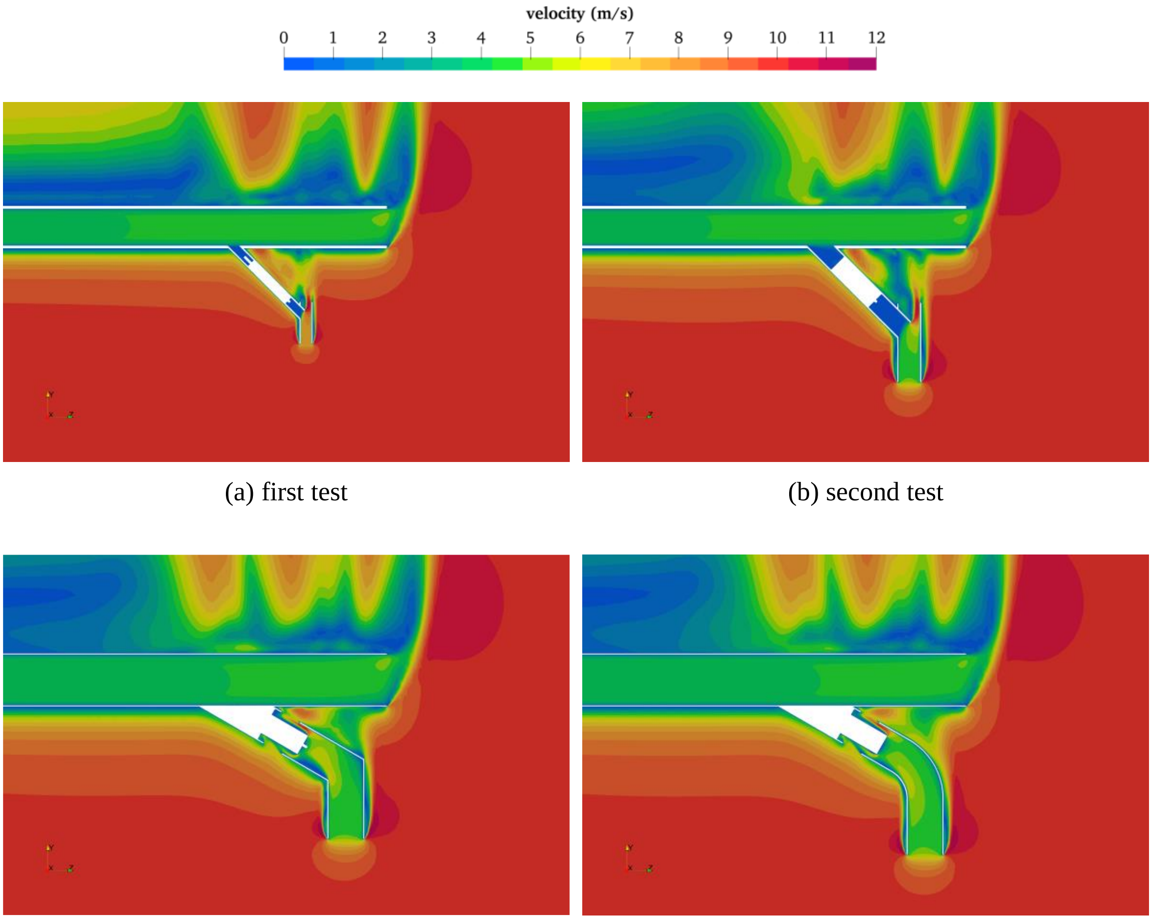
3.1. Design of the device shape

Figure 7 shows the velocity fields of the fluid region after 30 seconds, for the different geometries analysed, whereas temperature fields are displayed in Figure 8. Simulations carried out as first (Figure 7a, Figure 8a) and second (Figure 7b, Figure 8b) test, revealed the unsuitability of the setup originally conceived. In fact, even when enlarging the cross sections, the hot gas stream is not able to reach the thermowell and exchange efficiently, resulting in cold spots near the thermowells.

The third setup (Figure 7c and Figure 8c) is far better in terms of fluid dynamics and the flue gases are now able to reach the sensor. However, such solution still presents criticalities: (i) recirculation zones, due to the sharp edges of the outer auxiliary duct, are responsible for cold spots that must be avoided to improve the dynamic response of the device; (ii) building the instrument in this form would require the use of welding, not suitable for the extreme environments inside the combustion chambers. The above

Journal of Physics: Conference Series	**2685** (2024) 012011	doi:10.1088/1742-6596/2685/1/012011

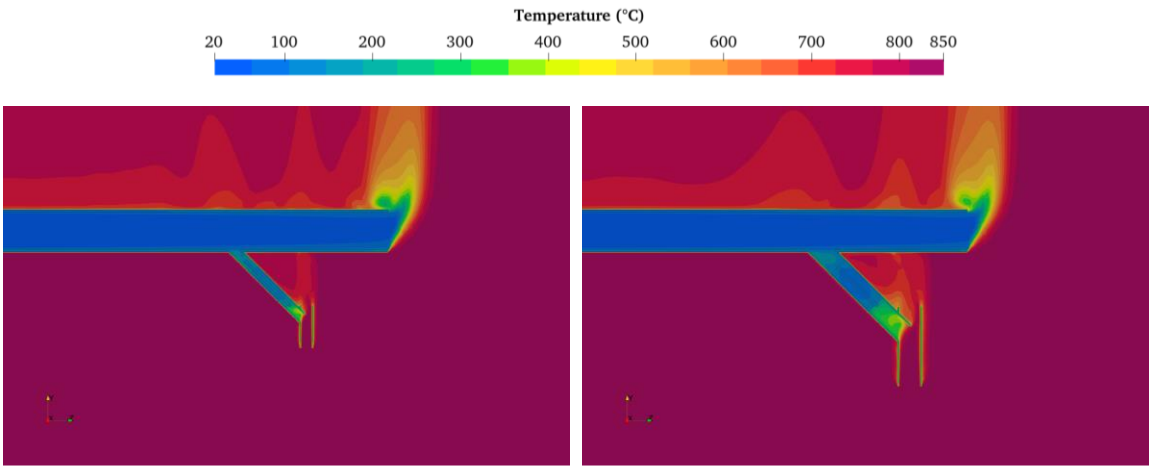
considerations led to the design of the fourth configuration (Figure 7d and Figure 8d), with a smoother shape. It presents no structural criticalities and avoids the formation of recirculation zones and hot spots; therefore, it is suitable for the construction of the novel pyrometer.



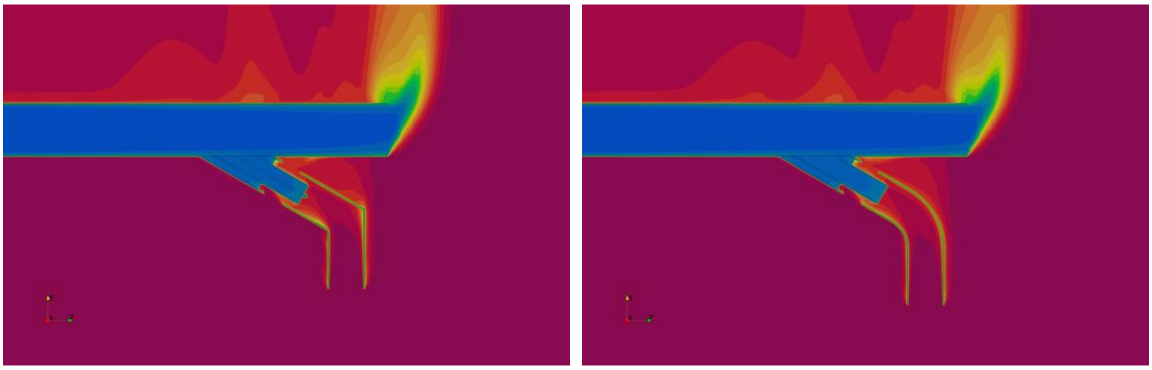
(a) first test	(b) second test

(c) third test	(d) fourth test

Figure 7. Velocity fields on the yz plane at x=0, after 30 seconds, for the different geometries considered.



(a) first test	(b) second test



(c) third test (d) fourth test

Figure 8. Temperature fields on the yz plane at x=0, after 30 seconds, for the different geometries considered.

3.2. Estimation of the measuring errors
Once the best shape for the device was selected, further analyses were conducted to get a first estimate of the measuring errors. For this purpose, two virtual probes were put in the computational domain, one in the fluid region (where the flow enters the outer auxiliary duct) and one inside the refractory (where the thermocouple would be placed). Temperature was monitored over time and the relative error calculated as $\left(T_{fluid} - T_{refractory}\right)/T_{fluid}$; the results, shown in Figure 9, reveal that in quasi-steady state conditions, the error is of the order of 2% (~26 K).

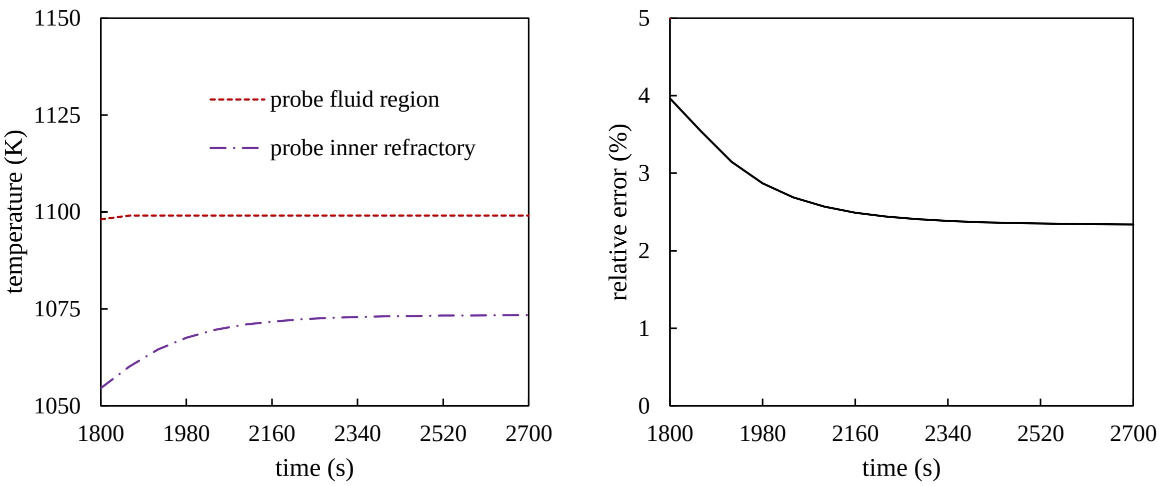


Figure 9. Temperature trends over time at the virtual probes and corresponding relative error.

Such a difference in temperature may be due to: (i) conductive fluxes within the solid media; (ii) ineffective convective heat transfer between the flue gases and the refractory.
The contribution of conduction and convection heat transfer mechanisms was assessed extracting a temperature profile straddling the fluid and the solid region, as depicted in Figure 10. As expected, a drop in temperature occurs at the interface; however, in the fluid and solid regions the temperature field is quite uniform, suggesting that the effect of conductive and convective heat transfer can be deemed negligible.

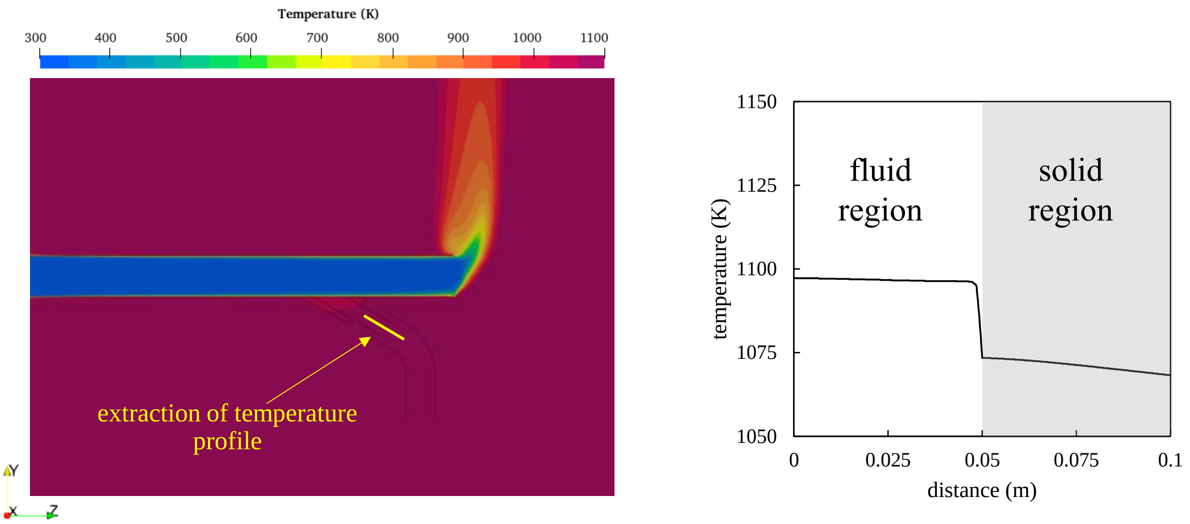


Figure 10. Temperature field and temperature profile extracted between the fluid and solid regions.

4. Conclusions

This work presents the preliminary results of the thermo-fluid dynamics design of a novel device aimed at measuring flue gases temperature inside WtE plants. The design is realised by means of transient CFD analyses, performed with the open-source OpenFOAM toolbox, taking into account the effects of thermal radiation and of conjugate heat transfer between fluid and solid media.

Numerical analyses allowed to find a suitable shape for the device, capable of shielding the sensing elements from incident radiation and of ensuring contact with the hot gas stream; they also allowed to give a first estimate of the measuring errors, which are of the order of 2% (i.e., 26 K).

Future simulations, reproducing the real operating conditions of the plant, will look at finding: (i) the time required to take measurements; (ii) the minimum flow rate of the cooling air, needed to preserve the structural integrity of the different components; (iii) the maximum temperature reached by the materials.

References

[1] F. Rinaldi, B. Najafi, Temperature Measurement in WTE Boilers Using Suction Pyrometers, Sensors. 13 (2013) 15633–15655. https://doi.org/10.3390/s131115633.

[2] A. Z'Graggen, H. Friess, A. Steinfeld, Gas temperature measurement in thermal radiating environments using a suction thermocouple apparatus, Meas. Sci. Technol. 18 (2007) 3329–3334. https://doi.org/10.1088/0957-0233/18/11/010.

[3] H. Sefidari, N. Razmjoo, M. Strand, An experimental study of combustion and emissions of two types of woody biomass in a 12-MW reciprocating-grate boiler, Fuel. 135 (2014) 120–129. https://doi.org/10.1016/j.fuel.2014.06.051.

[4] Jr. Baukal Charles E., ed., Industrial Combustion Testing, 0 ed., CRC Press, 2010. https://doi.org/10.1201/EBK1420085280.

[5] J.V. Nicholas, D.R. White, Traceable temperatures: an introduction to temperature measurement and calibration, 2nd ed, Wiley, Chichester, 2001.

[6] F.R. Menter, M. Kuntz, R. Langtry, Ten years of industrial experience with the SST turbulence model, Turbulence, Heat and Mass Transfer 4. (2003) 625–632.

[7] H.K. Versteeg, W. Malalasekera, An introduction to computational fluid dynamics: the finite volume method, 2nd ed, Pearson Education Ltd, Harlow, England ; New York, 2007.

[8] M. Costa, N. Massarotti, A. Mauro, F. Arpino, V. Rocco, CFD modelling of a RDF incineration plant, Applied Thermal Engineering. 101 (2016) 710–719. https://doi.org/10.1016/j.applthermaleng.2016.01.073.

[9] C.J. Greenshields, H.G. Weller, Notes on computational fluid dynamics: general principles, CFD Direct Limited, Reading, UK, 2022.

[10] Michael Modest, Radiative Heat Transfer, Elsevier, 2013. https://doi.org/10.1016/C2010-0-65874-3.