An Integrated Numerical-Experimental Approach for Heat Transfer Analysis of Industrial Furnaces

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Abstract: This paper deals with an integrated numerical and experimental analysis work aiming at the investigation of the thermal distribution inside an industrial furnace built for metal materials treatments. The main goal of the research is to find the geometrical and/or functional parameters responsible for a not homogenous thermal distribution inside the internal volume of the furnace. During the experimental measurements, 16 thermal probes were located inside the furnace chamber to monitor and record spot temperature values during a given heating process. Numerical FEM-based models were built in COMSOL Multiphysics environment to solve turbulent fluid flow and transport-diffusion/radiating heat transfer during the furnace operation. A multivariate analysis was also developed by applying multivariate linear regression and autoregressive models to build-up a predictive tool able to assess temperature state at several operational conditions of the furnace, from experimental temperature acquisitions and/or FEM-based results. A study of the recorded temperature variance of has been also carried out in order to understand the potential source of inhomogeneity due to burners operative conditions. Experimental time evolutions of temperature were firstly exploited to successfully validate numerical and analytical models. Then, several analyses were performed to evaluate the influence of many design parameters (burners location, thermal properties of insulating materials, surface thermal emissivity) on the thermal distribution inside the furnace.

Keywords: Transport-diffusion/radiating heat transfer, multivariate analysis.

1. Introduction

Homogeneous thermal distribution in chamber of industrial furnaces for metal materials treatments represents a fundamental issue of development for this kind of industrial applications. Generally, heat treatments are used to alter the physical, and sometimes chemical, properties of a material. Heat treatment involves the use of heating or chilling, normally to extreme temperatures, to achieve a desired result such as hardening or softening of a material. Heat treatment techniques include annealing, case hardening, precipitation strengthening, tempering and quenching. Metallic materials consist of a microstructure of small crystals called "grains" or crystallites. The nature of the grains (i.e. grain size and composition) is one of the most effective factors that can determine the overall mechanical behavior of the metal. Heat treatment provides an efficient way to manipulate the properties of the metal by controlling the rate of diffusion and the rate of cooling within the microstructure. There are two mechanisms that may change an alloy's properties during heat treatment. The martensite transformation causes the crystals to deform intrinsically. The diffusion mechanism causes changes in the homogeneity of the alloy. Many metals exhibit a martensite transformation when heated and then cooled quickly. When a metal is cooled very quickly, the insoluble atoms may not be able to migrate out of the solution in time. When the crystal matrix changes to its low temperature arrangement, the atoms of the solute become trapped within the lattice. The trapped atoms prevent the crystal matrix from completely changing into its low temperature allotrope, creating shearing stresses within the lattice. When some alloys are cooled quickly, such as steel, the martensite transformation hardens the metal, while in others, like aluminum, the alloy becomes softer. Proper heat treating requires very precise control over temperature, time held at a certain temperature and cooling rate. During the heat treatment it is in fact essential that an uniform thermal load is applied to pieces located inside the furnace at each time step of the process. As a consequence, furnaces need to be designed in order to avoid undesired spatial gradients of temperature value when working. In this framework, the present research is devoted to investigate on the main design parameters of an industrial furnace, whose variation could improve the homogenous thermal distribution inside the internal volume of the chamber. An integrated experimental and numerical approach is applied to achieve this goal. In the following, we firstly describe the considered industrial device and the experimental set-up used for measures, then mathematical and numerical techniques exploited for modelling are presented. Some findings are then reported in the results section.

2. Industrial device and experimental set-up

A CAD snapshot of the considered industrial furnace is reported in Figure 1.

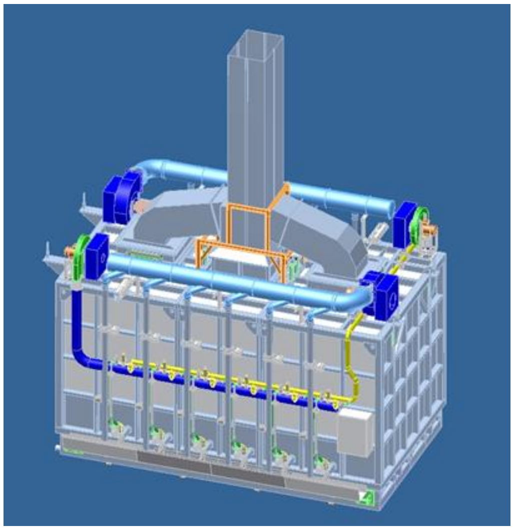


Figure 1. CAD representation of the furnace.

It is mainly composed by a multi-layer refractory basement, a insulating envelopment, an external structural frame, 12 high-velocity burners and their gas/air feeding system, waste lines for combustion product, other process and auxiliary electro-mechanical machines, mechanism for moving parts. Thermal power supplied by burners is controlled by a PID system, driving the ON/OFF state of each one during time as relating the chosen thermal transient and the step-by-step internal temperature measured inside the chamber. The experimental set-up employed for measurement is made of 14 thermal probes located inside the parallelepiped chamber as illustrated in Figure 2.

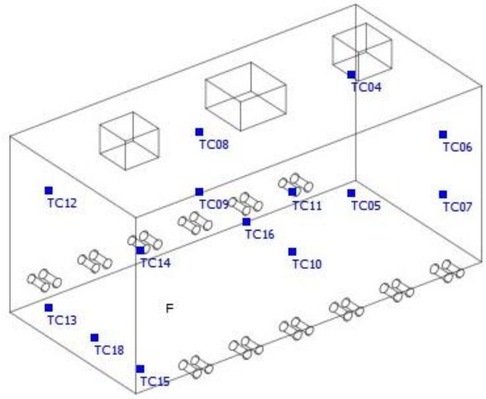


Figure 2. Location of thermal probes.

Temperature values are recorded each 10 seconds during a chosen thermal process. Figure 3 presents an extract of the time evolution of temperature acquired at the several probe locations during a piece-less test process made of 4 main “plateau” zones (570, 600, 900 and 1050 °C) and a final cooling.

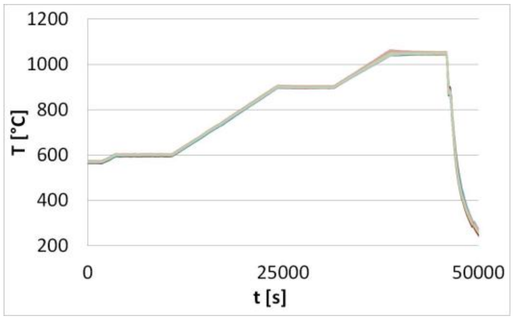


Figure 3. Time evolution of measured temperature during the test process.

3. Mathematical and numerical modelling

This section is devoted to describe the mathematical and numerical tools used for the device/process modelling. For the sake of clarity it is divided into two subsection, the first one related to the FE model, the second one related to the multivariate analysis.

3.1 FE model

FE-models are built-up in COMSOL Multiphysics environment. Geometry used for computations is derived by the original CAD of the furnace, depurated by all details not strictly needed for fluid-dynamical and thermal simulation. Solid domains considered in the model are graphically represented in Figure 4.

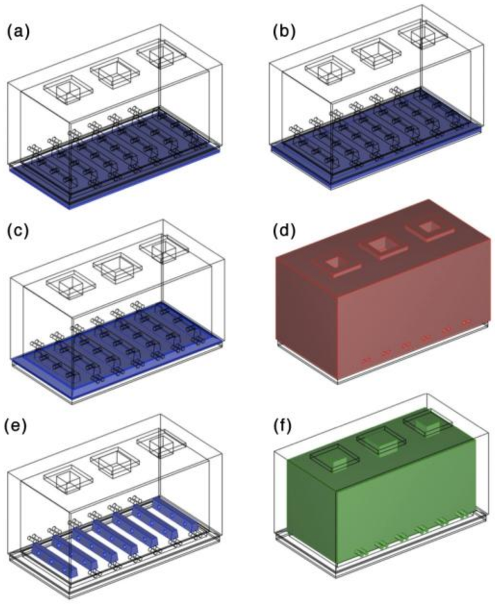


Figure 4. Computational domains for FE analysis: multi-layer refractory basement (a, b, c), insulating envelope (d), piece supports (e), air volume (f).

The multi-physical problem involves solution of mass, momentum and energy conservation laws. Under assumptions of Newtonian fluid and uncompressible turbulent flow, the Reynolds averaged Navier-Stokes equations read as in following:

$$\rho\frac{\partial\mathbf{U}}{\partial t}+\rho\left(\mathbf{U}\cdot\nabla\right)\mathbf{U}=\nabla\cdot\left[-p\mathbf{I}+\left(\mu+\mu_T\right)\left(\nabla\mathbf{U}+\left(\nabla\mathbf{U}\right)^{\mathrm{T}}\right)\right]+F \tag{1}$$

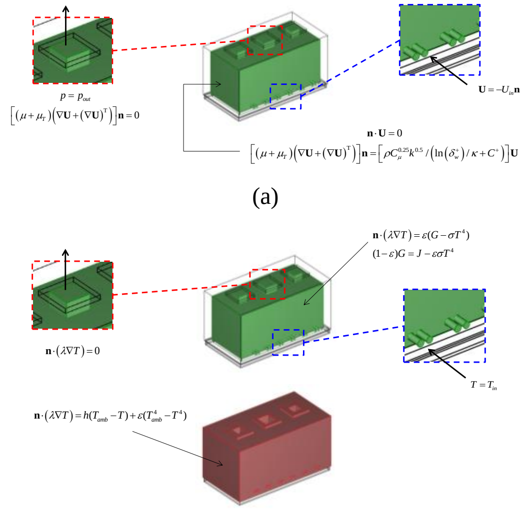
$$\nabla\cdot\mathbf{U}=0 \tag{2}$$

$$\rho\frac{\partial k}{\partial t}+\rho\mathbf{U}\cdot\nabla k=\nabla\cdot\left[\left(\mu+\frac{\mu_T}{\sigma_k}\right)\nabla k\right]+\frac{1}{2}\mu_T\left[\nabla\mathbf{U}+\left(\nabla\mathbf{U}\right)^{\mathrm{T}}\right]^2-\rho\varepsilon \tag{3}$$

$$\rho\frac{\partial\varepsilon}{\partial t}+\rho\mathbf{U}\cdot\nabla\varepsilon=\nabla\cdot\left[\left(\mu+\frac{\mu_T}{\sigma_\varepsilon}\right)\nabla\varepsilon\right]+\frac{1}{2}C_{\varepsilon 1}\frac{\varepsilon}{k}\mu_T\left[\nabla\mathbf{U}+\left(\nabla\mathbf{U}\right)^{\mathrm{T}}\right]^2-\rho C_{\varepsilon 2}\frac{\varepsilon^2}{k} \tag{4}$$

$$\rho C_p\frac{\partial T}{\partial t}+\rho C_p\mathbf{U}\cdot\nabla T=\nabla\cdot\left(\lambda\nabla T\right)+Q+\nabla q_r \tag{5}$$

A standard turbulence model [1, 2] is applied in solving momentum equations. Logarithmic wall functions are applied in the near wall flow, that is considered parallel to the wall. Turbulent production is assumed to equal dissipation at walls. Adopted physical properties are temperature dependent both for fluid and solid domains. The Rosseland approximation in invoked in order to express the radiating term in the energy equations [3, 4]. Governing equations are solved with boundary conditions graphically reported in Figure 5 for fluid and thermal analysis respectively.



(a)

(b)

Figure 5. Boundary conditions used for fluid (a) and thermal (b) analysis.

Continuous equations are spatially discretized on non-uniform and non-structured computational grids made of tetrahedral Lagrange elements of order 2. Influence of spatial discretization has been preliminary studied in order to assure mesh-independent results. In order to prevent arising and propagation of numerical instabilities, an artificial streamline diffusion technique, based on the Galerkin Least-Squared method.

3.2 Multivariate analysis

Statistical analyses have been carried out using an open source statistical software called R. In order to perform the data elaboration several statistical techniques have been used. First of all a multivariate regression approach, added also with autoregressive terms, has been computed, in order to be able predict the temperature monitored in some locations on the basis of the temperature recorded by the 3 monitoring thermocouples placed on the furnace walls. The final model equation, instead of trying to model at the same time the whole temperature trajectory making use also of autoregressive terms, have been split into 4 parts (Figure 6), in order to have a simpler and better performing set of functions.

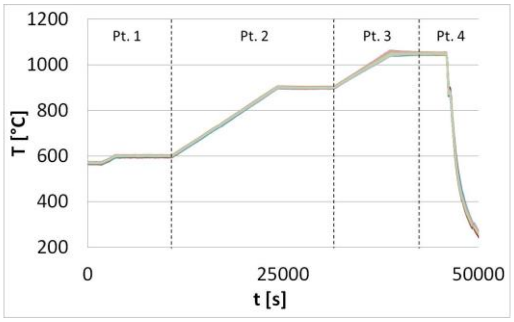


Figure 6. Process measured temperature splitting scheme.

The second step of the statistical elaboration concerned the evaluation of the temperature variance during the thermal process. To this aim a unsupervised multivariate analysis, Principal Components Analysis (PCA), has been performed. PCA, as reported by Einax et al. [5], is an unsupervised method, which enables various underlying components to be spotted, which are responsible for the covariation of the observed variables. PCA linearly transforms an original set of variables into a set of uncorrelated new variables (components), which represents all the variance (information) of the original dataset. In order to choose the appropriate number of components, a frequently chosen tool is the Scree Test Criterion [6], which retains the factors placed before the change in slope. For each sample, it is possible to compute a score that depends on the components calculated. The components, also called loadings, in this case have been used to analyze the correlation between the thermal probes and the variance associated to the whole system.

4. Validation of numerical tools

Some analyses have been preliminary carried-out in order to validate both autoregressive numerical and FE models by comparison to experimental data. Multivariate linear regression confirms a strong relationship between the monitored temperature by the 3 thermocouples and the temperature actually existing inside the furnace. Of course each thermocouple is not able to exactly sample the real temperature but from their readings it is possible to correctly infer the temperature of the inner space of the furnace itself.

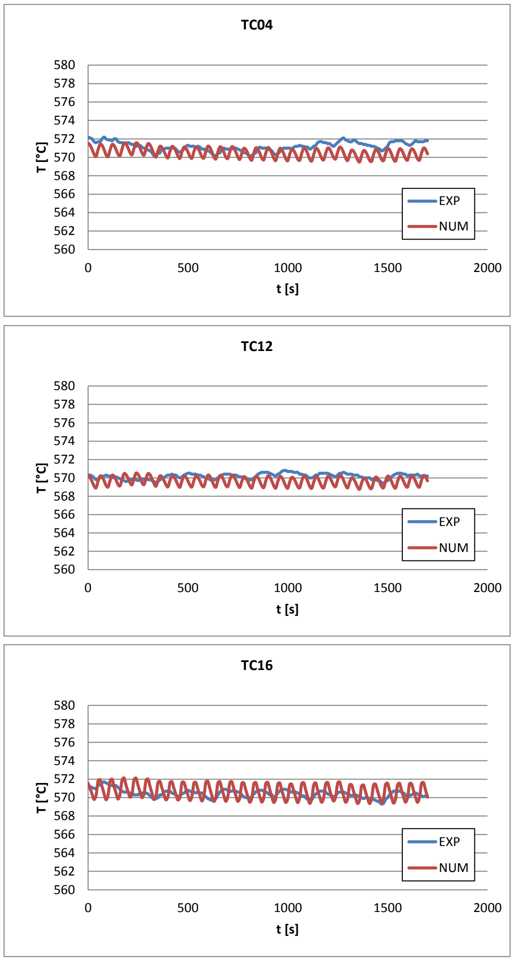


Figure 7. Comparison between experimental and numerical time evolution of temperature at several locations inside the chamber.

On the other hand, the PCA reveal a partial inhomogeneity of the temperature inside the furnace due to burners operative conditions. Such analyses, that have been preliminary carried-out in order to validate both FE and the statistical models, have been checked against experimental data. These computations are done by applying a periodic thermal flux as thermal input to the furnace chamber in the FE model, that simulates the real controlled ON/OFF working conditions for burners. An extract of validation evidence for FE model is reported in Figure 7, where time evolution of temperature numerically computed at some of probes locations are reported in combination to acquired data.

5. Results

Once validated, numerical models have been exploited to assess the influence of several functional parameters on the furnace performance. The envelope thermal resistance has been firstly analysed. Figure 8 shows the influence of the insulating layer thermal conductivity on the temperature profile along a longitudinal axis of the furnace. Temperature gap evaluated with respect to the mean temperature along this axis is also reported in Figure 9.

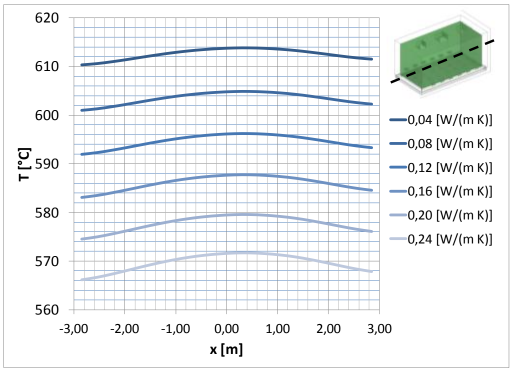


Figure 8. Temperature profile along x-axis as a function of the insulating layer thermal conductivity .

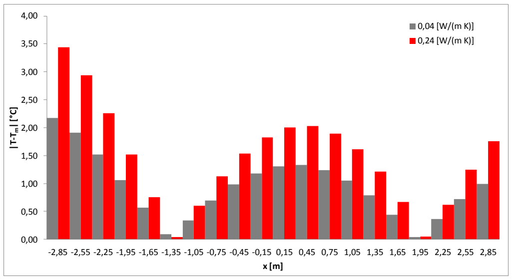
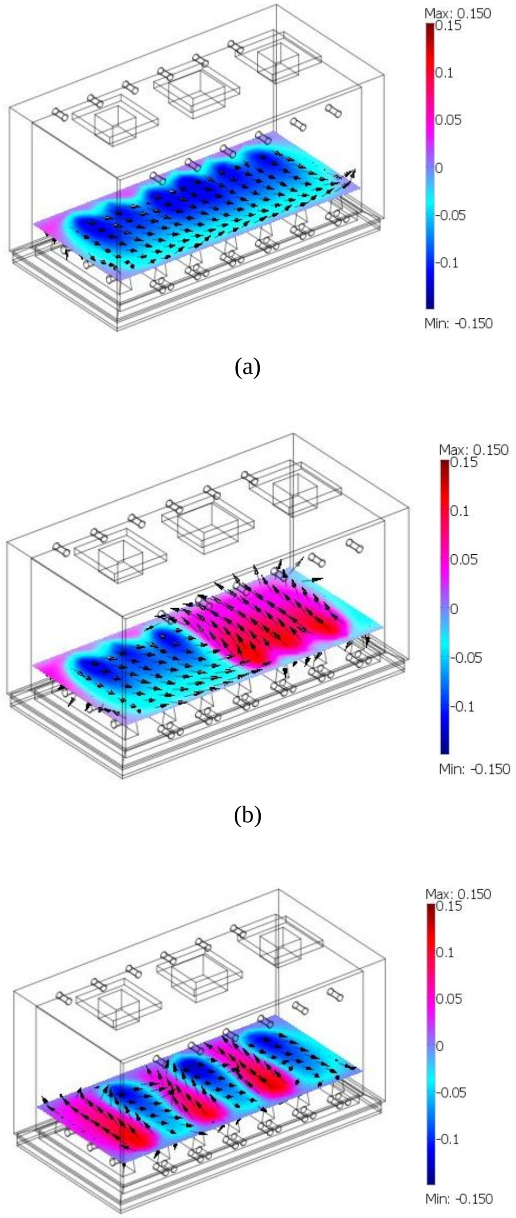


Figure 9. Temperature gap with respect to the mean temperature along the x-axis for chosen thermal conductivity values.

Influence of burners position on internal thermal field has been investigated also. Figure 10 presents the transversal (y-component) velocity fields in an horizontal section of the furnace obtained for alternative burners layouts.



(a)

(b)

(c)

Figure 10. Transversal component of velocity vectors and velocity vector in an horizontal slice of the furnace obtained for several burners layout: MOD_01 (a), MOD_02 (b), MOD_03 (c).

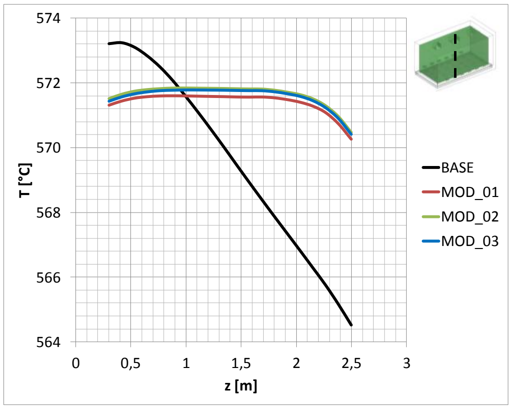


Figure 11. Temperature profile along z-axis for several burners layout .

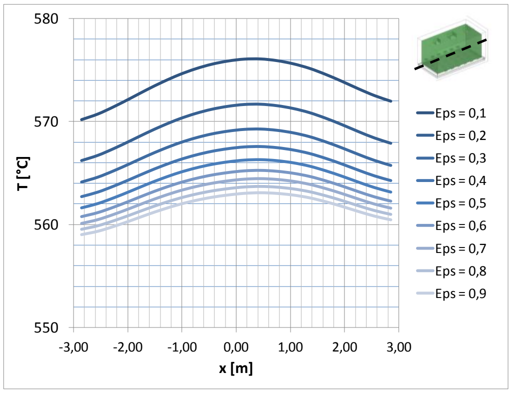


Figure 12. Temperature gap with respect to the mean temperature along the x-axis for chosen thermal conductivity values.

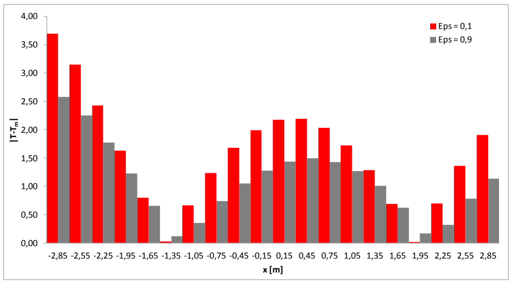


Figure 13. Temperature gap with respect to the mean temperature along the z-axis for chosen internal surface emissivity values.

Figure 11 shows the influence of the burners layout on the temperature profile along a vertical axis of the furnace. Temperature distribution appears much more homogeneous referring to the original layout. Influence of thermal emissivity of the internal furnace surface is finally analysed by the FE model. Results are mainly presented in Figure 12, where temperature profile along the x-axis is reported for the parametric analysis carried-out. Temperature gap evaluated with respect to the mean temperature along this axis is also reported in Figure 13.

6. Conclusion

An integrated experimental and numerical approach has been exploited in order to assess influence of several geometrical and functional parameters on the internal thermal distribution inside an industrial furnace. Experimental acquisitions have been used in order to validate FE models as well as input data for statistical analyses based on multivariate regression and unsupervised methods. Analyses allowed to analyze the correlation between the thermal probes and the variance associated to the whole system. Parametrical analyses simulating several working configurations of the device have been carried-out, highlighting optimization criteria related to some design parameters in order to obtain the most homogeneous thermal distribution inside the furnace.

8. References

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9. Acknowledgements

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