International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2013): 4.438

Modelling of An Industrial Blast Furnance Using Finite Element Method

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Abstract: ***Approximately 75% of energy consumption in petrochemical and refining industries is used by furnaces and heaters. Ambient air conditions (pressure, temperature and relative humidity) and operational conditions such as combustion air preheating and using excess air for combustion, can affect the furnace efficiency. If the furnaces are operated at optimized conditions, the huge amounts of savings in energy consumptions would be achieved. By modeling and optimizing of a furnace the optimal operation conditions can be obtained. The aim of this paper is providing a mathematical model which is able to calculate furnace efficiency with change in operating and combustion air conditions. In our project we deal with a simple but realistic optimization problem. We have to find the optimal temperature of an industrial furnace in which are made resin pieces, such as car bumpers. The heating system is based on electric resistances, and the first part of this study is to compute the temperature field inside the oven when the values of the resistances are known. This work is called the direct problem: the resistances' values are known and the temperature field is unknown. It is important here to emphasize that the mechanical properties of the bumper depend on the temperature during the cooking; so the second part of the study is devoted to computing the resistances' values in order to maintain the bumper temperature at the "good" value. This optimization problem is called an inverse problem: the temperature is an input and the resistances values are outputs. The computation of the temperature field is performed with the finite element method.***

Keywords: Finite element method , resistance temperature detection , coarse analysis , mesh analysis , thermal engineering

1. Introduction

Heat transfer is involved in almost every kind of physical process, and in fact it can be the limiting factor for many processes. Lately, the modeling of heat transfer effects inside industrial furnaces has started drawing attention of many more investigators as a result of the demand for energy conservation through efficiency improvement and for lower pollutant emissions. It also has become ever more important in the design of the products itself in many areas such as the electronics, automotive, machinery and equipment manufacturing industries. Both experimental work and numerical analysis through mathematical models has proven to be effective in accelerating the understanding of complex problems as well as helping decrease the development costs for new processes. In the past, only large companies could afford the cost of sophisticated heat transfer modeling tools, therefore the savings in large production runs justified the costs in specialized engineers and computer software. Nowadays, modeling has become an essential element of research and development for many industrial, and realistic models of complex three dimensional structure of the furnace are feasible on a personal computer.

A heat treatment furnace is a manufacturing process to control the mechanical and physical properties of metallic components. It involves furnace control, turbulent flow, conduction within the load, convection and thermal radiation simultaneously. The thermal history of each part and the temperature distribution in the whole load are critical for the final microstructure and the mechanical properties of workpieces and can directly determined the final quality of parts in terms of hardness, toughness and resistance. To achieve higher treatment efficiency, the major influencing factors such as the design of the furnace, the location of the work pieces, thermal schedule and position of the burners should be understood thoroughly.

The damage to the global environment and the prospective depletion of essential resources caused by growing human activity constitute a dual challenge that calls for coordinated measures by multilateral organizations such as ADEME, French Environment and Energy Management Agency. This is an industrial and commercial public agency, under the joint supervision of French Ministries for Ecology, Sustainable Development and Spatial Planning (MEDAD) and for Higher Education and Research with a mission to encourage, supervises, coordinate, facilitate and undertake operations aiming in protecting the environment and managing energy.

Since simulation of the heating up process of work pieces in heat treatment furnaces is of great importance for the prediction and control of the ultimate microstructure of the work pieces but specially the reduction of both energy consumption and pollutant emissions, this agency supports our research program and encourages all players and partners in this project to save energy, particularly sectors that consume high quantities of energy on daily basis.Heat transfer is involved in almost every kind of physical process, and in fact it can be the limiting factor for many processes. Lately, the modeling of heat transfer effects inside industrial furnaces has started drawing attention of many more investigators as a result of the demand for energy conservation through efficiency improvement and for lower pollutant emissions. It also has become ever more important in the design of the products itself in many areas such as the electronics, automotive, machinery and equipment manufacturing industries. Both experimental work and numerical analysis through mathematical models has proven to be effective in accelerating the understanding of complex problems as well as helping decrease the development costs for new processes. In the past, only large companies could afford the cost of sophisticated heat transfer modeling tools, therefore the savings in large production runs justified the costs in specialized engineers and computer software. Nowadays, modeling has become an essential element of research and development for many industrial, and realistic models of complex three dimensional structure of the furnace are feasible on a personal computer.

2. Finite Element Discretization

As mentioned previously, the major factor to be considered in the working of a furnace is the heat transfer by all the modes, which occur simultaneously. To either study a new furnace or to optimize the heating process in existing ones, the heat transfer in the furnace has to be modeled in the same way of a real situation as closely as possible. Given the geometry of the furnace, different boundary conditions along the furnace length, gas composition and properties and other complexities, an analytical solution in not feasible and computational modeling has to be resorted to. Over the last 20 years, the CFD (Computational Fluid Dynamics) has gained its reputation of being an efficient tool in identifying and solving such problems. Modeling the heating process involves solving coupled heat transfer equations. The tools used in this thesis are the Finite Element Method (FEM) and Computational Fluid Dynamics (CFD). This method is shown as an attractive way to solve the turbulent flow and heat transfer in the furnace chamber and it can be applied for a variety of furnace geometry and boundary conditions. The entire heat transfer process is a transient one, and iterations are necessary. The main process is detailed in the following flowchart:

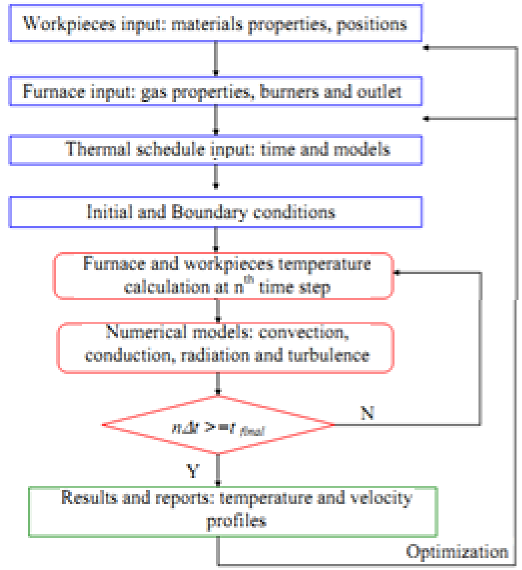

Figure 1: General flowchart for a heat treatment process

3. Numerical Solution and Results

In solving problem (11.11), the very first step is the mesh construction. Numerous packages are devoted to this work, and 2D meshes are easily created. See, for example the mesh displayed in Fig. 11.2(a) obtained with the INRIA code *emc2*. 1 There are altogether 304 triangles and 173 vertices. Another mesh, displayed in Fig. 11.2(b), was computed by the MATLAB "toolbox" PDE-tool, with 1392 triangles and 732 vertices. The mesh description, as provided by the code *emc2*, is summarized in the following list

1. Nbpt, Nbtri (two integers): number of vertices (points), number of triangles

1 http://www-rocq1.inria.fr/gamma/cdrom/www/emc2/eng.htm.

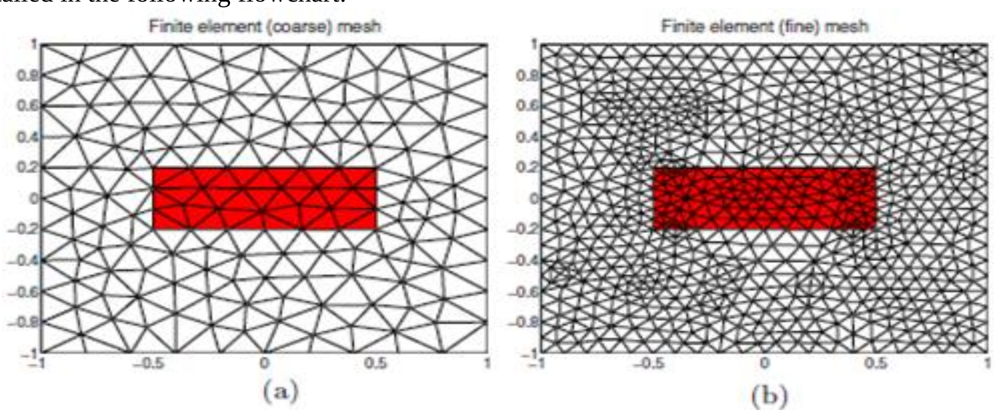

Figure 2: Mesh of the domain (a)Coarse (b) Fine

2. List of all vertices: for Ns=1,Nbpt
Ns, Coorpt[Ns,1], Coorpt[Ns,2] ,Refpt[Ns] (one integer, two reals, one integer): vertex number, coordinates, and boundary reference;

3. List of all triangles: for Nt=1,Nbtri,
Nt, Numtri[Nt,1:3], Reftri[N] (five integers): triangle number, three vertex numbers, and medium reference (air or resin).

4. Modify the linear system in order to take the boundary conditions into account. 2

5. Solve the resulting linear system.

6. Visualize the results, plot the isotherm curves.

Hint: Use the following algorithm to assemble *A* and *b*:
for K=1:Nbtri
(a) read data for triangle K
XY = coordinates of triangle K vertices
NUM = triangle K vertices numbers

(b) Compute element matrix AK(3,3) and right-hand side bK(3)
(c) Build global matrix A(Nbpt,Nbpt)
for i=1:3
for j=1:3
A(Num(i),Num(j))=A(Num(i),Num(j))+AK(i,j)

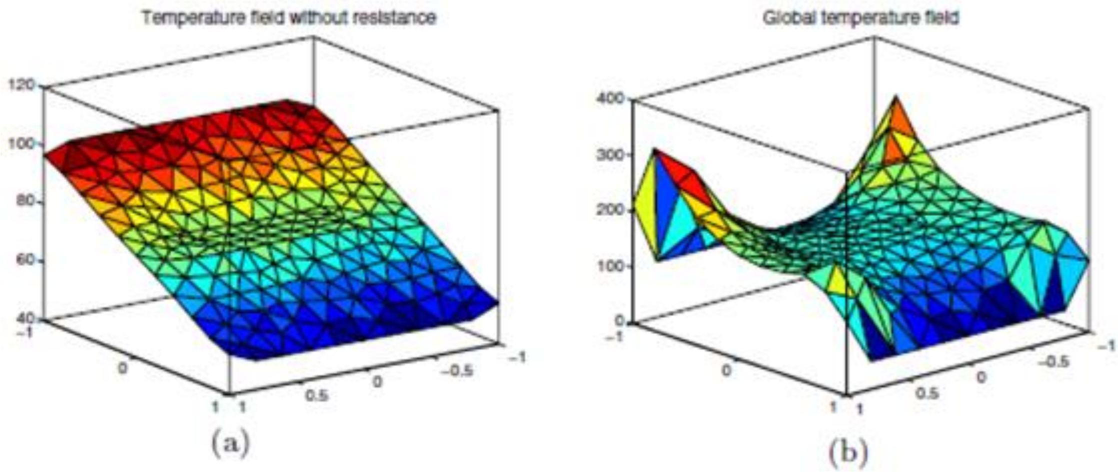

Figure 3: Temperature Field (a) Without Resistance (b) With Four Resistance

We have first to solve the *nwr*+1 direct problems in order to compute the temperature fields *T*0, *T*1, . . . ,*Tnwr*. They are obtained by the use of *nwr*+ 1 calls of the program written to solve the direct problem. Each computation corresponds to a distinct value of the data *TD*, *f*, and *F* (note that the localization of the resistances in the oven is a geometrical datum of great importance). The corresponding temperature fields are then stored in *nwr*+ 1 distinct arrays.\ Now we solve problem (11.1)–(11.2) without any heating term (F = 0), but with a temperature *TD* = 0 and thermal flux *f* = 0 given on the boundary. The solution of this problem is denoted by *T*0, and displayed in Fig. 11.3(a). We can see that the boundary conditions are well respected: temperature value is T = 100 when y = −1 and T = 50 when y = 1. The heat conductivity coefficient is set to the value c = 1 within the air and c = 10 within the object (air is a good insulation medium). The vanishing thermal flux on the other parts of the boundary corresponds to isotherm lines parallel to the normal vector when **x = −1 and x = 1**

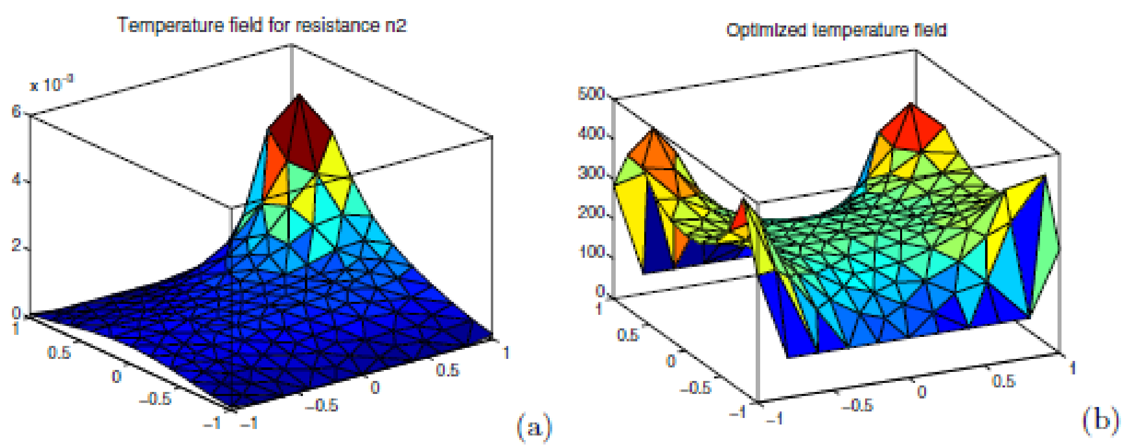

Figure 4: Temperature Fields (a) T2 (b) Optimized

Then we solve *nwr*successive problems (11.1)–(11.2) (one problem by resistance). Each case consists in computing the temperature field when only one resistance is heating the oven. The boundary conditions are temperature *TD* = 0 on $\partial\Omega D$ and thermal flux *f* = 0 on $\partial\Omega N$ for all cases. The *nv* components of array *Tk*represent the temperature field related to the *kth* V resistance. Figure 11.4(a) displays the temperature field associated with a single heating resistance. Note the tiny values of the temperature. We notice again that the boundary conditions are well satisfied: the temperature vanishes when $y = -1$ and $y = 1$ (Dirichlet condition), and the Neumann condition (null flux condition) leads to isotherm lines perpendicular to lines $x = -1$ and $x = 1$.

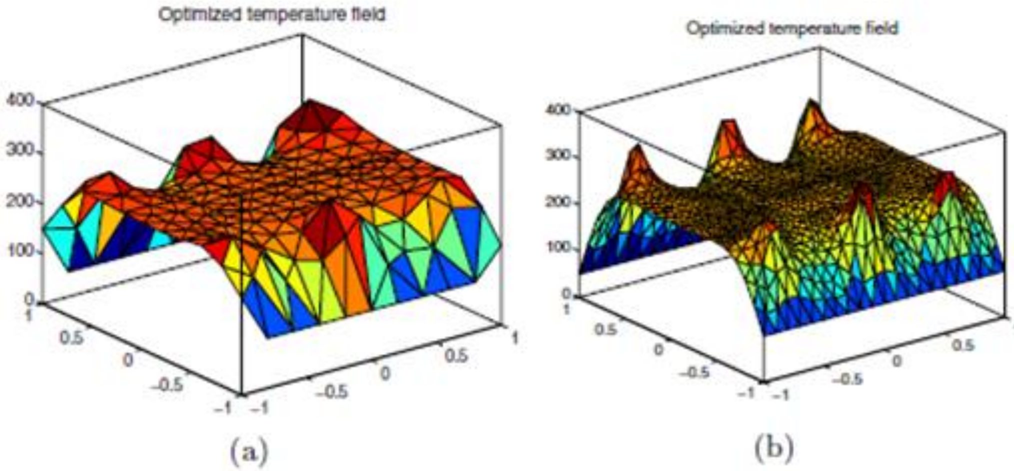

Figure 5: Optimized Temperature Field (a) Coarse (b) Fine

The file *THER oven ex1.m* contains the procedure THER oven ex1, which realizes the numerical experiment by defining the physical parameters of the problem (localization of the resistances, heat conductivity coefficients, boundary temperature values). It calls the procedure of the file *THERoven.m*, which computes the corresponding temperature field. The file *THER matrix dir.m*contains a procedure that builds the linear system arising from the heat equation problem. We notice that the right-hand side vanishes outside those elements that contain a resistance. The procedure of the file *THER local.m*builds the right-hand side for given resistances coordinates. The procedure contained in file *THER elim.m*takes the boundary conditions into account.

The file *THER oven ex2.m* contains the procedure THER oven ex2, which computes the resistances' values corresponding to the optimal temperature field. It calls the procedure of the file *THER matrix inv.m*computing matrix and right-hand side of the optimization problem. *Remark 11.4.*We also provide an interactive version of the solution of this project, allowing one to realize numerous numerical experiments by changing data through a graphical user interface. To launch the interface, just run the script *Main* from the subdirectory *interactive*

4. Conclusion

Finite element method is the most widely used method for optimization problems. As seen from the works of [1] that optimization could also lead to efficiency of the overall setup , an effort has been made by us in this research work to implement the concepts of FEM to a resistance and temperature problem of industrial furnace which is the heart of almost any industry . Also the above said method helped us learning the basics of Matlab and would increase our skill set.

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