

The „Gh.Asachi” Technical University of Iași

**EXPERIMENTAL AND CFD TECHNIQUES
FOR ENERGETIC OPTIMIZATION OF
ELECTRIC FURNACES BY MODIFYING
THE WORK SPACE GEOMETRY**

RESEARCH REPORT

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**The objectives and activities within the structure (II Annex) foreseen for the
unique stage of year 2007**

OBJECTIVES' NAME:

1. The establishment of a representative scientific method for studying the energetic optimization of electric furnaces.

ACTIVITIES' NAME:

1.1. The elaboration of an initial data base regarding the industrial applications of heat transfer processes. Intervention possibilities on the processes.

1.2. The critical analysis of intensifying the transfer processes and the establishment of research directions for electric furnaces.

1.3. The establishment of theoretic method for economic efficiency of thermal installations.

1.4. The team-work analyze of partial results at finalizing each objective

1.3. The determination of theoretical methods of economic efficiency of the heat installations

The theoretical methods of energetic efficiency are differentiated by heat installation specific. The main purpose is to reduce parking time of the charge in the installation therewith realizing the technologic objectives imposed by the process.

Hereinafter it will be emphasized some theoretical methods for energetic efficiency by presenting the physical-mathematical apparatus specific to chosen installation.

1.3.1. Particularities concerning the gas dynamics of electric resistors furnaces

Metals heating in the furnace are conditioned with the determination of metal heating time into a furnace with known basic characteristics. Heating time of the charge is main component of furnace function time and is traced in power consumption of the equipment.

The theoretic study of industrial furnaces gas dynamics used at theoretic determination of an optimum circulation of the air in the chamber for decreasing furnace function time. There are also obtained information regarding the dependency between the equipment walls temperature and the circulation speed of the air into work chamber.

Continuity equation

Continuity equation is a result of mass conservation law. For a moving gas with arbitrary speed distribution, this equation in pipe's section $i-i$ (fig.8.) is written such as:

$$\int_{A_i} \rho_i v \, dA = \text{const.} \quad (6)$$

Where index "i" specifies the section to which given sizes refer to. Because the speed distributions in pipe's section $i-i$ is not uniform in order to simplify the problem is introduced average speed of the current:

$$v = \int v \, dA / A = Q_v / A \quad \text{where } Q_v = \int v \, dA \quad (7)$$

with $Q_v =$ volume flow. So that relation (6) becomes:

$$\rho_1 v_1 A_1 = \rho_2 v_2 A_2 = \dots = \rho_i v_i A_i = \rho v A \quad (8)$$

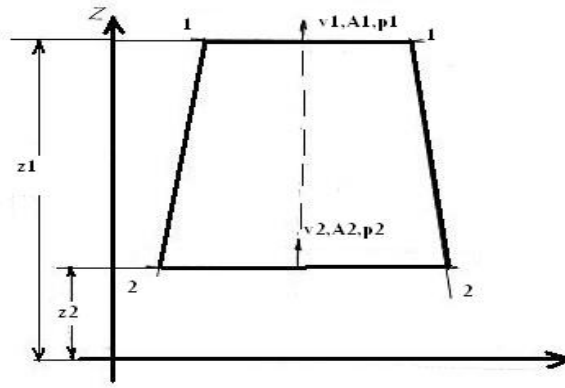


Figure 8. The appliance of continuity equation and energy equation in a i-i pipe's section

Under real conditions volume flow, gas current speed and its density depend on temperature, pressure and humidity after the laws:

$$Q_r = Q_{cn} \frac{T}{273} \frac{p_{cn}}{p_r} \left(1 + \frac{m}{0,804}\right); V_r = V_{cn} \frac{T}{273} \frac{p_{cn}}{p_r} \left(1 + \frac{m}{0,804}\right); \rho_r = (\rho_{cn} + m) \frac{273}{T} \frac{1}{\left(1 + \frac{m}{0,804}\right)} \frac{p_r}{p_{cn}} \quad (9)$$

In anterior relations Q_{cn} , v_{cn} , ρ_{cn} define volume flow, average speed, density of dried gas under normal conditions (0°C , $101,325 \text{ kPa}$, dried gas), Q_r , v_r , ρ_r volume flow, average speed and gas density under real conditions, m is content of water vapors in gas in kg/m^3 , and p_{cn} , p_r gas pressure under normal conditions in Pa, respectively real gas pressure in given section. As under the conditions imposed by the installation $m \approx 0$, anterior relations become:

$$Q_r = Q_{cn} \frac{T}{273} \frac{p_{cn}}{p_r} \quad v_r = v_{cn} \frac{T}{273} \frac{p_{cn}}{p_r} \quad \rho_r = \rho_{cn} \frac{273}{T} \frac{p_r}{p_{cn}} \quad (10)$$

Finally relation (8) is written:

$$\rho_r Q_r = \rho_{cn} Q_{cn} = \text{const.} \quad (11)$$

This means that under the installation imposed conditions only volume flow is dependent on temperature and pressure, mass flow is independent on these.

Power equation

In general case of a gas moving with non uniform speed and pressure in a section and supposing the existence of heat exchange and mechanical work with exterior, the corresponding equation of the energy per time unit is:

$$(p + \rho v^2/2 + \rho g z + \rho u) v dA = (p + \rho v^2/2 + \rho g z + \rho u) v dA + \Sigma N_l \quad (12)$$

where p defines static pressure in current point of the section $\rho v^2/2$ dynamic pressure, $\rho g z$ position pressure, with z = the altitude of section gravity center towards reference, ρu intern specific energy, ΣN_l Total loss on the part between sections 1-1 and 2-2, in W.

Static pressure, p , is constant in section even to a considerable non-uniformity of speed distribution and the variation of gas density in the section is neglected. So that instead of equation (12) it can be written down:

$$(\rho_1 z_1 g + p_1) v_1 A_1 + (\rho v^3 / 2) dA + u_1 \rho_1 v_1 A_1 = (\rho_2 z_2 g + p_2) v_2 A_2 + (\rho v^3 / 2) dA + u_2 \rho_2 v_2 A_2 + \Sigma N_1 \quad (13)$$

or considering the expression (4):

$$(\rho_1 z_1 g + p_1 + \alpha_1 \rho_1 v^3 / 2 + u_1 \rho_1) Q_1 = (\rho_2 z_2 g + p_2 + \alpha_2 \rho_2 v^3 / 2 + u_2 \rho_2) Q_2 + \Sigma N_1 \quad (14)$$

where we did the notations:

$$\alpha_1 = \frac{1}{A_1} \int_{A_1} \left(\frac{v}{v_1} \right)^3 dA, \quad \alpha_2 = \frac{1}{A_2} \int_{A_2} \left(\frac{v}{v_2} \right)^3 dA \quad (15)$$

Reporting equation (14) to mass flow Q_M , finally it is obtained:

$$z_1 g + p_1 / \rho_1 + \alpha_1 v^2 / 2 + u_1 = z_2 g + p_2 / \rho_2 + \alpha_2 v^2 / 2 + u_2 + \Sigma N_1 / Q_M \quad (16)$$

Balance equation

Combining (16) with (14) it results:

$$(u_1 - u_2) + g(z_1 - z_2) + \left(\frac{p_1}{\rho_1} - \frac{p_2}{\rho_2} \right) + \alpha_1 \frac{Q_M^2}{2\rho_1^2 A_1^2} \left(1 - \frac{\alpha_1 \rho_1^2 A_1^2}{\alpha_2 \rho_2^2 A_2^2} \right) = \frac{1}{Q_M} \Sigma N_1 \quad (17)$$

For applications in (17) it must be defined $z_1, z_2, p_1, p_2, \rho_1, \rho_2, A_1, A_2$ and α_1, α_2 . It is also necessary to be known power sources and power losses between the two sections of the channel.

If it is considered the installation from figure 9, temperature difference $\Delta T = T_f^{(1)} - T_f^{(2)}$ (see fig. 9) can determine using relation (17) under particular form:

$$\Delta Q = Q^{(1)} - Q^{(2)} \quad (18)$$

Indeed they will be differentiated only through the terms $\Sigma N_1 / Q_M$, source and loss terms, caused to the fact that regions 1 and 2 have the same characteristics. There are necessary supplementary hypotheses linked to gas transformation type. Thus, supposing that gas transformation in region 1 and 2 has the form:

$$p = a v^n, \quad a = \text{const.} \quad (19)$$

than molar heat corresponding to the process is get from first principle written under differential form:

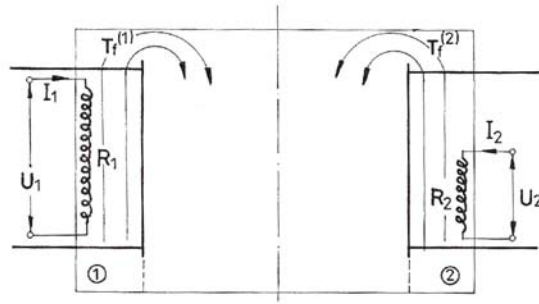


Figure 9. Thermal field of a furnace

$$dQ = \nu C dT = dU + dL = \nu C_v dT + p dV \quad (20)$$

Where I took in mind:

$$dU = \nu C_v dT, \quad dL = p dV \quad (21)$$

In anterior relations, ν represents moles number, C_v is molar heat at constant volume, U is internal power and L is mechanical work.

It successively results:

$$\nu (C - C_v) dT = p dV \quad (22)$$

$$\nu (C - C_v) dT = \nu R dT / (n+1) \quad (23)$$

which implies that:

$$C = C_v + \frac{R}{n+1} \quad (24)$$

In relation (23) I take into consideration that:

$$p \nu = \nu R T \quad (25)$$

or yet:

$$a \nu^{n+1} = \nu R T \quad (26)$$

where, through differentiation it results:

$$a (n+1) \nu^n d\nu = \nu R dT \quad (27)$$

So that,

$$Q = \nu C \Delta T = \nu \left(C_v + \frac{R}{n+1} \right) (T_f - T_i) \quad (28)$$

We particularize relation (28) for the two distinct regions of the furnace. Thus, for first region we will have:

$$Q^{(1)} = \nu \left(C_v + \frac{R}{n+1} \right) (T_f^{(1)} - T_i) = \eta R_1 I_1^2 t \quad (29)$$

And for second region:

$$Q^{(2)} = \nu \left(C_v + \frac{R}{n+1} \right) (T_f^{(2)} - T_i) = \eta R_2 I_2^2 t \quad (30)$$

Through subtraction it results:

$$\Delta Q = Q^{(1)} - Q^{(2)} = v \left(C_v + \frac{R}{n+1} \right) (T_f^{(1)} - T_f^{(2)}) = \eta (R_1 I_1^2 t - R_2 I_2^2 t) \quad (31)$$

So that temperature difference becomes:

$$\Delta T = T_f^{(1)} - T_f^{(2)} = \eta (R_1 I_1^2 t - R_2 I_2^2 t) / v \left(C_v + \frac{R}{n+1} \right) \quad (32)$$

Because $|n| < 1$ and $R_1 I_1^2 t > R_2 I_2^2 t$, then $T_f^{(1)} - T_f^{(2)} > 0$. Finally with $v = m/\mu$, the relation (32) becomes:

$$\Delta T = \eta \Delta P \mu / Q_M \left(C_v + \frac{R}{n+1} \right) \quad \Delta P = R_1 I_1^2 - R_2 I_2^2 \quad (33)$$

So, the temperature difference that appears into a furnace with constant section is directly proportional with efficiency η , the power differences on the two circuits Δp , gas molar mass from the furnace μ , and it is inverse proportional with mass flow and molar heat $C = C_v + \frac{R}{n+1}$.

Using definition relation of mass flow,

$$Q_M = \rho v A \quad (34)$$

Where ρ is air density at work temperature, v is air speed between panel land wall, and A is the surface through which air flows. Taking into consideration relation (10) and the fact that it is considered constant the air pressure in the chamber it results:

$$Q_M = \rho_{cn} \frac{273}{T_f^{(1)}} v_1 A = \rho_{cn} \frac{273}{T_f^{(2)}} v_2 A \quad (35)$$

Where $T_f^{(1),(2)}$ and $v_{1,2}$ are temperatures respectively speeds on the (1) or (2) wall.

Under these conditions relation (33), taking into account (35) becomes:

$$\Delta T = \frac{\eta \Delta P \mu}{C_v + \frac{R}{n+1}} \cdot \frac{T_f^{(1)}}{\rho_{cn} 273 v_1 L} \cdot \frac{1}{x} \quad (36)$$

where $A = L x$ and L is the width of radiant panel.

This relation represents the variation of temperature difference between walls according to panels position expressed through the distance x between the panel and the wall.

1.3.2. Particularities regarding the heating simulation of electric resistors furnaces

SIMTHERM2D was accomplished by the Center for Energy and Processes by Mines School from Paris. Simtherm is a tool for bi-dimensional modeling (x-y or r-z) of thermal convection, linear or not, in steady or in variable state.

The system is described as a set of defined objects by their geometry, internal solicitations and limit conditions. The special digitization of partial derivate equations is performed by quadrilateral finite elements. The obtained differential system is solved by the method of finite elements using an implicit scheme.

The modeling permits to obtain a temperature graphic in dynamic state as a function of thermal-physical properties and solicitations varying along time.

Simtherm2D system is composed of an assembly of basic objects represented by one of the following geometries: Rectangle, Disc, Annular space, any quadrangle.

The object is described relatively to a local reference mark defined at the same time as the object by the position of its origin and its rotation to the global reference mark. Global transformations can be applied to one or several objects at the same time.

Application domain:

SIMTHERM2D can be used in numerous applications requiring thermal analysis of a 2D system such as: furnaces, industrial processes, vehicles, Aérospatiale.

THERMETTE is a modeling environment of thermal systems described as networks of 0D components (volumes of uniform temperature) and 1D components (branches where heat transfer is performed usually at isothermal surfaces).

Non linear problems can be simulated both in steady and dynamic state.

Because THERMETTE is simple, it can be used as solver for more sophisticated applications.

More than that it permits the quickly obtain of a magnitude order of heat fluxes of a system (conduction, convection, radiation) by the application of some known equations and correlations.

VisSim is a block diagram language for creating complex nonlinear dynamic systems. Its fast execution speed is perfect for model based operator training, off-line controller tuning and hardware in loop testing. Its efficient C code generator makes it a great platform for model based embedded system development. By combining the simplicity and clarity of a block diagram interface with a high-performance mathematical engine, VisSim provides fast and exact solutions for linear, nonlinear, continuous time, discrete time, SISO, MIMO, multi-rate and hybrid systems. Moreover, VisSim's tightly integrated development platform makes it easy to pass freely between model construction, simulation, optimization and validation. This means you can create virtual prototypes on your desktop PC and make sure they are working properly before committing to the design. VisSim offers a comprehensive set of companion products targeted at linearization and frequency domain analysis, C code generation, communications system modeling, DSP and embedded system design, neural network simulation and real-time data I/O. Thousands of engineers and scientists spanning a broad range of industries and disciplines are using VisSim to speed their projects.

CHARACTERISTICS:

- Block diagram construction
- 110 linear and nonlinear blocks
- toolbox functions for control, electromechanical design, hydraulics, signal processing, process, chemical, thermal and turbines
- Euler, trapezoidal, Runge Kutta 2nd and 4th orders, adaptive Bulirsh-Stoer and Runge Kutta 5th order, stiff backward Euler and Lawrence Livermore integration algorithms.
- Matlab, Mathcad and Maple integration
- Triggered compound blocks
- „What-if” scenarios
- Parameter optimization
- Matrix constant construction
- Complex number support
- Implicit system solvers
- ActiveX support
- Vector and matrix operations
- Browser
- Tutor
- Embedded sub-diagrams with editing
- Automatic wiring and wire checking
- Goto tags
- spectrum display
- Interactive XY, time domain, FFT and discrete plots and strip charts
- audio and visual alarms
- Read and write audio data
- Integrated VisSim Viewer

FLUENT is the most performing program of numerical simulation of the flows and CFD software considered to be the appropriate solver for analysis and simulation of fluids dynamics, used for complex flows in incompressible regimes (subsonic), easily compressible (transonic) and strongly compressible (supersonic and hypersonic). It is due to an impressive gamma of options combined with numeric algorithms for stability and rapid convergence. FLUENT offers optimum and accurate efficiency for a varied flows domain. The multitude of physical models from FLLUENT permit the modelation and simulation of laminar and turbulent flows, heat transfer, chemical reactions,

multiphase flows and other phenomena, with a total flexibility towards digitization scale also offering the possibility of its adjustment based on an intermediary solution.

Simulation general capabilities:

- Two dimensional flows (plane or axial-symmetric) and three-dimensional
- Stationary or non-stationary flows
- All speed regimes (subsonic, transonic, supersonic and hypersonic)
- Laminar, transient and vortex flows
- Newtonian or non-Newtonian flows
- Complete scale of turbulence including: k-epsilon, k-omega, RSM, DES and LES
- Heat transfer (convection, conjugate, radiation <including solar radiations>)
- Mixtures and chemical reactions including combustion patterns, deposition/reaction on surfaces
- Models of free surface and for multiphase flows with heat transfer and chemical reactions
- LaGrange Calculus of disperse phase of trajectories (particles/drops/bubbles) coupled with continuous phase and jets models and liquid films.
- Models for applications with phase exchange (melting/solidification) cavitations and humid vapor
- Porous mediums with no isotropic permeability, inertial resistance, thermal conduction in solid and the option of speed calculi in interstices.
- Deflecting grids for flows modeling around the objects in relative move
- Reference inertial or non inertial systems
- Class of aero acoustic models
- Possibility to define volumetric sources of mass, impulse, energy and chemical species
- Data base for materials
- Additional modules: combustion cells, magneto-hydrodynamics, simulation of continuous fibers
- Functions defined by user

Numeric methods:

- Three solvers: implicit segregate, implicit coupled and explicit coupled that use finite volume method based on completely unstructured grids; time advance with adaptive step for implicit formulas; dynamic allocation, simple and double precision executables.
- Solver segregate: algorithms type SIMPLE, SIMPLEC, PISO; digitization schemes for convective terms: order I, order II, QUICK, MUSCL, with centered differences (for LES); temporal digitization schemes of I and II order; multiple schemes for pressure interpolation, including: PRESTO, linear, II order, inertial; implicit treatment for inertial forces; solver algebra multi-grid

linear with cycles V, W, F, flexible and Gauss-Siedel relax method; option for non-stationary non-iterative calculus.

- Coupled Solver preconditioning for incompressible flow regimes and mixed; coupled solutions for all main variables; decoupled solutions (segregate) for turbulence, radiation and transport equations defined by user; digitization schemes: I order, II order, MUSCL and II order LDF; implicit schemes of I order and II order for temporal digitization.
- Explicit Solver; time advanced algorithm type Runge-Kutta; multi-grid FAS method, local time step and softening of the residuum to accelerate convergence; advance algorithm in explicit global time for non stationary high precision solutions.
- Implicit Solver: complete linearization type Newton of all fluxes and source terms; solver algebra linear multi-grid with cycles V and F; Gauss-Siedel relax method.

Turbulence simulation:

- Spalart-Allmaras model; k- ϵ models (standard, feasible and RNG) with sub models for natural convection effect, compressible, small numbers Reynolds
- k- ω models with correctness for shear stresses and options for transitional flows
- Reynolds Stress Model (RSM) complete, with sub models; Model Detached Eddy Simulation (DES)
- Model Large Eddy Simulation (LES): turbulence for small vortexes (Smagorinsky-Lilly and WALE); dynamic models (Smagorinsky-Lilly dynamic and model of kinetic turbulent energy transport); wall functions Werner-Wengle
- V2F turbulence model (needs separate license)
- Options for simulation near the walls: standard functions of wall; sensitive wall functions in pressure gradient; Enhanced Wall Treatment model (EWT)
- The simulation of fixed laminar-turbulent transition through lamination zones defined by user
- Possibilities of modifying all the constants of the models, turbulent viscosities and of small vortexes and source terms from transport equations.

The simulation of heat transfer: laminar/turbulent forced convection including viscous heat; Natural and mixed convection with the option of using Bussinesq approximation; Conjugate heat transfer (fluid/solid) with iso/anisotropic conductivity in solid including conduction in thin walls and thermal convection in solid in relative move; Coupling with radiation transport, disperse phases and chemical species.

Heat transfer through radiation: DO model (Discrete Ordinates); DTRM model (Discrete Transfer Radiation Model); P-1 radiation model; Rosseland model; solar radiation model; radiant heat transfer for particles/drops (P-1, DO)

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