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NUMERICAL SIMULATIONS IN DESIGN AND OPTIMIZATION OF ELEMENTS OF EXPERIMENTAL INSTALLATION OF REGENERATIVE BURNERS FOR TUNDISH PREHEATING IN STEEL PLANT US STEEL-SARTID SMEDEREVO

PRIMENA NUMERIČKIH SIMULACIJA U KONSTRUISANJU I OPTIMIZACIJI ELEMENATA EKSPERIMENTALNOG POSTROJENJA REGENERATIVNIH GORIONIKA ZA ZAGREVANJE MEĐULONACA ZA LIVENJE ČELIKA U ČELIČANI US STEEL-SARTID SMEDEREVO

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ABSTRACT

An experimental installation of regenerative burners consists of two regenerative Pebble-bed heaters (PH), one fluid - dynamical valve (FDV), two burners, one fan for flue gas exhaust and one fan for combustion air supply. Experimental installation will be situated at stand for tundish preheating in US Steel Serbia d.o.o. Steel factory. The purpose of this facility is to reduce natural gas as fuel consumption at half of current (200-250 m^3/h at p=101325 Pa, T=273,15 K) by using high-preheated air for combustion.

Design optimization of fluid-dynamical valve and optimization of position of burner heads and off-gas exit at tundish top cover by application of StarCD software for numerical simulation was performed. New tundish is 1,9 times higher capacity (26,5 t) than old one.

Input parameters for numerical simulation and design optimization of fluid-dynamical valve are pressure difference between two inlet streams – high-preheated air and off-gas, and pressure value at outlet of high-preheated air. 3D model was made on basis of real valve geometry and consists of 177744 cells (control volumes). The result of numerical calculation and optimization procedure of FDV is optimal geometry definition, lowest pressure drop through the FDV and least value of two streams (high-preheated air and off-gas) mixing coefficient. 3D model of tundish and its top cover consists of 300195 control volumes. Optimization of position for burner heads and off-gas exhaust at tundish top cover brought uniform temperature field at inside of tundish refractory layer during transient process of preheating with minimal fuel consumption.

Key words: Numerical simulation, StarCD, regenerative burners, Pebble-bed technology, fluid-dynamical valve, tundish, high-preheated combustion air, reducing fuel consumption, design optimization, transient heating process.

IZVOD

Eksperimentalno postrojenje regenerativnih gorionika sastoji se od dva regenerativna zagrejača zasnovana na pebble-bed tehnologiji (PH), fluido-dinamičkog ventila (FDV), dva gorionika, ventilatora za otsisavanje dimnih gasova i ventilatora za snabdevanje postrojenja vazduhom za sagorevanje. Eksperimentalna instalacija će biti postavljena na stendu za zagrevanje međulonaca za livenje čelika u čeličani US Steel Serbia d.o.o. Namena ovog postrojenja je da se korišćenjem visokopredgrejanog vazduha za sagorevanje (t>1000 °C) smanji potrošnja gasovitog goriva na polovinu sadašnje, koja iznosi 200 - 250 m^3/h (na uslovima p=101325 Pa, T=273,15 K).

Primenom programa za numeričke simulacije StarCD izvršeno je definisanje i optimizacija geometrije fluido-dinamičkog ventila i optimizacija položaja otvora za gorionike i otvora za otsisavanje dimnih gasova na poklopcu novog međulonaca za livenje čelika.Novi međulonac je 1,9 puta veće zapremine i njegov kapacitet iznosi 26,5 t čelika.

Polazni parametri za numeričku simulaciju i optimizaciju geometrije fluido-dinamičkog ventila bila je razlika pritisaka ulaznih struja visoko-predgrejanog vazduha i dimnih gasova i potrebna vrednosti pritiska izlazne struje iz FDV visoko-predgrejanog vazduha. Trodimenzionalni model je definisan na osnovu realne geometrije ventila i sadrži 177744 ćelija (kontrolnih zapremina). Definisanje karakterističnih dimenzija FDV uz najmanji pad pritiska pri prolasku fluidnih struja i zadat procenat (odnos) mešanja struje vazduha i dimnih gasova predstavlja rezultat optimizacije geometrije FDV. Trodimenzionalni model novog međulonca i poklopca sastoji se od od 300195 kontrolnih zapremina. Optimizacijom položaja otvora za gorionike i otsis produkata sagorevanja na poklopcu međulonca kapaciteta 26,5 t čelika dobijeno je ravnomerno polje temperatura na unutrašnjem ozidu međulonca u definisanom vremenskom intervalu nestacionarnog zagrevanja uz prepolovljenu potrošnju goriva od 100 m^3/h, pri čemu je vreme i režim zagrevanja međulonca ostao nepromenjen.

Ključne reči: numerička simulacija, StarCD, regenerativni gorionici, Pebble-bed tehnologija, fluido-dinamički ventil, međulonac, visokopredgrejan vazduh za sagorevanje, smanjenje potrošnje goriva, optimizacija geometrije, nestacionarno zagrevanje.

INTRODUCTION

Fuel consumption in energy intensive high temperature processes takes important part in cost summary of whole process. In following paper, the procedure used in geometry optimisation for specific parts of experimental instalation of regenerative burner system will be presented, in order to reduce fuel consupmtion and to obtain more efficient tundish preheating process. The research work performed here is part of INCO Copernicus Project: "Reducing fuel consumption and air pollution of industrial furnaces by high efficiency pebble'heaters and fluid-dynamical valve", Contract Number: ICA2-CT-2002-10004. The experimental instalation and measurements will be set and performed in steel plant US Steel Sartid Smederevo. In present state, process of tundish preheating is irregular and unefficient with average fuel consumption of 200-250 m^3/h (at p=101325 Pa, T=273,15 K). The purpose of installation of regenerative burners is to utilize waste heat of exhaust gases from tundish and to return it to the combustion process via high-preheated combustion air. Expected result is to reduce fuel consumption (over 50 %) as well as the amount of CO_2 emitted in the atmosphere.

In optimisation procedure it has been used computational fluid dynamic code StarCD for numerical calculations. This method is very efficient in solving such a problems (geometry optimization) since the virtual models could be significantly changed and explored the consequences of such action without real model experiments. Depending on complexity of model optimization, procedure could be quick and also low money demanding.

Further work on all necessary simulations is going to be completed in the future in the Simulation Laboratory at Faculty of Mechanical Engineering, University of Belgrade.

EXPERIMENTAL INSTALLATION OF REGENERATIVE BURNERS

An experimental instalation of regenerative burners consists of two compact Pebble-Heaters (PH), a Fluid - Dynamical Valve (FDV) for the switching between two hot gas streams, and auxiliary equipment - one fan for off-gas exhaust, one fan for combustion air supply, piping, two burners, measuring and regulation devices.

"Pebble-Heater" is a common name for regenerators filled with bulk material mostly of a spherical shape (pebbles). The state-of-the-art design has a vertical column of pebbles through which gas flows axially. The problems connected with such designs (such as channeling, wall heat losses, pressure drop, scaling problems and inhomogeneous temperature field) are also well known in technical practice.

A new concept of the Pebble-Heater has been developed at ATZ-EVUS, Development Center for Process Technology from Germany. The main difference is in the flow direction: gas flows radially through the pebble-bed, which is fixed between two coaxial cylindrical grids. The inner grid, the so-called hot-grid, is made of porous ceramic bricks. The outer grid, referred to as cold grid, is made of a gas permeable steel construction (e.g. perforated steel plate). All other extraordinary characteristics result from that, at first sight, small difference. Higher flow velocity and/or smaller pebble diameters may be used, as there is no danger of fluidization. That provides a very high specific surface (or surface to volume ratio) and consequently an excellent heat transfer.

That results in a high thermal efficiency (units with more than 98% are in operation) and a temperature gradient in the range of 1500 – 2000 K/m. The pebble-bed does not have to be thick in radial direction, so that the pressure drop is also low. At the end, it leads to a very compact unit at low investment costs. The new technology has been developed primarily to substitute the technology of hot wind stoves (Cowpers) for supplying blast furnaces with hot blast *(Brotzmann & Stevanović, 1998)*. With those characteristics PH is very attractive for combustion air preheating in the scope of a regenerative burner system [2].

The Pebble Heaters in experimental installation have been designed for 2,000 m^3/h (p=101325 Pa, T=273,15 K) and 1200 °C, using the PBH-code developed previously by ATZ-EVUS, Germany.

The main dimensions are:

- inside diameter of hot grid 300 mm
- outside diameter of hot grid 400 mm
- cold grid diameter 754 mm
- pebble-bed thickness 177 mm
- outer shell diameter 790 mm
- active height of the hot grid 750 mm
- height of the cold grid 1015 mm
- total height of the outer shell 1200 mm

Important part of installation of regenerative burners is FDV. The usage of FDV makes it possible to achieve a rapid switching between two hot gas steams (above 1000 °C) without movable mechanical parts. The principle is based on interaction between velocity and pressure field in fluid channels of FDV. With a suitable design of flow ducts it is possible to increase the velocity and to decrease pressure and vice versa at certain parts of FDV so that two hot gas streams flow in different directions without considerably mixing. FDV operates faster and more reliably (without movable mechanical parts at high temperature) and it is has simpler design and it is much cheaper that conventional switching valve at hot gas streams side [2].

The facility is very compact due to the very short switching time – designed value is 1 min. The pebble-bed is consisted of alumna pebbles (resistant at high temperatures), mean diameter 4,5 mm, supplied by Alcoa. The hot grid is brick-layered of honeycombs, made of mulite and supplied by Rauschert GmbH. Each brick has originally dimensions 150 x 150 x 50 mm. The cold grid is manufactured from perforated steel with horizontal slots. Figures 1 and 2 show view of the separate system of two PH and experimental installation of regenerative burners at stand for tundish preheating in steel plant.

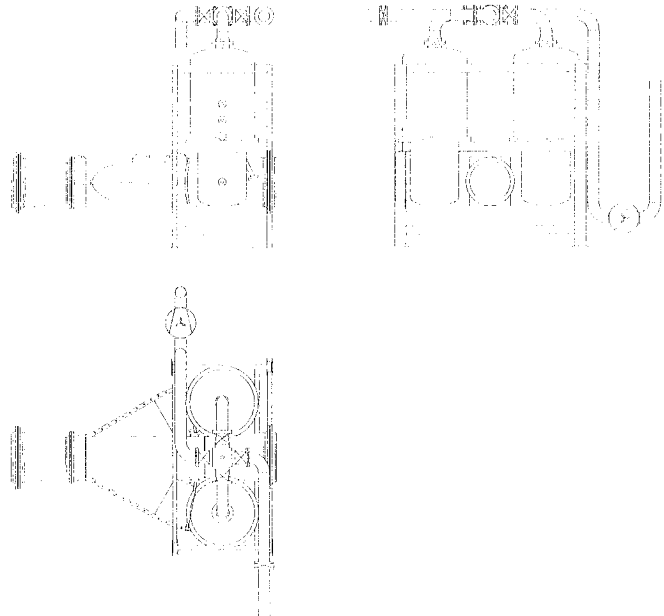

Figure 1 - View of two PH connected with FDV [1]

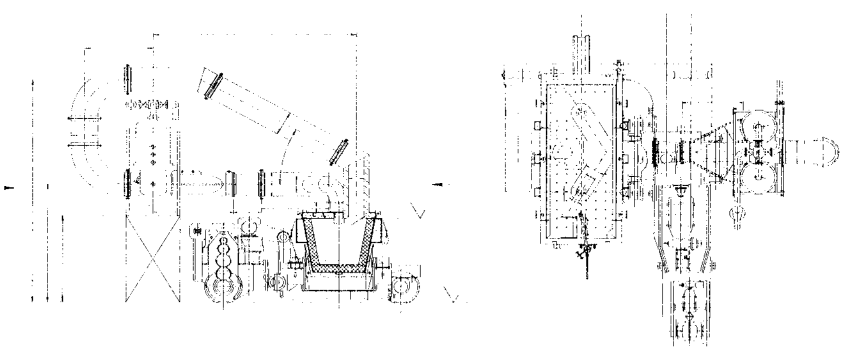

Figure 2 - View experimental installation of regenerative burners connected to the stand for tundish preheating in steel plant [1]

OPTIMISATION PROCEDURE AND RESULTS

Design and Optimisation of the FDV and Tundish Top Cover

The design and optimisation of the FDV and tundish top cover has been done using numerical CFD code StarCD. A steady state and transient 3D models were used. Due to simplification, a rectangular cross section of all flow channels of FDV has been adopted, although some of them are circular in the reality. Some previous experience has shown that such approach is justified due to significantly faster geometry modelling in pre-processing and small deviations from the real conditions. The simulation of transient heating of tundish with optimised top cover geometry and position of burner heads and off-gas exhaust has been performed using real geometry of tundish without any simplification.

The basic characteristics of the simulation model are given in Table 1 and 2. Tables 3 and 4 show parameters used in numerical simulation for optimisation of FDV and tundish top cover geometry. As it could be seen, most of the parameters for both models are equal. Radiation model coupled with conjugate heat transfer has been used for numerical simulation and optimisation of top cover geometry (both steady state and transient solution method with solution algorithm - Simple and Pisco respectively). The solution method for FDV design optimisation was only steady state (Simple solution algorithm) and the radiation model has been omitted.

Relaxation factor for pressure has to be kept low - 0,15 due to the sensitivity of solution and for other variables, relaxation factor was kept in range 0,5 to 1. Upwind (UD) and MARS differencing scheme has been used for model solving.

Table 1 - Characteristic parameters in numerical modelling and design optimization of FDV [1]

Item	Characteristics
Number of blocks	22
Number of cells in grid	177744
Type of the grid	Uniform
Cross section of FDV	Rectangular – with equivalent area of the round cross section
Geometry of: -inlets: Preheated air Off-gas -outlets: Preheated air Off-gas	 ϕ_{ekv} = 220 mm ϕ_{ekv} = 300 mm ϕ_{ekv} = 270 mm ϕ_{ekv} = 220 mm
Boundary conditions: -Inlets: Preheated air Off-gas -Outlets:	 V=67,2 m/s, t=1000 °C, ρ=0,285 kg/m^3 V=44,0 m/s, t=1100 °C, ρ=0,232 kg/m^3

Preheated air Off-gas	Splited Splited
Reference pressure	100900 Pa
Used models in simulation: Turbulence model Thermal model	 K-ε High Reynolds number Calculation of temperature field

Table 2 - Characteristic parameters in numerical modeling and design optimization of tundish top cover [1]

Item	Characteristics
Number of blocks	1009
Number of cells in grid	300195
Type of the grid	Uniform
Type of analysis	Steady state &Transient
Geometry of: -inlets: Burner 1 Burner 2 -outlets: Off-gas	Identical geometry with real tundish ϕ_{ekv} = 160 mm ϕ_{ekv} = 160 mm ϕ_{ekv} = 350 mm
Boundary conditions: -Inlets: Burner 1 Burner 2 -Outlet: Off gas	V=93,9 m/s, t=1450 °C, ρ=0,205 kg/m^3 V=93,9 m/s, t=1450 °C, ρ=0,205 kg/m^3 Splited
Reference pressure	101325 Pa
Used models in simulation: Turbulence model Thermal model	K-ε High Reynolds number Calculation of temperature field Radiation model coupled with conjugated heat transfer

Table 3 - Parameters used in solution and numerical simulation for FDV design optimisation [1]

Solution method	Steady state			
Solution algorithm	Simple			
Max. global residual tolerance	$1\cdot10^{-5}$			
Solver type	Scalar			
Primary variables	Relaxation factor	Number of sweep	Residual tolerance	Difference scheme
U-Momentum V-Momentum W-Momentum	0,5 0,5 0,5	100 100 100	0,01 0,01 0,01	UD
Pressure	0,15	1000	0,005	UD
Turbulence K-ε Turbulence Dissipation	0,5 0,5	100 100	0,01 0,01	UD
Temperature	0,7	100	0,01	UD
Density Viscosity	1 1			MARS

Table 4 - Parameters used in solution and numerical simulation for tundish top cover optimisation [1]

Solution method	Steady state/Transient			
Solution algorithm	Simple/Pisco			
Max. global residual tolerance	$1\cdot10^{-4}$			
Solver type	Scalar			
Primary variables	Relaxation factor	Number of sweep	Residual tolerance	Difference scheme
U-Momentum V-Momentum W-Momentum	0,5 0,5 0,5	100 100 100	0,01 0,01 0,01	UD
Pressure	0,15	1000	0,005	UD
Turbulence K-ε Turbulence Dissipation	0,5 0,5	100 100	0,01 0,01	UD
Temperature	0,7	100	0,01	UD
Density Viscosity	1 1			MARS

The optimisation of FDV design has been performed with slightly changes in the geometry of the flow channels, especially in the middle part of FDV, where the two hot gas streams comes in contact. The criteria for optimisation were:

- to get the same pressure difference at the entrance channels of FDV as calculated using the pressure drop estimation (Table 3),
- to achieve acceptable pressure drop through FDV and to obtain required pressure value at the outlet channel for preheated air due to necessary flow potential for burners at tundish top,
- to achieve relatively small mixing between two hot gas streams.

Geometry of FDV, which is used for numerical simulation, is shown in Figure 3.

Table 5 - Pressure drop estimation through the installation of regenerative burner [1]

Pipeline for hot air		Pipeline for off-gasses	
Pipeline part	Pressure drop, Pa	Pipeline part	Pressure drop, Pa
I part	1021	I part	185
Pebble-Heater	2000	II part	335
II part	745	Fluid-Dynamical Valve	2860
Fluid-Dynamical Valve	1475	III part	-180
III part	115	Pebble-Heater	2000
IV part	65	IV part	1375
Burners	760		
Sum:	Σ6181 Pa	Sum:	Σ6575 Pa
Characteristics of pipeline parts: ϕ, l, ζ,λ, V			
High preheated air		Off-gas	
I part - cold side of air from fan to the Pebble Heater entrance.	ϕ 200 mm; l=13,5 m; Σζ=3,3; λ=0,0252; V=17,88 m/s	I part - from tundish to first knee in horizontal part of the pipeline	ϕ 350 mm; l=8 m; Σζ=1,1; λ=0,0253; V=30,48 m/s
II part - knee from Pebble Heater to Fluid-Dynamical Valve	ϕ 300 mm; l=1 m; Σζ=0,4; λ=0,026; V=50,78 m/s	II part - two knees to the FDV	ϕ 350 mm; l=3,5 m; Σζ=0,8; λ=0,0253; V=30,53 m/s
III part - from Fluid-Dynamical Valve to Y part	ϕ 350 mm; l=13,5 m; Σζ=1; λ=0,0251; V=26,66 m/s	III part - diffusing knee	ϕ 350 mm; l=1 m; Σζ=0,4; λ=0,0252; V=61,32 m/s
IV part - from Y part to burners exit	ϕ 250 mm; l=2,5 m; Σζ=0,4; λ=0,0274; V=26,16 m/s	IV part – cold off gasses from Pebble-Heaters	ϕ 200 mm; l=2,5 m; Σζ=3,4; λ=0,0264; V=33,94 m/s

In the case of the regenerative burner systems, some mixing (up to 12 %) of flue gas and hot combustion air may be useful for minimising the NO_x formation. Namely, it is favourable to have some amount of the combustion gases mixed in the preheated air, reducing thus the oxygen concentration, which is relevant factor for kinetics of NO_x formation. It is the well-known technique of the off-gas recirculation. In this case, mixing is carried out on the hot side - inside the FDV, without costly system of recirculation piping. It is called *in-situ* recirculation.

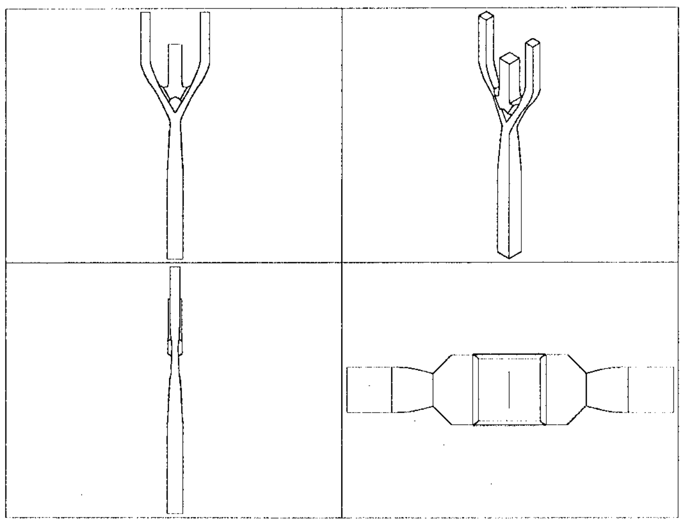

Figure 3 - Geometry of the model of FDV used in numerical simulation [1]

The results achieved with the final geometry are given in Figures 4-8. Figure 4 shows the pressure field in the middle plane of the whole FDV. The detailed pressure field for the middle part of the FDV is presented in Figure 5. In both cases the hot air enters through the top right-side pipe and leaves the FDV through the bottom central tube. The hot off-gas stream enters through the top central pipe, turns left and goes out through the top left-side pipe. Figure 6 shows intensity of velocity field in middle plane of FDV, which strongly depends on pressure field. Figure 7 shows detailed velocity field of middle part of FDV. It is obvious that the nozzle accelerates the hot air stream reducing its pressure, so that at location where the two streams get in contact, the pressure is almost identical from both sides (ochre yellow coloured field in Figure 5). In that way there is no potential for the significant mixing between the two streams. The long diffuser at the hot air outlet (see Figure 4) slows down the gas stream and recovers the pressure loss to some extent. Figure 6 shows the velocity vectors in the middle section of FDV. The hot air accelerates (up to 170 m/s), while the velocity of the off-gas at the contact location is considerable lower (approx. 10 m/s). The concentration field in the middle plane of the whole Fluid-Dynamical Valve is given in Figure 8. The air concentration at the outlet is higher than 92,8 % (red field), it means that about 7 % of off-gas is recirculated and goes into the tundish.

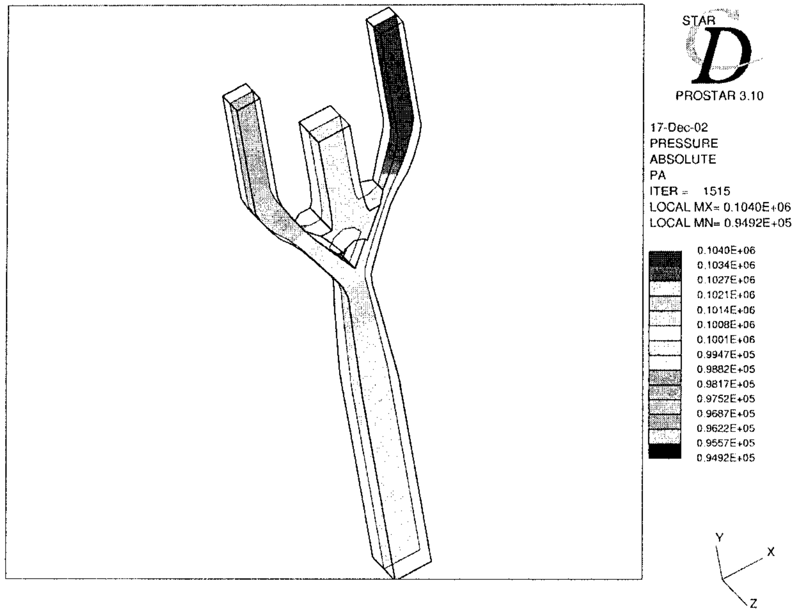

Figure 4 - Pressure field in the middle cross section of FDV [1]

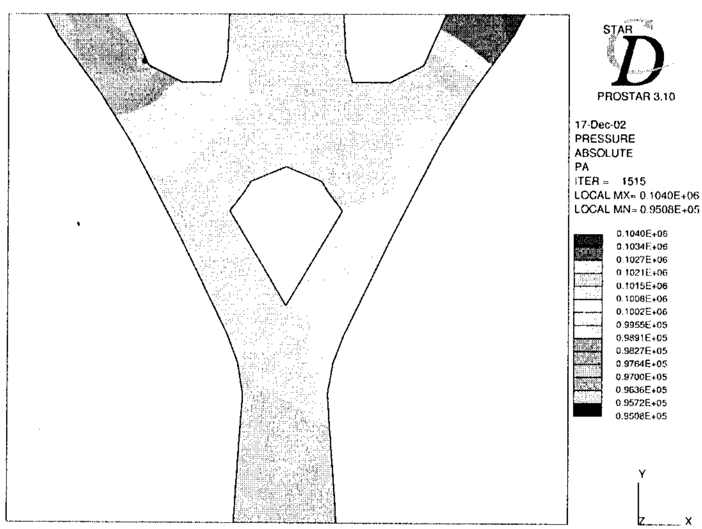

Figure 5 - Detail of pressure field in the central part of FDV [1]

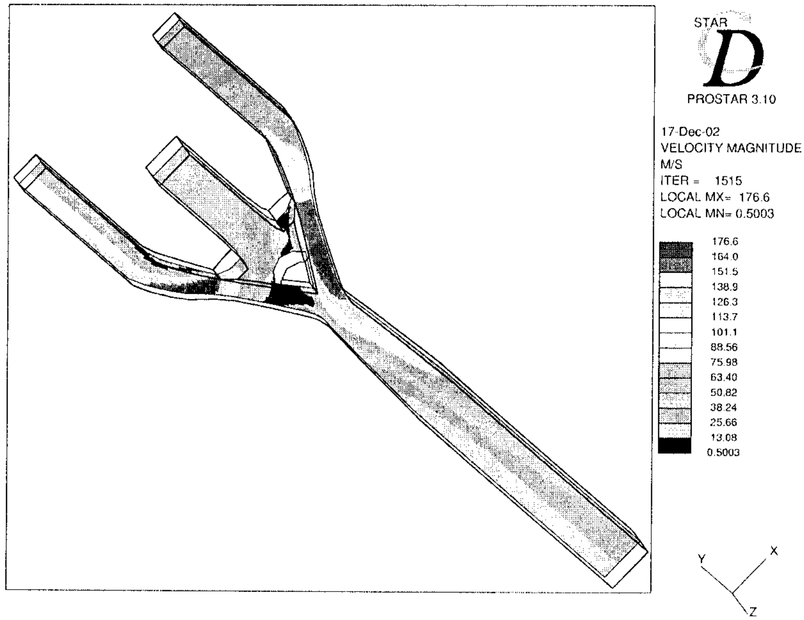

Figure 6. Velocity field in middle cross section of FDV [1]

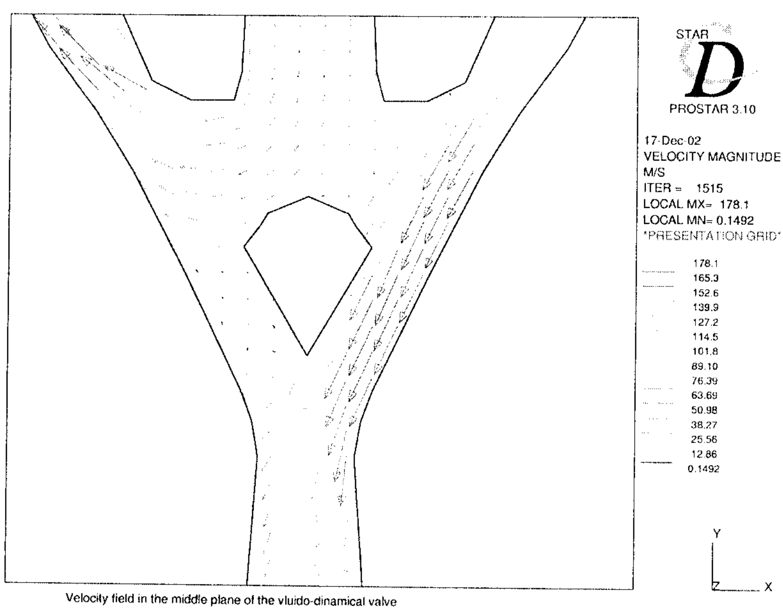

Figure 7 - Detail of velocity vectors in the central part of FDV [1]

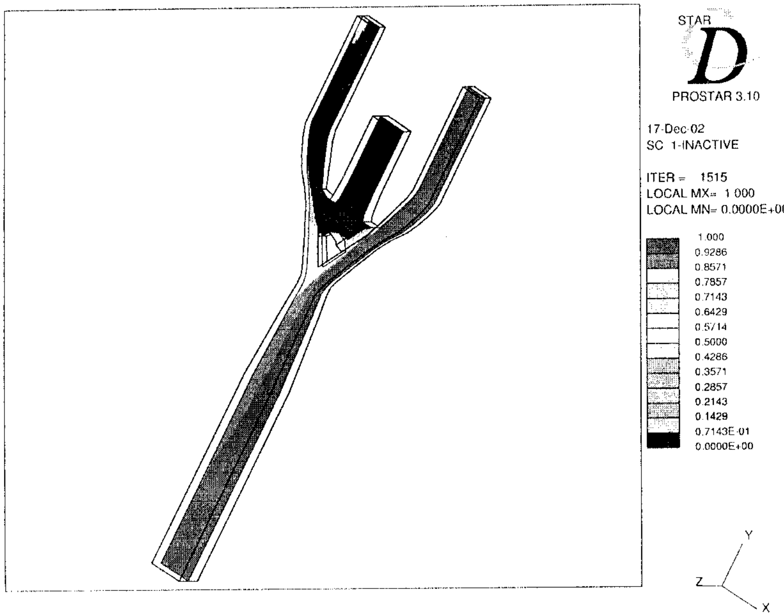

Figure 8 - Concentration field in middle cross section of FDV [1]

Model core for real FDV (showed in Figure 9) was build in order to verify obtained results of numerical simulation of FDV optimisation in experiment.

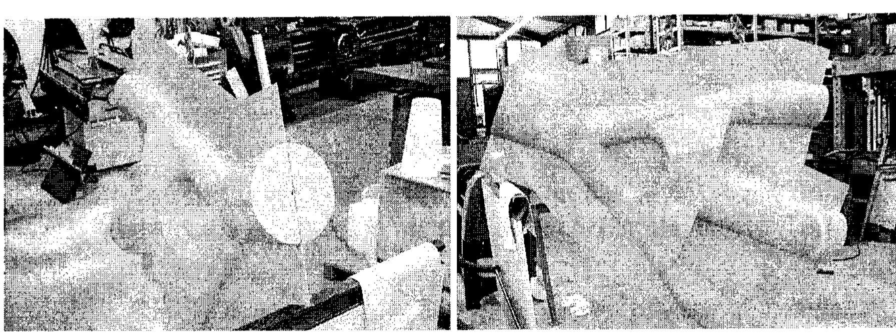

Figure 9 - Core model of FDV [1]

The optimization of tundish top coverage design has been performed without any changes or simplification in the geometry. Main criterion for optimization in this case was to achieve as uniform as it is possible temperature field at refractory layer of tundish in limited time of preheating by introduction of high-preheated air for combustion.

Drawing of tundish was presented at Figure 10 and geometry of tundish model and results of numerical simulation were shown at Figures 11-13.

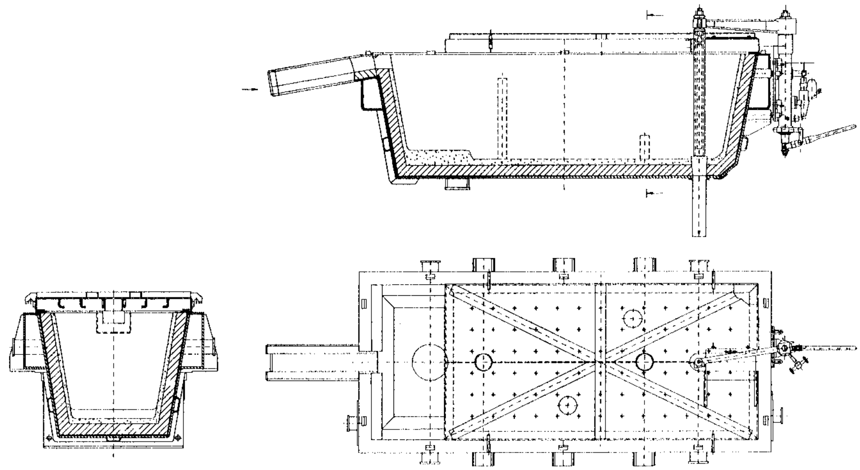

Figure 10 - Geometry of tundish at stand for preheating in steel plant [1]

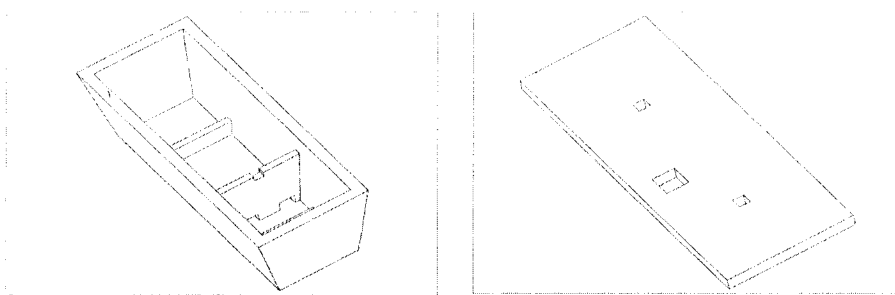

Figure 11 - Geometry of tundish model in numerical simulation [1]

Tundish has to be heated up to 1100 °C in 5-6 hours. In present situation average fuel consumption is 200 – 250 m^3/h, and the combustion is very irregular.

Parameters presented in tables 2 and 4 have been used for numerical modelling. As it could be seen, two cases were studied. First, it was stationary problem, with resulted final temperature field at the inner surface of tundish presented at Figure 12. It could be seen that uniformity of temperature field is satisfactory and as it is presented at Figure 12 temperature is in the range of: 1028-1096 °C (pink), 1096-1164 °C (violet) and 1164-1232 °C (red). Maximal temperature (red field) is obtained at the point where high velocity stream of hot combustion products contacts with tundish bottom. The maximal average temperature difference is 136 °C and the middle part of tundish is at the lowest temperature.

On the other hand, transient problem for 6 hours of tundish preheating has been analysed. This is real case in this solution. Result of this analysis is presented in Figure 13, where the time interval of 6 hours is divided into 12 short intervals of 30 minutes, lined in counter clockwise from case a) to case c). The solution of transient heating after 6 hours is presented at case c), lower right picture. Maximal temperature in the right separated part of tundish after 6 hours of preheating was 1193 °C - darker ochre colour (at the same position as in stationary case). The temperature field at the inner side of tundish refractory is uniform and it is in the range of 1089 – 1193 °C prevalence yellow colour and light ochre, with satisfactory uniformity of temperature field and maximal average difference 104 °C.

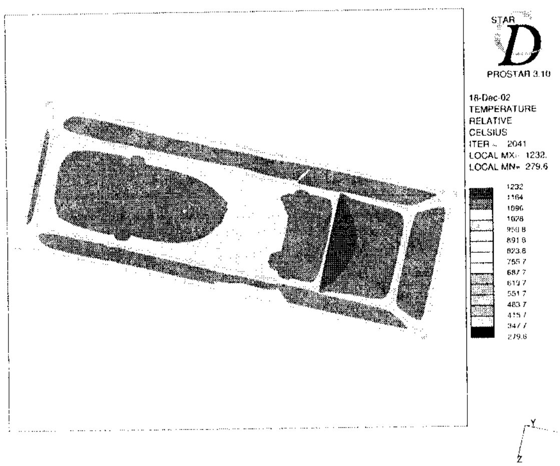

Figure 12 - Temperature field at inside refractory layer in tundish (stationary solution) [1]

Positions of burner heads and exhaust outlet have been determined in this simulation. Both burner heads are positioned at symmetrical axis of tundish top cover. Exhaust outlet is not symmetrical, and during simulation it has been showed that there is little, or no influence weather there are two symmetrical, or one unsymmetrical opening for exhaust gases. Because of simplicity of experimental installation, it was decided to use one exhaust opening. Two burner heads are positioned exactly above first smaller step of tundish, and the other in the right separated part of the tundish where melted metal touches first the tundish surface. It is important to keep high temperature at this surface, since high temperature differences could damage refractory surface, or cause problems in casting of iron. Uniform temperature field at inner side of tundish was obtained with considerable fuel reduction (all numerical simulations has been performed with 100 m^3/h of natural gas consumption) by using high-preheated air for combustion (up to 1100 °C) and high velocity burner heads.

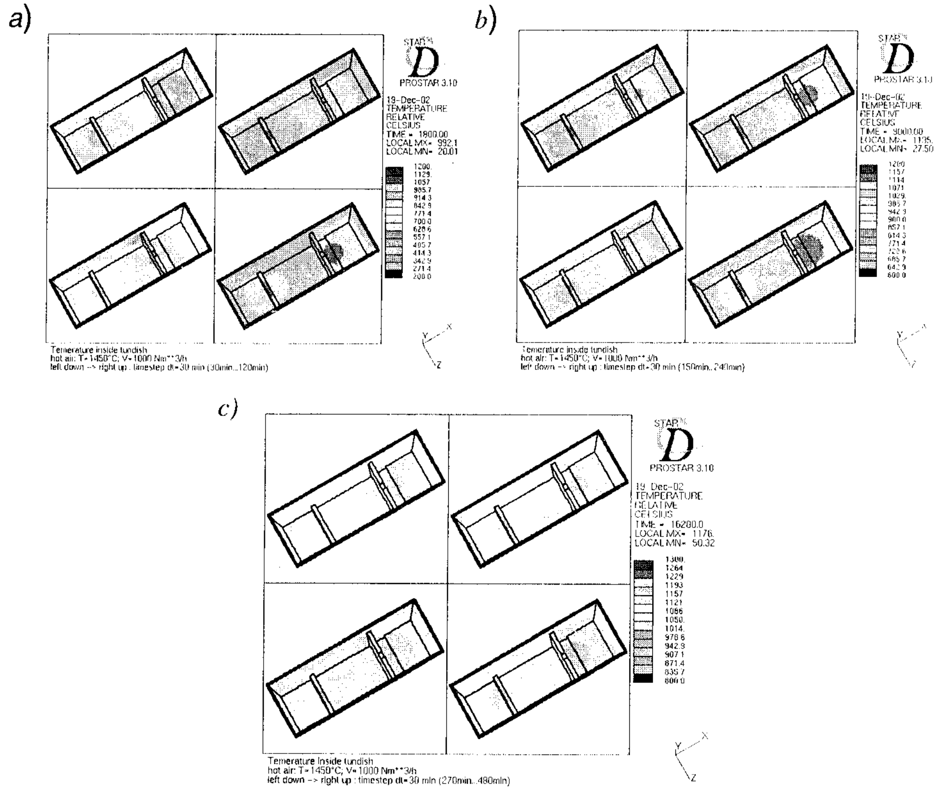

Figure 13 - Temperature field development during 6 hours (transient problem) [1]

CONCLUSIONS

With existing physical models, CFD can offer cost-effective solutions for many complex systems of interest in the metallurgical industry. Numerical simulations in design and optimization of elements of experimental installation of regenerative burners for tundish preheating in steel plant US Steel-Sartid Smederevo has been performed by using CFD code StarCD v 3.15 A. According to obtained result, the solution for geometry of FDV and tundish top cover was suggested.

Due to considerable pressure difference between two hot streams at inlets of FDV, one of the streams (the hot air) should accelerate (up to 170 m/s), while the velocity of the other (off-gas) at the contact location should be considerable lower (approx. 10 m/s). Adequate geometry of FDV channels was obtained as a result of numerical optimisation. The air concentration at the outlet is higher than 92,8 %, which means that about 7 % of off-gas is recirculated and goes into the tundish.

Positions of burner heads and exhaust outlet have been determined in this simulation. Both burner heads are positioned at symmetrical axis of tundish top cover. In this paper, two cases of tundish preheating were studied (stationary and transient). For both cases, uniformity of temperature field was satisfactory and the temperature was in the range of 1028-1232 °C for stationary and 1089 – 1193 °C for transient solution. Maximal temperatures are obtained at the point where high velocity stream of hot combustion products contacts with tundish bottom. Uniform temperature field at inner side of tundish was obtained as a result of optimisation of position of the burner heads, with considerable fuel reduction, up to 50 %, by using CFD code for numerical simulation.

Further work on all necessary improvements in simulations is going to be completed in the future in the Simulation Laboratory at Faculty of Mechanical Engineering, University of Belgrade.

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