

# THERMAL AND FLUID FLOW FIELDS IN A REGENERATOR WITH CERAMIC CHIMNEY BLOCK CHECKER WORK

LILIANA ZASHKOVA AND NINA PENKOVA

*Department of Silicate Technology,  
University of Chemical Technology and Metallurgy,  
Kl. Ohridsky 8, Sofia, Bulgaria  
zashkova@uctm.edu, nina\_ir@mail.bg*

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**Abstract:** Selected results of mathematical modelling and computer simulation of transient conjugate heat transfer in a vertical contraflow glass furnace regenerator are reported. The problem is solved three-dimensionally (3D) using the ANSYS 8.0/FLOTRAN program. The main regenerator fluid flow and thermal fields about a cyclic equilibrium of the regenerator are visualized. Heat and fluid flow parameters for the regenerator's cyclic equilibrium are presented by  $T_m = T_m(H', t)$ ;  $T_{m,f} = T_{m,f}(H', t)$ ;  $h_m = h_m(H', t)$ ;  $V = V(H', t)$ ;  $k = k(H', t)$  and  $\varepsilon = \varepsilon(H', t)$  graphics. Remarks about transient heat transfer in this kind of regenerators are made based on the obtained numerical values and relationships.

**Keywords:** glass furnace, regenerator, conjugate heat transfer, cyclic equilibrium, FEM, thermal fields, modelling

## *Nomenclature*

$T$  – temperature, [K]  
 $T_m$  – average temperature, K  
 $V = (V_x, V_y, V_z)$  – velocity vector, [ $\text{m} \cdot \text{s}^{-1}$ ]  
 $p$  – pressure, [Pa]  
 $t$  – time, [s], [min]  
 $k$  – turbulent kinetic energy, [ $\text{J} \cdot \text{kg}^{-1}$ ]  
 $h$  – heat transfer (film) coefficient, [ $\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ ]  
 $h_m$  – average heat transfer (film) coefficient, [ $\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ ]  
 $q$  – heat flux, [ $\text{W} \cdot \text{m}^{-2}$ ]  
 $H$  – regenerator height, [m]  
 $H'$  – dimensionless regenerator height,  $H' = N_j/N_r$   
 $H_r$  – height of the investigated regenerator, [m]  
 $N_r$  – checker row number  
 $N_j$  –  $j^{\text{th}}$  checker row

*Greek symbols*

- $\varepsilon$  – turbulent kinetic energy dissipation rate, [W·kg<sup>-1</sup>]  
 $\phi$  – degree of freedom

*Subscripts*

- $i$  – node number,  $i = 1, 2, \dots, 28236$   
 $c$  – cooling period  
 $h$  – heating period  
 $f$  – fluid  
 $in$  – inlet  
 $w$  – wall

## 1. Introduction

The analyse conjugate heat transfer in a regenerator, equations are solved that define the heat and fluid flow processes in the heat exchanger. In this context, the temperature equation is solved in a domain with both fluid and non-fluid (solid) regions [1]. Fluid flow effect over the heat transfer fluid/solid is rendered in account in this case. Local values of representative regenerator parameters are determined as result: velocity, pressure, temperature fields in the fluid and non-fluid regions, the fluid/solid heat flux, the heat transfer film coefficient, *etc.*

The heat transfer occurring in regenerators has been extensively studied by mathematical modelling, and analytical and numerical solutions of the model equations have been reported [2–7]. But solutions of transient conjugate heat transfer problems in a regenerator and a visualization of the thermal and fluid flow parameters have not been published yet.

The aim of research reported in the present paper has been to analyse the transient conjugate heat transfer problems in a vertical contraflow glass furnace regenerator. The checker work is made from chimney ceramic blocks (semicylindrical), offered by “Radex” [8]. In the checker heating period (lasting 30min) hot flue gases go into the top of the regenerator at a temperature of 1300°C. In the checker cooling period (also lasting 30min) air goes into the bottom of the regenerator at a temperature of 50°C. The object of modelling is a self-similar region in the centre of the checker, with symmetrical boundaries.

To achieve this aim, the continuity equation, the momentum equation for the turbulent case and the incompressible energy equation are solved under the terms of boundary conditions. The boundary conditions are specified according to a real regenerator’s work. The equations are discretized with a finite elements based technique. A two-equation standard turbulent  $k$ - $\varepsilon$  model is added to account for the effect of the turbulent velocity fluctuation of the mean flow. A Van Driest wall conductivity model [9] is used for the wall element. The radiation heat transfer between flue gases and checker blocks in the heating period is modelled by an increased, “artificial” gas conductivity. The mathematical model, boundary conditions and investigated regenerator parameters are described in detail in the preceding article.

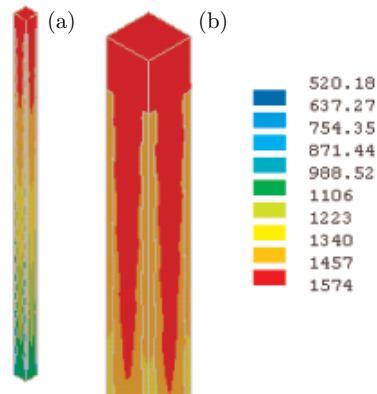
Seventeen consecutive checker heatings with flue gases and seventeen coolings with air are simulated until achieving a cyclic equilibrium of the regenerator. For every

time step of the heating and cooling periods from the initial conditions to the cyclic equilibrium, local degrees of freedom (velocity, fluid and solid temperature, pressure, turbulent kinetic energy, turbulent kinetic energy dissipation rate) and output derived values (heat flux, heat transfer (film) coefficient, shear stress) are calculated and saved.

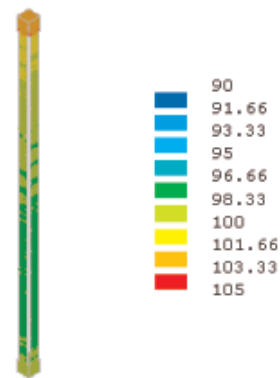
## 2. Results

In Figures 1–12 some specific thermal and fluid flow fields are shown for a fixed moment of the cyclic equilibrium of the regenerator (17<sup>th</sup> heating and cooling periods).

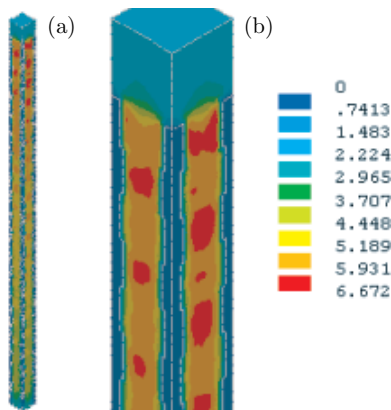
In Figures 13–24, average thermal and fluid flow regenerator parameters are presented as functions of time,  $t$ , and the dimensionless regenerator height,  $H' =$



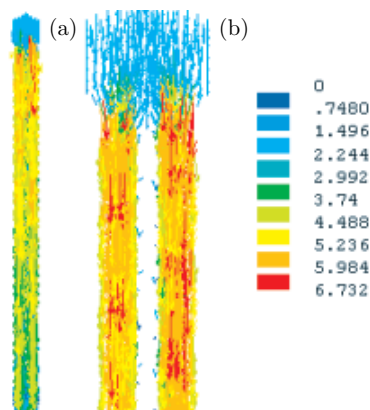
**Figure 1.** Temperature field in a heating period ( $t = 1$  min): (a) overall view; (b) magnified flue gases inlet



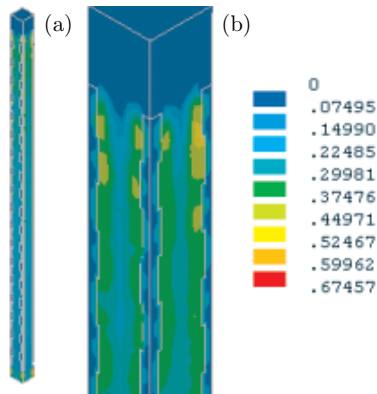
**Figure 2.** Relative pressure of the flue gases in a heating period ( $t = 1$  min)



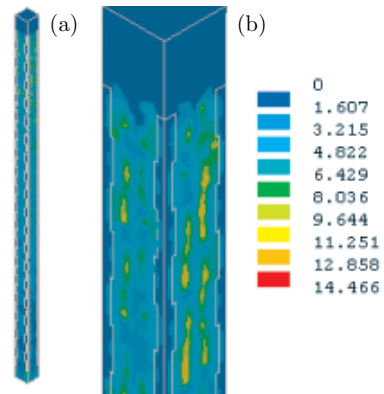
**Figure 3.** Flue gases' velocity fields in a heating period ( $t = 1$  min): (a) overall view; (b) magnified flue gases inlet



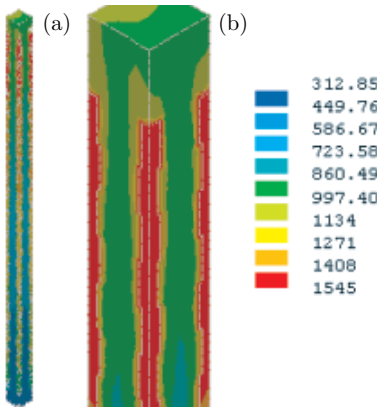
**Figure 4.** Velocity vectors in a heating period ( $t = 1$  min): (a) overall view; (b) magnified flue gases inlet



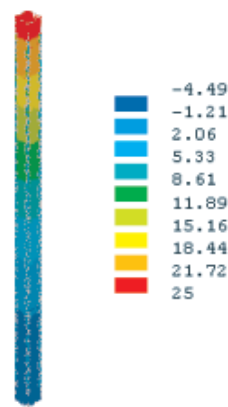
**Figure 5.** Turbulent kinetic energy field in a heating period ( $t = 1 \text{ min}$ ): (a) overall view; (b) magnified flue gases inlet



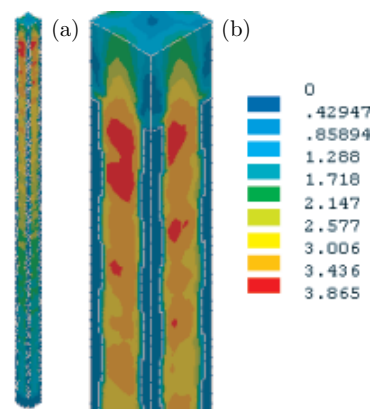
**Figure 6.** Turbulent kinetic energy dissipation rate in a heating period ( $t = 1 \text{ min}$ ): (a) overall view; (b) magnified flue gases inlet



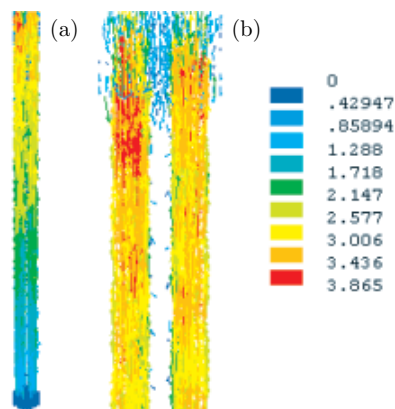
**Figure 7.** Temperature field in a cooling period ( $t = 1 \text{ min}$ ): (a) overall view; (b) magnified air outlet



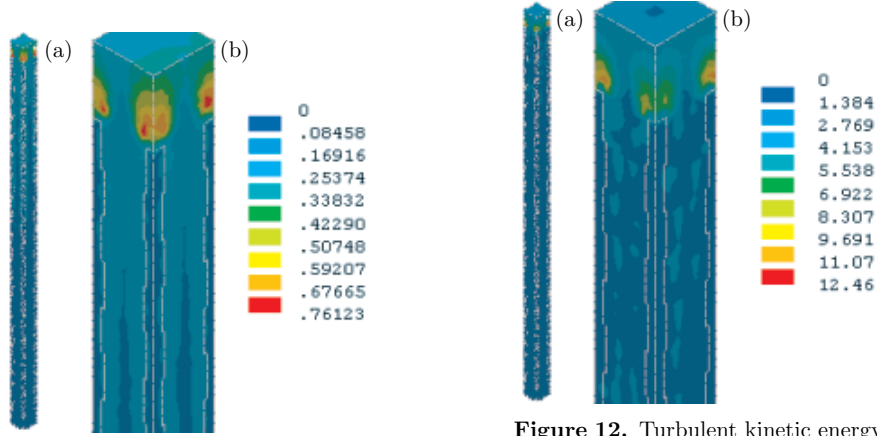
**Figure 8.** Relative air pressure in a cooling period ( $t = 1 \text{ min}$ ):



**Figure 9.** Air velocity field in a cooling period ( $t = 1 \text{ min}$ ): (a) overall view; (b) magnified air outlet



**Figure 10.** Velocity vector fields in a cooling period ( $t = 1 \text{ min}$ ): (a) overall view; (b) magnified air outlet



**Figure 11.** Turbulent kinetic energy of air in a cooling period ( $t = 1\text{min}$ ): (a) overall view; (b) magnified air outlet

**Figure 12.** Turbulent kinetic energy dissipation rate of air in a cooling period ( $t = 1\text{min}$ ): (a) overall view; (b) magnified air outlet

$N_j/N_r$ , in a cyclic equilibrium. Average values are calculated for each  $\Delta H$  of the regenerator's height (on the corresponding row level) from the following equation:

$$\phi_m = \frac{\sum_{i=1}^n \phi_i}{n}. \quad (1)$$

Average heat transfer coefficients are calculated for each  $\Delta H$  of the regenerator's height from the following equation:

$$h_m = \frac{\sum_{j=1}^{n_w} \left( \frac{q_{w,j}}{T_{m,f,j} - T_{w,j}} \right)}{n_w}. \quad (2)$$

Dimensionless velocity, turbulent kinetic energy and turbulent kinetic energy dissipation rate are calculated to render an account the stream convergences:

$$V' = \frac{V}{V_{in}}, \quad k' = \frac{k}{k_{in}}, \quad \varepsilon' = \frac{\varepsilon}{\varepsilon_{in}}, \quad (3)$$

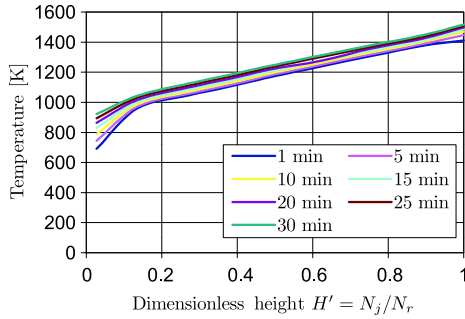
where  $V_{in}$ ,  $k_{in}$  and  $\varepsilon_{in}$  are undisturbed flow parameters at the regenerator's inlet:

- flue gases:  $V_{in} = 2.09\text{m}\cdot\text{s}^{-1}$ ,  $k_{in} = 6.55 \cdot 10^{-4}\text{J}\cdot\text{kg}^{-1}$ ,  $\varepsilon_{in} = 7.7 \cdot 10^{-4}\text{W}\cdot\text{kg}^{-1}$ ;
- air:  $V_{in} = 0.354\text{m}\cdot\text{s}^{-1}$ ,  $k_{in} = 1.88 \cdot 10^{-5}\text{J}\cdot\text{kg}^{-1}$ ,  $\varepsilon_{in} = 3.74 \cdot 10^{-6}\text{W}\cdot\text{kg}^{-1}$ .

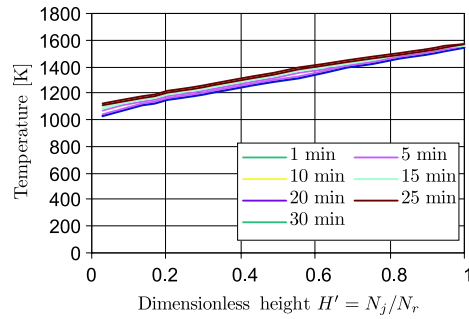
The changes of the above parameters (Figures 13–24) in numerical values at both regenerator's ends, within the limits of a cyclic equilibrium, are summarised in Table 1.

### 3. Conclusions

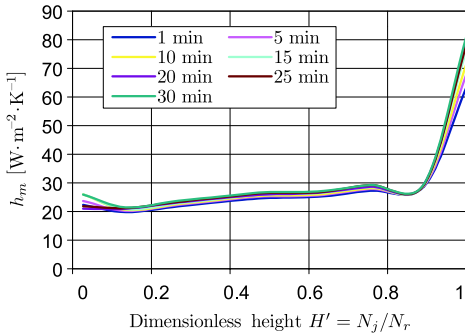
1. New data about the change of the average heat transfer coefficients with the height of this regenerator type within the limits of a cyclic equilibrium have been obtained:



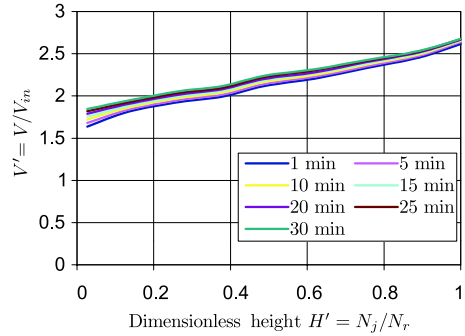
**Figure 13.** Average checker blocks' temperature in a heating period



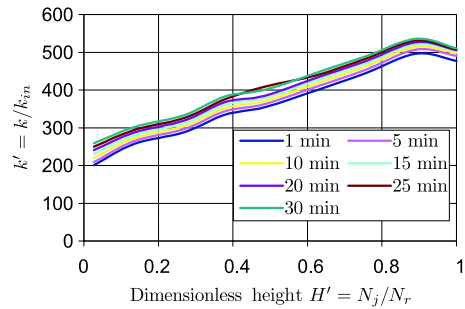
**Figure 14.** Average flue gases' temperature in a heating period



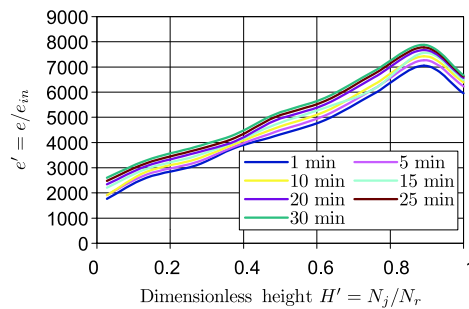
**Figure 15.** Average heat transfer coefficient in a heating period



**Figure 16.** Average dimensionless flue gases' velocity in a heating period



**Figure 17.** Average dimensionless turbulent kinetic energy in a heating period



**Figure 18.** Average dimensionless turbulent kinetic energy dissipation rate in a heating period

- relationships for the regenerator's height variation of the heat transfer coefficients have been determined by regression analysis, based on the obtained numerical values and graphics, as shown in Figures 15 and 21:

*heating period:*

$$h_m = 1.12 \cdot H^4 - 10.95 \cdot H^3 + 33.94 \cdot H^2 - 34.71 \cdot H + 29.6, \quad (4)$$

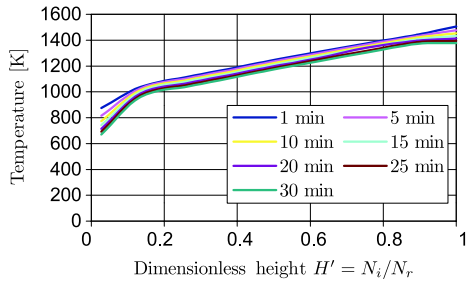


Figure 19. Average checker blocks' temperature in a cooling period

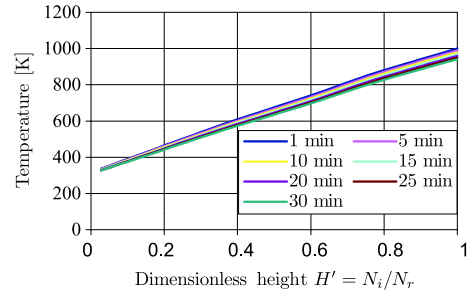


Figure 20. Average air temperature in a cooling period

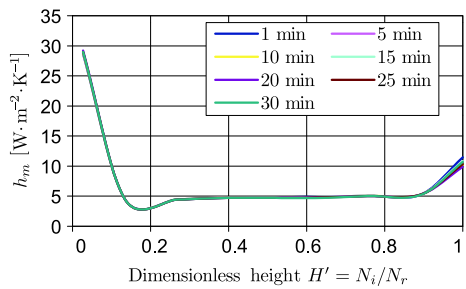


Figure 21. Average heat transfer coefficient in a cooling period

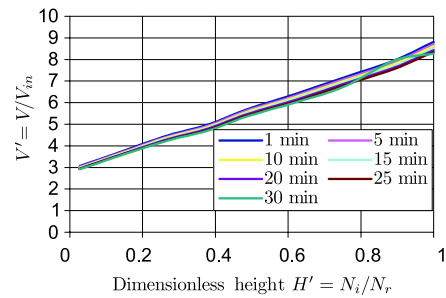


Figure 22. Average dimensionless air velocity in a cooling period

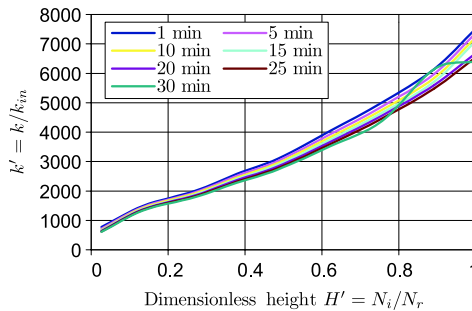


Figure 23. Average dimensionless turbulent kinetic energy in a cooling period

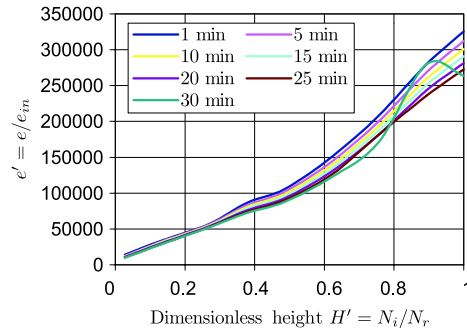


Figure 24. Average dimensionless turbulent kinetic energy dissipation rate in a cooling period

cooling period:

$$h_m = 0.644 \cdot H^4 - 7.88 \cdot H^3 + 33 \cdot H^2 - 53.73 \cdot H + 31.54; \quad (5)$$

- the average integral heat transfer coefficients for the entire regenerator can be calculated from relationships (4) and (5):

heating period:

$$h_{m,h} = \frac{1}{H_r} \int_0^{H_r} h_m dH = 0.224 \cdot H_r^4 - 2.74 \cdot H_r^3 + 11.31 \cdot H_r^2 - 17.34 \cdot H_r + 29.6, \quad (6)$$

**Table 1.** Numerical values of thermal and fluid flow parameters

Thermal and fluid flow parameters	Heating period				Cooling period			
	$H'=0.027$ (1 <sup>st</sup> checker row)		$H'=1$ (44 <sup>th</sup> checker row)		$H'=0.027$ (1 <sup>st</sup> checker row)		$H'=1$ (44 <sup>th</sup> checker row)	
	$t=1$ min	$t=30$ min	$t=1$ min	$t=30$ min	$t=1$ min	$t=30$ min	$t=1$ min	$t=30$ min
Average fluid temperature [K]	1033	1119	1573	1573	323	323	1003	941
Average checker blocks' temperature [K]	692	923	1410	1517	876	671	1504	1377
Average dimensionless velocity	1.64	1.85	2.62	2.68	3	2.9	8.8	8.26
Average dimensionless turbulent kinetic energy	201	259	477	510	774	609	7514	6401
Average dimensionless turbulent kinetic energy dissipation rate	1766	2607	5958	6673	13998	9893	325 440	263 856
Average heat transfer coefficient [ $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ ]	22	26	64	82	28.7	29	11.4	10.71

for the investigated regenerator:

$$h_{m,h} = \frac{1}{5.55} \int_0^{5.55} h_m dH = 27.5 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}, \quad (7)$$

cooling period:

$$h_{m,c} = \frac{1}{H_r} \int_0^{H_r} h_m dH = 0.13 \cdot H_r^4 - 1.97 \cdot H_r^3 + 11 \cdot H_r^2 - 26.87 \cdot H_r + 31.54, \quad (8)$$

for the investigated regenerator:

$$h_{m,c} = \frac{1}{5.55} \int_0^{5.55} h_m dH = 6.5 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}; \quad (9)$$

- the heat transfer coefficients in the first rows of the checker work are higher than the average integral coefficients in the cooling and heating periods (Table 1), due to turbulences in both air and flue gas streams at the regenerator's inlets. Therefore, the heat transfer coefficients decrease and oscillate around the average integral coefficients (Figures 15 and 21).
2. The regenerator's height variation of the flue gases' velocity, turbulent kinetic energy and turbulent kinetic energy dissipation rate are linear relationships (see Figures 16, 17 and 18).
  3. The regenerator height variation of the air velocity is a linear relationship (Figure 22). The turbulent kinetic energy and turbulent kinetic energy dissipation rate of air increase exponentially with the height of the regenerator (see



Figures 23 and 24). Free convection, of the same direction as the forced convection, occurs due to the temperature difference between checker blocks and air,  $\Delta T_m > 250\text{K}$ . This process intensifies turbulent fluctuations in the cooling period.

4. The regenerator's height variation of the checker blocks, flue gases and air temperatures are linear relationships, without maximums and minimums. This enables us to extrapolate the obtained relationships beyond the height of the investigated regenerator. There is a linear function divergence at the air inlet of the regenerator due to the great temperature difference between the air and the checker blocks in that area, *viz.*  $\Delta T_m > 350\text{K}$  (Table 1).
5. The obtained change of the average air temperature at the regenerator's outlet (or the glass furnace inlet),  $\Delta T_m = T_m^{1\text{min}} - T_m^{30\text{min}} = 62\text{K}$  (Table 1), enables us to investigate the regenerator's effect on the furnace's thermal work.
6. A large heating surface (regenerator height) is necessary for the full use of the flue gases' thermal energy, due to their high outlet temperature, according to the data in Table 1.
7. The new data obtained on the working of a thermal regenerator are an example of successful application of mathematical modelling and computer simulation in industrial studies.

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