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Comparison of Convection Models for Hot Blast Stove Regenerative Chamber

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Abstract : Low error numerical solutions of convective heat transfer in high-temperature air regenerative heat exchangers in the convective regime rely on the correct determination of the wall heat transfer coefficient. Presented are results of simulations computed using a similarity theory-based numerical model. They imply that the current empirical formulas based on the theory of similarity, derived for analogous model cases of convective heat transfer do not allow to achieve satisfactory accuracy. Actual dependencies of parameters and criteria yielding more representative heat transfer coefficient values might be obtained through the means of experimental research in thermodynamics of an experimental device.

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1 Introduction

The utilisation of numerical modelling proves extremely useful in an effort to control or optimise any thermodynamic system operation. The models based on the first principles of heat and mass transfer often yield highly reliable results utilising CFD algorithms. However, necessary computational power requirements do not allow operative and real-time data processing. Therefore, applications demanding immediate outputs have to take advantage of models mostly based on enthalpy balancing and the similarity theory.

Predictive modelling of hot blast stove (HBS) allows evaluating the upcoming operating conditions and qualitative technological indicators. NM of this nature can be used in testing the design of innovative elements and solutions aimed at increasing energy efficiency and reducing the environmental impact of equipment (examples include the use of alternative fuels, combustion air enrichment, use of alternative materials for regeneration, or elimination of heat losses). However, the primary benefit lies in the fact that their implementation into the automated system control of HBS technology has the potential to stabilise the qualitative indicators of the process and at the same time reduce the specific energy consumption.

The focus of this paper is an analysis of a simplified numerical model (NM) based on the similarity theory. Assuming that the CFD simulation provides a more detailed view of the thermodynamics, the accuracy of the NM outputs were compared to the referential CFD simulation. Identified were areas of concern in which further research is necessary. Application of newly obtained data in the following optimisation of the NM will yield lower theoretical errors.

Heat transfer in regenerative heat exchanger units occurs in the accumulation regime by radiation and convection of the fluid to the accumulation brick surfaces and by conduction in the volume of the bricks (in case of HBS ceramic checker bricks). However, when creating simplified models, the biggest problem arises in determining the convection heat transfer coefficient. Therefore, in the previous work, the attention was focused on the analysis of convective heat transfer. Consequently, in order to eliminate radiation, all presented simulations were conducted using dry air as a fluid domain. It applies for both accumulation and blasting regime of HBS models.

2 Methodology

Convective heat flux can be expressed by Newton's law of cooling, where the convective heat transfer coefficient is obtained by empirical correlations of the Nusselt criterion, depending on the nature of the turbulence. Alternatively, Zhong (2004) reports the calculation of the convection heat transfer coefficient based on empirical temperature dependence [1]. Its application, however, yields significantly nonrepresentative values even at relatively low temperatures—the reason being the fact that the correlation bases only on the temperature of the fluid and was derived for blasting regime only. However, convection is mainly affected by the temperature difference between the fluid and the wall surfaces. More accurate model of convective heat exchange in the channels with a turbulent fluid flow is described by the empirical formulas based on the Nusselt criterion, according to M. A. Michejev [2, 3]. It describes heat exchange in smooth pipes and ducts with relatively low error. However, with the higher temperatures of the fluid and the higher surface roughness of the channel walls, the inaccuracy of the calculation increases. Heat exchange in regenerative heat exchangers was addressed by Zatterholm (2015), who in the NM of HBS sets the Nusselt number depending on the nature of the turbulence using correlations of Gnielinsky and Hausen [4, 5].

2.1 Geometry

Standardly, perforated ceramic bricks form the accumulation filling of HBS (see Figure 2a)). The blocks fill the volume of the regenerative chamber and create streams that pass through the entire height of the chamber. In standard HBS, approximately 13,000 streams are created in this way. However, for NM purposes, it is necessary to ensure the simplicity of computational nodes. Geometric symmetry of the bricks (see Figure 2b)) facilitates the computation. The symmetry element is sufficient enough to determine the mean temperature of the checker bricks over the entire cross-section of HBS. To ensure relatively high accuracy of outputs and at the same time ensure carrying out the simulation in a sufficient timeframe, the optimal height of the calculation element has to be defined in order to discretise the model in height.

2.2 Numerical model

In a simplified manner the flowchart of Figure 1 describes the concept of the iterative algorithm for determining temperatures in a calculation element. Several simplifying assumptions have been adopted, which are described in detail by Zhong (2004). In particular:

- the possibility of reverse flow is neglected,
- thermal processes within a time step are considered to be quasi-stationary events,
- heat transfer by conduction along the height of the model is neglected,
- considered is an even distribution of the flow throughout the cross-section of the regenerative chamber [1].

2.2.1 Calculation procedure:

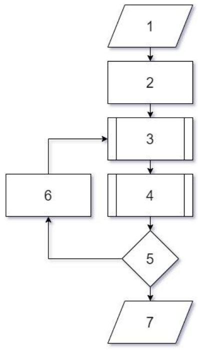

Figure 1 Iterative procedure for temperature calculation

1. reading temperatures from the previous time step and the previous zone (or boundary and initial conditions),
2. initial estimate of the fluid temperature at the end of the zone:

$$t_{f,2,i,e} = \frac{t_{f,1,i} + t_{s,i-1}}{2} \quad (1)$$

3. calculation of the mean brick temperature at the end of a time step:

$$t_{s,i+1} = \frac{c_i \cdot t_{s,i} - \dfrac{\Delta Q}{m_s}}{c_{i+1}} \quad (2)$$

$$\Delta Q = \Delta\tau \cdot \dot{m}_f \cdot \left(c_{p,2} \cdot t_{f,2,i,e} - c_{p,1} \cdot t_{f,1,i}\right) \quad (3)$$

4. calculation of the fluid temperature at the end of the zone:

$$t_{f,2,i} = \frac{c_{p,1} \cdot t_{f,1,i} + \dfrac{Q_K}{\dot{m}_f}}{c_{p,2}} \quad (4)$$

$$Q_K = \Delta\tau \cdot \alpha_K \cdot S \cdot \Delta t_{ln} \quad (5)$$

$$\alpha_K = f[Nu = f(Re, Pr)] \quad (6)$$

5. accuracy check of the estimate:

$$|t_{f,2,i,e} - t_{f,2,i}| < \varepsilon \ (\varepsilon = 0.001\ °C): \quad (7)$$

6. estimate correction:

$$t_{f,2,i,e} = \frac{t_{f,2,i,e} + t_{f,2,i}}{2} \quad (8)$$

7. output: temperature field.

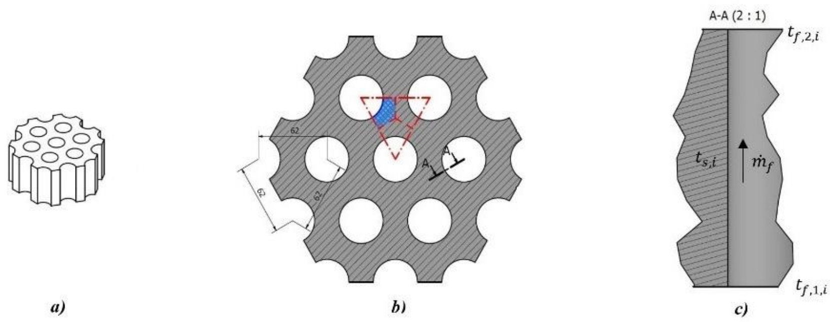

Figure 2 a) ceramic checker brick, b) cross-section of a brick with channels of a 40 mm diameter, symmetry elements are shown in red c) cross-section of brick filling in height, description of temperature field - indexes: s - solid (brick), f - fluid

2.3 *Referential CFD simulation*

CFD modelling is a powerful analytical tool that provides robust numerical methods for solving heat and mass transfer, the complexity of which allows to achieve relatively high accuracy of outputs. Since it is currently not possible to verify the NM results experimentally, the NM outputs are compared to a CFD simulation developed in ANSYS Fluent. However, the advantage is the possibility of eliminating inaccuracies caused by leaks, heat losses, or inhomogeneities of regenerative material that may occur on physical experimental device. However, it is still necessary to interpret the results only on a theoretical level. A simulation of a one-hour long accumulation of a 0.7 m high silica brick (Dinas) was performed. The 3D geometry is based on the sketches in Figure 2 under the conditions specified in Table 1.

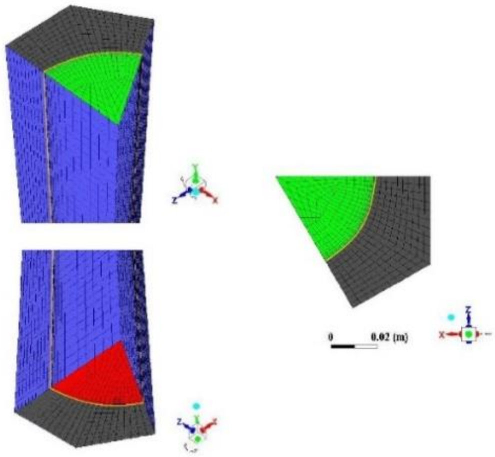

Figure 3 Symmetry element 3D geometry. Inlet, outlet, top view

Table 1 Simulation setup

Main setup	
solver	pressure-based
time	transient
turbulence model	k-ω, incompressible
energy equation	yes
Boundary conditions (see Figure 3 for colouring)	
walls	symmetry
walls	coupled wall, surface roughness 0.00025 m
walls	wall, null heat flux
inlet	$5.298.10^{-3}$ kg.s^{-1}, 921 K, 102 325 Pa
outlet	outflow
Initial conditions	
brick temperature	18 °C

2.4 *Physical properties of modeled materials*

The materials used for calculations are silica brick (Dinas, specific mass 2350 kg.m^{-3}) and dry air. Regression analyses of tabulated properties were carried out for the mean specific heat capacity of Dinas, the mean specific heat capacity of air at constant pressure and thermal conductivity [6]. The outputs are polynomial functions of temperature with coefficients of determination $r^2 > 0.99$. The functions are for individual properties in the following form:

$$A + B \cdot T + C \cdot T^2 + D \cdot T^3 \tag{9}$$

Table 2 Temperature dependence of specific heat capacity

Material	A (Jkg^{-1}K^{-1})	B (Jkg^{-1}K^{-2})	C (Jkg^{-1}K^{-3})	D (Jkg^{-1}K^{-4})
Dinas	805.71	0.25	0	0
Air	905.56	0.31	$-8.62 \cdot 10^{-5}$	$8.62 \cdot 10^{-9}$

Table 3 Temperature dependence of thermal conductivity

Material	A (Wm^{-1}K^{-1})	B (Wm^{-1}K^{-2})	C (Wm^{-1}K^{-3})	D (Wm^{-1}K^{-4})
Dinas	0.99	$6.4 \cdot 10^{-4}$	0	0
Air	0.01	$7.55 \cdot 10^{-5}$	$-2.06 \cdot 10^{-8}$	$4.04 \cdot 10^{-12}$

3 Results

In addition to the referential CFD simulation of the accumulation regime, calculations of the accumulation regime and air blasting regime were performed using the presented NM. For comparison, the method of Zhong and two Nusselt criterion-based methods (Michejev and Hausen) were used to determine the heat transfer coefficient.

The individual outputs differ significantly. The heat transfer coefficient is in the accumulation regime (Figure 4) at the levels around 34-35 W.m^{-2}.K^{-1} during the whole period (based on the reference model). Zhong's model appears to be unsuitable in the accumulation regime, mainly because it is based only on air temperature. In this regime, the blown air is at a temperature of 700°C. Consequently, the heat transfer coefficient becomes too high. Models based on the Nusselt criterion, on the other hand, achieve significantly lower values than the reference model. Nevertheless, they appear to be the more appropriate method.

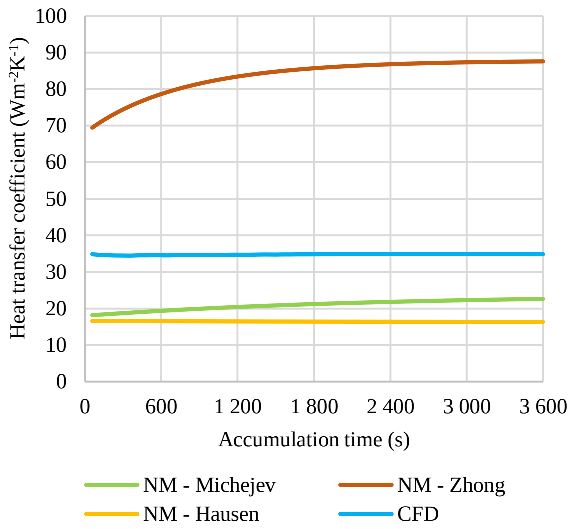

Figure 4 The course of the convective heat transfer coefficient value in the accumulation regime

The CFD simulation of the blasting regime (Figure 5) has not been carried out yet. Nonetheless, once again the outputs of the individual NM variants differ significantly. NMs based on formulas according to Michejev and Zhong have a decreasing course dependent on a gradual decrease in air temperature and a temperature difference. On the contrary, Hausen's model predicts an increasing course. However, by reducing the temperature difference, the value of the heat transfer coefficient should stabilize.

Based on the increasing and decreasing nature of the curves, it can be seen their differential decreases, so stabilization of the values can be expected with further heating. However, it is not clear which model has the potential to describe convective heat transfer with the lowest theoretical error, from the presented outputs.

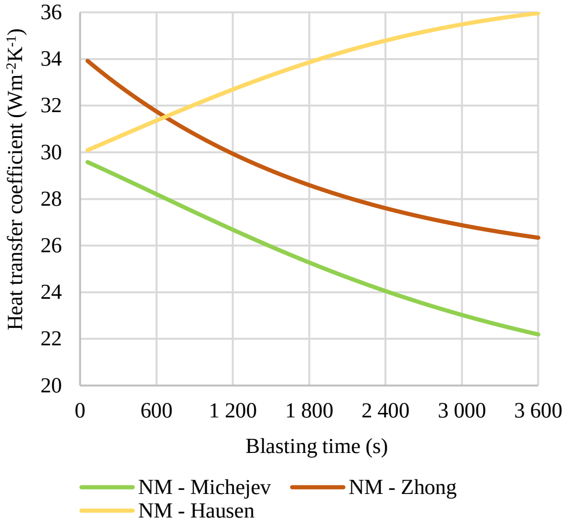

Figure 5 The course of the convective heat transfer coefficient value in the blasting regime

Heat transfer coefficient value primarily characterizes the intensity of heat transfer and thus affects the rate of temperature changes in any NM (Figure 6). Therefore, determining the correct value is crucial. A higher value of the factor according to the referential simulation causes a faster rise of temperatures in the accumulation process than in the case of NM, according to Michejev, which yields lower values.

The presented NMs bases on the concept of thin-wall body heating. However, the output of the reference CFD simulation proves that the heat accumulation in such regenerator does not behave as one of a thin-wall body. Value of Biot number also predicted such behaviour. The mean temperature inside the brick heats up (or cools down) with a delay which is influenced mainly by the thermal conductivity of the material (see Figure 7). Therefore, it will be necessary to incorporate a conduction heat transfer model into the future versions of NM. Its solution can be obtained by a numerical method. Experimental research of thermodynamics on a specific device, however, will allow solving the conduction analytically. The benefit would be a significant jump in the calculation speed.

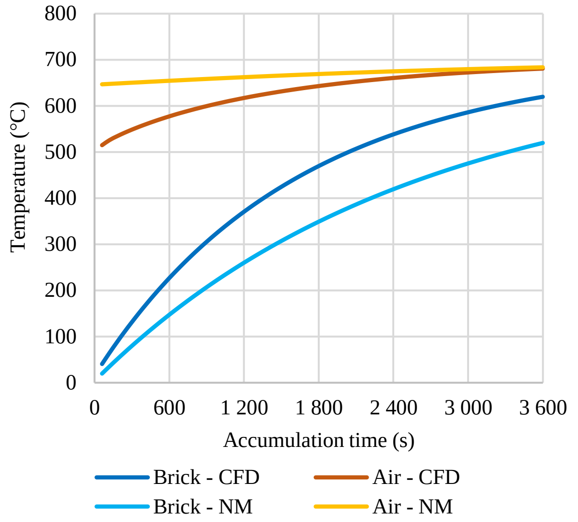

Figure 6 CFD simulation and NM outputs comparison

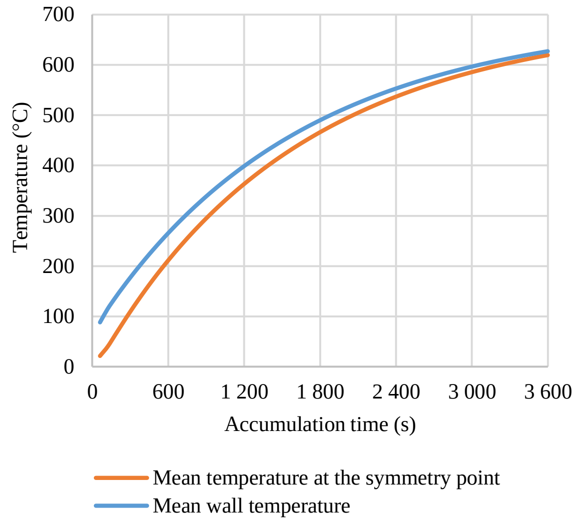

Figure 7 Brick temperature profile during the accumulation

4 Conclusions

The numerical solution of convective heat transfer is usually dependent on the accuracy of determining the convection heat transfer coefficient. The subject of this paper was to analyse the possible methods applicable to the convection solution and to compare those methods to the outputs of a referential CFD model. The ambiguity of the results of the known empirical correlations of the Nusselt criterion further encourages us to further research on this issue. It should include experimental research on heat transfer by convection in HBS. The research will aim to define an empirical dependence of the Nusselt criterion on the nature of the flow, geometrical similarity and thermo-physical properties of the processes in accumulation and blasting regime individually.

Nomenclature

- α_K: convective heat transfer coefficient *(W.m²·K⁻¹)*
- c: mean specific heat capacity *(J.kg.K⁻¹)*
- cp: isobaric mean specific heat capacity *(J.kg.K⁻¹)*
- ε: desired accuracy *(°C)*
- m_s: mass of the solid in a calculation element *(kg)*
- $\dot{m}_f$: mass flow rate of the fluid *(kg.s⁻¹)*
- Nu: Nusselt number *(-)*
- Pr: Prandtl number *(-)*
- ΔQ: change in enthalpy *(J)*
- Q_K: heat exchanged by convection *(J)*
- Re: Reynolds number *(-)*
- S: heat exchange surface *(m^2)*
- t_f: temperature in fluid domain *(°C)*
- t_s: temperature in solid domain *(°C)*
- Δt_{ln}: mean logarithmic temperature difference between wall temperature of solid and mean temperature of fluid in calculation element *(°C)*
- $\Delta\tau$: time step size *(s)*

Indexes:

- *i*: timestep
- *1,2*: position in a calculation zone
- *s*: solid (brick)
- *f*: fluid (air)
- *e*: estimate

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