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Simulation of Deposit Growth on Recuperator Tubes in Pit Furnaces

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Nowadays, the operation of pit furnaces without air preheating is not acceptable. However, a deposit growth on the tubes of air preheaters significantly decreases their efficiency. This paper presents a two-dimensional simulation of the phenomenon of deposition on the tubes of air preheaters with a staggered tube layout. It has been shown that it is possible to predict the deposit shape and its effect on heat transfer from combustion gas to combustion air.

Key words: pit furnaces, deposit, numerical simulation, heat transfer.

1. Introduction

Air preheating with U-tube recuperators, set up in two layouts: in line or staggered (Fig. 1), is a typical element of modern pit furnaces [1, 2]. During long time operation of pit furnaces, the surface of the tube is covered with deposit. This deposition affects the operation of furnaces: increasing heat transfer

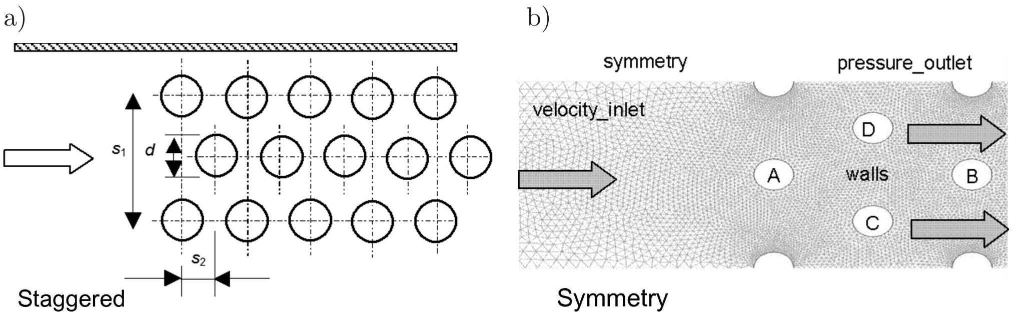

Fig. 1. a) Staggered arrangement of U-tube recuperators and b) a part of a 2-dimensional mesh of simulated recuperator.

resistance, resulting in lower temperature of air and higher of combustion gas increasing pressure drop along the combustion duct, resulting in an increase of energy demand for induced-draft fans, and causing possible acceleration of corrosion of the tube material. The publication [1] presents a review of the deposits found in Polish pit furnaces. In this study, the deposit height ranged from 4 to 6 mm after 3–4 years of operation, with sections where the deposits are 20 mm high. The main problem is that, as opposed to power boilers in which the mineral matter comes from solid fuel, there are no such sources in gas-fired pit furnaces. In coal-fired boilers the ash content of fuel is its standard parameter. In gas-fired pit furnaces, there is no mineral matter originating from fuel and what is found on the tube surface must come from insulation, wall materials and steel stock. Thus, the content of mineral, solid matter in the combustion gas is minimal and extremely difficult to assess or measure. This paper identifies this lack of the mechanism of deposition.

The observed deposits had porous structure with a density assumed as 350–500 kg/m^3, resulting from gas trapped in bubbles. However, some deposits showed grainy structure. To make matters worse, the deposits found on the recuperators are exposed to erosion from the same mineral matter hitting their surface, so what is found after years of operation does not reflect the true deposition process. A type of basic equation for deposition studies was presented in [3], where a correlation between flux of particles moving toward a tube and hitting its surface was formulated. This equation is still used in less complex cases for a comparison with numerical simulations. Since the CFD software is widely available, simulation of deposit formation is part of general studies of heat exchangers. An example of FLUENT code used for prediction of sites where solid particles hit tube surface forming a deposit is presented in [4]. Prediction of deposit shape and features during the operation of coal-fired boilers in the case of superheater and heater tubes was shown in [5]. The just mentioned paper described bonded deposit formation and was the first ever to present a two-dimensional modeling of deposit growth on heat exchanger tubes in commercial boilers. The most important tool for such a prediction is dynamic meshing option in FLUENT code, in which a single node can be moved independently during the calculations. As opposed to [5], the tubes were arranged in this study in a staggered mode. One of the latest publications on using dynamic meshing for prediction of deposition in power boilers is [6]. The authors used this method to compare mass deposited on the tube surface when the spacing between the tubes is changed. Such different arrangements influence the flow pattern of combustion gas and ash particles transported along the boiler ducting. The authors concluded that this method can correctly predict deposit shape, obviously depending on the available data regarding a solid matter.

2. Numerical modeling of deposit formation

A part of the furnace ducting where a recuperator is installed is shown in Fig. 1. The tube is 38 mm in diameter, and tube spacing is $s_1/d = 3$ and $s_2/d = 2.5$. The algorithm is shown in Fig. 2. The combustion gas is simulated by nitrogen and has a temperature of 1000°C at the inlet. Its velocity is 1, 3 or 5 m/s. This gas is treated as ideal in terms of density, its heat capacity is calculated by polynomial approximation, dynamic viscosity and heat transfer as a function of temperature. The solid matter has the same temperature and velocity as combustion gas at the inlet. Its particle distribution has been simulated by ash particles typical for coal, thus it is unknown. So the minimum diameter of these particles is 10 μm, the average one is 20 μm, and the maximum is 200 μm. The Rosin-Rammler parameter was taken as 0.8. As it has already been mentioned, there is no data on real particle distribution and its concentration in the combustion gas. Thus, some tests were required to obtain the probable value – it should be about 0.15 mg/m^3. The initial tube surface temperature was 300°C. The basic equation to calculate the deposi-

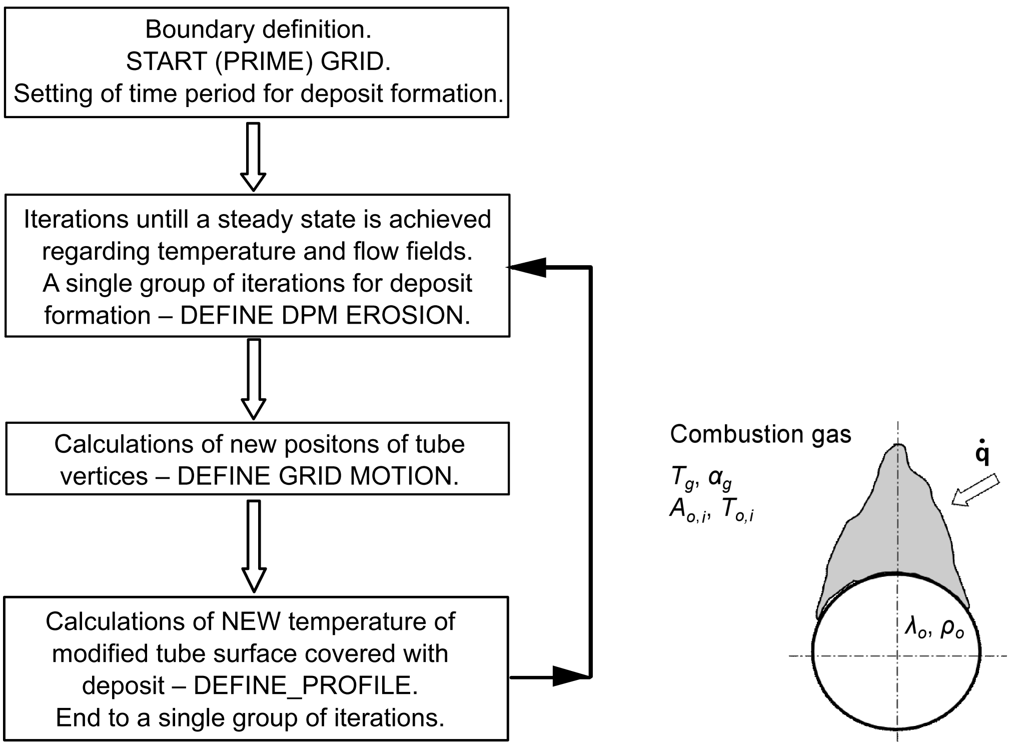

Fig. 2. Algorithm for deposition prediction and a schematic of data for calculation of temperature of deposit surface.

tion rate (which is called "accretion" rate in FLUENT's nomenclature) is as follows:

$$\dot{m}_A = P\frac{\dot{m}_p}{A}\sin\alpha, \tag{2.1}$$

where $\dot{m}_A$ – deposition rate, kg/(s·m^2), P – probability of staying on the surface or sticking efficiency, $\dot{m}_p$ – mass flow of particles hitting the tube surface, kg/s, A – area, m^2, and α – angle at which particles hit the surface, rad. Equation (2.1) is a FLUENT's relationship except for a sinus function. With this function, one can show, to some extent, erosion, because the highest deposit is found where particles hit the tube at a right angle and then sinus equals 1. The most important and, unfortunately, unknown is sticking efficiency in cases of deposition phenomena in pit furnaces. Therefore, in these simulations it was assumed that all particles stick to the surface after an impact, meaning the sticking efficiency was equal to 1. Growing deposit decreases the heat flow from combustion gas to combustion air flowing through a recuperator. Deposition results in increasing temperature of deposit surface and its area. In user defined files (Fig 2), there are equations for the calculation of the new temperature of deposit surface based on the following equation:

$$\dot{q}_i = \frac{T_g - T_{o,i}}{\dfrac{1}{\alpha_g} + \dfrac{g_o}{\lambda_o}}, \tag{2.2}$$

where $T_{g,o}$ – temperature of combustion gas (g), or tube (deposit) surface (o), K, α_g – heat transfer coefficient, W/(m^2·K), λ_o – conductivity of the deposit material, W/mK, and g_o – thickness of the deposit, m. When the growth of a new deposit layer has been simulated and vertices are moved by dynamic meshing, the new temperature of the surface is calculated for each face of the tubes by means of the following equation:

$$T_{o,i} = T_g - \frac{1}{\alpha_g}\dot{q}_i. \tag{2.3}$$

3. Results and discussion

The tube spacing, in a staggered arrangement, significantly influences a gas flow and, eventually, the tracks of solid particles. An example of such tracks for a uniform particle diameter of 100 μm (upper) and size distribution (bottom) and a velocity of 3 m/s is shown in Fig. 3. The second row of tubes is hit with more particles than the first one, because the flow path-lines are "squeezed" there by front tubes. Thus, it is likely there should be higher and faster growing

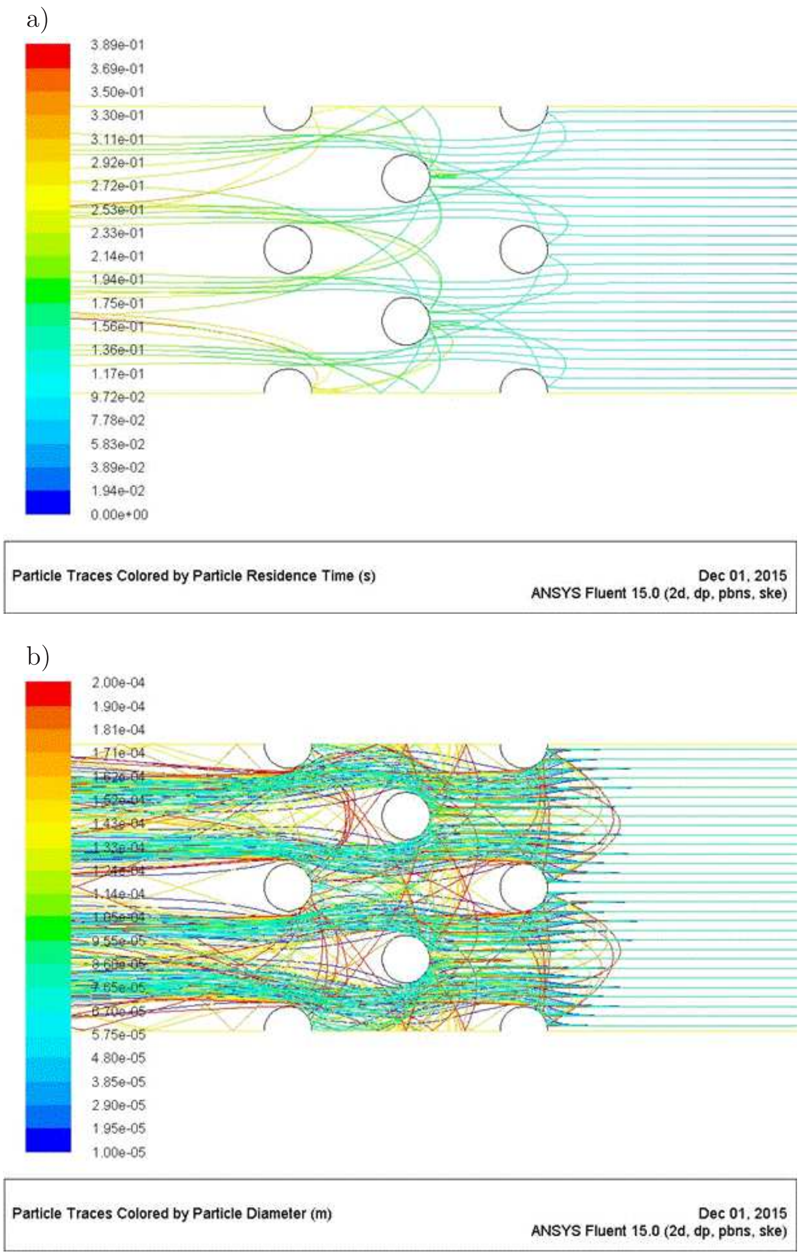

FIG. 3. Tracks of solid particle in the case of their 3 m/s velocity:
a) uniform 100 μm, b) size distribution.

deposits. In order to simulate the deposition phenomena when no real, dependable data is available, a set of velocities was tested: 1, 3 and 5 m/s and constant solid particle flux of $4.38 \cdot 10^{-7}$ kg/(s · m^2) or constant solid particle concentration of $1.46 \cdot 10^{-7}$ kg/m^3. The results showing deposit height on tubes A (first row) and C (second row) during a simulated three-year operation are presented in Fig. 4 for the cases of constant particle mass flow. Surely, during the simulation, as shown in Fig. 3, the temperature of deposit surface is calculated.

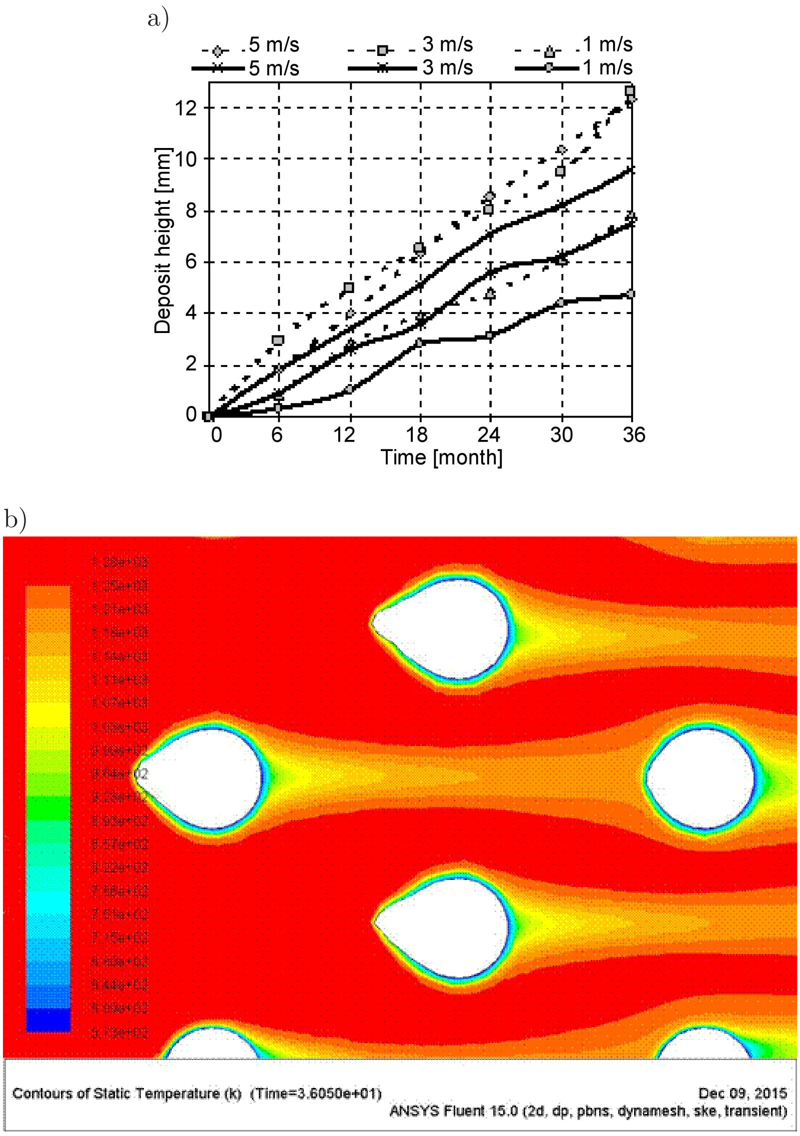

FIG. 4. a) Relationship between velocity of flow and deposit height for tubes in the first and second row, when particles mass flow is constant (solid lines – tube A, and dashed lines – tube C), and b) an example of temperature field, and deposit shape (after three years of operation, when velocity is 5 m/s).

An example of temperature field with deposit present on the tubes is shown in Fig. 4. In Fig. 4 one can notice that deposits grow faster on the first tubes of the second row than on the first row. Basically, the higher the velocity, the higher the deposit is. The reason for this is that the particles moving faster have less time to follow the changing gas path-lines due to their inertia. Such a relationship is shown in [3].

It is interesting to compare deposit growth on the first, front tube A (Fig. 1) and “shaded” by it, tube B. It is obvious that fewer particles hit its surface, leading to a slower deposit growth – see Fig. 5. It should be pointed out that this is particularly true when all particles stick to the tubes, as in our simulations. When some particles jump off the surface, the tube can be additionally hit by them.

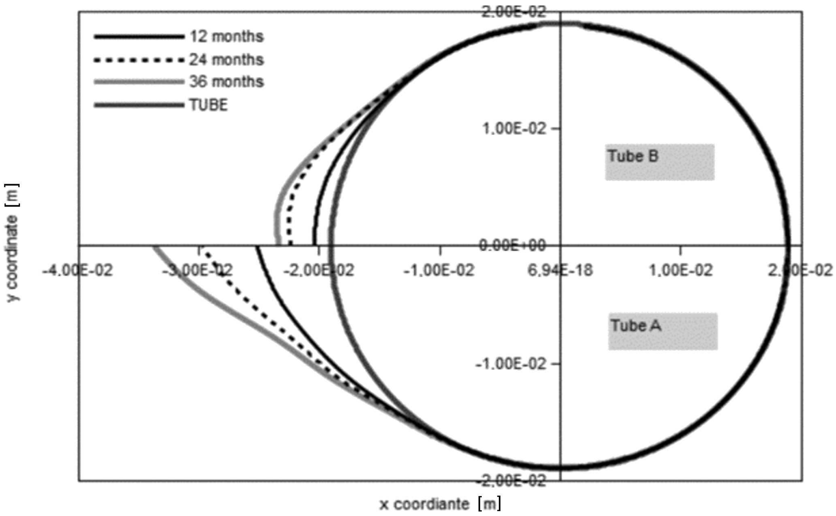

FIG. 5. Shape of deposits on tubes A and B when velocity is 5 m/s and solid particles mass flow is $1.67 \cdot 10^{-7}$ kg/s.

4. CONCLUSIONS

CFD software can be used for more advanced topics such as deposition prediction presented here. The unique feature that enables it is dynamic meshing, which means changing grid during calculations. The growing deposit can be reflected by changing the tube periphery into a bell-like one. In natural gas fired-pit furnaces, deposits grow slowly and their origin and real mechanism of formation is not known or studied. A staggered arrangement of tubes in recuperators applied in pit furnaces can be modeled using the proposed method. It was proved that the second rows are exposed to a faster deposit growth.

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