Applied Thermal Engineering 73 (2014) 399–407

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Three-dimensional simulation of rotary air preheater in steam power plant

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HIGHLIGHTS

- Three-dimensional thermal simulation of full-scale rotary air preheater is presented.
- Variation of isothermal lines in the air preheater are shown.
- Effect of separator plate on the temperature distribution is restricted to center of the matrix.
- Rotational speed of matrix has important role in the performance of preheater until certain limit.

ARTICLE INFO

Article history:
Received 10 April 2014
Accepted 3 August 2014
Available online 8 August 2014

Keywords:
Rotary air preheater
Thermal simulation
Matrix
Preheater performance

ABSTRACT

In this study, thermal behavior of a full-scale rotary air preheater is investigated using three-dimensional approach and treating preheater matrix as a porous media. Mass, momentum and energy equations are solved using moving reference frame (MRF) to incorporate the effect of rotational speed of the matrix. Temperature distributions of the matrix at different conditions have been presented and the effect of essential parameters such as rotational speed of the matrix, fluid mass flow, matrix material and temperature of inlet air on the performance of preheater have been discussed. Numerical results which are confirmed by experimental data show the significant effect of rotational speed, separator plate, fluid flow rate on the performance and temperature distribution of preheater. Increasing the rotational speed of the air heater increases the efficiency up to certain limit, after which it does not significantly change. It was also found that the effect of material change on the efficiency is very limited.

1. Introduction

Rotary air preheater is one of the important energy recovery systems in the steam power plant which was first introduced in 1920 by Ljungstrom [1]. It transfers heat from the hot fluid to the cold one by using a rotating matrix of compact plates as shown in Fig. 1. Considering the important effect of the air preheater on the cycle efficiency, there are many studies addressing preheater efficiency. Warren [2] published his studies on Ljungstrom as a particular type of air to air exchanger and base on the experimental results confirmed a minimum reduction of 10% in power plants fuel consumption. Skiepko [3,4] investigated the effects of heat conduction in the matrix, Peclet number and the length of the matrix on the preheater performance [5,6]. Investigating on the effect of separator plate on the preheater performance, Worsoe-Schmidt [7] stated that although the separator decreases the efficiency of the exchanger, but it cannot be removed due to its role in the reduction of the fluid leakage. Based on the several experimental and numerical analyses, Ghodsipour and Sadrameli [8] studied the effect of mass flow rate and rotational speed of the matrix on the preheater performance and showed that the flow rate effect was more significant than the rotational speed.

Drobnic and Tuma [9] used both numerical and experimental methods to estimate the pattern of Ljungstrom exhaust gas temperature. Sanaye et al. [10] specified the importance of optimizing the speeds of rotation and mass flow rate by using analytical relationships and empirical models. Using a three-dimensional rotary preheater model, Wang et al. [11] obtained the temperature distribution in the exchanger through a semi-analytical method. Passandideh-Fard et al. [12] modeled the exchanger and studied the effects of fluid flow rates and speed by using a two-dimensional finite volume method and periodic boundary conditions.

Despite many studies in this area, there are more rooms for better understanding of the periodic nature of heat transfer process

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http://dx.doi.org/10.1016/j.applthermaleng.2014.08.013
1359-4311/

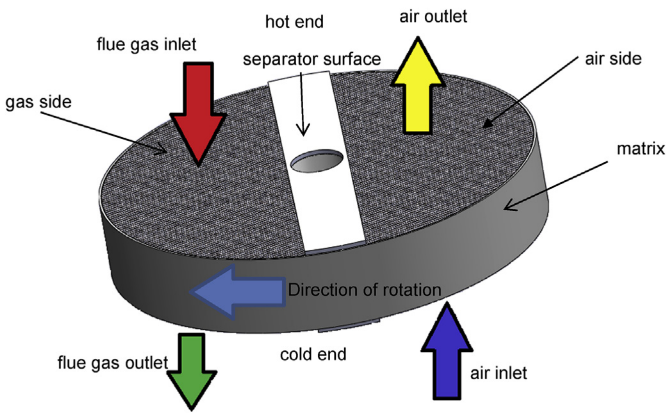

Fig. 1. A view of a rotary pre-heater.

in the rotary preheater. For example, three-dimensional temperature distribution of a preheater has not accurately been presented yet. Furthermore, the effects of influential parameters on the temperature distribution of the matrix have not been addressed sufficiently. In the present study, using three-dimensional approach and considering rotary matrix as a porous media, the governing equations of a full scale rotary preheater located in Ramin power plant located in Iran is simulated to clarify the exact temperature distribution inside the preheater. Moreover, the effects of some variables such as rotational speed of the matrix, fluid mass flow rate, plates' material, and inlet fluid preheating on the temperature distribution and the exchanger performance are investigated.

2. Mathematical modeling and governing equations

Considering the narrow passages of fluids compared to the overall dimensions of the preheater [Fig. 2], a porous media approach can be used to simulate fluids flows in the air heater matrix [13–15]. Using this approach can reduce the computational time while maintaining the results with acceptable accuracy. By experimental measurements of the volume, weight, and dimensions of the compact plates within the rotary preheater matrix, it was found that the porosity in the hot and cold layers is 0.84 and 0.76, respectively.

The Reynolds number of flow in the porous media based on the Eq. (1) is 10.2, which is less than the critical Reynolds number of 100 [16] which indicate that the flow is laminar. In this equation, D_H is the hydraulic diameter and V is the velocity.

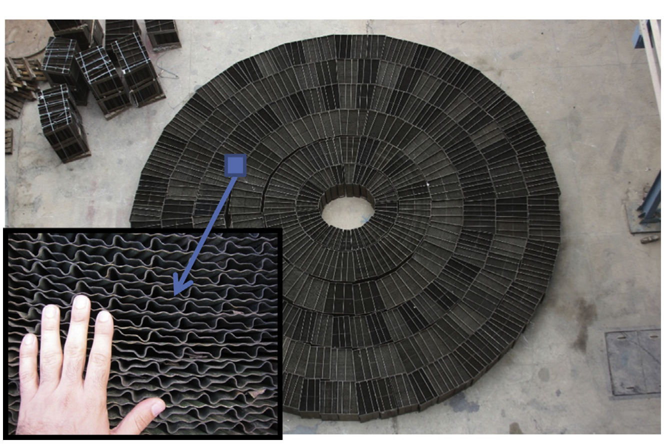

Fig. 2. The actual shape of the plates used in the matrix.

$$Re = \frac{V{*}D_H{*}\rho}{\nu} \tag{1}$$

To simulate the flow and heat transfer within the exchanger, Navier–Stokes equations in the porous medium can be used. Continuity and momentum equations are as follows [16]:

$$\gamma\frac{\partial\rho_f}{\partial t} + \nabla\left(\rho_f \boldsymbol{v}\right) = 0 \tag{2}$$

$$\rho_f\left[\gamma^{-1}\frac{\partial\boldsymbol{v}}{\partial t} + \gamma^{-2}\left(\boldsymbol{v}\cdot\nabla\right)\boldsymbol{v}\right] = -\nabla P - \frac{\mu}{K}\boldsymbol{v} \tag{3}$$

Energy equations for the solid and liquid phases are given in Eqs. (4) and (5), respectively [16].

$$(1-\gamma)(\rho c)_s\frac{\partial T_s}{\partial t} = (1-\gamma)\nabla\cdot(k_s\nabla T_s) + (1-\gamma)q_s^{'''} \tag{4}$$

$$\gamma(\rho c_P)_f\frac{\partial T_f}{\partial t} + (\rho c_P)_f\mathbf{v}\cdot\nabla T_s = \gamma\nabla\cdot\left(k_f\nabla T_f\right) + \gamma q_f^{'''} \tag{5}$$

In general, the energy equations for the liquid and solid phases must be solved separately (local thermal non equilibrium condition), but if the Sparrow number defined in Eq. (6) in a medium is above 100, local thermal equilibrium condition can be applied [17]. In the present medium the Sparrow number is 6061, so local thermal equation condition can be assumed.

$$Sp = \frac{2hL^2}{k_m D_h} \tag{6}$$

Combining solid and fluid phase equations, the energy equation for thermal equilibrium condition is as follow [13]:

$$(\rho c_P)_m\frac{\partial T}{\partial t} + (\rho c_P)_f\mathbf{v}\cdot\nabla T = \nabla\cdot(k_m\nabla T_m) + \gamma q_m^{'''} \tag{7}$$

The efficiency of a rotary preheater is obtained by calculating the ratio of the exchanged energy to the maximum transferrable energy as follow [12,18]:

$$\varepsilon = \frac{\text{heat transfered}}{\text{maximum possible heat transferred}} = \frac{\dot{m}_{\text{air,in}}{*}C_{p,\text{air}}{*}(T_{\text{air,out}} - T_{\text{air,in}})}{\dot{m}_{\text{flue,in}}{*}C_{p,\text{flue}}{*}\left(T_{\text{flue,in}} - T_{\text{air,in}}\right)} \tag{8}$$

To model the preheater, computational grids were used as shown in Fig. 3 and different grid sizes were employed for simulation as seen in Table 1. It was found grid number including 1,052,961 wedge cells is appropriate for the simulation and the results are independent of grid number. Boundary conditions were considered similar to that of real conditions. Inlet and outlet pressure conditions were used for the momentum equation boundary conditions and inlet temperatures of air and gas were used for energy equation boundary conditions. Also it was assumed that the surrounding wall of the air heater was insulated.

Moving Reference Frame (MRF) method was used to incorporate the effect of rotational speed of the matrix. Eqs. (9)–(11) were used for continuity, momentum, and energy equations, respectively. To solve the governing equations FLUENT 6.3 software was used employing SIMPLE algorithm to solve the Navier–Stokes equations.

$$\frac{\partial\rho}{\partial t} + \nabla\cdot\rho\overline{v_r} = 0 \tag{9}$$