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NUMERICAL MODELING OF THERMAL PERFORMANCE OF A COMPACT HEAT EXCHANGER FOR LATENT HEAT RECOVERY FROM EXHAUST FLUE GASES

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ABSTRACT
In this study, the performance of the compact heat exchanger in transient regime was theoretically examined to bring the system the vapour latent heat by condensation of water vapour in flue gas. A mathematical model was developed to examine the effects of inlet temperature, relative humidity, and velocity of flue gases on the overall thermal permeability (UA). In order to develop the mathematical model, the basic laws of heat transfer and thermodynamics and some empirical equations were used. The numerical algorithm of the mathematical model was solved by using the MATLAB R2010. The results show that if amount of water vapour in flue gas, and velocity of flue gas increase, the overall thermal permeability of compact heat exchanger also increase.
Keywords: compact heat exchanger, condensing boiler, heat and mass transfer, latent heat recovery.

1. INTRODUCTION
Considering the rapid depletion of fossil-based non-renewable energy sources, energy saving has utmost impotance nowadays. Energy is very important input for economic growth, and social development. Due to incessantly rising energy prices, countries are forced to separate the largest share of their budgets on energy costs. It is known that solid, liquid and gaseous fuels contain water which evaporates during burning and disposed as flue gas. The value of this gas is at least 10 % more than lower heating value. This is an energy loss. At the same time, the flue gas is exhausted with emission.
Although there are many studies in the literature about recovery of the latent heat in the flue gas, there are very few studies related with the multi-passage compact heat exchanger where water vapour in flue gas throughout thermal surfaces is condensed. In this study, the theoretical analysis of the multi-passage compact heat exchanger has been done.
Threlkeld [1] and Wang et al. [2] have stated that there are wide applications on winged piped heat exchangers in ventilation and cooling industries.
Shook [3] and Osakabe [4] have emphasized that the condensing heat exchangers are important equipments and stated that the studies are focused mainly on shell and tube heat exchangers.
In this study, a winged and plated heat exchanger was designed and a mathematical model was done by theoretically analyzing the system.

2. THEORY

In this study, the first law of thermodynamics, energy equations, Fourier heat transfer law, Newton's cooling law, and some empirical equations were used to make the theoretical analysis of the compact heat exchanger. Calculation of the total heat transfer coefficient of the heat exchanger in the model was carried out by taken into consideration and neglecting the effect of the latent heat. Partial differential equations were solved by using the finite difference method (FDM). While using the FDM, total plates were considered as one surface and, flowing area of water was divided into nodal points of equal spacing. Since exit of water in to the system and entry of water from the system is important in this system. The temperatures of interval values can be calculated by FDM.

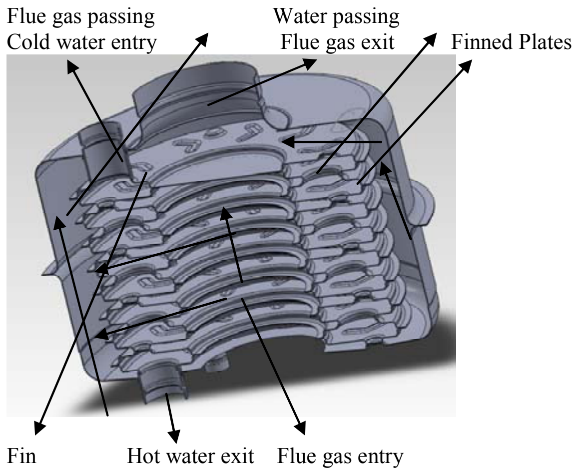

Figure 1. The cross-section of the multi passage compact heat exchanger

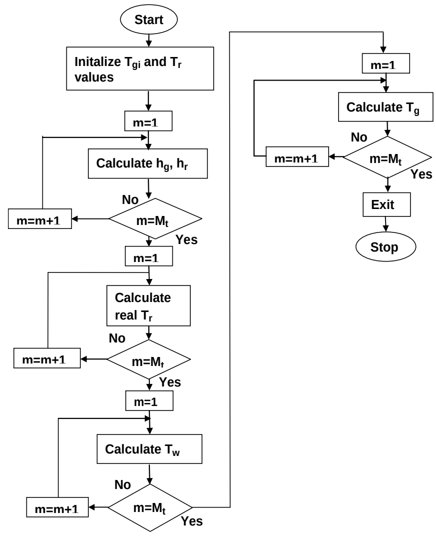

Figure 2. Numerical Algorthm

These nodal points formed the center of the control volumes and the solution was made by using the FDM. The cross section of the heat exchanger and the numerical algorithm are given in the Fig.1 and 2, respectively. Gauss-Seidel iteration method was used for the solution of numerical algorithm and by estimating the air temperature on each cell the calculation was started. First the temperatures on the cooler side and then the surface temperatures of the pipe were calculated. The air temperatures were obtained by using the cooler and the pipe surface temperatures.

The mathematical model to determine the total heat transfer of the heat exchanger was solved by the MATLAB R2010b programme with the numerical algorithm given in Fig.2.

2.1. Calculation of the heat transfer coefficient on the flue gas side

The relationship given below was used by Jaluria [5] for the transfer coefficient on the air side.

$$Nu_L = \frac{h_g L}{k_g} = 0.13(Ra)^{1/3} \qquad (1)$$

2.2. Calculation of the heat transfer coefficient on the water side

Naphon and Wongwises [6] suggest the equation given below for the transfer coefficient inside the pipe of spiral heat exchangers.

$$Nu_i = \frac{h_i d_i}{k} = 27.358 De^{0.287} \Pr^{-0.949} \qquad (2)$$

2.3. The Heat Transfer Coefficient of The Condensed Water Vapor in Flue Gas

Latent heat transfer occurs due to condensation of water vapor in flue gas. To find a transfer coefficient for the condensed water, the enthalpy of the water was used.. If the temperature of the flue gas drops to the temperatures of dew point, water starts to condense on the surface of the heat exchanger and forms a thin film. The heat transfer coefficient of the condensed water can be found by using the equations given below.

$$h_f\left(T_g - T_f\right) = m_f^{"} h_{fg} \tag{3}$$

$$h_f = \frac{m_f^{"} h_{fg}}{\left(T_g - T_f\right)} \tag{4}$$

2.4. Determination of the effective heat transfer coefficient.

The vaporization latent heat consists of condensing of water vapour. The gas having a certain temperature has the sensible heat. The heat convection coefficient involving the sensible heat is called the effective heat convection coefficient. The effective heat convection coefficient is given in the following form.

$$h_{eff} = h_g + \frac{m_f^{"} h_{fg}}{\left(T_g - T_f\right)} \tag{5}$$

2.5. Determination of the Total Heat Transfer Coefficient

The total heat transfer coefficient was calculated for two different conditions. First one is the calculation of the total heat coefficient by neglecting the latent heat in the flue gas. Equation (6) is for this calculation. The second one is the calculation of the total heat coefficient by taking into consideration the effective heat transfer coefficient. Equation (7) is for this calculation.

$$U_T = \frac{1}{\frac{1}{h_g} + \frac{z}{k_w} + \frac{1}{h_i}} \tag{6}$$

$$U_{Teff} = \frac{1}{\frac{1}{h_{eff}} + \frac{z}{k_w} + \frac{1}{h_i}} \tag{7}$$

2.6. Energy balance for the pipe side

The temperature of pipe surface was found by using the relation given below.

$$m_w\, c_{p,w} \frac{\partial T_w}{\partial t} = k_w\, A_w \frac{\partial^2 T_w}{\partial x^2} L_w + A_w\, h_{eff}\,(T_g - T_w) - U_{wr} A_w (T_w - T_r) \tag{8}$$

Where, m_w is pipe mass, $c_{p,w}$ is the specific heat of the pipe.

U_{wr} shows the coefficient of total heat transfer from the pipe to the cooler and this coefficient was calculated by using the equation given below.

$$U_{wr} = \frac{1}{\frac{z}{k_w} + \frac{1}{h_i}} \tag{9}$$

2.7. Energy balance for the cooler side

The energy balance for the cooler side can be written as

$$M_r\,.c_{p.r}\,.\frac{\partial T_r}{\partial t} + \dot{m}_r\, c_{p.r} \cdot \frac{\partial T_r}{\partial x} = A_w \cdot \frac{U_T}{L}(T_g - T_r) \tag{10}$$

Where $C_{p,r}$ and M_r are specific heat of the cooling fluid and the mass of the fluid per unit length, respectively.

2.8. Energy balance for the air side

The energy balance for the air side can be written as

$$M_g.c_{p,g}\frac{\partial T_g}{\partial t}+\dot{m}_g.c_{p,g}\frac{\partial T_g}{\partial y}=h_{eff}\cdot\frac{A_w}{t_w}(T_g-T_w)+\frac{h_{fg}}{t_w}.\dot{m}_{fg} \qquad (11)$$

Where M_g, $C_{p,g}$ and h_{fg} are the mass of the flue gas per unit length, specific heat of the gas and the vaporization enthalpy of the water vapor, respectively.

3. RESULT AND DISCUSSION

The flue gas temperatures are quite high in conventional and non-condensing boiler. If the temperature of the flue gas is dropped to less than 55° C, the lost heat given to the atmosphere can be recovered. This means saving energy at least 10 %. Besides this, particles are prevented to pollute the atmosphere, because of the increase in the particle density and so the emission values drops significantly and energy is saved more than 10%.

In this theoretically study, it is shown in **Fig. 3**. that the comparison as channel length of the total heat transfer coefficient, which calculated from the effective heat transfer coefficient in Equation (7), and U_T value in Equation (6). At the same time, Fig. 3. shows the effect of the latent heat in waste gas on total heat transfer coefficient of compact heat exchanger. The latent heat is in connection with condensing of water vapor in the flue gas.

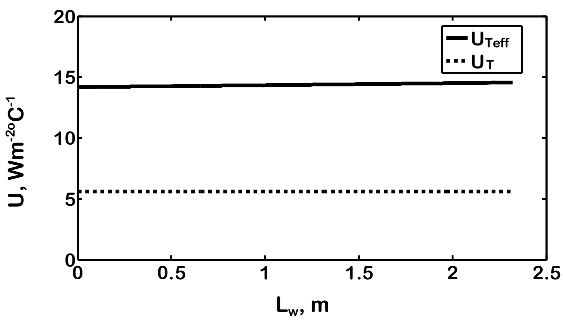

Figure 3. The effect of the latent heat in waste gas on total heat transfer coefficient of compact heat exchanger

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