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Heat Transfer Modeling and Analysis of a Rotary Regenerative Air Pre-heater

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Abstract: An air pre-heater (APH) utilizes the waste energy contained in the hot flue gas of a thermal power plant to increase the overall thermal efficiency. The analysis of an air pre-heater is important because it is a part of almost all thermal power plants and there is a global dependency of more than 80% on thermal power. An attempt was made to model the 3D structure using Comsol Multiphysics® and feeding the structure with proper inlet and boundary conditions similar to real life scenario. The primary objective of the work is to give a clear picture of the temperature profile present in different regions of an air pre-heater and identify regions which undergo maximum thermal fatigue stresses. On completion of simulation, the complete 3D temperature profile was obtained. Also, it was found out that the metal plates to the periphery of the APH are subjected the maximum thermal fatigue stress and plates to the centre experience the least thermal fatigue stress.

Keywords: Air pre-heater, Heat transfer, Thermal efficiency, Temperature Profile.

1. Introduction

A very good method to improve the overall efficiency of a thermal power plant is to preheat the air. If the incoming air for combustion is not preheated, then some energy must be supplied to heat the air to a temperature required to facilitate combustion. As a result, more fuel will be consumed which increases the overall cost and decreases the efficiency.

The rotary regenerative air pre-heater (APH) (Ljungstrom) is more widely used than any other type of heat exchanger for comparable service .Proven performance and reliability, effective leakage control, and its adaptability to almost any fuel-burning process, are the basis for its preference. It is both designed and built to operate over extended periods with durable service. Simplicity of design also makes it easy and economical to maintain while in operation.

For fossil fuel-fired power generators and industrial processes, the recovery of waste heat energy has proven to be one of the most effective ways to conserve fuel and lower operating costs. Fuel savings with the Ljungstrom APH are about 1-1½% for every 40°F to 50°F increase in combustion air temperature, depending on the application. They not only provide the highest fuel saving efficiency that is available, but their simplified design and operating integrity assure continuous reliable service throughout the life of the Plant. Heat energy is captured and transferred to incoming air for combustion before it is lost to the stack. The result is a substantial saving in fuel that would otherwise be required to bring the air up to combustion temperature.

A rotary regenerative APH consists of a central rotor which keeps rotating at a constant speed. The heat transfer surfaces which are referred to as matrix is attached to the central rotor. The APH is divided into two sectors. Hot flue gas enters from the top and leaves from the bottom in one sector; ambient air enters from the bottom and leaves from the top in the other sector.

During the heating phase, the hot flue gas comes in contact with the matrix and transfers its thermal energy. Moreover, the temperature of the matrix keeps increasing continuously in the heating phase as it is always in contact with the hot flue gas. Once the matrix comes to the other sector on rotation, energy is transferred in the form of heat from the hot metal matrix to the ambient air. As a result, the metal matrix cools down and the ambient air gets heated and leaves from the top. This cycle keeps happening in an APH continuously and heat is alternatively stored and rejected by the matrix.

Due to the continuous heating and cooling of the metal matrix, it is subjected to continuous thermal fatigue stress due to the temperature difference present between the heating and cooling cycle. It is crucial to identify the thermal fatigue stresses at different regions of the APH to predict the probability of a particular region to succumb before another. The research work aims to identify such regions by analyzing the three dimensional temperature profiles.

2. Literature survey

Fredrick Ljungstrom was the pioneer credited with coming up with the design for the APH. By the year 1926, the APH had become a part of many thermal power plants as a substantial amount of coal could be saved over a period of time. The first recognized work on the temperature distribution of an APH was done by Hausen and was used till 1948. Mondt provided an improvised model by taking into account the longitudinal conduction effects [1]. Lambertson came up with the complete solution for the temperature distribution for the APH in the hot and cold sectors [2]. An axial stationary conduction model for the APH was developed by Bahnke and Howard [3]. Lambertson, Mondt, Bahnke and Howard used the principles of finite difference method to treat steady-state behaviour with respect to both finite rotational speed and finite longitudinal heat conduction in a solid. Leong and Toh [4] developed software for the regenerator simulation using the ∑-NTU method. Beck [5] extended Bahnke and Howard's solution with matrix surface effects on the regenerator performance.

3. Analytical Model and Assumptions

The following assumptions were considered in modeling and carrying out the analysis for the APH.

3.1 Assumptions

1) The heat transfer between the gas and the matrix happens by only Forced convection.
2) The thermal properties of the fluids and the metal matrix remain constant with respect to time and temperature.
3) The possible mixing between the fluids is not taken into account.
4) The fluids travel in counter flow directions.
5) Heat loss from the air pre-heater walls to the surrounding is very negligible.
6) There is no heat exchange between the fluids at the entry or exit cross-section.
7) The inlet temperature of the flue gas and ambient air is assumed to be constant with respect to time.
8) There is a constant pressure gradient existing between the inlet and the outlet to keep the flow velocity of the flue gas and ambient air constant.

3.2 Governing Equations

Larsen [6] has used a simplified approach for calculating the empirical relations of heat transfer in an APH. By using the one dimensional conservation of energy for the moving fluid and the storage unit, the transient response of the storage unit is calculated. i.e., by considering an incremental volume Δz in the longitudinal direction, the energy entering the incremental volume is equal to the energy leaving the volume in addition to the energy accumulated.
A supplementary assumption includes infinite thermal conductivity in the longitudinal direction [7].

$$\frac{\mathrm{hA\Delta z}}{L}(\mathrm{t_m - t_f}) + \mathrm{m_f c_f t_f}|_{\mathrm{z}} = \mathrm{m_f c_f t_f}|_{\mathrm{z+\Delta z}} + \mathrm{S_f \Delta z \rho_f}\frac{\partial \mathrm{t_f}}{\partial \mathrm{r}} \tag{1}$$

$$\mathrm{t_f}|_{\mathrm{z}} = \mathrm{t_f}|_{\mathrm{z+\Delta z}} + \frac{\partial \mathrm{t_f}}{\partial \mathrm{r}}\Delta \mathrm{z} \tag{2}$$

The terms on the left of equation (1) indicate the energy transferred from the storage material to the fluid and the energy of the fluid entering the volume. The right hand side in equation (1) represents the energy of the fluid leaving the fluid plus the rate of accumulation of energy (can be neglected in most practical cases) in the incremental volume.
The final form of equation for the heat transfer in both the fluids is:

$$\frac{Lm_f c_f}{\mathrm{hA}}\frac{\partial t_f}{\partial z} = t_m - t_f \tag{3}$$

The boundary and the initial conditions are

$$\mathrm{r} = 0, \mathrm{t_m} = \mathrm{t_0} \tag{4}$$

$$\mathrm{r} > 0, \mathrm{t_m} = (\mathrm{t_0} - \mathrm{t_{fi}})\exp\left(\frac{\mathrm{r\,hA}}{S_m \rho_m c_m L}\right) + \mathrm{t_{fi}} \tag{5}$$

Non dimensional time, length are introduced to make the equations more simple.

Non-dimensional length:

$$\xi = \frac{hAz}{m_f c_f L}$$

Non-dimensional time:

$$\eta = \frac{hA\,\tau}{S_m \rho_m c_m L}$$

Non-dimensional fluid temperature:

$$\theta_f = \frac{t_f - t_0}{t_{fi} - t_0}$$

Non-dimensional solid temperature:

$$\theta_m = \frac{t_m - t_0}{t_{fi} - t_0}$$

Hence the simplified equation becomes

$$\frac{\partial \theta_f}{\partial \xi} = \theta_m - \theta_f$$

$$\frac{\partial \theta_m}{\partial \eta} = \theta_f - \theta_m$$

The initial & boundary conditions:

$\eta = 0, \theta_m = 0 \mid \xi = 0, \theta_m = 1.0 - \exp(-\eta)$

4. Numerical Analysis

Numerical Analysis has a marked advantage when compared to theoretical analysis for solving the temperature profile of a 3D APH. Considering equation (1), better solution can be obtained by considering the heat transfer in the radial direction. If considered, the equations become more complex and extremely strenuous to compute the temperature at one single point. Also, the solution of the previous equations is necessary for solving subsequent equations. When the rotation effects are considered, obtaining the right equations becomes a hard task without having sizeable assumptions. As a result, plotting the temperature profile at various regions of an APH becomes a tough task.
Without the temperature profile, identifying regions under thermal fatigue stress is impossible. These problems are negated in the numerical analysis as the computer can perform faster, more accurate calculations and by considering all the boundary conditions.
For the analysis, a miniature simplified version of the APH is considered as shown in Figure 1. The figure comprises of a central rotor, and supplementary plates which rotate at a constant 2 rpm. The material considered for the analysis is of carbon steel, as it is strong, durable and capable of withstanding high temperature for long period of time.

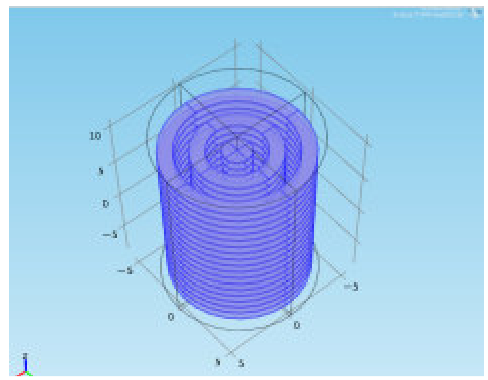


Figure 1: The rotary elements of the APH.

4.1 Heat transfer modeling in COMSOL Multiphysics

The physics used in COMSOL is heat transfer. The domains of rotary elements are solved for by using the heat transfer in solids. The rotation of the elements is also defined. The flue gas and the air to be heated are solved for by using the heat transfer in fluids.
The boundary conditions and material properties are listed in the Table 1 below.

Inlet temp. of flue gas	623 K
Inlet temp. of ambient air	298 K
Flow velocity of flue gas	7 m/s
Flow velocity of air	7 m/s
Rotations per minute	2
Overall diameter of APH	10 meters
Total height of APH	20 meters

Material	Density (Kg/m^3)	Thermal conductivity (W/m-K)	Heat capacity (kJ/Kg-K)
Carbon steel	7700	19	510
Flue gas	0.616	0.0454	1.047e3
Ambient air	0.580	0.0485	1.05e3

Table 1: Boundary conditions and material properties.

4.2 Mesh

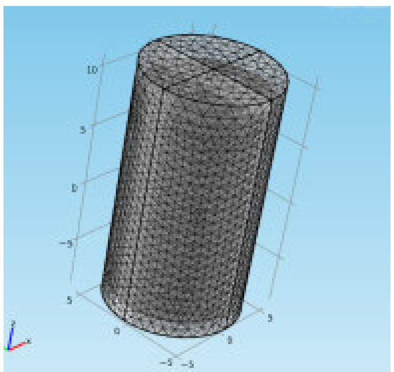
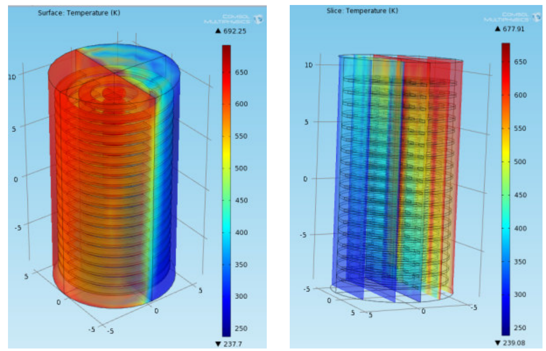


Figure 2: The model after meshing

The starting point for the finite element method is a mesh, a partition of the geometry into small units of a simple shape, mesh elements. The basic concept is the subdivision of the mathematical model into non-overlapping components called elements. The response of each element is expressed by unknown functions and the response of the whole model is then considered to be approximated by assembling the collection of all elements. Therefore, Finite-element requires discretization of the domain which is done by meshing, so that, nodal representation of the geometry and functional representation of the domain can be obtained. FEM is heavily meshing dependent. A tetrahedral mesh was used with a minimum element size of 0.2 units with an element growth rate of 1.45. The heat transfer analysis is carried out and the temperature profile is obtained.

5. Results

Figure 3(a) represents the actual temperature profile and figure 3(b) represents the temperature variation longitudinally at various planes parallel to the longitudinal axis of APH. The vertical plates in figure 3(b) are imaginary and aid in obtaining the temperature profile at various locations.



(a) (b)

Figure 3: (a) temperature surface plot and (b) temperature slice plot of the APH

The temperature at various points on the plate in the longitudinal direction was found out using the inbuilt tools of COMSOL, for both the flue gas and ambient air side. The temperature obtained was plotted and the graph given below (Figures 4 and 5) shows the temperature profile in the longitudinal direction at various radii.

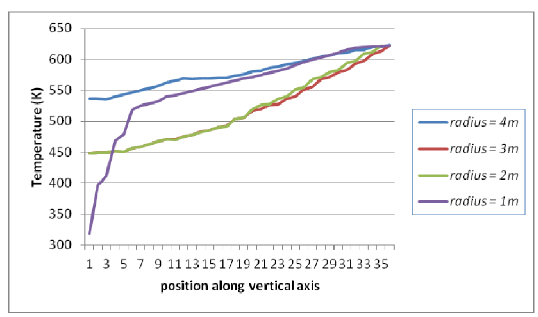


Figure 4: Temperature profile along the vertical direction on the flue gas side.

Also the radial temperature profile at different height is obtained and can be seen clearly in Figure 6 and Figure 7.

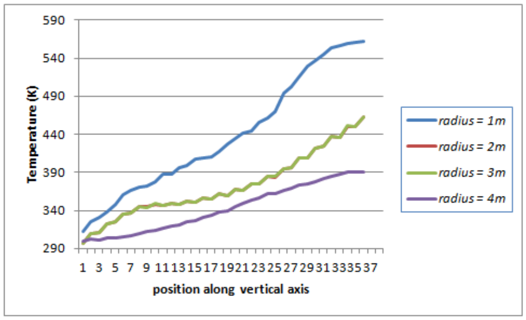


Figure 5: Temperature profile along the vertical direction on the air side.

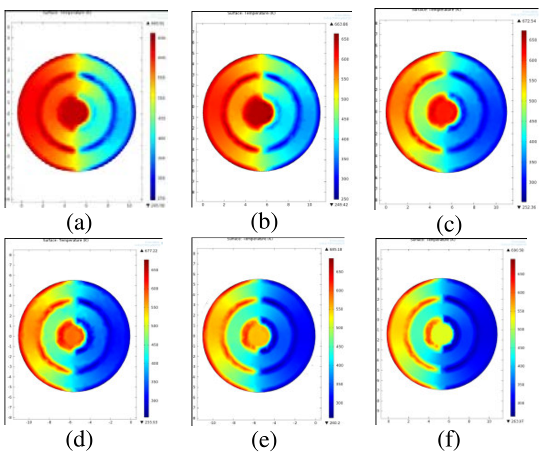


Figure 6: surface temperature plots at various heights. (a) shows the temperature near the top and (f) near the bottom, and the other ones inbetween.

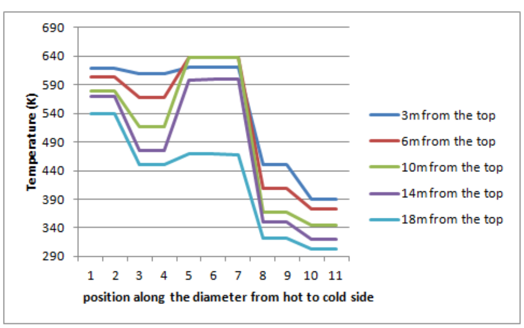


Figure 7: Temperature variation along the diameter at various heights from the top of APH

Since no surface/thermal losses are considered, the APH operates at almost 100% efficiency. The average outlet temperature of flue gas and ambient air are 477.92 K, 445.66 K respectively. The drop in temperature of the flue gas is almost equal to the gain in temperature of the ambient air as the mass flow rate and other physical properties are almost same.

6. Discussions

From Figure 7, we can see that along position 1-2 in the flue gas side, the plates of the APH are at an average temperature of 580 K. At position 10-11, the corresponding plate section at ambient air side experiences an average temperature of 340 K. There exists a temperature difference of 240 K, which is the greatest when compared to other regions. Regions 5-7 represent the central rotor and it experiences the least temperature change. Regions 2-3, 4-5, 7-8, 9-10 are hollow regions present between two plates of an APH.

7. Conclusions

From figures 4 and 5, we can observe that the temperature gradient in longitudinal direction is maximum at regions close to the rotor and decreases when moved outside in radial direction. As a result, maximum heat transfer from the flue gas to ambient air occurs at regions closer to the rotor and decreases near the periphery. From figure 6, we can see that there is a gradual decrease in temperature in the flue gas side as we move down the APH and a gradual increase in temperature in the ambient air side. Also the plates at the periphery/near the circumference are generally subjected to maximum thermal fatigue stress as they undergo the maximum change in temperature. Therefore, for longer life and better sustainability of the APH, they must be made of a tougher material capable of withstanding thermal fatigue stress. Another notable observation is that the rotor is subjected to the least thermal fatigue stress but in general is present at the highest temperature compared to other regions. Therefore, the rotor or the central medium must be made up of a material capable of withstanding high temperature for a long span of time.

8. Nomenclature

A : heat transfer area [m^2]
C : specific heat (J·kg·^{o}C^{-1}]
H : convective heat transfer coefficient [W·m2·^{o}C^{-1}]
L : matrix (rotor)'s height [m]
t : temperature [^{o}C]
z : height direction of rotor

Greek Letters

η : non-dimensional time
θ : non-dimensional temperature
ξ : non-dimensional length
ρ : density [kg·m^3]
r : time [s]

Subscript

c : cold air
f : fluid
h : hot gas
i : inlet, entering
o : outlet, leaving

9. References

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