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# Modeling of Heat transfer in Fluidized ash cooler

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**Abstract-**The fluidization technology has been used for various applications in the industry, from combustion of coal to gasification of fuel. The modeling of novel technique is used for cooling bed ash of fluidized bed boiler is proposed in this paper. Bed ash generated in boiler is about 850 Deg c and transportation of this hot ash is difficult, many technologies has been proposed such as rotary ash cooler, water cooler ash cooler to cool the ash to a temperature at which it can be transported easily and safely by conventional technology. In this paper the one dimensional heat transfer model of cooling of ash and heating of air due to fluidization is proposed. The finite difference numerical method has been used to solve the mathematical model of ash cooler. The ash cooler can be designed and manufactured based upon the actual inputs of ash generation in boiler.

**Index Terms –** Fluidization modeling, Ash cooler, Heat transfer

## 1. INTRODUCTION

When an evenly distributed air or gas is passed upward through a finely divided bed of solid particles such as sand supported on a fine mesh, the particles are undisturbed at low velocity. As air velocity is gradually increased, a stage is reached when the individual particles are suspended in the air stream – the bed is called "fluidized". With further increase in air velocity; there is bubble formation, vigorous turbulence, rapid mixing and formation of dense defined bed surface. The bed of solid particles exhibits the properties of a boiling liquid and assumes the appearance of a fluid – "bubbling fluidized bed. Circulating fluidized bed (CFB) boiler bottom ash contains large amounts of physical heat. While the boiler combusts the low-calorie fuel, the ash content is normally more than 40% and the physical heat loss is approximately 3%, if the bottom ash is discharged without cooling [2]. In addition, the red-hot bottom ash is bad for mechanized handling and transportation, as the upper limit temperature of the ash handling machinery is 200 °C. Therefore, a bottom ash cooler is often used to treat the high temperature bottom ash to reclaim heat, and to have the ash easily handled and transported. As a key auxiliary device of CFB boilers, the BAC has a direct influence on the secure and economic operation of the boiler. There are many kinds of BACs equipped for large-scale CFB boilers with the continuous development and improvement of the CFB boiler, such as water cooled ash cooling screw, rolling-cylinder ash cooler (RAC) [8], fluidized bed ash cooler and high-strength steel belt ash cooler. The RAC and FBAC have a large capacity, and have been commonly and reasonably applied in boilers. In CFBC boiler the ash generated due to combustion of coal is collected in major four areas. The temperature and fineness of ash collected in this area varies with each other. These are illustrated in the above figure 1 along with its collection percentage. The temperature of bed ash, cyclone ash, Air preheater ash and ESP ash are 850 Deg C, 420 Deg C, 170 Deg C and 150 Deg C. As the upper limit commonly and reasonably used in CFBC temperature of the boiler ash handling machinery is 200 °C.

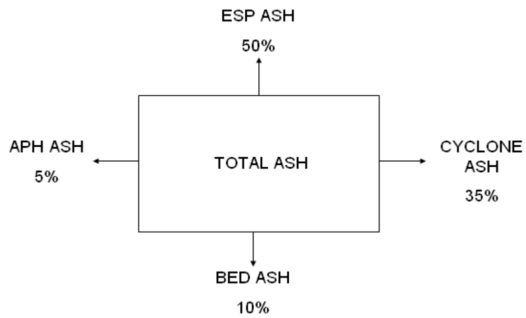


Fig 1 Typical Ash distribution in Boiler

Therefore, ash cooler is often used to treat the high temperature bottom ash to reclaim heat, and to have the ash easily handled and transported. This bed ash starts accumulating gradually in the boiler bed during the boiler operation. This accumulation of bed ash in the boiler bed increases the boiler bed height which in turn increase the static head of primary air required for fluidizing the bed. Therefore extra accumulated bed ash should be drained from the bed so as to maintain sufficient bed height (~1000mm) for proper fluidization and combustion. To facilitate the draining of this accumulated bed ash from the bed the bed ash drain pipes of 200NB are provided. Each ash drain pipe is connected to Fluidized air bed ash cooler. In FBAC bed ash at 850$^{o}$C is cooled to temperature of 200$^{o}$C with help of air at 40$^{o}$C which is tapped from PA fan discharge duct. Hot air at FBAC outlet after absorbing the heat from the ash is connected to the SA nozzles and fed to the furnace.

The typical proposed arrangement of ash cooler is shown in the figure 2. The ash cooler will be provided with the hot ah inlet and cooled ash outlet with isolation gate. The hot ash will be taken to cooler where it is cooled by cold air and hot air will be sent to boiler furnace.

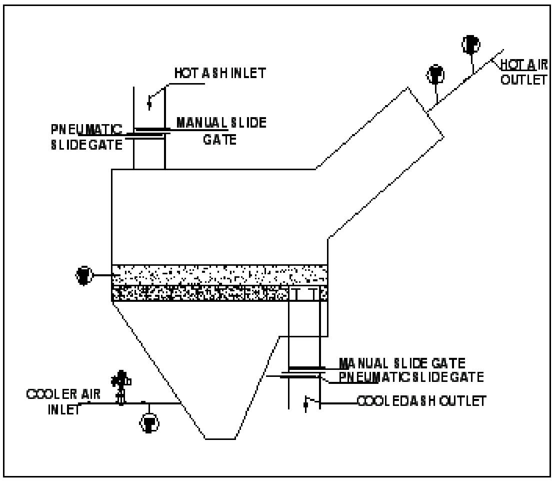


Fig.2 Typical proposed arrangement of ash cooler.

## 2. FLUIDIZATION DYNAMICS

The total heat duty of ash cooler is calculated by equation 1,

$$Q_{ash} = M_{ash} \times Cp_{ash} \times (Tai - Tao) \qquad \text{Eq. (1)}$$

Total air required for cooling of ash is calculated by energy balance equation i.e. heat lost by ash particle is equal to heat gained by air.

$$Q_{ash} = Q_{air}$$
$$M_{ash} \times Cp_{ash} \times (Tai - Tao) = M_{air} \times Cp_{air} \times (Tgi - Tgo) \qquad \text{Eq. (2)}$$

$$M_{air} = (Cp_{air} \times (Tgi - Tgo)) \div (M_{ash} \times Cp_{ash} \times (Tai - Tao)) \qquad \text{Eq. (3)}$$

The $U_{mf}$ minimum fluidization velocity, it is the velocity at which a packed bed becomes fluidized and is proportional to size and density of bed particle [3].

$$U_{mf} = \mathrm{Re}_{mf} \times \mu_g \div (d_p \times \rho_g) \qquad \text{Eq. (4)}$$

Reynolds number can be expressed in relation with Archimedes number as

$$\mathrm{Re}_{mf} = (33.7^2 + 0.0408 \times Ar)^{0.5} - 33.7 \qquad \text{Eq. (5)}$$

Archimedes number of solid particle

$$Ar = [g \times d_p^{\ 3} \times \rho_g \times (\rho_p - \rho_g)] \div \mu_g^{\ 2} \qquad \text{Eq. (6)}$$

The relation between pressure loss and fluid velocity in the packed bed region is described by the Carman-Kozeny equation 7 in the laminar regime and the Ergun equation [1].

$$\Delta P_{fb} = \frac{180\ H\ (1 - \varepsilon_g)^2\ \mu_g \times U_{mf}}{\varepsilon_g^{\ 3}\ (\phi_s \times d_p)^2} \qquad \text{Eq. (7)}$$

The pressure drop across fluidizing bed is given by [5]

$$\Delta P_b = g \times (1 - \varepsilon_g) \times H_b \times (\rho_p - \rho_f) \qquad \text{Eq. (8)}$$

The function of the air distribution grate or plate in a fluidized bed is to support the bed materials and uniformly distribute the fluidizing gas into the bed of solids. This is a critical part of designing a fluidized bed technology. Beyond the distributor, it is not possible to control or influence the distribution of air through the solids due to the absence of physical devices for this purpose. Furthermore, the non-uniform distribution of air in a cooler can result in reduced performance and agglomeration resulting in the complete collapse.

Distributor plates as shown in figure 3 can be broadly classified into three broad classes namely

- Porous and straight-hole orifice type plates (plate with punched or vertical drilled holes). Also it is called as plate-type distributor.
- Nozzle-type or bubble cap-type uses nozzles, which distribute air into the bed through horizontal vertically, or downward holes.
- Sparge pipe-type comprises air-carrying tubes with holes introduced directly into the fluidizing bed without a grid plate or plenum.

The nozzle type plate distribution grate was chosen for the design of the fluidized ash cooler in this case. This is due to the simplicity of the design, minimal operating constraints and the uniform distribution of air throughout area. Therefore, the ideal design of a distributor is vital in realizing a distributor pressure drop (ΔPd) which is a sufficient fraction of the bed pressure drop ΔPb . The relationship between bed pressure drop (ΔPb) and distributor pressure drop (ΔPd) is a function of bed depth and height at minimum fluidization [1,6].

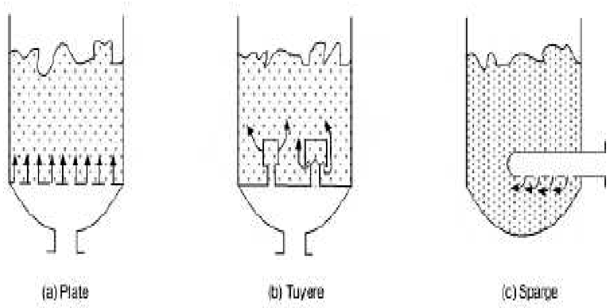


Figure.3 Generic forms of distributor plates [1,6].

In the design of bubbling fluidized beds, the distributor pressure drop (ΔPd) is maintained within a range of 15 to 30 % of the bed pressure drop ΔPb. So assuming pressure drop in the distribution plate is 20 % of bed pressure drop [1, 6].

## 3. GOVERNING EQUATIONS AND BOUNDARY CONDITION

### *3.1 Governing equation*

The following assumptions are made while writing governing equation for ash cooler.
Fluid flow is one dimensional.
Contribution of kinetic, potential energy as well as shaft work is negligible.
Heat lost from top, bottom and side of cooler is negligible.
Ash particle closely spaced to each other hence radiation heat transfer is neglected.
Based on above assumption, the governing equation and boundary conditions can be written

Conservation of mass in air phase

$$\frac{\partial(\varepsilon_g \rho_g)}{\partial t} + \frac{\partial}{\partial x}.(\varepsilon_g \rho_g U_g) = 0 \quad \text{Eq. (9)}$$

Conservation of mass in solid phase

$$\frac{\partial(\varepsilon_s \rho_s)}{\partial t} + \frac{\partial}{\partial x}.(\varepsilon_s \rho_s U_s) = 0 \quad \text{Eq. (10)}$$

Conservation of momentum in air phase

$$\frac{\partial(\varepsilon_g \rho_g U_g)}{\partial t} + \frac{\partial}{\partial x}.(\varepsilon_g \rho_g U_g.U_g) = -\varepsilon_g \frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\tau_g + \varepsilon_g \rho_g g \quad \text{Eq. (11)}$$

Conservation of momentum in solid phase

$$\frac{\partial(\varepsilon_s \rho_s U_s)}{\partial t} + \frac{\partial}{\partial x}.(\varepsilon_s \rho_s U_s.U_s) = -\varepsilon_s \frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\tau_s + \varepsilon_s \rho_s g \quad \text{Eq. (12)}$$

Energy equation in air phase

$$\frac{\partial(\varepsilon_g \rho_g e_g)}{\partial t} + \frac{\partial}{\partial x}.(\varepsilon_g \rho_g U_g.e_g) = \dot{q} + \frac{\partial}{\partial x}(k_g \frac{\partial T_g}{\partial x}) \quad \text{Eq. (13)}$$

Energy equation in solid phase

$$\frac{\partial(\varepsilon_s \rho_s e_s)}{\partial t} + \frac{\partial}{\partial x}.(\varepsilon_s \rho_s U_s.e_s) = \dot{q} + \frac{\partial}{\partial x}(k_s \frac{\partial T_s}{\partial x}) \quad \text{Eq. (14)}$$

q= Volumetric rate of heat convection from particle to gas

$$\dot{q} = h_{pg} s (T_p - T_g) \quad \text{Eq. (15)}$$

### *3.2 Boundary Condition*

The initial boundary conditions are set such that cold air enters the cooler at minimum fluidization velocity. The initial boundary condition for ash particle is maintained to furnace bed temperature $Tp_i^j$ = 850 $^0$C. The boundary condition for air is maintained at atmospherics temperature $Tg_i^j$ =40 Deg C.
The $U_{mf}$ minimum fluidization velocity calculated from equation (4).

## 4. SOLUTION OF GOVERNING EQUATION

The solution procedure for governing equation involve following steps

(1) The inlet air temperature ($T_{gi}^j$), Ash temperature ($T_{p\,j}^{\,i}$), fluidization velocity ($U_{mf}$), bed voids, density and specific heat of ash, air, are taken as input parameter to initiate the solution.
(2) The finite difference numerical methods are used to solve the conservation equation. The elemental time step Δt & Δx are selected such that stability criteria for difference equation are met.
(3) For each given time step by applying energy equation for air & ash particle with appropriate initial boundary condition, the temperature profile for ash particle in bed and outlet air temperature profile can be determined by using equation 16 & 17.

The energy equation for air becomes

$$T_{gi}^{\,j+1}\left[1 + U_{mf}\frac{\Delta t}{\Delta x}\right] = \frac{h_{pg} S \left(T_{pi}^{\,j} - T_{g_i}^{\,j}\right)\Delta t}{\varepsilon_g \rho_g cp_g} + T_{gi}^{\,j} + U_{mf} T_{gi}^{\,j}\frac{\Delta t}{\Delta x}) \quad \text{Eq. (16)}$$

The energy equation for ash particle, assuming the ash cooler is packed bed

$$T_{pi}^{j+1} = T_{pi}^{j}\left[1 - \frac{h_{pg} S \Delta t}{\varepsilon_s \rho_s cp_s}\right] + \frac{h_{pg} S T_i^{j}}{\varepsilon_s \rho_s cp_s} \quad \text{Eq. (17)}$$

The measured particle velocity at the wall of fluidization have usually been 1- 1.5 m/s. here wall downwards velocity is assumed 1 m/s [3]. The heat exchange between particle and gas is given by following equation [3,4],

$$Nu_{pg} = \frac{h_{pg} D_p}{K_g} = 2 + 1.8\left(\frac{\rho_g (U_{mf} - U_p)}{\mu_g}\right) pr^{1/3} \quad \text{Eq. (18)}$$

The numerical grid for first iteration is shown in figure 4. In first iteration initial boundary condition for gas and particle is put in the first iteration. After first iteration the reduced ash temperature will be used in next iteration. The air inlet temperature at the each iteration is same i.e. ambient temperature. The air outlet temperature after first iteration and drop in particle temperature is recorded. The drop in particle temperature is used in next iteration and numerical grid is shown in figure 5. After each iteration the air out temperature and particle temperature is recorded.

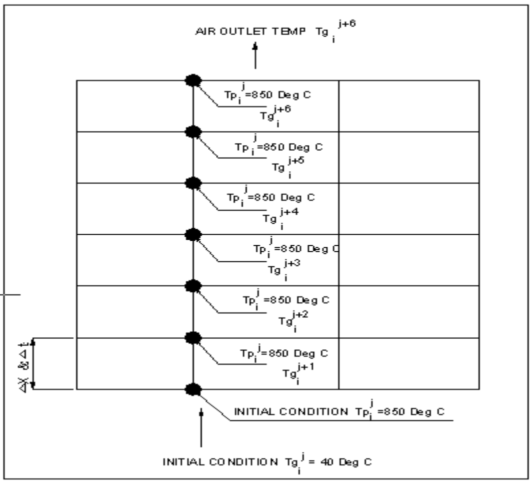


Fig. 4 Numerical grid for first iteration

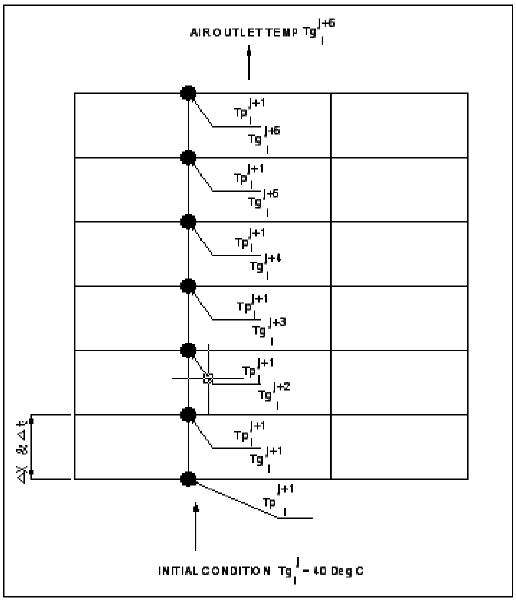


Fig. 5 Numerical grid after first iteration.

For solving the governing equation 16 and 17, a programme is written in Matlab software, and result is presented below.

## 5. RESULT & DISCUSSION.

### *5.1. Heat transfer coefficient with particle diameter*

As cold air moves to the cooler bed, the cooler bed loses the heat to air by convection. As the particle diameters in the bed varies from 0.5 mm to 8 mm. Fig 8 present the heat transfer coefficient for varying the particle diameter. This heat transfer coefficient is used in the governing equation for calculation of time required to cool the ash particle.

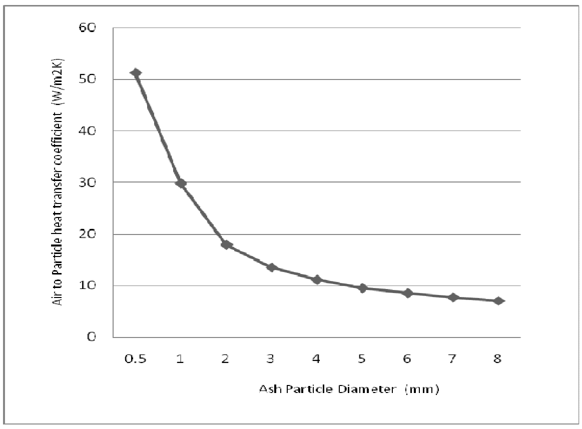


Fig.6 Heat transfer coefficient for air to ash particle for varying the ash particle.

### *5.2 Prediction of temperature profile of outlet air from cooler*

The energy equation-16 for air phase is solved for the initial and boundary condition. The initial condition already defined in above article. The governing equation is solved by difference method. The output for each time step is noted. Figure 7 represent the outlet air temperature profile for each time step.

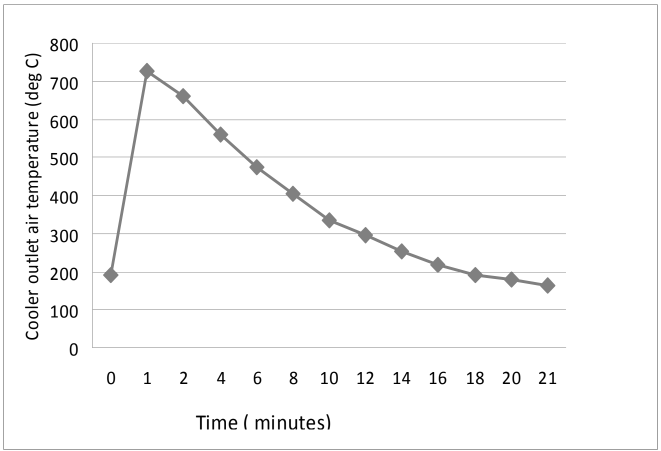


Fig.7 Temperature profile for outlet air from cooler with time.

### *5.3. Prediction of temperature profile of ash in the cooler*

The energy equation for solid phase is solved for the initial and boundary condition. The initial condition already defined in above article. The governing equation is solved by difference method. The temperature change for each time step is noted. Figure 8 present the bed ash temperature profile for each time step.

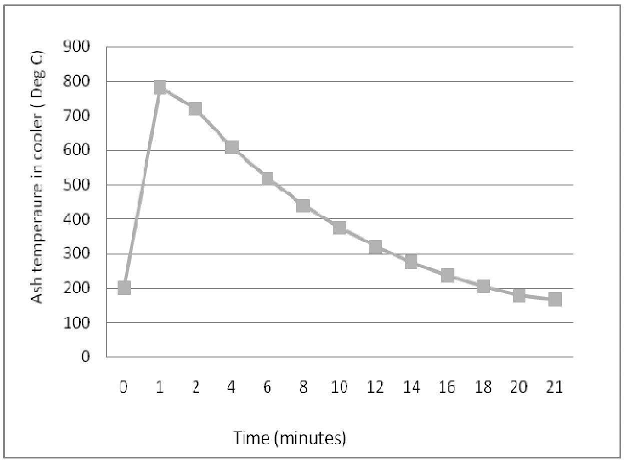


Fig.8 Temperature profile for ash in the cooler with time.

## 7. CONCLUSION

A one dimensional heat transfer model that couples gas convection, particle to gas convection is proposed for heat transfer in fluidized ash cooler. The forward difference method is employed to numerically solve the set of non linear, partial difference governing equation. With the above model prediction can be made and used to build fluidized ash cooler.

The model predicts that ash particle loose heat the cold air resulting increasing ash temperature leaving the cooler. The estimated time required for cooling the ash is predicted from the model.

Also if hot outlet air leaving from cooler can be send to boiler furnace then fluidized bed ash cooler has better energy conservation than water cooled ash cooler.

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