EGEE 520

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Influence of Particle Size on the Heat Transfer in an FBC Ash Cooler

Semester Paper

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Abstract

Fluidized bed combustors produce large amounts of ash at high temperatures (about 800 °C) which needs to be cooled prior to disposal. One of the common methods to extract this heat is by the use of an ash cooler, where a counter current of ambient air is flown through the falling ash to pre-heat the air prior to combustion. This paper models the heat transfer between a single (isolated) bottom ash particle and the air in an FBC ash cooler. The objective is to model the effect of particle size on the heat transfer from the ash particle to the air stream. The effect of air flow rate on the solid-gas heat transfer is also addressed. Radiation and convection heat transfer processes are modeled along with the coupled air flow near the particle. The ash particle was modeled as a 'concrete' sphere (diameter ca. 2 mm) in FEMLAB. The heat transfer flux was found to be increasing with particle size for particles at same initial temperatures. Based on the modeling studies conducted it was found out the radiation is the dominating mode of heat transfer in the given temperature range (ash at 800 °C and air at ambient conditions). Overall this paper presents a good test case for modeling heat transfer using FEMLAB on isolated hot spheres which could be further developed for models involving multiple sphere interaction.

1. Introduction

Coal combustion is the primary energy source for electricity generation around the world. However, coal combustion also leads to several environmental problems such as acid rain, heavy metal contamination of water sources and particulate matter pollution unless the emissions are carefully controlled [1]. Fluidized bed combustion is relatively new technology that serves the purpose of reducing emissions from coal based power generation at low operating costs [1]. FBCs have several advantages like fuel-flexibility, reduced SO_2 and NO_x emissions compared to pulverized and fixed-bed technologies, higher specific heat transfer area and lower investment costs [2]. However, fluidized bed combustors (FBC) produce large amounts of solid waste (bed ash, fly ash and unused sorbent). In general low cost fuels used in FBCs tend to be high ash fuels. Due to the high volumes of hot ash (at about 800-900 °C) produced on a continuous basis in a FBC combustor, ash handling and ash cooling are vital issues in day-to-day plant operations [2]. The ash needs to be cooled to about 175-200 °C before it can be handled by ash handling conveyors and other handling equipment. A well designed system should incorporate an ash cooler to extract the excess heat of the ash prior to ash disposal. The cooled ash (about 175 °C) is then collected and removed via conveyor systems [5]. However, the issues of ash collection and removal have usually been treated empirically and it is common to see built-in redundancies for capacity in the designs of ash coolers and ash conveyors [7]. Recent research has shown that ash generation rates can be predicted, in particular, the ash-split—which tells the rate of formation of bed ash and fly ash separately—can be predicted reliably if the fuel and sorbent compositions are known continuously [9]. One of the key factors in deciding the ash split is the particle size distribution in the ash. Since the bed particles are classified by their size [11] and get removed as part of the bottom ash if they are larger sized (~1-2 mm diameter or bigger) particles, it becomes important to study the particle size distribution (PSD) and its role in heat transfer. Experimental studies have shown that the bed-to-wall heat transfer increases with increasing suspension densities (*i.e.* increasing particle concentrations) [11]. Since experimental research is not feasible at all times, models would be useful tools to study the role of PSD. Modeling research in FBC systems has been carried out for several years, but most of the work has been on FBC combustion zones [12]. There has been hardly any direct research addressing the bottom ash cooling or on the heat transfer dependence on particle size distributions in the bottom ash.

This paper models the heat transfer between the bottom ash particles (falling) and the flowing air (upward) in a FBC ash cooler. The objective is to model the effect of particle size on the heat transfer from a single ash particle to an air stream. The effects of particle size and air flow rate on the solid-gas heat transfer are addressed. Research on particle size effects in FBCs include studies on mixing of the solids [18] and low density behavior in the bed (single particle behavior) [19]. In a wider field of research particle laden flow is an important realm of research in chemical engineering and it could be beneficial to apply analogies from similar problems in the food industry [20]. Particle-particle heat transfer is not considered in this paper. However, other authors have modeled particle-particle heat transfers for steady-state conduction and convection conditions while including radiation [21]. Some others have investigated transient conditions of heat transfer in FBCs [22].

2. Theory

Initially it will be assumed that the ash particle does not interact with any other ash particles, both physically and thermally. The following other assumptions are also made to simplify the problem. Figure 1 shows a schematic of the heat transfer model.

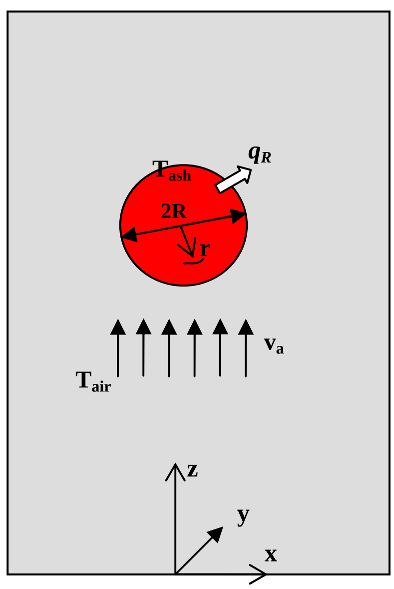

Figure 1: Hot ash particle moving down through an upward air flow in a bottom ash cooler. q_R denotes radiation flux. (Front view, not to scale)

Assumptions:

Geometrical and Thermodynamic

- Ash particles are spheres of uniform and constant density.
- Air flow is considered only in a cylindrical region around the particle. This region is much larger than the particle size.
- Physical properties of the ash are generally assumed to be constant with temperature. For the air, properties that are not assumed to be varying are calculated using standard correlations.

Heat Transfer

- Main mode of heat transfer from ash to air is by convection
- Radiation heat exchange between the particle and a nearby constant temperature surface is considered.
- Particle is assumed to be having uniform temperature throughout its volume.

Fluid Dynamics

- Particles are falling downward at constant (terminal) velocity with no rotation.
- Upward air flow is at uniform velocity v_{air} till it meets the ash particle.

2.1 Governing Equations

In the following paragraphs, the subscript ‘ash’ on symbols will refer to the ash solid and ‘air’ refers the gas phase. Assuming that the ash cooler walls are adiabatic, an overall heat rate balance can be written as:

$$\underline{M}_{ash,tot} \cdot C_{p_{ash}} \cdot \Delta T_{ash} = \underline{m}_{air} \cdot C_p \cdot \Delta T_{air} . \quad (1)$$

where $\underline{M}_{ash,tot}$ is the ash deposition rate (kg/s), $C_{p_{ash}}$ is the specific heat, ΔT_{ash} is the temperature difference between the hot ash leaving the bed (at about 800 °C) and the cooled ash reaching the end of the transitional hopper of the ash cooler (at about 175 °C). Typical values of ΔT_{ash} are around 800-200 = 600 ˚C); $\underline{m}_{air}$ is the air mass flow rate and ΔT_{air} is the rise in air temperature. The falling ash particle cools predominantly by a combination of radiation and convection processes. The conduction in the surrounding air is quite small in magnitude for most practical cases. This heat transfer is governed by the energy equation:

$$\overbrace{k_{air}\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T_{air}}{\partial r}\right)_{r>R}}^{\sim 0} + \varepsilon_{ash}\sigma(T_{ash}^4 - T_{air}^4) + h_{air}(T_{ash} - T_{air}) = \rho_{ash}C_{p,ash}V_p\frac{\partial T_{ash}}{\partial t} \quad (2)$$

(2)

<u>Conduction in air</u> <u>radiation</u> <u>convection</u> <u>transient cooling</u>

where T_{air}=T_{air} (r, t) is the temperature (of air), T_{ash}=T_{ash} (t) alone, R is the radius of the particle, k is the thermal conductivity, ρ is the density; h_{air} is the convection heat transfer coefficient[1], V_p is volume of the particle, $\frac{4}{3}\pi R^3$; T_{ash}(t=0)=T_{hot}=800 °C; T_{air}(t=0 or z=0)= T_{amb}; T_{air}(R) = T_{ash};

Flow conditions around the sphere are modeled as steady state and governed by Navier-Stokes equations:

$$\mathrm{v}_x\frac{\partial v_z}{\partial x} + \mathrm{v}_y\frac{\partial v_z}{\partial y} + \mathrm{v}_z\frac{\partial v_z}{\partial z} = -\frac{1}{\rho_{air}}\frac{dP}{dz} + \frac{\mu_{air}}{\rho_{air}}\left(\frac{\partial^2 \mathrm{v}_z}{\partial x^2} + \frac{\partial^2 \mathrm{v}_z}{\partial y^2} + \frac{\partial^2 \mathrm{v}_z}{\partial z^2}\right) + \underbrace{g(1-\beta(T-T_{ref})}_{\text{Boussineesq. approximation}} \quad (3)$$

where v_z = v_{air} in the free stream and v_x and v_y are assumed zero in the free stream. The pressure drop in the flow can be an experimentally measured parameter for large values of ‘z’ and depends on design and air flow rates in the cooler. T_{ref} is a reference temperature for the density of the air. Thus the N-S equations are coupled to the energy equation via the temperature of the air. However, under some cases if natural convection effects are neglected then the two equations can be decoupled and solved in an easier manner.

3. Problem Formulation and Solution in FEMLAB

3.1 Formulation

This section details both the model formulation and also the FEM solution of the problem. The problem was formulated using two different geometries in a coupled FEMLAB model incorporating “Convection & Conduction heat transfer” mode and a steady state “Incompressible Navier Stokes” mode. As shown in Figure 1 previously, the ash particle from the FBC is considered falling in an ash cooler through a cylindrical column of counter current air flow initially at temperature 298 K. The ash particle was modeled as a ‘concrete’ sphere (diameter ca. 2 mm) in FEMLAB. The terminal velocity for an ash particle

[1] See Appendix for detailed calculations of h_{air}.

of 2 mm diameter falling through quiescent air is calculated to be about 0.257 m/s (see Appendix math file). However, since the air flow was set at 0.1 m/s in the +z direction, the ash particle is considered to be falling downwards at 0.005 m/s (-z direction).

This problem was initially attempted using an axi-symmetric 2D model due to the symmetry in the problem. However, the geometrical shape of the mesh elements introduces asymmetry and hence a real 3D model was used subsequently (Figure 2, see following page). The current 3D model is improved over the previous 2D model also because radiation effects are taken into account in the newer model. Radiation is sometimes the main mode of heat transfer when large temperature differences are involved (like in industrial boilers), so it is quite crucial to include it in the model. Further, the new 3D model also uses a theoretically calculated convection heat transfer coefficient based on established correlations [24].

The coupled 3-D model was developed incorporating three modes of heat transfer: (1) Conduction from the sphere to the surrounding air, here the sphere is set to be at a uniform temperature; (2) Convection from the hot sphere to the surrounding air; the heat transfer coefficient (h_m = 17735 W/m.K for air at 298 K, v_z = 0.1 m/s)[2] was calculated using a standard correlation for forced convection around "submerged objects" [24]; and (3) Radiation heat exchange between the hot sphere to the cooler surrounding media (The emissivity (ε) of concrete was chosen as 0.95 and Stefan-Boltzmann law $q_{RAD} = \varepsilon\sigma(T^4\text{-}T^4_{amb})$ was used as a heat flux condition in the conduction sub-domain conditions in the model. The N-S equations were 'active' only in the cylindrical domain and its internal boundaries on the sphere. In the sphere (solid ash particle) the N-S equations and convection were disabled.

3.2 Solution

The NS equations were solved along with the conduction-convection equations for the surrounding air flow. A coarse mesh was used because of repeated program crashes while using fine meshes (Error: "damping factor is too small, solution stopped"). The eventual solution yielded estimates of the temperature field, the convective and conductive

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[2] The *h* values are obtained using standard correlations and can be obtained from any particle size and air velocity fairly easily using the Mathematica file "Convection.nb" in the Appendix (attachment).

heat fluxes across the particle along a horizontal plane and also along the axis of the fall (z axis). Using post processing plots temperature gradients were also obtained.

The results from the FEM solution are shown in Figure 3. The variation of the conductive heat flux (Figure 3a) and the temperature gradient (Figure 3c) along the z-axis show a linear relation as one would expect from the constitutive relationship (Fourier's law of heat conduction). The convective heat flux however does not show any clear relationship with the particle position indicating that the particle velocity is not affecting the overall relative convective velocity of the air past the particle. In fact most of the variations in the convective flux in Fig 3b can be attributed to numerical approximations (between z = 0.5 to 0.85) and only the region between z = 0.85 to 1.02 shows the effect of convective heat transfer at the air-particle boundary. Figure 3d shows the variation of the temperature along the axis of the cylinder at an instant of time. It is not clear if the temperature variation at z > 1 is due to numerical effects of solely due to convection and radiation heat transfer.

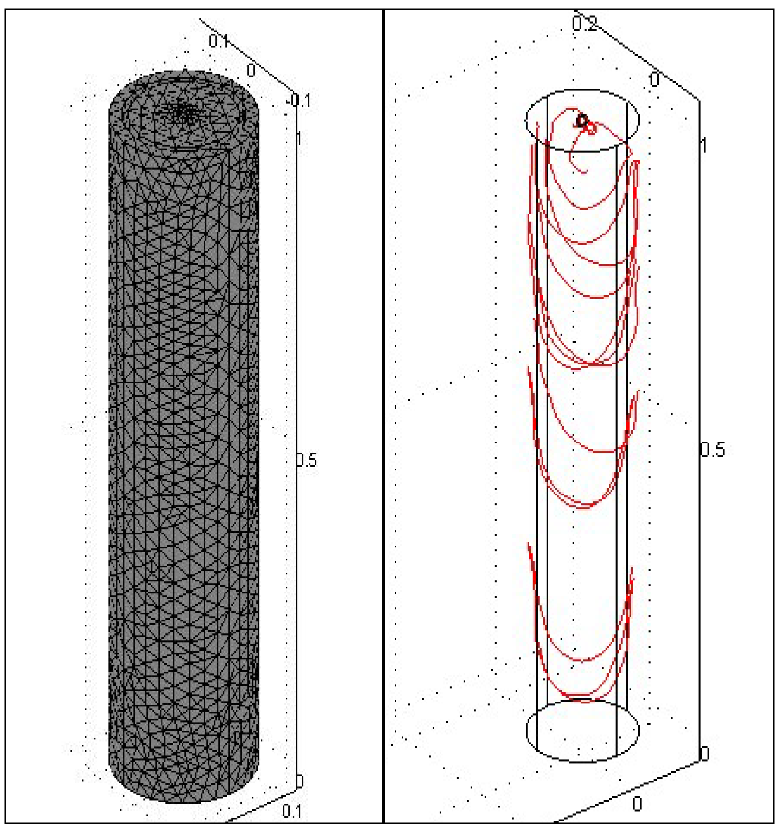

Figure 2: Representative figure of the FEM model and heat propagation wave incorporating effects of radiation and conduction.

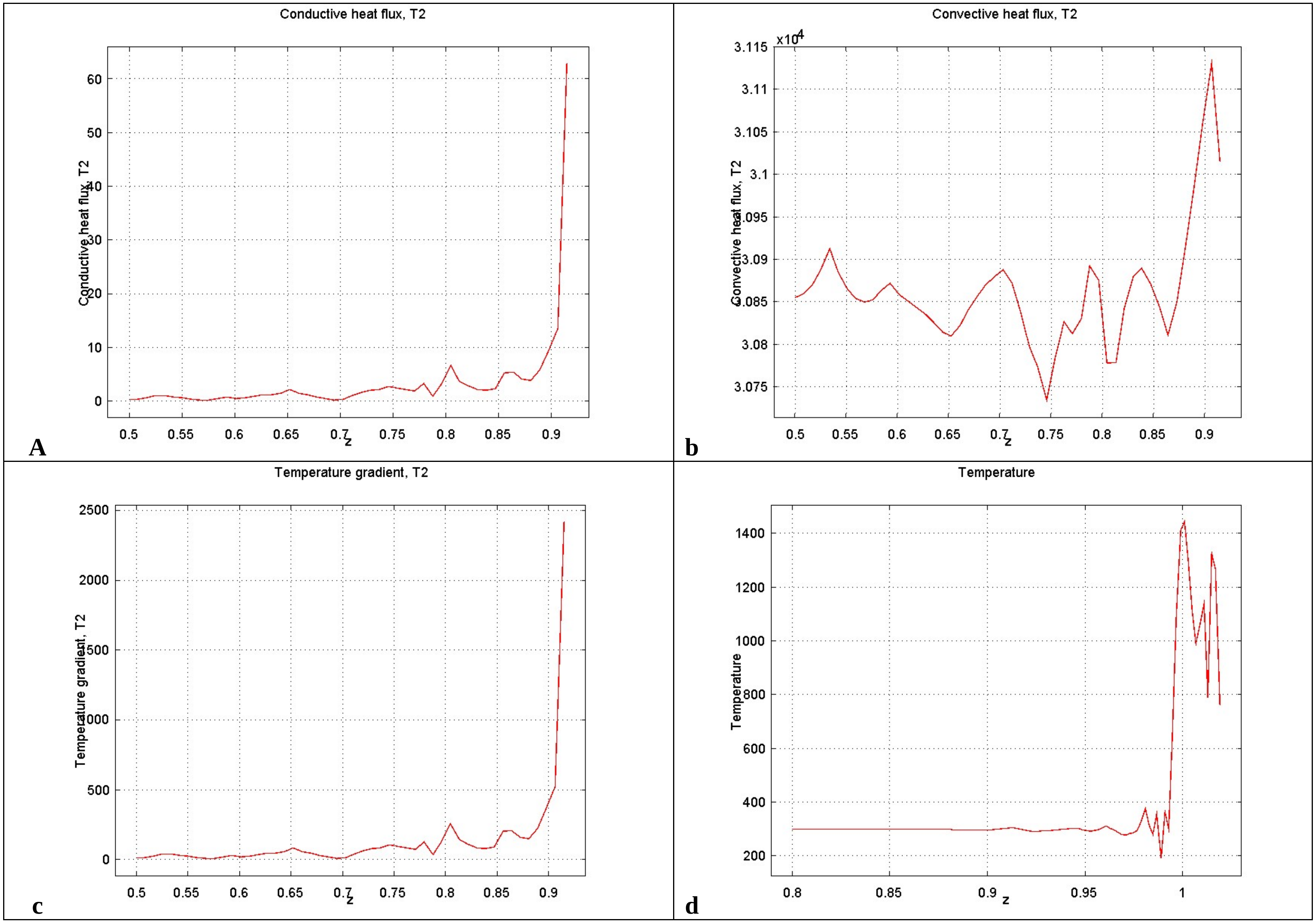

Figure 3: Variation of physical quantities along a vertical line from 0.5m to 1 m (**a,b,c**) and from 0.8 to 1.02 m (**d**).

4. Validation

To validate for the overall solution, the velocity of air flow was set to zero and the solution checked to see if it matches a conduction solution. Figure 4a and Figure 4c show the difference in conductive fluxes in the horizontal plane at the height of the particle in the tube and a little below the particle as the air is approaching the particle. Line plots are due to the symmetry of the problem. Figure 4b shows the heat flux along the vertical axis passing through the particle center and shows the sharp jump in temperature after the particle. Figure 4b actually represents a modified case in the validation where natural convection effects are incorporated. Obviously radiation effects increase (add) to the heat flux in Figure 4c. However, the steep rise in conductive flux along the particle air boundary regions is indicative of the solutions veracity. The absence of temperature gradients inside the particle shows that FEMLAB is calculating the heat fluxes correctly. Comparisons with Bird *et al.* [24] for flow past a hot metal sphere and Mihalykio's work on statistical modeling of heat transfer [25] also show agreement on the effect of heat transfer with particle size (i.e. local heat transfer rate increases, but heat flux/unit mass decreases.).

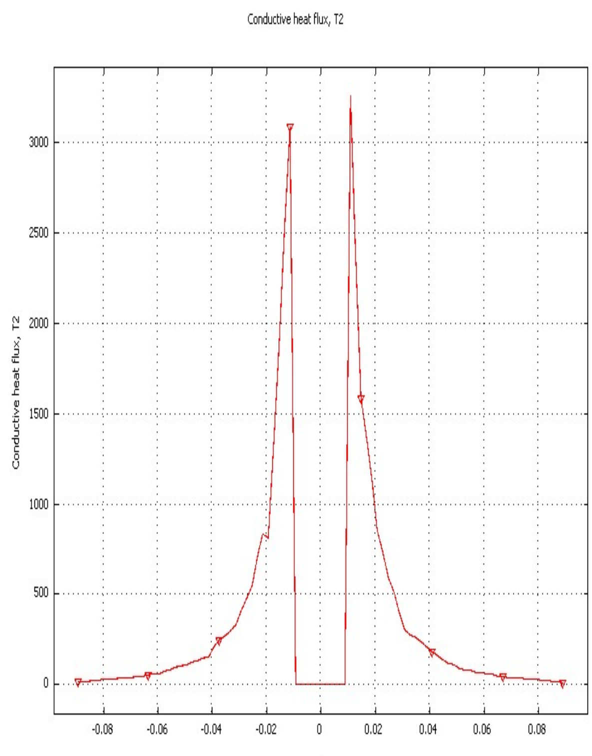

Figure 4a: Conductive flux along x-axis (z=1)

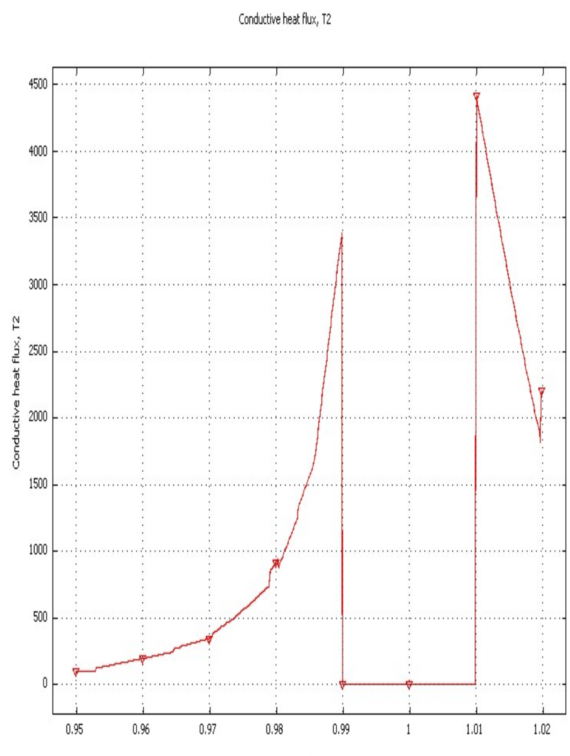

Figure 4b: Conductive flux along z axis (x=1)

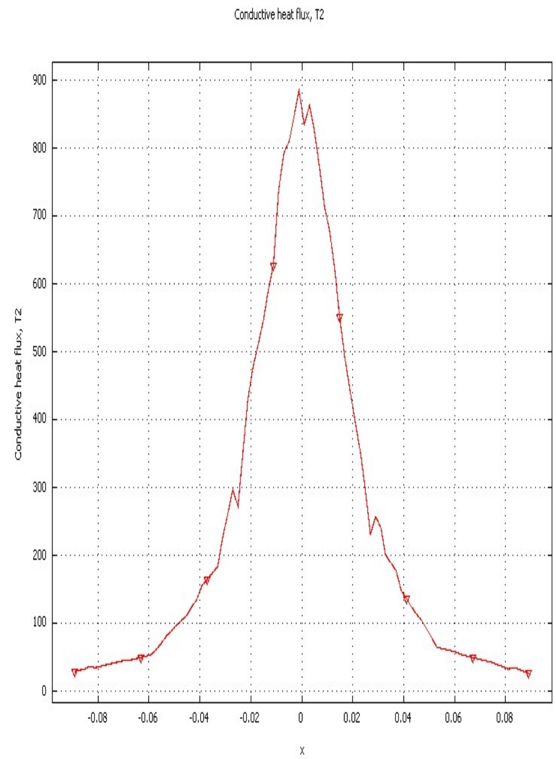

Figure 4c: Conductive flux along x axis at z =0.98**.**

5. Parametric Study

Particle size variation was the main parameter considered in the study. The area of a spherical particle is proportional to the square of its radius so any increase in particle size increases the overall heat transfer surface area, however the cooling is reduced if a heat/unit mass basis is considered. However since all particles are at same temperature to begin with particle size increase only serves to increase local air temperature at higher rates. (Figure 5)

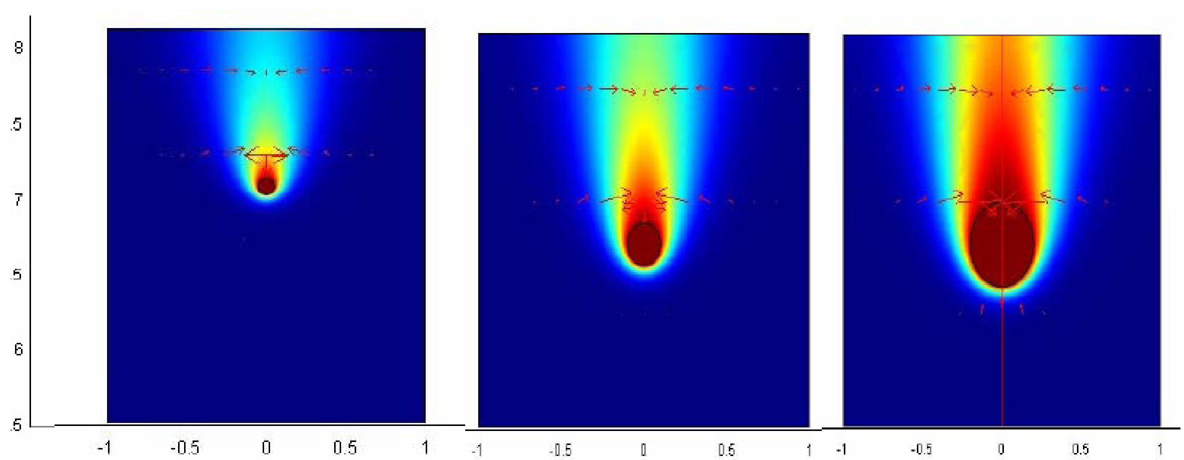

Figure 5: Heat transfer variation (flux≡temperature gradient) with particle diameter.

The temperature gradient plotted for two different flow rates (corresponding to convection coefficients of h = 17735 W/m.K and 35470 W/m.K) didn't show appreciable difference in heat transfer rates indicating that radiation was probably the dominant mode of heat transfer. Since radiation is independent of the air flow and dependent only on the temperature of the surfaces exchanging heat and the geometrical factors, further study needs to be conducted to evaluate effect of geometric factors on optimizing heat transfer.

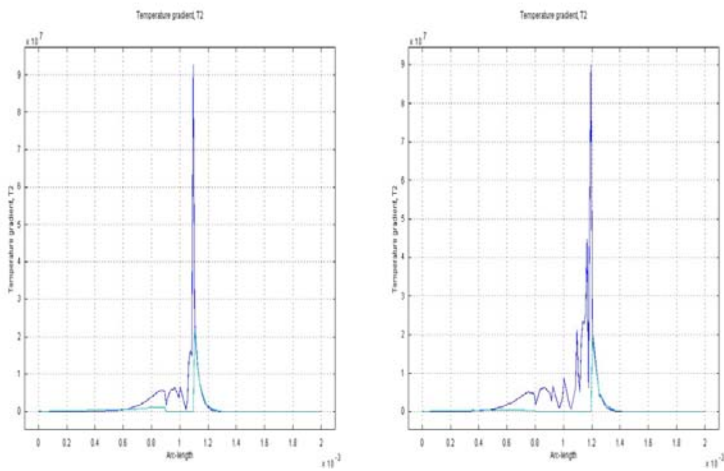

Figure 6: Spatial temperature gradient variation with convection coefficient: a) h and b) $2h$.

6. Conclusions

Based on the modeling studies conducted it was found out the radiation is the dominating mode of heat transfer in the given temperature range (ash at 800 °C and air at ambient conditions). Further evaluation of the effects of particle size on the local heat flux yielded FEM solutions that are consistent with other established analytical solutions and newer statistical solutions. The heat transfer increases with the increasing particle diameter as long as the initial particles are all at the same (high) temperature. It is also noted that since radiation is the dominating factor the emissivity assumptions need to be thoroughly addressed before this model can be expanded to include multiple particles and particle-particle heat transfer considerations could be taken into account. Overall it was found that FEMLAB is a useful tool in modeling heat transfer problems. However, it is quite complicated to incorporate anything more than a simple radiation model. Also, the program routinely crashes for small size geometries so it needs to be investigated if the level of the user or the scope of the program is satisfactory for small geometries involving high temperature gradient models.

6. References

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Appendix: Convection Heat Transfer Coefficient Calculations

The physical properties of the material were obtained from reference [23]. The thermal conductivity of air varies between 0.026 W/m.K at 25 °C to to 0.063 W/m.K at 900 °C.

$k = 1.5207 \times 10^{-11} T^3 - 4.8574 \times 10^{-8} T^2 + 1.0184^{-4} T - 3.9333 \times 10^{-4}$;

Boundaries: 5,6,12,17 –correspond to inner surface, 1173K; 1,2,11,18 to outer surface temp 1173 K; 7,8,9,10, 13,14,15,16 – sphere @ 1473K

(* Nusselt No calculation for spherical ash particle falling down in countercurrent air flow in an FBC ash cooler. *)

temp=298;(*in Kelvin*);

$$\mathbf{kair = 1.5207 * 10^{-11} * temp^3 - 4.8574 * 10^{-8} * temp^2 + 1.0184 * 10^{-4} * temp - 3.9333 * 10^{-4}} \text{ (* in W/m.K *)}$$

0.0260439

$$\mathbf{dia = 2 x10^{-3};}$$

vinf=0.81; (* m/s *)

$$\mathbf{rhoair = 0.525;}$$

$$\mathbf{viscair = 3.25 * 10^{-5};} \text{ (*viscosity in Pa-s *)}$$

specificheatair=1090; (* J/kg.K *)

$$\mathbf{convectioncoeft = kair / dia * (2 + 0.6 * (dia * vinf * rhoair / viscair)\text{^}0.5) * (specificheatair * rhoair / viscair)^{1/3}}$$

$$3.38774 \left(2 + 97.0614 \left(\frac{1}{x10^3}\right)^{0.5}\right) x10^3$$

$$\mathbf{3.3877350882536716` \left(2 + 97.06143970147505` \left(\frac{1}{10^3}\right)^{0.5`}\right) x10^3}$$

$$17.1736\, x10^3$$

$$3.38773508825367 16` \left(2 + 96.46043429622004` \left(\frac{1}{10^3}\right)^{0.5`}\right) x10^3$$

$17.1092 \, x10^3$

Clear[temp,kair]

$kair = 1.5207 * 10^{-11} * temp^3 - 4.8574 * 10^{-8} * temp^2 + 1.0184 * 10^{-4} * temp - 3.9333 * 10^{-4}$ (* in W/m.K *);

Temp wall, T_amb 850 ; Temp particle = 1473; Tbc12001473Temp air, T_inf40313

Appendix 2: Variation of Thermal Conductivity

(* Variation of thermal conductivity with Temperature *)

Plot[kair,{temp,300,1500},AxesLabel□{Temperature, k_air}]