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Numerical simulation of motions of liquid particles in gas flow fields: A case study of grease filtering in an air filter system for cooking

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Abstract

Numerical simulations of particle motions in fluid flow fields can be divided into 2 parts. The first part is the Eulerian analysis of the flow field. The other part is the Lagrangian analysis for the particle motions where the present of particles do not affect the flow field. The particle's trajectory results from the drag and body forces acting on the particle. Governing equations for the flow field and the particles are Vorticity-Stream function equations and the Newton second law of motion respectively. Fluent software has been used to verify the problem solving concept. On one hand, it has been found that those path lines of small size particles depend mainly on re-circulation zones of the flow field. On the other hand, large size particle motions depend on their inertia.

Keywords: Grease filter, Particle Dynamics, Euler-Lagrange method

1. Introduction

Euler-Lagrange[1] approach has been use for two-phase flow of gas-solid particles in this study. Velocity flow fields have been solved from Vorticity-Stream function equations while particle path lines have been solved from Newton's second law of particle dynamics. The assumption that the particles play no effects on the flow field has been used. The details of governing equations for the flow fields such as Vorticity-Stream function, pressure potential function, drag force, drag co-efficient and particle motion equations are described [2,3]. The concept used and solution obtained from this study will be applied to simulate a grease-filtering process in an air filter system for cooking [4].

2. Governing equations

2.1 Flow field equations

The assumptions for developing the governing equations for the flow field are that the flow is laminar and incompressible flow and that the flow field is not affected by the present of particles.

Vorticity-Stream function definitions

Since the flow in this work is a two-dimensional flow only the vorticity in z direction has been considered which is given by

$$\Omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \tag{1}$$

Stream function is defined in terms of its gradients as

$$u = \frac{\partial \varphi}{\partial y} \tag{2}$$

$$v = -\frac{\partial \varphi}{\partial x} \tag{3}$$

Potential equation for Vorticity and Stream Functions

Momentum equations along x and y axes can be combined and written in terms of transport equation for vorticity in which the pressure term has been canceled out , hence

$$\frac{\partial \Omega}{\partial t} + u\frac{\partial \Omega}{\partial x} + v\frac{\partial \Omega}{\partial y} = \upsilon\left(\frac{\partial^2 \Omega}{\partial x^2} + \frac{\partial^2 \Omega}{\partial y^2}\right) \tag{4}$$

From the definitions of vorticity and stream function given in equations (1)-(3), the stream function equation relating the voriticity can be written as

$$\frac{\partial^2 \varphi}{\partial x^2} + \frac{\partial^2 \varphi}{\partial y^2} = -\Omega \tag{5}$$

Equations (4) and (5) form a system of two equations and two unknowns. Once the stream function is solved the velocity flow field can, in turn, be given by equations (2) and (3).

Pressure equation for potential function

The stream function obtained from (4) and (5) can also be used to solve for the pressure flow field from the governing equation for pressure,

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} = 2\rho\left[\left(\frac{\partial^2 \varphi}{\partial x^2}\right)\left(\frac{\partial^2 \varphi}{\partial y^2}\right) - \left(\frac{\partial^2 \varphi}{\partial x \partial y}\right)^2\right] \tag{6}$$

2.2 Particle tracking equations

Particle trajectory results from interactions among drag, gravitatinal, and inertia forces. These interactions are then transformed to state equations for displacement and velocity along x and y co-ordinate.

Drag force

Drag force on an object of circular cross-section, moving within a flow field can be calculated using the definition for the drag coefficient

$$F = -c_D\left(\frac{\rho}{2}\right)\left(\frac{\pi D_p^2}{4}\right)(v - U)|v - U| \quad (7)$$

where

U = Flow field velocity vector

v = Particle velocity vector

| · | = Magnitude

c_D = Drag coefficient

The particle shape is assumed to be spherical shape so that the drag coefficient is modeled by [3]

$$c_D = 0.4 + \frac{24}{Re} + \frac{6}{(1 + Re^{0.5})} \quad (8)$$

where the Re is calculated from the relative velocity between the velocities of the particles and the flow field,

$$Re = \frac{\rho D_p |v - U|}{\mu} \quad (9)$$

Equation of motion for particles

Newton's second law for particles can be written in vector form as

$$F_{Drag} + F_{Body} = ma \quad (10)$$

or after substitutions of each term

$$-\left(\frac{c_D\rho}{2C}\right)\left(\frac{\pi D_p^2}{4}\right)(v - U)|v - U| - \left(\frac{\pi D_p^3}{6}\right)\rho_p g = \left(\frac{\pi D_p^3}{6}\right)\rho_p \frac{dv}{dt} \quad (11)$$

Then, we can write the acceleration vector for particle as

$$\frac{dv}{dt} = -\hat{j}g - \left(\frac{3c_D}{4}\right)\left(\frac{\rho}{\rho_p D_p}\right)(v - U)|v - U| \quad (12)$$

or in x and y components

$$\frac{dv_x}{dt} = Av_x + B \quad (13)$$

$$\frac{dv_y}{dt} = Av_y + D \quad (14)$$

where

$$A = -\left(\frac{3c_D}{4C}\right)\left(\frac{\rho}{\rho_p D_p}\right)\left[(v_x - U_x)^2 + (v_y - U_y)^2\right]^{\frac{1}{2}} \quad (15)$$

$$B = -AU_x \quad (16)$$

$$D = -AU_y - g \quad (17)$$

Equation (13) and (14) can be written in term of state equations as

$$\begin{aligned} \overset{o}{y}_1 &= y_3 \\ \overset{o}{y}_2 &= y_4 \\ \overset{o}{y}_3 &= Av_x + B \\ \overset{o}{y}_4 &= Av_y + D \end{aligned} \quad (18)$$

The solution for equation (18) is a locus of points (y_1,y_2) representing a path line of the interested particle. Note that U_x and V_y appear in equations (15), (16) and (17) are obtained from equations (2) and (3) respectively.

3. Problem formulation and solutions

3.1 Geometry of the problem

In this study, we used a simplified geometry filter or a fictitious filter in order to verify the calculating concept and to understand the filtering process. The filter is a rectangular shaped with one inlet at the bottom edge and one outlet at the right edge. The geometry of the fictitious filter is shown in Figure 1. Two cases of inlet geometry have been considered, the case with and without grid at the inlet. The purpose of these different inlets is to generate different pattern of flow fields those could affect the particles' trajectories and pressure drops across the filter.

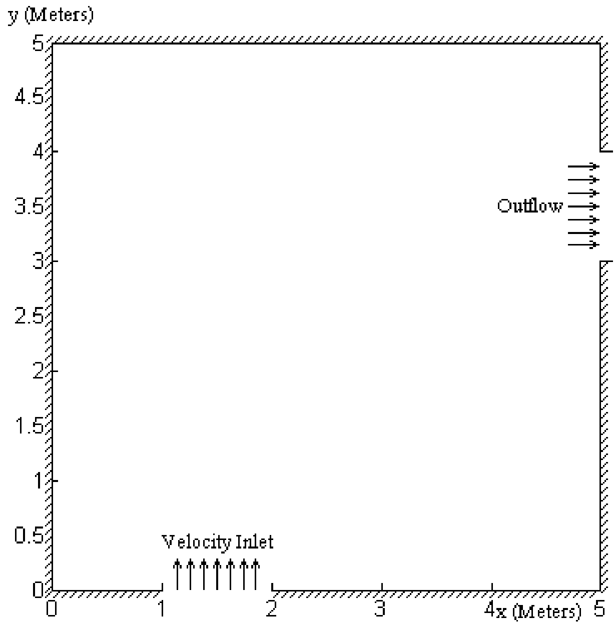

Figure 1: the geometry of the problem

The inlet velocities are assumed to be uniform. In order to see the effects of velocity flow field within the filter on the particle tracing and on pressure drops across the filter, the velocities are varied from 0.1 to 0.5 m/s. The given range of the velocities, ensure laminar flow conditions. Outflow boundary condition has been use at the outlet. Calculation begins when fluid is at rest until steady state condition has been reached.

After steady state of fluid flow field is reached, we then seed the particles along the inlet boundary at different locations. Particles used are liquid water whose maximum diameters are 100 micron whereas the gas-phase is air. Initial velocity of the particles at the inlet is set at zero velocity; they are then initially forced to move, starting at rest at the inlet, by the drag and gravitational forces.

Analyses of the path line of each particle within the filter and pressure drops across the filter have been advanced for different inlet velocities. As mention earlier that the present of the particles do not affect the fluid flow field and then pressure drops are calculated solely from the fluid flow fields.

3.2 Solutions

For the filters without and with inlet-grid, two trajectories of the 30 micron particles within those filters are shown below in Figures 2 and 3 respectively.

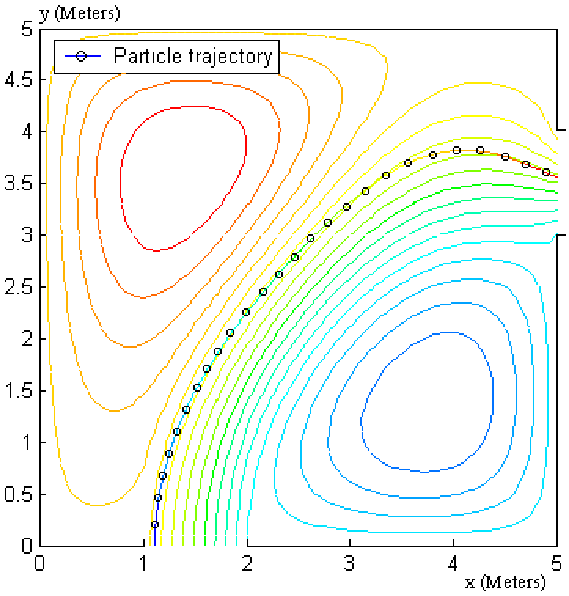

Figure 2: Stream function and particle trajectory of 30 micron-diameter particle without inlet grid.

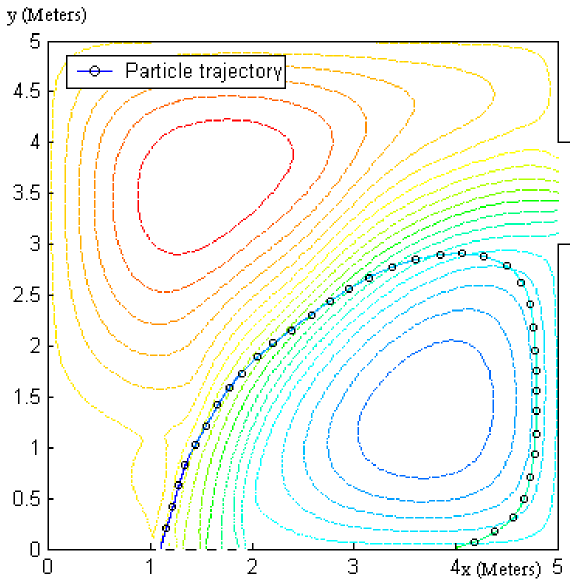

Figure 3: Stream function and particle trajectory of 30-micron-diameter particle with inlet grid.

It is clearly shown in the figures that both flow fields and trajectories are affected by the inlet boundary conditions when the grid-inlet do or do not exit. It has also been found that the trajectories of particles do not only depend on the flow fields but also depend on their sizes. This is because the inertia of the particles moving in the flow fields change when the sizes of the particle changes and so do their trajectories.

The effects of particle sizes on the filtering process can be observed by the efficiency chart shown in Figure 4. Smaller particles start to be trapped by the grid-inlet type filter earlier than those particles by the filter without grid-inlet. This is because the small-size particles flow along with the streamlines and are trapped within the recirculation zones behind the grid inlet.

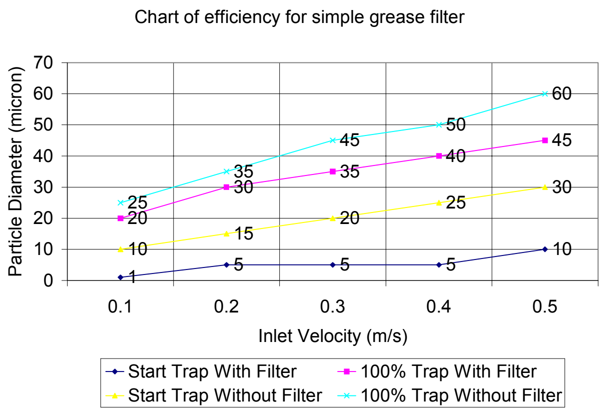

Figure 4: Chart of efficiency for filter with and without inlet-grid

On the same trend smaller size particles are trapped within the filter with the inlet-grid than those trapped with the filter without the inlet-grid. In this case, since the size of the particles is larger so that the inertia due to the acceleration field dominates and governs the trajectories of the particles. The onset directions of the velocities of the particles entering the filter depend on the direction of the accelerations at those points. The filter with grid-inlet form a more deviated directions of acceleration fields while the acceleration fields form by the filter without inlet-grid are regular.

The trajectories of the particles in the filter without inlet-grid conforming well to the large scale stream recirculation zones allowing larger particles escaping the filter. Larger particles in the filter with inlet-grid, on the other hand, are trapped because of the diverging directions of acceleration field due to the small scale recirculation zones just behind the inlet-grid.

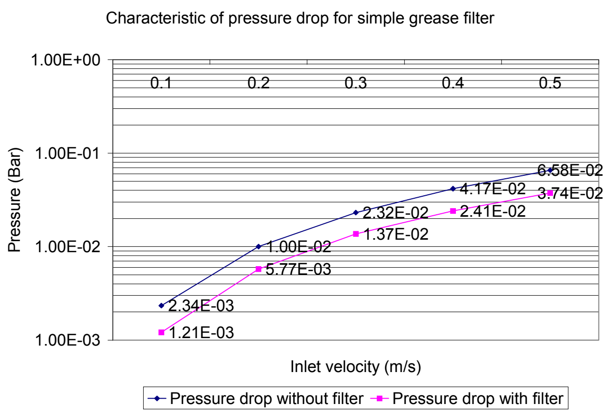

Figure 5 : The characteristic of pressure drop for simple grease filter

Lastly, the pressure drops across the filters at different velocity inlets have been studies. Figure5 shows that the filter with inlet-grid loss its pressure less than that the filter without inlet-grid due to reduction of air mass flow rate and the pressure drops increases exponentially with the velocity.

4. Conclusion

Numerical simulation of particles moving within fluid flow fields within a fictitious grease filter has been advanced. Two cases are of interested, the case with and without inlet-grid. Efficiency chart has been purposed in this study. It has been found from the chart that the filter with inlet-grid can trap smaller size particles by making use of recirculation zones, both large scale recirculation zones in the filter and small scale recirculation just behind the grid. This small recirculation zones however could not trap the large size particles because the particles occupy higher inertia forces than those the small sizes particles. These inertia forces in turn govern the trajectories of the particles. Although higher efficiency on capturing of smaller size particles is observed in the filter with the inlet-grid, its pressure drops become higher due to the loss at the grid.

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