Numerical Simulation of Gas-particle Motion in A Grease Filter: A Case Study in Grease Filtering System for Commercial Kitchen

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Abstract

Simulation of filtering process within grease filtering system for commercial kitchen has been advanced using Euler-Lagrange approach. Governing equations for the flow field and the particles are Vorticity-Stream function equation and the Newton's second law of motion respectively. Because the assumption that the grease is liquid particle, they stick to the wall when it touched. These condition leads to the critical inlet velocity for the commercial kitchen filter when the operating condition of the filter starts up. It can be concluded that for a particular commercial kitchen filter, the filtering efficiency is sensitive to the critical velocity. Aerosol particles of nanometer size, however, escape freely through the mechanical type filter.

Keywords: Grease filter, Particle Dynamics, Euler-Lagrange approach, critical inlet velocity

1. Introduction

A high incidence of lung cancer in Chinese women is believed to be caused by carcinogenic chemicals emitted from hot cooking oil used in stir frying. An aerosols are efficient transport vehicles for carcinogenic compounds into the human lung. The droplets of aerosol contents many differenct Polycyclic Aromatic Hydrocabons (PAH). PAH are dissolved in respireable droplets, they may present a serious cancer risk for exposed a person as cooking. [1] The ventilation system in occupied townhouse has been studied and experiment was performed to determine deposit and decay rates of aerosol [3,4].

In the grease filtering system for commercial kitchen, grease filters within a hood have been used to capture smoke and airborne grease above the cooking surface[5]. Simulation of flow fields within the grease filter has been advanced using Euler-Lagrange approach[6]. Governing equations for the flow field and the particles are Vorticity-Stream function equation and the Newton's second law of motion respectively[7,8]. Because the assumption that the grease is liquid particle, they stick to the wall when it touched. These conditions lead to the critical inlet velocity for the commercial kitchen filter when the operating condition of the filter starts up.

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 appear and is given by

$$\Omega = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \qquad (1)$$

Stream function is defined by

$$u = \frac{\partial \varphi}{\partial y} \qquad (2)$$

$$v = -\frac{\partial \varphi}{\partial x} \qquad (3)$$

Which u and v are velocity in x and y axis, Ω is vorticiry and φ is stream function. Note that Definitions (2) and (3) satisfy automatically the Continuity equation.

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 [7], hence

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

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

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

Equations (4) and (5) form a system of two equations and two unknowns, which the coefficient u and v in equation

(4) are preliminary known from the definition of shown function (2) and (3)

Pressure equation for potential function

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

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

Which p is pressure and ρ is density. The pressure solution is used to determine pressure drop of the system.

2.2 Particle tracking equations

Particle trajectory results from interactions of drag, and gravitational forces on the particle. These interactions define state equations for displacement and velocity along x and y co-ordinate.

External forces define

Drag force on an object of circular cross-section, moving within a flow field can be calculated using the definition for the drag coefficient in [8]

$$\mathrm{F_{Drag}} = -c_D\left(\frac{\rho}{2}\right)\left(\frac{\pi D_p^2}{4}\right)(V-\mathrm{U})|V-\mathrm{U}| \quad (7)$$

where

U	=	Flow field velocity vector
V	=	Particle velocity vector
$\lvert\cdot\rvert$	=	Magnitude
c_D	=	Drag coefficient
D_p	=	Diameter of the particle

The particle shape is assumed to be spherical shape so that the drag coefficient is modeled by [8]

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

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

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

Body or gravitational force can be defined by

$$F_{Body}=\left(\frac{\pi D_p^3}{6}\right)\rho_p g \quad (10)$$

Equation of motion for particles

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

$$F_{Drag}+F_{Body}=ma \quad (11)$$

or after substitutions of each term

$$-\left(\frac{c_D\rho}{2}\right)\left(\frac{\pi D_p^2}{4}\right)(\vec{V}-\vec{U})|\vec{V}-\vec{U}|-\left(\frac{\pi D_p^3}{6}\right)\rho_p g\hat{j}=\left(\frac{\pi D_p^3}{6}\right)\rho_p\frac{d\vec{V}}{dt} \quad (12)$$

Then, we can write the acceleration vector for particle as

$$\frac{d\vec{V}}{dt}=-\hat{j}g-\left(\frac{3c_D}{4}\right)\left(\frac{\rho}{\rho_p D_p}\right)(\vec{V}-\vec{U})|\vec{V}-\vec{U}| \quad (13)$$

or in x and y components

$$\frac{du_p}{dt}=Au_p+B \quad (14)$$

$$\frac{dv_p}{dt}=Av_p+D \quad (15)$$

where

$$A=-\left(\frac{3c_D}{4}\right)\left(\frac{\rho}{\rho_p D_p}\right)\left[(u_p-u)^2+(v_p-v)^2\right]^{\frac{1}{2}} \quad (16)$$

$$B=-Au \quad (17)$$

$$D=-Av-g \quad (18)$$

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

$$\begin{aligned} u_p &= x \\ v_p &= y \\ \overset{o}{u}_p &= Au_p+B \\ \overset{o}{v}_p &= Av_p+D \end{aligned} \quad (19)$$

The solution for equation (18) is a locus of points (x,y) representing a path line of the interested particle. Note that U and V which appear in equations (16), (17) and (18) are obtained from equations (2) and (3) respectively.

3. Simulation result

The geometry and boundary condition of cross section of commercial kitchen filter are shown in figure1.

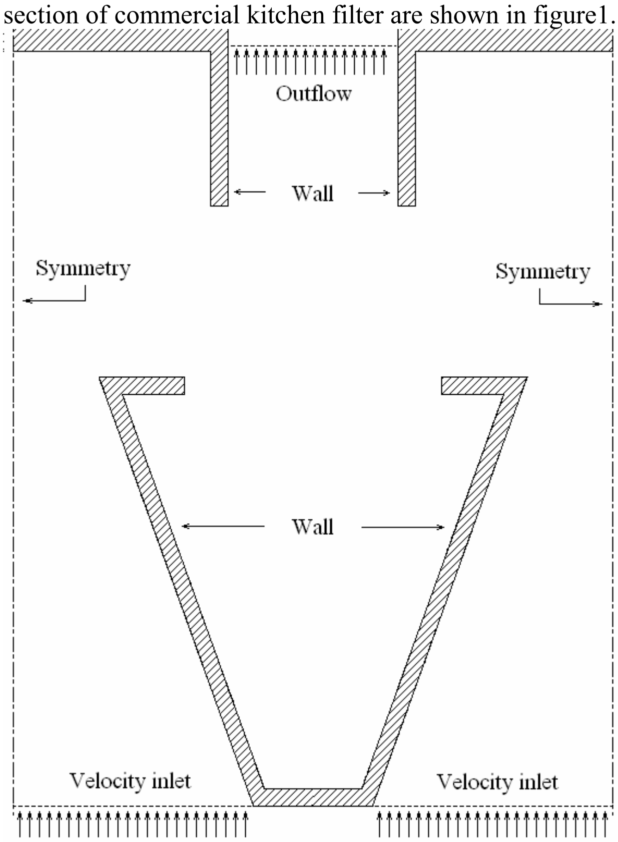

Figure 1: Geometry of cross-section of commercial kitchen filter.

The model is assumed to two-dimensional model which can be extruded to three-dimension. The size is 35 mm wide and 43 mm height. Air is working fluid with 1kg/m^3 density and 1.55e-5 (N s)/m^2 viscosity. Laminar and incompressible flow are assumed. For the particles properties, density of 1000 kg/m^3 is assumed. The solution shown in figure2 uses inlet velocity equal to 0.3 m/s. There exist two recirculation zones after the sudden expansions and a stagnation region at the bottom of the filter. At the exit there appear a Vena contracta resulting from orifice like behavior.

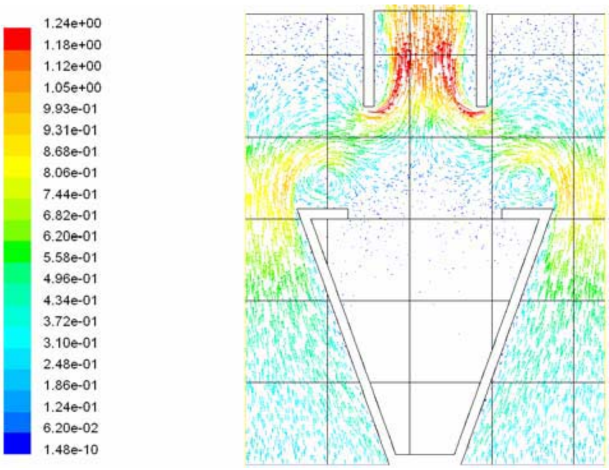

Figure 2 Velocity vector field for inlet velocity = 0.3 m/s. (Coloring with velocity magnitude in m/s)

Particles are injected into the flow field from 20 equally space points at the bottom inlet port. Particles that larger than 100-micron are all trapped. (see figure3)

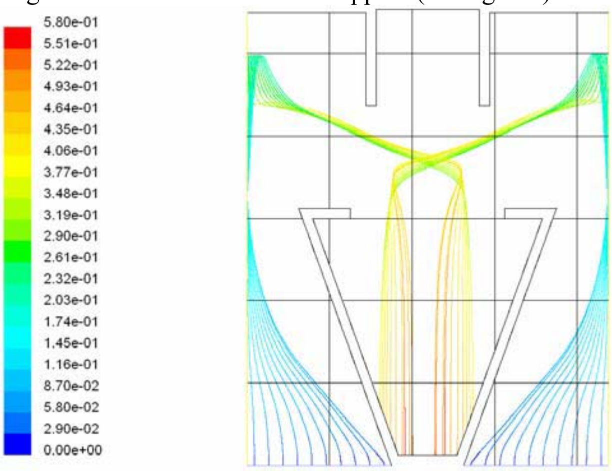

Figure 3 Particles trajectory for particle diameter 100 micron at inlet velocity 0.3 m/s (Coloring with residual time in second)

From the performance chart shown in figure4, it can be clearly seen that at high velocity starting from 0.5 m/s, smaller particles are trapped. The sizes of trapped particles become smaller when increasing the higher inlet velocity and here are more and more particle impact the filter and trapped at the wall. However, increasing the velocity will lead to break up of liquid particles. The liquid break up phenomena is beyond the scope of this study. The trajectories of smaller particles tend to follow the path lines of the flow field as shown in figure 5. It is cleary shown that the filter can not trap particle of these smaller sizes.

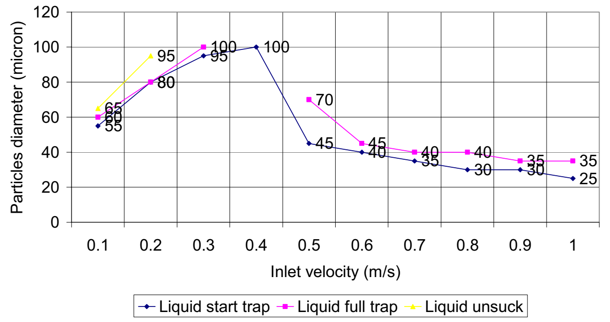

Figure 4 Chart of efficiency of liquid particle for commercial kitchen filter

The trajectories of very small particles are following to the path lines of the flow field as shown in figure 5.

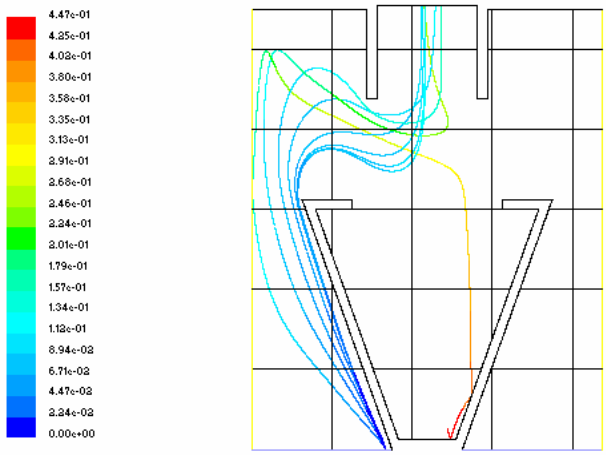

Figure 5 Particles trajectory for particle diameter 100, 80, 60, 40, 20, 10, 5, and 1 micron (from left to right) at inlet velocity 0.3 m/s (Coloring with residual time in second)

4. Conclusion

The velocity inlet of more than 0.5 m/s is appropriate for this grease filter. At the inlet velocity liquid particles start to impact and trapped at the wall. However, too high velocity inlet will lead to break up of liquid particles. These results can be shown clearly in the introduced efficiency chart for the commercial kitchen filtering system. This filter can trap only the particles diameter more than 25 micron for 1.0 m/s inlet velocity. The particles diameters less than those values can't be trapped by commercial kitchen filter. In actual, aerosol particles size is in range of 30-100 nanometers [1]

Acknowledgments

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2. Introduction

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Please use A4 paper (21.0 cm x 29.7 cm) and 2-column format. Each column width is 82 mm and the space between columns is 6 mm. Page margins should be set as follows: top and bottom, 25 mm; left and right, 20 mm. Paragraph tab should be set at 6.3 mm. The space between lines is *single-space*. One blank line should be given between section headings. No space is needed between subsection headings.

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Figure, table and equation must be numbered sequentially. Equation number must be right aligned as shown in the following example:

$$\bar{\lambda}_g = \frac{\mu}{p}\left(\frac{2kT}{m}\right)^{1/2} \tag{1}$$

where μ is the viscosity, p is the pressure, k is the Boltzmann constant, T is the temperature, and m is the mass of gas molecule.

Equation should be prepared using MathType, Equation Editor, or other equation software with the font size of TNR #10.

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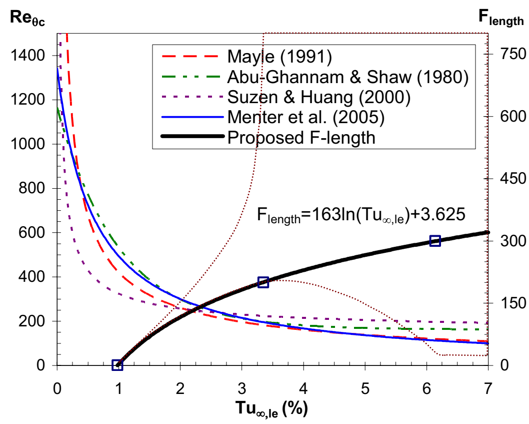

Figure 1. Example of a figure

Table 1. Example of a table

x	θ	ω_1
0.1	2.7470×10^1	2.7483×10^1
0.5	3.5352×10^1	3.5360×10^1
1.0	1.5352×10^2	9.5360×10^4

5. Conclusion

The manuscript should be checked by all the co-authors prior to the submission, if possible, to eliminate error(s) that may escape your review.

Acknowledgments

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References

The references must be listed in order of their appearance in the context. Please follow the format given below strictly. The headings; *Journal*, *Conference*, *Book* and *Website* should be omitted.

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