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Prediction of the Pipe Diameter to Lift the Impurities in Nuclear Power Plants

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1. Introduction

During the operation of nuclear power plants, the undesired impurities such as metal powder, dust and debris wear out from the inner surface of pipe are mixed with working fluid, water. These impurities cause many problems such as irregularity in the thermal characteristics and increase of radioactivity in the overall system. In order to eliminate impurities, water contaminated with impurities has to be filtered before return to the reactor coolant system. For this, impure particles should lift in the water to be carried by flow and finally removed at the filter. In this paper, a simplified model to lift a particle in the viscous fluid flow was developed by applying the Magnus effect, and the computational fluid dynamics (CFD) simulation was carried out to validate the model.

2. Analytical Model

When a sphere or circular cylinder body is spinning in a viscous fluid, the boundary layer created around it makes a more widespread circular motion of the fluid [1-3]. As can be seen in Fig. 1, if the fluid is moving with a velocity U_f around a rotating sphere body, the velocity at the boundary layer edge is a little greater than U_f on the forward-spinning side and a little less than U_f on the backward-spinning side. The Magnus force is induced due to this flow field and the body can move perpendicularly by this lift force. It is evident that lift force should greater than the gravity force of a particle to lift it perpendicularly.

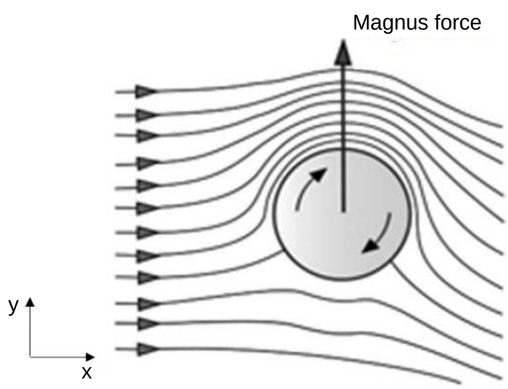


Fig. 1. The Magnus or lift force on a spinning particle in fluid.

From that point of view, a simple criterion can be suggested as follows:

$$\rho_f U_f d_p{}^3 \frac{dU_f}{dy} > (\rho_p \frac{\pi}{6} d_p{}^3) g \qquad (1)$$

Subscript f refers to the fluid and p to the particle. Assuming that the particle is drifted in the log layer, the velocity gradient of fluid becomes

$$\frac{dU_f}{dy} = \frac{u_\tau}{\kappa y} \qquad (2)$$

where, u_τ : friction velocity

If we use the following friction factor,

$$f \equiv \frac{\tau_w}{\frac{1}{8}\rho U_m{}^2} = \frac{\rho u_\tau{}^2}{\frac{1}{8}\rho U_m{}^2} \qquad (3)$$

where, τ_w : local wall shear stress
U_m : mean velocity

Therefore, $u_\tau = U_m \sqrt{f/8}$. Since $y^+ = (y u_\tau / \nu)$, the velocity gradient of fluid along y-direction is obtained as follows:

$$\frac{dU_f}{dy} = \frac{u_\tau}{\kappa y} = \frac{u_\tau{}^2}{y^+ \kappa \nu} = \frac{f U_m{}^2}{8 y^+ \kappa \nu} \qquad (4)$$

where, κ : Von Karman constant (=0.4)
ν : kinematic viscosity

From the logarithmic law of the wall,

$$u^+ = \frac{U_f}{u_\tau} = \frac{1}{\kappa}\ln\left(y^+\right) + B \qquad (5)$$

where, B : constant (=5.5)

Then the Eq. (1) is arranged by inserting the Eqs. (4) and (5) as follows:

$$\rho_f u_\tau \left\{\frac{1}{\kappa}\ln\left(y^+\right) + B\right\} \frac{f U_m{}^2}{8 y^+ \kappa \nu} > (\rho_p \frac{\pi}{6}) g \qquad (6)$$

Finally we obtain the minimum mean velocity condition to float the particle in viscous fluid flow as follows:

$$U_m > \left[\frac{\left(\rho_p \frac{\pi}{6} g\right) \times y^+ \kappa \nu}{\rho_f \left\{ \frac{1}{\kappa} \ln\left(y^+\right) + B \right\} \left(\frac{f}{8}\right)^{3/2}} \right]^{1/3} \quad (7)$$

In order to solve the Eq. (7), the friction factor has to be determined by one of the following equations [4-6].

Prandtl-Nikuradse equation

$$\frac{1}{\sqrt{f}} = 2.0 \log(\mathrm{Re}_D \sqrt{f}) - 0.8$$

$$\text{for} \quad 3 \times 10^3 < \mathrm{Re}_D < 3 \times 10^5$$

Blasius equation

$$f = \frac{0.3164}{\mathrm{Re}_D^{1/4}} \quad \text{for} \quad \mathrm{Re}_D \le 10^5$$

Nikuradse equation

$$f = 0.0032 + \frac{0.221}{\mathrm{Re}_D^{0.237}} \quad \text{for} \quad \mathrm{Re}_D \simeq 10^5 \sim 3 \times 10^6$$

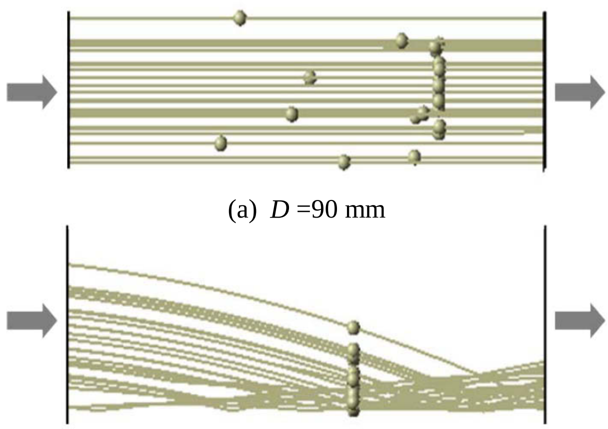
where, $\mathrm{Re}_D = (U_m D)/\nu$, $D = \sqrt{Q/(\pi U_m/4)}$

3. Particle Tracking Simulation

The CFD simulation was carried out to validate the suggested model. As an example, the impurities in water flow are the rust powders with $\rho_p = 7700\ \mathrm{kg/m^3}$ and the minimum value that the law of the wall can be applicable is $y^+ = 11$. And if the required volumetric flow rate is about 0.02 $\mathrm{m^3/s}$ and the Blasius equation is used to calculate the friction factor, the diameter of pipe must smaller than 100 mm to lift the rust powders in the pipe. The minimum mean velocity is 2.53 m/s for this case.

In the present study, the Lagrangian particle tracking with fully fluid-particle coupling was used to simulate the particle trajectories. The buoyancy and Schiller Naumann drag model were used [7-8]. To make the flow fully developed, the pipe length was taken to be 10 times of the diameter.

Fig. 2 represents the simulated particle trajectories with different diameters of the pipe. From an estimation of above example by the proposed model, the particles are expected to sink in the pipe if the diameter is larger than 100 mm, otherwise, the particles will be floated. As can be seen in Fig. 2-(a), particles in the pipe diameter of 90 mm are floated throughout the entire computational domain. The mean velocity is 3.14 m/s that is greater than the critical velocity, 2.53 m/s. On the other hand, as can be seen in Fig. 2-(b), particles sink to the bottom of the pipe after injecting at the inlet. The mean velocity of this pipe flow is 2.1 m/s. These simulations imply that particles will be piled up at the bottom of the pipe if the pipe diameter is not properly chosen.



(a) D =90 mm

(b) D =110 mm

Fig. 2. Particle trajectories in the different diameters of pipe: (a) D =90 mm, (b) D =110 mm.

4. Conclusion

A simple mathematical model based on the Magnus force has been suggested to predict a diameter of pipe in nuclear power plants. In order to simulate the particle trajectories in pipe flow, CFD simulation for the 3-dimensional pipe flow has been carried out by using the commercial code, CFX. The Lagrangian particle tracking technique was used to track the particle paths. The proposed model yields very similar results to those obtained by computational simulation.

Acknowledgement

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