Computational Prediction of Paste Separation from Industrial Waste by a Dry Separator Equipped with a Rotor

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Abstract: - Recycling of aggregates separated from industrial wastes becomes more important than ever because of increasing demand of urban redevelopment. The purpose of this study is to investigate the operating principle of a newly developed paste separator equipped with a rotor. We constructed one-dimensional model for the air flow and the particle motion is assumed to be governed by the air drag, centrifugal and gravitational forces. We demonstrate that there are several sections on the air flow route, where particle motions are stationary along the stream-wise direction while rotating in the azimuthal direction, called quasi-stagnant state. It was shown that it plays a key role in separation of particles. We report the critical curve in the parametric space where we can predict separation or non-separation of a given particle size, flow rate and rotor speed.

Key-Words: - Industrial waste, paste separation, numerical prediction, aggregate, rotor

1 Introduction

As per the continuing demand of urban re-development, the issue of “how to recycle the wastes including cement aggregates” has been uttermost important. Various technologies for producing the recycling materials from the wastes have been developed so far [1]. Detailed discussion on the technological process of manufacturing recycling products has been given, e.g., in [2].

The process is composed of complicated engineering stages, such as removing extra materials, crushing coarse aggregates, removing cement and mortar, and sorting the particles depending on their size, etc. [2] Not only the mechanical but also even the chemical principle (see e.g. [3]) is also utilized in the process. In the sorting process, in particular, liquid can also be used [4, 5], which is called wetting method compared with dry method.

In this study, we report the mechanism of sorting the fine size particles (pastes or cementitious powder [6]) by using a dry separator equipped with a rotor. We employ both theoretical and numerical methods to reveal the mechanism. In order to make the analysis feasible, we assume one-dimensional flow field and steady-state drag-force formula acting on the particles. It turns out that the rotor plays a key role in separating pastes from the wastes.

2 Problem Formulation

Figure 1 shows the geometry of the rotor rotating around the z-axis. We designate three regions; the inlet region, $r > R_{b1}$, the rotor channel, $R_{b2} < r < R_{b1}$, and the core, $r < R_{b2}$. Air carrying the solid particles is pushed into the rotor from the inlet section at $r = R_i$, enters the inlet of the rotor channel at $r = R_{b1}$, flows through the channel in between the rotating radial blades and exits the channel outlet at $r = R_{b2}$. In the core region, $r < R_{b2}$, air is guided to flow upward as well as toward the central axis, while showing a spiral trajectory due to the conservation of angular momentum.

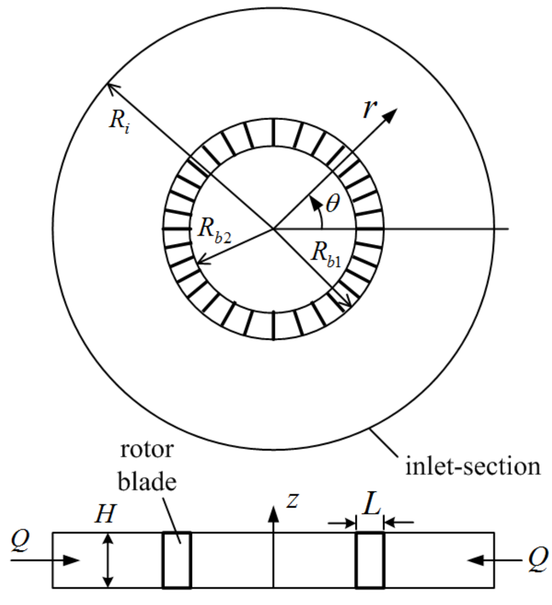


Fig. 1 Geometry of the rotor for separation of paste particles from wastes and the cylindrical coordinates for describing the motion of air and particles.

For the theoretical treatise to be feasible, we develop a much simplified flow model. In the inlet region, the air flow is assumed to be radial and uniformly distributed on the azimuthal plane. The flow velocity is inversely proportional to r. Within the rotor channel, too, the air flow is assumed to be purely radial and uniform. Its velocity is computed from the continuity equation. Since the area of the channel is reduced further due to the finite thickness of the blades, the velocity is suddenly increased at the interface, $r = R_{b1}$, while the fluid enters the channel. In the core, the air flow must be upward to be drawn to the outlet. So, in this region we propose an axi-symmetric flow model, where the vertical velocity component is taken to be proportional to z and is dependent on the radial position by a cubic polynomial function of r, from which the radial velocity component is decided from the continuity equation. On the other hand, the azimuthal component is determined from the principle of conservation of angular momentum applied throughout the core region. In the region connected to the outlet from there, the vertical component is taken to be independent of z and so the radial component is zero and the azimuthal component still follows the angular momentum conservation.

In terms of the inertial frame of reference, the particle motion is governed by the Newton's 2nd law of motion, where the air drag force acts along the air's relative velocity referred to the particle velocity, and the gravitational force acts downward with a constant magnitude. The air drag coefficient is given from

$$c_D = \frac{24}{\mathrm{Re}_p} + \frac{6\,\mathrm{Re}_p}{11.55 + \mathrm{Re}_p^{1.52}} + 0.194\,\mathrm{Re}_p^{0.06} \qquad (1)$$

where $\mathrm{Re}_p = \rho u_{ap} d_p / \mu$ is the particle Reynolds number, ρ the air density, u_{ap} the magnitude of the relative velocity of air, d_p the particle diameter, and μ the dynamic viscosity of air. Since cylindrical coordinates are used in the expression of the particle motion, both the centripetal and Coriolis acceleration terms appear on the left-hand side of the equations, but these are moved to the right-hand side and are treated as the centrifugal and Coriolis forces, respectively, for better understanding of the physics to be given in the discussion.

Two kinds of analysis for the particle motion have been conducted in this study; the first one is the quasi-stagnant analysis and the second one the numerical analysis with the full equations for the motion of a particle. In the first kind, the particle is assumed to be stagnant in the radial motion (but is allowed to rotate) and simultaneously sum of the horizontal forces (air drag plus centrifugal force) is assumed to be zero as the basic state. Then a small perturbation in its location is applied to determine the basic state's stability. In the second, after the particle is introduced at the inlet, its trajectory is followed with purely numerical integration of the equations for the particle motion in time so that we can confirm if the stability predicted in the first analysis is indeed relevant. Such a s table quasi-stagnant orbit of a particle turns out to be a crucial element in understanding the superior capability of the paste separation provided by the newly developed separator.

3 Results and Discussion

Figure 2 shows the radial distribution of the air drag, $-f_D$, and the centrifugal force, f_{ce}, acting on a particle at a quasi-stagnant state. At the outlet of the rotor channel, $r = R_{b2}$, the drag force $-f_D$ is larger than f_{ce} inside the channel, so that the particle tends to move toward the outlet. On the other hand, $-f_D$ is smaller than f_{ce} outside the channel, so that the particle tends to move toward the outlet, too. This implies that the particle's quasi-stagnant state is stable, and so the particle tends to accumulate there. During that time the gravitational force will make the particle fall down and be withdrawn through a hole on the bottom plate of the rotor. Such scenario is a fundamental route to understanding the superior capability of the paste separation. On the other hand, another quasi-stagnant state at the channel inlet, $r = R_{b1}$, is unstable because $-f_D$ is larger than f_{ce} inside the channel.

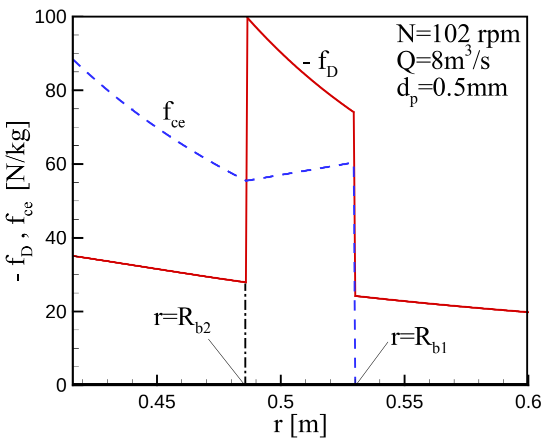
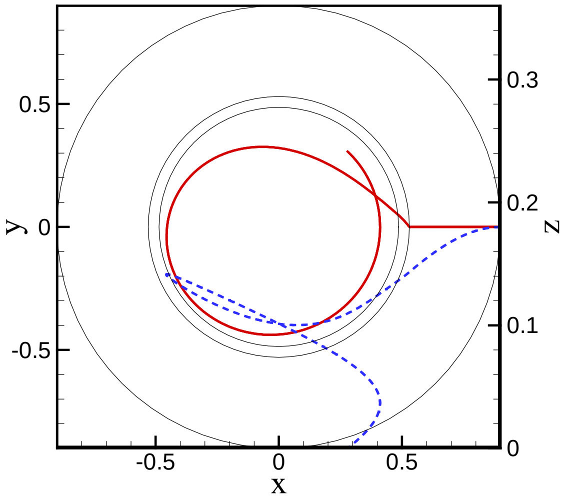
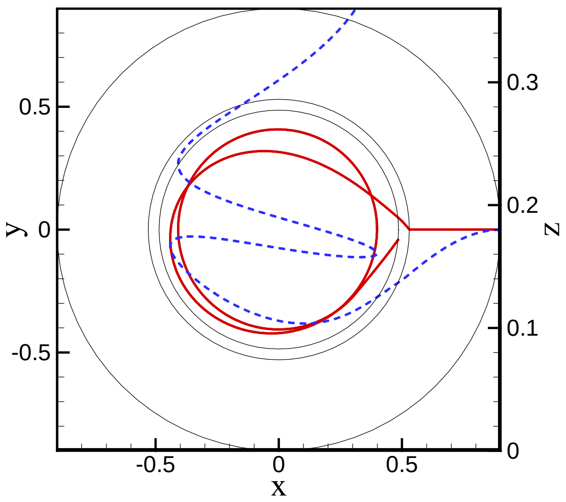


Fig. 2 Typical distribution of air drag and centrifugal forces along the radial position.

As the particle size is decreased, the drag force becomes more important and outside the outlet of the channel, it overtakes the centrifugal force and thus the quasi-stagnant state is no longer stable there. Instead the stable point moves to the core region. For a larger particle size, the channel inlet position now provides the stable steady-stagnant state.



(a)



(b)

Fig. 3 Particle trajectories projected on the (x, y) plane (solid curve) and on the (x, z) plane (dashed line) for (a) $d_p = 0.26$ mm and (b) $d_p = 0.25$ mm .

Figure 3 shows typical trajectories of particles having two slightly different diameters obtained from numerical simulation of the full equations. The slightly larger and smaller particles fall down (a) and rise up (b), respectively leading to non-separation and separation, respectively. The results are in good agreement with the prediction given by the theoretical analysis.

Figure 4 shows the limit curves from which we can classify, for the particle diameter 0.075mm, its separation (left-upper region) and non-separation (right-lower region) result. We can see very close agreement between the two results implying that a simple theoretical analysis based on the quasi-stagnant state and its stability analysis is a reliable tool in designing the separator.

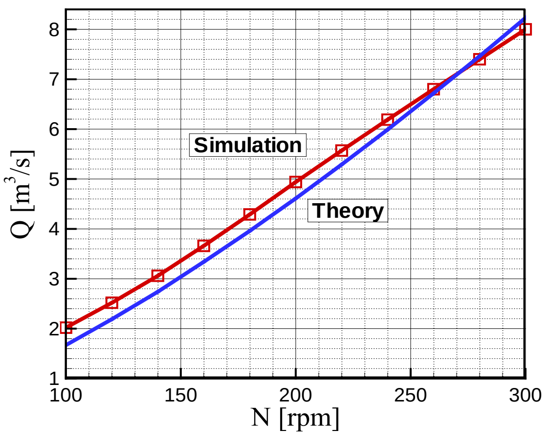


Fig. 4 Comparison of the limit curve for separation and non-separation of particles with diameter 0.075mm obtained from the theory (line without symbols) and the simulation (line with symbols).

4 Conclusion

Various simplifying assumption has been made for the air-velocity distribution in the fluid-passing route around the rotor and for forces acting on the particle for the theoretical analysis to be possible regarding the particle separation in a newly developed separator. It is found that the concept of quasi-stagnant state and its stability plays a key role in understanding the physical mechanism of the paste separation. We confirm that the rotation of the rotor equipped with blades creates the centrifugal force acting on the particle outward, and pushing the air from the outer- toward the inner-region through the rotor channel makes the air-drag force acting inward so that balance between the two forces can be achieved. We also confirm that blades of finite thickness on the rotating disc result in difference in the air drag force between inside and outside so as to cause the particle to show quasi-stagnant state in particular at the exit of the rotor channel such that the gravitational activity has enough time for the particles to settle down and be removed from the air.

Acknowledgment

This work was supported by NRF grant No. 2009-0083510 through Multi-phenomena CFD Engineering Research Center and by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean government Ministry of Knowledge Economy (No. 20114030200030). It was also supported by Kumho Machinery.

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