CFD Simulation of Dry Pressure Drop in a Cross-Flow Rotating Packed Bed

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Abstract: The cross-flow rotating packed bed (RPB) has attracted wide attention in recent years because of its advantages of large gas capacity, low pressure drop and lack of flooding limitation. However, the complex structure of the packing makes it difficult to obtain the gas flow characteristics in the cross-flow RPB by experiments. In this study, the dry pressure drop in the cross-flow RPB was investigated by computational fluid dynamics (CFD). The packing was modeled by the porous media model and the rotation of the packing was simulated by the sliding mesh model. The simulation results obtained by three turbulence models were compared with experimental results, and the RNG k-ε model was found to best describe the turbulence behaviors in the cross-flow RPB. Then, the effects of gas flow rate and rotating speed on dry pressure drop in different parts of the cross-flow RPB were analyzed. The results of this study can provide important insights into the design and scale-up of cross-flow RPB.

Keywords: rotating packed bed; cross-flow; computational fluid dynamics; dry pressure drop

1. Introduction

Rotating packing bed (RPB) is a novel process intensification device with many applications in absorption [1,2], distillation [3,4], polymerization [5] and waste treatment [6,7], due to its potential to increase the gas-liquid mass transfer [8]. With the characteristics of large gas capacity, low pressure drop and lack of flooding limitation, cross-flow RPB is seen as a promising candidate for the industry application among the clean tail gas with hydrogen sulfide and dust removal than countercurrent-flow RPB [9].

Pressure drop is an essential parameter that must be taken into account in detail when designing the cross-flow RPB and has been deeply investigated by experiments in many previous studies. Guo et al. [10] reported that the dry pressure drop increased with the increase of the square of the gas flow rate but remained unchanged with the acceleration of the rotating speed. Zhao et al. [11] found that the dry pressure drop increased at rotating speeds below 500 rpm but was kept constant at rotating speeds above 1400 rpm. Jiao et al. [12] found that the pressure drop in a cross-flow RPB was about one tenth of that in a countercurrent one. Liu et al. [13] demonstrated that as the rotating speed increased, the pressure drop decreased continuously in a sealed cross-flow RPB, while it firstly decreased and then increased in an open one. However, Lin et al. [14] found that the rotating speed almost had no effects on dry pressure drop. Jiao et al. [15] found that the pressure drop was lower in a cross-flow RPB with concentric annulus than in a countercurrent RPB with baffle. Many empirical equations have also been proposed to characterize the pressure drop in a cross-flow RPB. Liu et al. [16] analyzed the pressure drop from the following four parts: the gas inlet resistance drop, pressure drop of gas passed through packing, the circumferential kinetic energy transformed static pressure energy when the gas flew through an outlet plenum section and the gas outlet resistance drop. Conversely, Guo et al. [10] and Jiao et al. [12] adopted the power law to depict the...
pressure drop. Recently, Liu et al. [13] used four dimensionless parameters, including swirl ratio and Renault number to depict the pressure drop. However, it should be noted that these empirical equations can hardly be applied to other cross-flow RPBs because of different empirical parameters.

Computational fluid dynamics (CFD) provide an efficient way to investigate the hydrodynamic behaviors that are difficult to investigate experimentally, such as pressure drop, liquid flow and droplet diameter distribution in RPB [17–21]. Llerena-Chavez et al. [17] investigated dry pressure drop in three RPBs using single-phase flow model and proposed a semi-empirical equation based on CFD and Ergun equation. Yang et al. [20] investigated the effects of packing characteristics, such as opening porosity, distance, width and shape, on the pressure drop using a 3D single-phase flow model. Yang et al. [18] investigated the effects of the gas flow rate and rotating speed on the pressure drop and found that the calculated results were lower than experimental data due to the neglect of pressure drop in inlet and outlet tube. The difference between simulated and experimental pressure drop could also be attributed to the three-dimensional effect [22] and the simplified physical model of packing [23].

The hydrodynamic behaviors in a cross-flow RPB are so complex that they cannot be easily measured by experimental methods alone. In this circumstance, CFD can be used to clarify the important hydrodynamic characteristics without disturbing the flow field in RPB, such as drop diameter and resident time. A better understanding of pressure drop characteristics is of great importance for the design and scale-up of RPB, especially in the industrialization of desulfurization, denitrification and purification of fine particulate matter (PM2.5). In order to learn more about the spatial distribution of pressure drop, the pressure drop in different zones of the cross-flow RPB (cavity zone A, packing zone, cavity zone B and outlet zone) were analyzed in this study, and the effects of rotating speed and gas flow rate on total pressure drop, static pressure drop and kinetic pressure drop were also investigated.

2. Model

2.1. Physical Model

The cross-flow RPB (Figure 1a) consists of housing, liquid inlet and outlet, gas inlet and outlet, liquid distributor and packing. The liquid is introduced through the distributor and then contacts with the gas in a cross-flow way. According to the flow characteristics, the cross-flow RPB is divided into four zones (Figure 1b), including the cavity zone A from gas inlet (plane a$_1$) to 5 mm below the packing (plane a$_3$), the packing zone from plane a$_3$ to 5 mm above the packing (plane a$_5$), the cavity zone B from plane a$_5$ to gas outlet (plane a$_6$), where there is no change in diameter) and the outlet zone from plane a$_6$ to plane a$_7$. Plane a$_2$ and a$_4$ are added in the cavity zone A and packing zone, respectively. The characteristic parameters of the cross-flow RPB and packing are shown in Table 1.

2.2. CFD Model

The single-phase flow model is adopted to simulate the gas flow in the cross-flow RPB. Considering the complexity of the packing structure, the porous media model is used to describe the packing in order to simplify the calculation, and three parameters (porosity, viscous resistance coefficient $\alpha$ and inertial resistance coefficient $\beta$) that are determined experimentally are listed in Table 1. The sliding mesh model is used to simulate the rotating zone. As a complex flow characterized by expansion, contraction, free rotation and abrupt change in direction is formed in the RPB under the centrifugal force caused by the rotor, it is worth noting that no general model is available to describe the turbulence behaviors in a cross-flow RPB. In this paper, three turbulence models (RNG k-\(\varepsilon\) model, Realizable k-\(\varepsilon\) model and Reynolds stress model (RSM)) are used to obtain the turbulent flow characteristics in the cross-flow RPB for comparison. The conservation equation, momentum equation, turbulence model and porous media model are listed in Table 2.
Figure 1. The physical diagram and CFD model of cross-flow RPB. (a) Physical diagram; (b) CFD model.

Table 1. The characteristic parameters of the cross-flow RPB.

| RPB                        |          |
|----------------------------|----------|
| Diameter, mm               | 390      |
| Height, mm                 | 1020     |
| Gas inlet diameter, mm     | 160      |
| Gas outlet diameter, mm     | 160      |

| Packing                    |          |
|----------------------------|----------|
| Type                       | Wire     |
| Shape                      | Concentric ring |
| Internal diameter, mm      | 190      |
| External diameter, mm      | 375      |
| Height, mm                 | 180      |
| Porosity                   | 0.95     |
| Viscous resistance coefficient, \( m^{-2} \) | \( 2.35 \times 10^5 \) |
| Inertial resistance coefficient, \( m^{-1} \) | 42.3     |

| Operating condition        |          |
|----------------------------|----------|
| Gas type                   | air      |
| Gas flow rate, m³/h        | 0–1000   |
| Rotating speed, rpm        | 0–1000   |

2.3. Boundary Conditions and Numerical Solution

The 3D CFD model for the cross-flow RPB is established by using Ansys Fluent 15.0. A velocity inlet boundary condition is applied to inlet, a pressure out condition is applied to the outlet, and the enhanced wall function is applied to the wall. The SIMPLE algorithm is used to solve the pressure-velocity coupling and the residuals for all equations are controlled below \( 10^{-4} \). A grid with 3,281,495 meshes is selected in this work after the grid independence test.
3. Experimental Method

In order to verify the CFD model developed in this work, experiments were carried out in the cross-flow RPB described in Table 1, and the experimental setup is shown in Figure 2. The air is compressed into RPB by a roots blower, which flows axially from the bottom of the packing and then leaves the RPB via the gas outlet. The gas flow rate is measured by a rotameter and the pressure drop is measured by a manometer. The rotating speed of the rotor is varied from 0 to 1000 rpm, and the gas flow rate is varied from 0 to 1000 m$^3$/h.

![Figure 2. Schematic diagram of the experimental setup: (1) roots blower; (2) rotameter; (3) gas inlet; (4) gas outlet; (5) cross-flow RPB; (6) manometer.](image-url)
4. Results and Discussion

The effects of rotating speed and gas flow rate on dry pressure drop in the cavity zone $A$, packing zone, cavity zone $B$ and outlet zone are discussed in this section. The dry pressure drop is defined as the pressure drop as the gas passes through the cross-flow RPB without liquid and it consists of static and dynamic pressure drop. The static pressure drop is the pressure drop perpendicular to the gas flow direction, while the dynamic pressure drop is the kinetic energy loss as the gas passes. The average surface pressure is introduced for calculation due to different flow sections in cross-flow RPB.

4.1. Model Verification

The dry pressure drop at different gas flow rates and rotating speeds is calculated using the three turbulence models and compared with that obtained by experiment, as shown in Figure 3. Note that the average pressure of the cross section is used. The average error at the gas flow rate of 200 m$^3$·h$^{-1}$ is 5.2%, 6.3% and 182.9% for RNG k-$\varepsilon$, RSM and Realizable k-$\varepsilon$ model, while that at 800 m$^3$·h$^{-1}$ is 1.7%, 4.7% and 102.3%, respectively. Thus, both RNG k-$\varepsilon$ model and RSM can well describe the turbulence behavior in cross-flow RPB. It may be attributed to the unique structure of RPB, where gas suddenly expands at the inlet of RPB, then changes the direction at the bottom, and then suddenly narrows at the outlet. Figure 4 shows the pressure drop in cavity zone $A$. The realizable k-$\varepsilon$ model shows the largest error, implying that it is unsuitable to describe the turbulence in cross-flow RPB due to suddenly expansion of packing. The difference between RNG k-$\varepsilon$ and RSM becomes more pronounced with increasing rotating speed because of gas reflux. In case of no gas reflux, the gas-phase velocity and pressure loss would be kept constant even if the rotating speed is changed. Thus, energy loss caused by friction shows no significant change in this area, but the calculated pressure drop decreases. It is suggested that some gases in the packing area are sheared and the kinetic energy is returned to cavity zone $A$, resulting in a decrease of pressure drop. Thus, from the perspective of total energy, the pressure drop in the cavity zone $A$ should decrease with increasing rotating speed. In conclusion, RNG k-$\varepsilon$ is more suitable to reveal the flow pattern in cross-flow RPB and, thus, it is used in the following calculation.

![Figure 3](image-url)

Figure 3. Comparison of the experimental total pressure drop with calculated pressure drop for three turbulence models at different gas flow rates and rotating speeds. (a) Gas flow rate of 200 m$^3$·h$^{-1}$; (b) gas flow rate of 800 m$^3$·h$^{-1}$. 
4.2. Cavity Zone A

4.2.1. Effect of Rotating Speed

The rotating speed has significant effects on the pressure drop in cavity zone A, as shown in Figure 5. Figure 5a shows the pressure drop at the gas flow rate of 800 m$^3$·h$^{-1}$ decreases gently from 62.5 Pa to 38 Pa with the increase of rotating speed from 200 rpm to 1000 rpm, which is attributed to the gas reflux from the packing area to the cavity zone A. Figure 5b shows the effect of rotating speed on static pressure drop. Clearly, at a gas flow rate of 200 m$^3$·h$^{-1}$ and rotating speed below 400 rpm, the static pressure drop decreases from 2.5 Pa to 3 Pa and then more rapidly from 6 Pa to 20 Pa. A part of gas static energy is converted to internal energy and the rest is converted to dynamic pressure energy. At a gas flow rate of 800 m$^3$·h$^{-1}$, the static pressure drop decreases from −2.5 Pa to −6 Pa, which may be due to the packing 'block', low gas velocity and conversion of dynamic pressure energy to static pressure energy. In order to learn more about pressure drop, plane $a_2$ (Figure 1b) is added. The static pressure drop between $a_2$ and $a_3$ changes greatly because the cross section is expanded suddenly at the inlet and thus a part of the static pressure energy is converted to internal energy and kinetic energy. While the static pressure drop between $a_1$ and $a_2$ shows no significant change at the gas flow rate of 200 m$^3$·h$^{-1}$, it increases slightly at the gas flow rate of 800 m$^3$·h$^{-1}$. Figure 5c shows the effect of rotating speed on the dynamic pressure drop. It is seen that the dynamic pressure drop is kept at about 65 Pa at rotating speeds below 800 rpm but decreases rapidly from 64 Pa to 44 Pa when the rotating speed is above 800 rpm. The gas at the lower part of the packing zone is driven to the cavity zone A by centrifugal force, which leads to an increase of gas kinetic energy.

4.2.2. Effect of the Gas Flow Rate

The effect of the gas flow rate on the pressure drop in the cavity zone A is shown in Figure 6. As the gas flow rate increases at 200 rpm, the pressure drop increases rapidly from 6.5 Pa to 97 Pa due to the formation of more swirls at high gas flow velocities (Figure 6a), while the static pressure decreases from 2.5 Pa to −4 Pa due to the conversion of static energy to kinetic and inner energy. However, note that as the gas flow rate increases from 200 m$^3$·h$^{-1}$ to 1000 m$^3$·h$^{-1}$ at the rotating speed of 200 rpm, the dynamic pressure drop increases markedly from 4 Pa to 101 Pa (Figure 6c). This is because more kinetic energy is transformed to static energy, and more energy is consumed by swirls formed at high gas flow rates. In the cavity zone A, the dynamic pressure drop accounts for a major portion of pressure drop at rotating speeds below 800 rpm, while the static pressure plays an important role in pressure drop at a gas flow rate of 200 m$^3$·h$^{-1}$.

Figure 4. The pressure drop in cavity zone A for three turbulence models at different rotating speeds. (a) Gas flow rate of 200 m$^3$·h$^{-1}$; (b) gas flow rate of 800 m$^3$·h$^{-1}$.
4.3. Packing Zone

4.3.1. Effect of Rotating Speed

The effect of rotating speed on the pressure drop in the packing zone is shown in Figure 7. Figure 7a shows that as the rotating speed increases from 200 rpm to 1000 rpm, the pressure drop at the gas flow rate of 200 m$^3$·h$^{-1}$ decreases to a minimum of 0.2 Pa, because the energy overcomes the frictional force caused by packing, after which it increases rapidly to 6 Pa because of the increase of gas kinetic energy by rotating. However, the pressure drop decreases significantly from 16.5 Pa to 6 Pa at a gas flow rate of 800 m$^3$·h$^{-1}$.

Figure 7b shows that static pressure drop increases slowly at a low rotating speed of 600 rpm because of the conversion of static pressure energy to kinetic energy. Then, the packing zone is subdivided into two parts: Section 1 (plane $a_3$ to plane $a_4$) and Section 2 (plane $a_4$ to plane $a_5$). In Section 1, at a gas flow rate of 200 m$^3$·h$^{-1}$ and rotating speed of 400 rpm, the static pressure drop increases to a maximum of 2 Pa and then decreases to $-5$ Pa at a rotating speed of 1000 rpm (Figure 8a). The reason can be explained as follows. The gas velocity in the lateral direction increases more quickly than that in the vertical direction due to the friction of packing, and the gas moves mainly in the lateral direction and collides with the wall, leading to the conversion of kinetic energy to static pressure energy. This is also confirmed by the static pressure cloud. To be more specific, the pressure drop at the edge of the packing area is larger than that in surrounding areas (red color shown in Figure 8c,d). In Section 1, at the gas flow rate of 800 m$^3$·h$^{-1}$ and rotating speed of 400 rpm, the static pressure drop is kept constant and then increases to 18 Pa at a rotating speed of 800 rpm, which may be attributed to the initial gas distribution. There would be a balance between the increase of static pressure energy by collision and the conversion to kinetic energy at low rotating speeds, and the latter is predominant over the former with the increase of the rotating speed. In Section 2, the static pressure drop goes up to 17 Pa at
the gas flow rate of 800 m$^3$·h$^{-1}$ as the rotating speed is increased from 200 rpm to 1000 rpm due to less collision.

Figure 7c illustrates that dynamic pressure drop first decreases to $-4$ Pa and then increases to 2 Pa when the gas flow rate and rotating speed are kept at 200 m$^3$·h$^{-1}$ and 400 rpm, respectively. Finally, it decreases from 2.5 Pa to $-28$ Pa at gas flow rate of 800 m$^3$·h$^{-1}$. As shown in Figure 9, the dynamic pressure drop in Section 1 decreases gradually both at low and high gas flow rates, while that in Section 2 increases with the increase of rotating speed from 200 rpm to 800 rpm due to the conversion of more static pressure energy to kinetic and internal energy.

4.3.2. Effect of the Gas Flow Rate

The effect of the gas flow rate on the pressure drop in the packing zone is shown in Figure 10. As the gas flow rate is increased from 200 m$^3$·h$^{-1}$ to 800 m$^3$·h$^{-1}$ at 200 rpm, the pressure drop increases rapidly from 1.4 Pa to 27.6 Pa (Figure 10a), while the static pressure drop increases from 2 Pa to 37 Pa (Figure 10b). This is partly because the high gas flow rate leads to the conversion of more static pressure energy to kinetic energy, and partly because the kinetic energy increases with increasing gas flow rate. Figure 10c reveals that the dynamic pressure drop decreases to $-2$ Pa at gas flow rate of 600 m$^3$·h$^{-1}$ and a rotating speed of 200 rpm, and then increases to 4 Pa at the gas flow rate of 1000 m$^3$·h$^{-1}$. The increase of kinetic energy caused by the lateral friction force acting on the gas is lower than the consumption of frictional force. However, the kinetic pressure drop decreases from $-2$ Pa to $-20$ Pa at a rotating speed of 800 rpm. In the packing zone, a static pressure drop plays an important role in the pressure drop at a gas flow rate of 200 m$^3$·h$^{-1}$ and rotating speed of 200 rpm, but dynamic pressure drop becomes dominant at a gas flow rate of 600 m$^3$·h$^{-1}$ and rotating speed of 800 rpm.
Figure 7. The effect of the rotating speed on the pressure drop in the packing zone. (a) Pressure drop; (b) static pressure drop; (c) dynamic pressure drop.

Figure 8. Cont.
Figure 8. The static pressure drop in the packing zone. (a) Plane a3 to a4; (b) plane a4 to a5; (c) gas flow rate 200 m$^3$·h$^{-1}$, rotating speed 1000 rpm; (d) gas flow rate 800 m$^3$·h$^{-1}$, rotating speed 1000 rpm.

Figure 9. The dynamic pressure drop in the packing zone. (a) Plane a3 to a4; (b) plane a4 to a5.

4.4. Cavity Zone B

4.4.1. Effect of Rotating Speed

The effect of rotating speed on the pressure drop in the cavity zone B is shown in Figure 11. Figure 11a shows that the pressure drop at a gas flow rate of 800 m$^3$·h$^{-1}$ increases markedly from 1.5 Pa to 27 Pa with an increase of rotating speed from 200 rpm to 1000 rpm. The gas turbulence in the cavity zone B is enhanced by the rotating packing and more gas will collide with each other, leading to the loss of more energy and, consequently, the increase of the pressure drop. An interesting finding is that the pressure drop at a gas flow rate of 200 m$^3$·h$^{-1}$ is larger than that at 800 m$^3$·h$^{-1}$ when the rotating speed is kept at 200 rpm. At a low gas flow rate, the contact time between packing and gas is prolonged, and collision and pressure drop occur simultaneously. However, when the rotating speed is higher than 200 rpm, the wall friction loss will increase, resulting in a larger pressure drop at a high gas flow rate. Figure 11b shows that the static pressure drop decreases from −2 Pa to −15 Pa as the rotating speed is increased from 200 rpm to 800 rpm at a gas flow rate of 800 m$^3$·h$^{-1}$. It is also seen that the difference between a gas flow rate of 200 m$^3$·h$^{-1}$ and 800 m$^3$·h$^{-1}$ becomes less noticeable with increasing rotating speed, which is attributed to the increase of collision and conversion of kinetic energy to static pressure and internal
energy at high rotating speed. Figure 11c shows that dynamic pressure drop increases markedly from 1 Pa to 43 Pa with the increase of rotating speed from 200 rpm to 800 rpm. The same trend is observed at a low gas flow rate.

![Figure 10](image-url)

**Figure 10.** The effect of the gas flow rate on the pressure drop in the packing zone. (a) Pressure drop; (b) static pressure drop; (c) dynamic pressure drop.

### 4.4.2. Effect of Gas Flow Rate

The effect of the gas flow rate on the pressure drop in the cavity zone B is shown in Figure 12. Figure 12a shows that the pressure drop at a rotating speed of 200 rpm increases slightly to 2.5 Pa at a gas flow rate of 400 m\(^3\)·h\(^{-1}\) and then decreases slowly to 1 Pa. At low Reynolds, the friction coefficient increases with the decrease of Reynolds. However, the pressure drop at a rotating speed of 800 rpm increases slightly to 17 Pa as the gas flow rate is increased from 200 m\(^3\)·h\(^{-1}\) to 600 m\(^3\)·h\(^{-1}\), after which it levels off. At high Reynolds, the friction coefficient depends only on the relative coarseness and the influence of the gas flow is negligible. Figure 12b shows that static pressure drop decreases slightly from −9 Pa to −12 Pa with the increase of gas flow rate from 200 m\(^3\)·h\(^{-1}\) to 1000 m\(^3\)·h\(^{-1}\) due to the conversion of more dynamic pressure to static pressure energy when the gas passage is expanded at the rotating speed of 800 rpm. As shown in Figure 12c, the dynamic pressure drop increases slowly from 24 Pa to 28 Pa as the gas flow rate is increased from 200 m\(^3\)·h\(^{-1}\) to 1000 m\(^3\)·h\(^{-1}\) at a rotating speed of 800 rpm. The reasons are similar to that for the static pressure drop. Similar trends are found for the static and dynamic pressure drop at a rotating speed of 200 rpm. In the cavity zone B, the dynamic pressure drop plays a dominant role in the pressure drop at rotating speeds higher than 600 rpm, while the static pressure drop shows a constant ratio for the pressure drop with the increase of the gas flow rate from 200 m\(^3\)·h\(^{-1}\) to 1000 m\(^3\)·h\(^{-1}\) at a rotating speed of 200 rpm and 800 rpm.
Figure 11. The effect of rotating speed on the pressure drop in the cavity zone B. (a) Pressure drop; (b) static pressure drop; (c) dynamic pressure drop.

Figure 12. The effect of the gas flow rate on the pressure drop in cavity the zone B. (a) Pressure drop; (b) static pressure drop; (c) dynamic pressure drop.
4.5. Outlet Zone

4.5.1. Effect of Rotating Speed

The effect of rotating speed on the pressure drop in the outlet zone is shown in Figure 13. Figure 13a shows that pressure drop is kept at 60 Pa with the increase of rotating speed from 200 rpm to 800 rpm at gas flow rate of 800 m$^3$·h$^{-1}$, even if the section of the outlet area is reduced. It should also be noted that both the static pressure drop (Figure 13b) and dynamic pressure drop (Figure 13c) are kept constant with the increase of the rotating speed. In conclusion, rotating speed has no significant effect on the pressure drop in the outlet zone.

4.5.2. Effect of the Gas Flow Rate

The effect of the gas flow rate on the pressure drop in the outlet zone is shown in Figure 14. Both the pressure drop (Figure 14a) and static pressure drop (Figure 14b) increase linearly as the gas flow rate is increased from 200 m$^3$·h$^{-1}$ to 1000 m$^3$·h$^{-1}$, which is because more swirls are formed and more energy is consumed. The gas flow passage in the outlet zone becomes smaller and the gas velocity increases, and more static pressure energy is converted to dynamic pressure energy. Figure 14c shows that the dynamic pressure drop decreases from −5 Pa to −135 Pa at a rotating speed of 200 rpm and 800 rpm. In the outlet zone, the ratio of dynamic pressure drop to pressure drop is kept at 65% with the increase of rotating speed at a gas flow rate of 200 m$^3$·h$^{-1}$ and 800 m$^3$·h$^{-1}$.

![Figure 13](image-url)  
Figure 13. The effect of rotating speed on the pressure drop in the outlet zone. (a) Pressure drop; (b) static pressure drop; (c) dynamic pressure drop.
Figure 13. The effect of rotating speed on the pressure drop in the outlet zone. (a) Pressure drop; (b) static pressure drop; (c) dynamic pressure drop.

4.5.2. Effect of the Gas Flow Rate

The effect of the gas flow rate on the pressure drop in the outlet zone is shown in Figure 14. Both the pressure drop (Figure 14a) and static pressure drop (Figure 14b) increase linearly as the gas flow rate is increased from 200 m$^3$·h$^{-1}$ to 1000 m$^3$·h$^{-1}$, which is because more swirls are formed and more energy is consumed. The gas flow passage in the outlet zone becomes smaller and the gas velocity increases, and more static pressure energy is converted to dynamic pressure energy. Figure 14c shows that the dynamic pressure drop decreases from $-5$ Pa to $-135$ Pa at a rotating speed of 200 rpm and 800 rpm. In the outlet zone, the ratio of dynamic pressure drop to pressure drop is kept at 65% with the increase of rotating speed at a gas flow rate of 200 m$^3$·h$^{-1}$ and 800 m$^3$·h$^{-1}$.

Figure 14. The effect of the gas flow rate on the pressure drop in the outlet zone. (a) Pressure drop; (b) static pressure drop; (c) dynamic pressure drop.

4.6. Comparison of the Pressure Drop in Different Zones

Figure 15a shows that as the rotating speed is increased from 200 rpm to 1000 rpm at 200 m$^3$·h$^{-1}$, the ratio of pressure drop is increased slightly from 12% to 20% in the packing zone but more dramatically from 13% to 75% in the cavity zone B, but it is decreased from 48% to 22% in the outlet zone. Figure 15b shows that as the rotating speed is increased from 200 rpm to 1000 rpm at 800 m$^3$·h$^{-1}$, the ratio of the pressure drop is decreased from 43% to 30% in the cavity zone A and from 13% to 5% in the packing zone, but it is increased from 0.3% to 19% in the cavity zone B and more slowly from 43% to 46% in the outlet zone. Figure 15c shows that as the gas flow rate is increased from 200 m$^3$·h$^{-1}$ to 1000 m$^3$·h$^{-1}$ at 200 rpm, the ratio of the pressure drop is increased from 37% to 42% in the cavity zone A, but decreased markedly from 12% to 0.4% in the cavity zone B. Figure 15d shows that as the gas flow rate is increased from 200 m$^3$·h$^{-1}$ to 1000 m$^3$·h$^{-1}$ at 800 rpm, the ratio of pressure drop is increased from 6% to 40% in the cavity zone A, but it is kept at 44% in the outlet zone. Thus, the pressure drop mainly occurs in the cavity zone A and outlet zone. Notably, the pressure drop plays a more important role in the cavity zone B than in other zones when the gas flow rate is 200 m$^3$·h$^{-1}$ and the rotating speed exceeds 600 rpm.
Figure 15. Comparing the pressure drop in different zones. (a) Gas flow rate of 200 m$^3$·h$^{-1}$; (b) gas flow rate of 800 m$^3$·h$^{-1}$; (c) rotating speed of 200 rpm; (d) rotating speed of 800 rpm.

5. Conclusions

In this work, a 3D CFD model is established to investigate the dry pressure drop in the four zones of the cross-flow RPB, namely the cavity zone A, packing zone, cavity zone B and outlet zone. It was found that there is a good agreement between simulated and experimental results. Then, the effects of rotating speed and gas flow rate on dry pressure drop are investigated by the proposed model. In the cavity zone A, the static pressure increases with increasing rotating speed and decreasing gas flow rate, while the dynamic pressure drop decreases with increasing rotating speed and decreasing gas flow rate. In the packing zone, the static pressure increases slightly with increasing rotating speed and gas flow rate, while the dynamic pressure drop decreases with increasing rotating speed and decreasing gas flow rate. In the cavity zone A, the static pressure increases, while the dynamic pressure drop decreases with the decrease of rotating speed and gas flow rate. In the cavity zone B, the static pressure increases, while the dynamic pressure drop decreases with the decrease of rotating speed and gas flow rate. In the outlet zone, both static and dynamic pressure drop remain constant with increasing rotating speed. However, the static pressure drop increases linearly with a decreasing gas flow rate, while the dynamic pressure drop decreases with an increasing gas flow rate.

The pressure drop occurs mainly in the cavity zone A and the outlet zone, but it is more remarkable in the cavity zone B than in other zones at a gas flow rate of 200 m$^3$·h$^{-1}$ and rotating speeds over 600 rpm. The results of this study can provide some insights into the dry pressure drop in cross-flow RPB and, thus, they are helpful for the design and scale-up of the device. In the future, a two-phase CFD model could be developed to investigate the wet pressure drop in the cross-flow RPB.
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**Nomenclature**

\[ C_1, C_2, C_1r, C_2r \]

Turbulence model constants for velocity field

\[ g \]

gravity acceleration (m·s\(^{-2}\))

\[ k \]

turbulent kinetic energy (m\(^2\)·s\(^{-2}\))

\[ p \]

pressure (Pa)

\[ t \]

time (s)

\[ u \]

velocity vector (m·s\(^{-1}\))

\[ a \]

viscous resistance coefficient (m\(^{-2}\))

\[ \beta \]

inertial resistance coefficient (m\(^{-1}\))

\[ \epsilon \]

dissipation rate of turbulent kinetic energy (m\(^3\)·s\(^{-3}\))

\[ \mu \]

molecular viscosity (kg·m\(^{-1}\)·s\(^{-1}\))

\[ \mu_{eff} \]

effective viscosity (kg·m\(^{-1}\)·s\(^{-1}\))

\[ \mu_t \]

turbulence induced viscosity (kg·m\(^{-1}\)·s\(^{-1}\))

\[ \rho \]

density (kg·m\(^{-3}\))

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