The mechanism investigation into the wall perforation of a novel filter vacuum container

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Abstract. Upon the observation, small patches near the bottom of the vacuum container are found perforated in some situations, which severely affect the work efficiency and safety of the system. To investigate the mechanism of the damaging perforation, in this paper, a numerical method based on Fluent software is implemented to simulate wall shear stresses of the vacuum container. It is shown that the numerical method implemented accurately captures the flow pattern and the wall shear force distributions during the operation of the vacuum container. With such a simulation approach, the area prone to perforation can be effectively yet clearly identified and predicted. The wall shear stresses of the vacuum container are closely correlated with the inlet velocity. It is demonstrated that the wall shear stresses of the vacuum container tends to increase in magnitude with the increase of the inlet velocity.

1. Introduction

A rubber belt filter is an efficient solid-liquid separation equipment, widely used in chemical, mining, and food processing industries [1]. As a core part of the rubber belt filter, the vacuum container plays an important role in the operation of the filter. During operation, the vacuum container is stationary, and the filtrate enters the top of the vacuum container from the channels of the filter cloth. The water filtration flows adequately in the vacuum container. The outlet pipe is connected to the drainage tank, where the filtrated water is discharged [2]. According to the feedback from the factories, the bottom of the vacuum container is sometimes perforated, which severely affects the work efficiency and safety. In order to find the cause of wall perforation, a series of studies are carried out in this paper.

The wall shear stress (WSS) is symbolized as the frictional resistance of the wall, and reflected the scratch wearing of the wall to a certain extent [3]. In industry, the wall shear stress is commonly used to study erosion-corrosion behaviour. Fan et al. studied the influence of impingement velocity on CO₂ erosion-corrosion behaviour of X70 steel at high-temperature and high-pressure conditions. The result shows that the most serious erosion-corrosion occurs at the maximum wall shear stress [4]. In the wear-resistant selection of a mud pump impeller, Liu et al. mainly investigated the effect of wall shear stress [5]. Therefore, a numerical method based on Fluent software [6], together with a Realizable $k - \varepsilon$ turbulent model, is implemented to simulate the wall shear stress of vacuum container in this paper, in order to investigate the perforation behaviour, with an aim to provide theoretical basis for the future optimal design.
2. Numerical analysis

2.1 Geometrical model and mesh generation

The simplified geometric model of vacuum container is shown in Figure 1. In this model, \(D_1\) is the diameter of inlet, 30 mm; \(h_1\) is the length of inlet pipe, 60 mm; \(D_2\) is the diameter of outlet, 50 mm; \(h_2\) is the length of outlet pipe, 80 mm; \(L\) is the length of vacuum container, 600 mm, and other parameters are shown in Figure 1.

![Figure 1. Geometric model.
1. Inlet pipe, 2. Vacuum cavity, 3. Outlet pipe.](image)

The grid of the vacuum container was generated by ANSYS ICEM [7]. In order to capture the details of internal flow field, the local grid refinement was employed on the wall surfaces and pipelines, totally generated 1,467,290 grid cells. Grid diagram of vacuum container is shown in Figure 2.

![Figure 2. Grid diagram.](image)

2.2 Initial and boundary conditions

The wall shear stress of vacuum container was numerically simulated by Fluent software. In order to simplify the simulation process, water was used as a pure fluid. The velocity-inlet type condition is selected as the inlet boundary condition, with an inlet velocity of the four inlets being 0.7 ms\(^{-1}\) vertically downwards. The outlet boundary condition adopted the pressure outlet type with a static pressure of...
40,000 Pa. A periodic boundary condition was applied to the connected sidewall regions of the container, and the other boundary conditions were set as wall boundary conditions. In the calculation, the SIMPLE method for pressure-velocity correction, the Green-GSUSE Node Based method of interpolation were selected. In this paper, Realizable $k-\varepsilon$ turbulent model is selected to simulate the wall shear stress of vacuum container. The Realizable $k-\varepsilon$ turbulent model is proposed on the basis of the Standard $k-\varepsilon$ turbulent model, which has better prediction of impinging jets, separation flows, secondary flows and swirling flows [8].

The turbulent kinetic energy and turbulent dissipation rate equations of the Realizable $k-\varepsilon$ model are:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho ku_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon \tag{1}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 \frac{\varepsilon^2}{k + (\varepsilon/\omega)^{1/2}} - \rho C_2 \frac{\varepsilon^2}{k + (\varepsilon/\omega)^{1/2}} \tag{2}
\]

\[
C_1 = \max \left( 0.43, \frac{\delta}{\delta + 5} \right) \tag{3}
\]

where $k$ is the turbulent kinetic energy, $t$ is the time, $\mu_t$ is the turbulent viscosity, $G_b$ is the turbulent kinetic energy by buoyancy force, $G_k$ is the turbulent kinetic energy by velocity gradient, model constants $C_2=1.9$, $\delta_k=1.0$, $\delta_\varepsilon=1.2$.

2.3 Grid independence study and method verification

In this paper, three sets of grids with the number of nodes, 1,043,355 (mesh1), 1,467,290 (mesh2) and 2,070,275 (mesh3) were generated. Under the same working conditions, the internal flow fields of three groups of grids were simulated. The static pressure values of each point on the central axis of the outlet pipeline are shown in Figure 3. It shows that the static pressure distribution curves of the three groups of grids are similar, the static pressure of mesh1 is relatively small, and the static pressure curves of mesh2 and mesh3 are almost identical. Considering the calculation time and stability of internal flow field, mesh2 with 1,467,290 cells was selected for further calculations.

![Figure 3. Grid independence verification.](image-url)
3. Result and discussion
The photographic image of the actual vacuum container is shown in Figure 4. There were some perforations on the bottom of the vacuum container, marked with a steel plate repairment.

Figure 4. Photographic image of the vacuum container.

Figure 5 presents the contour plot of the wall shear stress at rated operating condition. At "position 1" of the vacuum container, the wall shear stress is very large and uneven. Comparing the photographic image of the vacuum container with the contour plot of the wall shear stress, it is found that the area with high wall shear stress is consistent with the perforated area of the vacuum container.

Figure 5. The contour plot of wall shear stress.

When equipped with different filtering materials, the inlet velocity of the vacuum container is different. To evaluate the effects of the inlet velocity on the wall shear stress of the vacuum container, a range of the inlet velocity at 0.5 ms\(^{-1}\), 0.7 ms\(^{-1}\) and 0.9 ms\(^{-1}\) are considered in the simulation of the internal flow fields of the vacuum container. The variation of maximum wall shear stresses with different inlet velocities is plotted in Figure 6. The wall shear stress contours of different inlet velocities are given in Figure 7. It is shown that the wall shear stresses of the vacuum container tend to increase in magnitude with the increase of the inlet velocity, with a more obvious change in color gradient displayed.
Figure 6. Maximum wall shear stresses with different inlet velocities.

Figure 7. Wall shear stress contour plots under different inlet velocities.
4. Conclusion

In this paper, Fluent was implemented to calculate the wall shear stress distribution of the vacuum container. The main finding and conclusions are summarized as:

- The simulated wall shear stress can be served to predict the perforation location of the vacuum container to a certain extent. The area with a high wall shear stress is consistent with the perforated area of the vacuum container. It is shown that numerical method implemented in this paper accurately calculates the wall shear force distribution of the vacuum container and effectively predicts the area prone to perforation during the operation of the vacuum container.

- The wall shear stress of the vacuum container is closely correlated with the inlet velocity, and the wall shear stresses of the vacuum container tend to increase in magnitude with the increase of the inlet velocity.

- To save resources, improve the service life of the vacuum container, and reduce the occurrence of the wall perforation, we may optimize the design of the vacuum container, such as the structural layout, the locations of the inlet and outlet pipes, and the thickness of the steel plate at the bottom sides of the vacuum container.

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