Analysis of drag of bristle based on 2-D staggered tube bank

Xiaolei Song[1], Meihong Liu[1(*)], Xiangping Hu [2(*)], Yuchi Kang[1], Baodi Zhang[1]

[1] Faculty of Mechanical and Electrical Engineering,
Kunming University of Science and Technology, Kunming Yunnan 650500, China
[2] Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway.
*Corresponding author: Meihong Liu (64115737@qq.com) and Xiangping Hu (Xiangping.Hu@ntnu.no)

Abstract. In this paper, a 2-D staggered tube bank of bristle pack is established to examine the effect of flow on bristle pack, and Gambit is used to generate the mesh. The Resistance of the bristle in the transient condition is analyzed using simulation with Fluent. The resistance of the brush seal includes friction drag, pressure drag, and interference drag. Results show that the pressure drag plays the leading role owing to the shape of the bristle, and pressure drag increases slowly in the axial direction but increases significantly in the end row. The drag grows gradually with increasing pressure. The results also show that when the value of bristles gap decreases, the drags in the front rows increases more slowly but decrease significantly in the end row.

Keywords: Brush seal; staggered tube bank; Fluent; Pressure drag

1 Introduction

Brush seal is a contact seal, and it has been widely applied to aero-engine and gas turbine. Due to the excellent sealing performance, the brush seal can reduce the leakage effectively. Comparing to a labyrinth seal, the leakage rate of brush seal is only 5%~10% of leakage from the labyrinth seal, and the leakage mainly occurs between the small gap of bristles. The inhomogeneity of the bristle pack leads to self-sealing effect. The researches on the brush seal develop in two directions, experimental measurements and numerical simulation. Numerical simulation has become an important approach for studying performance of the brush seal. The staggered arrangement of tube bank model can analyze the bristles' pressure drop and flow media. Therefore, this model is an important model for analyzing the performance of the brush seal.

Air passing through the bristle pack can be treated as flowing around a cylinder. When air passes through the bristle pack, drag will be produced. Depending on how the drag generates, the drags of the brush seal can be divided into friction drag, pressure drag, and interference drag. Because the bristles are blunt body, the pressure drag is much greater than the friction drag. Therefore, the main analysis is focused on the pressure drag.

Dai et al. [1] analyze the pressure distribution and the velocity of the flow field in the compact cross-sectional tube bank. Huang et al. [2] create a 3-d bristles model to study both the flow and temperature fields. Kang et al [3] analyze the entry number of brush seals built on the 2-D staggered tube bank model. Liu et al. [4] analyze the flow resistance of the brush seal based on a 2-D staggered arrangement of elliptical tube bank model. Fuchs et al. [5] analyze the both 2- and the 3-D brush seal models without the front and back plates, and they found that when the bristle's gap δ=0.008mm（that is the ½ diameter of bristles in the literature, the leakage rate of the 2-D model was the most consistent with the experimental data. In this paper the 2-D staggered arrangement of tube bank is used to analyze the pressure drop and the bristle gap effects on the bristle drop.

2 Model

2.1 Simulation model

In this paper, a 2-D staggered model of a tube bank is established by intercepting the bristles back at the gap of the back plate. The diameter of the bristles is 0.076mm. The model has 15 and 6 rows of bristles in the axial and radial directions, respectively. To avoid the inlet and outlet back flow, the length of upstream is chosen to be 15 time of the bristle's diameter, and the length of downstream is 20 time of the bristle's diameter, as shown in Fig 1. The values of the geometry parameters are given in Table 1, and the design formulas are:

$$S_D = S_T = \mathrm{d} + \delta \tag{1}$$

$$S_L = \frac{\sqrt{3}}{2}(\mathrm{d} + \delta) \tag{2}$$

where S_T and S_L are the radial spacing and the axial spacing, respectively. S_D is the slant spacing. d is the diameter of bristle, and δ is the gap between bristles.

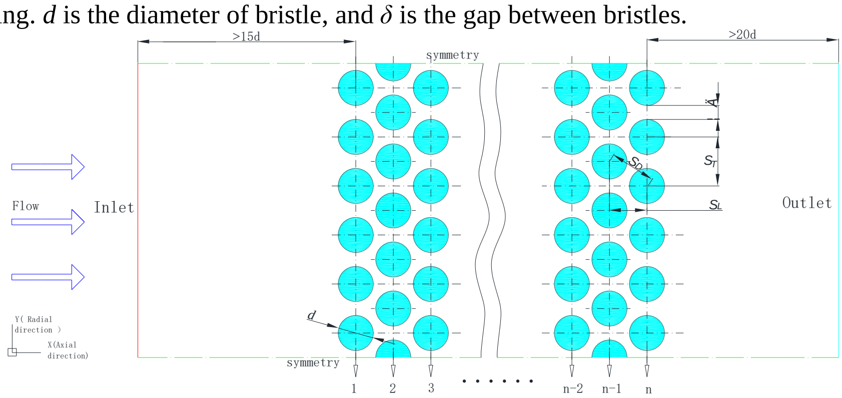

Fig. 1. The sketch of 2-D staggered arrangement of tube bank model

Table 1. Geometry parameters of the simulation model

Unit: mm

S_D/d	1.05	1.10	1.15
δ	0.0038	0.0076	0.0114
S_T	0.0798	0.0836	0.0874
S_L	0.0691	0.0724	0.0757

2.2 Condition assumptions

According to the structure and operating condition of the brush seal, the following assumptions are implicitly used for the model:

1. the bristles are rigid bodies;
2. the medium is an ideal-gas;
3. the effects of the front plate, the back plate, and the cant angle of the bristles are negligible;
4. the bristles are arranged in a hexagonal arrangement;
5. the surface of the bristles is smooth.

3 Mesh Generation

Since the size of the brush seal is at the micron level, the mesh has to be very dense. In this paper the mesh is generated using Gambit. The zone of the bristle pack is the important domain in the simulation, so the mesh of this zone requires very high quality. According to Tan's test of the grid independence, the node of the cylinder surface is 220 [6]. The bounding layer is four. The mesh of the bristle is the unstructured mesh, and it must ensure that the mesh between the gap is greater than 2. However, since the zone of the upstream and the downstream is not the essential computational domain, sparser structure grid can be used. The final structure of grid used here is presented in Fig.2.

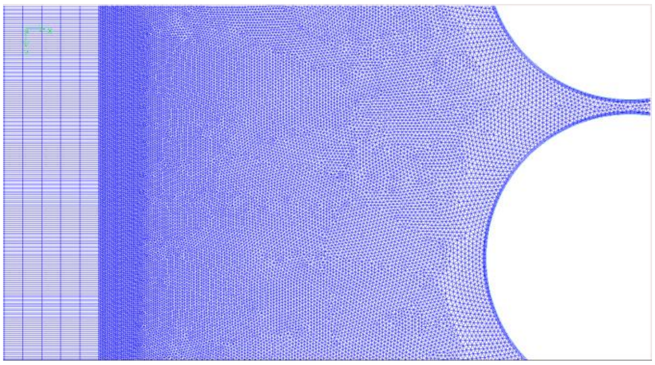

Fig. 2. The structure of mesh

4 Computing Method

4.1 Governing equations

This simulation model uses the equation of continuity, Navier-Stokes equations, and energy equation as follows,

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0 \tag{3}$$

$$\begin{aligned}&\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}=-\frac{\partial p}{\partial x}+\\&\frac{\partial}{\partial x}\left\{\mu\left[2\frac{\partial u}{\partial x}-\frac{2}{3}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\right]\right\}+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\right]\end{aligned} \tag{4}$$

$$\begin{aligned}&\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho vu)}{\partial x}+\frac{\partial(\rho vv)}{\partial y}=-\frac{\partial p}{\partial y}+\\&\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)\right]+\frac{\partial}{\partial y}\left\{\mu\left[2\frac{\partial v}{\partial y}-\frac{2}{3}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\right]\right\}\end{aligned} \tag{5}$$

$$\frac{\partial(\rho T)}{\partial t}+\frac{\partial(\rho uT)}{\partial x}+\frac{\partial(\rho vT)}{\partial y}=\frac{\partial}{\partial x}\left(\frac{k}{C_P}\,grad\,T\right)+\frac{\partial}{\partial y}\left(\frac{k}{C_P}\,grad\,T\right) \tag{6}$$

where p is the gas pressure; ρ is the gas density; u and v are the axial velocity and the radial velocity, respectively; μ is the viscosity of fluid; C_P is the specific heat; k is the heat transfer coefficient of the fluid; T is the temperature, and *grad* stands for the gradient.

The gas medium is an ideal-gas, and satisfies the ideal gas state equation,

$$p = R\rho T \tag{7}$$

where R is the gas constant.

4.2 Determination of Reynolds number

Whether a flow is the laminar flow or the turbulent flow can be determined by the Reynolds number. When $S_D/d=1.10$ and $\Delta p=0.5$MPa, the velocity of the gap of the last row is about 400m/s, the air density is $\rho=1.177 kg\cdot m^{-3}$ and the viscosity is $\mu=1.716\times10^{-5} kg\cdot m^{-1}\cdot s^{-1}$. With these settings, we can obtain the Reynolds number,

$$Re=\frac{\rho ud}{\mu}=2085 \tag{8}$$

where Re is the Reynolds number. The flow of bristle pack is considered as the unsteady circular cylinder. This state belongs to the subcritical area, when $300<Re<3\times105$. The boundary layer is the laminar boundary layer, but the flow separation can occur around the cylinder and the Karman vortex street can be formed. These phenomena influence the downstream [7]. Therefore, the standard k-ε Model is selected in this paper.

4.3 Solver

In this paper, the standard software Fluent is used for conducting the simulation, and the two-dimensional pressure-based solver is chosen. As discussed above, the working medium is an ideal-gas. Furthermore, the standard k-ε model is selected with viscidity follows the Sutherland Formula. Since the Karman vortex street influences the flow condition of the downstream, the analysis uses the transient state.

Fluent is based on the finite volume method. The staggered mesh calculates and stores the pressure and velocity components on the nodes in different mesh systems. For the 2-D simulation model, the p, u, and v are stored in three different mesh systems.

The calculation firstly uses SIMPLE format for the steady value, and the result is the initial value for the transient state simulation. Since PISO is superior to both SIMPLE and SIMPLEC in the transient state, it is adopted for the transient state in the simulation, and the time step is 10^{-4}. The reference area is the frontal area, and it used the diameter of the bristle.

The boundary layer of the upstream is the pressure inlet, and the values can be 0.201325MPa, 0.301325MPa, 0.401325MPa, 0.501325MPa or 0.601325MPa. The boundary layer of the downstream is the pressure outlet and the value is 0.101325MPa. The top and bottom margins are the symmetric boundary conditions. The surface of the bristle is the non-slip wall.

5 Theoretical analysis of Drag

When there is a relative velocity between the body and fluid, the force from the fluid will be acted on the body. The drag is the component of the force that is parallel to the direction of the relative speed.

Pressure drag is dependent on the pressure drop between the front and back of the body. Usually, unless the value of Re is very low, the separation phenomenon is inevitable in the flow of the pure bluff body. Therefore, the pressure is the leading role in the drag. The pressure drag can be calculated by the following equation,

$$F_P = \int_A \mathrm{p}\cos\theta dA \tag{9}$$

where p is the pressure acts upon the area of elements dA; F_P is the pressure drag; θ is the angle of the normal of dA and the flow direction, shown in Fig.3.

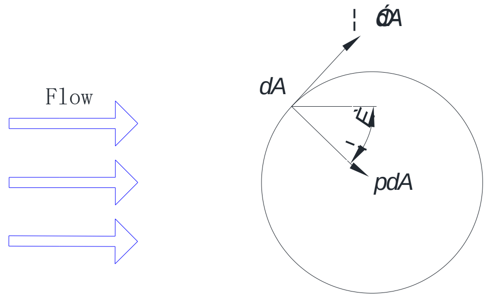

Fig. 3. The pressure drag acting on the body

6 Discussion

The effect of Δp on the drag are shown in Fig. 4. The drag increases with Δp and with the number of rows. When Δp is higher than 0.2MPa, the drag in the end row will increase significantly. The reason might be that the bristles are the blunt body, and the pressure drag plays a leading role in the drag of the bristles [8]. The pressure drop at the end row of the bristles is higher than the other rows, as illustrated in Fig. 5. The drag in the end row increases dramatically. In the end row the drag can reflect the pressure drop. The decline of pressure leads to the stress concentration and the friction between the back plate and the bristles. The multistage brush seal can be adopted to decrease the pressure in the end row.

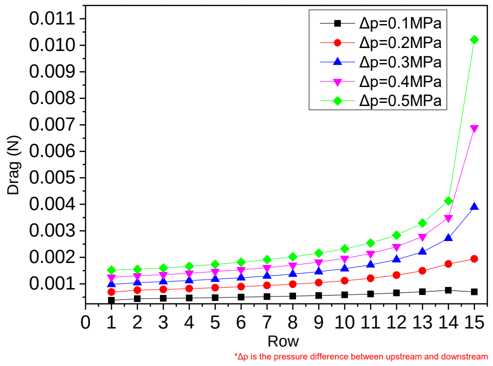

Fig.4. The change curve of drag of bristles (S_D/d=1.10)

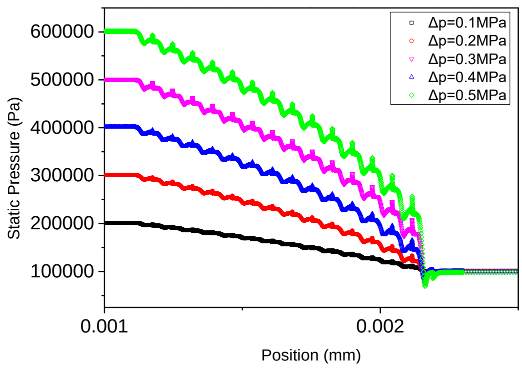

Fig. 5. Pressure distribution along axial gap of bristle under pressure differentials

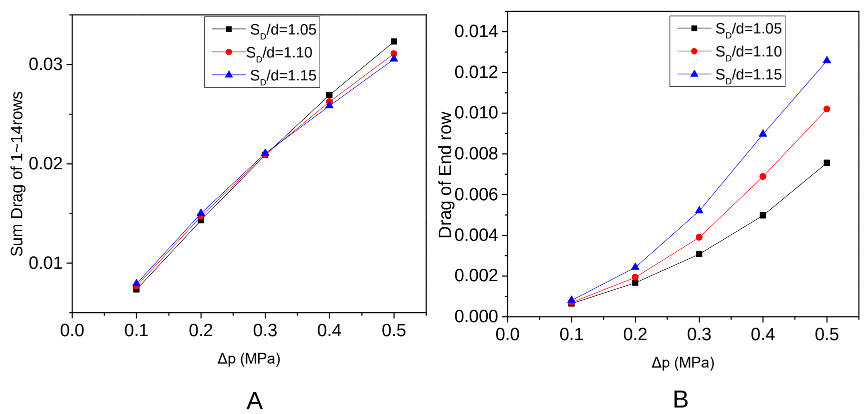

Fig. 6. The drags in the front rows (A) and the end row (B)

When Δp is lower than 0.3MPa, the resistance reduces with decreasing δ. However, the rate of rise increases when δ decreases, as shown in Fig.6 (A). In Fig.6 (B), it shows that the drag in the end row can be cut down by reducing the δ, since small δ could lead to the turbulence intensity power. The uniformity of the pressure distribution becomes well with decreasing δ [10]. The pressure in the front rows may increase indistinctively and the turbulent flow reduces the pressure drag at a low Δp [9]. When Δp increases, the pressure in the anterior rows increases obviously and the effect of the turbulent flow weakens. Therefore, the increasement of the drag in the front rows is more observable with reducing δ.

7 Conclusion

In this paper, the drag of bristle based on 2-D staggered tube bank is analyzed using numerical simulation with Fluent. From the results, the following conclusion can be drawn,

(1) The drag increases when the pressure difference increases. Due to the shape of the bristles, the reduction of the pressure drop is reflected by the drag.

(2) The reduction of the gap between bristles can decrease the drag in the end row, but the drag increasement in the front row is not significant. Due to the reduction of gap, the rate of increment is quicker with the increasing pressure difference.

Reference

1. Dai W, Liu Y. Numerical simulation of fluid flow across compact staggered tube array[J]. Manufacturing Automation, 33(2): 107-110(2011). (in Chinese)
2. Huang S, Suo S F, Li Y, et al. Flows in brush seals based on a 2-D staggered tube bundle model. Journal of Tsinghua University (Science and Technology), 56(2): 160-166(2016). (in Chinese)
3. Kang Y, Liu M, Kao-Walter S, et al. Predicting aerodynamic resistance of brush seals using computational fluid dynamics and a 2-D tube banks model. Tribology International (2018).
4. Liu J, Liu M, Kang Y, et al. Numerical simulation of the flow field characteristic in a two-dimensional brush seal model, (2018).
5. Fuchs A, Oskar J. Numerical investigation on the leakage of brush seals. Proceedings of Montreal 2018 Global Power and Propulsion Forum (2018).
6. Tan Y, Liu, M, Kang Y, et al. Investigation of brush seal vortex separation point based on 2-D staggered tube bundle mode. Journal of Drainage and Irrigation Machinery Engineering, 35(7):602-608(2017). (in Chinese)
7. Jiang K, Zhang D, Qi Y, et al. Study on the Characteristics of Flow Around Cylinder at Subcritical Reynolds Number. Ocean Engineering Equipment and Technology, 4(1): 37-42(2017). (in Chinese)
8. JSME, Zhu B, et al. Fluid Mechanics. Peking University Press (2013). (in Chinese)
9. Shigenao M, Wang S, et al. Heat Transfer. Peking University Press (2011). (in Chinese)
10. Kang Y, Liu M, et al. Numerical simulation of pressure distribution in bristle seal for turbomachinery. Journal of Drainage and Irrigation Machinery Engineering, 36(5):58-63(2018). (in Chinese)