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Pressure Loss Analysis of the Perforated Tube Attenuator Used in the Reciprocating Compressor

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ABSTRACT

Oversize resistance loss of gas pulsation attenuator will cause the compressor exhaust back pressure higher, increase the compressor power consumption and increase the exhaust temperature, which leads to the deterioration of the compressor operation. Therefore, proper control the pressure loss of the attenuator used in reciprocating compressor is especially important. This paper presents an investigation of the pressure loss of the Perforated Tube Attenuator (PTA). Three-dimensional computational fluid dynamics (CFD) has been used to investigate the influence of porosity, flow velocity, diameter of the holes on the pressure loss. The results showed that the pressure loss of PTA decreases with porosity increasing following nearly a hyperbolic trend, ascents according to a parabola law with the inlet velocity increasing and descents little with the hole diameter rising.

1. INTRODUCTION

The reciprocating compressor plays an important role in refineries and petrochemical plants. Excessive vibration in the reciprocating compressor piping not only degrades the compressor performance but also causes piping severe fatigue, pipe damage, high-pressure gas leakage and even explosion. Vibration of the reciprocating compressor piping is mostly caused by gas pulsation in the piping (Dang and Chen,1984). Therefore, reasonable analysis and proper control of the gas pulsation and then the piping vibration become significant in engineering.

Various pulsation attenuators used for decreasing gas pulsation have been researched and developed worldwide for decades. Among them the perforated tube attenuator (PTA) is practical and commonly used because of its wide silencing frequency band and high amount of noise elimination. Brablik(1976) proposed a PTA to reduce gas pulsation in the pipe between the valve chamber and the surge tank, and the experiments results showed that PTA was able to damp the gas pulsation in a very wide frequency range. Wang(1995) developed a numerical scheme for the attenuation analysis of the perforated intruding tube attenuator and found that the porosity is an important factor which should be taken into account in the attenuator design. Luo *et al*.(1995) presented a new approach for modeling concentric partially perforated intruding tube attenuations .For acoustic impedance in the linear regime, a closed form solution of the partially perforated intruding tube attenuation transmission loss was first obtained. The distributed parameter method is extended for the analysis of attenuators employing concentric multiple pipes and it is seen that increasing the diameter of the co-axial pipe improves the noise reduction for the higher frequencies, while decreasing it tends to improve it for the lower frequencies(Dokumaci,2001). Siano(2011) employed one-dimensional and three-dimensional approaches to predict the acoustic behavior of a three-pass perforated tube muffler with an end resonator.

For the attenuator design, pressure loss and transmission loss are the two equally significant parameters characterizing its performance. Even if an attenuator can greatly reduce the compressor pressure pulsation, but cause large pressure loss, it will not be used yet. So it's necessary to pursue the attenuator with low pressure loss as well as low pressure pulsation. The traditional method of calculating pressure loss of the attenuator is according to empirical formulas, which only fit for simple structures(Hu,2007). But for PTA, generally consisting of hundreds of small holes distributed along a pipe, both the structure and the flow in it are complex, and the current empirical formulas are not available to calculate the pressure loss.

So this paper predicts pressure loss of the PTA with various geometry parameters using three dimensional CFD.

2. THEORETICAL ANALYSIS

2.1 Physical Model

Structure of PTA studied in this paper is shown in Figure 1. It is a concentric perforated tube with a radial baffler at the end of the inner tube in the attenuator. Air flows through the holes on the inner tube into the chamber, and then flows out of the export of container. The basic dimensions of the physical model are as follows:

$$L_1 = 500mm\,,\ L_2 = 60mm\,,\ D_1 = 250mm\,, D_2 = 54mm\,.$$

2.2 Governing equation and numerical method

A three-dimensional CFD model of the PTA was established under the following assumptions:

(1) The physical parameters of the solid and fluid domain of the attenuator are constant;
(2) The flow is steady turbulent flow;
(3) The influence of the gravity is ignored;
(4) The inlet velocity of the PTA is homogeneous without pulsation.

The standard k - ε model is used to describe the turbulent flow in the PTA. The flow in the PTA follows the law of mass conservation, momentum conservation and energy conservation. The general equation can be expressed as Equation (1).

$$\frac{\partial\left(\rho\phi\right)}{\partial \mathrm{t}} + div(\rho v\phi) = \mathrm{div}(\Gamma\,\mathrm{grad}\,\phi) + S \tag{1}$$

Where ϕ is the general variable which represents different physical variables. S and Γ are respectively the generalized source item and generalized diffuse coefficient according to ϕ. ρ is the air density and v is the velocity vector. The corresponding relations are shown as Table 1, where u , v , w are the velocity in three directions x , y , z ; T is the absolute temperature; k is turbulent dynamic and ε is the dissipation ratio of turbulent dynamic;

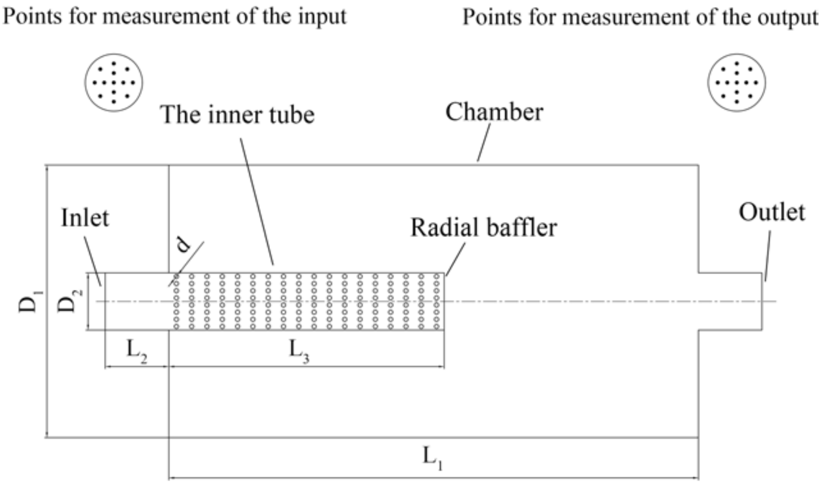

Figure 1 Physical model of PTA and measurement points

μ is the viscosity coefficient and μ_t is the viscosity coefficient of turbulence; G is the stress of turbulence. C_μ, C_1, C_2, σ_ε, σ_T and σ_k are all constants. Pr is Prandtl number; S_u, S_v, S_w are the source item of three directions x, y, z, respectively. μ_t and G can be expressed as Equations.(2)and(3).

$$\mu_t = C_\mu \rho k^2 / \varepsilon \tag{2}$$

$$G = \frac{\mu_t}{\rho}\left\{2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2\right] + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2\right\} + \frac{\mu_t}{\rho}\left[\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2\right] \tag{3}$$

Table 1 Values of ϕ and related equations

Equation	General variable ϕ	Diffuse coefficient Γ	Source item S
Mass	1	0	0
x	u	$\mu + \mu_t$	S_u
y	v	$\mu + \mu_t$	S_v
z	w	$\mu + \mu_t$	S_w
Energy	T	$\mu / \mathrm{Pr} + \mu_t / \sigma_T$	0
k equation	k	$\mu + \mu_t / \sigma_k$	$pG - \rho\varepsilon$
ε equation	ε	$\mu + \mu_t / \sigma_\varepsilon$	$\frac{\varepsilon}{k}\left(C_1 \rho G - C_2 \rho \varepsilon\right)$

The values of the constants are set as: C_μ =0.09, C_1 =1.44, C_2 =1.92, σ_ε =1.3, σ_T =0.95, σ_k =1.0.
The solution of the model was implemented with the finite volume method.

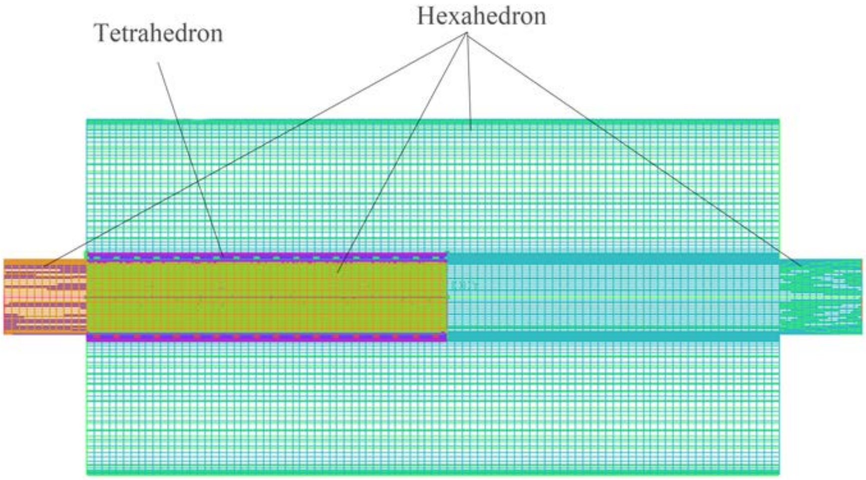

Figure 2 Grids in the PTA

2.3 Grids and Boundary conditions

The grids meshed for the calculation domain was determined by compromising the calculation time and the solution precision, so the type of mixed-mesh composed of tetrahedron and hexahedron was chosen, as shown in Figure 2. The gas column 2mm around the pipe was meshed with the type of tetrahedron, the other part of the attenuator is meshed with the hexahedron element. The solution independency of the grid number was validated in the calculation. The grid number in the model was 457,231 and the relative error for the calculated pressure loss was less than 1% compared to a case with 503,561 grids. At the inlet of PTA, velocity of gas flow was given. At the outlet of the PTA, 450K Pa absolute pressure was given as the boundary condition according an operating compressor.

2.5 Pressure loss calculation of PTA

As shown in Figure 1, 13 uniformly distributed points were selected to calculate the average pressure at the inlet/outlet of the attenuator. The modifying factor used to calculate the dynamic pressure is expressed as Equation (4)

$$\alpha = \left[\frac{1}{\mathrm{N}} \sum_{i=1}^{\mathrm{N}} v_{\mathrm{i}} \right] / v_m \tag{4}$$

Where N is the number of the points selected in the cross-sections of the duct, v_{i} is the velocity of each point which the unit is m/s, v_m is the velocity at the center of the cross-section with the unit of m/s.

The calculation formula for the mean dynamic pressure is expressed as follows:

$$\overline{p_v} = \alpha^2 \cdot p_{vm} \tag{5}$$

Where α is the factor obtained from Equation (4) and p_{vm} is the dynamic pressure at the center of the cross-section with the unit of Pa.

The mean total pressure can be obtained with Equation (6)

$$\overline{p_t} = \overline{p_v} + p_s \tag{6}$$

Where $\overline{p_t}$, p_s are the mean total pressure and the static pressure with the unit of Pa, respectively.

Thus the pressure loss of the PTA can be expressed as follows:

$$\Delta p = \overline{p_{t1}} - \overline{p_{t2}} \tag{7}$$

Where Δp is the pressure loss of the PTA and $\overline{p_{t1}}$, $\overline{p_{t2}}$ are the inlet/outlet mean total pressure at the cross-section of the duct, respectively.

3. RESULTS AND DISCUSSION

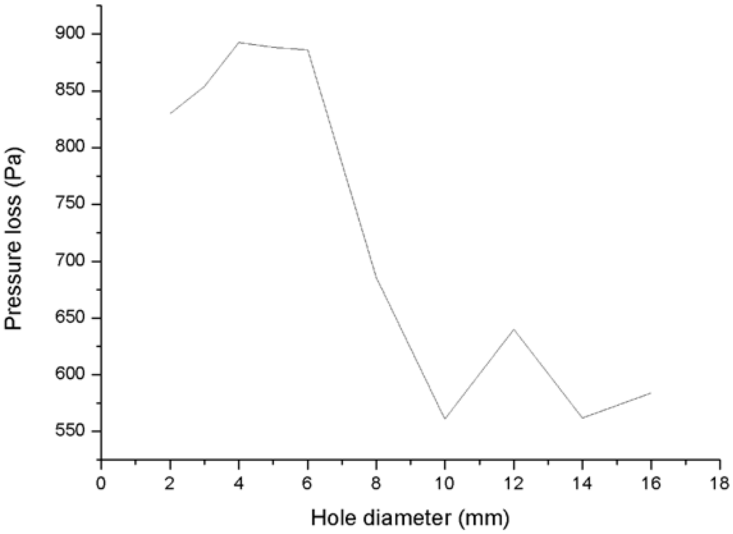

Figure 3 Pressure loss of PTA with different hole diameters

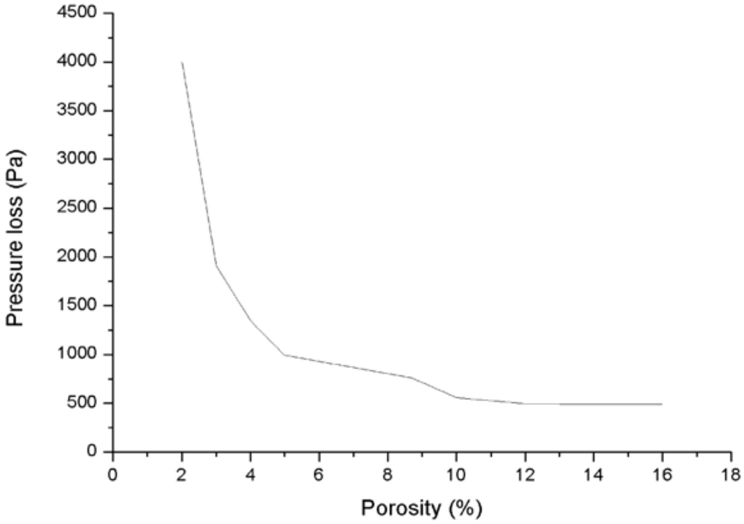

Figure 4 Pressure loss of PTA with different porosities

3.1 Influence of the hole diameter on pressure loss

Transmission loss of PTA is associated with the drilling hole diameter, the smaller the diameter, the better attenuation effect. Attenuators used in reciprocating compressors are normally for attenuation of low frequency sound waves, so the drilling hole diameter is generally greater than 2 mm. The hole diameters studied in this paper were: 2mm, 3mm, 4mm, 5mm, 6mm, 8mm, 10mm, 12mm, 14mm, and 16mm. The porosity was 8.7% and the input velocity was 10m/s.

Figure 3 shows the relationship between the pressure loss and the hole diameter. The pressure loss changed gently when the hole diameters were 2mm to 6mm, and declined sharply when the diameters increases from 6mm to 10mm, and changed little when the hole diameters were 10mm to 16mm. For PTA used in the reciprocating compressor, the hole diameters are generally from 2mm to 5mm, so the hole diameter has little influence on the pressure loss according to Figure 3.

3.2 Influence of the porosity on pressure loss

The porosity of PTA is the area ratio of holes drilled in the pipe. The intersection area of gas-flow between the chamber and the perforated duct increases with the porosity growing, causing gas-flow more smoothly and lowering the pressure loss of attenuator. The porosities chosen in this paper were: 2%, 3%, 4%, 5%, 6%, 7%, 8.7%, 10%, 12%, 14%, 16%. Air velocity of the inlet is 10 m/s and the hole diameter: $d = 4mm$.

Figure 4 shows the relationship between the pressure loss and the porosity. The pressure loss decreased with the increasing of porosity, in line with a hyperbolic curve. The pressure loss rises very quickly with the porosity descent when the porosity is smaller than 5%, but goes up gently when the porosity is higher than 10%. The results suggest that the porosity has two threshold values for PTA design. The pressure loss increases sharply as the porosity decreases when the porosity is smaller than the low threshold and rises gradually with the porosity reduction when the porosity is greater than the high threshold.

3.3 Influence of the input velocity on pressure loss

When the porosity is 8.7% and the drilling hole diameter is 4mm, the relationship between the pressure loss and the input velocity was shown in Figure 5. The velocities are 8m/s, 10m/s, 12m/s, 14m/s, 16m/s, 18m/s, 20m/s, 22m/s, 24m/s, 26m/s, and 28m/s.

The pressure loss increases with the input velocity ascent according to the form of parabola. And the relationship between the pressure loss and the input velocity has been fitted to be a parabola equation with the method of the least square fitting, which is depicted as Equation (8)

$$\Delta p = 6.64v^2 - 28.238v + 208 \tag{8}$$

Where Δp is the pressure loss with the unit of Pa, and v is the input air velocity m/s.

These results indicate that the input velocity is an important influencing factor of the pressure loss for the PTA design since the pressure loss rises with velocity following a parabola trend. The higher gas velocity may bring much more additional pressure loss. So the diameter of the input duct should be computed to be a proper value to ensure the velocity is limited to an allowable value.

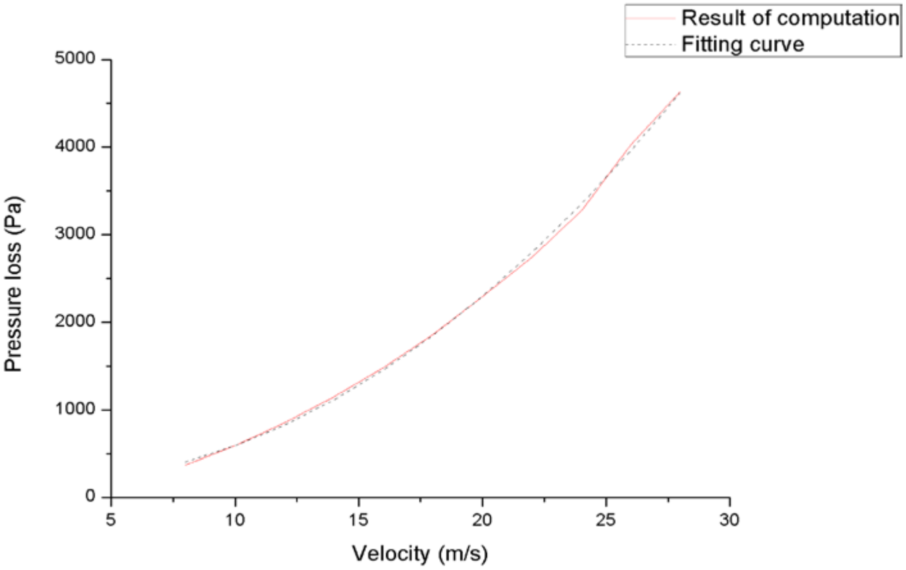

Figure 5 Pressure loss of PTA with different input velocities

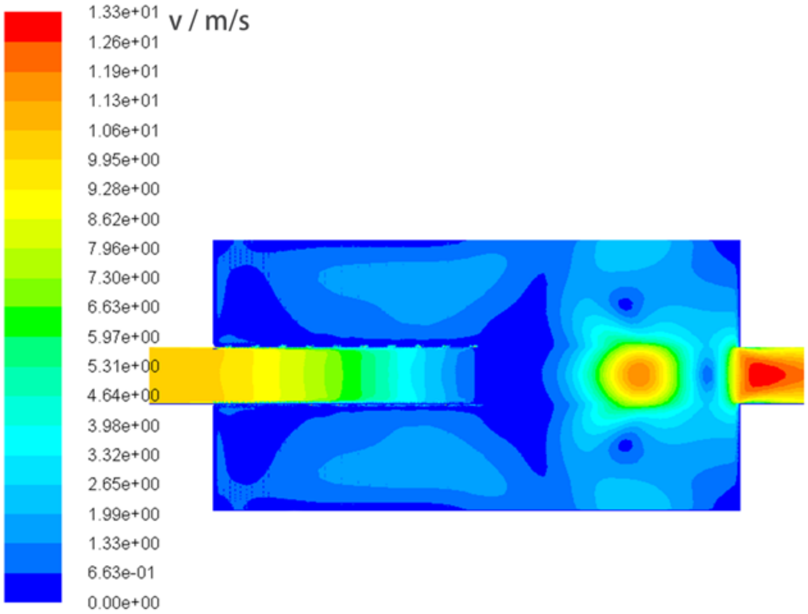

Figure 4 Velocity profile of PTA center plane

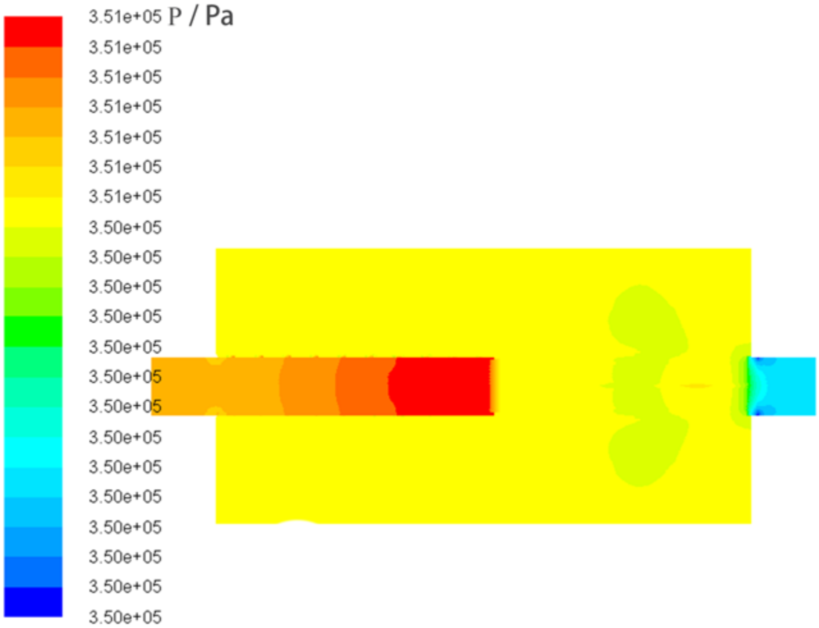

Figure 5 Static pressure profile of PTA center plane

3.4 Analysis of the velocity field and static pressure filed

Figure 4 and Figure 5 respectively show the internal velocity profile and internal pressure profile in the PTA. Air passed through import into the perforated pipe, punched into the cavity and flowed out of the export. Velocity decreased and static pressure increased in a cascaded mode along the centerline of PTA. Velocity filed and static pressure field is relatively uniform in the cavity. In the outlet, fluid turbulence was relatively severe, which resulted in large flowing velocity and static pressure change.

4. CONCLUSIONS

Based on the analytical investigation on pressure loss of PTA presented in this paper, the following conclusions may be drawn:

- Compared to the porosity and the input velocity, the drilling hole diameter from 2 mm to 5 mm has smaller impact on the pressure loss of PTA used in the reciprocating compressor.
- Relationship between the porosity and the pressure loss generally follows a hyperbolic curve. There are two threshold values of porosity for each PTA. Pressure loss increases sharply when the porosity is less than the low threshold value, and changed smoothly when the porosity is greater than the high threshold value.
- Input velocity of PTA links with the pressure loss following a parabolic curve, and the polynomial equation were fitted from the investigated results.

NOMENCLATURE

L	tube length	(mm)
D	tube diameter	(mm)
ρ	air density	(kg/m^3)
ϕ	physical variables	(-)
v	velocity vector	(m/s)
S	generalized source item	(-)
Γ	generalized diffuse coefficient	(-)
T	absolute temperature	(K)
u	velocity at x direction	(m/s)
v	velocity at y direction	(m/s)
w	velocity at z direction	(m/s)
k	turbulent dynamic	(m^2/s^2)
ε	dissipation ratio of turbulent dynamic	(m^2/s^3)
μ	viscosity coefficient	(Pa • s)
μ_t	viscosity coefficient of turbulence	(Pa • s)
G	stress of turbulence.	(Pa/s)
Pr	Prandtl number	(-)
S_u	source item at x direction	(-)
S_v	source item at y direction	(-)
S_w	source item at z direction	(-)
N	the number of the points selected in the cross-sections of the duct	(-)
v_{i}	velocity of each point	(m/s)
v_m	velocity at the center of the cross-section	(m/s)
α	modifying factor	(-)
p_{vm}	dynamic pressure	(Pa)
$\overline{p_t}$	mean total pressure	(Pa)
p_s	mean static pressure	(Pa)
Δp	pressure loss of the PTA	(Pa)

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