

# Experimental research on pressure loss of rotary pressure exchanger

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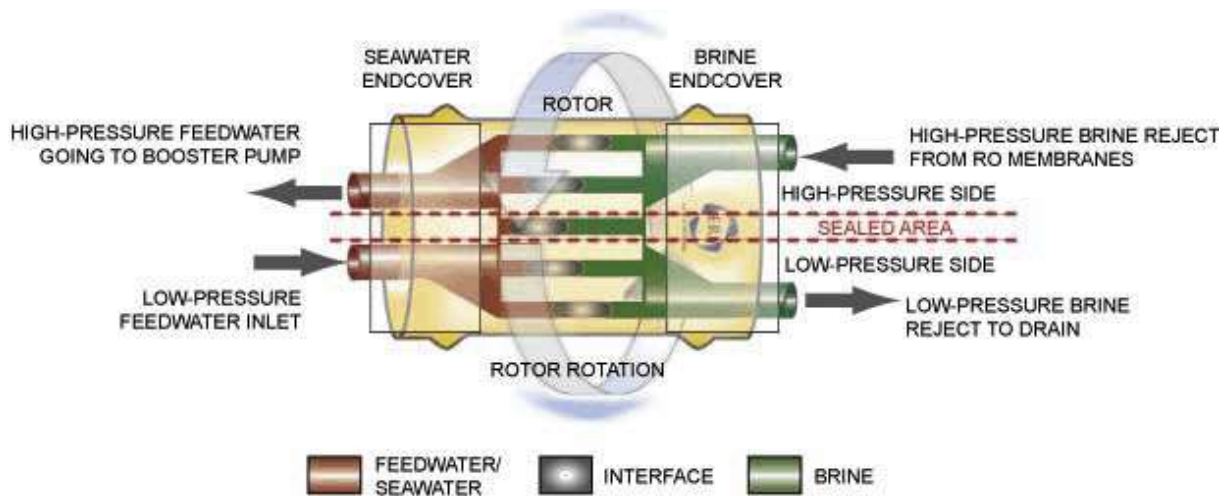
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**Abstract.** In order to research the phenomenon ‘Pressure Loss’ of Rotary Pressure Exchanger when it worked in a certain working condition, such as pressure and flow, two different series of experiments were performed respectively in the same experimental apparatus. One is to set pressure as constant when flow is changeable, the other one is to set flow as constant when pressure is changeable. Then, the curves and tables depicting the relationship between the pressure loss rate and working conditions were illustrated. Results from the curves and tables show that flow and pressure has an impact on pressure loss, and the relationship present some of regularity. According to the regularity, an empirical formula which can be used to approximately predict the magnitude of pressure loss for subsequent engineering application was provided by regression analysis on the basis of experimental data. Meanwhile, a 3-Dimensional geometric model of passageway in rotary pressure exchanger were built to verify the accuracy, making a steady calculation on pressure field by Fluent. At last, the feasibility was verified in a field application in a desalination factory.

## 1. Introduction

With the intention of reducing the cost of water, the rotary pressure exchanger is expected to be playing an important role in the field of seawater desalination. There are three characteristics below: First, simple mechanism, its core part consists of two end covers and a rotor with some passageways [1]. Second, good adaptation, the rotate speed is capable of adjusting itself to flow automatically [2]. Third, high work efficiency, high-pressure fluid and low-pressure fluid meet together directly in the course of pressure exchange [3]. At present, rotary pressure exchanger (PRE) energy recovery device in widespread use on the market is based on the principle of positive displacement [4]. The working principle of rotary pressure exchanger is illustrated by **Figure 1-1**.





**Figure 1-1** Working principle of the rotary pressure exchanger

However, the transmission of power from high-pressure flow to low-pressure flow is not in full force in actual engineering application. The friction, between the wall of rotor and the water film covering the rotor, exhausts a portion of power in the process of rotation of the rotor. The macroscopic performance is that the pressure in the high-pressure outlet is not bigger than the one in the high-pressure inlet, namely, pressure loss [5]. (The research object is the ‘pressure loss in high pressure side’, which is to be replaced by ‘pressure loss’ for convenience in this article, because the effect in engineering application brought by the ‘pressure loss in high pressure side’ is much bigger.) It is the pressure loss that make seawater pressurized by rotary pressure exchanger cannot go to reverse osmosis desalination directly, because the pressure cannot reach the operation standard. Thus, the high-pressure outlet goes immediately to booster device, such as booster pump. Given that pressure loss affects the working conditions of rotary pressure exchanger and the movement of rotor, it is meaningful to research the pressure loss of rotary pressure exchanger. Furthermore, an empirical formula which can be used to approximately predict the magnitude of pressure loss caters to actual demand.

Now, making a number of experiments is the only way which must be passed, in order to research the working conditions of rotary pressure exchanger. For example, Li Gui-Song and his colleagues summarized that there is a positive correlation between the end cover leakage and the flow, the pressure respectively [6]. They also found that the rotor speed has a positive correlation with the flow, and has a negative correlation with the pressure.

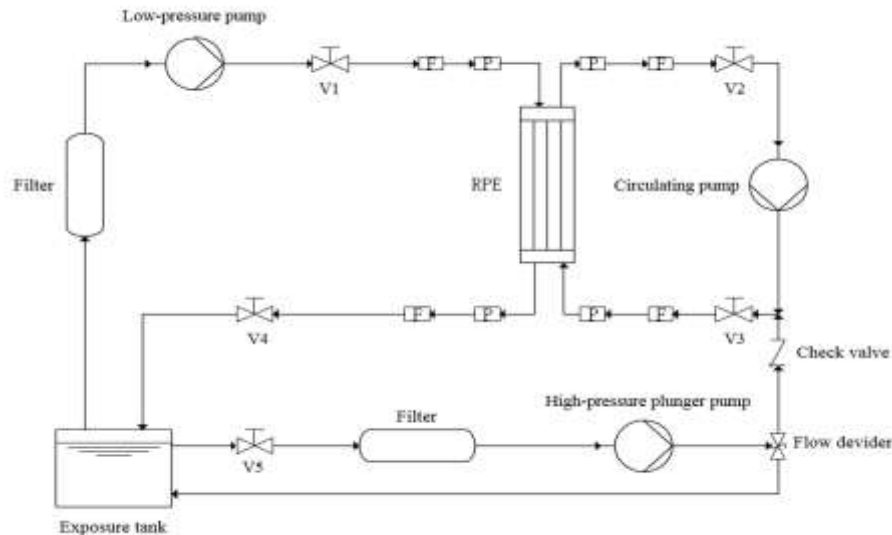
To research the pressure loss of rotary pressure exchanger, all the work is in the same way based on two different series experimental programs, which were performed in the experimental apparatus of SWRO system. In a series of experiments, measure the high-pressure pressure loss when the pressure of experiment system was constantly kept on 2.8 MPa, 3.4 MPa, 4 MPa, 4.5 MPa, 4.9 MPa, 5.3 MPa and 6.1 MPa, while the volume flow rate of cycle system was set on 69 m<sup>3</sup>/h steadily. In another series of experiments, measure the high-pressure pressure loss when the volume flow rate of cycle system was constantly kept on 50 m<sup>3</sup>/h, 55 m<sup>3</sup>/h, 60 m<sup>3</sup>/h, 65 m<sup>3</sup>/h, 70 m<sup>3</sup>/h and 75 m<sup>3</sup>/h, while the pressure of the experiment system was set on 5.9 MPa steadily. First of all, propose an empirical formula which can be used to approximately predict the magnitude of pressure loss, on the basis of two series of experimental data. Then, take advantage of numerical calculation and field application to verify the accuracy and feasibility of the formula.

## 2. Experiment

The flow diagram of experimental apparatus is illustrated in **Figure 2-1**.

### 2.1 Experimental Device

The experimental apparatus contains seven parts, including filter, low-pressure pump, high-pressure plunger pump, circulating pump, electromagnetic flow meter, pressure sensor and data acquisition system.



**Figure 2-1** Flow diagram of experimental apparatus

## 2.2 Experimental Process

When there is enough water for the experiment, open the valves V1, V2, V3, V4 and V5. Firstly, open the low-pressure pump to fill the whole pipeline. Secondly, take turns to open the circulating pump and high-pressure plunger pump. Thirdly, control the flow divider and the valves V1, V2 to make sure that the flow in the high-pressure outlet and the pressure in the high-pressure inlet meet the experimental requirements. One series of experimental data includes the flow in the high-pressure outlet and the pressure in the high-pressure inlet in the meantime. Change the pressure or flow to continue next experiments, when one series of experimental data has been noted. All in all, we can reach the goal that experimental conditions are under control by controlling the flow divider and the valves V1, V2.

## 2.3 Experimental Method

The design flow of experimental apparatus ranges from 50 m<sup>3</sup>/h to 90 m<sup>3</sup>/h. The design pressure of experimental apparatus is not bigger than 6.3 MPa. The experiment uses orthogonal experimental method: When the pressure of experiment system was constant, make some recording spots of the volume flow rate of cycle system while the value fluctuated from 50 m<sup>3</sup>/h to 90 m<sup>3</sup>/h; When the volume flow rate of cycle system was constant, make some recording spots of the pressure of experiment system while the value fluctuated from 0 MPa to 6.3 MPa. Then, the data acquisition system captured real time data with the frequency of 12 Hz, to finish the record of the flow and pressure in the high-pressure inlet and outlet.

## 3. Data processing and analysis

### 3.1 Pressure loss characteristic

In practical application, there are a lot of factors affecting the pressure loss. Apart from the flow and pressure closely related to the working conditions, the inherent specifications owned by rotary pressure exchanger has something to do with pressure loss [7]. Hence, it is unmeaning to have a research without taking specifications into consideration. The specifications of rotary pressure exchanger is illustrated in Table 3-1.

Symbol	Specification	Parameter
/	Material	Corundum ceramic
R	Rotor outer diameter	190mm
L	Axial length	190mm
T	Outside wall thickness	10mm
t	Wall thickness of passageways	5mm
$\alpha$	Inclination of end covers	22°
$\tau$	Clearance of end face	30 $\mu$ m
s	Clearance of radial direction	35 $\mu$ m

**Table 3-1** Specifications of rotary pressure exchanger

The computational formula of pressure loss  $\Delta P$  is:

$$\Delta P = P_{Hin} - P_{Hout}$$

The computational formula of pressure loss rate  $\rho$  is:

$$\rho = \frac{\Delta P}{P_{Hin}}$$

Where  $P_{Hin}$  denotes the pressure in the high-pressure inlet and  $P_{Hout}$  denotes the pressure in the high-pressure outlet.

The relationship between pressure loss, pressure loss rate and the pressure in the high-pressure inlet is illustrated in **Table 3-2**.

The relationship between pressure loss, pressure loss rate and the flow in the high-pressure outlet is illustrated in **Table 3-3**.

**Figure 3-1** illustrates the X-Y scatter plot of pressure loss rate and the pressure in the high-pressure inlet. The scatter plot reveals that the bigger the pressure in the high-pressure inlet is, the smaller the pressure loss rate is. That is to say, there is a negative correlation between them. In addition, regression method is used to analyze these data, because the distribution of data points has its regularity, roughly on a curve. Linear function is used to fit these data points shown in Figure 3-1. The regressive curve equation acquired from regressive analysis is:

$$y = -0.0033x + 0.0422$$

Where y denotes pressure loss rate and x denotes the pressure in the high-pressure inlet, the fitting degree index  $R^2$  reaches 0.9816.

**Figure 3-2** illustrates the X-Y scatter plot of pressure loss rate and the flow in the high-pressure outlet. The scatter plot reveals that the bigger the flow in the high-pressure outlet is, the bigger the pressure loss rate is. That is to say, there is a positive correlation between them. In addition, regression method is used to analyze these data, because the distribution of data points has its regularity, roughly on a curve. Linear function is used to fit these data points shown in Figure 3-2. The regressive curve equation acquired from regressive analysis is:

$$y = 0.0004x - 0.01$$

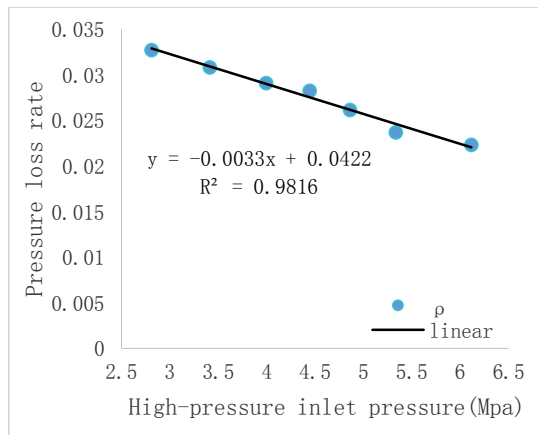
Where y denotes pressure loss rate and x denotes the pressure in the high-pressure inlet, the fitting degree index  $R^2$  reaches 0.9728.

No.	$P_{Hin}$	$P_{Hout}$	$Q_{Hout}$	$\Delta P$	$\rho$
	MPa	MPa	m <sup>3</sup> /h	MPa	/
1	2.812	2.719	69.9	0.092	0.0327
2	3.413	3.307	69.9	0.105	0.0309
3	3.996	3.879	69.0	0.116	0.0291
4	4.446	4.320	68.7	0.126	0.0283
5	4.863	4.735	68.8	0.127	0.0262
6	5.335	5.209	68.9	0.126	0.0237
7	6.115	5.978	68.8	0.137	0.0224

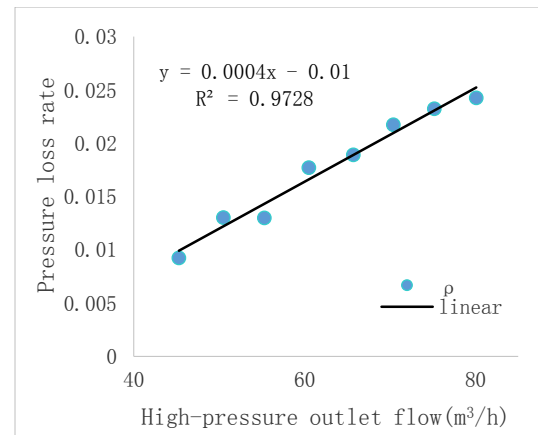
**Table 3-2** the relationship between pressure loss, pressure loss rate and the pressure in the high-pressure inlet

No.	$P_{Hin}$	$P_{Hout}$	$Q_{Hout}$	$\Delta P$	$\rho$
	MPa	MPa	m <sup>3</sup> /h	MPa	/
1	5.935	5.791	80.1	0.144	0.0243
2	5.810	5.675	75.2	0.135	0.0232
3	5.977	5.847	70.4	0.130	0.0217
4	6.031	5.916	65.7	0.114	0.0189
5	5.804	5.702	60.5	0.103	0.0177
6	5.894	5.817	55.3	0.077	0.01301
7	5.801	5.726	50.5	0.076	0.01302
8	5.872	5.818	45.3	0.054	0.0092

**Table 3-3** the relationship between pressure loss, pressure loss rate and the flow in the high-pressure outlet



**Figure 3-1** the X-Y scatter plot of pressure loss rate and the pressure in the high-pressure inlet



**Figure 3-2** the X-Y scatter plot of pressure loss rate and the flow in the high-pressure outlet

### 3.2 Empirical formula

The relationship summarized in section 3.1 between pressure loss rate and the pressure, as well as pressure loss rate and the flow, indicates that pressure loss rate is not only linearly correlated with the pressure in the high-pressure inlet, but also with the flow in the high-pressure outlet. Now, a general relationship could be acquired when we take two factors, pressure and flow, into consideration together. In consequence, if the pressure and flow is confirmed, we could get the pressure loss rate by calculation to further predict the pressure loss in these working conditions.

Available functions:

$$y = -0.0033x_1 + 0.0422 \quad (1)$$

$$y = 0.0004x_2 - 0.01 \quad (2)$$

Where  $y$  denotes pressure loss rate,  $x_1$  denotes pressure in the high-pressure inlet (MPa) and  $x_2$  denotes flow in the high-pressure outlet ( $\text{m}^3/\text{h}$ ).

Suppose (3) as the general relationship:

$$y = k_1x_1 + k_2x_2 + t \quad (3)$$

Plug the experimental conditions that  $x_1 = 5.9$  and  $x_2 = 69$  into (3) separately:

$$y = k_1x_1 + 69k_2 + t \quad (4)$$

$$y = k_2x_2 + 5.9k_1 + t \quad (5)$$

In this way, (1) is equivalent to (4), (2) is equivalent to (5).

Thus:

$$k_1 = -0.0033, \quad k_2 = 0.0004 \quad (6)$$

$$5.9k_1 + t = 0.0422 \quad (7)$$

$$69k_2 + t = -0.01 \quad (8)$$

Get  $t_1$  and  $t_2$  after plugging (6) into (7) and (8):

$$t_1 = 0.0146, \quad t_2 = 0.00947$$

Respectively, calculate the standard deviation of the value of flow in table 3-2, as well as the

standard deviation of the value of pressure in **table 3-3**. Then,  $\sigma_{3-2} = 0.4865$ ,  $\sigma_{3-3} = 0.802$ . Comparing the two values, the data error in table 3-2 is relatively smaller. Hence, the value derived from (1) is more reliable than (2). In a word,  $t = 0.0146$ .

Ultimately:

$$y = -0.0033x_1 + 0.0004x_2 + 0.0146 \quad (9)$$

Empirical formula of pressure loss is:

$$\Delta P = P_{Hin}(-0.0033P_{Hin} + 0.0004Q_{Hout} + 0.0146) \quad (10)$$

## 4. Verification

### 4.1 Field application



**Figure 4-1.** The figure shows that the energy recovery device is in field application. The location of the field application is in Changtu desalination factory in Daishan County in Zhoushan City. The amount of processing of this factory achieves  $5000\text{m}^3/\text{d}$  [8]. The field application was operated by plunging the energy recovery device into technological process of the desalination factory.

The test began when the device was in regular work. One series of data was record every hour, totally eight times. The data includes the flow and pressure in high-pressure side, either in the inlets or in the outlets. Each series of data results in two values about pressure loss, of which one is the experimental value, another one is the theoretical value calculated by empirical formula. The feasibility of empirical formula would be verified by comparing the two values.

No.	$P_{Hin}$	$P_{Hout}$	$Q_{Hout}$	$\Delta P_e$	$\Delta P_t$	$\varepsilon$
	MPa	MPa	m <sup>3</sup> /h	MPa	MPa	%
1	3.3880	3.2773	72.1	0.1107	0.1093	1.239
2	3.3425	3.2331	72.2	0.1094	0.1085	0.834
3	3.3517	3.2450	72.6	0.1067	0.1092	2.371
4	3.3377	3.2309	72.0	0.1068	0.1081	1.194
5	3.3284	3.2237	70.8	0.1047	0.1063	1.490
6	3.3379	3.2307	72.3	0.1071	0.1085	1.264
7	3.3592	3.2529	71.9	0.1063	0.1084	2.039
8	3.3547	3.2442	72.5	0.1105	0.1091	1.266

**Table 4-1** Data in field application

**Table 4-1** illustrates data in field application. Where  $\Delta P_e$  denotes the experimental value of pressure loss,  $\Delta P_t$  denotes the calculated value of pressure loss,  $\varepsilon$  denotes the data error of two. From the table 4-1, the pressure in the high-pressure inlet was fluctuating on the level of 3.35 MPa, while the flow in the high-pressure outlet was approximately 72 m<sup>3</sup>/h. Although there were some small changes in the working conditions, the experimental value of pressure loss was stabilized in the range between 0.1~0.11 MPa. Meanwhile, the theoretical value is identical with the experimental one, data error being under 3%. Hence, the feasibility of empirical formula is verified for this kind of specification.

#### 4.2 Numerical simulation

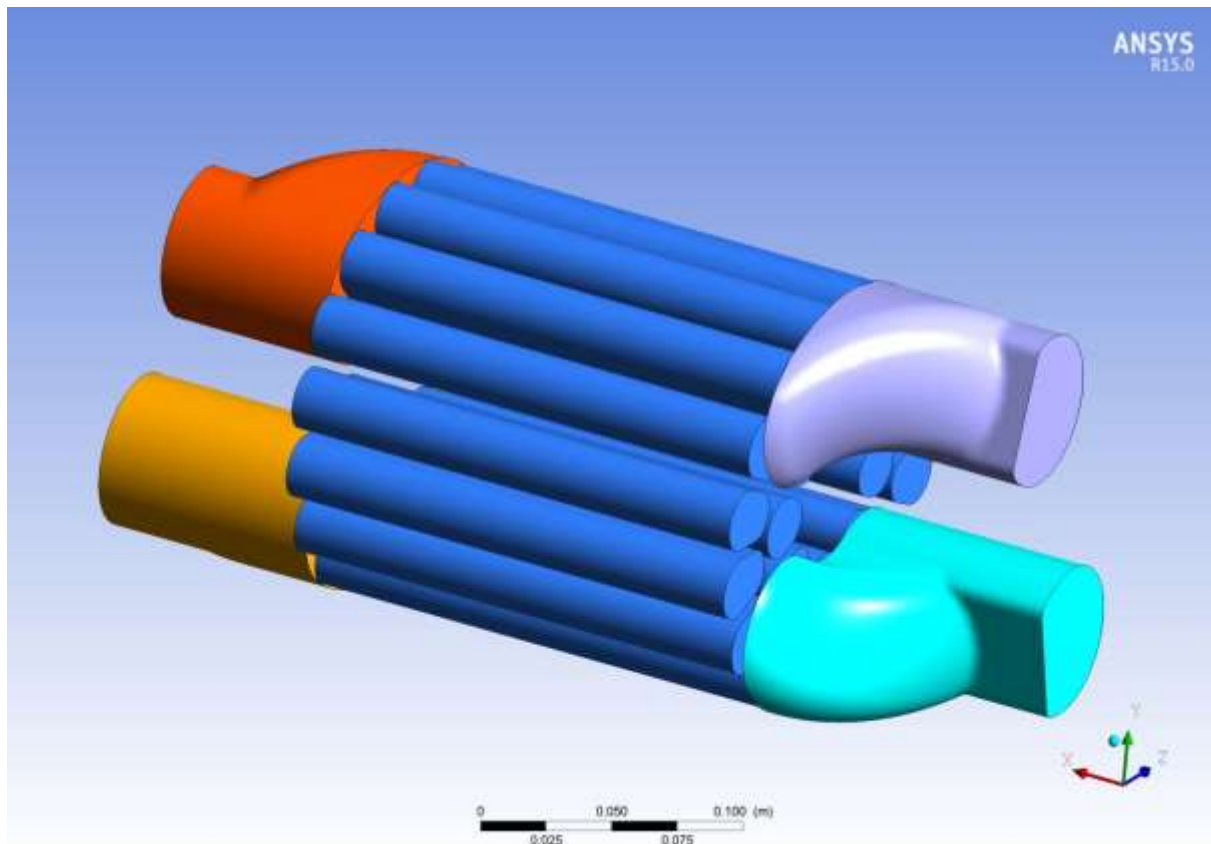
According to the working conditions and device specification in field application, a steady numerical analysis would be made in the software ANSYS FLUENT, on the basis of the fourth series of data in **table 4-1**.

**4.2.1 Numerical process** Firstly, establish the geometry model of the energy recovery device with the software—Solidworks, including rotor, sleeve and two end covers. Then, extract the computational domain of passageways to get the geometry model of computational domain. The geometry model of computational domain is shown in **Figure 4-2**.

Secondly, make the mesh generation on the geometry model with the software—ANSYS ICEM. Among all parts, the part of rotor domain is made of structured grid of high qualified, the part of end cover domain is made of unstructured grid for the complexity of details. The mesh quality of whole mesh is more than 0.4, meeting the requirements of numerical calculation.

Thirdly, set the parameter value on computation when the mesh had been imported into Fluent. Concerning the boundary conditions, all the inlets are Velocity Inlet and all the outlets are Pressure Outlet. Namely,  $V = 7.6358$  m/s for the inlet in the high-pressure side,  $P = 3.23$  MPa for the outlet in the high-pressure side,  $V = 7.4294$  m/s for the inlet in the low-pressure side and  $P = 0.05$  MPa for the outlet in the low-pressure side. As to other conditions, the rotation of rotor domain is considered by the use of the multiple rotating reference frame (MRF) method, with the rotation speed set as 700 rpm. At the same time, the effects of turbulence are modelled using the k- $\varepsilon$  turbulence with standard wall treatment in the simulation. Numerical convergence absolute criteria is set to a maximum of  $1 \times 10^{-4}$ . Setting the number of iteration as 1000 with accepting the rest of the default choices.





**Figure 4-2** Geometry model of computational domain

**4.2.2 Numerical results analysis** After calculation, the computational value on the pressure in the high-pressure inlet came up,  $P_{hin} = 3.251$  MPa. Obviously, the error was far beyond prediction value. It is important to note that the model could not simulate the leakage phenomenon. So, it is necessary to compensate the flow by taking leakage into consideration. A correction term comes to manifest the effect of leakage.

Correction term: 
$$\gamma = \frac{\Delta Q \times P_{Hin}}{Q_{Hout}}$$

And an extra relationship: 
$$P_{Hin} = \gamma + P_{hin}$$

Where  $P_{Hin}$  denotes the corrected pressure and  $\Delta Q$  denotes leakage.

Finally, outcome comes that  $P_{Hin} = 3.344$  MPa. It means that the real pressure loss  $\Delta P_c = 0.114$ , in the numerical calculation. The data error is about 5%, so the accuracy of empirical formula is verified for this kind of specification.

## 5. Conclusion

It is concluded that:

1. With regard to rotary pressure exchangers of the specification, there is a negative linear correlation between pressure loss rate and the pressure in the high-pressure inlet, while there is a positive linear correlation between pressure loss rate and the flow in the high-pressure outlet.
2. An empirical formula coming from the derivation of two linear relationship, is capable of predicting the performance of energy recovery device in a certain condition, especially in the ranges from 50 m<sup>3</sup>/h to 75 m<sup>3</sup>/h and from 2.8 MPa to 6.1 MPa.

3. The effect of leakage in the clearance surrounding the rotor cannot be ignored, in the numerical calculation about pressure loss in the rotary pressure exchanger. Furthermore, the pressure loss caused by leakage play the backbone, compared with other inherent factors of the device.
4. The correction term  $\gamma$  can offset the effect of leakage, and the correction term is relevant to the value of leakage, the pressure in the high-pressure inlet and the flow in the high-pressure outlet.

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