DOI: 10.3901/CJME.2010.**.***, available online at www.cjmenet.com; www.cjmenet.com.cn

# Comprehensive Parameter for Analyzing Condensation in Pneumatic System

JIN Yingzi[1], LI Yi[1], WANG Yanping[1], WANG Jie[1], ZHU Zuchao*[1, 2,]

1 *Zhejiang Province Key Laboratory of Textile Machinery, Zhejiang Sci-Tech University, Hangzhou 310018 China*
2 *The State Key Lab of Fluid Power Transmission and Control, Zhejiang University, Hangzhou 310027, China*

Received February 1, 2009; revised July 27, 2010; accepted July , 2010; published electronically July , 2010

**Abstract:** The condensation in pneumatic system is a complex physical phenomenon dependant upon status variation and phase transitions, which are related to the parameters of the compressed air, atmospheric conditions and the dimensions of the pneumatic components. Up to now, general research method for this problem is to calculate the status variation and movement quantity by numerical simulation and experiment directly. The comprehensive parameters composed of several different effect factors are rarely used to study the condensation. The composed components and the working conditions of each cylinder are different, a large number of experiments and complex calculations are necessary to determine the condensation. Additionally, the transferability of the determined results is poor. In this paper, the charging and discharging systems of serials cylinder with different structure parameters are studied. The condensation of the systems is observed and the effects of the structure parameters on condensation are analyzed. The changing trends of relative humidity, natural frequency and average speed against the structural parameters of the components during discharge of the pneumatic systems are analyzed. Three comprehensive parameters used to analyze and determine condensation composed by structure parameters of components are proposed, namely, the ratio of the effective area of the discharge tube and the container volume, the square root of the effective area of the discharge tube divided by the product of the container volume and the length of the discharge tube, and the discharge dimensionless tube-volume. The experimental results show that these comprehensive parameters can be used to quantitatively determine whether internal, external or zero condensation occurs in a pneumatic system, and can be also used to quantitatively analyze the experimental data of condensation in pneumatic systems directly. At the same time, the effect factors are too much and the effect relationships are very complex, which causes that the conclusions can't be put forward by using single effect factor in experimental data processing individually. The three obtained comprehensive parameters can be used to resolve the above problem. The proposed parameters can also resolve the problem of poor transferability in determining the state of condensation in pneumatic systems, and provide a novel method for the further study of condensation theory.

**Key words:** pneumatic system, condensation, comprehensive parameter, structure parameter

## 1 Introduction *

In pneumatic system, cooling caused by the expansion of compressed air will produce water droplets, which is known as condensation. If water droplets occur inside a component, the phenomenon is called internal condensation. Contrarily, it is called external condensation[1].

Former research shows that condensation in pneumatic systems is closely related to the state and motion parameters of the compressed air. The condensation is effected by the system operating condition, the structural parameters of the pneumatic components, the initial status of the compressed air and the atmospheric conditions.

The condensation in pneumatic system was proposed by WANG[1–2] firstly, during his work at SMC in Japan. Based on a large number of experiments, the condensation was divided into internal condensation and external condensation, The mechanisms of condensation in a pneumatic system was analyzed, and the impact trend of parameters, such as supply pressure, dew-point temperature, inner volume of cylinder, the length of the discharge pipe on pneumatic condensation, were presented.

JIN, et al [3–5], studied the effects of structural parameters of pneumatic components on condensation according to a large number of experimental data. Integrated with fluid net theory, physical characteristics used for analyzing the system condensation were presented; the distribution of experimental data revealing when internal, external or no condensation would occur. The state and movement parameters of the compressed air during the exhausting process of pneumatic systems were derived by using mathematical analysis; Effect of different factors on condensation in pneumatic system was investigated by using dimensional analysis. The above work provided a novel approach for the quantitative analysis of condensation.

ZHANG[6] studied the internal condensation from the

* Corresponding author. E-mail: zczhu@zjinfo.gov.cn
This project is supported by National Natural Science Foundation of China (Grant No. 50575209 )

perspective of phase change. The effects of heat transfer coefficient, condensation coefficients and boundary conditions on the formation and growth of water droplets in compressed air were studied via numerical simulation methods.

IKEO, et al[7–8], simulated the filling and discharging process of pneumatic systems by using bond graph simulation program(BGSP), discussed the effects of condensation coefficients and boundary conditions on condensation, and proposed condensation critical curves under different condensation coefficients, which provided a theoretical basis for the quantitative analysis of condensation within a certain range of physical parameters.

LI, et al[9], provided a numerical method to determine the internal condensation. The flow computation for discharging process of pneumatic system was simulated and the water droplet production calculated.

Amongst the factors, the effect of structural parameters of the system components is obvious. However, the effect can not be entirely determined quantitatively by theoretical methods. The research on the influence of a single factor depends mostly on experimental data. Currently, most studies focus on the influence of single factors on condensation, and the methods of preventing condensation are proposed from the point of such single factors. If the condensation could be discriminated or prevented based upon comprehensive system parameters, it would have great significance for predicting condensation at the design stage or before the system was utilized.

In this paper, the comprehensive parameters composed of different single factors were proposed based on a large amount of experimental data combined with theoretical analysis of state and motion parameters of compressed air. Then, the method to distinguish between the internal and external condensation by quantitative parameters was proposed. This work provides a method for experimental study and analysis of pneumatic system condensation.

## 2 Experimental Setup and Principles

As shown in Fig. 1, the experimental setup consists of a compressed air source, relief valve, directional valve, large vessel, cylinder (experimental container), timer, and a certain length of pipe. The large vessel is used to provide gas. The internal temperature and pressure of larger vessel are measured by a temperature sensor and a pressure sensor, respectively. The average temperature and humidity are recorder by hygrothermograph. The charging process and discharge process of cylinder (experimental container) can be implemented by reversing valve. The reversing valve is controlled by timer. The formation of the water droplet or ice was observed after eight hours of continuous operation of cylinder (container).

In the author's experimental configuration, a total of 10 cylinders of different volumes ranging from 1 922.66 mm$^3$ to 206 088 mm$^3$ were used. For every volumetric of cylinder, there are four different inner diameters of the discharge pipes, namely, 2 mm, 4 mm, 5 mm and 6 mm. The length of discharge pipe is discrete and varies from 100 mm to 20 100 mm. The lengths of every discharge piper are chosen according to condensation or no condensation occured in previous experiment. Until the length of discharger pipe nears to the critical length, the condensation occurs. the initial status parameters of compressed air is that pressure is 0.5 MPa, temperature,15 ℃ dew temperature of the air supply: 2℃, atmosphere temperature, 25℃, atmosphere humidity, 35%–40 %.

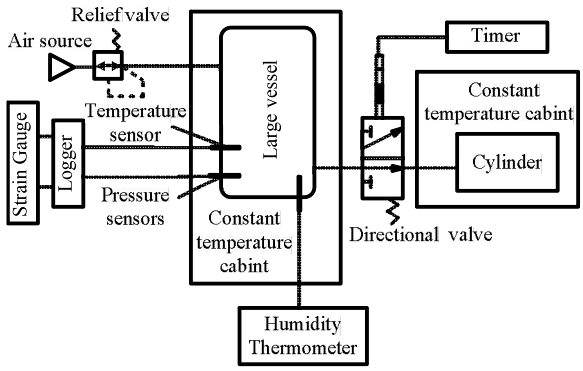


Fig. 1. Experimental setup

## 3 Effect of Condensation for a Single Parameter

### 3.1 Internal condensations

As we known, internal condensation occurs in a pneumatic system when water droplets are produced as the temperature of compressed air drops to or sub-dew point temperature during expansion. The effecting factors include atmospheric temperature and pressure, initial pressure, temperature and humidity of the compressed air and structural parameters of the system components such as inner volumes, effective sectional areas of the cylinder outlet, the reversing valve, the discharging pipe, and the length of discharging pipe.

In operating of pneumatic systems, atmospheric temperature and pressure, initial pressure and temperature of the compressed air are relatively stable. Hence, in this paper, only the effects of the structural parameters on condensation are investigated. The experiments indicate that the effects of different structural parameters of the system components on internal condensation are different[3–4]. When the other structural parameters are fixed, for smaller cylinder volumes, longer lengths of gas pipe or bigger cross section of air pipes, internal condensation is more prone to occur. Effective areas of cylinder and directional valve have no obvious effect on condensation.

Changing the volume of cylinder, effective area and length of discharging pipe, the distribution of experiment points at which the condensation or no condensation occurs are shown in Fig. 2. Where, $V$ is volume of cylinder, $A$ is the effective cross section, and $l$ is the length of discharging pipe.

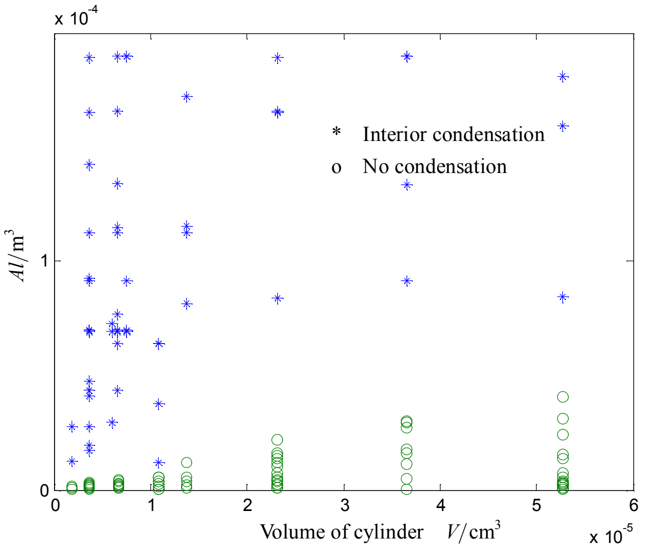


Fig. 2. Effects of structure parameter of system on interior condensation

In order to investigate the effect of area at the outlet of cylinder and the effective area at outlet of valve on condensation, the area at the outlet of cylinder and the cross section of reversing valve were changed and the experiments were repeated as the procedure shown in Fig. 1. One cylinder volume is 3 620 $mm^3$, another is 5 640 $mm^3$. The regulator orifice inner diameter of each cylinder is 0.7 mm, 1.1 mm and 2.5 mm, and the effective area of directional valve are 2.7 $mm^2$, 12 $mm^2$ and 17.1 $mm^2$, respectively. The experimental results expressed that the effective area of cylinder outlet and directional valve have no effect on condensation. Therefore, the volume of cylinder, effective cross section, and length of discharging pipe are focused on in this paper, and the outlet area of cylinder and effective area of regulator orifice are not be concerned.

### 3.2 External condensations

During cooling of compressed air due to expanding, heat transfer takes place between the air and surface of components, as well as the atmosphere near the outer surface of components, which causes the temperature decrease dramatically. When the temperature drops below the dew point, the water molecules separate from atmosphere and form to water droplet, condensation creates. If the temperature of the atmosphere is enough lower, the water droplet will change to ice[2–3].

The factors effecting on the external condensation include temperature, pressure and humidity of atmosphere, initial pressure, temperature and humidity of compressed air, structure parameters of system component such as inner volume of cylinder, effective cross section area at outlet of cylinder, effective cross section area of reversing valve, effective cross section area and length of discharging pipe. In this paper, only the effects of structure parameters of system component were studied.

Similar to internal condensation, the effects of every structural parameter of system components on external condensation are also different. Keeping the other structure parameters unchanged, the bigger volume of cylinder, the shorter length of discharging pipe, and the bigger cross section of discharging pipe, the external condensation are more prone to occur.

## 4 Condensation Analysis Based on Comprehensive Parameter

The condensation in a pneumatic system is a quite complicated phenomenon involving many factors. The analysis on effects degree of every factor relates to hydrodynamics, heat transfer theory and phase transformation, the calculation are troublesome and the prediction measures of condensation are difficult to find out, that is why the study on condensation in pneumatic system strongly depends upon empirical and semi-empirical analysis method based on a large number of experimental data.

In all of the factors, the effects of the structural parameters of system components are very important. Each of structural parameter effects the condensation in different trend and degree, which brings a lot of difficulties to analyze data when the condensation in pneumatic system was studied by experiment method.

It is particularly important to adopt the method of theoretical analysis or dimensional analysis and choice the comprehensive parameter with certain physical interpret to describe the effect of every structural parameters of component on condensation phenomenon in pneumatic system when we studied the condensation in pneumatic system.

### 4.1 Bringing up of comprehensive parameters based relative humidity of compressed air

The different single effect factor on condensation is reflected by the effect on status parameters and movement parameters of compressed air. The charging-discharging air system is shown in Fig. 3.

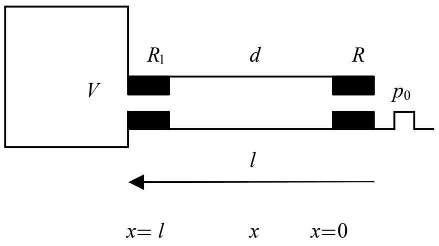


Fig. 3. Filling and exhausting processes

The following assumptions were made: (1) The solid boundary of system is set as controller; (2) The boundary of the system is superimposed with that of controller at the beginning/initial moment.

From Clapeyron's equations, Dalton's law, and the definition formula of humidity, the humidity of compressed air in any position of system can be derived from Eq. (1)[10]:

$$\phi_{(x,t)} = \frac{p(x,t)x_0}{(x_0+0.622)p_{\infty(x,t)}}, \quad (1)$$

where $\phi_{(x,t)}$ is the relative humidity, $x_0$ is the initial absolute humidity of compressed air, $p$ is the pressure, $p_{\infty(x,t)}$ is the saturated vapor pressure in plane liquid surface under a certain temperature, which can be obtained by empirical expressions or look-up the table. For Eq. (1), when the condensation doesn't occur, we can instead the absolute humidity with initial absolute humidity. Empirical expression is as follows:

$$p_{\infty(x,t)} = 10^{11.405\,1-\frac{2\,353}{T_{(x,t)}}}, \quad (2)$$

where $T_{(x,t)}$ is the temperature.

We can assume as follows[11]: (1) Viscous of air in pipe is very small and can be regard as ideal gas; (2) The pressure, temperature and density in cylinder is uniform; (3) There is no heat transfer between air and pipe wall, namely, the pipe wall is heat insulation, the flow of air in pipe is adiabatic reversible; (4) The temperature of air in pipe is radial uniform distribution; (5) The relation $\rho \cdot (\partial u/\partial t)$□ $u \cdot (\partial p/\partial x)$ stands while the flow is unsteady flow.

According to fluid net theory, the pressure and temperature in Eq. (1) can be derived from Eq. (3) and Eq. (4)[3]:

$$p_{(x,t)} = p_s + \frac{p_0}{2}\left[2-(1-\eta)\exp\left(-s_0\left(t-\frac{2l-x}{a}\right)\right)\right], \quad (3)$$

$$T_{(x,t)} = \frac{\sqrt[n]{p_s}}{R_g □ \rho_s}\left\{p_s + \frac{p_0}{2}\left[2-(1-\eta)\exp\left(-s_0\left(t-\frac{2l-x}{a}\right)\right)\right]\right\}^{\left(1-\frac{1}{n}\right)}, \quad (4)$$

where $\rho$ is the density of compressed air, $u$ is the axial velocity, $t$ is the time, $p_s$ is the initial absolute pressure of compressed air, $p_0$ is the pressure variation of compressed air at the beginning moment/initiation of discharging, $s_0$ is a comprehensive system parameter, $s_0=A \cdot a/V$. $a$ is the local speed of sound, $n$ is the polytrophic exponent, $R_g$ is the gas constant, $\rho_s$ is the initial density of compressed air, $\eta$ is the reflectance for flow resistance at the end of pipe, here, $\eta \approx -1$.

Pressure, temperature, and corresponding saturated vapor pressure, relative humidity and the derivation of relative humidity at arbitrary time and position can be derived from Eqs. (1)–(4), hence[3]

$$\frac{\partial \phi_{(x,t)}}{\partial x} > 0, \quad \frac{\partial \phi_{(x,t)}}{\partial t} > 0.$$

Namely, at the end moment of cylinder discharging, the humidity of compressed air reaches to a maximum. The condensation in pneumatic system is caused by water droplet produced when the humidity of compressed air in system reaches to hundred percent during the operation process of cylinder. In the following study, the maximum humidity at the inlet of container is analyzed. Set $x=l$, according to Eqs. (1)–(4), the derivation of air humidity at outlet of cylinder is

$$\frac{\partial \phi_{(l,t)}}{\partial s_0} > 0.$$

With the increasing of $s_0$, the saturation or super saturation is easier to reach. $s_0$ was defined as a comprehensive parameter. Hence, the local speed of sound is considered as constant, then $A/V$ is an important comprehensive parameter.

### 4.2 Proposed comprehensive parameter based on natural frequency and average speed

The average velocity of air $u_m$ during discharge[3] is expressed as follows:

$$u_{\mathrm{m}} = \frac{1}{A_1} \cdot \frac{1}{Z_{\mathrm{c}}} \cdot \frac{\sqrt[n]{p_{\mathrm{s}}}}{\rho_{\mathrm{s}}} \cdot \frac{1}{\left(1-\frac{1}{n}\right)} \cdot \left[ \left( p_{\mathrm{s}} + \frac{p_0}{2}(1+\eta) \right)^{\left(1-\frac{1}{n}\right)} - (p_a + p_a \times 10^{-5})^{\left(1-\frac{1}{n}\right)} \right] \Bigg/ \left[ \frac{l}{a} - \frac{1}{s_0} \cdot \ln\left( -\frac{p_a}{p_0} \cdot \frac{2}{1-\eta} \times 10^{-5} \right) \right], \tag{5}$$

where $A_1$ is the effective section area at the outlet of container, $Z_{\mathrm{c}}$ is the characteristic impedance of pipe, $Z_{\mathrm{c}}=a/A$.

According to Eq. (5), the partial derivatives of average velocity to $s_0$ and $l/a$ can be obtained as follows:

$$\frac{\partial u_{\mathrm{m}}}{\partial s_0} < 0, \quad \frac{\partial u_{\mathrm{m}}}{\partial (l/a)} < 0.$$

The above results show that the effect trend of $s_0$ and $l/a$ on average velocity is the same. The larger $s_0$ is, the bigger $l/a$ and the lower average velocity are, the easier internal condensation occurs. Therefore, $s_0 \bullet l/a = Al/V$ was proposed as a comprehensive parameter of evaluating condensation and its physical interpret is motion performance of compressed air. The comprehensive parameter is called dimensionless volume of discharging pipe and used to analyze internal condensation and external condensation instead of volume of container. The discharging process can be considered to the spreading process of decompression wave in system with natural frequency of fluid network theory[11]. The system in Fig. 3, if the length of pipe is shorter and $\omega_{\mathrm{n}} l/a$ is smaller, the natural frequency of system is

$$\omega_{\mathrm{n}} = \frac{a}{2\pi} \cdot \sqrt{\frac{A}{Vl}}, \tag{6}$$

The natural frequency $\omega_{\mathrm{n}}$ effects the motion performance of system directly, $\sqrt{A/(Vl)}$ is a comprehensive parameter too.

### 4.3 Analysis of interior condensation and exterior condensation using dimensionless volume

Using the dimensionless volume of discharging pipe $Al/V$, $\sqrt{A/(Vl)}$ and $A/V$ as comprehensive parameter of condensation, we could analyze the distribution of all the experimental points at which internal condensation and external condensation creates, and the analyzing results revealed the distribution of experimental points at which condensation or no condensation occurs in a certain regular rule as shown in Fig. 4, in which $A/V$ is abscissa axis and $\sqrt{A/(Vl)}$ is ordinate axis.

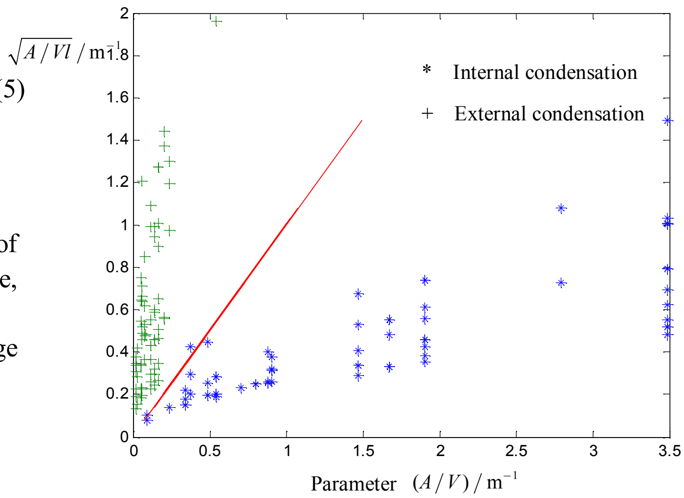


Fig. 4. Distribution of experimental points at which internal condensation or external condensation occurs

The following can be noted by observing Fig. 4:

(1) The structural parameters of system in which internal condensation or external condensation meet a certain distribution. In the area of upper left, external condensation occurs, and that of the lower right, internal condensation occurs.

(2) It is assumed there is a critical line between the distribution points at which internal condensation and external condensation occurs. Let $\sqrt{A/(Vl)} = k \bullet A/V$, then $k^2 = V/(Al)$ can be obtained. The results states that the dimensionless volume is an important comprehensive parameter, which is agree with the comprehensive parameters $Al/V$ based average speed.

(3) Drawing a boundary along the dividing line of internal condensation and external condensation (the solid line in Fig. 4). The authors found that the dimensionless volume in this critical line is equal to 1, namely, $Al/V=1$. The dimensionless volume is an important parameter used for discriminating between internal condensation and external condensation. $Al/V \geq 1$, only internal condensation could occur; $Al/V < 1$, only external condensation could occur.

## 5 Conclusions

(1) The dimensionless volume of discharging pipe is proposed as the first parameter to discriminate occurrence of internal condensation or external condensation in a pneumatic system. If the value of dimensionless volume is larger than or equal to 1, the internal condensation occurs in system possibly, and no external condensation occurs; oppositely, If the value of dimensionless volume is smaller than 1, the external condensation occurs in system possibly, and no internal condensation occurs.

(2) Condensation is defined that interior condensation occurs in smaller volume cylinder and exterior condensation occurs in larger volume cylinder. The problem of dividing line for cylinder volume exists in this

definition. Instead of the volume of cylinder, the dimensionless volume can be directly used to determine whether internal condensation or external condensation occurs in system, which provides an effective quantitative definition method for internal condensation or external condensation. Meanwhile, the authors provide a possibility of evaluation and discrimination of condensation by using comprehensive parameter in experimental study.

(3) The study on condensation in pneumatic system involves many problems, such as the whole process of internal condensation including status of compressed air changes during charging and discharging, the water droplets producing and growing, the water droplets keeping in the system and the internal condensation occurring, or heat transfer taking place between the air and surface of component, as well as the atmosphere near the components during operating process of compressed air. Hence, the condensation is very complicated, and there are many problems to be resolved which will cost a long explore time.

## References

[1] WANG Zuwen. The study on condensation. Paper One: Classification and fluential factor of condensation[R]. *SMC Technology Report*, 1991: 1–4. (in Japanese)

[2] WANG Zuwen. The study on condensation. Paper Two: Fluential factor of condensation[R]. *SMC Technology Report*, 1991: 1–5. (in Japanese)

[3] JIN Yingzi. *Study on condensation in pneumatic systems*[D]. Hanbin: Hanbin Institute of Technology, 1998. (in Chinese)

[4] JIN Yingzi, YANG Qingjun. Effect of structure sizes of pneumatic components on condensation[J]. *Chinese Journal of Mechanical Engineering*, 2004, 40(4): 40–43, 49. (in Chinese)

[5] JIN Yingzi, YANG Qingjun, WANG Zuwen, et al. Analytical solution of filling and exhausting proess in pneumatic system[J]. *Chinese Journal of Mechanical Engineering*, 2006, 19(1): 50–55.

[6] ZHANG Huping. *Study on condensation of water vapor in pneumatic systems*[D]. Tokyo: Sophia University, 1995. (in Japanese)

[7] IKEO S, ZHANG Huping, TAKAHASHI K, et al. Similation of pneumatic systems using BGSP[C]//*The Sixth Bath International Fluid Power Workshop*, Bath , UK, 1993: 11–14.

[8] IKEO S, ZHANG Huping, TAKAHASHI K, et al Condensation of water in pneumatic systems[C]//*The Seventh Bath International Fluid Power Workshop*, Bath, UK, 1994: 21–25

[9] LI Jun, WANG Zuwen, BAO Gang. Study on the interior condensation of water vapor in pneumatic system[J]. *Chinese Journal of Mechanical Engineering*, 2001, 37(10): 54–58. (in Chinese)

[10] FENG Qing, YUAN Shiwu, ZHANG Li. *Engineering thermodynamics*[M]. Xi'an: Xi'an Technological University Press, 2009. (in Chinese)

[11] LUO Zhichang. *Fluid grid theory*[M]. Beijing: China Machine Press, 1988. (in Chinese)

## Biographical notes

JIN Yingzi, female, born in 1963, professor/postdoctor. She graduated from Harbin Institute of Technology, China, 1998. And she returned from Japan in 2002. Her current research interests include hydrodynamics, pneumatic system. She has published more than 30 papers.
E-mail: Jin.yz@163.com

LI Yi, female, born in 1973, assistant professor/master. She graduated form Jiangsu University, China, in 2001. Her current research interests include fluid dynamics, fluid machinery. She has published more than 20 papers.
E-mail: liyi0511@163.com

WANG Yanping, female, born in 1971, assistant professor/ postdoctor. She graduated from Nanjing Science and Technology Univeristy, China, in 2006. Her current research interests include thermodynamics, phase change process. She has published more than 10 papers.

WANG Jie, male, born in 1982, master. He graduated form Zhejiang Sci-Tech University, China, in 2009. His current research interests: pneumatic technology.

ZHU Zuchao, male, born in 1966, professor/postdoctor. He graduated form Zhejiang University, China, 1997. His current research interests include hydrodynamics, hydro-mechanism. He has published more than 50 papers.
E-mail: zczhu@zjinfo.gov.cn