FLOMEKO 2022

Study on Numerical Simulation Method of Piston Type Micro Liquid Flow Standard Device

Haiyang Li[1], Xinhong Yao[2],
Liang Zhang[3], Xuejing Li[4]

[1,2,4] Shanghai Institute of Measurement and Testing Technology, 1500 Zhang Heng Road,201203, Shanghai, China
[3]National Institute of Metrology, China, Beijing 100029, China
E-mail (corresponding author): lixj@simt.com.cn

Abstract

The piston type micro liquid flow standard device is a kind of flow standard device with volume-time method. Because it can easily obtain micro flow due to its working principle, this kind of standard device is widely used in micro flowrate value traceability. In addition, the rapid development of precision machining technology also makes the processing of the piston, the master standard in the piston flow standard device, more and more precise, which plays a significant role in reducing the uncertainty of the whole standard device. In this paper, the simplified geometric model of the piston type micro liquid flow standard device is established by using modeling software, the geometric model is meshed, and finally the grid is solved to obtain the internal flow field of this type of flow standard device.

1. Introduction

In recent years, microelectronic manufacturing, fine chemical industry and biomedical technology have made great progress, followed by the increasing demand for micro flow measurement. Therefore, more and more flow measurement engineers have shifted their focus to the research of micro flow measurement value traceability method and the development of micro flowrate standard device[1~3]. The piston type micro liquid flow standard device can convert the liquid flowrate value into the piston cylinder or piston rod volume value, and then trace it to the length and time standard. The active piston type flow standard device takes the precision machined piston as the master standard, of which the piston rod is driven by the stepping motor to generate flow. By the reading of the grating ruler connected with the piston rod, the moving distance of the piston rod can be obtained in real time. While the cross-sectional area of the piston rod is known, the accumulated fluid volume caused by the movement of the piston rod in a certain time can be acquired. Usually, the piston type micro liquid flow standard device is also connected with a high-precision electronic balance for self-calibration using the principle of mass method. The structural schematic diagram of a typical piston type liquid flow standard device is shown in Figure 1.

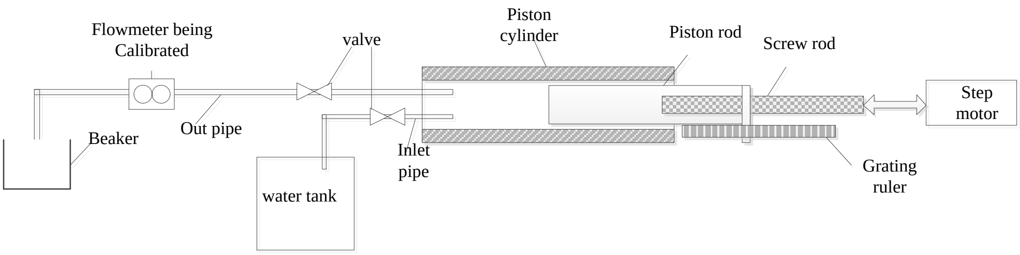

Figure 1: The structural schematic diagram of a typical piston flow standard device

Computational fluid dynamics (CFD) is a method of using computer to solve basic flow equations and study fluid motion. With the rapid development of computer and microelectronic technology, this method greatly saves the cost of real flow experiment. In recent years, more and more researchers have applied CFD to the flow field simulation and pre design flow standard devices. Dai Yi, the student of Shanghai Jiao Tong University, put forward the optimal geometry of low-speed wind tunnel through CFD numerical simulation. Lu, F., researcher of University of Shanghai for Science and Technology, through comparing the flow field of the downstream pipeline of the butterfly valve with different opening, studied the method of keeping flowrate constant under variable head conditions based on the flow control function of butterfly valve. However, there is no report on the application of numerical simulation method to the flow field simulation of piston type flow standard device. In this paper, the simplified 3D geometric model of piston type micro liquid flow standard device is established by using modeling software, then the model is meshed, and finally the grid is solved to obtain the internal flow field of this device. Besides, through the comparison of two different model of the device, the influence of the gap between piston rod and piston cylinder on the flow field in the outlet pipe is analysed[4,5].

2. Flow model selection

Due to the non-closure of the Average Reynolds N-S equation, most numerical calculation software provide a variety of flow models for users to choose, which are used to close the equation and provide numerical calculation methods under different flow regimes. Therefore, the quality of numerical simulation results largely depends on the accuracy of flow model selection. The choice of flow model depends on the Reynolds number of the flow. The fluid flow in the piston type micro liquid flow standard device simulated in this paper belongs to very low-speed liquid flow of 0.5m / s ~ 1m / s, from the formula:

$$R_e=vd/\upsilon \qquad (1)$$

Where d is the diameter of the pipe, in m; v is the velocity of the fluid, in $\mathrm{m/s}$; and υ is the kinematic viscosity of the liquid; in $\mathrm{m^2/s}$. Through calculation, the Reynolds number of the flow in the pipe of the standard device changes around 300 ~ 500 according to the different flow velocity. Therefore, it can be confirmed that the flow in the pipe is mainly laminar flow, which is selected as the flow model for numerical solution.

3. Geometric modeling and mesh generation of the standard device

3.1 Geometric modeling

In order to facilitate the mesh generation, it is properly simplified in modeling of the piston type micro liquid flow standard device. The geometric model of the standard device mainly includes piston cylinder, piston rod, inlet pipe and outlet pipe. The working process of the device is as follows: the motor pushes the piston rod to move into the cylinder after the piston cylinder absorbs water, and then the water is discharged into the beaker through the tested flowmeter. So, the water inlet is in a cut-off state during the flow process. The 3D geometric model of the standard device is shown in Figure 2.

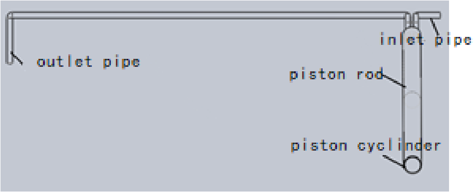

Figure 2: 3D geometric model of the Piston type micro liquid flow standard device.

It is worth noting that there is a gap between the piston cylinder and the piston rod. When the piston rod enters the piston cylinder, the gap between the piston cylinder and the piston rod is also a fluid flow area, as shown in the partial section of the piston in Figure 3.

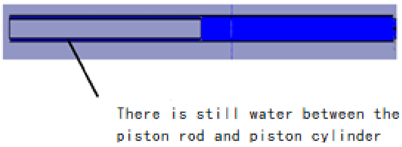

Figure 3: Gap between the piston cylinder and the piston rod.

3.2 Grid meshing

According to the geometric parameters of the actual piston type micro liquid flow standard device, the length of the piston rod and the piston cylinder is the same of 100mm(in the geometric model in this paper, the piston rod is pushed into 50% position of the cylinder). The outer diameter of the piston rod is 3.3mm, while the outer diameter of the piston cylinder is 3.6mm, and the gap between them is 0.15mm. The outer diameter of the inlet pipe and outlet pipe is the same of 1mm, and the length of the outlet pipe is 90mm, which is bent to the negative direction of Z axis at the negative 80mm of X axis, so as to discharge the liquid into the beaker. The length of the inlet pipe is 20mm, which is connected with the water source. Since the numerical simulation is in the drainage state, the water inlet is cut off.

After the 3D geometric model is designed, it needs to be meshed. In order to reduce the number of grids and save computing time on the premise of ensuring the fitting accuracy, unstructured grids are used for the whole computing domain, and local grids are densified for the gap between piston rod and piston cylinder, pipe bends and near wall surfaces of inlet and outlet. In the process of grid generation, reasonable setting of the maximum grid element is the key point. If the maximum grid element is set too large, the calculation accuracy is relatively low and the result is not easy to converge; on the contrast, the calculation accuracy will be improved but with the disadvantages of extension of the computing time and excessive consumption of computing resources. After several trial calculations, in this project, the normalized maximum grid element is set to 0.0002; and the actual number of generated grids is about 5.5 million, while the number of nodes is about 1 million. After the grid is generated, the grid independence is verified. Continuing to increase the number of grids will only extend the calculation time, but could not bring any changes to the calculation results. The generated grid is shown in Figure 4a, and Figure 4b is a partial enlargement of the inlet and outlet pipes of the standard device.

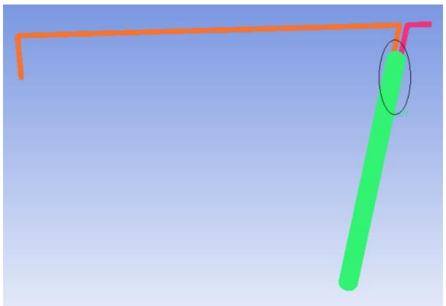

Figure 4a: Grid meshing of geometric model of standard device.

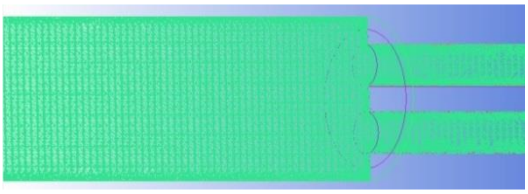

Figure 4b: Partial enlargement of the inlet and outlet pipes

4. Parameter setting and result analysis of numerical calculation

Import the grids generated in Section 3 into the numerical calculation software. Check the quality of the grids and set the size of the calculation domain to ensure that there is no negative volume grid and that the grid size unit is consistent with the size unit of the actual geometric model. From the above, the laminar model is selected as the flow model. Assuming that there is no heat exchange in the flow process, the energy equation is closed. Set water as the working medium, the inlet is surface of the piston rod entered the piston cylinder which is the pressure inlet with initial static pressure of 2000Pa, while the outlet is at the end of the outlet pipe, which is the pressure outlet with the pressure of 1500Pa, and the pressure loss of the pipe is 500Pa.Select SIMPLE algorithm as the coupling mode of pressure and velocity. The calculation converges in about 700 steps. The velocity nephogram of the central section plane with coordinates z = - 15.5 and y = 0 is shown in Figure 5a, and the partial enlargement of the velocity nephogram at the front end of the outlet pipe is shown in Figure 5b.

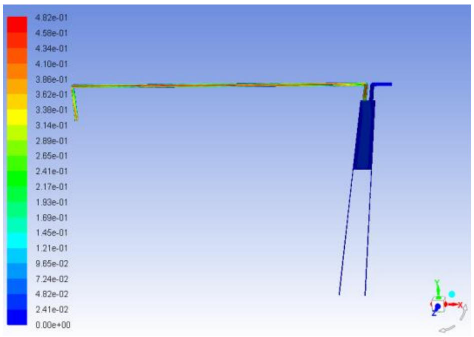

Figure 5a: Velocity nephogram of the whole flow

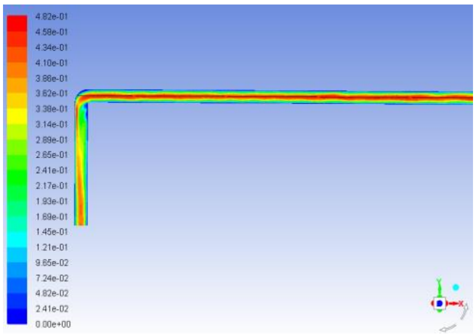

Figure 5b: Partial enlargement of the front end of the outlet pipe

In order to quantitatively evaluate the flow field, the velocity nephogram at the outlet pipe and the velocity-position scatter diagram of the axis of the outlet pipe were drawn, as shown in Figure 6 and Figure 7. As quantitative evaluation indices, the velocity uniformity of the axis of the outlet and the outlet pipe (expressed by the standard deviation of the velocity and pressure), which were represented by $\mathrm{Std}_{\text{velocity-outlet}}$, $\mathrm{Std}_{\text{velocity-outlet pipe}}$, $\mathrm{Std}_{\text{pressure-outlet}}$, $\mathrm{Std}_{\text{pressure-outlet pipe}}$, and the vortex degree of the flow field of the outlet and outlet pipe (expressed by the vortex value of the outlet and the central section plane of the outlet pipe), which are represented by $\mathrm{Vortex}_{\text{outlet}}$, $\mathrm{Vortex}_{\text{outlet pipe}}$ are introduced, as shown in Table1.

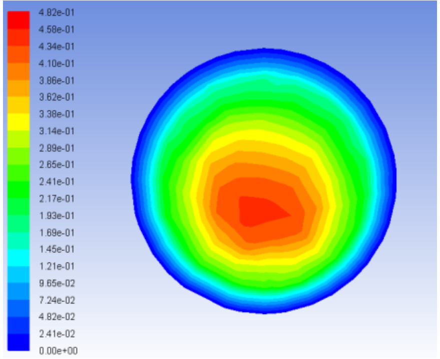

Figure 6: Velocity nephogram of the outlet

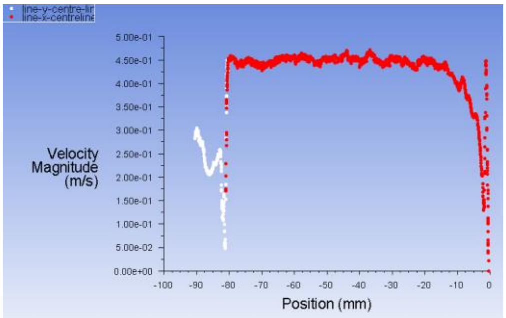

Figure 7: Velocity-position scatter diagram of the axis of the outlet pipe

It should be explained that there are two reasons for the depression point in the velocity-position scatter diagram near 80mm. The first reason is that the velocity-position scatter diagram of two 90 degree vertical axes are displayed in the same coordinate system during the drawing process, so there will be breakpoints in the diagram. In addition, due to the problems of vortex and secondary flow near the elbow, the closer to the elbow, the smaller the velocity is, and the farther away from the elbow, the greater the velocity is. Finally, the velocity increases the same as that in front of the elbow.

Table 1: Quantitative evaluation indices characterizing flow field quality.

Quantitative evaluation indices	**value**
Std$_{velocity\text{-}outlet}$	0.12568（m/s）
Std$_{pressure\text{-}outlet}$	28.7479（pa）
Std$_{velocity\text{-}outlet\ pipe}$	0.05796（m/s）（x axis） 0.07049（m/s）（y axis）
Std$_{pressure\text{-}outlet\ pipe}$	15.7519（pa）（x axis） 19.3175（pa）（y axis）
Vortex$_{outlet}$	1035.604（1/s）
Vortex$_{outlet\ pipe}$	1131.0083（1/s）（z=-15.5 plane） 333.8655（1/s）（y=0 plane）

In order to further improve the flow stability at the outlet and reduce the uncertain factors such as the vortex or secondary flow the geometric model of the piston liquid flow standard device is improved as follows: appropriately increase the gap between the piston rod and the piston cylinder to 0.3mm, and the external diameter of the piston cylinder expands to 3.9mm but the geometric dimension of the piston remains unchanged. The geometric dimensions of all other parts remain unchanged too. The modified geometric model of the standard device is re meshed and numerically calculated and the new flow field velocity nephogram is obtained as shown in Figure 8.

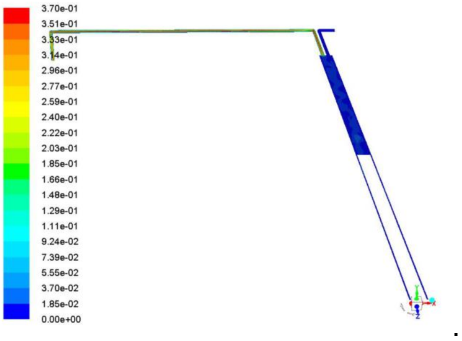

Figure 8: Flow field velocity nephogram of the modified standard device

Through comparison, it is found that under the same inlet and outlet conditions, the average outlet velocity decreases from 0.30m/s before improvement to 0.23m/s. The reason is that the increase of working medium in the gap increases the consumption of inlet pressure potential energy. However, the improved piston flow standard device has been greatly improved in terms of flow field quality, and the relevant flow field evaluation indices are shown in Table 2.

Table 2: Quantitative evaluation indices characterizing flow field quality after improvement.

Quantitative evaluation indices	**value**
Std$_{velocity\text{-}outlet}$	0.10069（m/s）
Std$_{pressure\text{-}outlet}$	18.5682（pa）
Std$_{velocity\text{-}outlet\ pipe}$	0.04741（m/s）（x axis） 0.06482（m/s）（y axis）
Std$_{pressure\text{-}outlet\ pipe}$	12.5202（pa）（x axis） 16.2814（pa）（y axis）
Vortex$_{outlet}$	800.2694（1/s）
Vortex$_{outlet\ pipe}$	909.8727（1/s）（z=-15.5 plane） 138.0455（1/s）（y=0 plane）

It can be seen from the above indices that the flow field quality of the geometric model after increasing the gap between the piston rod and the piston cylinder is significantly better than that of the geometric model before improvement. However, considering the decrease of outlet flow rate due to the increase of gap, greater inlet pressure is required for balance. Thus, the gap between the piston rod and the piston cylinder cannot be increased indefinitely.

5. Conclusion

This paper introduces a numerical simulation method of piston liquid flow standard device. Firstly, according to the working principle of piston liquid flow standard device, the geometric model of the device is designed. Then the geometric model is meshed. On this basis, the numerical simulation of the situation when the piston rod entered to the 1/2 position in the piston cylinder is carried out, and the velocity nephogram, pressure nephogram and velocity-position scatter diagram are obtained. The correctness of the numerical simulation method to study the flow field of the piston flow standard device is verified. In addition, the geometric model of the standard device is improved, and the improvement of flow field quality is analyzed quantitatively. The results show that the flow field quality of the improved model has obvious improvement compared to that of the original model, which further guides the design of the actual piston flow standard device.

References

[1] Bing Xu, Shaogan Ye, Junhui Zhang. Numerical and experimental studies on housing optimization for noise reduction of an axial piston pump [J]. Applied Acousties ,2016(110):43-52.

[2] Bissig H., Tschannen M. and de Huu M., “Micro-flow facility for traceability in steady and pulsating flow”, *Flow Meas. and Instrum.*, 44, 34-42, 2015.

[3] Bissig H., Petter H.T., Lucas P et al., “Primary standards for measuring flow rates from 100 nl/min to 1 ml/min – gravimetric principle”, *Biomed Eng – Biomed Tech*, 60(4), 301-316, 2015.

[4] Dai Yi. Numerical simulation of low speed wind tunnel and CFD-based optimal design[D].Shanghai: Shanghai Jiao Tong University, 2013.

[5] Lu, F. , Zhang, J.M. , Shen, Y.M. . Simulation and research on flow-field of butterfly valve in standard variable head flow device[C]. 18th International Flow Measurement Conference, FLOMEKO 2019, International Measurement Confederation, IMEKO-TC9-2019-025.