

Critical flow sonic nozzles gas flow facility with medium-pressure and closed-loop pipelines

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Abstract

The requirement of gas flow facility with high pressure is increasing. But, the experiences of development the closed-loop high pressure facility are not enough. Critical flow sonic Nozzles gas flow facility with medium-pressure and Closed-Loop pipelines at Tianjin University Flow Lab was presented in the paper. The performance indexes, the flow loop, the uncertainty analysis of the facility were described. Discharge coefficient correction of nozzles at medium pressure and the flow rate stability control were shown in detail. The pressure of the facility is 0.3~1.6 MPa, the flow rate is 0.5~120 m³/h at working status, the uncertainty is better than 0.3% ($k=2$).

Introduction

Gas flow facility with positive pressure is more easily accepted by customer than that with negative pressure for the working condition of flowmeter under test is close to that of meter at working field. The test under positive pressure condition is important for the flowmeter whose performance is impacted by gas density. The turbine gas flowmeter need test under pressure above 4 bar as its maximum working pressure is higher than 4 bar [1]. So the requirement of the gas flow facility with medium or high pressure is increasing. But the cost of long-term running for high pressure facility is expensive because the large power of gas source devices. So, most of high pressure facilities in the world are online, especially for the calibration of natural gas flowmeter.

In order to improve the efficiency of the utilization of high pressure compressed air, gas flow facilities with closed-loop pipeline were developed in the world, as a statistics in Tab 1. But, the experiences of development and debugging the closed-loop facility are not enough published in references [2].

Critical flow sonic Nozzles gas flow facility with medium-pressure and Closed-Loop pipeline (for short, CNCL) was developed at Tianjin University Flow Lab (TUFL) China, as shown in Tab 1. The performance indexes, the flow loop, the analysis of uncertainty of the CNCL facility were described in the paper. Two key problems of flow rate stability control and discharge coefficient correction of sonic nozzles at medium pressure were presented in detail.

Flow loop of the CNCL facility

The flow loop of the CNCL facility was shown in Fig 1 and Fig 2. The CNCL facility includes two compressed air

source systems. The double screw compressor, devices for cleaning and drying the air, and the storage tank make up the system 1. The system 2 was composed of the frequency converter controlled piston type compressor, the bypass pipe, the switch valves for pipeline structure conversion operation, and regulating valves for flow rate adjusting. At the stage of preparing the test work, dry air with dew -65 °C is imported into the closed-loop pipeline by the system 1. As the pressure of pipeline reaches the set point, the system 1 stop working and then the system 2 propels the air to run in the closed-loop.

Like most of the facilities with high pressure in Tab 1, two rotary flowmeters (Roots flowmeter) were adopted as the standard flow meter for its high repeatability. In order to improve the uncertainty level of the facility, and check the meter factors of the rotary flowmeter periodically without removing it out from the facility, critical flow sonic nozzles were included in the closed-loop pipeline. A pressure regulating valve was set upstream the stagnation collecting pipe for changing the working pressure of nozzles, so the working flow rate of nozzles can be adjusted continuously. Considering the large pressure loss of sonic nozzle, the ability of pressure improvement of piston type compressor is high. The piston type compressor in the CNCL with inlet air pressure 0.6 MPa, output air pressure 1.6 MPa, exhaust value 25 Nm³/min, inlet air temperature ≤35 °C, output air temperature ≤40 °C, motor power 90 kW.

By changing the condition of switch valves, the CNCL facility can run in the open-loop pipeline mode air flow supplied by compressed air source system 1 or 2, adopting the rotary meters or the nozzles as the standard devices. The comparison of nozzle with rotary meters can be made in the modes of open-loop and closed-loop respectively.

Uncertainty analysis of the CNCL facility

According to JJF1240-2010 [4], the relative standard uncertainty of volume flow rate at critical flow Venturi nozzles gas flow facility is u_r

$$u_r(q_v) = \left\{ u_{r,c_d}^2 + \frac{1}{4} [u_{r,T_0}^2 + u_{r,M}^2 + u_{r,R}^2] + u_{r,p_0}^2 + u_{r,T}^2 + u_{r,p}^2 + u_{r,\lambda}^2 + u_{r,c_v}^2 + u_{r,z}^2 + (c_{r,0} u_{r,0})^2 \right\}^{0.5} \quad (1)$$

Where, u_{r,c_d} is the relative standard uncertainty of the discharge coefficient of sonic nozzle, u_{r,T_0} is the relative standard uncertainty of the stagnation temperature measurement of sonic nozzle, $u_{r,M}$ is the relative standard uncertainty of the Moore mass, $u_{r,R}$ is the relative standard uncertainty of general gas constant, u_{r,p_0} is the relative

standard uncertainty of the stagnation pressure measurement of sonic nozzle, u_{rT} is the relative standard uncertainty of the temperature measurement at the flowmeter under tested, u_{rp} is the relative standard uncertainty of the pressure measurement at the flowmeter under tested, u_{rA_s} is the relative standard uncertainty of the throat area of the sonic nozzle, u_{rC_s} is the relative standard uncertainty of the critical flow function, u_{rZ} is the relative standard uncertainty of the compression coefficient, C_{r0}, u_{r0} is the relative standard uncertainty of the sensitivity coefficient of the humidity.

u_{rA_s} is ignorable for the nozzles were calibrated by PVTt facility. u_{rM} , u_{rR} and u_{rZ} are ignorable for the fluid at PVTt is air also. C_{r0}, u_{r0} was ignored for the humidity of air at north of China is low, and there is strict cleaning and drying process at the compressed air source system 1. Considering the value of u_{rC_s} is small, so its impact is ignored.

Uncertainty sub-items of the CNCL facility were shown in Tab 2. According to the calibration certificates of nozzles, the maximum uncertainty of discharge coefficient C_d of nozzle was 0.16% ($k=2$). But, the C_d on the certificates was got from PVTt facility under the condition close to the atmosphere. The C_d should be corrected according to the Re_{nt} at the throat of nozzle, as it was working at high pressure condition. The C_d correction method would be described in next paragraph, the uncertainty of it is better than 0.2% ($k=2$). So, the u_{rC_d} is

$$u_{rC} = \sqrt{\left(\frac{0.16\%}{2}\right)^2 + \left(\frac{0.2}{2}\right)^2} = 0.128\% \quad (2)$$

The error of temperature transmitter is better than $\pm 0.05^\circ\text{C}$, according to the rectangle distribution, the uncertainty of the stagnation temperature measurement of sonic nozzle u_{rT_0} is

$$u_{rT_0} = \frac{0.05}{\sqrt{3}(273.15+20)} = 0.01\% \quad (3)$$

The error of pressure transmitter is better than 0.04%, it is often used at pressure points near the 2/3 of full scale, according to the rectangle distribution, the uncertainty of the stagnation pressure measurement of sonic nozzle u_{rp_0} is

$$u_{rp_0} = \frac{0.0004 \times \frac{3}{2}}{\sqrt{3}} = 0.035\% \quad (4)$$

The uncertainty of the temperature measurement at the flowmeter under tested u_{rT} is equal to u_{rT_0} . The error of pressure transmitter is better than 0.04%, it is often used at pressure points near the 4/5 of full scale, according to the rectangle distribution, the uncertainty of the pressure measurement at the flowmeter under tested u_{rp} is

$$u_{rp} = \frac{0.0004 \times \frac{5}{4}}{\sqrt{3}} = 0.029\% \quad (5)$$

Based on the formula (1), the uncertainty of the CNCL facility was shown in Tab 2.

Two rotary meters were calibrated by critical flow Venturi nozzles air flow facility with negative pressure, whose uncertainty was 0.25% ($k=2$). Meter factors of rotary meters and repeatabilities of them were shown in Tab 3. If rotary meter is regarded as the master meter of the facility, the uncertainty of facility is mainly including the repeatability of the rotary meter and the uncertainty of the facility used for calibrating the rotary meter. The other uncertainty items of the time, the temperature, the pressure, the electrical signal collection and processing are much smaller than that of the rotary meter. So, those small items can be ignored. In this way, the uncertainty of the facility is better than 0.3%, as two rotary meters are running at their calibrated flow rate points. If the rotary meters are running in their whole flow rate range, considering the uncertainty of meter factor interpolating function, the uncertainty of the facility is better than 0.5%.

Correction of nozzles discharge coefficients

Parameters of nozzles

The parameters of 9 nozzles utilized at CNCL facility were shown in Tab 4. In order to easily machining, the geometric shape of the nozzle was slightly different to the toroidal-throat Venturi nozzle presented at ISO 9300-2005 [5]. There is a Cylindrical Stage Downstream the Throat (for short, CSDT), as shown in Fig 3, and the length of the cylindrical stage is recorded as l .

The nozzles were calibrated at Shanghai Inspection and Testing Institute of Instruments and Automatic Systems (SITIIS) by PVTt gas flow facility. The expanded uncertainty of PVTt gas flow facility is 0.07% ($k=2$). The temperature of air flow is $(20.7\sim 21.9)^\circ\text{C}$, the humidity of it is 75%, atmosphere pressure is $(100.6\sim 101.7)$ kPa.

In the Tab 4, the throat diameter is d mm, the ratio of the curvature radius to throat diameter is r_c/d , divergent angle is α° , the repeatability of the discharge coefficient C_d is $E_r\%$, the expanded relative uncertainty of the C_d is u_{rC_d} ($k=2$)%, as the nozzle is calibrated by the PVTt facility the volume flow rate of it under standard condition (20°C , 101 325 Pa) is Q , the throat Reynolds number of nozzle at calibrated condition is Re_{nt} , the critical back pressure ratio tested at the CNCL facility by rotary flowmeter is r .

As discharge coefficients shown in Fig 4, there is obviously difference between the coefficients of CSDT nozzles and that of ISO toroidal-throat Venturi nozzles. So, to correct the coefficients according to the formula in ISO 9300-2005, will produce large errors especially for the small nozzles.

CFD Simulation of flow field in nozzles

The cylindrical stage downstream the throat play a important role on the flow field in the nozzle, so there is a variation of its discharge coefficient. Based on the Computational Fluid Dynamics (CFD) simulation software package Fluent, the flow fields in the nozzles were

analyzed. The related simulation conditions were shown in Tab 5. The discharge coefficients got from simulation were shown in Tab 6, calibrated coefficients and those calculated by ISO 9300-2005 toroidal-throat Venturi nozzle formula were shown also for making a comparison.

The difference of flow velocity in nozzles were shown in Fig 5~ Fig7. In the figure for axial velocity comparison, two vertical lines were added to point out the positions of cylindrical stage start and stop. It can be seen from the velocity distribution that the cylindrical stage downstream the throat, the step connected it and the divergent surface, decrease the flow speed. So, the mass flow rate of nozzle with cylindrical stage downstream the throat is smaller than that of the ISO 9300 toroidal-throat Venturi nozzle if the throat diameters of them are same. Therefore, the discharge coefficient of it is smaller than that of ISO shape nozzle. But the effect of cylindrical stage decreases as the diameter of the nozzle increases.

Discharge coefficient correction

The discharge coefficients of 8 nozzles (except for #5) got by CFD simulations were shown in Fig 8. In order to make a comparison, the coefficients calibrated by PVTt were shown in Fig 8 also. The maximum relative deviation of simulation coefficients from calibration one is 0.95%. Two trend lines were got separately from simulated and calibrated coefficients. The deviation of simulation coefficients from calibration one decrease to below 0.2% as Re_{nt} increases at relative high pipeline pressure. But, the uncertainty of discharge coefficient correction by CFD simulation will be verified by strict tests.

Pressure and flow rate control

It is important for the facility with medium-pressure and closed-loop pipeline to easily adjust the pressure and the flow rate and keep them stable at one set point. The brief flow loop for the pressure control was shown as Fig 9. Opening the valve 1 and regulating valve 2, dry air can be injected into closed-loop by compressed air source system 1. The speed of air injection can be regulated by change the open degree of regulating valve 1. Adversely, the valve 43 and regulating valve 42, play the role of releasing air into the atmosphere from closed-loop. The valve 5 and regulating valve 4 at the bypass pipe, modify the working condition of piston compressor according to the pressure and the flow rate required by test flowmeter. So, very low working frequency of motor can be avoided. The pressure upstream the self-operated pressure regulating valve 7 can be controlled by the strategy shown in Fig 10.

Considering the pulse effect of piston compressor on pressure stability, two 0.4 m³ damping tanks were arranged respectively at the inlet and the outlet of the compressor. In order to improve the pressure stability further, one 0.8 m³ damper tank was added at the position near the inlet of piston compressor, for overcome the pulse of suction. Another 0.8 m³ damper tank was added at the downstream of the self-operated pressure regulating valve 7, to increase the stability of the pressure at the test flowmeter.

Assessment of pressure and flow rate stabilities

Flow rate stability between the integration intervals

According to JJF 1240-2010 [4] and ISO 9368-1 [6], flow rate stability should be tested when the test flowmeter is not fixed at the pipeline of facility. Flow rate stability should be tested at the maximum flow rate, the minimum flow rate and more than two middle flow rate points in the flow rate range of the facility. Then, the worst stability would be regarded as the flow rate stability index. The time of one integration interval is longer than 60 s. To continuously test n ($n \geq 10$) times of integration interval, get q_i ($i=1, 2, \dots, n$; $n \geq 10$), then to calculate the flow rate stability between the integration intervals S , following the formula as below.

$$\bar{q} = \frac{\sum_{i=1}^n q_i}{n} \quad (6)$$

$$S = \frac{1}{q} \left[\frac{\sum_{i=1}^n (q_i - \bar{q})^2}{n-1} \right]^{\frac{1}{2}} \times 100\% \quad (7)$$

Where, \bar{q} is the average flow rate, m³/h; S is the flow rate stability between the integration intervals.

Flow rate stability within the integration interval

According to JJG643-2003 [7] and ISO 9368-1 [6], to continuously record the electrical signal responding flow rate value, q_{li} ($i = 1, 2, \dots, n$; $n \geq 60$), the flow rate stability within the integration interval E_{q1} can be calculated as below.

$$q_1 = \frac{1}{n} \sum_{i=1}^n q_{li} \quad (8)$$

$$E_i = \frac{q_{li} - q_1}{q_1} \times 100\% \quad (9)$$

$$R_j = \frac{1}{n-j} \sum_{i=1}^{n-j} E_i \times E_{i+j} \quad (10)$$

$$E_{q1} = k \sqrt{\frac{2}{n} \sum_{j=0}^{j_{\min}} |R_j|} \quad (11)$$

Where, the q_1 is average flow rate; the E_i is relative error; the R_j is correlation function, $j = 0, 1, 2, \dots, n-1$; the k is coverage factor $k = t_p(v)$, $t_p(v)$ is t distribution coefficient with a 95% confidence level; for monotonic decreasing function $r_j = \frac{R_j}{R_0}$, $r_{j_{\min}} \leq 0.1$, as $j = j_{\min}$.

Stabilities of CNCL facility

Stabilities in closed-loop mode

Based on the methods mentioned above, the flow rate stability between integration intervals and that within the

integration interval were tested as facility running in the closed-loop mode, and the results were shown in Tab 7 and Tab 8. According to the same methods, the stagnation pressure stability and the stagnation temperature stability were tested, and the results were shown in Tab 7 and Tab 8 also. It can be seen from the data shown in Tab 7 and Tab 8 that the stability of volume flow rate is better than 0.01%, the stability of mass flow rate is better than 0.1%, the stability of the pressure is better than 0.1%, the stability of temperature is better than 0.03%.

Sabilities in open-loop mode

Based on the methods of the flow rate stability test, stabilities of the flow rate, the pressure and the temperature were tested as facility running in open-loop mode, the air flow is supplied by the air sources system 1, and the results were shown in Tab 9 and Tab 10. The double screw air compressor in gas source system 1 was turned off during the stabilities test to simulate the case of gas supply is not enough for keeping the pressure. The pipeline pressure was set at 0.4 MPa during the tests. It can be seen from the data shown in Tab 9 and Tab 10 that the stabilities of the flow rate and the pressure are good as flow rate is small, the impact of gas source lack on the stabilities of the flow rate and the pressure appears as flow rate increases.

Conclusions

Critical flow sonic Nozzles gas flow facility with medium-pressure and Closed-Loop pipelines (CNCL) was developed at Tianjin University Flow Lab (TUFL). The working pressure range of the facility is 0.3 ~1.6 MPa, the flow rate range of it is 0.5~120 m³/h at working status, the uncertainty of it is better than 0.3% ($k=2$).

By changing the condition of switch valves the CNCL facility can run in the open-loop pipeline mode also. The standard device of it can be the rotary meters or the critical flow Venturi nozzles. The comparison of nozzles with rotary meters can be made in the modes of open-loop and closed-loop respectively.

The cylindrical stage downstream the throat play a important role on the flow field in the nozzle and the discharge coefficient of it. The variation of discharge coefficient, as the throat Re_{nt} increases at relative high pipeline pressure, can be corrected by CFD simulation.

The volume flow rate stability of the CNCL facility is better than 0.01%, the mass flow rate stability is better than 0.1%, the pressure stability is better than 0.1%, the temperature stability is better than 0.03%.

References

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Tab.1 Statistics of closed-loop pipeline gas flow facilities

Lab.	Elster	RMG	SwRI-MRF HPL [3]	SwRI-MRF LPL [3]	Force Technology	CPC HP	TUFL Wet gas	TUFL CNCL
Nation	Germany	Germany	USA	USA	Danmark	China Taipei	China	China
Fluid	Dry air	Air	Natural gas/ Nitrogen	Natural gas/ Nitrogen	Air/ Natural gas	Air	Air-water	Dry air
Temperature of fluid □	-	-	4.4~48.8	4.4~48.8	10~30	-	-	10~30
Pressure /MPa	0.1~2.5	0~2.5	1.03~8.27	0.14~1.45	0~2.5 (Air) 0~5 (NG)	1~6	0~1.6	0~1.6
Flow rate range /m ³ /h	5~1600	5~1800	~2378.6	~1234.6	8~10000	~4000	1~300(Air) 0.05~8(Water)	0.5~120
Pipeline /mm	DN50~DN200	DN25~DN250	DN50~DN500	DN25~DN200	DN50~DN400	-	DN50, DN80	DN2.5~DN40
Standard devices	Turbine meter, Rotary meter	Turbine meter, Rotary meter	Weigh tank, Nozzle, Turbine meter, Orifice plate	Nozzle, Turbine meter, Orifice plate	-	Rotary piston prover	Turbine meter(air) Electromagnetic flowmeter(water)	Nozzle, Rotary meter
Uncertainty (k=2) /%	-	<0.3	0.1~0.25	0.1~0.25	0.2	-	1.0	0.2~0.3

Tab.2 Uncertainty of the CNCL facility

Subitem	Relative standard uncertainty	Sensitivity coefficient	$ C_{rx_i} u_{rx_i} / \%$
	$u_{rx} / \%$	C_{rx}	
u_{rC_d}	0.128	1	0.128
u_{rp_0}	0.035	1	0.035
u_{rT_0}	0.01	-0.5	0.005
u_{rp}	0.029	1	0.029
u_{rT}	0.01	-1	0.01

Standard uncertainty of CNCL facility $u_i=0.136\%$
Expanded uncertainty of CNCL facility $U=0.272\%$ ($k=2$)

Tab.3 Parameters of two rotary meters at the CNCL facility

Rotary meter	Q_v (m ³ /h)	K (1/m ³)	E_r (%)
G16-FCM-I (DN50)	0.4943	4721.18	0.02
	0.9631	4755.18	0.02
	25.03	4796.00	0.08
G100-FCM-I (DN80)	0.9678	947.01	0.03
	8.033	954.09	0.02
	160.95	955.08	0.01

Tab.4 Parameters of the nozzles at the CNCL facility

Nozzle	d (mm)	r_c/d	α (°)	l (mm)	C_d	E_r (%)	u_{rC_d} (%)	Q_v (Nm ³ /h)	Re_{in} ($\times 10^4$)	r
#1	0.9637	6.2260	5	0.5	0.9444	0.05	0.12	0.4926	1.26	0.4496
#2	1.1908	5.0386	5	0.5	0.9528	0.05	0.13	0.7588	1.57	0.5271
#3	1.3385	4.4826	5	0.5	0.9659	0.07	0.16	0.9669	1.76	0.5418
#4	1.9196	3.1257	5	0.5	0.9611	0.07	0.16	1.989	2.57	0.5507
#5	2.680	2.9851	5	0.5	0.9593	0.07	0.16	3.868	3.56	0.6254
#6	3.7974	2.0014	6	1	0.9761	0.07	0.15	7.905	5.11	0.6293
#7	5.3833	2.0434	6	1	0.9736	0.04	0.11	15.846	7.26	0.6623
#8	7.6325	1.9653	6	1	0.9893	0.06	0.14	32.368	10.5	0.6666
#9	10.759	2.0448	6	1	0.9878	0.04	0.11	64.217	14.8	0.6734

Tab.5 Simulation conditions of flow fields analysis in nozzles

Fluid	Ideal-gas
Turbulence model	Spalart-Allmaras, Strain/Vorticity- based production
Boundary conditions	Pressure-inlet, Pressure-outlet
Solver	Based on density, Steady
Flux type	Roe-FDS
Discretization	Second order upwind for flow, first order for turbulence viscosity
Monitors	Residual monitor, mass flow rate at the inlet and the outlet surfaces

Boundary layer	8 layers, first layer thickness 0.02~0.05, increasing factor 1.05
Total number of grid element	About 290 thousands, hexahedral

Tab.6 Discharge coefficients got from simulation

Throat diameter <i>d</i> mm	0.9637		1.1908	1.3385	1.9196	3.7974		5.3833	7.6325	10.759	
	ISO	CSDT	CSDT	CSDT	CSDT	ISO	CSDT	CSDT	CSDT	ISO	CSDT
Simulation C_d	0.9615	0.9491	0.9571	0.9655	0.9697	0.9844	0.9784	0.9828	0.9863	0.9891	0.9879
ISO Calculated C_d	0.9678	-	-	-	-	0.9832	-	-	-	0.9894	-
Calibrated C_d	-	0.9444	0.9528	0.9659	0.9611	-	0.9761	0.9736	0.9893	-	0.9878
Deviation %	-0.6510	0.4930	0.4513	-0.0414	0.8948	0.1221	0.2356	0.9449	0.3032	-0.0303	0.0101

Tab.7 Stabilities of the flow rate, the pressure and the temperature between integration intervals, as the facility is running in closed-loop mode

Flow rate (m ³ /h)	Stability of volume flow rate (%)	Stability of mass flow rate (%)	Pressure stability (%)	Temperature stability (%)
0.5	0.0012	0.0138	0.01438	0.0020
0.75	0.0027	0.0168	0.0194	0.0053
44	0.0042	0.0917	0.0956	0.0286
86	0.00144	0.06173	0.00288	0.01665
126.25	0.00528	0.08062	0.07484	0.01151

Tab.8 Stabilities of the flow rate, the pressure and the temperature within the integration interval as the facility is running in closed-loop mode

Flow rate (m ³ /h)	Stability of volume flow rate (%)	Stability of mass flow rate (%)	Pressure stability (%)	Temperature stability (%)
0.5	0.0053	0.0189	0.0246	0.0110
0.75	0.0003	0.0236	0.0235	0.0005
44	0.0083	0.0566	0.0647	0.0167
86	0.0010	0.0407	0.0405	0.0021
126.25	0.0096	0.0952	0.0942	0.0206

Tab.9 Stabilities of the flow rate, the temperature and the pressure between integration intervals as the facility is running in open-loop mode

Flow rate (m ³ /h)	Stability of volume flow rate (%)	Stability of mass flow rate (%)	Pressure stability (%)	Temperature stability (%)
0.5	0.0056	0.0138	0.0092	0.0112
0.75	0.0010	0.0026	0.0031	0.0018
44	0.0052	0.4603	0.4644	0.0093
86	0.0024	0.4156	0.4123	0.0057
126.25	0.0040	1.2199	1.2213	0.0054

Tab.10 Stabilities of the flow rate, the temperature and the pressure within the integration interval as the facility is running in open-loop mode

Flow rate (m ³ /h)	Stability of volume flow rate (%)	Stability of mass flow rate (%)	Pressure stability (%)	Temperature stability (%)
0.5	0.0052	0.0136	0.0123	0.0070
0.75	0.0054	0.0149	0.0143	0.0091
44	0.0003	0.0152	0.0150	0.0009
86	0.0073	0.6365	0.5379	0.0134
126.25	0.0065	0.8123	0.6838	0.0116

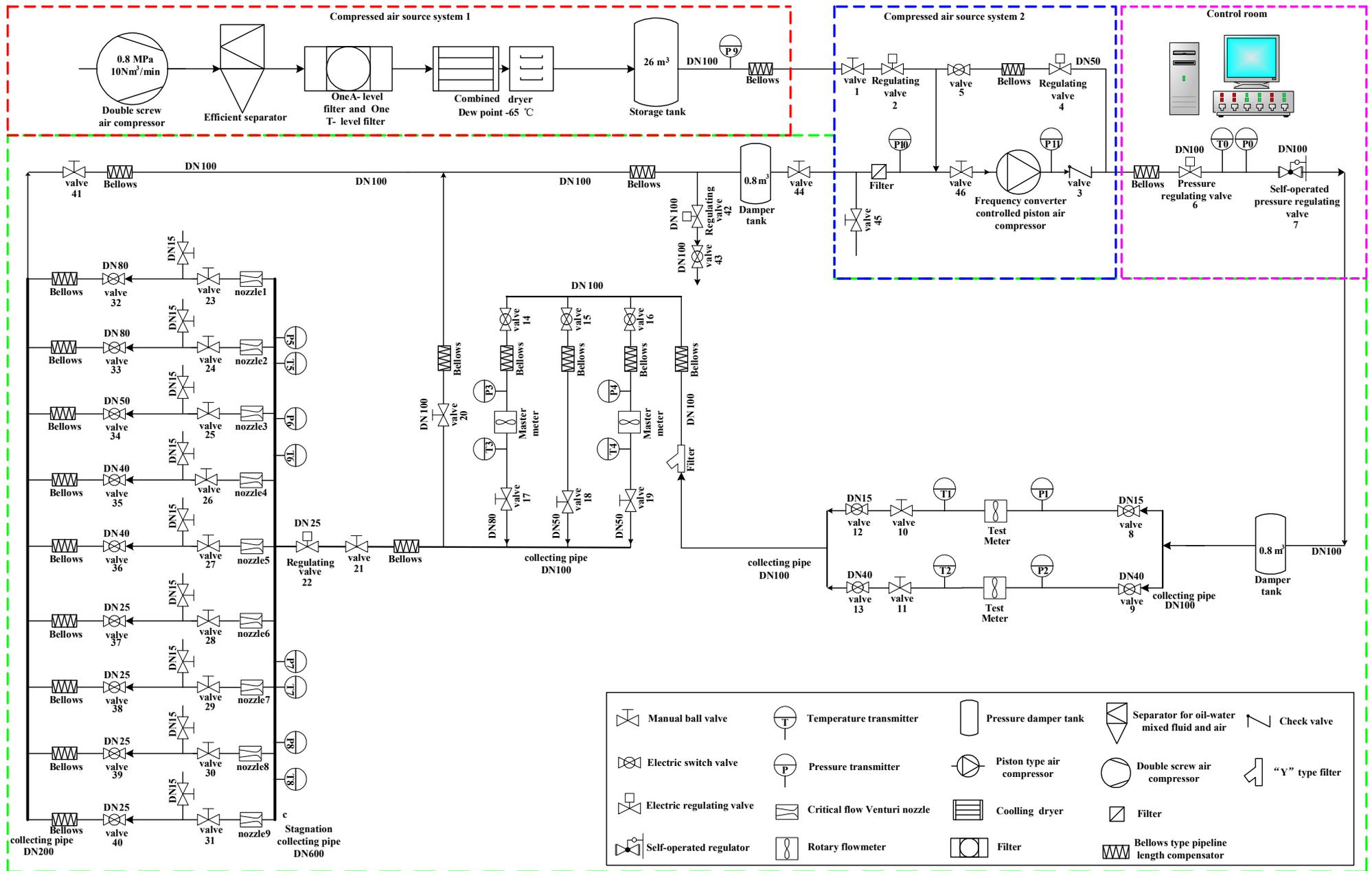


Fig. 1 Flow loop of the Critical flow sonic Nozzles gas flow facility with medium-pressure and Closed-Loop pipeline (CNCL)



Fig. 2 Photos of the Critical flow sonic Nozzles gas flow facility with medium-pressure and Closed-Loop pipeline (CNCL)

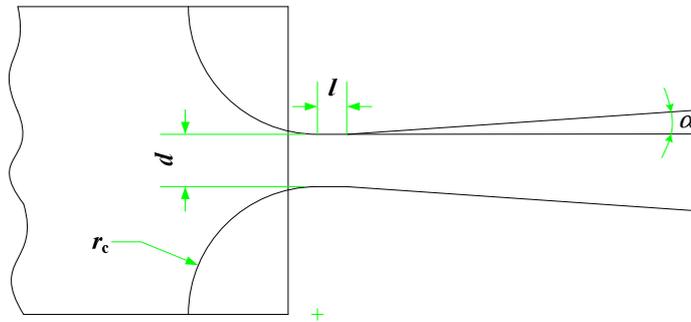


Fig. 3 Shape of nozzle with Cylindrical Stage Downstream the Throat (CSDT)

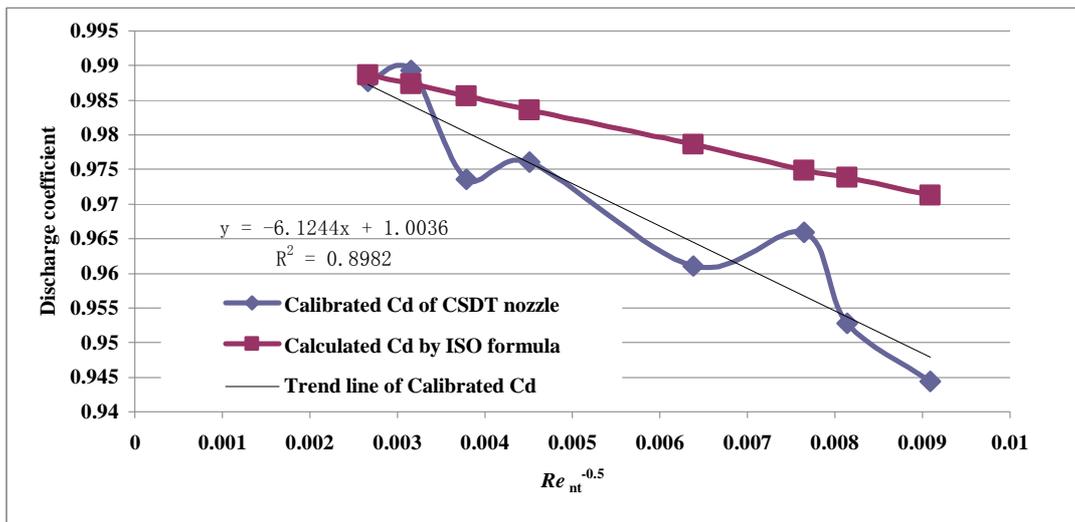


Fig. 4 Discharge coefficients of CSDT nozzles and ISO toroidal-throat Venturi nozzles

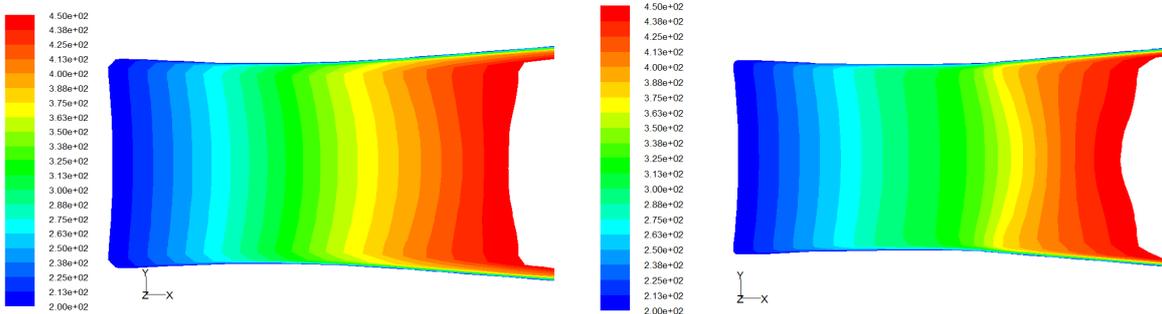
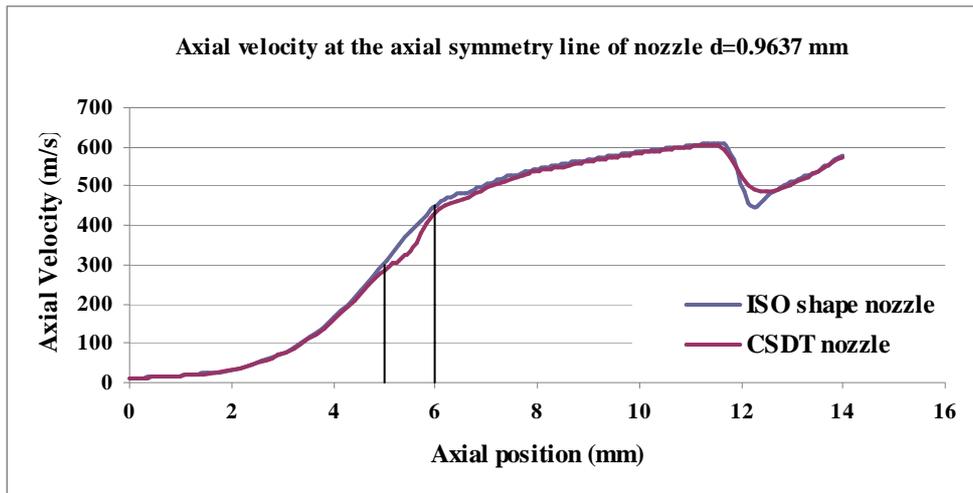


Fig 5 Velocity distribution of nozzles ($d=0.9637$ mm)

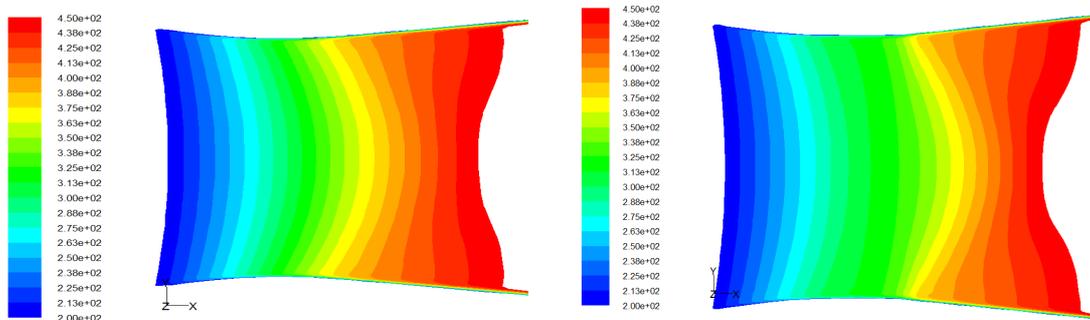
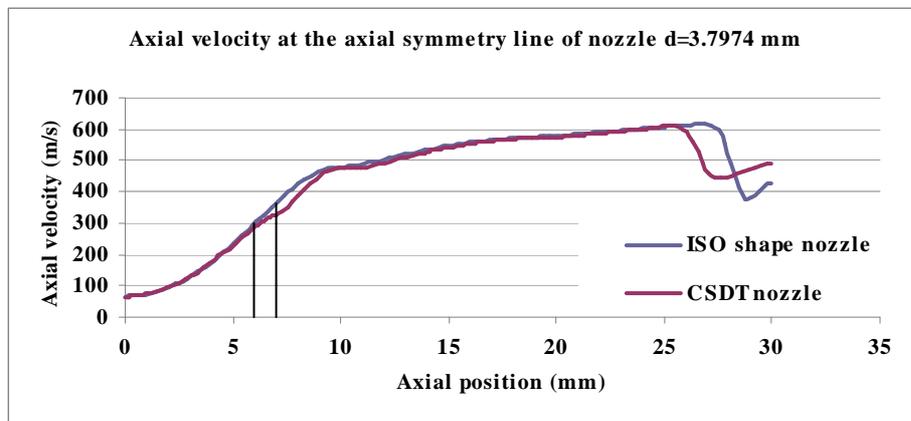
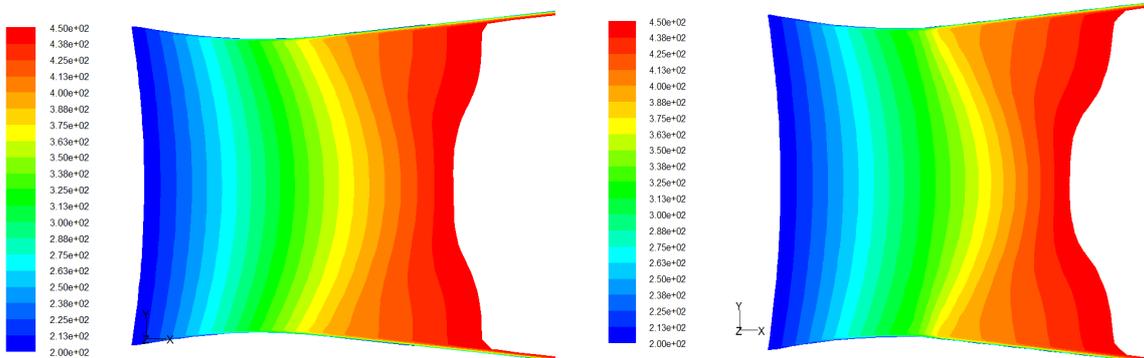
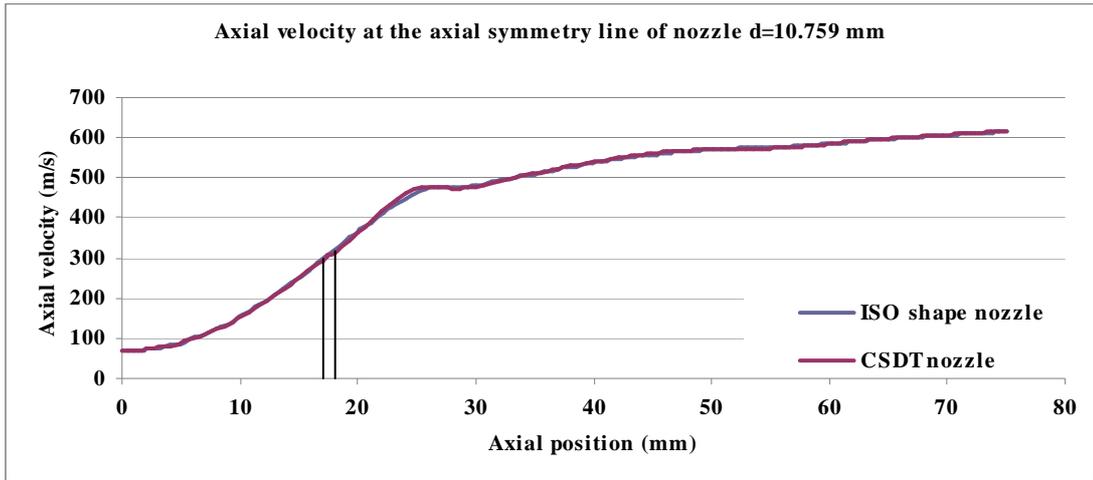


Fig 6 Velocity distribution of nozzles ($d=3.7974$ mm)



Velocity magnitude near the throat of ISO shape nozzle Velocity magnitude near the throat of CSDT nozzle
 Fig 7 Velocity distribution of nozzles ($d=10.759\text{mm}$)

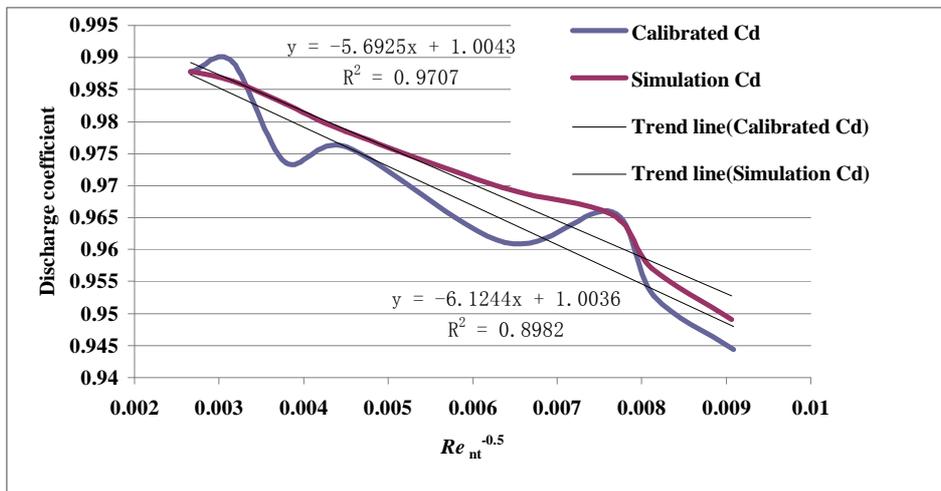


Fig. 8 Discharge coefficients of CSDT nozzles got by calibration and simulation

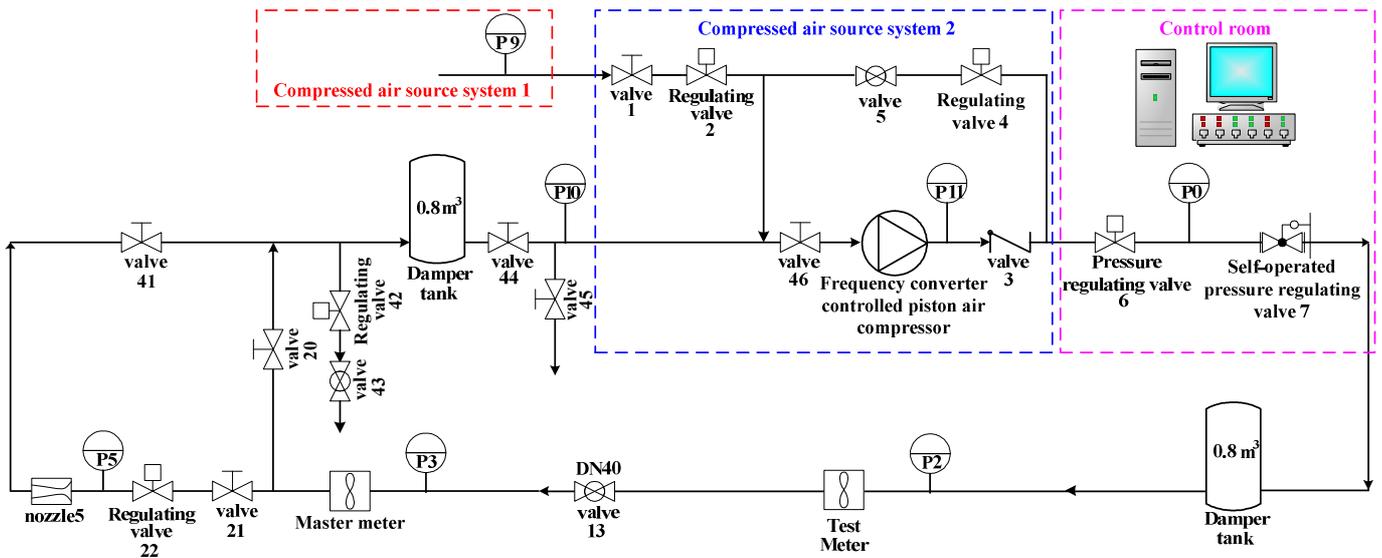


Fig. 9 Brief flow loop for the pressure and the flow rate control

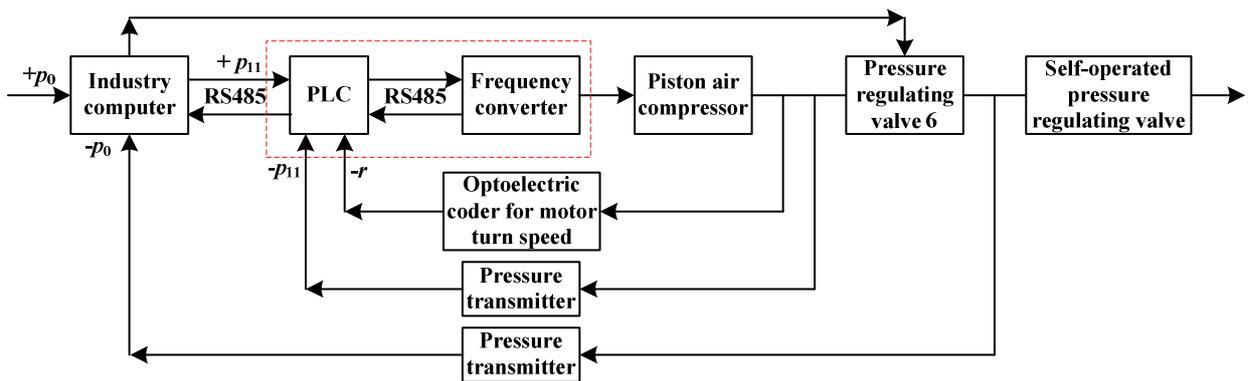


Fig. 10 Control strategy for the pressure regulation and flow rate stability control