Research on Temperature Control Technology of high-Pressure Loop Gas Flow Standard Facility

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Abstract

The high-pressure loop gas flow standard facility (hereinafter referred to as the facility) is a working measurement standard[1] for gas flowmeters to perform measurement performance tests under different pressures. It can study and improve the measurement performance of flowmeters under different pressures and different gas media, which is of great significance to the research of flow measurement technology. This paper studies the temperature control technology of the facility, the purpose is to make the temperature meet the working requirements of the facility and as close as possible to the existing international advanced level. Through theoretical analysis and experimental methods, combined with the author's company and the experience of external construction facilities, this paper designs an intelligent control system including its various subsystems, and realizes the design requirement that the temperature change of the facility's working gas is not greater than ±0.1 ℃/min. This paper shares the construction experience, and proposes a technical route for further improvement by using advanced control methods such as fuzzy control and neural network control to reach the existing international excellent level of ±0.05 °C/min.

Keywords: high-pressure loop; gas flow standard facility; temperature control; intelligent control; heat exchanger

1. Introduction

The high-pressure loop gas flow standard facility is a working measurement standard for verifying, calibrating or testing the flowmeter under test (MUT) with standard meter(s) in a closed loop pipeline with a stable pressure and temperature of the gas medium. The test gases include natural gas, air, carbon dioxide, etc. With the increasing application of hydrogen energy under the trend of carbon emission reduction, a facility design that mixes a certain proportion of hydrogen with natural gas as a test medium has emerged. According to incomplete statistics[2], there are currently about 6 sets of facilities using natural gas as the medium in the world; about 2 sets of facilities using carbon dioxide as the medium; about 2 sets using nitrogen as the medium; no less than 10 sets using air as the medium. At present, the comparison table of the main technical indicators of some high-pressure loop gas flow standard facilities in various countries in the world is shown in Table 1. Figure 1 shows the main loop part of the high-pressure loop facility of Tancy Instrument Group Co., Ltd. The flowmeter to be tested may include gas ultrasonic flowmeter, gas turbine flowmeter, gas rotary flowmeter, gas vortex flowmeter, gas differential pressure flowmeter, and the like.

The main components of the high-pressure loop gas flow standard facility are: the gas source part, the power part, the pressure regulating system, the heat exchange system, and the loop part. The PI&D(pipe instrument and diaphragm) and schematic diagram of the facility are shown in Figure 2 and Figure 3. At present, the design working pressure of the air medium facility is generally not more than 4.0 MPa. When the facility is working, the temperature of the working medium will increase due to the heat caused by the operation of the blower and the heat generated by the fluid flow and the friction of the pipeline. Studies have shown that when the working pressure is 600 kPa, 1 500 kPa, and 2 500 kPa at a flow rate of 80 m^3/h, the maximum temperature difference of the medium is 4.42 ℃, 6.55 ℃, and 5.65 ℃ in the first 12 minutes of the facility operation. After that, the temperature changes relatively slowly, but it is still not conducive to the accuracy of the test results[6].

This facility keeps the working medium at the set temperature through the automatic control system of the heat exchanger (hereinafter referred to as the "heat exchange system"). Through theory and practice, the heat exchange system studied in this paper realizes that the temperature change is not greater than ±0.1 ℃/min within a certain pressure range and flow rate range, and the verification period meets the Chinese flowmeter verification regulations JJG 1030[7], JJG 1037[8] and other regulations stipulate that the temperature change should not be greater than ±0.5 °C, which meets the requirements of verification, calibration and testing.

Figure 1: The main loop of the facility of Tancy Instrument Group Co., Ltd..

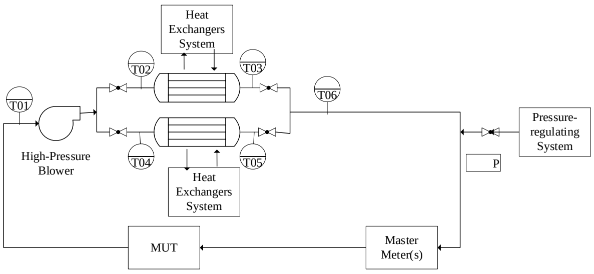

Figure 2: PI&D of the facility.

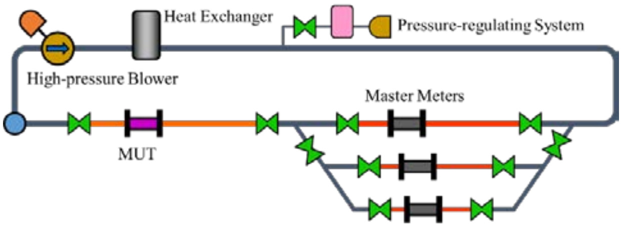

Figure 3: Schematic diagram of the facility.

Table 1: Comparison table of main technical indicators of some international high-pressure loop gas flow standard facility.

Technical indicators	SWRI GRI high pressure Loop, U.S. [4]	SWRI GRI low pressure Loop, U.S.[4]	European Gas Loop[4]	FORCE Gas Loop, Denmark[5]	RMA Loop, Germany[5]	Chengdu Loop, China[5]	Terasen Loop, Canada[4]	National Institute of Metrology Loop, China[2]	Institute of Metrology of Hebei Province Loop, China	Tancy Instrument Group Co., Ltd. Loop, China	Denmark MEGA Loop[3]
q_{max} or flow range/(m^3•h^{-1})	2 379	906	30 000	41 000	13 000	16～4 000	6 800	40～1 400	16～7 500	20～2 500	6500
Working pressure/MPa	1.035～8.275	0.14～1.45	0.1～6.5	0.3～ 6.5	0.1～ 5.0	0.3～ 6.0	0～1.655	0.19～ 2.5	1.8～4.0	0.2～ 2.0	6.5
Pressure stability/(kPa•min^{-1})			≤±0.5		≤±2	≤±2 kPa •(6 min)$^{-1}$	≤±0.5	≤±0.5	≤±0.5	≤±0.5	
Working temperature/℃	4.44～48.89	4.44～48.8	5～35	15～25	5～35	5～30	5～40		5～35	5～35	
Temperature stability/(℃•min^{-1})	≤±1	≤±1	≤±0.05		≤±0.2	≤±0.2 ℃ •(6 min)$^{-1}$	≤±0.5	≤±0.1		≤±0.1	
The diameter of the MUT	DN50～DN500	DN25～DN200	DN50～DN750	DN50～DN1250	DN50～DN400	DN50～DN250	DN50～DN300	DN50～DN200	DN50～DN300	DN25～DN200	DN1500 (60")
Uncertainty (k=2)/%	0.20～0.25	0.20～0.25	0.15	0.18～0.30	0.23～0.29	0.29	0.27	0.16	0.30; 0.35(< 40 m^3/h)	0.33	
Test medium	natural gas or nitrogen	natural gas or nitrogen	natural gas, air, carbon dioxide	natural gas, air	natural gas	natural gas	carbon dioxide	air	air	air	with up to 25% hydrogen in natural gas
Build time	1994	1994	2011	2015	2015	2018	early 21st century	2014	2018	2014	To be completed by May 1, 2023

2. Heat Exchanger Selection Calculation

2.1 Selection of heat exchangers

It has been mentioned above that the main reason for the temperature change in the facility is the working temperature rise of the blower. Considering the effect of controlling the temperature balance, a heat exchanger is installed in the facility loop path immediately downstream of the blower. The gas flow channel and water flow channel of the heat exchanger are shown in Figure 4. According to the heat balance equation (without considering the fouling coefficient for the time being)[9][10], there will be

$$\emptyset = q_{m1}c_{pm1}\left(T'_{f1} - T''_{f1}\right)\varphi = q_{m2}c_{pm2}\left(T''_{f2} - T'_{f2}\right) \quad (1)$$

Where: $\emptyset$—heat exchange of heat exchanger; q_m—mass flow rate of heat carrier; c_{pm}—average specific heat capacity of heat carrier at constant pressure; φ—heat dissipation coefficient, generally 0.97～0.995; T_f—fluid temperature.

Angle mark: 1 represents the gas in the loop, 2 represents the water in the heat exchange tube of the heat exchanger; ' represents the inlet, ” represents the outlet.

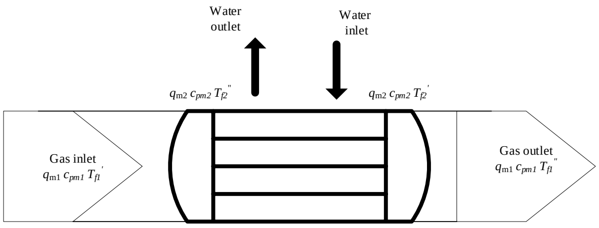

Figure 4: Schematic diagram of heat exchange treatment of the facility

Taking the facility of Tancy Instrument Group Co., Ltd. as an example, the length of the loop is about 70 m, the maximum average diameter of pipe is 200 mm, p_{max} =2.0 MPa, q_{max} =2500 m^3/h, according to the ideal gas equation of state, $q_{m,max}$ can be obtained About 18 kg/s. Assuming that the difference between the inlet temperature and the outlet temperature of the heat exchanger is $T'_{f1} - T''_{f1} = 7$ °C , and the outlet temperature of the heat exchanger is $T''_{f1} = 20$ °C, look up the table to get $c_{pm1} = 1009$ J/(kg · K)[9], according to the formula (1) The heat exchange power of the facility is calculated as $\emptyset = 127$ kW.

Considering that the working flow of most of the tested flowmeters does not exceed 800 m^3/h, for energy saving and economic considerations, two heat exchangers are designed to work in parallel, and their heat exchange power is 45 kW and 90 kW respectively, which can meet the calculated Maximum heat exchange requirement.

The facility adopts a shell-and-tube heat exchanger[10][11][12], which is composed of a tube bundle and a shell, and the tube bundle is fixed in the shell by a tube sheet. The water flows in the tube, and the gaseous medium flows in the tube shell. Under the same temperature conditions, the average temperature difference is the largest in countercurrent, so the water flow direction and the gas flow direction are nearly opposite, as shown in Figure 4.

2.2 Heat exchange tube water flowrate and water temperature calculation

According to formula (1), it is necessary to control the q_{m2}, T''_{f2}, T'_{f2} of the heat exchanger water pipe to meet the balance requirement of heat exchange with gas, c_{pm} is a parameter related to temperature, and the value is shown in Table 2.

Table 2: Constant pressure average specific heat capacity c_{pm} table of water

Temperature/℃	10	20	30	40
$c_{pm}/(J \cdot k_g^{-1} \cdot K^{-1})$	4191	4183	4178	4178

Two temperature buffer tanks (low temperature water storage tanks) are set up in the heat exchange system, and tank 1 and tank 2 are named according to the direction of flow to the heat exchanger, as shown in Figure 5. The temperature of tank 1 is 5 ℃～8 ℃ (the lower limit of the temperature can be lower depending on the capacity of the chiller), the temperature of tank 2 is 8 ℃±0.1 ℃, and part of the return water mixed with the effluent of tank 2 goes to the inlet of the heat exchanger is about 10 ℃.

For 45 kW heat exchange water pipe, assuming that the nominal diameter of the water pipe is DN50, $q_{m2} = 3\ \mathrm{kg/s} = 10.8\ \mathrm{m^3/h}$, and the inlet temperature of the water pipe is T'_{f2}=10 ℃, it can be calculated according to formula (1). At 45 kW, $T''_{f2} = \frac{\emptyset}{q_{m2} \times c_{pm2}} + T'_{f2}$=13.58 ℃.

In the same way, for 90 kW heat exchange water pipe, at the same q_{m2}=3 kg/s, T''_{f2}=17.16 ℃. And if the 45 kW water outlet pipe is kept at the maximum heat exchange power, the same temperature of the water outlet pipe is T''_{f2}=13.58 °C, it is only necessary to adjust the flow rate in the 90 kW heat exchange water pipe to $q_{m2} = 6\ \mathrm{kg/s} = 21.6\ \mathrm{m^3/h}$, which is easy to achieve.

According to the heat transfer requirements, the heat transfer equation is used to calculate the results, and the heat exchange tube material and the required number of tube passes can be selected[9][10].

3. Design of Automatic Control Heat Exchange System

3.1 Composition and principle of heat exchange system

The heat exchange system we expect is a typical constant value control system, which requires the controlled quantity - the operating temperature of the loop to be equal to a constant value. The basic requirements for the system include stability, speed and accuracy. According to the requirements, the main components of the heat exchange system are: heat exchanger, inlet/outlet pipe, three-way regulating valve, flow meter, temperature buffer tanks, frequency conversion control water pump, chiller, etc., and are divided into 4 main parts according to the control sequence. The main parts (subsystems): 1) High-pressure blower heat exchange subsystem; 2) Temperature buffer tank temperature control subsystem: The output of the second stage temperature buffer tank (tank 2) is accurately controlled to (8±0.1) °C; 3) 45 kW heat exchanger subsystem; 4) 90 kW heat exchanger subsystem. The principle block diagram of the heat exchange system is shown in Figure 5.

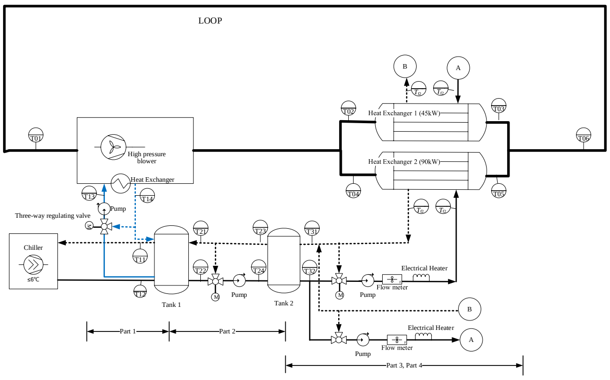

Figure 5: Principle block diagram of heat exchange system

The main working process of the system is:

1) The chiller provides water with a low temperature not higher than 5 °C and flows to the tank 1; the temperature of the water in the tank 1 is affected by the reflux heat exchange, and the temperature variation range is 6 °C to 8 °C;

2) One outlet of the tank 1 flows to the heat exchanger of the high-pressure blower, and the high-pressure blower heat exchange subsystem controls the temperature rise of the blower.

3) The other outlet of the tank 1 flows to the tank 2, and the temperature value of the output tank 2 is 8 °C±0.1 °C through the temperature buffer tank temperature control subsystem;

4) Through the 45/90 kW heat exchanger subsystem, control the opening of the three-way control valve according to the predetermined mathematical model, and use the water pump to fine-tune the correction; when the maximum value of the mixed water temperature of the inlet pipe cannot meet the working temperature requirements of the loop gas, control the electrical heater is turned on to increase the temperature of the inlet water, so that the temperature of the working gas in the loop can meet the requirements.

The function of the temperature buffer tank in the control system is to store more capacity of low temperature water, which is the key to the stability of the system and the "energy storage element" of the system. There is a time course for the temperature to return to the desired value. In the control process, when the gas temperature value of the controlled variable loop has returned to the expected value and the deviation is zero, the execution should stop working immediately, but due to the inertia of the system, the control action continues to proceed in the original direction, resulting in a symbol exceeding the expected value. The opposite deviation (overshoot) is repeated in this way. The gas temperature of the controlled variable loop swings back and forth near the expected value. The transition process presents an oscillation form and gradually weakens[13]. Finally, the equilibrium is reached, and the purpose of achieving a constant temperature is expected, and an ideal control is expected. The results are shown in Figure 6. In addition, the temperature buffer tank is also designed with functions such as automatic exhaust gas at the top and sewage at the bottom.

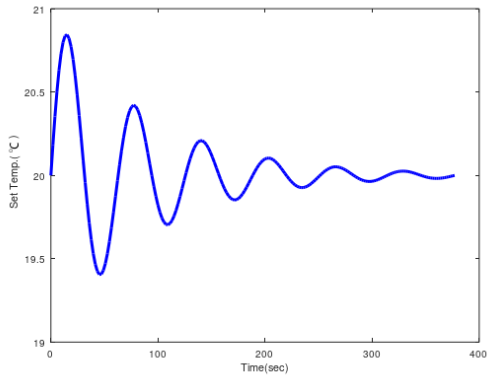

Figure 6: Schematic diagram of the stability of the control system

3.2 High-pressure blower heat exchange subsystem (Part1)

From the tank 1 to the heat exchanger tube in the blower (controlling the water pump), it is used to cool the temperature rise of the blower when it is working, so that the temperature of the gas flowing out of the blower and the temperature rise of the blower meet the requirements, see Figure 7 Block diagram of the control system.

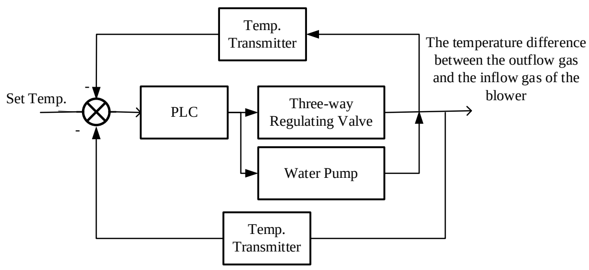

Figure 7: Block diagram of high-pressure blower heat exchange subsystem

3.3 Temperature Buffer Tank Temperature Control Subsystem (Part 2)

The water flows from the tank 1 (6 ℃～8 ℃) to the tank 2, the return water from the tank 2 to the tank 1 is mixed with the return water from the 45/90 kW heat exchanger, and the water pump is fine-tuned by adjusting the three-way regulating valve correction, control tank 2 outlet water temperature is (8±0.1) ℃. See Figure 8 for the block diagram of the control system.

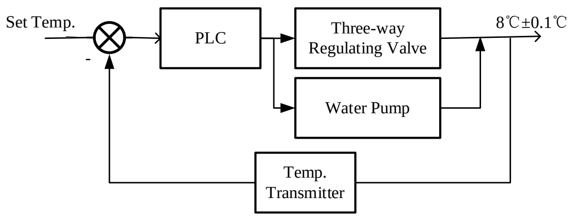

Figure 8: Block diagram of temperature control subsystem of temperature buffer tank

3.4 Heat Exchanger (45 kW, 90 kW) Subsystem (Part 3, Part 4)

Using temperature negative feedback, if the gas outlet temperature is too high, the three-way regulating valve will be closed, increasing the temperature difference of the exchanger, increasing the heat exchange, and reducing the gas outlet temperature; if the outlet temperature is low, the three-way regulating valve will be enlarged. Reduce the temperature difference between the water inlet and outlet of the exchanger, reduce the heat exchange, and increase the temperature of the gas outlet; control the pump to fine-tune the temperature. When the three-way regulating valve is fully opened and the gas outlet temperature is lower than the ambient temperature, the electric heater is controlled for temperature compensation. The working principle of the 45 kW subsystem is the same as that of the 90 kW. The block diagram of the control system is shown in Figure 9.

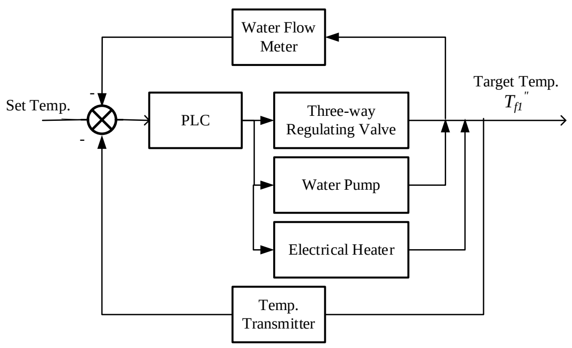

Figure 9: Block diagram of heat exchange system

3.5 Heat exchange system control method

A temperature transmitter is installed about 5 m downstream of the heat exchanger, and the detected temperature value is used as the controlled object, so that the temperature change is less than or equal to ±0.1 °C to meet the requirements.

The system controller adopts PLC, and uses the PID control algorithm that comes with PLC to control each temperature control subsystem.

With the rapid development of computing technology and the wide application of computers, the optimization theory and control theory of dynamic systems are further developed. On the basis of conventional PID control, we are still seeking better control technologies, such as fuzzy adaptive PID[14], Smith predicts fuzzy PID[15], neural network control, etc. to improve the performance of the existing control system, and it is expected to improve the temperature control accuracy to ±0.05 ℃, reaching the international advanced level of similar products.

The working flow chart of the heat exchange subsystem is shown in Figure 10.

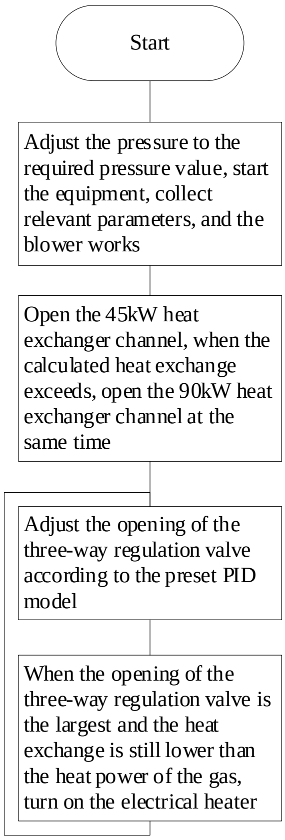

Figure 10: Workflow of Heat Exchanger Subsystem

4. Field measured data

After the system is completed, after a period of verification, the temperature is generally stable within 10 min to 20 min, and the temperature change meets the expected requirements and does not exceed ±0.1 °C. Figure 11 shows the data of the flow rate of 80 m^3/h, the pressure of 1.6 MPa, and the monitoring duration of 60 min. The oscillation attenuation trend is consistent with the aforementioned Figure 6. Figure 12 is the test result report during routine work, and the results all confirm that the temperature control effect meets the requirements.

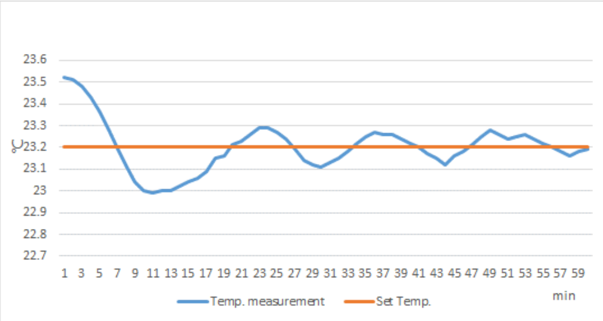

Figure 11: Set temperature value and measured temperature value

5. Conclusion

(1) The temperature rise caused by gas flow friction is much smaller than the working temperature rise of the high-pressure blower. The facility mainly solves the problem of the working temperature rise of the blower, so the heat exchanger is installed on the downstream side of the blower.

(2) In terms of control algorithm, fuzzy adaptive PID algorithm, Smith prediction fuzzy PID and neural network control algorithm can be further studied to improve temperature control accuracy and reduce energy consumption.

(3) The metal pipes and components of the facility, as well as the pipes and components of the heat exchange system, are wrapped with thermal insulation materials to reduce the influence of the ambient temperature on the temperature of the test medium. If the ambient temperature of the facility is relatively stable, and the ambient temperature also meets the test requirements, the ambient temperature is generally set as the target temperature for the control of the heat exchange system.

(4) The temperature buffer tank should be as large as possible. The second-level temperature buffer tank is the basis and guarantee for accurate control of the temperature of the loop and system stability.

(5) The ambient temperature of the pressure-regulating system should be the same as that of the main loop as much as possible to avoid large fluctuations in the gas temperature during the process of pressure regulation and gas supply in the loop channel.

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FLOMEKO 2022

TANCY 天信

High pressure calibration facility — Test Report of Turbine Flowmeter

Customer:	TANCY	Meter type:	Turbine	DN[mm]:	100	Certificate:	3041
Manufacturer:	TANCY	Model:	TQBM-G400-DN100	PN:	ANSI600	TestMedium:	Air
Flowrating:	(32.5-650)[m3/h]	Number:	004201	G-rating:	400	Regulation:	JJG1037-2008
		Accuracy:	1.0			Date[DD-MM-YYYY]:	17-06-2021

No.	Fs (m3/h)	Ps (kPa(a))	Ts (℃)	Time (s)	Fm (m3/h)	Vm (m3)	Pulse	Pm (kPa(a))	Tm (℃)	Reynolds	K (1/m3)	Avg K (1/m3)	El (%)	Er (%)
3	32.4477	213.51	23.85	60.985	32.3508	0.548	7371	213.31	23.98	15558	13409.848	13409.982	0.114	0.035
	32.4273	213.46	23.86	60.998	32.3260	0.548	7367	213.26	23.97	15550	13407.997			
	32.4411	213.44	23.86	60.994	32.3413	0.548	7370	213.24	23.96	15551	13408.648			
	32.3638	213.44	23.86	60.995	32.2707	0.547	7354	213.24	23.96	15523	13411.302			
	32.3967	213.44	23.86	61.002	32.3067	0.547	7363	213.24	23.96	15535	13412.641			
	32.3980	213.44	23.87	60.997	32.3003	0.547	7361	213.24	23.95	15535	13409.457			
6	161.2690	213.64	24.11	61.000	161.1180	2.730	36719	213.22	23.99	77453	13437.407	13437.505	0.320	0.008
	161.3072	213.64	24.12	60.999	161.1589	2.731	36728	213.23	24.00	77474	13437.631			
	161.2633	213.65	24.13	61.000	161.1158	2.730	36719	213.23	24.00	77470	13437.698			
	161.3241	213.65	24.14	61.001	161.1793	2.731	36734	213.23	24.00	77497	13437.932			
	161.3178	213.65	24.15	61.000	161.1597	2.731	36729	213.23	24.00	77483	13436.821			
	161.3392	213.65	24.17	61.001	161.1897	2.731	36736	213.23	24.01	77493	13437.542			
6	261.1755	213.60	24.01	60.999	260.6855	4.417	59410	212.46	24.01	124861	13424.764	13425.564	0.230	0.008
	261.1813	213.60	24.01	61.000	260.7031	4.417	59415	212.46	23.99	124895	13425.373			
	261.1147	213.60	24.02	61.001	260.6468	4.417	59403	212.46	23.99	124864	13425.898			
	261.1833	213.60	24.02	61.001	260.7131	4.418	59418	212.46	23.98	124890	13425.788			
	261.1585	213.60	24.03	61.001	260.6899	4.417	59413	212.46	23.98	124897	13425.865			

Coefficient:	13394.709[1/m3]	Boundary Flow Qt:	20% of Qmax		
MediumPressure:	206.74 [kPa(a)]	K-factor :	13450.000[1/m3]		
Atmospheric	100.74 [kPa(a)]	Weighted avg error:	0.072[%]		
Medium Temp.:	23.55[℃]	<Qt El:	0.114[%]	<Qt Er:	0.035[%]
Humidity:	47.00[%]	≥Qt El:	0.320[%]	≥Qt Er:	0.054[%]

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Figure 12: The testing report of the result