The control system of a 2kW@20K helium refrigerator

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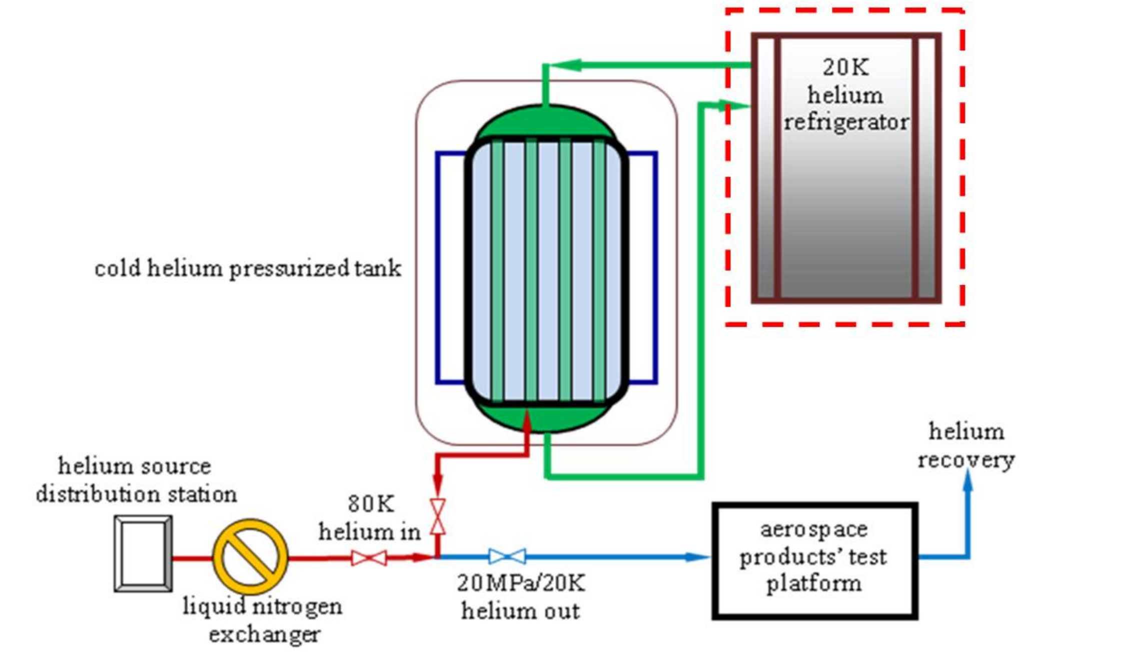
Review

At present, in our aerospace field, the system-level test platform of pressurization transport only has the capability of system tests in liquid nitrogen temperature area. It does not meet actual conditions of the cold helium pressurization system on the rocket, and also can not simulate some key characteristics, such as system's start impact, magnetic valves' temperature drop, and so on. So it is very necessary to extend the platform's test capability to liquid hydrogen temperature area. In the past, we usually used the way of soaking in liquid hydrogen to cool the helium to 20K, and then finished tests in liquid hydrogen temperature area. But hydrogen belongs to flammable and explosive medium, so tests are very difficult to be controlled, and have very high risk. It's almost impossible to test the vibration environment in this way.

After years of research, a 2kW@20K helium refrigerator has developed by Technical Institute of Physics and Chemistry, Chinese Academy of Sciences. Using this helium refrigerator as a cold source does not need hydrogen medium, and has much higher safety. It can also satisfy large flow experimental studies of the pressurization system, and realize the coupling of cryogenic and vibratory environment, so that better reflect the real work situation on the rocket. It enables the pressurization system to have the capability of hydrogen temperature area and high pressure system experiments, and also enhances the authenticity and coverage of the experiments.



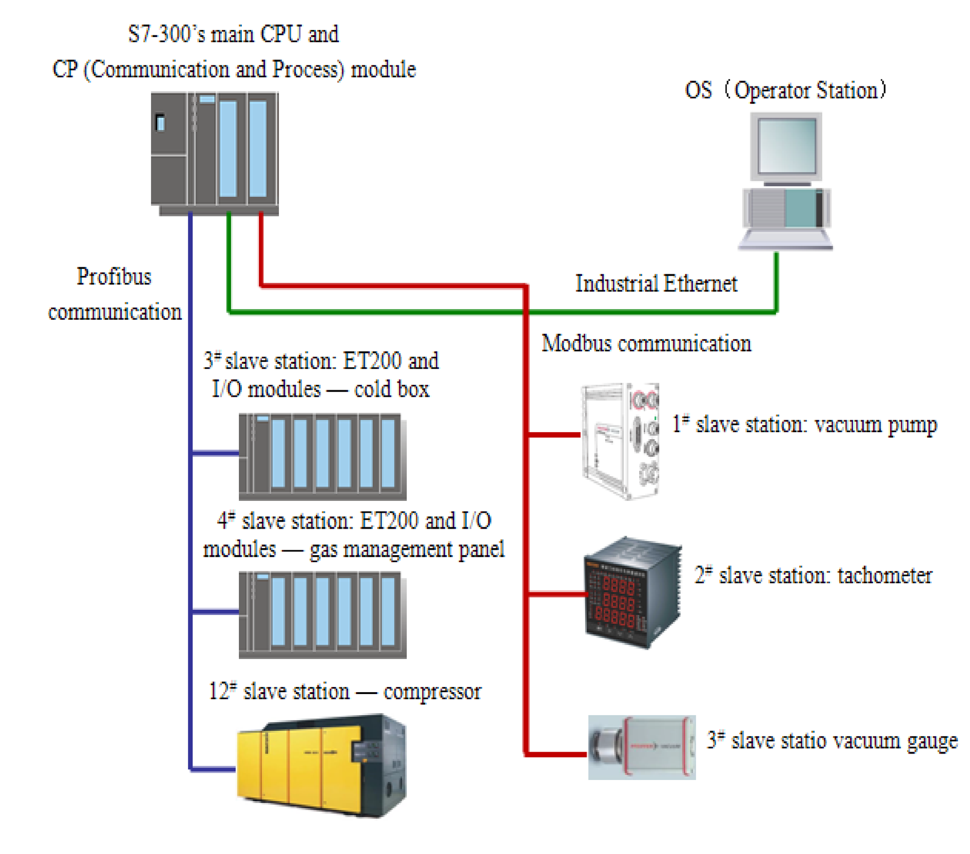
The principle diagram of new aerospace products' performance test platform in liquid hydrogen temperature area with 2kW@20K helium refrigerator

◆First, the high-pressure helium from the helium distribution station comes through the liquid nitrogen exchanger, and is cooled to be 80K.

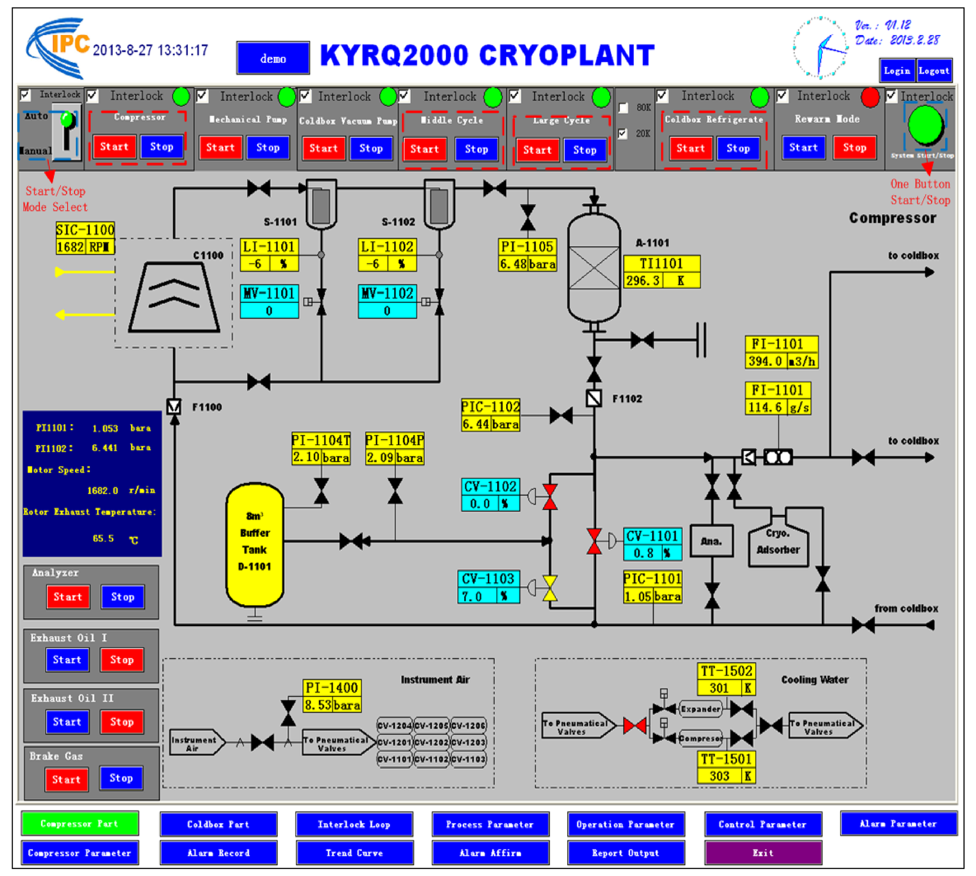
◆Then the 80K helium is injected into the pressurized tank to be further cooled and pressurized. Cold helium from the 20K helium refrigerator exchanges heat with the injected helium inside the pressurized tank through its shell and tube heat exchanger, then returns to the helium refrigerator after heating up. In this way, the helium in the pressurized tank is constantly cooled, pressurized and cooled again.

◆Finally, the helium reaches the temperature of 20K and pressure of 20MPa, and the system is kept stable by the cooling capacity of the helium refrigerator.

General introduction of the control system of 20K helium refrigerator



Structure diagram of 2kW@20K helium refrigerator's control system



The human and machine interface of the refrigerator made by WinCC V6.2

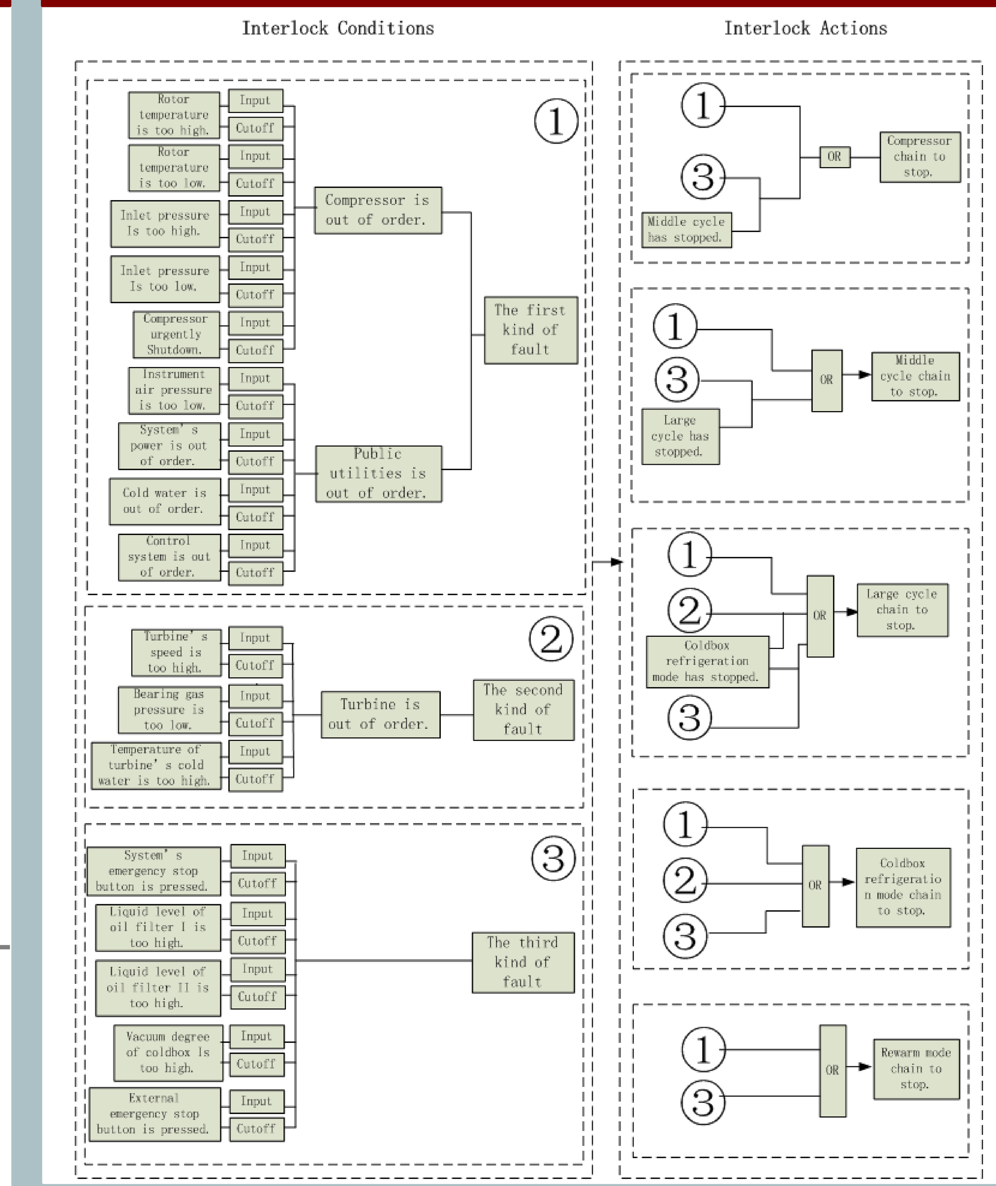
For a refrigerator applied in aerospace field, to realize its equipments unmanned monitored, temperature precise controlled stable and fast interlock responding to accidents to ensure the system's security, is the main factor to proof its stability and reliability during its running. And all of these need to be realized by the control system.

The process control system of 2kW@20K helium refrigerator uses PLC S7-300 with its matching programming and configuration software Step7, and industrial monitoring software WinCC. It is dual-CPU redundant configured, and uses Profibus as its system bus and distributed I/O ET200M as its extension mode.

◆On the hardware, uses one PLC main frame and three PLC slave stations (3#, 4# and 12# stations), two ET200 distributed I/O and I/O modules, one host computer operating station, and so on. The slave computer uses S7-300 PLC control system, and uses CPU315-2PN/DP as its central process unit. According to the requirement of I/O points, the system uses the form of two distributed I/O and Profibus (field bus) communication to extend I/O modules, which can support the extension of 16 modules at most. The communication between the slave computer and the operator station (host computer) is depending on Industrial Ethernet. The vacuum pump, tachometer and vacuum meter in the system use Modbus to communicate with the slave computer, through the CP communication module on the PLC main frame. This makes the system compatible with more communication modes.

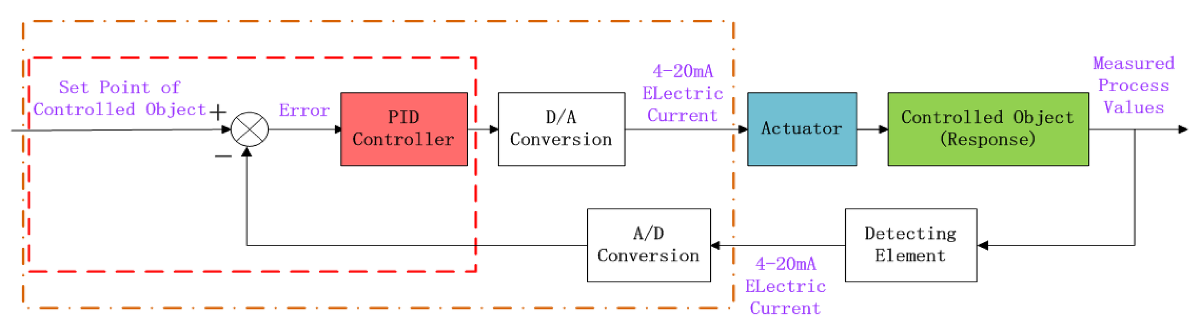
◆On the software, uses Step7 V5.4 as slave computer programming software, and WinCC V6.2 as host computer process monitoring software. Functions of the slave computer include hardware configuration, logic programming and communication configuration. The host computer is used for configuring the system flow chart screen, parameter display screen, PID control screen, trend curve screen and alarm screen. And it can also confirm alarms, record events and print reports.

Fault protection interlock strategy of the refrigerator



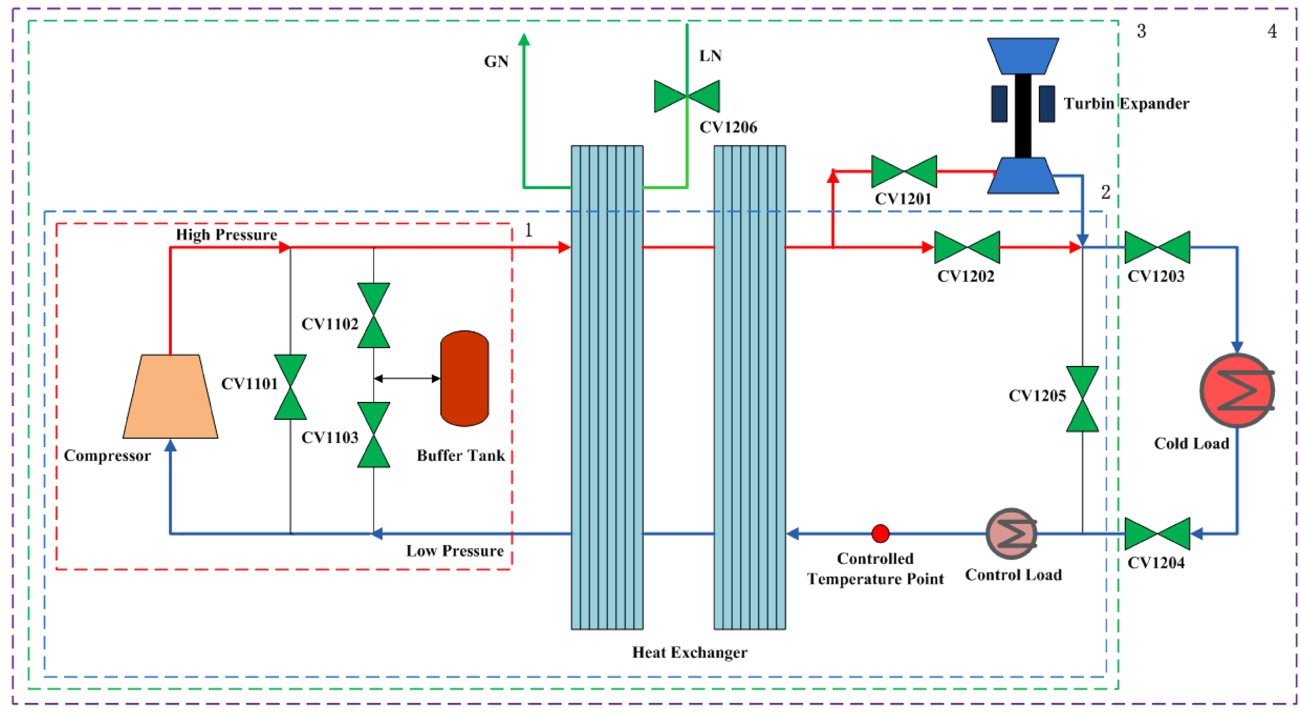
This control system has established comprehensive and effective interlock protection measures. According to the experiences of similar equipments at home and abroad and also the needs of users, we divide system's interlocks into three categories. When each type of interlock faults occurs, the system will respond different equipment responses in its need. This can fully ensure the safety of the system, and realize the safety guarantee of the unmanned operation. In system's "manual" mode, we can input or cutoff each mode and equipment interlock independently anytime we need. And in system's "auto" mode, all the mode and equipment interlocks is automatically input or cutoff in a certain order, which realizes one-button start and stop of the system.

Structure Principle Diagram of PID Control Loops



The small box encloses the part performed by digital PID controllers, and the big box encloses the part performed by S7-300 PLC. When the controlled object deviates from its set point, the PID controller will calculate a movement using PID control algorithm to cause actuator acting for adjusting the controlled object close to its set point value.

Sequence control strategy for the refrigerator's one-button start and stop



Two alternative modes to start and stop the refrigerator: In "manual" mode, all the parts can be manual started and stopped independently through their own "start" and "stop" button; In "auto" mode, the entire system can be started and stopped automatically just through one button — "system start and stop" button.
The refrigerator's automatical start order is: compressor→middle cycle→clodbox refrigeration→large cycle; and its automatical stop order is: clodbox refrigeration→large cycle→middle cycle→compressor.

In order to meet the needs of different stages of the experiment, and also to operate the refrigerator in a better order, we divide the system into four modes.

1. Compressor mode. The compressor and three control valves (CV1101, CV1102, CV1103) in the gas management panel act, and makes system's high and low pressure reach to the set value and remain stable.
2. Middle cycle mode. Turbine's bypass valve (CV1202) and cold load's bypass valve (CV1205) act, on the base of the last mode. It feeds through the whole system (connect the cold box and room temperature part), and makes the system's high and low pressure stable.
3. Coldbox refrigeration mode. Turbine's control valve (CV1201) and turbine act, on the base of the last mode, meanwhile CV1202 closes, which makes system's refrigeration begin.
4. Large cycle mode. The cold load's gas supply valve (CV1203) and gas return valve (CV1205) act, on the base of the last mode, meanwhile CV1205 closes, which supplies the interface to users.

Position-type PID Control Algorithm

All the control loops of the 2kW@20K refrigerator use the FB41 (CONT_C) digital controller in Step 7. And the FB41 controller uses a position-type PID control algorithm as follows.

$$u(n) = K_P\left\{e(n) + \frac{T}{T_I}\sum_{i=0}^{n} e(i) + \frac{T_D}{T}[e(n) - e(n-1)]\right\} + M$$

$e(n)$ - deviation;
M - integral initial value;
K_P - proportional coefficient, set by GAIN pin;
T_I - integral time constant, set by TI pin ;
T_D - differential time constant, set by TD pin;
T - sampling time, set by CYCLE pin.

PID Control Coefficients

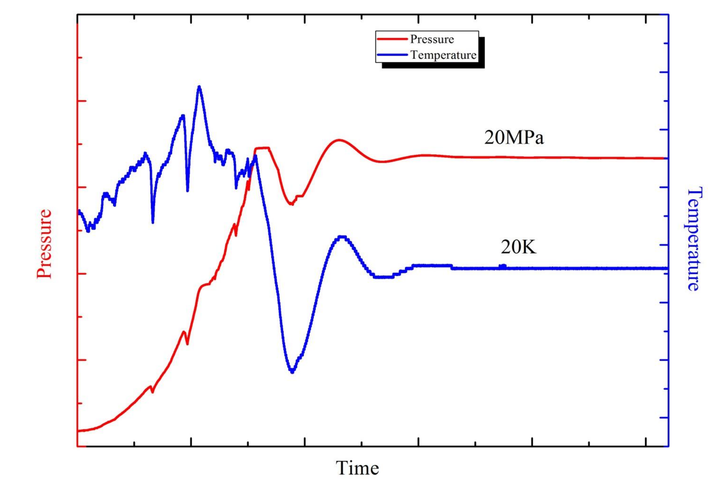
Controlled Object	Actuator	K_P	T_I	T_D
High pressure	Compensation gas valve (CV1102)	-82	190	0
	Exhaust valve (CV1103)	5.3	180	0
Low pressure	Bypass valve(CV1101)	55	180	0
	Compressor	-52	180	0
Turbine expander speed	Control Valve(CV1201)	2.6	200	0
Controlled Temperature	Control load	1.1	650	0

In 2kW@20K refrigerator， we use six PID control loops in total.

The Test Result of Cold Helium Pressurization

The 2kW/20K helium refrigerator in test site.

The helium refrigerator has run at the cooling capacity of 2kW@19.7±0.3K for 9 days itself . And we also have used this refrigerator finished the cold helium pressurization experiment with the test condition of 20MPa@20K.



The result of cold helium pressurization by 2kW/ 20K helium refrigerator.

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