

Study on a novel variable capacity technology and control strategy for refrigerated shipping container unit

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Abstract. A novel variable capacity system based on variable frequency compressor combined hot-gas bypass technology, was developed in the refrigerated shipping container unit. Then, numerical study had been carried out on control strategy for the variable capacity system. The schematic of variable capacity control in chilled mode/frozen mode was presented respectively. The detailed control models for the electronic expansion valve, inverter compressor, electronic hot-gas valve were developed. Finally, the novel variable capacity technology and control strategy was implemented in the experimental refrigeration unit system. Experimental tests for the refrigeration unit were carried out. The results of the experimental tests showed that in the refrigeration unit system, the novel variable capacity technology and control strategy based on combining variable frequency compressor with hot gas bypass technology, which could keep the inner temperature more stable. Therefore, the novel variable capacity technology and control strategy have been proved to be workable.

1. Introduction

Today, with the development of refrigeration science and technology and the improvement of food safety requirements, the refrigerated shipping container has been widely applied in transportation of cold chain logistics because of its efficiency, facility and safety. However, due to the complex and variable transportation conditions, as well as the strict requirements for the temperature control of the goods, the precise control of temperature in container has become a challenge for the refrigerated unit. The stable and accurate control of temperature in container is mainly completed by the variable capacity system of refrigerated unit. Nowadays, the variable capacity technologies are adopted in the refrigerated container mainly include the hot-gas bypass, suction pressure adjustment, digital scroll compressor and inverter compressor, which can obtain the precision of temperature control risen from $\pm 1^{\circ}\text{C}$ to $\pm 0.5^{\circ}\text{C}$, the energy-saving effect of refrigerated unit risen 50%, compared to the on-off control of compressor. But the control method of variable capacity for the reefer container in the market still exists a disadvantage, that is, when the refrigerated shipping container unit is operated on low load condition, the refrigerated unit is applied the on-off control of compressor to avoid a big fluctuation for temperature. If so, the temperature precision and stability in container is obviously extensively affected. Consequently, in this paper, a novel variable capacity technology and control strategy were developed, which was to achieve the high temperature accuracy from low load to full load for the refrigerated shipping container unit.

2. The Structure of new type of refrigerated shipping container unit

The whole structure of new type of refrigerated shipping container unit is presented in Fig. 1. The refrigerant of refrigerated unit is R134a. The new type of refrigeration unit was adopted



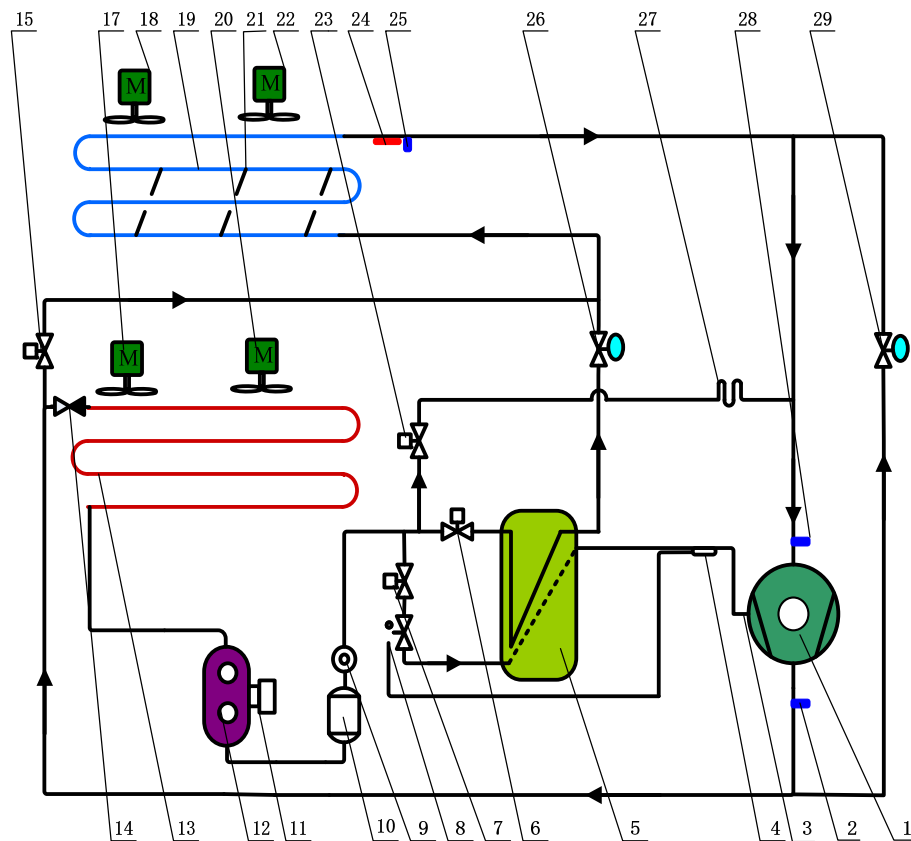


Fig.1- schematic view of the refrigerated shipping container unit

1-inverter compressor 2-pressure sensor 3-compressor inlet 4-thermal bulb 5-superchilled economizer 6/7-solenoid valve 8-thermal expansion valve 9-sight glass 10-dry filter 11- fusible plug 12-accumulator 13-condenser 14-check valve 15-solenoid valve for hot gas defrosting 17/20-Condenser fan 19-evaporator 18/22-evaporator fan 21-electrical heating rod 22-the injecting solenoid valve 24-Pt100 sensor 25-pressure sensor 26-electronic expansion valve 27-coil 28-pressure sensor 29-electronic hot-gas valve

the technology of multi-stage piston inverter compressor, electronic expansion valve, electronic hot-gas valve, used to the capacity control of refrigerated shipping container unit. Meanwhile, combined the high-low speed evaporator fan could save energy on different working condition and improve the chilled efficiency of evaporator. Besides, the evaporator, condenser was adopted inner grooved copper tube, with finned tube of Hydrophilic aluminum foil, to increase heat exchange efficiency among the refrigerant, evaporator and air. To increase the superchilled degree of refrigerant entering into evaporator, refrigerating unit was equipped with an economizer. Under the high-temperature and high load environment, to keep the compressor run continually and steadily.

3. The variable capacity technology and control strategy for refrigerated unit

3.1. The variable capacity technology and overall control strategy

The refrigerated shipping container developed in the paper was adopted the variable capacity technology of the multi-stage piston inverter compressor, electronic expansion valve, electronic hot-gas valve. Owing to the characteristics of the wider range of refrigerant flow control, the better linear ratio, the higher precision of flow adjustment, electronic expansion valve has become an important variable capacity technology. Besides, the inverter compressor combined electronic hot-gas valve as a novel variable capacity was applied in the refrigerated unit. The operating principle as

follows:

When the heat load in container was within the capacity control range of inverter compressor, variable capacity of the refrigerated unit was achieved only by the inverter compressor and electronic expansion valve. Whereas if the heat load in container was less than the capacity control range of inverter compressor, the inverter compressor often was only operated at the minimum operating frequency to meet the requirements for its lubrication and oil return of the refrigerated unit. Therefore, at this time, the inverter compressor couldn't adjust the capacity for the refrigerated unit. Variable capacity of the refrigerated unit was achieved only by the electronic hot-gas valve and electronic expansion valve. That is, the hot-gas was bypassed from outlet to inlet of compressor by the electronic hot-gas valve, which was to get the evaporating pressure stable.

According to the set point, the refrigeration unit can operate on chilled mode or frozen mode. In this paper, -5°C was used as the cut-off point of chilled/frozen mode. When the refrigeration unit was operated on chilled/frozen mode, supply air temperature/return air temperature was regarded as control parameter respectively.

Basing on the Programmable Logic Controller (PLC) technology, controller of refrigeration unit can control the complex logic actions of the inverter compressor, electronic expansion valve, electronic hot-gas valve to achieve variable capacity control of refrigerating system respectively. The whole structure of variable capacity control of refrigerated shipping container unit in chilled/frozen mode is shown in Fig. 2, Fig. 3 respectively.

As shown to the Fig. 2, when the refrigerated container unit was operated in chilled mode and if the supply air temperature was more than $\text{setpoint}+1.5^{\circ}\text{C}$, the controller was gone into the fast pull down mode with the working frequency of compressor increasing rapidly. Then, the supply air temperature was down to between $\text{setpoint}+1.5^{\circ}\text{C}$ and setpoint, the controller went into reducing frequency zone, which was a buffer zone to avoid a big fluctuation for the supply air temperature. While the supply air temperature was down to between setpoint and $\text{setpoint}-1.5^{\circ}\text{C}$, the controller was gone into variable frequency capacity control zone, where the variable capacity of the refrigerated unit was achieved only by the inverter compressor and electronic expansion valve. If the supply air temperature was down to between $\text{setpoint}-1.5^{\circ}\text{C}$ and $\text{setpoint}-2^{\circ}\text{C}$, the controller was gone into hot-gas capacity control zone, variable capacity of the refrigerated unit was achieved only by the electronic hot-gas valve and electronic expansion valve. Vice versa, the controller could switch automatically according to the demarcation point of zone (such as $\text{setpoint}+0.3^{\circ}\text{C}$, $\text{setpoint}+0.5^{\circ}\text{C}$, $\text{setpoint}+3^{\circ}\text{C}$).

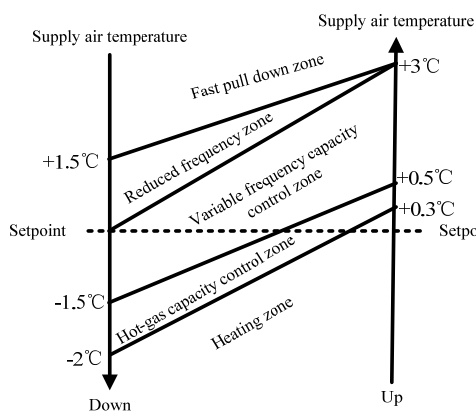


Fig.2 structure of variable capacity control in chilled mode

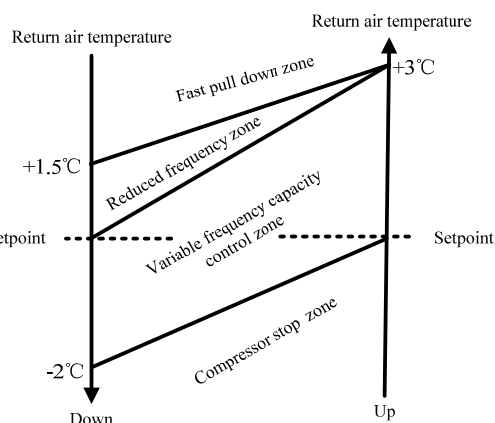


Fig.3 structure of variable capacity control in frozen mode

When the refrigerated container unit was operated in frozen mode, the variable capacity technology

was achieved by inverter compressor and electronic expansion valve. Fig. 3 is showed the refrigerated container unit was operated in variable frequency capacity control zone, when the return air temperature was dropped down from setpoint to setpoint -2°C or risen up from setpoint to setpoint $+3^{\circ}\text{C}$. If the return air temperature was fell to the cut-off point (setpoint -2°C) in variable frequency capacity control zone, inverter compressor would be stopped by the controller.

3.2. The detailed control strategy for key parts in refrigerated unit

The key parts in refrigerated unit by controller were composed of the electronic expansion valve, inverter compressor, electronic hot-gas valve. The schematic control views for above-mentioned key parts are presented in Fig. 4~Fig. 6.

The superheat of evaporator outlet, an important parameter to evaluate the performance of evaporator, was controlled by the open of electronic expansion valve. According to the minimum stable signal line theory of Z.R.Huelle, each operating condition had a minimum stable superheat. Consequently, the minimum stable superheat was regarded as desired setpoint, as well as the control parameter. As shown to the Fig. 4, the real-time superheat was calculated on the basis of the outlet temperature/pressure of evaporator by the main controller. Then, a desired control result (the real-time superheat was close to setpoint) was got by Proportion Integration Differentiation (PID) controller.

As shown to the Fig. 5 and Fig. 6, the temperature control in container was a complicated system of strong nonlinearity, multi-variable and time variance. Therefore, the temperature in container was adjusted precisely by PID controller when the refrigerated unit was operated in variable frequency capacity control zone. Similarly, the supply air temperature was adjusted precisely by PID controller when the refrigerated unit was operated in hot-gas capacity control zone.

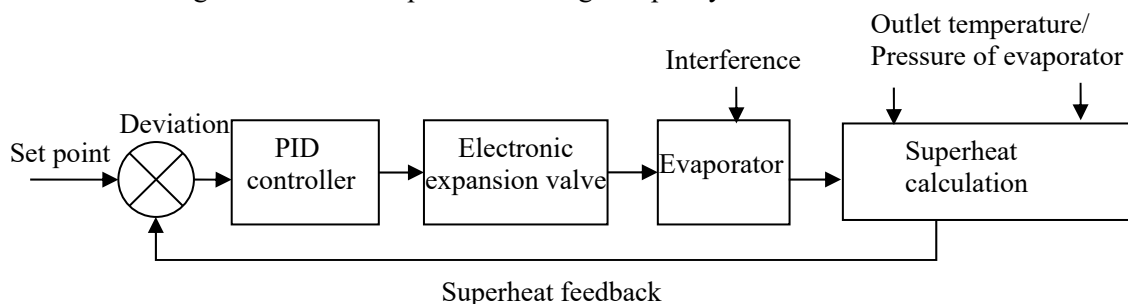


Fig.4 schematic control view for electronic expansion vavle

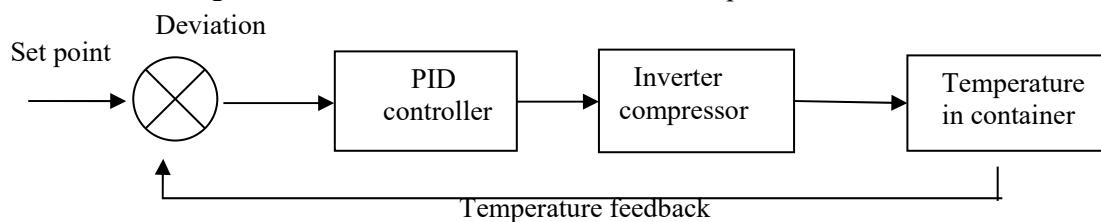


Fig.5 schematic control view for inverter compressor

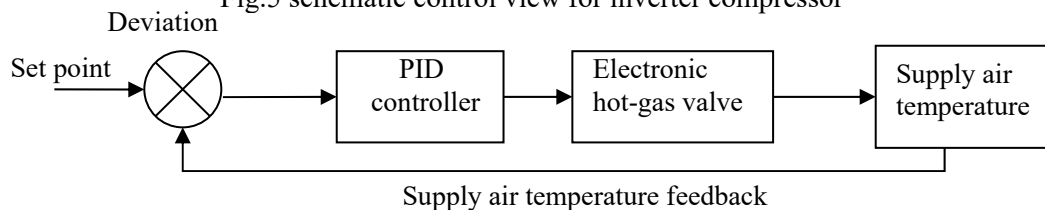


Fig.6 schematic control view for electronic hot-gas vavle

4. Variable capacity experimental test

4.1. Refrigeration unit variable capacity experiment

Refrigeration units were combined with 20 feet standard heat preservation box, Preparations of variable capacity experiment can refer to the paper(Hua et al ,2014).

4.2. Variable capacity experiment for empty container

Variable capacity experiment was tested in ambient temperature $22^{\circ}\text{C}(\pm 1^{\circ}\text{C})$ and humidity 76%. Setpoint is 0°C in chilled mode, the refrigerating unit was runned in chilled model, the temperature in container is represented as the supply air temperature. The experimental data are shown in Fig. 7 and Fig. 8.

As shown to Fig. 7 and Fig. 8, the initial temperature in the container was 4.1°C . When the time was less than 208s, the refrigerating unit was runned in pull down zone, the frequency of compressor was increased rapidly from 25.2Hz to 33.4Hz. When the time was between 208s and 400s, the supply air temperature was down from 1.5°C to 0°C , the refrigerating unit was runned in reducing frequency zone, the frequency of compressor was reduced from 33.4 Hz to 27.2Hz. When the supply air temperature was got to setpoint 0°C , the refrigerating unit was runned in variable frequency capacity control zone, the frequency of compressor was adjusted to 25.2 Hz(the minimum operating frequency) due to the supply air temperature continuously dropped. The supply air temperature was got to -1.5°C (610s), in this case, the refrigerating unit was runned in hot-gas capacity control zone. The electronic hot-gas valve was opened by the controller. The supply temperature finally was close to setpoint by variable volume technology, which was operated automatically by controller of refrigerating unit. Controller accuracy was $\pm 0.2^{\circ}\text{C}$.

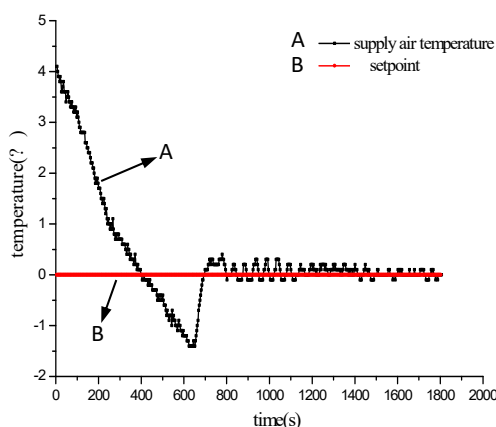


Fig.7 Supply air temperature in the variable capacity experiment

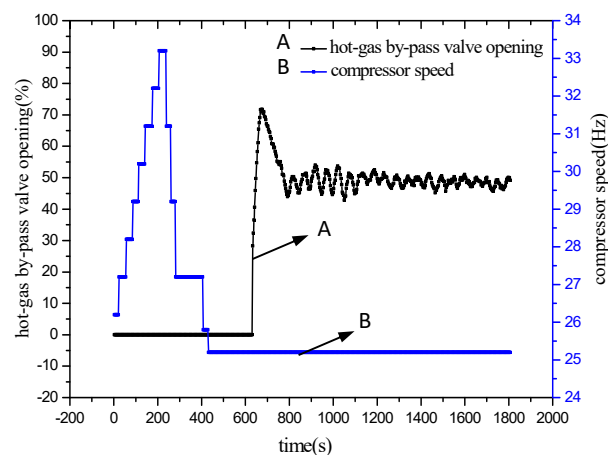


Fig.8 Opening of hot-gas valve and compressor frequency in the variable capacity experiment

5. Summary

The temperature control in container is a complicated system of the strong nonlinearity, multi-variable and time variance. The inner temperature of marine refrigerated container usually fluctuated obviously when on/off control was adopted due to low system load, especially in chilled mode. The novel variable capacity technology and control strategy was developed and implemented in the experimental refrigeration unit system. Experimental tests for the capacity controller were carried out, the results of the experimental tests showed that in the refrigeration unit system, the novel variable capacity technology and control strategy is based on variable frequency compressor and hot gas bypass

technology, which can keep the inner temperature more stable. Therefore, the novel variable capacity technology and control strategy have been proved to be workable.

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