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Mixed refrigerant composition shift due to throttle valves opening in auto cascade refrigeration system☆

Xiongwen Xu [1,2], Jinping Liu [1,3,*], Le Cao [1]

[1] School of Electric Power, South China University of Technology, Guangzhou 510640, China
[2] Guangdong Province Key Laboratory of Efficient and Clean Energy Utilization, Guangzhou 510640, China
[3] State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou 510640, China

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ABSTRACT

Auto cascade refrigeration (ACR) cycle with phase separators is widely used in the cryogenic system. The composition of mixed refrigerant has a great effect on the performance of the system. Based on the assumption of infinite volume of phase separator, ACR system with one phase separator is simulated in this paper. The variation of refrigerant composition under different valves opening is obtained. A related experimental system is set up to verify the variation. The result shows that when the valve opening connected to the evaporator increases or the valve opening under the phase separator decreases, the low-boiling component concentration of the working mixture passing through the compressor and condenser increases, while the high-boiling component concentration decreases. Furthermore, the variations of condensation pressure and evaporation pressure under different valves opening are also observed. This paper is helpful to deepen the understanding of ACR system.

1. Introduction

Auto cascade refrigeration (ACR) system employing non-azeotropic mixed-refrigerant is widely used in many industrial fields with cooling temperature ranging from −200 °C to −40 °C, such as natural gas liquefaction, cooling infrared sensors, cryosurgery, cryo-preservation, and water vapor cryo-trapping. Nowadays, the idea is extent to many refrigeration cycles, such as Alexeev and Quack [1] refrigerator, Missimer [2] refrigerator and many natural gas liquefaction cycles [3–7].

In the ACR system, liquid fraction enriched with high-boiling components separated at a relatively high temperature level, is throttled to precool the separated vapor fraction that contains more low-boiling components. Then, the separated vapor is condensed and throttled to obtain a lower temperature level.

In all refrigerators employing non-azeotropic mixture, the working refrigerant composition is decisive. Lots of literatures reported the composition shift because of the different dissolubilities to the lubricant oil [8,9], liquid hold up [10–16] and leakage [17–19]. Nevertheless, few people focused on the composition shift due to the throttle openings in ACR system with phase separators. Moreover, some even neglected it and adopted the composition of charged refrigerant as working refrigerant to analysis ACR system [20].

However, the system mechanism would somewhat be confused if the composition shift caused by the throttles opening is neglected. For example, in the simplified flow sheet illustrated in Fig. 1, when the throttle valve opening under the phase separator (Valve G in Fig. 1) increases, the flow resistance of the system decreases. As a result, the condensation pressure goes down and the evaporation pressure goes up. The decreased condensation pressure decreases the liquid fraction ratio of the mixed refrigerant stream entering the phase separator. In order to keep the balance between the liquid inflow and outflow of the phase separator, the refrigerant flow rate passing through the throttle valve under the

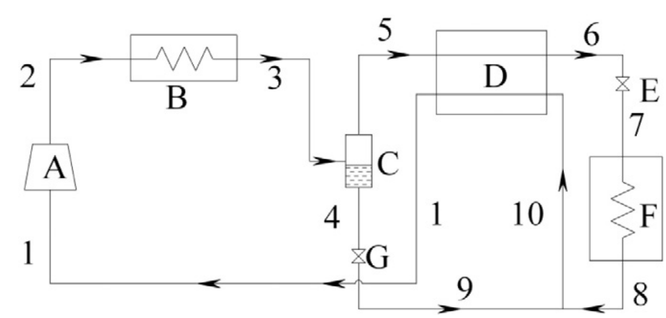

Fig. 1. Flow Sheet of ACR cycle with one phase separator. A—compressor; B—condenser (after cooler); C—phase separator; D—evaporative condenser (regenerative heat exchanger); E, G—throttle valves; F—evaporator; 1–10 are node numbers in ACR cycle.

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* Corresponding author.
E-mail address: mpjpliu@scut.edu.cn (J. Liu).

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phase separator should decrease. That is, the increase of the throttle valve opening under phase separator decreases the flow rate passing through it, which violates our common sense.

The operation principle of ACR cycle with phase separators is extremely complicated, of which the throttles are intensively interacted. Guangming Chen *et al.* reported experimental research on the throttle opening in ACR system [21], but the experiment result was irregular because the effect of throttle devices opening on circulated mixed refrigerant composition was not considered.

Thus, the effect of the throttle valves opening on the working refrigerant composition is essential to understand the mechanism of ACR system equipped phase separators. Thus, a mathematical model to simulate the working process under different throttle devices opening is set up in this paper. Then, experiments are done to verify the phenomenon of the working mixed refrigerant composition variation in ACR system.

2. Mathematical Component Model

2.1. Heat exchanger

Heat transfer with mixed-refrigerant gas–liquid flow is a complex process that no mathematical model can precisely descript up to now. Fortunately, it is not the focus of this paper and moreover, some assumptions of refrigerant hold-up in this paper make it meaningless to seek a precise model for the heat exchanger simulation. Therefore, the simplest model, fixed minimum temperature approach model is applied to heat transfer simulation, namely,

$$\Delta t_{\min} = \text{constant}. \tag{1}$$

Assuming the flow rate of the second heat transfer fluid is large enough, the minimum temperature approach occurs at the outlet of the refrigerant side in the condenser and evaporator. Hence, the fixed temperature of the second heat transfer fluid will fix the temperature of the refrigerant at the outlet of the heat exchangers as well.

2.2. Compressor

The mass flow rate through compressor (m_c) is dependent on the density of the refrigerant at the compressor inlet (ρ_{suc}), the displacement rate of the compressor (V_{comp}) and its volumetric efficiency (η_v). Assuming the expanding process of the gas in clearance volume as isentropic process, the mathematical model of compressor can be descripted through Eqs. (2) and (3) [22].

$$\eta_v = 1 - c\left[\left(\frac{p_d}{p_s}\right)^{\frac{1}{k}} - 1\right] \tag{2}$$

$$m_c = \rho_{suc} V_{comp} \eta_v \tag{3}$$

where c represents the clearance volume ratio of compressing cavity in compressor, p_d and p_s represent the discharge pressure and suction pressure of compressor respectively, and k is the isotropic expansion coefficient of refrigerant, which could be gotten as follows:

$$k = \frac{c_p}{c_v} \tag{4}$$

where c_p and c_v are the specific heat at constant pressure and constant volume, respectively.

2.3. Throttle valves

Using Wile's empirical formula, the mass flow rate through throttle valve (m_{va}) can be calculated as

$$m_{va} = C_D A_{va} \sqrt{2\rho_{in}(P_{in} - P_{out})} \tag{5}$$

$$C_D = 0.02005\sqrt{\rho_{in}} + 0.634 v_{out} \tag{6}$$

where C_D is the flow factor, A_{va} is the minimum flow area in valve, ρ_{in} represents the density of inlet fluid and v_{out} is the specific volume of outlet fluid.

2.4. Simulation

In a given ACR system, the mixed-refrigerant distribution is inhomogeneous and hard-modeled. Thus, it is difficult to obtain the working refrigerant composition. To elucidate the relationship between the composition in circulation and the charged composition, Lakshmi-Narasimhan and Venkatarathnam conducted numerous experiments and summarized the results to conclude the linear relationship between these variables [23]. However, this result was only applicable to the particular system they tested.

To realize the system simulation, at least one refrigerant stream composition needs to get from the charged composition. Therefore, the following condition that an enough large scale of phase separator is employed in the system and enough refrigerant is charged is assumed. It can guarantee that most refrigerant is stored in the phase separator when the system is running so that the liquid refrigerant composition in the phase separator is approximate to the charged refrigerant composition.

As the system is running, the liquid and gas refrigerant in the phase separator can be considered as saturated state, respectively. When the refrigerant temperature at the outlet of the condenser (T_3) is fixed, the pressure in the phase separator (condensation pressure, p_c) can be determined as follows:

$$p_c = P_{satliq}(R_l, T_3) \tag{7}$$

$$R_g = RV_{satliq}(R_l, T_3) \tag{8}$$

where R_l and R_g represent the refrigerant composition of liquid and gas in the phase separator, respectively, P_{satliq} and RV_{satliq}, which are related to the physical property of the refrigerant, are the mathematical functions to get the bubble point pressure and bubble composition of a given refrigerant by the temperature, respectively. Eqs. (7) and (8) mean that the pressure and the gas composition in the phase separator are certain and irrespective of the valves opening because of the fixed temperature ($T_4 = T_3$) and fixed refrigerant composition of the liquid in the phase separator. Thus, the composition of the refrigerant stream to the evaporator is invariable under 100% separation effectiveness of the phase separator.

In the whole simulation process, three conditions must be guaranteed. First, the refrigerant sucked by compressor is wholly gasified. Secondly, the refrigerant before the valve to evaporator is wholly liquefied. Thirdly, the system can make refrigeration effect, *i.e.*, the temperature of node 7 is less than node 8. For simplification, heat loss in the whole system and pressure drop in the heat exchangers and joint pipes are neglected.

Sequential modular method is applied in this paper to simulate ACR system. The mathematical models representing individual units are