

# Composition Shift of a Mixed-Gas Joule-Thomson Refrigerator Driven by an Oil-Free Compressor

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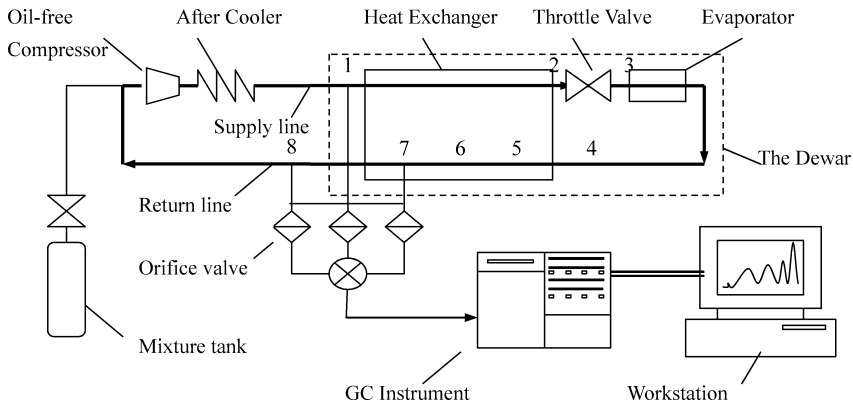
## ABSTRACT

A mixed-gas Joule-Thomson refrigerator (MJTR) driven by an oil-free compressor is built to study the mixture composition shift feature due to the differential liquid holdup in the two-phase flow. A typical multicomponent mixed-refrigerant for refrigeration at 120 K is used to measure the difference of the circulating composition from the original charge. A prediction model is proposed to calculate the mixture composition variation due to phase holdup in the two-phase flow. Both the measured and calculated data show that the composition shift is large for those mixtures which reach a low temperature range. The parameters influencing the mixture composition variation were also analyzed.

## INTRODUCTION

Great achievements in the development of mixed-gases Joule-Thomson refrigerators have been achieved in recent years. Commercial products based on this kind of refrigeration have also become available, such as freezers for biomaterials preservation, and small scale cryocoolers for scientific research (Cryotiger). Meanwhile, there are still many problems needing further research. The composition shift is one of the most important problems.<sup>1,2</sup> The change of the mixture compositions leads to variations of the thermodynamic properties of the refrigerant. In turn, this will influence the performance of the refrigerator. It is necessary to conduct research on the composition shift features of MJTRs.

There are several possible reasons for the change in the mixture compositions. One important reason is the different solubility in the lubricant oil for components with different boiling points. Another important reason is the differential phase holdup in the two-phase flow at low temperatures. The study of composition shift due to different solubility in lubricant oil is presented in another paper.<sup>3</sup> In this paper, the composition shift caused by liquid holdup in the two-phase region is investigated theoretically and experimentally. A mixed-gases Joule-Thomson refrigeration system driven by an oil-free compressor is built to measure the composition variations. A prediction model is also proposed to calculate the composition shift due to the differential liquid holdup in the two-phase flow.



**Figure 1.** Experimental system, the digital numbers from 1 to 8 indicate different sampling points

## EXPERIMENTAL RIG

An experimental system was developed based on a real mixture refrigeration system, where an oil-free compressor was used to compress the mixed-refrigerant. Figure 1 shows the schematic diagram of the experimental system. It consists of two parts: one is the refrigeration system, and the other is the mixture sampling and analyzing system.

The mixture refrigeration system consists of a compressor unit and a cryostat. The compressor unit includes a compressor with an aftercooler. The cryostat, enclosed in a metal dewar (illustrated as a dashed rectangle in Figure 1), includes a counter-flow heat exchanger, a throttle valve, and an evaporator. There are eight sampling positions in this system. Sampling point 1 and 2 are fixed at the inlet and outlet of the high pressure passage of the heat exchanger. Point 3 is at the inlet of the evaporator, and point 4 locates the outlet of the evaporator. Points 5 to 7 are fixed evenly at the low-pressure passage of the heat exchanger. The last point, 8, is at the return line before the inlet of the compressor. The temperature of sampling position 8 is near the ambient temperature. During operation, only this point was used to sample the circulating composition, which ensures a gas-phase state sample. That is, the sampling point 8 is used to monitor the composition shift during the cooling down process. When the steady cooling temperature is reached, the cryostat will be cut off by closing the two valves which connect the cryostat and the ambient units (the compressor and after cooler), and the system will be turned off. When the temperature of the cryostat increases to the room temperature, the sampling points from 1 to 8 will be used to measure the local compositions. The local compositions measured at different points can partially indicate the composition distribution in the system during the operating period.

A gas chromatography instrument (GC3400, Beifen China) with a Thermal Conductivity Detector (TCD) was used to analyze the mixture composition. An elaborated capillary column is used to ensure that all of the mixture's components can be separated and detected. The signal generated by the detector is sent to the workstation (BF9202, an auxiliary of the GC3400). With the workstation, the chromatogram of the sample can be obtained. The Normalizing Peak Areas Method is used to determine the compositions of the mixture. A reference mixture is used to calibrate the chromatograph. This mixture was prepared with a precise balance (Sartorius BS 4000S). The detail description of the system can be found in the reference by Gong, et al.<sup>2</sup>

## PREDICTION MODEL

The multicomponent mixtures used in MJTRs for low temperature applications are typical non-azeotropic mixtures, where the difference between the bubble and the dew point temperatures can be as large as 100 K, or more. The compositions of the liquid and vapor phases of the two-phase region are quite different. Therefore, the phase holdup caused by the velocity difference in the two-phase flow is one of the most important reasons for the composition shift of multicomponent mix-

tures. The phase holdup can be described as:<sup>4</sup>

$$H_L = \frac{V_L}{V_p} \quad (1)$$

$$H_L + H_G = 1 \quad (2)$$

where  $H_L$  is the liquid holdup,  $V_L$  is the liquid phase volume,  $V_p$  is the volume of the flow passage, and  $H_G$  is the vapor holdup. If the liquid and vapor phases have the same velocities, the phase holdup can be expressed as:

$$H_{L0} = \frac{U_L}{U_L + U_G} = \frac{U_L}{U_{TP}} = \frac{Q_L}{Q_{TP}} \quad (3)$$

where  $U$  is the facial velocity,  $Q$  is the volume flow rate, and the subscripts of  $L$ ,  $G$  and  $TP$  indicate liquid phase, vapor phase and the total two-phase flow, respectively. It is obviously that there will be no composition shift if the vapor phase has the same velocity as the liquid phase. The composition shift is caused by the velocity difference of vapor and liquid phases. This part of the holdup liquid can not circulate in the cycle any more. This will finally influence the circulating compositions. The volume and mole of the holdup liquid can be express as:

$$\Delta V = (H_L - H_{L0}) \times V_p \quad (4)$$

$$\Delta n = (H_L - H_{L0}) \times V_p \times \rho_n \quad (5)$$

where  $\Delta V$  is the volume of the holdup liquid,  $\Delta n$  is the mole quantity of the holdup liquid,  $\rho_n$  is the density of the local holdup liquid in mol/m<sup>3</sup>. Therefore, the composition shift can be expressed as:

$$z_j^n = \frac{nz_j - \Delta nz_j'}{n - \Delta n} \quad (6)$$

$$R = \frac{z_j^n - z_j}{z_j} \times 100\% \quad (7)$$

where  $z_j$  is the initial composition of  $j$  component,  $z_j'$  is the holdup liquid composition, and  $z_j^n$  is the circulating composition;  $R$  is the relative composition shift.

In the model described above, no dead volume in the system is considered. There are a number of liquid holdup prediction models (void fraction models). Here, the Beggs-Brill-Moody model<sup>5</sup> was used to calculate the liquid holdup (void fraction).

## RESULTS AND ANALYSIS

A typical mixture for 120 K refrigeration<sup>6</sup> was used to measure its composition shift feature in the experimental system described above. The measured results of the maximum relative composition shifts are listed in Table 1 at different initial charged amounts. It can be found that for the same initial composition, the larger amount charged, the less the circulating composition will change. That is, for a system with a fixed volume cryostat, the initial charged mixture quantity can influence the composition shift feature; a larger charged amount will lead to a relative small composition

**Table 1.** Composition Shift for a Typical Mixture at Different Charged Amount

| *Number | R /%  |       |        |        |        | **T <sub>c</sub> /K |
|---------|-------|-------|--------|--------|--------|---------------------|
|         | N2    | CH4   | C2H6   | C3H8   | iC4H10 |                     |
| A       | 41.24 | 28.17 | -35.95 | -52.53 | -60.00 | 133.6K              |
| B       | 46.86 | 23.28 | -43.21 | -58.03 | -65.05 | 129.5K              |
| C       | 35.22 | 8.29  | -28.25 | -36.82 | -41.96 | 110.3K              |
| D       | 34.97 | 5.74  | -21.23 | -33.49 | -41.07 | 103.7K              |

\* The amount of mixture charged is A<B<C<D;

\*\* T<sub>c</sub> is the minimum cooling temperature achieved without heat loads.

shift. This conclusion is easily obtained from Eq. (6). It is obvious that when the amount ( $n$ ) of the initial charge mixture increases, the composition variation degree ( $R$ ) will decrease. The local compositions at different sampling points are also presented in Figures 2 and 3 for number A and C (Table 1), respectively. The measurements were conducted as the procedure described above. These measured compositions at different sampling points can partially indicate the composition distribution in the system.

From Figures 2 and 3, it can be found that high-boiling components (isobutane and propane in this study) are accumulated at the low temperature section (points 3~6), while the composition of the low-boiling component (nitrogen in this measurement) decreases greatly. Moreover, when the system was shut off, the accumulated liquid of high-boiling components will drop from the top of the cryostat, this will make the composition of the high-boiling components in the eight sampling point larger than the initial charged one. The composition shift degree for those components with middle-boiling temperatures (methane and ethane in this paper) is relatively small compared with the high and low boiling components.

The circulating composition variation along with the refrigeration temperature is also measured, and is shown in Figure 4. The calculated result is presented in Figure 5. The calculation was conducted with the model described above. Same mixture composition was used in the calculation, while the circulating mole flow rate is 0.124 mol/s. It can be found that the composition shift trend of both calculated and measured results are similar to each other. The measure data shows a higher composition shift than the calculated results because it is very hard to eliminate the dead volume in the real refrigeration system.

Furthermore, accurate prediction of the low temperature two-phase flow is difficult to determine, especially for multicomponent mixtures. A more accurate prediction requires further study.

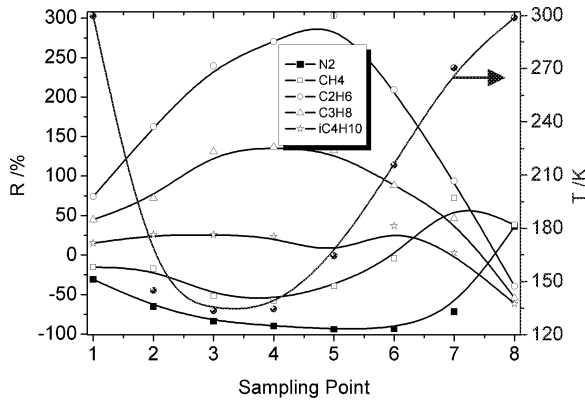


Figure 2. Local composition distributions for Number A measurement

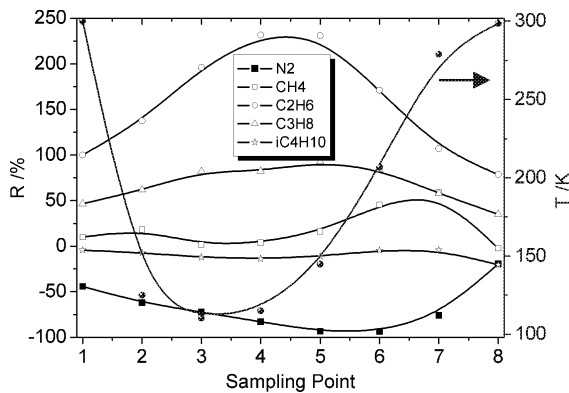


Figure 3. Local composition distributions for Number C measurement

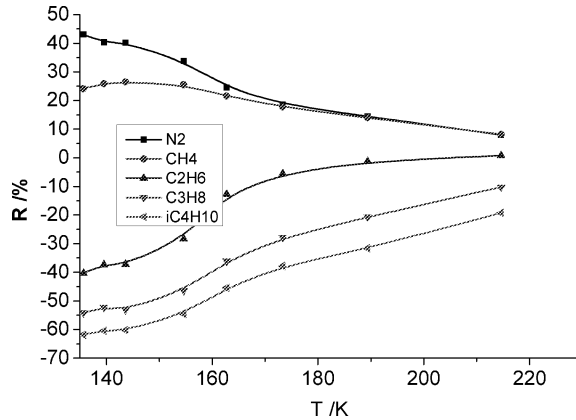


Figure 4. Measured composition shift along with the refrigeration temperature

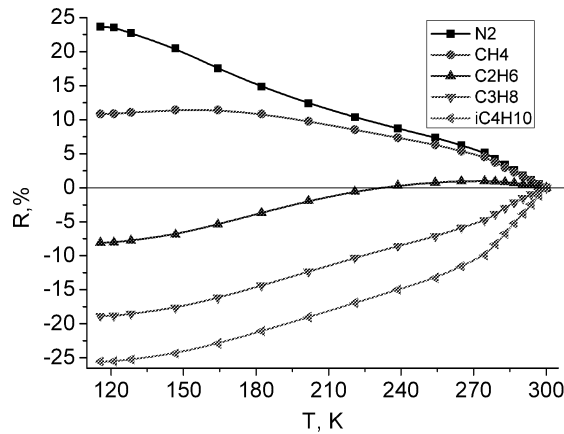


Figure 5. Calculated results for composition shift along with the refrigeration temperature

However, the calculated results show a good trend. This work can provide a good reference if there are no other measurements.

## CONCLUSION

A real mixed-gases Joule-Thomson refrigerator driven by an oil-free compressor was built to study its composition shift features due to liquid holdup in a two-phase flow. A prediction model was also proposed by calculating the liquid holdup with a void fraction model. From this study, it is found that a variation in mixture composition was found to be caused by the liquid holdup in the low temperature two-phase flow. The composition of high-boiling components will decrease due to the liquid accumulation in the low temperature section in the cryostat. The initial charge refrigerant amount will influence the composition shift degree. The increase of the charged amount will decrease the degree of composition shift. The calculated results show a good agreement with measured data in presence of the composition shift trend.

## ACKNOWLEDGMENT

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