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A strategy to optimize the charge amount of the mixed refrigerant for the Joule–Thomson cooler

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ABSTRACT

The performance of the mixed refrigerant (MR) Joule–Thomson cooler is mainly dependent on the MR circulation composition for a given hardware. However, it is difficult to charge the MR to the desired circulation composition, due to the composition shift. In the present study, a novel strategy was proposed to solve this problem. In this strategy, the MR Joule–Thomson cooler is first charged with the initial charge amount, which is obtained by estimating the MR inventory in the cooler using the homogeneous model. Afterwards, the cooler is started and the MR circulation composition is adjusted to the corresponding optimal composition by adding the MR charge amount stepwise. Additionally, this strategy was verified by an experiment with a ternary mixture of methane, ethane and i-butane. The experimental results indicated that the MR circulation composition was able to be adjusted to the corresponding optimal circulation composition approximately within the relative deviation of ±5%.

Une stratégie pour optimiser la quantité de charge du frigorigène mixte pour le refroidisseur Joule-Thomson

Mots clés : Frigorigène mixte ; Composition de circulation ; Composition shift ; Stratégie ; Quantité de charge

1. Introduction

For its high efficiency, high reliability and no moving part in the cold end, the mixed refrigerant Joule–Thomson cooler (MR J–T cooler) is widely used to obtain the low temperature from 80 K to 230 K. There are five basic components in the refrigeration loop, which include a compressor, an after-cooler, a recuperative heat exchanger, an expansion valve and an evaporator. The performance of the cooler is highly dependent on its hardware and the mixed refrigerant composition. Hence, it is important to run the MR J–T cooler with an appropriate mixed refrigerant composition for a given hardware.

Many researches have been conducted on the effects of the mixed refrigerant composition on the MR J–T cooler (Lakshmi Narasimhan and Venkatarathnam, 2011; Rajapaksha, 2007; Rajesh Reddy et al., 2010; Venkatarathnam and Srinivasa Murthy, 1999; Venkatarathnam et al., 1996) and how to optimize the mixed refrigerant composition (Derking et al., 2009; Keppler et al., 2004). However, it is hard to run the MR J–T cooler with the

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Nomenclature

a	constant in Eq. (21)
b	constant in Eq. (21)
c	circulation molar composition [%]
COP	coefficient of performance
F	function
m	mass [g]
M	molar mass [g·mole^{-1}]
n	number of the component
o	mixed refrigerant mass composition in the two-phase region [%]
P	pressure [bar]
r	ratio of the circulation composition to the optimal composition ($r = c/y$)
T	temperature [°C]
V	volume [L]
V_{total}	total volume of the cooler [L]
w	mixed refrigerant molar composition in the two-phase region [%]
x	molar charge composition [%]
y	optimal molar circulation composition [%]
z	molar charge quantity of the mixed refrigerant [mole]
Δz	adding molar charge quantity of the mixed refrigerant [mole]

Greek letters

ρ	density [g·L^{-1}]
σ	the relative deviation between x and y [%]
η	relative Carnot efficiency [%]
φ	variable defined by Eq. (29)

Subscripts

a	ambient
con	air cooler
d	discharge of the compressor
eva	evaporator
G	vapor phase
i	component number
k	element number in the heat exchanger two-phase region
l	low pressure
L	liquid phase
others	rest parts of the MR J–T cooler, excluding the air cooler, the recuperative heat exchanger, and the evaporator
r	ratio
rec	recuperative heat exchanger
rec-c	cold part of the recuperative heat exchanger
rec-h	hot part of the recuperative heat exchanger
sp	single-phase
t	target
tp	two-phase

Superscripts

j	jth process of optimizing the charge amount of the mixed refrigerant

optimal mixed refrigerant composition, due to the existence of the composition shift between the charge composition and the circulation composition. The composition shift is caused by three reasons, including the differential hold-up in the two-phase flow, the differential solubility in the lubricant oil and the differential leakage of the mixed refrigerant. Other than the differential leakage, the other two causes of the composition shift are inevitable. Consequently, the composition shift induces that the MR J–T cooler cannot be charged with the optimal composition directly. The desired charge amount and charge composition are mostly obtained by trial and error, which are inefficient.

Furthermore, the composition shift has been studied by many authors (Chen and Kruse, 1995; Corr et al., 1994; Gong et al., 2002, 2007; Xu et al., 2012; Youbi-Idrissi et al., 2005). Chen and Kruse (1995) analyzed the composition shift due to the differential hold-up of the two-phase flow in the condenser and evaporator. A method was proposed to estimate the differential hold-up in the heat exchangers' two-phase regions and predict the circulation composition. However, the pressure and the heat flux in the heat exchangers were assumed to be constant, which might cause great deviation for the mixed refrigerant with a large temperature glide. Moreover, the accuracy of this method depends on the void fraction model. However, no general valid void fraction model was proposed for all kinds of heat exchangers. To predict the void fraction of the mixed refrigerant accurately and generally, a complicated approach was developed by Xu et al. (2012) based on the two-phase flow conservation. And it predicted the mixed refrigerant composition shift and was verified by the experimental data. Nevertheless, the methods mentioned above just focus on predicting the accuracy of the void fraction, whereas the prediction on the two-phase heat transfer coefficient has not been the concern. The composition shift in a complete MR J–T cooler cannot be predicted accurately with only a valid void fraction. The two-phase region is also necessary to be estimated accurately with suitable correlation to predict the two-phase heat transfer coefficient. However, there is no general method on predicting the mixed refrigerant two-phase heat transfer coefficient, which is applicable to all mixed refrigerants. Therefore, it is still difficult to estimate the composition shift in a MR J–T cooler exactly.

In order to overcome this difficulty, Lakshmi Narasimhan and Venkatarathnam (2010) proposed a method for estimating the mixed refrigerant charge composition to get the desired composition in circulation. The charge composition varies linearly with the circulation composition for a desired heat load; the number of refrigerant moles to be charged and a given hardware were found. Consequently, the charge composition for a desired circulation composition can be obtained with the linear relationship. However, there was no detail on the operating condition of the MR J–T cooler when optimizing the circulation composition and only some optimizing methods were illustrated. Moreover, there is strong coupling relationship between the operating condition of the MR J–T cooler and the corresponding optimal composition. The actual operating condition will differ from the assumptive operating condition, when the MR J–T cooler is charged with the charge composition obtained by the optimal