Numerical study of the effect of the helium-based multi-component gas mixture on the internal purifier

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Abstract. The performance of the internal purifier has a direct impact on the liquefaction capacity of the helium liquefier. With increasing impurity level in helium, liquefaction capacity of the helium liquefier reduced significantly. In order to ensure the helium liquefier operates safely and stable, remove the impurities from the helium in the helium liquefier and improve the utilization of the helium, it is necessary for us to develop the technology of purification. In this paper, the impact of changes of multi-component helium mixture on the performance of the internal helium has been developed numerically. The final results show that as the impurities in the helium mixture increases, the performance of the internal purifier decreases first and then increases. It can help us design more efficient and compact internal purifier.

1. Introduction

Since the first helium crisis in around 2007, which was due to ExxonMobil shutting down its Shute Creek helium plant in southwestern Wyoming for maintenance and the Bureau of Land Management failed to supply helium [1], there have been two more helium shortage so far. They are the Helium Shortage 2.0 [2] and Helium Shortage 3.0 [3], which occurred in 2011/2012 and 2017/2018 separately. To summarize the above these crises, we observe that the basic reason for helium deficit is the imbalance between supply and demand. In other words, the helium shortage is the result of gradually diminished production capacity, the lack of new capacity coming into market and growing demand in helium. Without helium, scientists are forced to abandon areas of research and development related to helium. This has a significantly negative impact on innovation. In order to alleviate the effects of helium crisis, helium should be recycled, purified and reused.

The internal purifier plays an important part in the purification of impure helium. It is installed inside the coldbox and utilizes the cooling capacity of the coldbox to condensate, freeze and separate impurities. And it has the advantages of high integration, effective purification, maintenance friendly and high degree of automation. As a result, many researchers have focused on the investigation of the internal purifier[4][5][6]. However, most of them concentrate on how to extend the purify mode time, shorten the regeneration mode time, improve purification performance when helium with higher impurity level and make the entire process operate more effectively. Present problem is that data on how to design, fabricate and test the performance of heat exchangers for the internal purifier lacks, especially lacking specially research which
discusses from the numerical view. In this paper, a simplified model of heat and mass transfer for the first stage heat exchanger of the internal purifier has been built [7]. The impact of changes of multi-component helium mixture on the performance of the internal helium purifier has been developed numerically.

2. Numerical model
An overview of the prototype of the heat exchanger is shown in figure 1. The heat exchanger consists of a helical finned-tube bounded on a mandrel and wrapped in a shell [8][9]. It is a two-stream counter-flow heat exchanger with cold source helium flowing inside the finned-tube and impure helium outside. The impure helium is a helium-based binary mixture, namely, helium-nitrogen mixture and helium-oxygen mixture. The cooling source helium inside tube provides cooling power to impure helium for condensation, separation and purification.

There are several ways of examining heat exchangers. An efficient approach is by minimization of entropy generation, as for example that has been by Lerou et al. [10]. In this investigation, the Finned tube wound heat exchanger (FTWHE) has been divided into elements, where each element consists of a single band of the helical finned-tube. A single element is presented in figure 1(c).

The model will be investigated based on the following assumptions.

(1) The axial heat conduction through mandrel is neglected, and the heat from the impure helium to the cooling source helium is transferred through finned-tube wall.

(2) The physical properties of helium and impure helium at every single element of FTWHE remain the same.
3. Physical properties and physical dimensions

The main characteristic of low temperature heat transfer is that the physical properties of working fluid change dramatically under low temperature environment. The calculation workload of physical property data is extremely arduous. If the average physical property is adopted, it will bring about big error. What is more, manual calculation using general charts makes designers overburdened. Therefore improving the accuracy of physical property data becomes particularly urgent for the study of the performance of heat exchangers at low temperatures. In order to consider the effect of variable physical properties on FTWHE, we call the physical properties of helium and helium-based gas mixture at different temperatures in the NIST database by programming\[11\], so that the influence of the variable properties on heat transfer is minimized.

![Figure 2. A schematic view of a single element and heat transfer of FTWHE](image)

A schematic view of a single element and heat transfer of FTWHE are shown in figure 2. It is known that the inlet temperature of the impure helium gas is 300 K, the inlet temperature of the cooling source helium is 65 K, and the geometric parameters of the FTWHE are shown in table 1. The FTWHE is described by iteration calculation in stages to obtain its temperature field. For each element, heat and mass transfer are calculated. The outlet temperature of the previous element is taken as the inlet temperature of the next element, and the analogy is made until the last element of the heat exchanger is calculated.

According to the Law of Conservation of Energy, the enthalpy drop at the side of impure helium gas with higher relative temperature is equal to the enthalpy rise at the side of cooling source helium with lower relative temperature. As a result, for a single element the equation is given by

\[
h_{\text{high}}[i-1] - h_{\text{high}}[i] = h_{\text{low}}[i-1] - h_{\text{low}}[i] = dQ_i
\]

Heat transfer area in tube of the element is:

\[A_{\text{low}} = \pi d_i \times \pi D_m = \pi^2 d_i D_m\]

The area of heat transfer fins is given by:
Table 1. Geometric parameters of fin and mandrel of FTWHE.

| Parameters                                      | Values   |
|------------------------------------------------|----------|
| Diameter of FTWHE mandrel (Dc)                  | 133 mm   |
| Outer diameter of wound tube (D_{HEX})          | 162 mm   |
| Inner diameter of wound tube (Dm)               | 148.5 mm |
| Fin Tube Outer Diameter (d_f)                   | 14 mm    |
| Fin tube root diameter (d_o)                    | 10 mm    |
| Fin tube inner diameter (d_i)                   | 6 mm     |
| Fin thickness (δ_f)                             | 0.4 mm   |
| Fin pitch (p_f)                                 | 5 mm     |
| Fin tube length (L)                             | 12000 mm |
| Height of FTWHE (H)                             | 1046 mm  |
| External diameter of FTWHE (D)                  | 194 mm   |
| Wall thickness of stainless steel outer shell (δ)| 16 mm    |

$$A_{fin} = \pi^2 D_m [\frac{d_f^2 - d_o^2}{2p_f} + d_f(1 - \frac{d_f}{p_f})]$$  \hspace{1cm} (3)

The area of convective heat transfer for the outside fin tube is:

$$A_{high} = A_{fin} + \pi^2 D_m d_o \frac{\delta_f}{p_f}$$  \hspace{1cm} (4)

The cross section area of the impure helium side is:

$$A_{cross, high} = \frac{\pi}{4} (D_{HEX}^2 - D_c^2) - \pi D_m [d_o(1 - \frac{\delta_f}{p_f}) + d_f \frac{\delta_f}{p_f}]$$  \hspace{1cm} (5)

The equivalent diameter of the impure helium side is:

$$D_{high} = \sqrt{\frac{4A_{cross, high}}{\pi}}$$  \hspace{1cm} (6)

4. Thermodynamic analysis

The governing equations for the energy balance of an element are:

$$h_{high}[i] = h_{high}[i - 1] - \frac{Q_i}{\dot{m}_h}$$  \hspace{1cm} (7)

$$h_{low}[i] = h_{low}[i - 1] - \frac{Q_i}{\dot{m}_c}$$  \hspace{1cm} (8)

$$Q_i = \varepsilon_i C_{\min}(T_{high}[i - 1] - T_{low}[i])$$  \hspace{1cm} (9)

Where i is the element index, Q_i is the heat transfer of each element; \(\dot{m}_h\) is the mass flow of the impure helium, \(\dot{m}_c\) is the mass flow of the cooling source helium, \(C_{\min}\) is smaller thermal capacity rate between two steams; \(\varepsilon\) is the effectiveness of each element.

The \(\varepsilon\)–NTU relationship associated with FTWHE is as follows.
\[
\varepsilon_i = \frac{1 - \exp[-NTU(1 - C_r)]}{1 - C_r \exp[-NTU(1 - C_r)]}
\]

(10)

\[
NTU = \frac{UA}{C_{\text{min}}}
\]

(11)

Where \( C_r = C_{\text{min}}/C_{\text{max}} \). \( UA \) is related to the convective heat transfer characteristics of two streams and the conduction through the tube wall.

\[
UA = \frac{1}{\eta h c_{\text{high}} A_{\text{high}} + \ln(d_o/d_i) + \frac{1}{2\pi k_f H}} + \frac{1}{h c_{\text{low}} A_{\text{low}}}
\]

(12)

\[
\eta = 1 - \frac{A_{\text{fin}}}{A_{\text{tube}}} (1 - \eta_f)
\]

(13)

Where \( A_{\text{high}} \) is the outer surface of the finned tube, \( A_{\text{low}} \) is the inner surface of the finned tube, \( \eta \) is total heat transfer efficiency, \( \eta_f \) is the efficiency of the fin.

There are several correlations in the literature for determining the convective heat transfer coefficient for two streams[12][13][14]. The heat transfer coefficients of the FTWHE are highly dependent on the local distribution of pressure and temperature. In this paper the heat transfer coefficients of each element for impure helium proposed by Tzabar[8] has been adopted:

\[
h c_{\text{high}} = 0.26Re^{0.75} Pr^{1/3} \left( \frac{k_{\text{high}}}{D_{\text{high}}} \right)
\]

(14)

The correlation for presenting the convective heat transfer coefficient for the cooling source helium could be written as:

\[
h c_{\text{low}} = 0.023Re^{0.8} Pr^{1/3} (1 + 3.5 \frac{d_l}{D_m}) \left( \frac{k_{\text{low}}}{d_i} \right)
\]

(15)

Where \( k_{\text{high}} \) denotes the thermal conductivity of the impure helium and \( k_{\text{low}} \) indicates the thermal conductivity of the cooling source helium [15].

5. Results and discussion

The calculation of the numerical model is divided into two parts. The first part is the shell side fluid of FTWHE with helium and nitrogen mixture. The second part is helium and oxygen mixture as shell-side fluid of FTWHE. In order to simplify the calculation model, this model only studies the condensation separation and purification of binary mixed gases, and the mixture of more than three components is not considered. Additionally, in a helium refrigeration system, the pressure of recovery and purification of impure helium is generally less than 30 bara. Therefore, in the process of numerical simulation, the impure helium pressure is simulated in the range of 10 bara to 30 bara. And the pressure of the cooling source helium is 7 bara. Among binary helium-based gas mixtures, the volume fraction of impurity gases is up to 30%. Based on the above conditions, the influence of impurity gas in impure helium on UA value of FTWHE under different partial pressures is investigated.

The mass flow rate of the cooling source helium is 0.34 g/s and the mass flow rate of the impure helium is 0.48 g/s. The selection range of impurity gas components in impure helium is between 0%V and 30%V. Every 5%V is the point of numerical calculation, that is, the helium concentration in impure helium is 70%V, 75%V, 80%V, 85%V, 90%V, 95%V and 100%V respectively. The variation of UA values with composition under pressure of 10 bara, 20 bara and 30 bara is calculated numerically. The calculated results are plotted as a curve as shown in figure 3.
Figure 3. Under pressure of 10 bara, 20 bara and 30 bara, the UA values vary with the composition of helium-nitrogen mixture

Figure 3 indicates that with the increase of nitrogen concentration, UA value of the FTWHE first decreases and then increases. The significance of this is in the fact that, at the beginning of the increase of nitrogen composition, the liquid film formed by nitrogen condensation on the surface of finned tube increases the resistance of two fluids to further heat transfer, resulting in the decrease of UA value of FTWHE. As the nitrogen component continues to increase, UA value gradually increases after reaching the minimum value. This is mainly because the contribution of nitrogen condensation heat exchanger to UA value is greater than that of heat transfer resistance produced by liquid film formed by nitrogen condensation, so UA value increases.

When a two-component helium-based mixture is a helium-oxygen mixture, the variation of UA values with composition under pressure of 10 bara, 20 bara and 30 bara is plotted in figure 4. As shown in figure 4, it clearly indicates that UA value of the FTWHE first descended and then raised with the increase of oxygen content. This is basically consistent with the variation trend of helium-nitrogen mixture gas composition. The difference is that the minimum UA value of helium-oxygen mixture occurs at 95% of helium volume fraction, while the minimum UA value of helium-oxygen mixture occurs at around 90% of helium volume fraction. The reason for this is that the physical properties of nitrogen and oxygen are different.

The UA value of heat exchanger is also affected by different pressure. With the decrease of pressure, UA value tends to increase. The helium-nitrogen mixture is obvious in this aspect, but the helium-oxygen mixture is not so obvious. The main reason for this is that the boiling point of oxygen is lower than that of nitrogen, and most of oxygen becomes liquid at low temperature, while the amount of liquefaction of nitrogen is less than that of oxygen, so the influence of pressure on helium-oxygen mixture is less.

6. Conclusions
A numerical model has been developed for analyzing FTWHE. Because of its compact structure and high heat transfer efficiency, FTWHE is commonly used in cryogenic systems. Especially in the case of large temperature difference, the advantage of FTWHE is outstanding, which is shown by its insensitivity to stress caused by excessive temperature difference. Based on the
above reasons, the influence of two-component helium-based gas mixture on UA value of heat exchanger was studied.

Through numerical analysis of the prototype for the FTWHE, the results show that in the process of condensation, separation and purification of helium-nitrogen mixture, the UA value of FTWHE decreases first and then increases to a certain extent with the increase of nitrogen component. The minimum UA value appears at about 90% of helium gas volume component. In the simulation process of condensation separation and purification of helium-oxygen mixture, the effect of oxygen component on UA value of FTWHE is basically the same as that of helium-nitrogen mixture. UA value decreases first and then increases with the increase of oxygen component volume, but the minimum UA value appears at about 95% of helium component. In the future FTWHE design, the minimum UA value will provide some valuable suggestions for manufacturing a more safe and reliable FTWHE.

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