Cooling-capacity characteristics of Helium-4 JT cryocoolers

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Abstract. Cooling capacity of a Helium-4 JT cryocooler may be achieved at a temperature higher than liquid helium temperature. The latent cooling capacity, which should be obtained at liquid helium temperature, is defined as a special part of cooling capacity. With the thermodynamic analysis on steady working conditions of a Helium-4 JT cryocooler, its cooling capacity and temperature characteristics are presented systematically. The effects of precooling temperature and high pressure on the cooling capacity and latent cooling capacity are illustrated. Furthermore, the JT cryocoolers using hydrogen and neon as the working fluids are also discussed. It is shown that helium JT cryocooler has a special cooling capacity characteristic which does not exist in JT cryocoolers using other pure working fluids.

1. Introduction

Precooled Joule-Thomson cryocoolers (PJTCs) working at liquid helium temperature (LHT) are widely applied in space missions\cite{1} due to their long lifetime, constant cooling temperature\cite{2}, low level of vibration and electromagnetic interferences\cite{3}. However, their efficiencies are relatively low, which is worth further research.

The low pressure, $p_l$ being the standard atmospheric pressure and the system being ideal, the specific cooling capacity, $q_s$, is determined by the high pressure, $p_h$, and the precooling temperature, $T_{pre}$. For a given $T_{pre}$, there is an optimum $p_h$ that maximizes the cooling capacity\cite{4}. Based on thermodynamic analysis, de Waele\cite{6} analysed the effect of $p_h$ on the cooling capacity of a JT cryocooler working at LHT. He illustrated the relationship between cooling capacity and cooling temperature, and showed that the cooling capacity might not be acquired at LHT. Liu et al. \cite{7} explained the thermal behaviour of a PJTC working at LHT under the steady and overloaded conditions with one set of $p_h$ and $T_{pre}$.

However, the thermal behaviour of a JT cryocooler working at LHT under steady working conditions has not been analysed systematically, which will be helpful to improve its cooling efficiency.

This paper discusses temperature and cooling capacity characteristics of JT cryocoolers with different $T_{pre}$ and $p_h$ based on thermodynamics. Each working state point in the JT cryocooler can be
clearly shown in a $p$-$h$ diagram. Specific latent cooling capacity, $q_L$, is a special part of $q$, which can be obtained at LHT. The effects of $T_{pre}$ and $p_h$ on the $q_L$ and $q$ are studied with Helium-4 as the working fluid. Furthermore, JT cryocoolers using other working fluids like hydrogen and neon are analysed.

| Nomenclature | Subscripts |
|--------------|------------|
| $h$          | L          | latent |
| $p$          | pre        | precooling |
| $q$          | h, l       | high- and low-pressure side |
| $T$          | a-e        | state points |
| $\dot{Q}$    | opt        | optimum |
| $m$          |            | mass flow (kg/s) |
| $\Delta$     | difference |

**Table 1.** List of symbols.

2. **JT unit**

The JT unit is an essential part of a PJTC[4]. It can achieve LHT when $T_a$ is precooled below 45 K. As shown in figure 1, a JT unit contains a recuperator (CFHX), a JT valve, and a cold heat exchanger (CHX). The precooled Helium-4 enters the high-pressure passage of the CFHX at state a and leaves it at state b. Then, helium flow passes a JT valve before it enters the CHX, where it absorbs the heat load, $\dot{Q}$. After that, the fluid flows into the low-pressure passage of the CFHX at state d and leaves it at state e.

![Figure 1. Schematic diagram of a JT unit.](image)

Before the thermodynamic analysis, some assumptions are made to simplify the problem:

1). Kinetic and potential energies of the fluid are neglected.
2). Pressure drops only in the JT valve.
3). The CFHX is perfect. That is, the heat exchange efficiency is 100 percent and there is no pressure drop in CFHX.
4). Heat conduction in the flow direction is neglected and there is no heat transfer between the system and ambient.

3. **The effects of $p_h$**

In the steady state analysis, the pressure-enthalpy ($p$-$h$) diagrams will be used, because specific cooling capacity, $q$, and enthalpy differences can be indicated by the length of the horizontal line segments. All the numerical data for Helium-4 are derived from EES[9], which are the same with Refprop data.

The throttling process is isenthalpic, that is, $h_b=h_c$. When the recuperator is thermally isolated, $\Delta h_{ab}=\Delta h_{ed}$. Then $q$, defined as $\dot{Q}/\dot{m}$, can be achieved when $T_a=T_c=T_{pre}$ and

\[ \text{Figure 1. Schematic diagram of a JT unit.} \]
\[ q = \Delta h_L = \Delta h_{at} = \Delta h_T = h(T_{pre}, p_h) - h(T_{pre}, p_i) \]  

(1)

\( \Delta h_T \) is the intrinsic limitation on the cooling capacity of a JT cryocooler. The JT cryocooler will be warmed up continuously when the heat load exceeds \( \Delta h_T \)[6-8].

However, when \( q \) is achieved by the JT cryocooler, the cooling temperature may be already higher than the LHT. So, the specific latent cooling capacity, \( q_L \), should be defined as the part of \( q \) which can be obtained at LHT. It is found that there exist a \( p_{hopt} \) and a \( q_{hopt} \) that maximize the \( q \) and the \( q_L \) respectively for a given \( T_{pre} \). Therefore, the effects of \( p_h \) on \( q \) and \( q_L \) can be discussed according to the different ranges of \( p_h \).

In the following analysis, \( T_c = T_{pre} \) is fixed at 15 K while \( p_i \) is the standard atmospheric pressure 0.101 MPa.

3.1. \( p_h < p_{hopt} \)

Consider the process when \( p_h \) is 1 MPa for example, as shown in figure 2. The \( \Delta h_T \), as indicated by the length of the line segment between state a and the vertical dashed line, is 7.66 kJ/kg. The temperature of state b, \( T_h \), turns out to be 4.2 K as the helium flow is sufficiently cooled in the recuperator. State d is in the two-phase region, which means that the cooling temperature is 4.2 K. Thus, \( T_c = T_{pre} = T_d = 4.2 \) K. In this situation, \( q_{L} = q = \Delta h_T \).

If \( p_h \) rises, state a will move along the isothermal line of 15 K. As \( h_a \) decreases, \( \Delta h_T \) increases. Meanwhile, state b will move along the isothermal line of 4.2 K and its enthalpy will rise. As \( h_c = h_d \), the enthalpy of state d will also increase, with a speed higher than that of state c.

![Figure 2. p-h diagram for JT unit when \( p_h < p_{hopt} \).](image1)

3.2. \( p_h = p_{hopt} \)

As the pressure rises to \( p_{hopt} \), \( q_{L} = q_{hopt} \) is achieved and the fluid at state d becomes saturated vapor. The cooling temperature is still 4.2 K and \( q = q_{L} = \Delta h_T \).

For \( T_{pre} = 15 \) K, the \( p_{hopt} \) is 1.82 MPa, as shown in figure 3. The \( q \) is increased to 12.32 kJ/kg. This is the situation when the \( q_L \) is maximized. If \( p_h > p_{hopt} \), \( q_L \) will decrease as \( p_h \) rises. It is also the last moment when \( q_L \) equals \( q \) in the \( p_h \) increasing process. After that, \( q_L \) will be limited by state d. Because state d is fixed at the saturation point to ensure that the cooling temperature is 4.2 K.

![Figure 3. p-h diagram for JT unit when \( p_h = p_{hopt} \).](image2)

3.3. \( p_{hopt} < p_h < p_{hopt} \)

If \( p_h \) continues increasing, the process that obtains \( q \) and \( q_L \) will no long be the same, because in the former situation, state d will move to the right and enter the superheated region in the process that obtains \( q \), while in the latter one, state d is kept at the saturation point to keep the cooling temperature at 4.2 K.
To differentiate the two situations, we use a’-e’ to describe the process that obtains $q$ on the $p-h$ diagram. State b’ will move immediately because of the requirement that $T_b \geq T_a'$ in the CFHX determined by the second law of thermodynamics. Then state c’ and d’ will also move to right until $T_b = T_a'$ making the system steady. So, the cooling temperature will become higher than 4.2 K. And a-e is to describe the process that obtain $q_l$, state d is kept at the saturation point. Thus, $q_l$ becomes smaller than $q$. Meanwhile, $T_c$ becomes lower than $T_a$.

Take the process when the $p_h = 3$ MPa for example, as shown in figure 4. The $q$ is 14.85 kJ/kg, while the $T_a'$ is 6.4 K. The $q_l = 6.27$ kJ/kg.<

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{p-h diagram for JT unit when $p_{h,\text{opt}} < p_h < p_{h,\text{opt}}$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{p-h diagram for JT unit when $p_h = p_{h,\text{opt}}$.}
\end{figure}

3.4. $p_h = p_{h,\text{opt}}$
When $p_h$ increases to $p_{h,\text{opt}}$, $q_{\text{opt}}$ can be achieved, as shown in figure 5. At this time, state a hits the leftmost end of the 15 K isothermal line. This is the moment when $\Delta h_T$ is maximized. The $q_{\text{opt}}$ is 14.91 kJ/kg while $T_a'$ is 7.0 K. The $q_l$ decreases to be 4.97 kJ/kg under this condition.

3.5. $p_h > p_{h,\text{opt}}$
If $p_h$ rises continuously, the $q$ will decrease as state a moves to the right. The cooling temperature also keeps rising. Take the process when $p_h = 4.2$ MPa for example. As shown in figure 6, this is the moment when $q_l$ decreases to zero. The working condition with zero cooling capacity $q$ happens when $p_h$ is about 9.1 MPa.

According to the cooling capacity and temperature behaviours under steady working conditions discussed above, $q$ and $q_l$ vary with $p_h$. When $p_h$ is lower than $p_{h,\text{opt}}$, $q$ and $q_l$ are the same and they are both limited by $\Delta h_T$. The cooling temperature $T_a$ remains at 4.2 K as the fluid leaving the CHX is in the two-phase region. When $p_h$ is increased to $p_{h,\text{opt}}$, the process is under a special condition because the fluid evaporates completely in the CHX and leaves it as saturated vapor. This is also the condition when $q_l$ is maximized. After that, $q_l$ will decrease until it reaches 0, which happens when $p_h$ is 4.2 MPa. When $p_h > p_{h,\text{opt}}$, $q_l$ is lower than $q$ because $q_l$ is limited by state d, which remains at saturation point. There exists a $p_{h,\text{opt}}$ at which $q$ is maximized. When $p_h > p_{h,\text{opt}}$, $q$ and $q_l$ will both decrease as $p_h$ increases. The effects of $p_h$ on $q$ and $q_l$ are shown in figure 7.
As discussed above, for achieving $q$, cooling temperature will increase continuously as $p_h$ increases when $p_h > p_{h,opt}$. As shown in figure 8. When $p_h$ is higher than 6.6 MPa, $T_d$ is 15 K and the heat exchanged in CFHX is 0. In such a situation there is no cooling effect any more when $q=\Delta h_T$ is achieved.

4. The effects of $T_{pre}$

For a given $T_{pre}$, there exist a $p_{h,opt}$ and a $p_{h,\text{Lopt}}$ that maximize the $q$ and the $q_L$ respectively. The effects of $T_{pre}$ on the $q_{\text{opt}}$, $q_{\text{Lopt}}$ and $p_{\text{h,opt}}$, $p_{\text{h,\text{Lopt}}}$ are presented in figure 9 and figure 10. The $q_{\text{opt}}$ and $q_{\text{Lopt}}$ are different when $T_{pre}<28.7$ K.

Usually, the precooling temperature is below 20 K. In this region, as $T_{pre}$ goes lower, $q_{\text{opt}}$ and $q_{\text{Lopt}}$ increase and $p_{\text{h,opt}}$ and $p_{\text{h,\text{Lopt}}}$ decrease. It means that lower $T_{pre}$ not only improves the cooling capacity but also reduces the pressure ratio requirement on the compressor. It shows the importance of improving the efficiency of the precooler.
5. JT cryocoolers using other pure working fluids

So far, the steady working conditions for Helium-4 JT cryocoolers have been illustrated systematically. It shows the difference between $q$ and $q_L$. A similar difference also exists in JT cryocoolers using hydrogen as working fluid.

As shown in figure 11, taking $T_{pre}=60$ K for example, the intersection of $q$ and $q_L$ is $p_h=20.7$ MPa. When $p_h$ is lower than 20.7 MPa, $q$ and $q_L$ are the same. When it is higher than 20.7 MPa, $q_L$ will be lower than $q$ because of the limitation of the saturated vapor point. Thus, it can be deduced that the cooling temperature for achieving $q$ is higher than the boiling temperature when $p_h$ is higher than 20.7 MPa.

Besides, it is worth mentioning that the optimum points for both $q$ and $q_L$ are the same, which is 265.3 kJ/kg when $p_h$ is 13 MPa. That is, $p_{hop}=p_{hLop}=13$ MPa.

However, for a neon JT cryocooler, there is no difference between $q$ and $q_L$ at all, as shown in figure 12. The $q$ and $q_L$ are always the same and the $q_{opt}=q_{Lopt}=49.19$ kJ/kg when $p_h=20.5$ MPa. It indicates that the difference between $q_{Lopt}$ and $q_{opt}$ is a special characteristic for helium JT cryocoolers.
6. Conclusions
This paper discusses the steady working conditions of the Helium-4 JT cryocooler systematically and explains the cooling capacity and temperature behaviours of the Helium-4 JT cryocooler. For a given $T_{pre}$, there exists a $p_{hopt}$ and a $p_{L, opt}$ that maximize the $q$ and $q_L$ respectively. The $q_{opt}$ and $q_{L, opt}$ are different when $T_{pre} < 28.7$ K for a Helium-4 JT cryocooler. Furthermore, JT cryocoolers using other working fluids such as hydrogen and neon are also analysed. It is found that the helium JT cryocooler is unique which has the characteristic that $q_{opt} \neq q_{L, opt}$. This characteristic does not exist when other pure working fluids are applied.

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