Performance of different throttle refrigeration cycles*

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Numerous cycle configurations were presented based on the Joule-Thomson effect of real gases for different refrigeration applications from cryogenic temperature to room temperature. Using throttle device to produce refrigeration is the general feature among those refrigeration cycles, such as the vapor-compression cycle, the cascade cycle, the single-stage recuperative cycle with mixed-refrigerants, and the dual mixed-refrigerant cascade recuperative cycle. In this paper, thermodynamic models were presented to analyze the thermodynamic performances of those throttle refrigeration cycles, especially the recuperative mixed-refrigerant cycles for low temperature refrigeration applications. The results show that with optimal mixture and cycle configuration, the low-temperature recuperative refrigeration cycle can achieve a high performance as good as the commercial vapor-compression cycle.

INTRODUCTION

The vapor-compression refrigeration cycle is widely used in commercial refrigeration applications near room temperature range from 230 K to 320 K, such as industry and domestic refrigerators, air -conditioners, heat pumps, etc. The effective lowest refrigeration temperature for the single-stage vapor-compression cycle is about 230 K, limited by the refrigerant properties and the compressor characteristics. When a lower refrigeration temperature of 210 K is required, traditional measurement is using a two-stage compression cycle to provide such low temperature refrigeration. However, when the refrigeration temperature is even lower e.g. 190 K, usually a two-stage cascade cycle is used, which uses a warm refrigeration loop to precool a cold refrigeration loop. For much lower temperature applications, multistage cascade cycle is used, for example, in the former natural gas liquefaction system, three stage cascade cycle using three refrigeration loops of pure propane, ethylene, and methane to reach a cryogenic temperature of 110 K. The theoretical number of stages is unrestricted, but in practice the number is determined by economic and complexity considerations. In recent years, the number of stage is usually no more than two.

In recent years, there has been a remarkable development of the mixed-refrigerant recuperative refrigeration cycle [1-3]. Driven by an oil-lubricated single-stage compressor, the mixed-gases recuperative refrigerator has many merits over other type coolers. Those obvious merits are high reliability because of no moving parts at the coldest end, high efficiency with optimal mixtures, low cost, and easy to be built in industry scale, etc. Without any modification of the hardware, and only with different mixed-refrigerants charged, the mixed-gases Joule-Thomson refrigerator can produce cryogenic

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and ultra-low cooling covering a large temperature range from below liquid nitrogen temperature (77K) to warmer than 230K. Therefore, this refrigeration method is quite reliable and flexible in many applications, such as infrared detectors, cryosurgical devices, HTS devices, material studies, biomedical storage, gas chiller or liquefaction, etc. Numerous mixed-gases refrigeration cycle configurations were developed in the past few years. Among those cycle configurations, the single-stage recuperative cycle has the simplest cycle configuration. Former study shows that this cycle with optimal mixture has the highest thermodynamic efficiency [1, 4].

It may be wonder what about the thermodynamic performances of those throttle refrigeration cycles with different configurations and refrigerants at ideal conditions. In this paper, the thermodynamic performances of those throttle cycles were studied. The Carnot efficiencies of four typical throttle refrigeration cycles at different cooling temperature levels were calculated, including a vapor-compression cycle, a two-stage cascade cycle, a single-stage mixed-refrigerant recuperative cycle, and a dual mixed-refrigerant recuperative cycle.

THEORETICAL EFFICIENCIES OF THE CYCLES

The expressions of Carnot efficiencies of these four throttle cycles can be listed as the following.

Vapor-compression cycle (VCC)

Figure 1 shows a typical vapor-compression refrigeration cycle. The efficiency of this cycle can be listed as [6]:

$$COP_{VCC} = \frac{h_1 - h_5}{h_{2r} - h_1} \tag{1}$$

$$\eta_{VCC} = COP_{VCC} \times \frac{T_0 - T_c}{T_c} = \frac{h_1 - h_5}{h_{2r} - h_1} \times \frac{T_0 - T_c}{T_c} \tag{2}$$

where T_0 and T_c are ambient temperature and refrigeration temperature, and h is specific enthalpy, η is the Carnot efficiency.

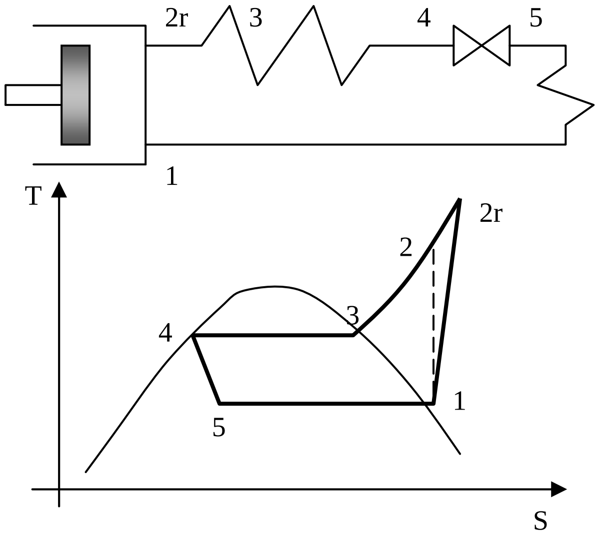

Figure 1 A vapor-compression cycle

Cascade refrigeration cycle (CRC)

Figure 2 shows a typical two-stage cascade refrigeration cycle. The efficiency of this cycle can be expressed as [6]:

$$COP_{CRC} = \frac{h_{1s} - h_{5s}}{(h_2 - h_1)\beta + (h_{2s} - h_{1s})} \tag{3}$$

$$\eta_{CRC} = \frac{h_{1s} - h_{5s}}{(h_2 - h_1)\beta + (h_{2s} - h_{1s})} \times \frac{T_0 - T_c}{T_c} \tag{4}$$

where $\beta = m_w/m_c$ is the flow rate ratio of the warm and cold refrigeration loops; m_w and m_c are flow rates of the warm and low refrigeration loops; all subscript expressions denote the steady states in the cycle.

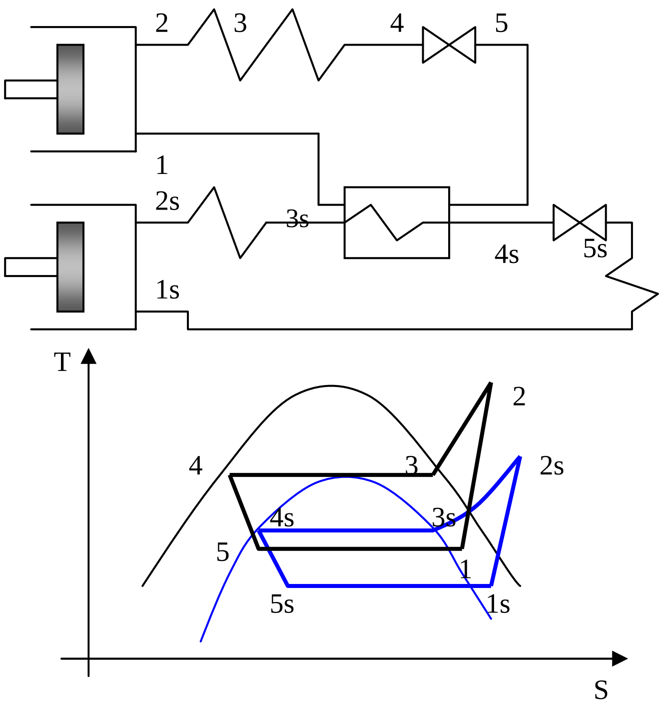

Figure 2 Schematic diagram of a two-stage cascade refrigeration cycle

Single-stage mixed-refrigerant recuperative refrigeration cycle (MRC)

Figure 3 shows the schematic diagram of a typical single-stage mixed-refrigerant recuperative refrigeration cycle. For mixed-refrigerant recuperative cycle, the thermodynamic performance can also be presented as [1, 5]:

$$q_c = h_6 - h_5 = h_6 - h_4 = h_1 - h_3 = \min(h(T)_{pl} - h(T)_{ph}) - (h_{1s} - h_1) = \Delta h_T - q_{loss} \quad (5)$$

$$q_{loss} = h_{1s} - h_1, \quad \Delta h_T = \min(h(T)_{pl} - h(T)_{ph}) \quad (6)$$

$$COP_{MRC} = \frac{q_c}{h_2 - h_{1s}} \quad (7)$$

$$\eta_{MRC} = COP_{MRC} \times \frac{T_0 - T_c}{T_c} = \frac{q_c}{h_2 - h_{1s}} \times \frac{T_0 - T_c}{T_c} \quad (8)$$

where q_{loss} is the loss of recuperator.

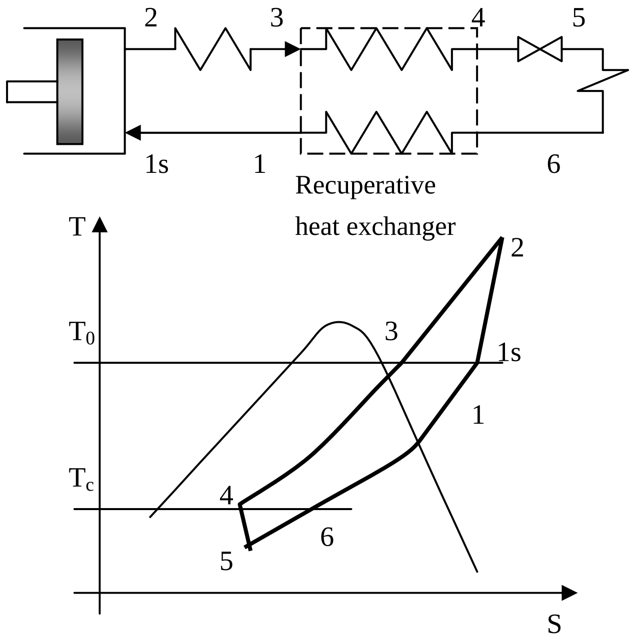

Figure 3 A mixed-refrigerant recuperative cycle

Dual mixed-refrigerant recuperative cycle (DMRC)

A schematic diagram of a typical dual mixed-refrigerant recuperative cycle is shown in Figure 4. The efficiency of the cycle can also be expressed as [1, 5]:

$$q_c = \min(h(T)_{pl} - h(T)_{ph}) - (h_{1s} - h_1) = \Delta h_T - q_{loss} \quad (9)$$

$$\Delta h_T = \min(h(T)_{pl} - h(T)_{ph}), \quad q_{loss} = h_{1s} - h_1 \quad (10)$$

$$COP_{DMRC} = \frac{q_c}{(h_2 - h_{1s}) + (h_b - h_a)\beta} \quad (11)$$

$$\eta_{DMRC} = COP_{DMRC} \times \frac{T_0 - T_c}{T_c} = \frac{q_c}{(h_2 - h_{1s}) + (h_b - h_a)\beta} \times \frac{T_0 - T_c}{T_c} \quad (12)$$

where β is the flow rate ratio of the warm and cold refrigeration loops, can be calculated with Eq. (4).

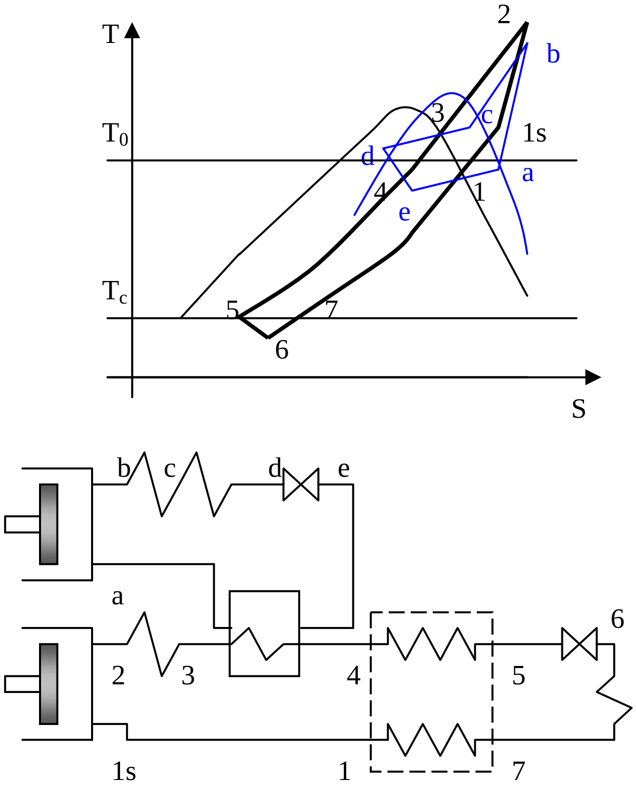

Figure 4 Schematic diagram of a dual mixed-refrigerant recuperative cycle

SIMULATION RESULTS

Above equations describe the thermodynamic performance of those throttle refrigeration cycles. The Carnot efficiencies of those cycles can be calculated with Equations (2), (4), (8) and (12). It should be mentioned here that there should be no temperature profile cross in recuperative heat exchangers in MRC and DMRC cycles [3-5]. Using an appropriate optimization method, the performance of the cycles can be optimized. Typical optimization results of those cycles were presented in Table 1.

Table 1 Thermodynamic performance comparisons of the four throttle cycles

<table>
<tr><td>Items</td><td>VCC</td><td colspan="2">CRC</td><td>MRC</td><td colspan="2">DMRC</td></tr>
<tr><td>Refrigerants</td><td>R407C</td><td>Warm loop: R407C</td><td>Cold loop: R23</td><td>Multicomponent mixtures consisting of N_2, CH_4, C_2H_6, C_3H_8, iC_4H_{10}, iC_5H_{10}</td><td>Warm loop: R407C</td><td>Cold Loop: multicomponent mixtures of N_2, CH_4, C_2H_6, C_3H_8, iC_4H_{10}</td></tr>
<tr><td>T_0, K</td><td>300</td><td>300</td><td>300</td><td>300</td><td>300</td><td>300</td></tr>
<tr><td>T_c, K</td><td>245.1</td><td>241.9</td><td>198</td><td>120</td><td>251.8</td><td>120</td></tr>
<tr><td>p_h, MPa</td><td>1.3</td><td>1.2</td><td>1.2</td><td>1.8</td><td>1.3</td><td>1.8</td></tr>
<tr><td>p_l, MPa</td><td>0.15</td><td>0.15</td><td>0.15</td><td>0.3</td><td>0.15</td><td>0.3</td></tr>
<tr><td rowspan="2">COP</td><td rowspan="2">2.28</td><td>1.67</td><td>/</td><td rowspan="2">0.341</td><td>2.36</td><td>/</td></tr>
<tr><td colspan="2">1.00</td><td colspan="2">0.338</td></tr>
<tr><td>η, %</td><td>51.2</td><td colspan="2">51.3</td><td>51.2</td><td colspan="2">50.7</td></tr>
</table>

From Table 1, it can be found that all the throttle cycles can provide almost equivalent values of the Carnot efficiencies for different refrigeration temperatures from cryogenic to near room temperature ranges. The calculation results were obtained at ideal compression conditions that there is an ideal adiabatic compressing process without entropy generation in the compressor. The results shown in Table 1 indicate that the mixed-refrigerant recuperative throttle cycle can achieve quite good performance as high as the commercial vapor-compression refrigeration cycle. However, because of the additional loss in the recuperators and heat isolation at low temperatures, the practical performance of the low temperature recuperative cycle is hard to achieve a high performance as good as the vapor-compression cycle.

SUMMARY

Thermodynamic performances of throttle cycles including the widely used commercial vapor-compression cycle, the cascade cycle, the single-stage mixed-refrigerant recuperative cycle, and the dual mixed-refrigerant recuperative cycle were illustrated and analyzed in this paper. The Carnot efficiency was used as a comparison criterion in the comparisons of all those throttle cycles at different refrigeration temperature ranges. The optimized results at ideal compressing-process conditions show that all the throttle cycles can provide near equivalent values even providing refrigeration from cryogenic temperature to near room temperature ranges.

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