Performance Analysis of Joule-Thomson Cooler Supplied with Gas Mixtures

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Abstract. Joule-Thomson (J-T) cryo-coolers working in closed cycles and supplied with gas mixtures are the subject of intensive research in different laboratories. The replacement of pure nitrogen by nitrogen-hydrocarbon mixtures allows to improve both thermodynamic parameters and economy of the refrigerators. It is possible to avoid high pressures in the heat exchanger and to use standard refrigeration compressor instead of gas bottles or high-pressure oil free compressor. Closed cycle and mixture filled Joule-Thomson cryogenic refrigerator providing 10-20 W of cooling power at temperature range 90-100 K has been designed and manufactured. Thermodynamic analysis including the optimization of the cryo-cooler mixture has been performed with ASPEN HYSYS software. The paper describes the design of the cryo-cooler and provides thermodynamic analysis of the system. The test results are presented and discussed.

1. Joule-Thomson cooler – introduction
Joule-Thomson coolers are widely known and appreciated because of their simple construction, see Figure 1a, no moving elements working at low temperatures and short start-up time. However to produce cooling power exceeding all losses, high working pressure, up to 200 bar for pure nitrogen is required, see Figure 1b. It results in high investment costs and the limitation of the system applications. Replacing pure gases with gas mixtures causes higher (up to 120 K) and variable temperature of cooling power, see Figure 1c. Nevertheless, this loss is covered by the significant reduction of the working pressure, even by factor 10.

![Figure 1. Joule-Thomson cooler a) system elements, b) thermodynamic processes of N₂, c) thermodynamic processes of gas mixture](image-url)
Table 1 gives the comparison of Joule-Thomson cooler supplied with pure nitrogen and gas mixture.

Table 1. The comparison of Joule-Thomson cooler supplied with pure N$_2$ and gas mixture

| Joule-Thomson cooler fed with: | pure nitrogen | gas mixture |
|-------------------------------|--------------|-------------|
| Working pressure              | 100-200 bar  | 10-20 bar   |
| Cooling power produced at temperature | Constant 78 K | Variable 80-120 K |
| Phase transition inside the recuperative heat exchanger | NO | YES |
| Temp. difference at the cold end of the recuperative heat exchanger | 70-90 K | 5-15 K |

The idea of replacing pure gases with mixtures as working medium of J-T cryocoolers was presented in 1971 [2]. Firstly, refrigerants as CFCs and HCFCs have been considered as the admixtures [4,9,10]. However, most of them have been or will be soon forbidden because of the Montreal Protocol. Nowadays, most commonly used cryogenic mixtures include nitrogen and hydrocarbons [11,12,13]. According to the literature, to produce cooling power at temperature 80-120 K, mixtures based on nitrogen and methane, ethane, propane and i-butane should be analyzed [10,11]. From thermodynamic point of view, several positive effects can be observed in the system supplied with mixtures. Apart pressure decrease, gas mixtures improve the efficiency of the system by decreasing heat losses in the recuperative heat exchanger (adjustment of the stream temperatures) and by limitation of expansion losses by throttling liquid-gas state instead of gas only (phase transition starts in the recuperative heat exchanger, see Fig. 1c).

Due to the fact, the development of reliable, relatively cheap one-stage cooler which would fill the gap of medium capacity cryogenic coolers on the global market, J-T systems supplied with gas mixtures have been constantly developed, tested and improved by several research groups [3,4,5,6,7,8]. However, the commercialization of this kind of coolers requires special attention on the following problems:

1. The limitation of the investment costs
2. The analysis and stability of working parameters
3. The repeatability of the working parameters.

1.1. Investment cost limitation

Due to reduction of the working pressure down to 25 bar by the gas mixtures, followed by the replacing specialized high-pressure compressor with low-pressure one, the limitation of the investment costs can be expected. Since gas mixtures using for J-T systems are composed mostly of hydrocarbons which do not react with copper, hermetically-sealed (hermetic) compressors can be used. In hermetic compressors, the working fluid is in contact with the windings of the motor because both motor and all compressor elements are assembled together within a steel common housing. Fig. 2 shows hermetically-sealed refrigeration compressor. The compressor container parts are welded together, so no gas can enter or escape from it. Only fluid lines (suction and discharge tubes) and electrical connections penetrate the housing. Power to the crankshaft is provided by the electric motor. The crankshaft revolves in its bearing, driving the piston(s) in the cylinder(s). The crankshaft is design to carry oil from the bottom of the compressor to all bearing surfaces (splash lubrication). Low pressure gas is sucked into the shell and surrounds the compressor crankcase and the motor. Gas flows through the shell to the cylinder(s), via the suction valves. The gas is compressed by the moving piston and is released through the discharge valves and compressor-discharge tube [14,15].
Hermetic compressors are commercially available devices, produced in large quantities resulting in relatively low price. They are expected to run for decades with no leaks of the working fluid. These compressors are widely used in refrigeration, air-condition or heat-pumps systems.

Table 2 presents the comparison of compressor parameters used for refrigeration and cryogenic technologies. Main restriction of using hermetic compressors arises from the temperature limit at the discharge side. The final gas temperature of the compression can’t exceed 150°C to avoid thermal decomposition of the oil. Replacing refrigerants with gas mixtures, increasing pressure ratio and increasing of the inlet gas temperature require to use additional (external) cooling system of the oil. Due to the effect of oil solubility by hydrocarbons, high efficiency oil separator is required to avoid freezing oil at low temperature points of the cooler.

Table 2. The comparison of compressors used for refrigeration and cryogenic technology.

|                        | Refrigeration                      | Cryogenics                      |
|------------------------|------------------------------------|---------------------------------|
| Working medium         | Refrigerants (one component or mixtures): R 134a, R404a Hydrocarbons: R290, R600a | 3,4 and 5-components mixtures of nitrogen and hydrocarbons |
| Temperature limit at the discharge side | up to 8 | 150°C |
| Pressure ratio limit   | Low temperature refrigerant vapor  | up to 25 Gas mixture at ambient temperature |
| Inlet medium           | Oil (splash lubrication)           | Oil (splash lubrication)        |
| Lubrication            | Either oil trap or oil separator   | High efficiency oil separator   |
| Oil removal            |                                    |                                 |

1.2. The working parameters of analysis and stabilization

The lowest evaporating temperature should not exceed the value resulting from Joule-Thomson cooler application. Assuming both evaporating temperature, working pressure ratio and cooling power depend on mixture composition and they can be predicted by the theoretical analysis.

The optimization of the mixture composition has been based on the following desired properties:

1. High isothermal throttling effect of the isenthalpic expansion for relatively low compression pressure.
2. The evaporating temperature limitation and cooling power requirement (based on the cooler application).
3. The compression temperature and pressure ratio limitation (for hermetic compressor).
4. No solid phase in any point of the system.
The analysis has been completed by Aspen HYSYS software. Both steady state and dynamic simulation of Joule-Thomson cooler have been analyzed. The chosen mixtures of 20% methane, 30% ethane, 10% propane, 20% and i-butane 20% have been tested at J-T cooler test stand designed and manufactured at Wrocław University of Technology. Figures 3a, 3b and 3c show picture of the cooler test stand, scheme of Joule-Thomson system and Aspen HYSYS simulation configuration together with an example of the analysis results.

Figure 3. Joule-Thomson cooler scheme, test stand and simulation configuration.

Figure 4. Joule-Thomson cooler test results.
Figure 4a, b show the test results of the J-T cooler supplied with mixture of nitrogen 20%, methane 30%, ethane 10%, propane 20% and i-butane 20% for working pressure of 24 barg. Special attention should be focused on the stability of the temperature after throttling valve, see Figure 4a which often is main problem to be solved. The measurements were done for the cooling capacity of 6W.

The lowest temperature achieved was about 100 K with pressure ratio 25. System produces from 4 to 12 W of cooling power at 100 and 108 K respectively. Power consumption \( P \) during producing 12W of cooling power \( Q \) was 440W. The COP of the cooler equals:

\[
COP = \frac{Q}{P} = 0.0272
\]

(1)

To compare the efficiency with other coolers the percent of Carnot was calculated. For temperatures \( T_1=300K \), \( T_5=108K \) and COP calculated in eq. 1 the percent of Carnot is:

\[
\%_{\text{Carnot}} = \frac{COP}{\eta_C} \cdot 100\% = 4.84\%
\]

(2)

The value is slightly lower than 5%. The efficiencies compared to Carnot were presented by Strobridge and for the cryocoolers which use J-T effect to reduce the temperature and generate about 10W, the value of % Carnot is in the range between 3 and 10%. As can be seen the received value is located within the range [16].

1.3. Repeatability of the working parameters

To commercialize closed Joule-Thomson cooler supplied with gas mixtures, the repeatability of the working parameters is one of the most important issue. Cooler working in the closed system should not significantly change main parameters like temperature or cooling power during the operation time. Preliminary tests of temperature and cooling power have been done within 28 days, see Figure 5. The results show the repeatability of the working parameters for this period of time.

![Figure 5. Preliminary tests of the cooler working parameter repeatability.](image)

2. Conclusions

Joule-Thomson coolers supplied with gas mixture are well known and tested in both industrial and laboratory scale. However, medium capacity systems (up to 50 W) are not commercially available yet. The experimental analysis of J-T refrigerator of capacity 4 – 12 W has been presented to discuss 3 main issues of potential commercialization of this cryocoolers. The results can be summarized with the following conclusions:

1. The possibility of use hermetic refrigeration compressors (relatively cheap and commercially available) has been confirmed.
2. Five-components mixtures of nitrogen, methane, ethane, propane and i-butane allow to achieve cryogenic stable temperature down to 100 K with working pressure ratio up to 24 barg.
3. The repeatability of the working parameters has been preliminary confirmed.
3. References

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