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Characterization of a scroll-type compressor for driving JT cryocoolers working at liquid helium temperature

Y W Shen[1,2], Z H Gan[1,2], D L Liu[1,2,3*], S F Chen[1,2], Y F Yao[1,2]
[1] Institute of Refrigeration and Cryogenics, Zhejiang University Hangzhou 310027, P.R. China
[2] Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province, Hangzhou 310027, P.R. China
[3] Institute of Advanced Technology, Westlake Institute for Advanced Study, Westlake University, Hangzhou 310024, P.R. China

* E-mail: ldlzju@zju.edu.cn

Abstract The real performance of the compressor significantly affects the optimization results of a Joule-Thomson (JT) cryocooler working at liquid helium temperature. A compressor experimental setup has been built to measure an oil-free scroll-type compressor. The measured mass-flow rate decreases from 11.7 mg/s to 10.9 mg/s as the pressure ratio increases from 4.2 to 23.3. By fitting the processed measurement results, models of suction volume flow and exergetic efficiency of the compressor are obtained. It is shown that the suction volume flow and exergetic efficiency can be expressed as functions of the pressure ratio. Combining these models, a method to optimize the discharge pressure and precooling temperature for optimal coefficient of performance of the complete JT cryocooler is proposed. The effects of the real performance of the compressor on the optimal parameters of the JT cryocooler are presented with the calculation results.

1. Introduction

A DC flow compressor is a critical component for cryocoolers, for example Joule-Thomson cryocoolers (JTCs) [1], Reverse-Brayton cryocoolers [2], GM cryocoolers, or GM-type pulse tube cryocoolers [3, 4]. In a JT cryocooler (JTC), its compressor usually dominates the efficiency and the weight of the system.

Nowadays, precooled JT cryocoolers (PJTCs), employing valved linear compressors to achieve long lifetimes, are the main cooling technology at liquid helium temperature for space applications. These PJTCs and the valved linear compressors (typically 2-stage) on which they depend were developed by Rutherford Appleton Laboratory [5], Sumitomo Heavy Industries, Ltd. [6, 7], Ball Aerospace & Technologies Corp. [8-10], Northrop Grumman Aerospace Systems [11-13] and the Chinese Academy of Sciences [14]. Additionally, the National Institute of Standards and Technology [15] attempted to build a similar cryocooler system for superconducting nanowire single photon detectors used on ground. However, research into the effects of the real performance of compressors on the JTCs are rare.

In the present work, a scroll-type compressor developed by Advanced Scroll Technologies (Hangzhou) Inc. [16] is measured. This new kind of scroll-type compressor can achieve a high-pressure ratio without liquid oil lubrication. Based on the experimental data, models of suction volume flow and exergetic efficiency of the compressor are built. These two models are combined with the model of a complete PJTC system, considering characteristics of the precooling cryocooler. Finally, the influences of the compressor's real performance on the PJTC are discussed.

2. Experimental setup

The oil-free scroll-type compressor SCF-4/25 was tested with the same method described in reference [3] using a measurement system built at Zhejiang University. The external parameters were measured and used to describe the compressor's suction volume flow and exergetic efficiency. The experimental setup is shown in Figure 1. The helium discharged by the compressor package flows through a discharge flexible line, a regulating valve (RV), a mass-flow meter (MFM) and a suction flexible line. Two pressure sensors, Ph and Pl, monitor the discharge pressure, p_d, and suction pressure, p_s, respectively [3]. The subscripted indexes, s and d, represent the suction state and the discharge state respectively. The input electrical power of the compressor package is measured by a power meter. The details of the measuring instruments are listed in Table 1.

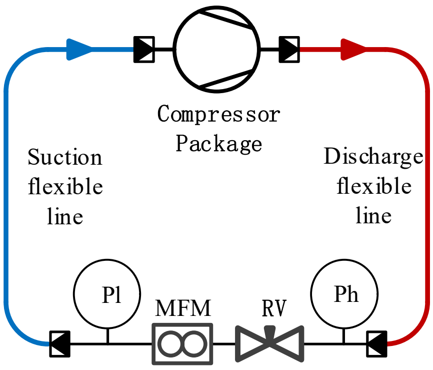

Figure 1. Schematic of the experimental setup [3]

Figure 2. The picture of the compressor SCF-4/25

Table 1. Details of the measuring instruments

Measuring instrument	Corresponding abbreviation in Figure 1	Brand/type
Pressure sensors	Ph and Pl	GE UNIK 5000
Mass-flow meter	MFM	Bronkhorst F-111B
Power meter	The input electrical power of the compressor	(UNI-T)UT230A -II
Regulating valve	RV	Swagelok ss-ss4

3. Real performance model of the compressor

The compressor SCF-4/25 shown in Figure 2 was tested using the experimental setup (see Figure 1). During the measurement, the suction pressure, p_s, was fixed at 0.101 MPa. The discharge pressure, p_d, was adjusted between 0.433 MPa and 2.377 MPa by varying the helium filling pressure and the opening of the regulating valve. Then the pressure ratio, r_p, increased from 4.2 to 23.3 as the mass flow, $\dot{m}$, decreased from 11.7 mg/s to 10.9 mg/s and the electrical power, $\dot{W}_e$, increased from 240 W to 493 W.

3.1. *Suction volume flow*

As the compressor is cooled by flowing water, the suction temperature, T_s, is assumed as 300 K. The suction volume flow, $\dot{V}_s$, of the compressor SCF-4/25 can be calculated as

$$\dot{V}_s = \frac{\dot{m}}{\rho(T_s, p_s)} \quad (1)$$

The suction volume flow, $\dot{V}_s$, has been proved to decrease linearly with the increasing r_p for scroll-type compressors [3], where r_p is defined as

$$r_p = p_d / p_s \quad (2)$$

This linear relationship is also shown to apply to the suction volume flow, $\dot{V}_s$, and the pressure ratio, r_p, of the compressor SCF-4/25 (see Figure 3). The linear fitting result of the suction volume flow is:

$$\dot{V}_{\mathrm{s}} = \left(72.381 - 0.263 r_{\mathrm{P}}\right)\ \mathrm{cm^3/s} \tag{3}$$

The fitting range is $4.2<r_{\mathrm{P}}<23.3$.

3.2. *Exergetic efficiency*

If it is assumed that the suction temperature, T_{s}, discharge temperature, T_{d}, and environmental temperature, T_0, are constant at 300 K, the exergetic efficiency, η_{ex}, can be calculated based on the measured data,

$$\eta_{\mathrm{ex}} = \Delta\dot{E}/\dot{W}_{\mathrm{e}} \tag{4}$$

in which

$$\Delta\dot{E} = \dot{E}_{\mathrm{d}} - \dot{E}_{\mathrm{s}} \tag{5}$$

$$\dot{E}_{\mathrm{d}} = \dot{m}\left[h\left(p_{\mathrm{d}},T_{\mathrm{d}}\right) - T_0 s\left(p_{\mathrm{d}},T_{\mathrm{d}}\right)\right] \tag{6}$$

$$\dot{E}_{\mathrm{s}} = \dot{m}\left[h\left(p_{\mathrm{s}},T_{\mathrm{s}}\right) - T_0 s\left(p_{\mathrm{s}},T_{\mathrm{s}}\right)\right] \tag{7}$$

$h(p,T)$, $s(p,T)$ and $\dot{E}$ are the functions of specific enthalpy, specific entropy and exergy determined by temperature and pressure.

The relationship between η_{ex} and r_{p} can be obtained by a third-order polynomial fit, which is verified by other commercial compressors as measured in the reference [3]. For the compressor SCF-4/25, the exergetic efficiency, η_{ex}, is about 5% as shown in Figure 4. It achieves the maximum when $r_{\mathrm{p}}=10$. The fitting result of the η_{ex} is

$$\eta_{\mathrm{ex}} = 0.02658 + 5.42\times10^{-3} r_{\mathrm{P}} - 3.49\times10^{-4} r_{\mathrm{P}}^{2} + 6.33\times10^{-6} r_{\mathrm{P}}^{3} \tag{8}$$

The fitting range is $4.2<r_{\mathrm{P}}<23.3$.

Based on the suction volume flow and the exergetic efficiency models, the effects of the compressor's real performance on a PJTC can be analyzed.

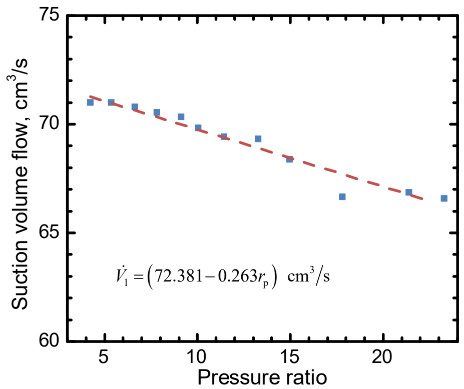

Figure 3. Suction volume flow vs pressure ratio

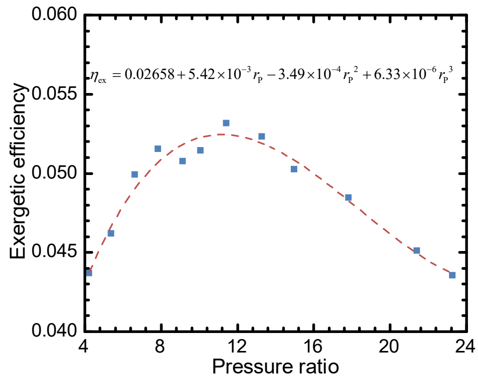

Figure 4. Exergetic efficiency vs pressure ratio

4. Model correction of a PJTC

According to figure 1 of reference [17], the PJTC described therein includes a two-stage Stirling-type precooler and a JTC. In addition, the method to calculate the performance of the PJTC was briefly introduced. In that work, it was assumed that the exergetic efficiency of the compressor was constant. After the measurement of the compressor SCF-4/25, the PJTC model [17] can be corrected with the suction volume flow and exergetic efficiency models acquired in the Section 3. In the corrected PJTC model, the mass flow, $\dot{m}$, is a function of the pressure ratio, r_{p},

$$\dot{m} = \rho_{\mathrm{s}}\dot{V}_{\mathrm{s}}\left(r_{\mathrm{P}}\right) \tag{9}$$

in which ρ_s is the helium density at the suction inlet of the compressor, depending on the suction pressure, p_s, and the suction temperature, T_s. When p_s and T_s are fixed, the mass flow, $\dot{m}$, is a function of the discharge pressure, p_d. In the same way, the exergetic efficiency, η_{ex}, is also a function of p_d.

It is assumed that the suction pressure, p_s, of a PJTC was 0.101 MPa, the first-stage precooling temperature was 89.99 K, and the heat exchanger effectiveness was 0.97. The characteristics of the precooling cryocooler were determined from a fitting correlation of Stirling-type cryocoolers proposed by Ladner [18], which explained the relation between the relative Carnot efficiency, FOM_{ST}, and the precooling temperature, T_{ST}. Thus, the performance of the precooler can be obtained as:

$$\mathrm{FOM_{ST}} = 3.2995\times10^{-3}T_{ST} - 9.9354\times10^{-6}T_{ST}^{\ 2} - 3.5335\times10^{-9}T_{ST}^{\ 3} \tag{10}$$

Before correction, the relationship between COP and p_d with the different second-stage precooling temperatures, T_a, (10 K, 15 K and 20 K) is shown in Figure 5. The mass flow, $\dot{m}$, and the exergetic efficiency, η_{ex}, are fixed at 8.66 mg/s and 27.16%, respectively. The COP_{opt} line connects peak points of COP lines at different T_a. The optimized T_a is 16.6 K while the corresponding p_d is 2.03 MPa.

After the PJTC model is corrected by the real performance of the compressor, the relationship between COP and p_d is shown in Figure 6. Compared with Figure 5, it can be found that the optimized T_a turns to 11.6 K when the corresponding p_d is 1.38 MPa. Moreover, Figure 6 shows that the COP increases with a proper reduction of T_a and p_d.

The main reason for the differences between the COP_{opt} lines in Figure 5 and Figure 6 is that the real exergetic efficiency, η_{ex}, is lower than the assumed 27.16%. Moreover, as shown in Figure 4, the optimal r_p for the η_{ex} is between 10 and 15, which leads to a higher COP in the relevant p_d range in the corrected results.

The compressor SCF-4/25 still has the potential to improve its exergetic efficiency because it is modified directly from a current product without any optimization. Meanwhile, the measured results show that the compressor can achieve a pressure ratio above 20 with only one motor and meet the mass flow required by the PJTC at the same time, which is not realized by any linear compressor.

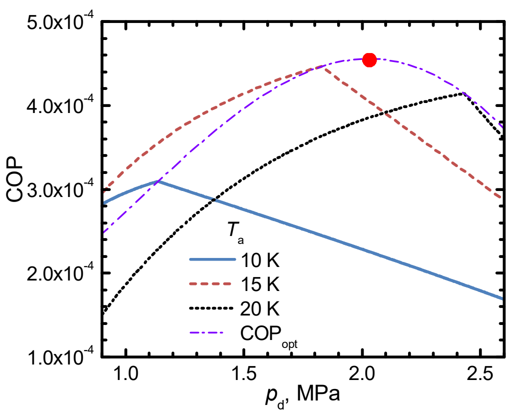

Figure 5. Effect of p_d on COP

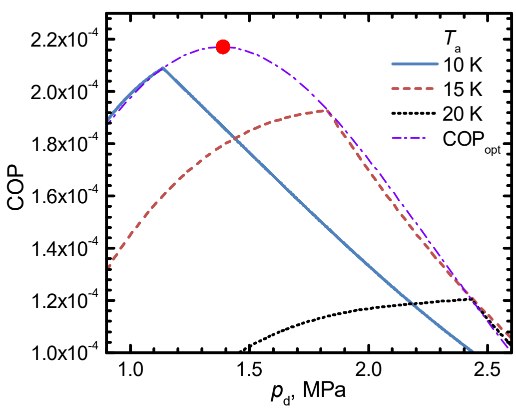

Figure 6. Effect of p_d on COP with corrected compressor model

5. Summary

The oil-free scroll-type compressor SCF-4/25 is measured with a compressor experimental setup. The suction volume flow and the exergetic efficiency models are obtained to correct the PJTC model.

The analysis shows that the real performance of the compressor has a significant impact on a PJTC. The optimized precooling temperatures and corresponding discharge pressures can be different when different compressors are used.

The compressor SCF-4/25 can achieve a pressure ratio above 20 while also providing the required mass flow with only one motor. In the future, the manufacture plans to apply a new kind of material to achieve a long-lifetime of the compressor. Its efficiency can be improved with an

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optimized design for a certain working condition.

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