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Study on the coupling performance of a turboexpander compressor applied in cryogenic reverse Brayton air refrigerator

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ABSTRACT

A small cryogenic reverse Brayton air refrigerator with turboexpander compressor (TEC) is presented in this study. Because of stable process, simple matching between expander and brake blower, and easy regulation, a turboexpander with brake blower is usually used in small reverse Brayton refrigerator. However, a turboexpander with brake blower just consumes and wastes the output energy during the enthalpy drop. In contrast, the output energy of TEC is absorbed by its coupled compressor for recycling. Thus when employing a TEC, the reverse Brayton refrigerator will achieve lower refrigeration temperature, larger cooling capacity and more effective energy use. TEC overall performance, which has an important impact on the refrigerator thermal performance, is mainly determined by the coupling between expander and compressor. In a TEC, the compressor and expander should seek balance among energy, rotating speed, mass flow rate and pressure, though restricted by individual working characteristics. The coupling relations among compressor efficiency, expander efficiency, compressor pressure ratio and expander expansion ratio are quite complex. In this study, theoretical coupling analysis between expander and compressor was conducted. The aerodynamic performances of compressor and expander were calculated using CFX simulation with SST model. The performance curves of compressor and expander were obtained through simulation results, which were validated by experimental data. Based on the coupling analysis and numerical simulations, the automatic coupling model between compression process and expansion process was established via Matlab code. The refrigerator was tested under varied coupling parameters (compressor inlet pressures and expander inlet temperatures). The calculated coupling performance was validated by experimental data. With good coupling, the cooling capacity of refrigerator reached 48.0 W at 99.6 K. The coupling performance was calculated through the coupling model, and mutual relations and interactions among coupling parameters were quantitatively described and clarified. The coupling model could effectively predict the coupling performance and therefore allow for the further design and optimization of TEC.

1. Introduction

The research of cryogenic field early started in 1877, when Cailletet first liquefied the oxygen [1]. Until now, with its rapid development, cryogenic technology has been widely used in many fields beyond gas liquefaction and separation, such as high-energy physics, space applications, superconducting, and medical applications [2]. A schematic diagram of a typical reverse Brayton air cycle and its *T-s* plot are illustrated in Fig. 1. Expanding the gas through an expander would always be more effective to get low temperatures comparing with an isenthalpic expansion through a J-T valve. In addition, the expansion work in an expander could be recycled (as shown in Fig. 1). Therefore, employing high-efficiency turboexpander with gas bearing and compact heat exchanger, the reverse Brayton refrigerator could realize small size, light weight, long life, high operating reliability, wide range of refrigeration temperature and cooling capacity. Thus, it has been widely applied in many fields, such as space applications [3], environment simulation [4], air-conditioning [5], heat pump [6], and superconducting [7,8]. With working fluid of air, the reverse Brayton air refrigerator has special advantages of no pollution, easy access, and low cost.

When the reverse Brayton air refrigerator is applied in cryogenic fields, it will undergo great changes of temperature. In addition, the refrigerator might run under varied working conditions as cooling load changes. Both changes of temperature and cooling load will put a refrigerator to test. Much research has been done to enhance the flexibility of the refrigerator. Hiraia et al. [8]

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Nomenclature

c_s	isentropic spouting velocity (m s^{-1})
D_{1E}	inlet diameter of expander impeller (m)
h_{0E}	expander inlet enthalpy (J kg^{-1})
h_{2E}	expander outlet enthalpy (J kg^{-1})
h_E	real enthalpy drop of expander (J kg^{-1})
h_{Es}	isentropic enthalpy drop of expander (J kg^{-1})
K_C	air adiabatic exponent of compressor
K_E	air adiabatic exponent of expander
n	rotating speed (rpm)
p_{0C}	compressor inlet pressure (MPa)
p_{2E}	expander outlet pressure (MPa)
W_C	compression work of compressor (W)
W_E	expansion work of expander (W)
q_{mC}	compressor mass flow rate (kg s^{-1})
q_{mE}	expander mass flow rate (kg s^{-1})
R	gas constant of air (J kg^{-1} K^{-1})
T_{0C}	compressor inlet temperature (K)
T_{0E}	expander inlet temperature (K)
u_1	expander impeller inlet peripheral velocity (m s^{-1})
Greek	
ε_C	compressor pressure ratio
ε_E	expander expansion ratio
η_C	compressor isentropic efficiency
η_E	expander isentropic efficiency
η_M	mechanical efficiency
η_{TEC}	TEC overall efficiency

developed a turbo-compressor to control the cooling capacity. Deserranno et al. [9] designed a Brayton cryocooler for ZBO liquid hydrogen storage in space. With optimization of the compressor and turboalternator, the Brayton cryocooler reached a relatively high COP under different cooling power. Kato et al. [10] used a type of variable nozzle vane height to control cooling capacity. Smooth operation of changing capacity was obtained. Due to advantages of high reliability, simple matching between expander and brake blower, easy regulation and so on, a brake blower is often used to regulate the turboexpander in small reverse Brayton refrigerator [5,11]. Hou et al. [11] proposed a brake pressure feedback control to reverse Brayton air refrigerator, with which the maximum turboexpander efficiency could be obtained under different operating conditions. The refrigerator cooling capacity could be regulated through the brake blower. A brake blower has sense in an experimental set-up for a test of the expander, but the expansion work is just consumed and wasted, the energy efficiency is unacceptable. In practical air-cycle refrigeration system, a TEC should be used to use energy efficiently. The reverse Brayton refrigerator equipped with a TEC could achieve lower refrigeration temperature and larger cooling capacity because of energy recycling.

As shown in Fig. 1, in a TEC, the gas is first compressed in the centrifugal compressor (hot end of TEC) and then is expanded in the turboexpander (cold end of TEC). The output energy of expander could be recycled by the compressor. The refrigerator with TEC could promote energy efficiency. It can be seen from the working process of TEC that, compressor and expander should seek balance among energy, rotating speed, mass flow rate and pressure, though restricted by individual working characteristics. Thus the coupling relations among compressor efficiency, expander efficiency, compressor pressure ratio and expander expansion ratio are quite complex. It also indicates that the coupling between compressor and expander is automatically established. For the automatic coupling characteristics, TEC could not be regulated so easily as the turboexpander with brake blower. Whether the TEC could operate well under varied working conditions and stand the test for great changes of refrigerating temperature and cooling capacity depends on its coupling performance.

Some research on TEC for energy recycle and refrigeration has been done. Neseli et al. used a turboexpander for energy recovery from natural gas pressure reduction, and they carried out an energy and exergy analysis [12]. A booster compressor was applied in a cryogenic air separation unit for improving energy efficiency by Van der Ham [13]. Davis and Land [14] invented an integral turbo compressor-expander system for refrigeration, and the power was recovered to drive the compressor. Giroux [15] invented a sealing system for TEC. Both labyrinth seals and mechanical seals were used for preventing leakage in his invention. Spence et al. [16] described an air-cycle refrigeration system using a TEC for road transport, which achieved good performance. Zhang et al. [17] researched a power recovery turboexpander in a refrigeration system, and a maximum of 10.4% isentropic efficiency was

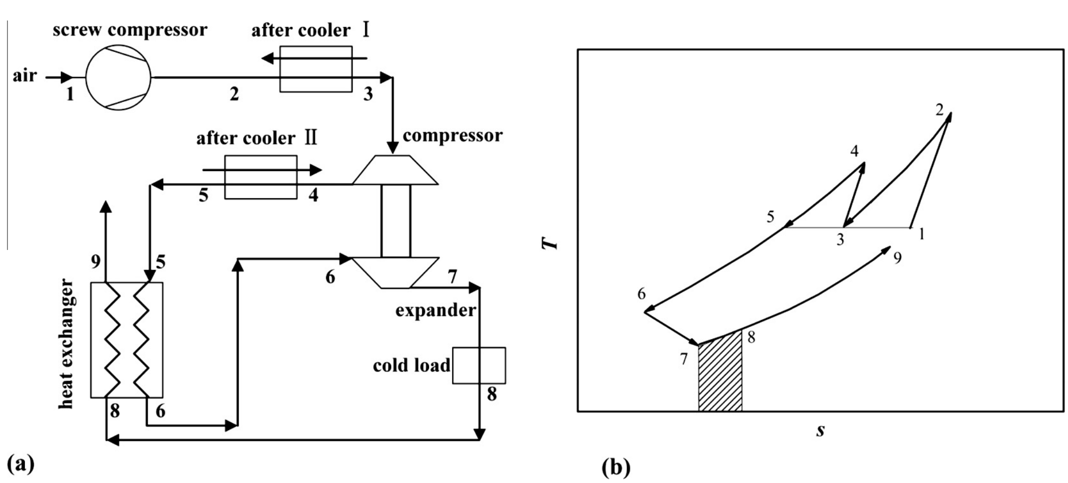

Fig. 1. Schematic view and *T-s* diagram of a reverse Brayton air cycle with regeneration (a) schematic view; (b) *T-s* diagram.