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Research paper

Evaluation and analysis on the coupling performance of a high-speed turboexpander compressor

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ABSTRACT

A high-speed turboexpander compressor (TEC) for small reverse Brayton air refrigerator is tested and analyzed in the present work. A TEC consists of an expander and a compressor, which are coupled together and interact with each other directly. Meanwhile, the expander and compressor have different effects on the refrigerator. The TEC overall efficiency, which contains effects of the expander's expansion, the compressor's pre-compression, and the pressure drop between them, was proved. It unifies influences of both compression and expansion processes on the COP of refrigerator and could be used to evaluate the TEC overall performance. Then, the coupling parameters were analyzed, which shows that for a TEC, the expander efficiency should be fully utilized first, followed by the compressor pressure ratio. Experiments were carried out to test the TEC coupling performances. The results indicated that, the TEC overall efficiency could reach 67.2%, and meanwhile 22.3% of the energy output was recycled.

1. Introduction

As an important equipment in the energy field, turboexpanders have been widely applied in cryogenic engineering, power engineering, chemical industries, etc. When working as an energy recycling machine, it has been applied in LNG plant [1–4], gas recovery [5,6], waste gas utilization [7,8], air separation plant [9–11], ORC cycles [12–15] and so on. For turboexpander applied in reverse Brayton refrigerator, it was mainly used to produce cooling. When the gas is expanded through an expander and low temperature is obtained, there will be energy output, which must be absorbed to keep balance. For advantages of simple matching, high reliability, easy regulation and so on, the energy output from the expansion process was consumed by a brake blower, an alternator or an oil brake in some refrigerators. For example, Hirai et al. [16] described a turbo-Brayton refrigerator with Neon as working fluid for HTS power machines, using an alternator as its brake. Hou et al. [17] developed a Helium reverse Brayton refrigerator for space environment simulation with a blower as brake and proposed a brake pressure feedback control later on [18]. Kardine et al. [19] described a high speed turboexpander with oil brake for hydrogen plant. But in these cases, the expansion energy is just expended, the energy-utilization ratio is relatively low. In actual air-cycle refrigeration equipment and large cryogenic plant, a TEC should be applied to recycle energy and improve energy efficiency.

In a TEC, the working fluid will be compressed firstly in the hot end (the compressor) before going to the cold end (the expander) and thus the output power during expansion process could be recycled. Compressor and expander should not only satisfies equilibrium relationship of energy, mass flow, rotating speed, and pressure, but also follow their individual working characteristics. Therefore, relations among compression efficiency, pressure ratio, expansion efficiency, expansion ratio, rotating speed, mass flow, and energy are extremely complex. It also can be seen that, for a certain TEC, when the operating parameters are settled, the performances of compressor and expander will be fixed after automatically coupling. The expander and compressor have different effect on the refrigerator. How the expander and compressor couple with each other will influence the refrigerator performance greatly.

Much research on TEC has been done both experimentally and theoretically. Morgese et al. [20] showed a simple and rapid method to design an axial impulse turbine for energy recovery. Zhang et al. [21] developed a turboexpander for expansion power recovery in the refrigeration system. Davis et al. [22] devised an integral turbo expander-compressor system for refrigeration. Stephen [23] researched an air refrigerator applied in road transport, which used a TEC and achieved good thermal performance. But research on the coupling between compression process and expansion process of TEC is less. Kosarim et al. [24] analyzed influences of expansion efficiency and compression

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Nomenclature

c_s	isentropic spouting velocity (m s^{-1})
D_{1E}	expansion impeller inlet diameter (m)
h_{0C}	inlet enthalpy of compressor (J kg^{-1})
h_{0E}	inlet enthalpy of expander (J kg^{-1})
h_{2C}	outlet enthalpy of compressor (J kg^{-1})
h_{2E}	outlet enthalpy of expander (J kg^{-1})
h_E	real enthalpy drop of expander (J kg^{-1})
h_T	TEC real enthalpy drop (J kg^{-1})
k_C	adiabatic exponent of air in compressor
k_E	adiabatic exponent of air in expander
k	ideal adiabatic exponent of air
n	rotating speed (rpm)
p_{0C}	inlet pressure of compressor (MPa)
p_{0E}	inlet pressure of expander (MPa)
p_{2E}	outlet pressure of expander (MPa)
W_C	compression work (W)
W_E	expansion work (W)
q_{mC}	mass flow rate of compressor (kg s^{-1})
q_{mE}	mass flow rate of expander (kg s^{-1})
Q_0	cooling capacity (W)
R	gas constant of air (J kg^{-1} K^{-1})
T_{0C}	inlet temperature of compressor (K)
T_{0E}	inlet temperature of expander (K)
u_1	inlet peripheral velocity of expansion impeller (m s^{-1})

Greek

$\Delta\varepsilon$	relative pressure drop
ε_C	compressor pressure ratio
ε_{C1}	screw compressor pressure ratio
ε_E	expander expansion ratio
η_C	compressor isentropic efficiency
η_{C1}	screw compressor isentropic efficiency
η_E	expander isentropic efficiency
η_M	mechanical efficiency
η_R	heat exchanger efficiency

efficiency on the refrigerating capacity and found that the expansion efficiency had a greater impact on the cooling capacity than the compressor efficiency did. Krishnasing et al. [25] researched interactions between the expander and compressor of TEC. They thought the compressor load influenced the turboexpander efficiency and the compressor selection was quite important in ethylene applications. In order to achieve balance between the expander and compressor, the efficiency of turboexpander could be adversely affected. Zaki et al. [26] investigated a new approach to enhance the performance of gas turbines operating in hot climates. The results show that for fixed pressure ratio and ambient conditions, power and efficiency improvements are functions of the extraction pressure ratio and the fraction of mass extracted from the air compressor. Park et al. [27] simulated and analyzed the operating characteristics of an open-air cycle refrigeration system. Compared two partial load-operating strategies, the fixed shaft speed operation and the variable speed operation. Both operations accompanied a reduction in the coefficient of performance compared to the design value, but the variable speed operation had a less reduction at the same refrigeration capacity. Chen et al. [28] analyzed the effect of heat resistance on the performance of an air refrigeration cycle with a finite time heat transfer analysis. This work extended the recent studies on refrigerator performance by incorporating nonisentropic compression and expansion. The results showed that the COP had a maximum value and that the cooling load had a parabolic dependence on the COP. Zhou et al. [29] derived the analytical relationships between cooling load density and pressure ratio, as well as between coefficient of performance (COP) and pressure ratio. This paper studies the influences of the effectivenesses of the regenerator, the efficiencies of the expander and the compressor, the pressure recovery coefficient, and the temperature ratio of the heat reservoirs on the cooling load density and COP. Daneshi et al. [30] researched the application of TEC, and indiciated that expanders applied in refrigeration were usually loaded with low-pressure compressors. They also pointed out that expander efficiency determined the amount of refrigeration. But parameters that unifies the effects of expander and compressor hasn't been seen. And details about how the two parts interact, doesn't appear on these work, until Yang et al. [31] first proposed a coupling calculation method for TEC. The complex interactions among coupling parameters could be quantitatively calculated through the model. The coupling model could provide a basis for performance prediction and optimization of TEC.

As the relations between expander and compressor are quite complex, parameters that could unify influences of compression and expansion processes on the overall performance of refrigerator might be necessary. Two parameters of efficiency were proposed and analyzed in the present work. The TEC overall efficiency could be used to represent the whole performance of TEC in the refrigerator. Thus it could be a target parameter for coupling evaluation between expander and compressor. In a TEC, the output power during expansion process is recycled by compressor. The energy recycling ratio is defined as the ratio of the energy absorbed by the compressor to the energy going into the

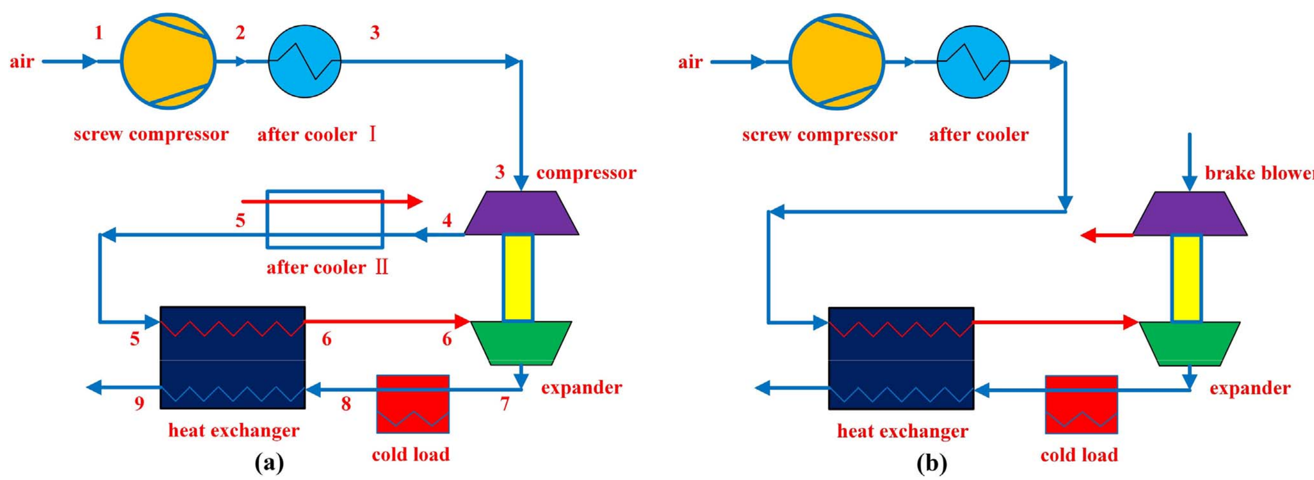

Fig. 1. Schematic view of two turboexpanders in reverse Brayton refrigerator: (a) TEC; (b) turboexpander with brake blower.