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Thermodynamic analysis of air cycle refrigeration system for Chinese train air conditioning

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Abstract

The air cycle refrigeration system used in Chinese train air conditioning engineering is investigated. The effects of possible parameters affecting system performance are examined through sensitive analysis of the thermodynamic model. The results show that, the pressure ratio should be in the range of 2-2.5, the COP will be in the range of 1-1.2, and the cold air distribution system can be used. To increase the COP, higher efficiencies of compressors, expanders and heat exchangers are expected.
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Keywords : Chinese train; air conditioning engineering; air cycle refrigeration system; pressure ratio; COP

1. Introduction

The air cycle refrigeration was the principle form of mechanical refrigeration in the second half of the 19th century. However, the air cycle refrigeration began its decline after the introduction of synthetic refrigerants in the early 1930s. Several disadvantages prevented air from being used as a working fluid in refrigeration. These included low volumetric refrigerating effect, which may lead to a large compressor, and poor energy efficiency as a result of low efficiencies of compressors and expanders. Recently, with CFCs and HCFCs problems becoming pressing issues, air, as a natural refrigerant, has been attracting more and more attention.

Chinese train air conditioning is identified as one of the few applications of fluorocarbon refrigerants where the direct effect of refrigerant emissions is a significant fraction of the greenhouse effect. Air cycle systems, which are more robust, have small amounts of air leakage, possess no safety or environmental hazards and can be automatically replenished by a small air compressor. So air cycle systems would be an acceptable substitution technology for providing air-conditioning in trains [1], especially for high-speed trains in China.

Compared with conventional vapour-compression refrigerating systems, the air cycle refrigeration system possesses the following advantages:

- Air is everywhere available and totally free, non-toxic, environmentally friendly, with no ODP (ozone depletion potential) and GWP (global warming potential).

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- As simple components can be used, the maintenance is simple and cheap, and highly qualified personnel for maintenance and operation is not needed.
- Speaking of operation, it is easy to adjust the cooling temperature and capacity to the required level, and its performance does not deteriorate as much as that in vapour-compression systems, when operated away from its design conditions.
- Low pressures and pressure ratios lead to simple, cheap and safe piping and vessel constructions.

NormalAir Garrett developed and commercialised an air cycle air conditioning pack that was fitted to ICE 3 high speed trains in Germany in the 1990s [2]. They have been in service for several years now and have demonstrated that this future-proof technology is superior to traditional vapour cycle air conditioning concepts in terms of eco-friendliness and life-cycle costs. As part of an European funded programme [3], a range of applications for air cycle refrigeration were investigated and several demonstrator plants were constructed. Spence et al. reported the design, construction and testing of an air-cycle refrigeration unit for road transport and performance analysis of a feasible air cycle refrigeration system for road transport [4,5]. However, the working fluid is often regarded as dry air for the facility of calculation according to the mentioned above, but in fact the working fluid in the cycle is wet air when the system is open. And there are few cases where a self-contained air cycle system has been studied for the challenging application of Chinese train air conditioning.

In this paper, an air cycle system used for Chinese train air conditioning is designed. Then a thermodynamic model with the humidity variation of a wet air cycle taken into consideration is developed. Based on this model, a steady-state simulation of the air cycle, using Engineering Equation Solver (EES) [6] software and the wet air property data in REFPROP [7], has been carried out. Accordingly, the performance of the system is investigated, and the possible parameters affecting the system performance are analysed by the sensitive analysis of the thermodynamic model. Moreover, several suggestions to the optimal operating parameters for the improvement of the system performance are proposed.

2. System design

The system that is built for Chinese train air conditioning is shown schematically in Fig. 1. It is an "open system" where the cold air from the expander is blown directly into the air conditioning train space, removing the need for a heat exchanger in the train space. The work done by the air in the expansion process is used to compress the air. This is done by mounting the compressor, expander and motor on a common shaft. In the interests of efficiency, the exhaust air from the cold space is used to cool the high-pressure heat exchanger.

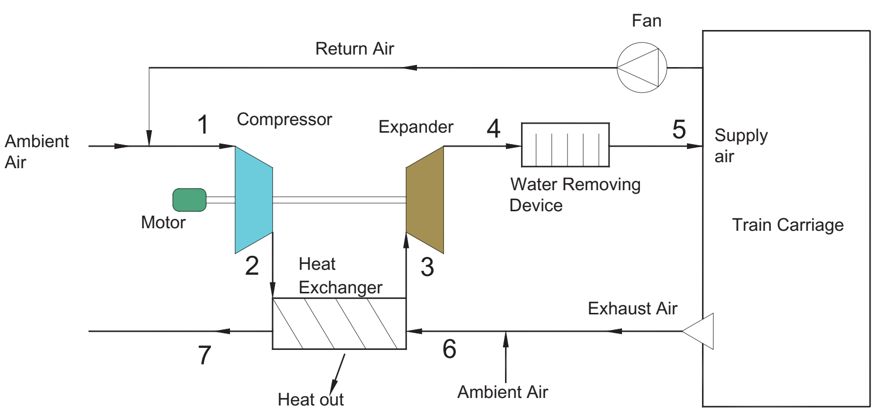

Fig. 1. Schematic diagram of the air cycle refrigerator used for Chinese train air conditioning system.

3. Cycle analysis and simulation

3.1. properties of wet air

The humidity ratio of wet air, d, is obtained from

$$d=0.622\varphi\, p_{q,b}/(p-p_{q,b}) \tag{1}$$

The enthalpy of wet air, h, is calculated from

$$h=c_{p,g}t+(r_0+c_{p,q}t)d \tag{2}$$

Where φ is the relative humidity of the wet air, $p_{q,b}$ is the partial pressure of saturated steam at the same temperature, $c_{p,g}$ is the specific heat capacity at constant pressure of air, $c_{p,q}$ is the specific heat capacity at constant pressure of water vapor, r_0 is the latent heat of vaporization of water at 0℃, r_0=2500.

3.2. Compression process

The outlet pressure of the compressor, p_2, is obtained from

$$p_2=p_{atm}PR \tag{3}$$

where p_{atm} represents the atmosphere pressure, PR is the overall cycle pressure ratio.

The outlet temperature of the compressor, T_2, is obtained from

$$T_2=T_1[1+(PR^{(k-1)/k}-1)/\eta_c] \tag{4}$$

where k is the ratio of specific heat at constant pressure to specific heat at constant volume, η_c represents the overall (compressor and motor) isentropic efficiency. η_c is determined as

$$\eta_c=(h_{2s}-h_1)/(h_2-h_1) \tag{5}$$

where h_1 is the inlet air enthalpy, h_{2s} is the air outlet enthalpy for an isentropic process occurring between the inlet condition and the outlet pressure, h_2 is the air outlet enthalpy.

For a specified inlet condition and outlet pressure, the input specific compression work is determined as

$$w_c=(h_2-h_1) \tag{6}$$

The inlet and outlet enthalpies of wet air are evaluated using psychrometric relations given three independent properties (e.g. pressure, temperature, relative humidity). The humidity ratio does not change during the compression, so that the humidity ratio of exit air is equal to that of inlet air.

3.3. Heat exchange process

The impact of pressure loss in the heat exchange process is neglected, and so that

$$p_3=p_2 \tag{7}$$

The specific energy transfer rate in the heat exchangers is modelled using an effectiveness concept, and so that

$$q_h=\eta_h q_{max} \tag{8}$$

where η_h is the overall effectiveness for energy transfer of the heat exchanger, q_{max} represents the maximum possible energy transfer rate for the heat exchanger. The second law of thermodynamics prescribes the specific maximum possible energy transfer rate. In a general sense,

$$q_{max}=h_2-h_{3min} \tag{9}$$

where h_{3min} represents the minimum possible exit air enthalpy of the hot stream. For a sensible heat exchange process, h_{3min} is evaluated at the hot stream inlet pressure and humidity ratio and the cold stream inlet temperature. For a sensible and latent heat exchange process, the limiting exit state for the hot and wet air would occur if the air were cooled to the inlet temperature of the cold stream and were saturated (100% relative humidity). In this case, h_{3min} is evaluated at the hot stream inlet pressure, the cold stream inlet temperature, and a relative humidity of 100%.

3.4. Expansion process

The overall expander isentropic efficiency, η_e , is determined as

$$\eta_e=(h_3-h_4)/(h_3-h_{4s}) \tag{10}$$

where h_3 is the inlet air enthalpy, h_{4s} represents the air outlet enthalpy for an isentropic process occurring between the inlet condition and the outlet pressure, h_4 represents the air outlet enthalpy.

For a specified inlet condition and outlet pressure, the specific output work generated is determined as

$$w_e=h_3-h_4 \tag{11}$$

where h_3 is the inlet air enthalpy, h_{4s} represents the air outlet enthalpy for an isentropic process occurring between the inlet condition and the outlet pressure. The inlet and outlet enthalpies of wet air are evaluated using psychrometric relations given three independent properties (e.g. pressure, temperature, relative humidity). Two cases [8] are considered: (1) dry expansion and (2) wet expansion. Initially, the process is assumed to be dry so that moisture does not condense out of the air. In this case, the exit humidity ratio is set equal to the inlet humidity ratio. However, if the exit temperature from the dry analysis is below the dew point of the air at the exit pressure, condensation is occurring in the expander, leading to wet expansion. The properties in this case are evaluated using an exit relative humidity of 100%.

3.5. Water removal process

The condensed water is removed in the water removing device, and then the exit enthalpy is

$$h_s=h_4-h_w \tag{12}$$

where h_w denotes the condensed water enthalpy.

3.6. Performance

The specific cooling capacity, q ,can be determined by the enthalpy difference between the inlet of the compressor and the outlet of the expander by using the following formula:

$$q=h_1-h_5 \tag{13}$$

The net work consumed by the refrigeration cycle is calculated by

$$w_0 = w_c-w_e \tag{14}$$

The coefficient of performance (COP) is the main evaluating tool when the performance of one refrigeration cycle is analyzed by the first thermodynamics law. The theoretical COP of this cycle is defined as

$$COP= q/w_0 \tag{15}$$

4. Results and discussion

The operating conditions of Chinese train air conditioning and the assumptions of the system are tabulated in Table1.

Table 1. Operating conditions and assumptions

Item	Value
The isentropic efficiency of compressor, η_c	0.85
The isentropic efficiency of expansion, η_e	0.85
The effectiveness for energy transfer of the heat exchanger, η_h	0.9
The ambient air temperature and relative humidity (RH)	35℃ , 55%
The indoor temperature and relative humidity (RH) in train	25℃ , 55%
The fresh air ratio	30%

The influence of the pressure ratio on the COP and the specific cooling capacity is presented in Fig. 2. It is seen from Fig. 2 that there exists an optimal pressure ratio PR_{opt} which gives a maximum COP. As the pressure ratio is increased, the COP increases rapidly when the pressure ratio is less than PR_{opt}, but decreases relatively slowly when the pressure ratio is greater than PR_{opt}. It is also noted from Fig. 2 that the specific cooling capacity increases with the system pressure ratio. Consequently, if a higher system pressure ratio is used, the required cooling duty could be achieved with a smaller flow rate of air, and the weight and volume of the refrigerator will be decreased.

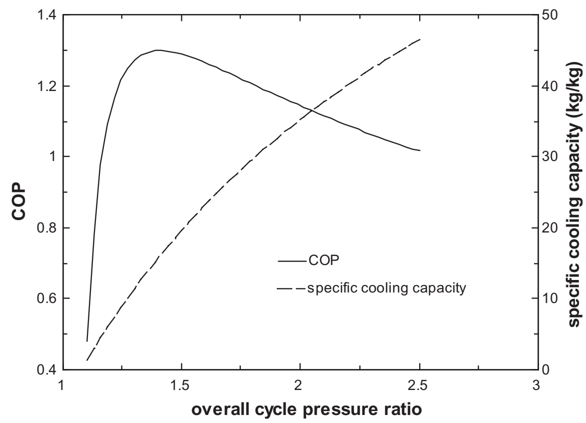

Fig. 2. The influence of the pressure ratio on the COP and the specific cooling capacity.

The influence of the pressure ratio on the supply air temperature and humidity ratio is presented in Fig. 3. It is seen evident from Fig. 3 that the supply air temperature and humidity ratio decreases with increasing pressure ratio. These results suggest that it is desirable that the air cycle system should operate above its optimal pressure ratio in order to keep its maximum COP and the specific cooling capacity.

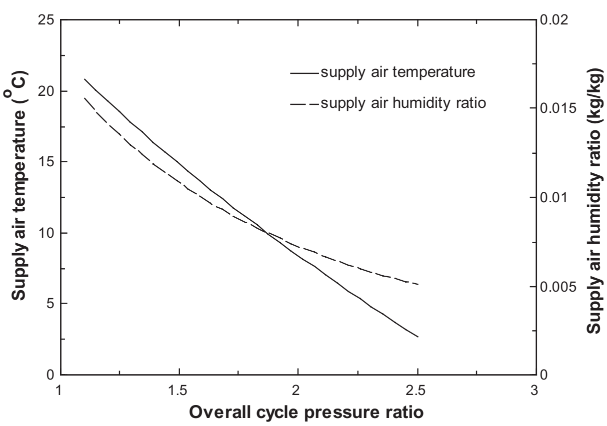

Fig. 3. The influence of the pressure ratio on the supply air temperature and humidity ratio.

Considering the factors above, the applicable cycle pressure ratio is within the range of 2-2.5, in this case, the COP is within the range of 1-1.2, and the supply temperature is within the range of 1-6℃, and the cold air distribution system which has been used in ice thermal storage air conditioning for years can be used.

The COP and the specific cooling capacity calculated for different isentropic efficiencies of the compressor and the expander are presented in Fig. 4. It is seen from Fig. 4 that the COP increases rapidly as the isentropic efficiencies of the compressor and the expander are increased. The COP will reach about 2.0 if ηc=ηe=0.95.

Therefore, it is a potent measure to improve the isentropic efficiencies of compressors and expanders for the improvement of the system COP.

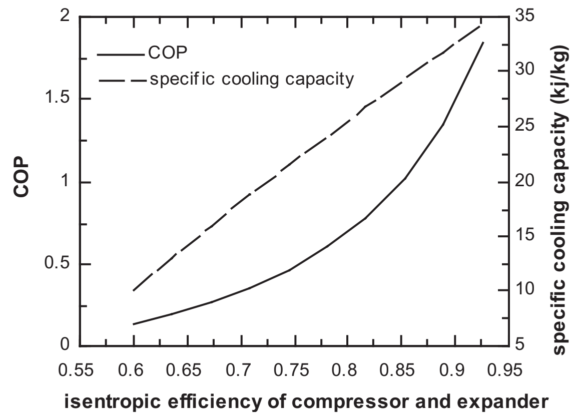

Fig. 4. The influence of the isentropic efficiencies of compressor and expander on COP and the specific cooling capacity.

The COP and the specific cooling capacity calculated for different efficiencies of the heat exchanger are presented in Fig. 5. The COP is seen to increase gradually with the increase of the effectiveness of the heat exchanger. But the effect of the effectiveness of the heat exchanger is seen to be relatively small as compared with the discussed isentropic efficiency for the compressor and the expander.

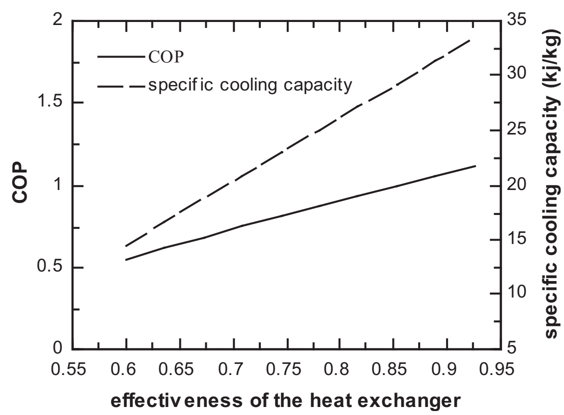

Fig. 5. The influence of the effectiveness of the heat exchanger on the COP and the specific cooling capacity.

5. Concluding remarks

Air is a natural refrigerant. It has many advantages comparing to other refrigerant. Therefore, the air cycle refrigeration system for train air conditioning engineering in China has been presented. With the thermodynamic analysis and sensitive simulations, it is found that the applicable cycle pressure ratio is within the range of 2-2.5, the COP is within the range of 1-1.2, the supply temperature is within the range of 1-6℃ and the cold air distribution system can be used. To increase the COP, higher efficiencies of compressors, expanders and heat exchangers are expected. The results of this study are of significance to the design of air cycle system for train air conditioning in China.

Acknowledgements

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