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An important feature of air heat pump cycle: Heating capacity in line with heating load

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ABSTRACT

In the conventional vapor-compression heat pumps, the heating capacity and the heating load usually vary in opposite directions, which results in a mismatch of the heating capacity and the heating load at off-design conditions. Air (reversed Brayton) cycle is a potential substitute for the conventional vapor-compression cycles. This paper proved that in theory the air heat pump cycle can make the heating capacity in line with the heating load at a stable level of heating COP (coefficient of performance). A thermodynamic model for the air heat pump cycle with practical compressor and expander was developed. The optimal heating COP and the corresponding pressure ratio were derived from the model. Then the cycle performance was analytically expressed under the optimal COP conditions. The heating capacity under different operating conditions was found in line with the heating load. Comparisons between the air heat pump cycle and two typical vapor-compression heat pump cycles were numerically done for further verification. It also turned out that the energy efficiency of air heat pump is comparable to the transcritical CO_2 heat pump, particularly at large temperature difference.

1. Introduction

The phase-out of CFC (chlorofluorocarbon) and HCFC (hydrochlorofluorocarbon) refrigerants facilitates the development of new refrigeration/heat pump technology. Air is definitely an environmentally benign and safe refrigerant. Therefore, the reversed Brayton cycle using air as the refrigerant is a potential substitute for the conventional vapor-compression cycles. Particularly, in open/semi-open air cycles, elimination of the cold side heat exchanger can make a frost-free refrigeration/heat pump system, which much improves the refrigeration/heat pump system performance under frosting conditions.

Most investigations on the air (reversed Brayton) cycles were taken for refrigeration applications. The air cycle is primarily served as the aircraft air conditioner for both temperature and humidity control [1,2]. Limited by the energy efficiency, however, air cycle is more competitive in cryogenic applications [3–5]. In moderate refrigeration temperature range, some researches were also conducted, which covers a variety of fields such as transportation air conditioning [6–9] and refrigerated storage of food [10–12]. Besides, the optimal part-load operation strategy [13] and an integrated air conditioning and desiccant system [14] were also investigated for searching some approach to maximizing the utility of system. Nevertheless, the relatively low energy efficiency still constrains air cycles from wide applications in daily refrigeration temperature range.

Recently, air heat pump cycles brought increasing attention. Angelino and Invernizzi [15] found appropriate selection of the cycle operating parameters leading to the location of the expansion process in the vicinity of the critical point allows the design of closed regenerated real-gas cycles with efficiencies similar to those of conventional vapor-compression cycles. Braun, Bansal [16] proposed an air cycle heat pump clothes dryer with practical components and found significant efficiency improvement over conventional dryers. White [17] pointed out, for domestic heating applications, recuperation improves the cycle work ratio, thereby making it less susceptible to losses. But in practice this advantage is compromised when realistic values of recuperator effectiveness are considered. Zhang, Chen [18] illustrated the COP (coefficient of performance) of heat pump can be optimized by properly allocating the fixed heat conductance inventory between the hot and cold side exchangers and the fixed flow area among the compressor inlet and the expander outlet. From the existing literature we can find that the air cycles in heat pump applications have more potential in energy efficiency than it in normal temperature refrigeration applications.

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Nomenclature

c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
COP	coefficient of performance
h	enthalpy, J kg^{-1}
h_{fg}	latent heat of vaporization, J kg^{-1}
q_L	heat absorption per unit mass flow from low-temperature environment, J kg^{-1}
$q_{L,v}$	volumetric heat absorption, heat absorption per unit volume flow at compressor inlet, J m^{-3}
q_H	heating capacity per unit mass flow, J kg^{-1}
$q_{H,v}$	volumetric heating capacity, heating capacity per unit volume flow at compressor inlet, J m^{-3}
Q_H	heating capacity, W
p	pressure, Pa
p_r	pressure ratio
R	gas constant (=8.314), J K^{-1} mol^{-1}
T	temperature, °C, K
$\dot{V}$	volume flow rate, m^3 s^{-1}
w_0	net power consumption per unit mass flow, J kg^{-1}
w_c	compressor power consumption per unit mass flow, J kg^{-1}
w_e	expander power recovery per unit mass flow, J kg^{-1}

Greek symbols

π	derived pressure ratio defined in equation (14)
θ	temperature ratio defined in equation (15)

Subscripts

in	inlet
H	high-temperature side; hot side; heating
L	low-temperature side; cold side
opt	optimal
out	outlet
r	refrigerant
s	saturated refrigerant
v	volumetric

In order to take the effects of irreversibilities into account, the finite-time thermodynamics was applied to develop the air cycle heat pump model [19]. Based on the model, Bi, Chen [20] [21] and Bi, Xie [22] took the heating load, heating load density and COP as the optimization objective and derived analytical formulae that illustrated the effects of pressure ratio, heat exchanger effectiveness and inlet temperature ratio of the heat reservoirs on those key performance indices. Furthermore, the expressions of the exergetic efficiency and the ecological function of the heat pump cycle were also derived, which provided guidelines for the design and optimization of practical air heat pump cycles [23,24].

In summary, most investigations were concentrated on the energy efficiency of air cycles and didn't pay close attention to other features of air cycles. In this work, we find the air heat pump can make the heating capacity in line with the heating load at a stable level of heating COP, which can potentially avoid the capacity modulation of heat pump systems and be more energy effective when the temperature difference of heat source and heat sink gets bigger. To prove it, we develop a thermodynamic model for the air heat pump cycle with practical compressor and expander. In addition, numerical comparisons between the air heat pump cycle and two typical vapor-compression heat pump cycles are also made to verify the point and get more details.

2. Thermodynamic model of air heat pump cycle

The schematic of an air heat pump is shown in Fig. 1. The basic air heat pump consists of a compressor, an expander, and zero, one or two heat exchangers in case of open, semi-open, or closed cycle. In this work, we focus on the semi-open air cycle without cold side heat exchanger. But the results can apply to the closed air cycle as well.

The temperature–entropy diagram of air heat pump cycle is shown in Fig. 2. A compressor that raises the air pressure from low-temperature environment to its highest value (e.g., compression: 1–2). A hot side heat exchanger where the air high temperature is lowered (e.g., isobaric heat rejection: 2–3). An expander where the air pressure and temperature are reduced (e.g., expansion: 3–4). A cold side heat exchanger that raises the air temperature at a constant pressure (e.g., isobaric heat absorption: 4–1). It would perform like an ideal heat exchanger if there is no cold side heat exchanger in a semi-open cycle.

Irreversibilities of the air heat pump are considered in the following assumptions.

1) Isentropic efficiencies are constant for the compressor and expander.
2) Temperature difference between the expander inlet and high-temperature heat sink is given.
3) Temperature difference between the compressor suction and low-temperature heat source is given. In case of the semi-open cycle without cold side heat exchanger, the temperature difference is zero.

In addition, the following two assumptions are taken as well.

4) The air is ideal gas.
5) Both the heat absorption and rejection processes are isobaric.

Accordingly, the thermodynamic model of the air heat pump cycle is as follows.

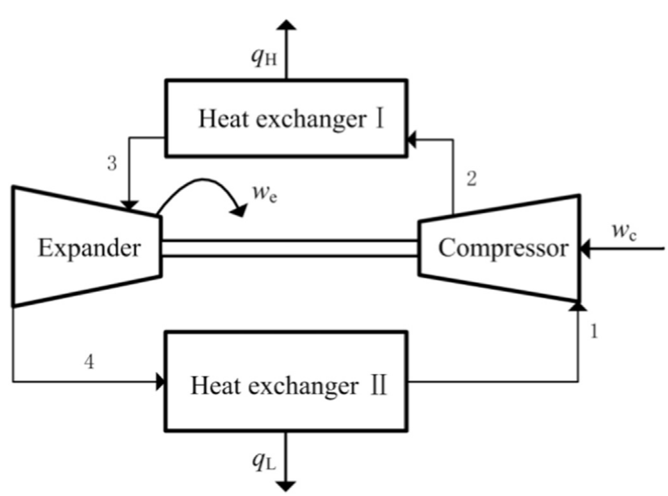

Fig. 1. Schematic of air heat pump.