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Performance modeling of air cycle heat pump water heater in cold climate

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ABSTRACT

Air (reverse Brayton) cycle has promising features in cold climate heat pump applications. In this study, an air cycle heat pump water heater (ACHPWH) simulation model considering the off-design performance of components was developed and validated with experimental data from literature. With this model, the performance of ACHPWH was numerically compared with two typical vapor compression heat pump water heaters (VCHPWH) under two different heating schemes, namely instantaneous heating and recirculation heating. For instantaneous heating, the COP of ACHPWH is comparable to that of VCHPWH when supplying high temperature water or operating at low ambient temperature. A significant improvement on annual performance would be achieved as well if higher efficient compressor and expander were applied in ACHPWH system. For recirculation heating, although the COP gap got larger, ACHPWH would save plenty of heating time when operating at low ambient temperature.

1. Introduction

As the fourth major energy consumer in residential energy consumption [1], water heating is becoming indispensable in modern life. Shown by some relevant studies, water heating accounts for 17% of residential energy consumption in United States, 14% in European Union and 22% in Britain [2]. This figure in China is high up to 27% [3]. Besides the domestic usage, the hot water is widely used in the public and industrial applications, such as the space heating, sanitation and desalination, etc.

To begin with, the electric water heater is widely applied because of its simplicity. However, the inefficiency of electric water heater makes it gradually replaced by the vapor compression heat pump water heater (VCHPWH). As an energy saving equipment, the VCHPWH is 2–3 times more efficient than electric water heater and becomes one of the mainstream products in market. However, there are still some inherent drawbacks limited its application, especially in cold climate region. For example, the problem of frosting in evaporator haven't been well settled during the heating in winter. As we all know, frost forms on the surface of evaporator when the surface temperature gets lower than 0 °C, which not only adds the heat resistance but also blocks the air flow, and therefore inevitably degrades the energy efficiency quickly [4]. To address this problem, researchers have proposed many solutions, such as electric heater defrosting [5], reverse-cycle defrosting [6] and hot-gas bypass defrosting [7]. Indeed, these approaches do work in defrosting, but they all sacrifice the system efficiency to achieve that. The other drawbacks of VCHPWH are associated with off-design performances: heating capacity and heating efficiency decrease with the increasing of heating load in cold climate. Specifically, when the ambient temperature falls down, the heating load goes up naturally, however the heating capacity provided by VCHPWH decreases. It leads to a mismatch between the heat demand and heat capacity in cold climate [8]. Meanwhile for a recirculation VCHPWH, the condensing temperature rises in the heating process, which results in a growth of power consumption and hence a significant performance degradation. More importantly, the above weaknesses of VCHPWH are actually the inherent characteristics of vapor compression cycle and hence hard to be solved.

By comparison, the air (reverse Brayton) cycle heat pump water heater (ACHPWH) could be a solution to all aforementioned disadvantages of VCHPWH. Using air as the refrigerant, air cycle can be a semi-open configuration, namely low temperature heat exchanger (relative to the evaporator in vapor compression cycle) is no longer needed [9]. Such a cycle eliminates the possibility of a

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Nomenclature

A	heat transfer area, m^2
b_1,b_2	correlation constants
C	heat capacity rate, W K^{-1}
C_r	heat capacity ratio
c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
COP	coefficient of performance
d	tube inner diameter, mm
f	friction factor
k	specific heat ratio
L	tube length, m
m	mass flow rate, kg s^{-1}
N	rotational speed, rev s^{-1}
NTU	number of transfer unit
Nu	Nusselt number
Q	heating capacity, W
p	pressure, Pa
p_r	pressure ratio
Pr	Prandtl number
Re	Reynolds number
T	temperature, °C, K
U	overall heat transfer coefficient based on A, W m^{-2} K^{-1}

Greek symbols

α	heat transfer coefficient, W m^{-2} K^{-1}
ε	effectiveness of heat exchanger
η	isentropic efficiency of compressor or expander
τ	heating time of recirculating water heater

Subscripts

c	cold fluid, compressor
de	design point
e	expander
in	inlet
h	hot fluid
max	maximum
min	minimum
opt	optimal
out	outlet
w	wall

frosted evaporator and hence protects the system from the performance degradation under the frosting conditions. More importantly, the air cycle has completely different operation characteristics which makes it a better performance in off-design conditions. Firstly, air cycle has a more stable COP when operating in different ambient temperature. Gigiel [10] revealed that the performance deterioration of air cycle at off-design conditions is not as much as the vapor compression cycle. Later Pelsoci [11] and Spence, Doran and Artt [12] experimentally came to the same conclusions. Secondly, the mismatch of heating capacity and heating demand in VCHPWH does not happen in ACHPWH. Zhang and Yuan [13] proved that the heating capacity of basic air cycle heat pump can be naturally consistent with the heating load at off-design conditions. Later, Yuan and Zhang [8] found that the regenerative air cycle has the same feature and is more efficient for the applications in large temperature difference, such as the heat pump water heater in cold climate.

Although the unique features of air cycle seems to provide a natural solution to the bottleneck problems of VCHPWHs, the air cycle efficiency is still a concern for applications. In reality, not only the cycle efficiency but also the component efficiency are a function of wide operating conditions. So far, there was no comprehensive and quantitative comparison between ACHPWH and VCHPWHs at this point. In this work, we pick two typical VCHPWHs in markets as benchmark cases, namely trans-critical CO_2 VCHPWH and subcritical R134a VCHPWH. The numerical comparisons between ACHPWH and VCHPWHs are based on more physics-based models not simple cycle analysis. Design condition, winter condition, low temperature condition and annual operating conditions (bin hours) are taken into account to fully evaluate ACHPWH performance, especially in cold climate. More comprehensive and quantitative conclusions are expected from this study.

2. Air cycle heat pump water heater

Fig. 1 shows the schematic of ACHPWH, which consists of two units, heat pump unit and water heating unit. In the heat pump unit, a regenerative air cycle is applied to have a higher COP compared with the basic air cycle. The outdoor air is preheated in regenerator and goes into compressor directly, so the evaporator can be removed from the system and ACHPWH becomes a frost free system. The configuration of water heating unit is similar to that of the traditional VCHPWHs, which includes the heat exchanger and water storage tank. However, it should be noted that there are two different heating schemes. One is the recirculation heating scheme, shown by the solid line in Fig. 1. Recirculation heating is carried out through a water storage tank, and the water will recirculate between the water tank and heat exchanger until it is hot enough for utilization. Another heating scheme is instantaneous heating, shown by the dashed line in Fig. 1. In this scheme, the inlet of heat exchanger is connected with tap and the tap water flows once through the heat exchanger where it will be heated up to the supply temperature at the outlet of heat exchanger. Thus, instantaneous heating is also called once-through heating. Obviously, the once-through heating scheme has the advantage of instantaneity and

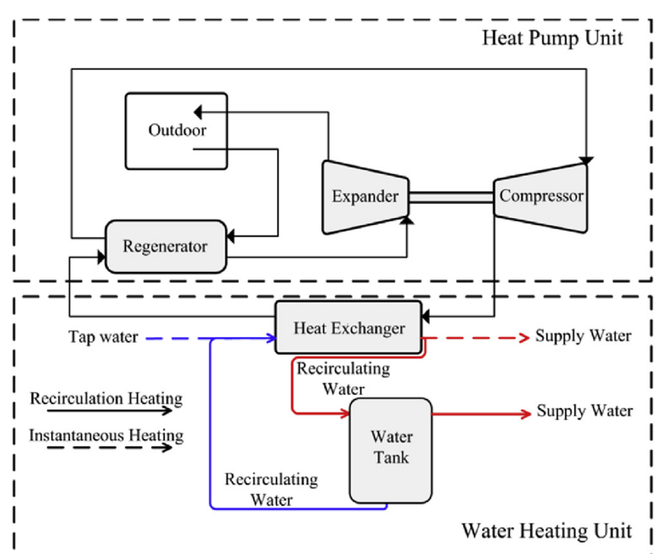

Fig. 1. Schematic of ACHPWH.