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Transcritical carbon dioxide microchannel heat pump water heaters: Part II – System simulation and optimization

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A B S T R A C T

This paper presents the development of a transcritical CO_2 heat pump water heating system model incorporating analytical heat exchanger models and an empirical compressor model. This study investigated the effects of a suction line heat exchanger (SLHX) and once-through versus recirculating water heating schemes. The once-through systems outperformed the recirculating systems by 10% for the system without an SLHX and 15% with an SLHX. However, a gas cooler twice as large is required. The SLHX was shown to benefit system performance at higher evaporator temperatures with improvements of 16.5% for the once-through and 4% for the recirculating systems. This study can be used to improve the design of microchannel based transcritical CO_2 heat pumps; evaluate the impact of varying water inlet temperature, desired outlet temperature and evaporation temperature on system performance; and quantify the effect of differential diurnal electricity rates on system operating costs for these different operation schemes.

Systèmes de chauffage d’eau sanitaire à pompe à chaleur au dioxyde de carbone transcritique : Partie II – Simulation et optimisation du système

Mots clés : Refroidisseur à gaz ; Microcanal ; Pompe à chaleur ; Transcritique ; Cycle ; Dioxyde de carbone

1. Introduction

Heat pump water heaters have been shown to be one of the most promising applications for using low global warming potential (GWP) CO_2 as a working fluid (Kim et al., 2004; Neksa et al., 1998). The high temperature lifts required in water heating match well with the temperature glide exhibited by the supercritical CO_2 during heat rejection. The glide allows water delivery temperatures of up to 90 °C without significant degradation in system efficiency (Kim et al., 2004). Heating

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Nomenclature

a	constant coefficient (–)
c_p	specific heat (kJ kg^{-1} °C^{-1})
ε	effectiveness (–)
η	efficiency (–)
i	specific enthalpy (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
N	compressor speed (rad s^{-1})
P	pressure (kPa)
$\dot{Q}$	heat duty (kW)
Q	total heat (kJ)
T	temperature (°C)
V	volume (m^3)
$\dot{V}$	volumetric flow rate (m^3 s^{-1})
W	total work (kJ)
z	COP (–) or gas cooler water outlet temperature (°C)

Subscripts

d	displacement
dis	discharge
evap	evaporator
gc	gas cooler
hp	heat pump
j	index notation
ref	refrigerant
s	isentropic
suc	suction
vol	volumetric

water to this temperature with a conventional system (*e. g.*, R134a) can only be done by raising the compressor discharge pressure substantially to avoid temperature pinches. In conventional systems therefore, as the condenser saturation pressure increases, the available enthalpy difference across the vapor-liquid dome decreases, and the compressor pressure ratio increases, drastically reducing system efficiency.

Neksa et al. (1998) developed and validated a system model assuming a tube-in-tube gas cooler in a 50 kW system, heating water from 8 to 60 °C with a COP that varied from 3.0 to 4.3. Neksa et al. (1998) demonstrated a decreasing COP with increasing water temperature at a fixed evaporator pressure. Cecchinato et al. (2005) and Rigola et al. (2005) each presented comparisons between R134a and CO_2 based heat pump water heaters. Again, each researcher assumed a tube-in-tube gas cooler. Cecchinato et al. (2005) showed CO_2 offers improved performance at many operating conditions. However Rigola et al. (2005) showed operating at high gas cooler water inlet temperatures can severely degrade CO_2 heat pump performance. Thus, Cecchinato et al. (2005) also show that CO_2 systems benefit from stratified storage tanks when used in a closed water heating loop, as the water temperature entering the heat pump is kept at a minimum. Similar observations on the impact of water inlet temperature were made in models developed by White et al. (2002), Stene (2005), and Sarkar et al. (2006, 2009). Kim et al. (2005) discussed the impact of a suction line heat exchanger (SLHX) on system level performance of a CO_2 heat pump for water heating. One impact of the SLHX is the increase in superheating of the refrigerant at the compressor suction port. The additional heating and pressure drop through the SLHX resulted in reduced specific volumes at the suction port, and therefore lowered the system mass flow rates. This reduction in mass flow rate would typically lead to reduced component capacities, but the relatively constant compressor work input increases the discharge temperature and enthalpy. The increased discharge temperature leads to an increase in the driving temperature difference through the gas cooler and effectively offsets the penalty due to the reduced mass flow rate.

Many of the experimental facilities and simulations that have been used to explore the suitability of CO_2 for water heating applications have been based upon concentric tube-in-tube heat exchangers. While these heat exchangers have a high effectiveness at long lengths, they are generally far from compact at the capacities needed for domestic water heating. Little work has been performed on the use of microchannel-based heat exchangers in these systems, especially for use in hydronically-coupled systems. Microchannel heat exchangers have been shown to reduce heat exchanger size and refrigerant charge of heat pump systems and could aid in the continued successful commercialization of CO_2 water heaters. One additional means of reducing heat exchanger size that has not previously been widely investigated is through repeated recirculation of tank water at a high water flow rate through the gas cooler to meet the desired high water temperature needed for domestic purposes. Much of the prior research used an SLHX in the experimental facilities for cycle testing. Little has been reported on the direct impact of these components, although their use is common. Further research is required to analyze the potential benefit of these components and determine which system operating conditions will benefit the most from their use.

Therefore, this work focuses on extending the previous work on CO_2 heat pump water heaters to include compact microchannel heat exchangers. Two water heating schemes are investigated to analyze the impact on system heat exchanger size and the associated performance tradeoffs. Finally, the performance impacts of an SLHX on the heat pump water heater system are analyzed.

2. Simple system model and component design

Initially, a simplified thermodynamic state model was developed with *Engineering Equation Solver* (EES) (Klein, 2007) to determine the required heat exchanger design conditions at the desired operating condition. With the design conditions fixed, the component models developed in Part I were used to fix the physical dimensions of the heat exchangers, which were then incorporated into the detailed system model described in the following section. Two system configurations were investigated: one with the inclusion of an SLHX and one without. For each configuration, two water heating strategies were investigated: one to heat water to a usable temperature