Chapter 10

Study on Cooling Heat Transfer of Supercritical Carbon Dioxide Applied to Transcritical Carbon Dioxide Heat Pump

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ABSTRACT

Understanding the heat transfer characteristics of supercritical fluids is of fundamental importance in many industrial processes such as transcritical heat pump system, supercritical water-cooled reactor, supercritical separation and supercritical extraction processes. This paper addresses recent experimental, theoretical and numerical studies on cooling heat transfer of supercritical CO₂. A systematic study on heat transfer coefficient and pressure drop of supercritical CO₂ was carried out at wide ranges of tube diameter, mass flux, heat flux, temperature and pressure. Based on the understanding of temperature and velocity distributions at cross-sectional direction provided by the numerical simulation, a new prediction model was proposed, which agreed well with the experimental results. In addition, the effect of lubricating oil was also discussed with the focus on the change in flow pattern and heat transfer performance of oil and supercritical CO₂.

INTRODUCTION

Re-Discovering of Carbon Dioxide Refrigerant

Carbon dioxide, hereafter CO₂, was initially applied as a refrigerant in late 1800s because it was proven safe and highly efficient. It was commonly used on board ship till it was substituted by CFCs (chloro-fluorocarbons) in 1930s because the latter was operated at lower system pressures. Things have changed

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since 1990s. Due to two treatments on environmental protection, i.e. the Montreal Protocol and Kyoto Protocol, carbon dioxide has been re-discovered and is expected to be a promising refrigerant in applications such as hot water heater, automotive A/C, and low temperature refrigerators.

Lorentzen (1995) compared several common alternative refrigerants. In contrast with CFCs and HCFCs, the alternatives, such as ammonia, hydrocarbons, and CO₂, have an ODP (Ozone Depletion Potential) of zero and a negligible GWP (Global Warming Potential). As for HFC134a, although its ODP is zero, it has a GWP as high as 1200 (100 year) or 3100 (20 year). With respect to the safety of “old” refrigerants, only CO₂ can compete with the non-flammable HFCs. Although CO₂ is also listed as a greenhouse gas, it is because of the large amounts emitted from many industrial applications. In comparison with HFCs, the GWP of CO₂ is negligible when CO₂ is used as a refrigerant. Therefore, the use of CO₂ as a refrigerant has major benefits of being environmentally benign and safety.

When CO₂ is applied to conventional vapor compression cycle, it shows significantly different characteristics comparing with other refrigerants. Due to its low critical temperature \( T_{cp} = 31.1ºC, P_{cp} = 7.38 \text{ MPa} \), the CO₂ heat pump cycle has to be operated trans-critically when the ambient temperature is near or higher than the critical temperature. In this case, the heat absorbing process takes place at subcritical pressure whereas the heat rejection takes place at supercritical state. This kind of trans-critical cycle is initially proposed by Lorentzen and his coworkers for automotive air conditioning and hot water heat pump systems (Figure 1).

Due to the temperature glide in the gas cooler at supercritical pressure, the temperature profiles of the CO₂ and the secondary fluid can be advantageously adapted in order to minimize heat transfer loss and hence improve energy efficiency. In addition, high discharge temperature of coolant about 90ºC-100ºC can be obtained without increasing the refrigerant side pressure and temperature so much. Thus an obvious preferable application of CO₂ heat pump could be hot air or water production.

Although the high vapor pressure requires the redesign for more durable compressor and other parts, the high pressure and low viscosity of CO₂ may lead to a small pressure loss. Furthermore, the pressure ratio of CO₂ heat pump is quite low, only 2-3, compared to the value of 4-5 in conventional vapor compression cycle. Higher compressor efficiency can be achieved for the CO₂ trans-critical cycle.

In Japan, since the commercialization of the “Eco Cute” in 2001, the production of CO₂ heat pump water heaters has increased steadily. According to JRAIA (The Japan Refrigeration and Air Condition-