Chapter 7
Principles, Experiments, and Numerical Studies of Supercritical Fluid Natural Circulation System

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ABSTRACT

Due to the unique thermal and transport properties, supercritical natural circulation loop (NCL, or thermosyphon) has been proposed in many energy systems, such as solar heater, nuclear cooling, waste heat recovery, geothermal, etc. This chapter presents the principals of supercritical natural circulation loop and its application challenges. A specially designed experimental prototype system is introduced and compared with numerical findings. The system is operated in wide range of pressures from around 6.0 MPa to 15.0 MPa in the near-critical region. It is found that in a supercritical natural circulation system, very high Reynolds number natural convection flow can be achieved only by simple heating and cooling. Thermal performance analysis and parameter effects are carried out along with the experimental development. The heat transfer dependency on operation and its mechanisms are also explained and summarized in this chapter. The comparison of experimental and numerical results contributes to better understanding of NCL stability phenomena and applications in energy systems.

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BASIC DESIGN AND PRINCIPALS OF SUPERCRITICAL NATURAL CIRCULATION LOOPS (NCLS)

Thermosyphon (or called NCL: natural circulation loop) is one basic loop heat and mass transfer mechanism by fluid buoyancy forces under terrestrial conditions. Due to the absence of mechanical components, natural circulation provides a reliable way of heating/cooling and energy conversion from heat source to heat sink. Representative applications of NCL can be found in solar heating and cooling systems (Huang, 1980; Kalogirou, 2004; Yamaguchi et al., 2010), geothermal process (Kreitlow and Reistad, 1978), nuclear power plant (Zvirin, 1981; Dimmick et al., 2007) and others. Zvirin (1981) and Grief (1998) have made general reviews on NCL systems.

However, the efficiency of NCL systems is still a problem. Water based NCL is now mostly utilized, for example in solar collectors, which has very low circulation flow rate and it takes a long time for heat accumulation (Kalogirou, 2004). Therefore, it is not preferable for high intensity and fast energy conversion processes. Also, for applications in higher temperature and pressure, possible two phase flow and system instabilities are found in NCL (Huang, 1980; Kalogirou, 2004; Yamaguchi et al., 2010). Due to the of density and loop friction variations when the thermosyphon loop heat input is varied, fluid 'density waves' or flow reversals are also found, both for single-phase and two-phase flows (Vijayan et al., 1995; Chatoorgoon, 2001; Kumar and Gopal, 2012). Since 1960s, Welander (1967) and others (Holman and Boggs, 1960) have begun to study the fluid dynamics and stability laws for such NCL systems. Later, a lot of experimental and analytical/numerical studies have been carried out to investigate the system behaviors (for normal fluids) under various input and geometric effects as briefly reviewed by Chen et al. (2010). For some studies, NCL power-flow rate curves are proposed to describe the stability threshold (Dimmick et al., 2002; Jain and Rizwan-uddin, 2008). However, it is later reported that system stability cannot be judged by single parameters due to the complex effects from specific system design and fluid properties (Zhang et al., 2010). Therefore, the NCL controlling parameter correlations are analytically developed by one-dimensional modeling of Vijayan et al. (2004). Also, stability maps have been proposed analytically by Cammarata et al. (2003) and others (Misale et al., 2007).

Although comprehensive studies were conducted by earlier researchers as discussed above, most of these studies were limited to using water as the working fluid operated under normal pressure conditions. Recently, there is an increasing interest in the study of near-critical/supercritical CO_2 based NCL (Yamaguchi et al., 2010; Dimmick et al., 2002; Chatoorgoon, 2001; Kumar and Gopal, 2012; Chen et al., 2010; Jain and Rizwan-uddin, 2008; Zhang et al., 2010). For high power systems, supercritical water (critical point: Tc = 647.1 K and Pc = 22.06 MPa) is proposed, and supercritical CO_2 (critical point: Tc = 304.13 K and Pc = 7.378 MPa) is also promising as it can operate under relative lower temperature and pressure compared with supercritical water. Indeed, supercritical CO_2 NCL systems have already been tested in solar heater (Yamaguchi et al., 2010) and proposed in new generation nuclear plant design and other energy conversion designs (Dimmick et al., 2012; Holman and Boggs, 1960; Chen et al., 2010; Jain and Rizwan-uddin, 2008; Zhang et al., 2010; Vijayan et al., 2004), where relative higher circulation and heat transfer efficiencies have been identified and optimized. Near the critical point, the fluid is characterized by the feature of large thermal and transport properties variations with even a very small change in temperature and/or pressure, as shown in Figure 1. Near-critical fluid is very dense and highly expandable, which property can help produce effective natural convective flow in NCL with large density difference. Sometimes the critical diverges will also happen in the transition process in the near-critical region. The high specific heat and low viscosity of near-critical/supercritical CO_2 fluid