Abstract

Natural circulation loop (NCL) based secondary fluid systems are simple and reliable due to the absence of any moving components such as pumps. While water based NCLs are widely used in applications such as solar collectors, nuclear reactors, etc., a wide variety of brines is used for low temperature applications. In recent years, a growing popularity of carbon dioxide as a secondary fluid has been witnessed in both *forced* as well as in *natural* circulation loops. This may be attributed to the favourable thermo-physical properties of CO_2 in addition to the environmental benignity of the fluid. However, an extensive literature review shows that theoretical and experimental studies on CO_2 based NCLs are very limited. Also most of the studies on natural circulation loops do not consider the 3-dimensional variation of the field variables. Further, due to lack of reliable correlations for friction factor and heat transfer coefficient, the correlations developed for forced convection in internal pipes are routinely used in the design and analysis of natural circulation loops. Also studies on natural circulation loops operating near the supercritical region are scarce. Thus there is a need for further studies on these aspects of natural circulation loops.

In the present work, 3-dimensional computational fluid dynamics (CFD) models of NCLs have been developed to study their steady and transient. Studies have been carried out on subcritical as well as supercritical CO_2 loops. Several configurations (i.e., isothermal source and sink, end heat exchangers, heat input at constant heat flux) of the loop have been considered. Results are obtained for different operating pressures, operating temperatures, tilt angles of the loop, heat inputs, mass flow rates of external fluid, etc. For the same source and sink temperatures, comparison of CO_2 with water as loop fluids show that liquid CO_2 as well as supercritical CO_2 near pseudocritical region exhibit very high heat transfer rates compared to water. Correlations have been proposed for quick estimation of optimum operating conditions for supercritical fluids. Validation of simulation results against test data reported in the literature with respect to modified Grashof number (Gr_m) and Reynolds number (Re) exhibit good agreement. Additionally, new correlations are proposed for Re in terms of Gr_m, friction factor (f) in terms of Re, and Nusselt number in terms of *Re* and Prandtl number (*Pr*). It is expected that these correlations will be useful in the design and analysis of natural circulation loops.

Transient results for NCL with heater (constant heat flux) show that the system reaches steady state for higher heat inputs (100 W and 150 W) while it never attains steady state at the lower heat input of 50 W as the supplied energy is not adequate to maintain steady flow. Start-up time is seen to decrease with increase in heat input. As loop tilt angle in the XY plane increases, start-up time, amplitude of fluctuation and time to reach steady state decrease at a higher heat input of 100 W. At a lower heat input of 50 W, the system never reaches steady state at any angle of tilt in any plane of rotation. Transient results with end heat exchangers show that the system reaches steady state faster if the loop tilt angle is higher. Results also show that as tilt angle increases mass flow rate as well as heat transfer rate decrease. A loop tilt on the YZ plane yields higher mass flow rate as well as heat transfer rate compared to that on the XY plane.

An experimental test-rig of CO_2 based natural circulation loop is developed to study the actual behaviour of the loop and to validate the theoretical simulation results for subcritical as well as supercritical CO_2 for various operating conditions. Test results show that near critical/pseudocritical region, the system reaches steady state faster due to good thermophysical properties of fluid. Die down time (pull down time) of the system is also less near the critical/pseudocritical region. Measured time required to reach steady state for the test data is found to be longer than the simulation predictions. Measured loop fluid temperature is observed to be less than the simulation results, which may be attributed to the heat loss to the ambient through insulation. Within the range of study, the NCL is found to be stable. A reasonably good agreement is exhibited between the simulation predictions and the measured test data for a host of operating parameters and calculated results.

Key words: Heat transfer, natural circulation loop, CFD, supercritical carbon dioxide, correlations.