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Research Paper

Experimental and theoretical studies on the natural circulation behavior of molten salt loop

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HIGHLIGHTS

- A Molten Salt Natural Circulation Loop (MSNCL) has been setup.
- Various steady state and transient experiments have been carried out in the loop.
- Natural circulation steady state correlation is compared with the experimental data.
- In-house developed code, LeBENC, has been validated with the steady state and transient experimental data.

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ABSTRACT

Molten salts are increasingly getting attention as a coolant and storage medium in solar thermal power plants and as a liquid fuel, blanket and coolant in High Temperature Reactors (HTR). A Molten Salt Natural Circulation Loop (MSNCL) has been setup for thermal hydraulics, instrument development and material related studies relevant to HTR and solar power plants. The loop mainly consists of heated section, air heat exchanger, valves, various tanks and argon gas control system. All the components and piping of the loop are made of Inconel 625. Steady state natural circulation experiments at different power level have been performed in the loop. Transient studies for startup of natural circulation, loss of heat sink, heater trip and step change in heater power have also been carried out. A one dimensional code LeBENC, developed in-house to simulate the natural circulation characteristics in closed loops, has been validated with the experimental data obtained from MSNCL. This paper deals with the description of the loop and experimental studies carried out in the loop. Detailed validation of the LeBENC code with the experimental data has also been discussed in the paper.

1. Introduction

High Temperature Reactor (HTR) and solar thermal power plants use molten salt as a coolant, as it has comparatively low melting point and high boiling point, enabling us to operate the system at low pressure. Molten fluoride salt and molten nitrate salt has been proposed as a candidate coolant for HTR and solar power plant respectively. Bhabha Atomic Research Centre (BARC) is developing a 600 MW_{th} high temperature reactor, cooled by natural circulation of fluoride salt and capable of supplying process heat at 1000 °C to facilitate hydrogen production by splitting water. Beside this, BARC is also developing a 2 MW_e solar power tower system based on natural circulation flow of molten nitrate salt.

A lot of research has been done on Natural Circulation Loop (NCL) to investigate its behavior under varying conditions, but most of the studies were with water as working fluid. Thermal-hydraulic data pertaining to natural circulation of molten salts are very scarce in open literature. Welander [1], from his theoretical investigation on the NCL consisting of point heat source and point heat sink, explained the occurrence of instability by proposing a theory based on transport of warm pocket and cold pocket generated at the heater and cooler respectively. Later, Creveling et al. [2] experimentally studied the stability characteristics of a single phase toroidal natural circulation loop working with water. They observed the instabilities at intermediate heat transfer rate and they observed stable flow in low and high heat transfer rate. Huang and Zelaya [3] performed theoretical investigation of the thermal performance of a

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rectangular natural circulation loop. They mentioned that the steady state natural circulation flow rate obtained was shown to be a function of non-dimensional group. Vijayan and Austregesilo [4] carried out the theoretical and experimental observations on the power-to-volume scaling laws for simulating single-phase natural circulation loops each having same elevation (and length) but different diameters. Vijayan et al. [5] carried out the experimental studies on single-phase natural circulation loop to study the steady state and transient behavior. They found the instabilities in a loop with both heater and cooler are horizontally placed i.e. at Horizontal Heater Horizontal Cooler (HHHC) configuration. Later, Vijayan et al. [6] studied effect of heater and cooler orientation on the single phase rectangular natural circulation loop. Pilkhwal et al. [7] predicted the dynamic behavior related to a single phase natural circulation loop by using one-dimensional (1-D) code and 3-D CFD code. Swapnalee et al. [8] developed a generalized correlation for single phase natural circulation loop. This correlation is applicable in conditions where flow condition in a loop is varying from laminar-transition- turbulent. Naveen Kumar et al. [9] studied the effect of mixed convection in a single-phase natural circulation loop using numerical method. They proposed a steady state correlation for predicting the flow in natural circulation loop for Vertical Heater Vertical Cooler (VHVC), Vertical Heater Horizontal Cooler (VHHC) and Horizontal Heater Vertical Cooler (HHVC) configurations.

Previous studies performed on molten salts mainly focused on measuring its physical properties [10–12]. Compatibility of molten salts with different structural materials and its heat transfer characteristics have also been studied. Tortorelli and DeVan [13] studied the corrosion of Fe-Ni-Cr alloys with mixture of 60% $NaNO_3$ – 40% KNO_3 salt in a series of thermal convection loops made of alloy 800, stainless steels 304 L and 316. S. H. Goods [14] has studied the effect of molten nitrate salt environment on mechanical properties of Incoloy alloy 800 with different strain rates. Mandin et al. [15] used the Navier–Stokes and energy conservation equation to estimate thermal gradient in a molten salt. Ferri et al. [16] introduced the property definitions for molten salts in the RELAP5 code to perform transient simulations at the Prova Collettori Solari (PCS) test facility. Kearney et al. [17] investigated the feasibility of utilizing a molten salt as the heat transfer fluid and for thermal storage in a parabolic trough solar field. Bradshaw and Siegel [18] identified a range of quaternary molten salt compositions, based on solar nitrate salt. Yu-ting et al. [19] studied experimentally the forced convective heat transfer behavior of molten salt ($LiNO_3$) in laminar-turbulent transition region and generated a correlation based on experimental data. Liu et al. [20] performed a forced circulation experiments with molten salt ($LiNO_3$) and used the well known convective heat transfer correlations given by Dittus–Boelter, Sieder–Tate, Hausen, and Gnielinski for comparison purpose. Srivastava et al. [21] had theoretically investigated the heat transfer and pressure drop characteristics of molten fluoride salt flowing in a circular pipe. Zhang et al. [22] had developed a molten salt cavity receiver testing system and studied the thermal performance and transient behavior of the same. Lu et al. [23] had experimentally measured the heat transfer of ternary molten salt mixture ($NaNO_2$– KNO_3–$NaNO_3$) in an annular duct at different operating temperature and flow velocities. The experiments were performed in forced circulation loop within a temperature range of 200–550 °C.

Although the low melting point and high boiling point is the benefit of these heat transfer and storage medium, it also causes difficulties in performing experiments. These difficulties include salt solidification and container corrosion during experiments. Molten Salt Natural Circulation Loop (MSNCL) has been setup with an objective to get operating experience with molten salts, to perform natural circulation studies, to develop high temperature instruments, and test/calibrate them in the loop for material compatibility studies and validation of an in-house developed code. The detailed description of the loop, steady state experimental results at different power levels and various transients viz. startup of natural circulation, loss of heat sink, and heater trip step power increase have been reported in this paper. In-house code LeBENC, an acronym of **Le**ad **B**ismuth **E**utectic **N**atural circulation **C**ode, was developed to study the steady state and stability (transient) behavior of natural circulation rectangular loops. The code has a capability of incorporating uniform or non-uniform diameter loop. Moreover, it can be used for different coolants by incorporating their temperature dependant or constant thermo-physical properties. LeBENC has already been validated with water and Lead–Bismuth Eutectic. Validation of the LeBENC code with respect to molten salt has been carried out in this paper using the experimental data generated in MSNCL. Comparison of steady state correlation has also been performed with the same.

2. Description of the Molten Salt Natural Circulation Loop (MSNCL)

The Molten Salt Natural Circulation Loop (MSNCL) mainly consists of a heated section, air heat exchanger, valves, various tanks and Argon gas control system. Fig. 1a and b show the schematic and photograph of the loop respectively. It has been designed in a way such that effect of four different orientations of heater and cooler viz. VHVC, VHHC, HHHC and HHVC on natural circulation mass flow rate can be studied. Any of the above combinations of heater and cooler can be chosen prior to the experiment. This paper reports the experimental results of VHHC orientation. All the components and piping of MSNCL are made of Inconel 625. Vessels of the loop have been equipped with band heaters and piping with trace heaters. The loop has been provided with an adequate thermal insulation in order to reduce heat loss to the environment. In the main heater section of the loop, heat was generated by electrical heaters and transferred to the molten salt coolant as sensible heat. Heating of molten salt in this section was carried through coil type heaters having ceramic insulation. The expansion in the molten salt due to heating and contraction due to cooling was accommodated with the help of an expansion tank which was partially filled with molten salt. It is located in between the cooler and the main heater in cold leg region. The cover gas provided over the surface of the molten salt in the expansion tank acted as a cushion. The cover gas pressure was maintained with the help of a regulating valve provided in the cover gas system. The cooler is a tube-in-tube type cooler having air as secondary side coolant. The molten salt flows in the central pipe and air flows in the outer annular jacket.

Initially, salt mixture was in powder form which was melted in the melt tank provided at the bottom. Molten salt in the melt tank was then pressurized by Argon gas system. Due to pressurization molten salt flowed into the loop and subsequently filled up the entire loop. After filling, the loop was isolated from the melt tank by a control valve. Natural circulation of the molten salt took place in the loop due to heating of the salt in the heater section and cooling in the cooler section. Adequate care was taken to prevent contact of air with the molten salt to avoid formation of carbonate precipitate from CO_2 present in the air which may choke the piping of the loop. Before filling up with molten salt, the loop was preheated and purged with Argon gas to drive out air from the loop.

The instrumentation and control of the MSNCL was realized by means of a PID based controllers and Data Acquisition and Control System (DACS). DACS used in MSNCL consists of an industrial PC with a 12 bit ADC Card, 16 channel amplifiers with multiplexer, Windows XP 32 bit operating System & 32 bit ELIPSE SCADA Software. The overall accuracy of DACS was ± 0.165% of range. Monitoring of various parameters like pressure, temperature, levels in different components of the loop, valve positions etc. have been done through DACS. Different sensors of the loop have provided inputs