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Natural circulation studies in a LBE loop for a wide range of temperature

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HIGHLIGHTS

- A high temperature Lead Bismuth Eutectic loop named as Kilo Temperature Loop (KTL) has been made.
- Natural circulation experimental studies were carried out and reported in the range of 200–780 °C.
- The experiments at high temperature were carried in inert atmosphere to avoid oxidation of the loop material.
- Theoretical studies are carried out to simulate the loop with natural circulation in primary as well as in the secondary side.
- The predictions of the code LeBENC used to simulate the natural circulation in the loop are compared with the experimental results.

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ABSTRACT

Lead–Bismuth Eutectic (LBE) is increasingly getting more attention as a coolant for advanced reactor systems. It is also the primary coolant of the Compact High Temperature Reactor (CHTR) being designed at Bhabha Atomic Research Centre (BARC). A high temperature liquid metal loop named as Kilo Temperature Loop (KTL) has been installed at BARC for thermal hydraulics, instrument development and material related studies. Natural circulation experimental studies were carried out for the power range of 200–1200 W in the loop. The corresponding LBE flow rate is calculated to be in the range of 0.075–0.12 kg/s. Transient studies for start-up of natural circulation in the loop, loss of heat sink and step power change have also been carried out. The maximum temperature of the loop operated so far is 1100 °C. A computer code named LeBENC has been developed at BARC to simulate the natural circulation characteristics in closed loops. The salient features of the code include ability to handle non-uniform diameter components, axial thermal conduction in fluid and heat losses from the piping to the environment. The code has been modified to take into account of two natural circulation loops in series so that the natural cooling by argon gas in the secondary side of the loop can be simulated. This paper deals with the description of the loop and its operation. The various experimental studies carried out in the loop are discussed. Further the theoretical analysis using LeBENC code and the comparison of the predicted results with the experimental data are discussed in the paper.

1. Introduction

The design of the Compact High Temperature Reactor (CHTR) is in progress in BARC. CHTR is a ^{233}U-Thorium fuelled, Lead Bismuth Eutectic (LBE) cooled and beryllium oxide moderated reactor (Dulera and Sinha, 2008). This reactor is being developed to generate about 100 kWth power with refueling interval of 15 years and several advanced passive safety features to enable its operation as compact power pack in remote areas not connected to the electrical grid. The reactor is being designed to operate at about 1000 °C, to facilitate demonstration of technologies for high temperature process heat applications such as hydrogen production by thermo-chemical processes.

The high boiling point (1670 °C) of LBE ensures that the coolant can be operated at high temperatures without the risk of coolant boiling, which improves the thermal efficiency. It also improves the plant safety by reducing the risk of leakage at high temperatures

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Nomenclature

A	area (m^2)
C_p	specific heat (J/kg K)
D	diameter (m)
f	friction factor (dimensionless)
Gr_m	modified Grashof number, $= \frac{D_i^3 \rho_o^2 \beta g Q_h \Delta Z_c}{A_r \mu^3 C_p}$ (dimensionless)
g	acceleration due to gravity (m/s^2)
H	loop height (m)
h	heat transfer coefficient (W/m^2 K)
K	thermal conductivity (W/m K)
k	local loss coefficient (dimensionless)
l	length (m)
N_G	geometrical parameter, Eq. (14), (dimensionless)
Nu	Nusselt number, Eq. (9), (dimensionless)
Nu'	Nusselt number based on the annular spacing, Eq. (10), (dimensionless)
P	pressure (N/m^2)
q	heat flux rate (W/m^2)
Q	heat transfer rate (W)
Ra	Rayleigh number based on the annular gap, Eq. (10).
Re	Reynolds number, $\frac{vD_h}{\upsilon}$
Re_o	Reynolds number corresponding to the departure from Hagen–Poiseuille law for pressure drop coefficient
Re_1	Reynolds Number, indicating the flow regime change from laminar to transition
Re_2	Reynolds Number, indicating the flow regime change from transition to turbulent
t	time (s)
T	temperature (°C)
T_o	reference temperature (°C)
U	overall heat transfer coefficient (W/m^2 K)
v	velocity (m/s)
W	mass flow rate (kg/s)
x	length wise distance (m)
z	height (m)

Greek

Δ	roughness (m)
$\bar{\Delta} = \frac{\Delta}{D_h}$	dimensionless
μ	dynamic viscosity, (Ns/m^2)
ρ	density (kg/m^3)
ρ_o	density at reference temperature (kg/m^3)
Δp	pressure drop (N/m^2)
Δx	length difference (m)
Δz	height difference (m)

Subscript

Ar	Argon
acc	acceleration
c	center
eff	effective
Enc	enclosure
f	fluid
h	heater
hx	heat exchanger
i	i-th node
in	inside
LBE	Lead Bismuth Eutectic
o	outside
r	reference
ss	steady state
w	wall
1	primary side
2	secondary side

as pressurization is not required. Though LBE reacts with air to form insoluble lead oxide, it does not lead to cause fire when it comes in contact with air or water. Hence, an intermediate coolant is not essential in the reactor. LBE systems are also excellent choice as spallation targets for Accelerator Driven Systems (ADS) (Cheng et al., 2004). The various desirable properties as a coolant make LBE the most suitable choice for CHTR. In order to design the reactor, it is necessary to study the behaviour of liquid LBE under various operating conditions.

This paper deals with the brief on literature survey carried out on experimental and theoretical studies carried out on liquid metals. The description of KTL which has been installed in BARC for thermal hydraulic and material compatibility related studies, is given. A number of experimental studies for a wide range of temperature levels (from 200 to 1100 °C) are carried out on LBE natural circulation in this loop. The 1D computer code LeBENC (Lead Bismuth Eutectic Natural Circulation) which was developed for natural circulation studies in LBE systems has been modified for theoretical studies of the KTL. The descriptions of the computer code LeBENC and its validation with the experimental data are also given.

2. Literature review

A literature survey was carried out for experimental loops using liquid metal as working fluid. Table 1 shows the brief of the loops with maximum operating temperature up to 550 °C. Most of the loops are found to be used for material compatibility and coolant chemistry control related studies under forced flow. The loops used for these studies are, STELLA (Beauchamp et al., 2010), LECOR (Fazio et al., 2003), DELTA (Hosemann et al., 2008), JLBL-1 (Kikuchi, 2009), MESLOOP2001 (Mikinori et al., 2003), CORRIDA (Carsten et al., 2011), LISOR (Kirchner et al., 2003), CorrWett, CIRCO (LBE handbook, 2007), LINCE (Martín-Muñoz et al., 2011), KPAL-1 (Cho et al., 2006), Natural convection quartz harp loop (Abraham et al., 2000), LBE corrosion test loop (Takahashi et al., 2002), DRAGON-1 (Wu et al., 2012), KYLIN-I& KYLIN-II (Wu et al., 2014) and LIFUS-3 (Technical Report, 2009). There are few loops found in literature where material compatibility studies were carried out under natural circulation also. The loops are DRAGON-I (Wu et al., 2012), KYLIN-I (Wu et al., 2014), KYLIN-II (Wu et al., 2014) and the thermal convection loop reported by Pawel (2014). The experimental studies on forced flow heat transfer in heater rod bundles were carried out in several loops like THESYS (Schulenberg et al., 2005), TALL (Ma et al., 2006) and HELIOS (Cho et al., 2011). The two phase studies are also carried out in some of the loops as reported by Loewen and Tokuhiro (2003) and Abdulla et al., in press. The facilities like THEADES (Schulenberg et al., 2005), CHEOPE (LBE handbook, 2007) and JLBL-3 (Kikuchi, 2009) were used for thermal hydraulic design and testing of ADS components. Magnetohydrodynamics (MHD) effect on thermal hydraulics is important in fusion reactor technology development. Facilities like MaPLE (Smolentsev et al., 2013), MHD loop reported by Uda et al. (2001) and LIMITS (Tanaka et al., 2004) are made to study the effect of MHD on heat transfer and flow pattern in liquid metals. There are large facilities like CIRCE (Bandini et al., 2015) and ATENA (OECD/NEA Report, 2011), where full scale components and system level studies of ADS are carried out. Some loops like JLBL-2 (Kikuchi, 2009) and JLBL-4 (Toshinobu and Hiroyuki, 2014) are extensively used for advanced flow measurement technique development.