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Experimental and CFD Study on Natural circulation Phenomenon in Lead Bismuth Eutectic Loop

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Abstract

A test loop, HANS (Heavy metal Alloy Natural circulation Study loop) is installed in BARC (Bhabha Atomic Research Centre) for thermal hydraulic, instrumentation development and material compatibility related studies in Lead Bismuth Eutectic (LBE) coolant. Steady state natural circulation characteristics in the LBE loop were investigated at different power levels. Significant natural convection flow was observed in the experiments. It was found that the natural circulation was easily established and stabilized. It took only a few minutes to have a stable natural circulation at a constant power level. The natural circulation flow rate depends on the loop resistance and the temperature difference between the hot leg and the cold leg, as determined by the power level and the heat sink capacity. The heater power is varied from 1200W to 2700W and the temperature difference found across the heater is 80°C to 165°C. The natural circulation in the loop is simulated in a CFD code PHOENICS. The predictions of PHOENICS code are found to be in good agreement with the experimental data.

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Keywords: Lead Bismuth Eutectic; Heavy Liquid Metal; Natural circulation; CFD.

1. Introduction

Natural convection is the phenomenon of fluid movement driven by hydrostatic head due to a change in density. In a closed system without the use of pumps, circulation of fluids is generally maintained by thermal convection. This is why natural circulation is designed for the so-called Generation IV nuclear reactors, which like to employ passive safety and reliability. As a result, more and more attention has been given to natural circulation in the advanced reactor designs. As compared to sodium based liquid metal coolant, LBE has high boiling point (1670°C) and can potentially allow hydrogen production through chemical process. Due to high boiling point, it can be used at high temperatures without the risk of boiling of water. LBE also does not readily

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react with air and water unlike sodium or NaK which ignite spontaneously in air and react explosively with water and thus, an intermediate coolant is not essential in the reactor.

Compact High Temperature Reactor (CHTR) is being designed in BARC which is a ^{233}U-Th fuelled, Lead Bismuth Eutectic (LBE) cooled and beryllium oxide moderated reactor [1]. This reactor is being developed to generate about 100kWth power, with refuelling 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^{o}C, to facilitate demonstration of technologies for high temperature process heat applications such as hydrogen production by thermo-chemical processes.

Experimental studies were carried out in TALL facility with forced flow and natural circulation of LBE for ADS systems [2]. The numerical results from TRAC/AAA and RELAP5 analysis were compared with the experimental results. Single phase natural circulation studies in a LBE-water two phase boiling experiments are carried out [3]. A 1-D code was developed and showed that the natural circulations of single phase HLM could be linearly unstable in a high Reynolds number region, and any increase in loop friction makes the forward circulation more stable, but destabilizes the corresponding backward circulation under the same heating/cooling conditions [4]. In general, while the interest in natural circulation in HLM is high, its study is still quite limited. Steady state pre-test analyses of a LBE loop are also carried out in NACIE [5]. They performed steady state 1D analytical as well as 3D CFD studies and compared the results. In general, while the interest in natural circulation in HLM is high, its study is still quite limited. Although some analytical works for the thermal-hydraulics of HLM-cooled reactors is carried out [6-7], little experimental data have been published to demonstrate the thermal-hydraulic performance of HLM-cooled systems, let alone the characteristics of natural circulation. A HLM loop called Heavy metal Alloy Natural circulation Study (HANS) loop is designed and constructed at BARC to investigate the thermal-hydraulic studies related to CHTR [8]. The present paper is focused on the experimental studies carried out on natural circulation performed on HANS loop. The steady state natural circulation characteristics in the LBE loop were investigated at different power levels. Significant natural convection flow was observed in the experiments. It was found that the natural circulation was easily established and stabilized. It took only a few minutes to have a stable natural circulation at a constant power level. The natural circulation flow rate depends on the loop resistance, and the temperature difference between the hot leg and the cold leg, as determined by the power level and the heat sink capacity. The heater power is varied from 1200W to 2700W and the temperature difference found across the heater is 80^{o}C to 165^{o}C. The natural circulation in the loop is simulated in a CFD code PHOENICS. The predictions of PHOENICS code are found to be in reasonable agreement with the experimental data.

Nomenclature

A	area (m^2)
c_p	specific heat (Jkg^{-1}K^{-1})
C	coefficient
G	geometrical multiplier
m'	mass flow rate (kgs^{-1})
Q	heater flux (W)
t	time (second)
T	temperature (^{o}C)
Ú	vector velocity
v	velocity (ms^{-1})
L	low
V́	value
S	source term
y	point position

Subscript

bc	boundary condition
CFD	computational fluid dynamic
exp	experiment
E	east
H	high

N	north	Greek letter	
P	point centre	ρ	density (kgm^{-3})
S	south	Δ	difference
T'	cell centre at previous time step	ν	kinematic viscosity (m^{2}s^{-1})
W	west	Γ_ϕ	the diffusive exchange coefficient for ϕ

2. Lead-bismuth test loop, HANS

The LBE test loop mainly consists of a heated section, air heat-exchanger (cooler), valves, various tanks and argon gas control system. Fig.1 (a) shows the LBE loop along with insulation. The LBE before commencing of experimentation is in solid form in melt tank which is melted and made to rise in the sump tank from where it is further transferred to the loop by creating pressure by argon gas system. Due to pressurization molten LBE flows into the loop and subsequently fills up the loop. After filling, the loop was isolated from the sump tank by a valve. Now for natural circulation of LBE to take place, heating of the LBE is started in heater section by turning ON the main heater and cooling in the heat exchanger by sending air through heat-exchanger. After losing heat in the heat exchanger LBE enters the heated section through 15 mm Nominal Bore (NB) pipeline. Adequate care has been taken to prevent contact of air with the molten LBE to avoid formation of insoluble metal oxide which may block the piping of the loop. Preheating and purging in loop with high purity argon gas is done before lifting of LBE is done in loops as to drive out air from the loop. During the operation of the loop high purity argon gas was used as cover gas in the vessels. Intermittently Argon + 5% H_2 gas was used to maintain the chemistry of the LBE coolant in the loop.

All the vessels of the loop are equipped with band heaters and piping with trace heaters. To reduce heat loss to the environment, the loop is provided with adequate thermal insulation. In the main heated section of the loop, heat is generated by electrical heaters and transferred to the liquid metal coolant as sensible heat. It mainly consists of 'U' shaped mineral insulated immersion type heater elements mounted on a stainless steel flange. The LBE after getting heated in heater section expands. To accommodate this expanded LBE in loop, expansion tank is attached to loop between heater and heat exchanger where coolant will get contracted due to cooling. Expansion tank is prefilled with some amount of LBE and level sensors are applied in expansion tank so as to know the level of molten LBE in it. Two types of level sensors are used; discrete type which are based on electrical conduction principle, where the electrical circuit is closed when liquid LBE surface touches a metallic rod hanging from the top flange of expansion tank and continuous type which are based on gas bubbling technique. Here, inert gas is bubbled by injecting via an SS tube into the liquid. While measuring the differential gas pressure between the bubble tube and the cover gas in the tank, the level of LBE can be recorded continuously. The heat exchanger is a tube-in-tube type heat exchanger. The liquid metal flows in the central pipe and cooling air flows in the outer annular jacket.

Data Acquisition and Control System (DACS) is used to monitor and control various parameters like pressure, temperature, levels in different components of the loop, valve positions etc. Different sensors of the loop provide inputs to the DACS. All operational and safety conditions are built into the program. Levels in the tanks, temperatures in the loop, cover gas pressure; flow and other parameters are measured. Warnings, alarms and automatic trips are incorporated into the program for safe operation of the loop. DACS also has oxide sensors which indicate the amount of oxygen present in the loop. When the oxygen level goes below the limit, commercial argon was bubbled in the expansion tank, so that the oxygen present in the argon gas as impurity helps to increase the concentration of oxygen in the molten LBE. When the oxygen level increases Argon +5% H_2 gas mixtures was bubbled so that the oxygen level remains well below the PbO formation level. The instrumentation of the loop was designed to control the loop parameters in the event of postulated accidents. High temperature pneumatically operated Control Valves (CV) and Pressure Regulating Valves (PRV) is used for the control and operation of the loop. Besides these, pressure relief valves are used to relieve argon gas in case of high system pressure. Non-return valves are used to prevent ingress of liquid metal into the impulse lines from the main loop, during any event. All the valves are made of SS 316L and are PLC controlled. The instrumentation and control systems are designed in such a way that the loop can be operated remotely as far as possible. High temperature pressure transmitters are used to measure the gas pressure in the main loop. Fifty six ungrounded K-type, SS (Stainless Steel) sheathed thermocouples are installed in the loop. Most of the thermocouples are installed on the surface and some are inserted into the piping and vessels through special fittings. Thermocouple readings are read through analogue input modules of the PLC. Fig.1 (b) shows the flow diagram of the loop with cover gas system. Table 1 gives detailed specifications of the loop.

a

b

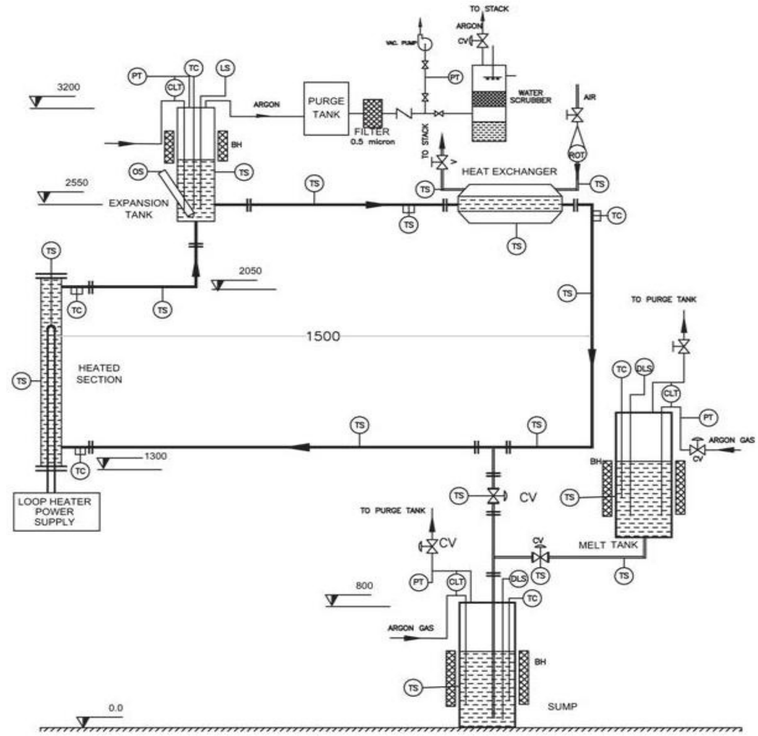


Fig.1 (a) View of the HANS loop. (b) Flow diagram of lead bismuth

BH	: Band heater	CV	: Control Valve
OS	: Oxygen sensor	TC	: Temperature sensor in coolant
CLT	: Continuous level transducer	DLS	: Discrete level switch
PT	: Pressure transducer	TS	: Temperature sensor on piping surface

Table.1 Design parameters of the loop

Sr. No.	Parameters	Values
1	Fluid used	Lead bismuth eutectic
2	Fluid circulation mode	Natural circulation
3	Line size	15 mm NB Sch 80
4	Centreline elevation difference between heat exchanger and heated section	750 mm
5	Total circulation length	5500mm
6	Loop material	SS 316L
7	Design pressure of the loop	490332.5 N/m^2
8	Coolant inventory	500 kg
9	Maximum main heater power during experiments	2.5 kW
10	Maximum operating temperature	500°C
11	LBE mass flow rate	0.09-0.15 kg/s

3. CFD modelling

Modelling of HANS loop is done in SALOME. SALOME is open-source software that provides a generic platform for Pre and Post-Processing for numerical simulation. It is based on an open and flexible architecture made of reusable components. SALOME is a cross-platform solution. It is distributed as open-source software under the terms of the GNU LGPL license. SALOME can be used as standalone application for generation of CAD models, their preparation for numerical calculations and post-processing of the calculation results. SALOME can generate solid geometry which are compatible to many softwares like PHOENICS, TRIO-U, CFDACE etc. Fig.2 (a) shows the modelling done in SALOME.

a b

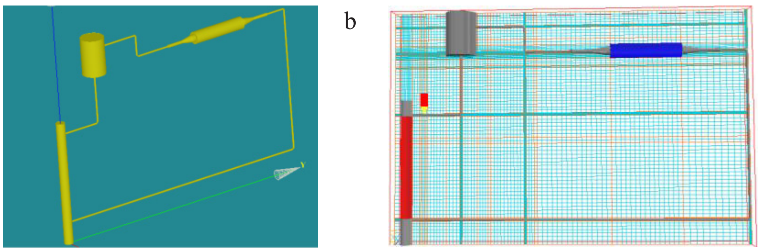


Fig.2 CFD figures. (a) modelling in SALOME. (b) meshing in PHOENICS X-Z plane

The geometry modelled in SALOME with dimensions of inner diameter of pipes so that it can be directly treated as fluid and is imported in PHOENICS, a general-purpose software package. PHOENICS is used because it is the licensed software extensively used in BARC for research and development on nuclear thermal hydraulics. It has its own solid-modelling, grid-generation and graphical results-display modules; but its users are free to use their own, or third-party, packages instead. Fig.2 (b) shows meshing done in PHOENICS. The geometry was made in SALOME because it contains elbows which modelling in PHOENICS is rather hard. Before importing model, a box was modelled of domain size which can be treated as wall boundary condition and then the model was imported. PHOENICS treats the imported geometry as a single entity so cooler, heater are to be modelled separately in PHOENICS. Also dummies are modelled and place in such positions so that mesh density can be modified as per our requirement. Once meshing is done, boundary conditions are given. Various boundary conditions are as follows:

- Heater power with fixed heat flux varying from 1200W to 2700W
- Cooler with constant temperature as the value of output temperature of cooler obtained from different heater power in experimental process
- Box with laminar wall boundary condition.

The single phase conservation equation solved by PHOENICS [9] can be written as:

$$\frac{\partial(\rho\phi)}{\partial t} + \frac{\partial}{\partial x_k}\left(\rho\acute{U}\phi - \Gamma_\phi \frac{\partial\phi}{\partial x_k}\right) = S_\phi + S_{bc1} + S_{bc2} + \ldots + S_{bcn} \tag{1}$$

The finite-volume discretization of the differential equation thus yields, for each cell point centre P in the domain, the following algebraic equation:

$$a_P\phi_P = \sum_{N,S,E,W,H,L,\acute{T}} a_k\phi_k + S_\phi + \sum_{N,S,E,W,H,L,\acute{T}} GC(\acute{V} - \phi_P)$$

$$\phi_P = \frac{\sum a_k\phi_k + S_\phi + \sum GC\acute{V}}{a_P + \sum GC} \tag{2}$$

Now for boundary condition of fixed heat flux, numerical procedure is to fixing source by setting the value of C to small number so that the denominator can be changed and setting $\acute{V}$ as source value. G then ensures that final source is per cell and for boundary condition of fixed value at cooler, numerical practice is the value of ϕ can be fixed in any cell by setting C large number and $\acute{V}$ to required value. The equation (2) thus becomes as:

$$\phi_{P_{\text{fixed heat flux}}} = \frac{\sum a_k\phi_k + S_\phi + \text{source}}{a_P}\ ;\ \phi_{P_{\text{fixed value at cooler}}} = \frac{\text{very small number} + GC\acute{V}}{\text{very small number} + GC} \sim \frac{GC\acute{V}}{GC} = \acute{V} \tag{3}$$

Whereas for laminar wall boundary condition, a special patch is provided which automatically sets:

$$T = \nu \times \rho \times \frac{\text{area of cross}-\text{section for LBE flow}}{\Delta y} \tag{4}$$

After this, domain is then assigned as LBE along with its properties as stated in HLMC handbook [10]. The initial temperature for the CFD calculation is given with that value of temperature which we achieve while experimentation for steady state at the enter point of heater for corresponding heater power. Since this is natural circulation study, gravitational force is applied and the Buoyancy model is set to BOUSSINESQ. Since the flow is very low Reynolds number is in the range of 600-800, the flow is assumed to be laminar hence in models part in PHOENICS, turbulence model was turned to LAMINAR.

Different meshes were formed and there results were compared with each other for same heater power. However mesh only for pipes of diameter 14mm were changed since expansion tank, cooler and heater are huge in size as compared to pipe and does not get affected that much by mesh size. It was noted that when radial mesh in pipe were 4×4 the heater outlet temperature for 1500W heater power was found to be 224°C. This went increasing with the increase in mesh. However it was observed that when radial mesh were 10×10 the heater outlet temperature was found to be ~270°C which later did not change even after increasing radial meshes. Even the flow obtained was smooth.

4. Results and discussions

4.1 Experimental results and discussions

Various experiments are carried out HANS loop to generate data for different heater power which could be compared with the CFD results obtained. Heater powers at which loop operated are1200W, 1500W, 2100W, 2700W. Initially loop was running for heater power 1200W heater power with air flow rate 240lpm through cooler. After achieving steady state, power was raised to 1500W heater power.

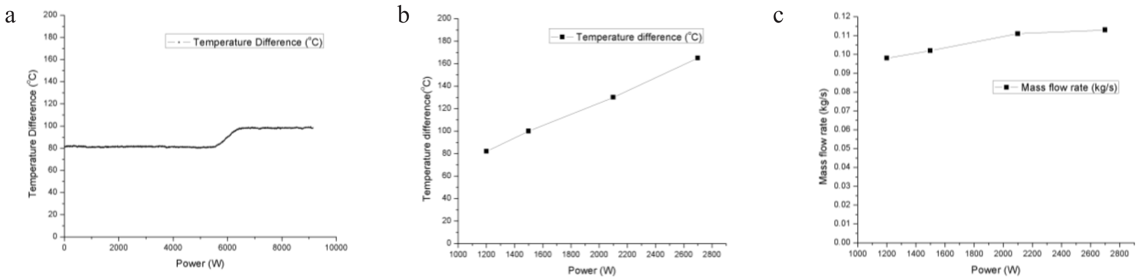


Fig.3 Experiment results. (a) change in temperature difference across heater due to change in heater power from 1200Wto 1500W. (b) Temperature difference across heater for various heater powers. (c) Mass flow rate different heater powers

From Fig.3 (a), since loop was running for 1200W heater power, steady state was achieved at the temperature difference of about 82°C across heater. The power was then raised to 1500W and so the steady state was achieved with temperature difference across heater about 100°C.

$$Q = m'_{exp}\, c_p \Delta T \tag{5}$$

Value for c_p by formulation from HLMC handbook [10] at centre of heater section is found to be 146.38 J/kg-K Hence for heater power 1500W, $m'_{exp} = 0.102\text{kg/s}$

Similarly, steady state was achieved for 2100W and 2700W heater power with same heater power.

From Fig.3 (b) it can be seen that as the heater power is increased keeping the air flow rate same in the cooler, temperature difference obtained across heater increases for steady state to achieve. Temperature difference is considered because, it is observed during experimentation that inlet and outlet temperature obtained for steady state to achieve for same heater power are different depending upon the initial heater power at which loop was operated. Similarly from Fig.3 (c) it is observed that mass flow rate of LBE at increases as the heater powers increases from 1200W to 2700W.

4.2 CFD results and discussions

CFD results for 1200W, 1500W, 2100W, 2700W was obtained using PHOENICS. Results obtained for heater power 1500W are shown in Fig.4. Cooler was given temperature equivalent experimental heater inlet temperature. This is because, in CFD we assumed perfect insulation and so there are none heat losses in CFD and so after achieving steady state in CFD, the cooler outlet temperature remains constant throughout till it reach heater inlet.

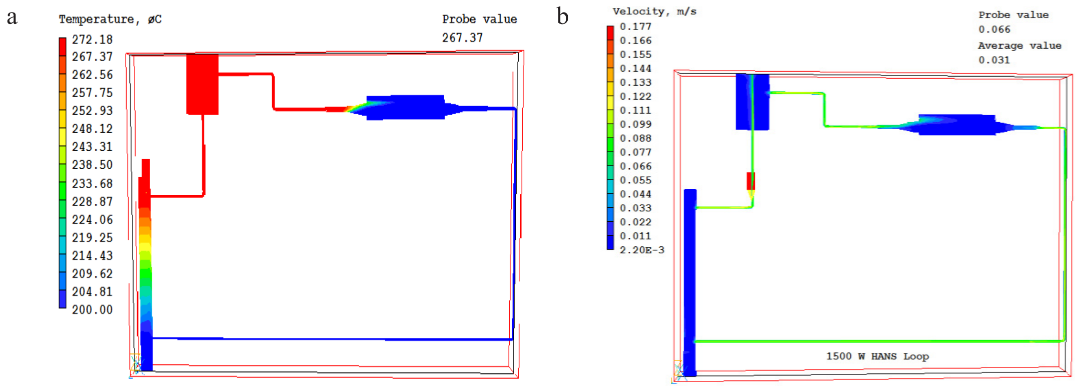


Fig. 4 CFD results. (a) temperature profile in loop for heater power 1500W. (b) velocity profile in loop for heater power 1500W

Fig.4 (a) shows that when heater power was kept 1500W, heater outlet temperature obtained was 270°C and hence the temperature difference of 70°C across heater. Since steady state is achieved, heater outlet temperature is constant till cooler inlet where temperature decreases drastically and almost falls to 200°C till centre of heat exchanger. Fig.4 (b) shows the velocity profile in a loop for heater power 1500W. It can be seen that as steady state is achieved, velocity through all pipes of small diameter (14mm) is almost constant. However velocity in heater, cooler and expansion tank is low due to their huge cross sectional area as compared to small pipe with diameter 14mm. The velocity of main stream entering expansion tank through centre decreases slowly and in case of entering cooler (heat exchanger) decreases slowly from upper side of cooler. Probe value shows that velocity of LBE in pipe is about ~0.07m/s.

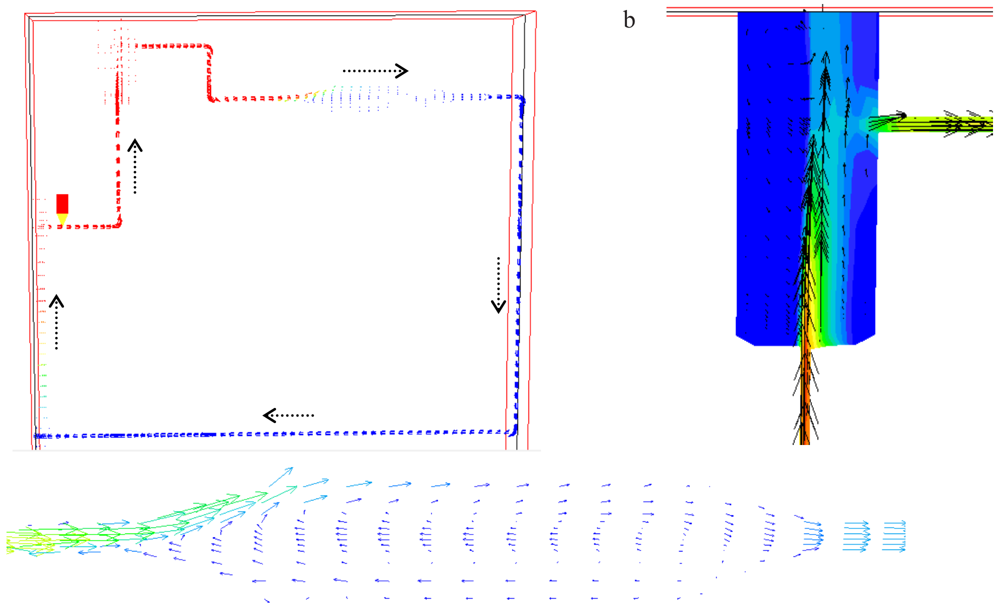
$$m'_{CFD} = \rho A v \qquad (6)$$

Value of ρ at 270°C by equation from HLMC handbook [10] is 10368.06kg/m^3

Hence mass flow rate comes to be 0.11kg/s

Fig.5 (a) shows the flow of LBE in loop which is from heater to expansion tank from there to cooler and back to heater that is from hot leg to cold leg and back to hot leg. Fig.5 (b) shows that when LBE enters expansion tank its speed slowly decreases as it goes up, some part enters horizontal pipe to right rest goes up till top where it circulates comes down again mixes with the up going flow and this procedure continues. Fig.5 (c) shows the flow pattern in cooler. LBE entering cooler has high velocity than LBE already in cooler, however since temperature of LBE entering cooler is more than LBE already in cooler, its density is lower and hence it rises up where it comes in contact with the surface of cooler, cools and its density increases so it comes down at the same time it is pushed by LBE coming from behind resulting in circulation. Or in other words natural circulation is very slow process so the velocity is very less and the diameter is large which result in local recirculation which is very important from point of view of nuclear safety as we will not be able to filter or monitor the coolant which get stuck in that area. LBE exist cooler from right end and finally goes to heater portion.

a b



c

Fig.5 (a) Flow pattern in loop. (b) Flow pattern in expansion tank. (c) Flow pattern in heat exchanger

4.3Comparison Experimental and CFD results

Graph for experimental result in comparison with CFD results are plotted.From Fig.6(a),temperature difference in experimental data is found to be more than CFD data. The reason is, in CFD we assumed no heat loss and so the temperature from cooler outlet to heater inlet remains constant however, in experimentation, there are some heat losses through pipes even after insulation. This causes decrease in heater inlet temperature and thus the difference is more. Temperature difference is maximum for heater power 2700W. Temperature difference from experimental data is 165°C whereas from CFD data it is 126.20°C. Figure 6 (b) the LBE flow rate at 2700W from experimental result is 0.113kg/s whereas in CFD result is found to be 0.13kg/sec, which is equivalent to ~0.083m/s velocity in the 14mm NB pipe line. Thus difference of 13.07% is found between experimental and CFD data. It can also be seen from Fig.6 (a) and Fig.6 (b) that since temperature difference in experimental data is more, mass flow rate is less as compared to CFD data.

It is found that the maximum difference in experimental data and code prediction is 13.07% for mass flow rate and 23.5% for temperature difference across the heater section.

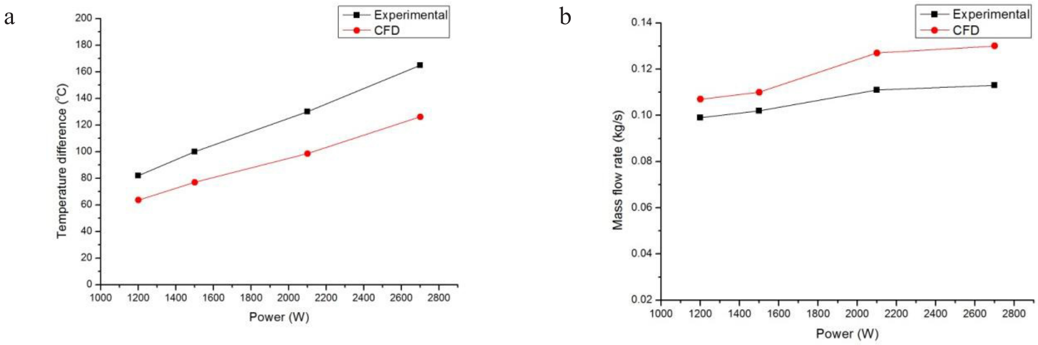


Fig.6 (a) Comparison of ΔT across Heater of experimental result with CFD code at steady state. (b) Comparison of mass flow rate of experimental result with CFD code at steady state

4. Conclusions

a) Steady state studies have been carried out in a lead bismuth eutectic test loop.
b) It is found that as the heater power is increased, the temperature difference across heater increases and so thus the mass flow rate.
c) A CFD solution with help of SALOME and PHOENICS, is developed to predict the behaviour of the loop and steady state natural circulation experimental studies were studied with main heater power ranging from 1200W to 2700W and the same was simulated in CFD analysis.
d) The CFD solution is validated against the steady state experiment results. It is found that the predictions are in good agreement with the experimental data.

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