Characterization of LBE Non-isothermal Natural Circulation by Experiments with HELIOS Test Loop and Numerical Analyses

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Abstract. We present results of experiments with lead-bismuth eutectic (LBE) non-isothermal natural circulation in a full-height scale test loop, HELIOS, and numerical modeling results performed by a system thermal-hydraulics code. The experimental studies were conducted under steady state as a function of core power conditions from 9.8kW to 33.6kW. Local surface heaters on the main loop were activated and finely tuned by trial-and-error approach to make adiabatic wall boundary conditions. Activities on numerical modeling were carried out by a thermal-hydraulic system code MARS-LBE using the well-defined experimental data. It is found that the predictions were mostly in good agreement with the experimental data in terms of mass flow rate within 7% and temperature difference within 7%, respectively.

Key Words: Lead-bismuth eutectic, Natural circulation, Non-isothermal experiment, HELIOS, Numerical modeling.

1. Introduction

Lead-bismuth eutectic (LBE) has been studied as an option for next-generation reactor coolant because of its favorable features as nuclear reactor coolant: chemical inertness with air, water, and steam, low melting point (398K) and high boiling point (1,943K), and high thermal conductivity (11.8W/m K at 573K) for better heat transfer. In addition to this, normal operation of a reactor under natural circulation has been of interest for enhanced safety in terms of a simple and compact design. In this regard, we have conceptualized a pool-type LBE-cooled small modular reactor (SMR) which solely relies on natural circulation for normal and accident cooling [1].

The characterization of LBE natural circulation has been studied worldwide not only by experiments with several loop facilities but also numerical modeling with the experimental results. An experimental study on single-phase LBE natural circulation was performed with a test apparatus for direct contact water boiling tests [2]. ENEA carried out several experiments with NACIE facility on non-isothermal natural circulation made in various heater power conditions and gas-induced circulation [3, 4]. The test results were used for the code benchmark of RELAP5/MOD3.3 for LBE. In Sweden, a medium-size facility named TALL at KTH was utilized for lead-cooled fast reactors and accelerator-driven systems characterization [5, 6]. Various natural circulation phenomena were tested including natural circulation capability and stability, start-up from different initial conditions, and accident simulations. Similarly, the test results were compared with numerical analyses by TRAC/AAA and RELAP5 codes. Recently, a part of the facility was substituted to a large-size pipe so that local three-dimensional phenomena can be studied [7]. Experimental studies on the steady-state and transient natural circulation of LBE were also conducted with the HANS facility at BARC in a range of core power from 900W to 5,000W [8]. A house code called LeBENC was validated with the test results and the maximum temperature deviation was within 15% range in transient simulations.

We present results of experiments with LBE non-isothermal natural circulation experiments in a full-height scale test loop HELIOS (Heavy Eutectic liquid metal Loop for Integral test of Operability and Safety of PEACER) at Seoul National University (SNU) and the computational modeling with a system thermal-hydraulics code, MARS-LBE. As precedent studies, the investigation of hydraulic loss over each constituent component of the loop was performed in an international collaboration program where guidelines on pressure loss estimation in LBE loop configurations were suggested [9, 10].

2. Descriptions on Experimental Facility and Numerical Method

2.1.HELIOS Facility

HELIOS is an integral test facility at SNU which was originally designed to validate the operation capability and safety characteristics of a prototypic LBE-cooled burner, PEACER-300 [11]. The loop has maximum mock-up core power with 60.0kW by electrical heater rods and the total facility height is about 12m. It is capable of thermal-hydraulic experiments and materials corrosion tests in LBE flow conditions [12, 13].

There are two main fluid systems in HELIOS; each system adopts working fluids as LBE and a single-phase, high flashing-point heat transfer oil (Dowtherm© RP), respectively. The primary loop is arranged with several components made up of 316L stainless steel. The detailed design and exact dimensions of the components can be found in a report [9].

For the temperature measurements, K-type thermocouples are selected and installed through the piping for fluid temperature measurement both in primary and secondary fluids. The error of the sensor was reported as about ±1.0K in a temperature range from 200^{o}C to 1000^{o}C by the manufacturer. The location of each thermocouple is depicted as *FIG. 1*. The secondary fluid temperatures are measured from inlet and outlet.

Among various methods to measure mass flow rate of a fluid, pressure drop measurement is used to obtain LBE mass flow rate. An orifice is located in cold leg and the pressure drop over it is measured by a differential pressure transducer (Rosemount 3051 CD3A) with capillary probes. The total measurement error in terms of differential pressure is ±0.065% in the full range of 0.8 bar. The locations of differential pressure measurement are also shown in *FIG. 1*. The conversion equation from measured differential pressure to mass flow rate was investigated and formulated in a previous research [10].

Due to a large surface area of the system compared to its volume, the outer surface of HELIOS components is enclosed by thermal insulation and local surface heaters to mitigate heat loss to environment. These heaters are activated during most of natural circulation operations. In addition, these surface heaters are also necessary in pre-test stage by increasing system temperature above the melting temperature of the liquid metal.

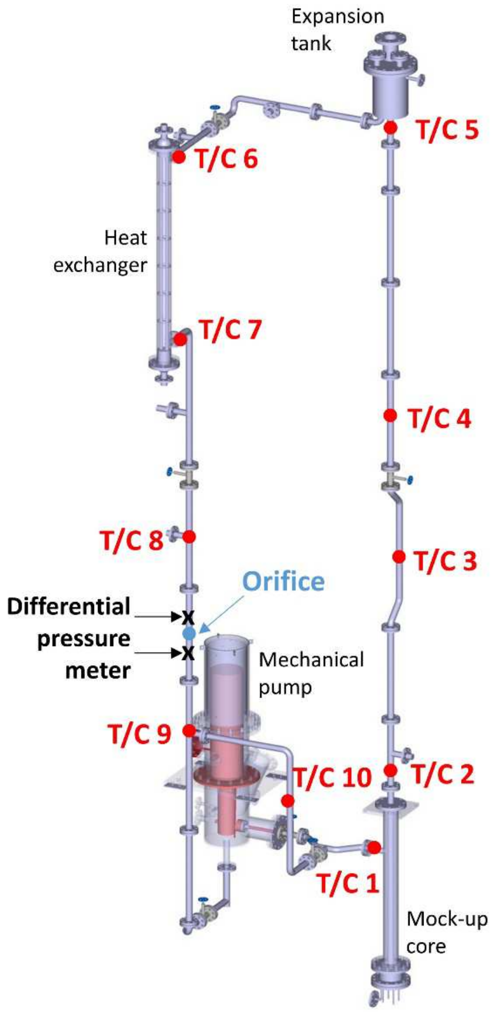

FIG. 1. HELIOS constituent components and instrumentation system.

2.2.Descriptions on Numerical Simulation Code: MARS-LBE

MARS is a system safety analysis code developed by KAERI (Korea Atomic Energy Research Institute) integrating RELAP5/MOD3 [14] and COBRA-TF [15] which are widely used codes in the thermal-hydraulic analyses for LWR. These two codes are coupled implicitly by using dynamic link library techniques. The integrated code is capable of one-dimensional thermal-hydraulic system analysis and multi-dimensional subchannel analysis where its backbone codes are applicable, respectively [16]. We have improved the code by modifying some calculation schemes in convective heat transfer suitable for heavy liquid metal and updating LBE thermophysical property table: the updated code is called MARS-LBE 3.11.

HELIOS hydrodynamic components are interpreted for MARS-LBE input and are described with several components such as pipes, junctions, time-dependent volumes and junctions to impose unsteady boundary conditions with about 170 hydrodynamic cells. In addition, heat structure models are included where heat transfer occurs between solid bodies such as heater rods and the heat exchanger.

In MARS-LBE, convective heat transfer is treated in an internal subroutine by calculating convective heat transfer coefficient from Nu, Nusselt number, which is generally given by Reynolds number (Re) and Prandtl number (Pr) of a fluid in a calculation cell. For LBE, Seban-Shimazaki correlation [17] is applied to any heat transfer conditions:

$$\mathrm{Nu}_{LBE} = 5.0 + 0.025(\mathrm{Re}\,\mathrm{Pr})^{0.8}, \quad (1.)$$

and modified Sieder-Tate correlation [18] is used for secondary side oil at a given condition:

$$\mathrm{Nu}_{oil} = 0.027\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.33}. \quad (2.)$$

MARS-LBE predicts pressure loss in a component due to friction and flow condition change by following relation:

$$\Delta p_i = \sum_i \frac{\rho_i v_i^2}{2}\left(f\frac{l}{d_h} + K\right)_i. \quad (3.)$$

In case of friction loss coefficient ($f(l/d_h)_i$), an internal subroutine in the code calculates the value in a given component with specified pipe roughness. However, form loss coefficient (K_i) should be explicitly provided except the case of using internal sudden area change model. The hydraulic loss coefficients in HELIOS were investigated in previous activities [9, 10] and the results were utilized in this study. Pipe roughness is designated to be 2.53μm as measured.

3. Experimental Procedure and Conditions

3.1.Experimental Procedure

In HELIOS, no instrumentation system for measuring heat loss is available so the uncertainties given by heat loss are inevitable and ideal adiabatic test conditions cannot be generated. However, a sufficiently adiabatic condition can be achieved by compensating heat dissipation to the environment with the surface heaters.

In this regard, heat compensation is made in several steps: firstly, the amount of heat loss over each section defined by a region between two adjacent thermocouples is estimated from temperature distribution along the main loop with measured mass flow rate and temperature difference at a given state. Secondly, electric power ratings equivalent to the estimated heat loss over sections are supplied to local surface heaters. Followed by heat addition to the system, temperature transients are expected to take place. The local surface heaters are tuned by trial and error until hot leg and cold leg temperatures are respectively in close ranges and the mock-up core power rating and the heat withdrawn by the secondary side oil are in balance.

3.2.Experimental Conditions and Test Matrix

Experimental activities carried out in HELIOS were classified with the total mock-up core power ratings. Following the experimental procedure, a final steady-state, adiabatic condition can be reached after heat compensation on the main loop is achieved and heat balance between the mock-up core power rating and heat transferred to the secondary side oil become consistent.

For the natural circulation experiment conditions, four total mock-up core power ratings were selected: 9.8, 15.0, 27.0, and 33.6kW. Each condition was directly designated to be test numbers from NC1.0 to NC4.0. Other than this, the main LBE loop and secondary side oil conditions in final steady states are illustrated in TABLE 1. In NC1.0 and NC2.0 cases, all four electrical heater rods in the mock-up core were in active, while only three rods were activated in the cases NC3.0 and NC4.0.

TABLE 1: TEST MATRIX ON ADIABATIC, NON-ISOTHERMAL NATURAL CIRCULATION EXPERIMENTS IN HELIOS.

No.	Total mock-up core power (kW)	No. of active heater rods	Avg. oil inlet temperature (°C)	Avg. oil mass flow rate (kg/s)	Total experimental time (hr)
NC1.0	9.8	4	99.65	0.374	80
NC2.0	15.0	4	122.63	0.374	70
NC3.0	27.0	3	155.03	0.382	72
NC4.0	33.6	3	167.60	0.390	48

4. Experiment and Numerical Analysis Results

4.1.Experiment Results

Non-isothermal natural circulation experiments were performed with four different core power conditions. Owing to ambient temperature fluctuation within a day, the whole system reacted to it and temperature distribution along the main loop had periodical changes. To overcome this, the system had been maintained and observed without any intervention or manipulation in the last 24 hours out of full test history after reaching adiabatic wall boundary conditions.

Well-defined data for numerical analyses were generated from the measurements given in 6-7 hours which showed rather moderate fluctuation out of 24-hour observation. In this regard, the steady state temperature distributions for hot leg and cold leg lied in 5-7°C ranges. In TABLE 2 the well-defined experimental data are summarized.

TABLE 2: HELIOS STEADY-STATE NATURAL CIRCULATION RESULTS.

	No.	NC1.0	NC2.0	NC3.0	NC4.0
LBE side	Total mock-up core power (kW)	9.8	15	27	33.6
	Avg. hot leg temperature (°C)	273.84	315.84	367.63	394.43
	Avg. cold leg temperature (°C)	237.32	266.83	300.85	315.31
	Avg. temperature difference (°C)	36.52	49.01	66.78	79.12
	Avg. LBE mass flow rate (kg/s)	1.8	2.09	2.74	2.83
Oil side	Avg. oil inlet temperature (°C)	99.65	122.63	155.03	167.6
	Avg. oil outlet temperature (°C)	114	144.33	187.52	204.18
	Avg. oil mass flow rate (kg/s)	0.374	0.374	0.382	0.39

4.2.Numerical Modeling Results and Discussion

Using the well-defined experimental data, we carried out numerical calculation with MARS-LBE code. In this activity, boundary conditions such as the mock-up core power rating, secondary side inlet temperature and mass flow rate were designated explicitly as forms of the time-dependent volumes and junctions, heat structures, and property tables in the model.

The code calculation results for the cases from NC1.0 to NC4.0 are summarized in TABLE 3. Considering that the measured and calculated oil side outlet temperatures are within a few degrees, it can be concluded indirectly that the experiments from NC1.0 to NC4.0 were performed in adiabatic wall boundary conditions sufficiently.

TABLE 3: NUMERICAL MODELING RESULTS FOR STEADY-STATE EXPERIMENTS.

	No.	NC1.0	NC2.0	NC3.0	NC4.0
LBE side	**Total mock-up core power (kW)**	9.8	15.0	27.0	33.6
	Avg. hot leg temperature (^{o}C)	247.11	314.39	369.60	397.47
	Avg. cold leg temperature (^{o}C)	212.64	268.74	302.43	318
	Avg. temperature difference (^{o}C)	34.47	45.64	67.18	79.48
	Avg. LBE mass flow rate (kg/s)	1.9	2.23	2.76	2.9
Oil side	**Avg. oil outlet temperature (^{o}C)**	113.43	143.09	189.10	208.03

Most of parameters of interest in natural circulation estimation such as mass flow rate and temperature difference of LBE show good agreement between experiment and computational modeling results. LBE mass flow rates measured and calculated for all cases are compared in *FIG. 2*, as a function of mock-up core power rating. Modeling results show good agreement with measurement data within maximum 7% discrepancies.

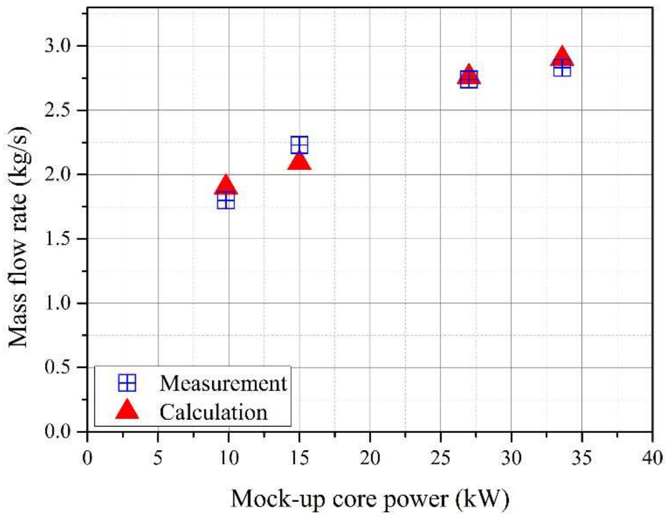

FIG. 2. Mass flow rate comparisons between measurement and calculation in terms of core power.

Comparisons between experiment and calculation results on LBE temperature distribution and the secondary side temperature distribution for each case are shown in *FIG. 3 (a)-(d)*. The absolute temperatures of LBE along the main loop are benchmarked closely within 1% range except the NC1.0 case, as shown in *FIG. 3 (a)*. In that case, the code calculation shows about 25^{o}C temperature underestimation. However, as depicted in *FIG. 4*, the temperature differences between measurement and calculation are in a close range, within 7%.

Potentially, this discrepancy may be caused by the convective heat transfer correlation because the final temperature distribution over a heat structure model depends on MARS-LBE calculation scheme. If one of the correlations for LBE and secondary oil (or both) is not applicable in terms of flow regime and temperature condition, then it misleads the calculation results by nature. Eqn. (1) is recommended to be applicable to Re range over $0<Re<5\times10^{6}$ and LBE flow regime in NC1.0 case lies in Re~25,000, while Eqn. (2) is suitable for using in high turbulent regime (Re>10,000) but oil was under low turbulent regime (Re~6,000). However, this potential cause cannot be confirmed or evaluated due to the absence of heat transfer measurement system in the heat exchanger.

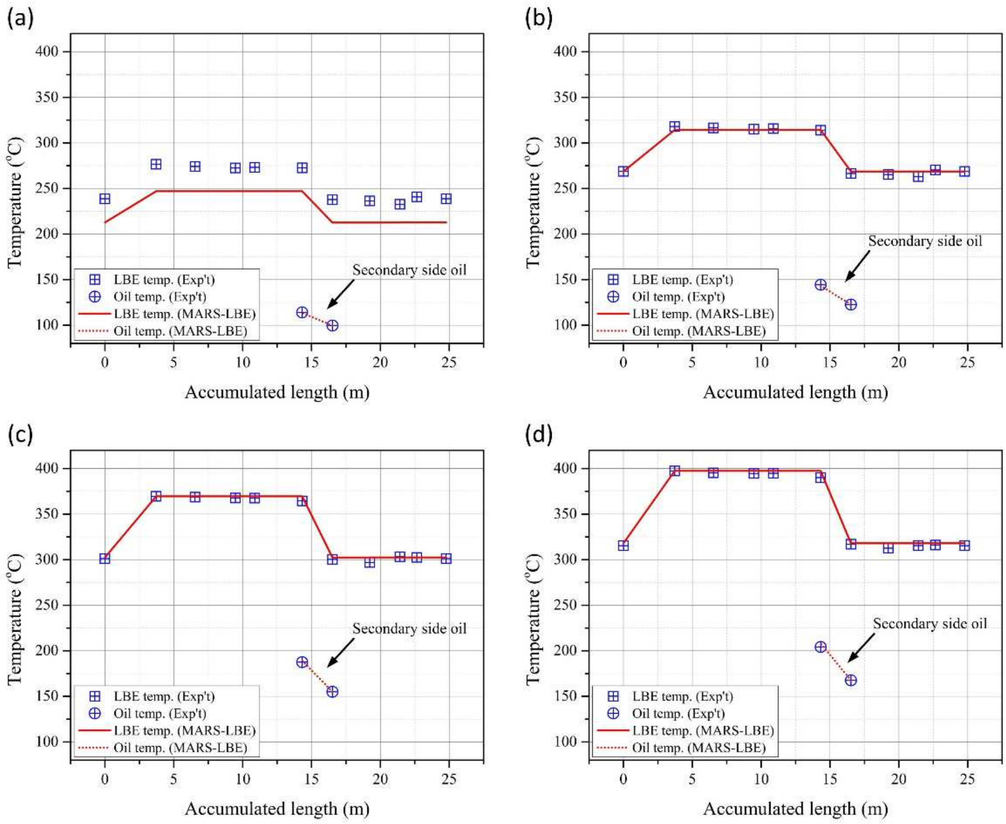

FIG. 3. Steady state experiment and calculation results of HELIOS in cases (a) NC1.0 (9.8kW power), (b) NC2.0 (15.0kW power), (c) NC1.0 (27.0kW power), and (d) NC1.0 (33.6kW power).

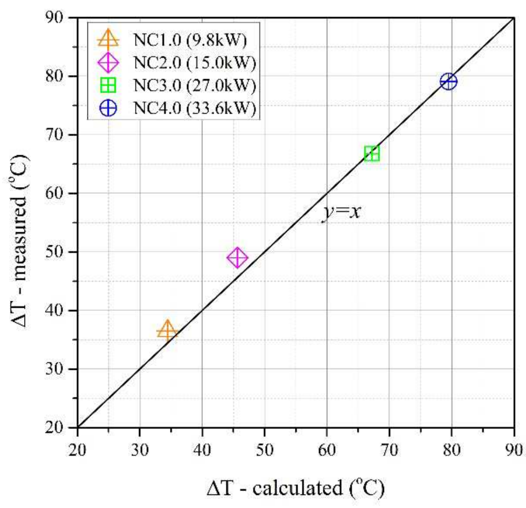

FIG. 4. Comparison of temperature differences between average hot leg and cold leg temperatures in experiment and code calculation results.

5. Conclusion

For the characterization of LBE non-isothermal natural circulation, several experimental studies and numerical modeling were conducted with a full-height scale integral test loop, HELIOS, under steady state at varying heat source conditions ranging from 9.8kW to 33.6kW. In order to make adiabatic wall boundary conditions, the local surface heaters on the main loop were activated and electric power given to each heater was finely tuned by trial-and-error approach. Not only heat transferred to the secondary side oil but temperature distribution along the main loop were adjusted. The well-defined data were taken from the experimental data by averaging measured values over 6-7 hours when system temperature fluctuation given by ambient temperature swing in a day was moderate.

For the numerical modeling, a system code called MARS-LBE, which is modified from the original MARS code to perform thermal-hydraulic analyses of heavy liquid metal systems, was utilized. It is found that the predictions were mostly in good agreement with the experimental data in terms of mass flow rate within 7% and temperature difference within 7%, respectively. On the other hand, absolute LBE temperature distributions in a low power case showed underestimation as much as about 25^{o}C. The discrepancy can be drawn from the selection of heat transfer correlation but we cannot assure it to be the cause due to lack of measurement on heat transfer in the heat exchanger. In conclusion, mass flow rate benchmark results performed with MARS-LBE showed good agreement.

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