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# Experimental studies and computational benchmark on heavy liquid metal natural circulation in a full height-scale test loop for small modular reactors

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## HIGHLIGHTS

- Experimental studies on natural circulation for lead-bismuth eutectic were conducted.
- Adiabatic wall boundaries conditions were established by compensating heat loss.
- Computational benchmark with a system thermal-hydraulics code was performed.
- Numerical simulation and experiment showed good agreement in mass flow rate.
- An empirical relation was formulated for mass flow rate with experimental data.

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## ABSTRACT

In order to test the enhanced safety of small lead-cooled fast reactors, lead-bismuth eutectic (LBE) natural circulation characteristics have been studied. We present results of experiments with LBE non-isothermal natural circulation in a full-height scale test loop, HELIOS (heavy eutectic liquid metal loop for integral test of operability and safety of PEACER), and the validation of a system thermal-hydraulics code. The experimental studies on LBE were conducted under steady state as a function of core power conditions from 9.8 kW to 33.6 kW. Local surface heaters on the main loop were activated and finely tuned by trial-and-error approach to make adiabatic wall boundary conditions. A thermal-hydraulic system code MARS-LBE was validated by using the well-defined benchmark data. It was found that the predictions were mostly in good agreement with the experimental data in terms of mass flow rate and temperature difference that were both within 7%, respectively. With experiment results, an empirical relation predicting mass flow rate at a non-isothermal, adiabatic condition in HELIOS was derived.



## 1. Introduction

In recent years, nuclear industry has found a breakthrough with the development of small modular reactors (SMRs) for continuous and sustainable nuclear energy utilization even though there have been some perspectives that nuclear power will be slowly phased out after the Fukushima accident. Interests on SMR are growing and as supporting this, more than 50 SMR concepts are under development worldwide and three of those reactors including CAREM in Argentina (Marcel et al., 2013), HTR-PM in China (Zhang et al., 2006), and KLT-40s in the Russian Federation (Mitenkov and Polunichev, 1997) are under construction and are expected to start their first operations in the near term, within 2020. In addition, a study on the economics of SMRs states that SMRs that will be built in 2020–2035 could generate up to 21GWe of the world's electricity based on an optimistic prospect (OECD Nuclear Energy Agency, 2016).

In terms of safety enhancement to the extreme level, heavy liquid metal like lead-bismuth eutectic (LBE) and pure lead has been widely studied for new generation reactor coolant. LBE has favorable features as innovative coolant compared to conventional coolant, water: chemical inertness with air, water, and steam which excludes the possibility of pressure boundary failure with hydrogen explosion, low melting point (398 K) and high boiling point (1943 K) which enables a system to be free of pressurization, high

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**Nomenclature**

| | |
|---|---|
| $\Delta H$ | thermal height center difference (m) |
| $\Delta p$ | pressure loss due to hydraulic resistance (Pa) |
| $\Delta T$ | temperature difference between the mock-up core inlet and outlet (°C) |
| $A$ | flow area (m$^2$) |
| $A_s$ | projected grid cross section (m$^2$) |
| $A_v$ | undisturbed flow area (m$^2$) |
| $C_p$ | heat capacity (J/kg K) |
| $C_v$ | modified loss coefficient |
| $d_h$ | hydraulic diameter (m) |
| $f$ | Darcy-Weisbach friction factor |
| $g$ | gravitational acceleration (m/s$^2$) |
| $K$ | form loss coefficient |
| $K_{Re}$, $K_{loc}$, $K_{fr}$ | constants given in Nippert (1929) |
| $k$ | thermal conductivity (W/m K) |
| $l$ | length (m) |
| $\dot{m}$ | mass flow rate (kg/s) |
| Nu | Nusselt number |
| Pe | Peclet number |
| Pr | Prandtl number |
| $Q$ | mock-up core power (W; kW) |
| Re | Reynolds number |
| $v$ | flow velocity (m/s) |

*Greek*

| | |
|---|---|
| $\beta$ | thermal expansion coefficient (K$^{-1}$) |
| $\varepsilon$ | pipe roughness (m) |
| $\mu$ | dynamic viscosity (Pa s) |
| $\rho$ | density (kg/m$^3$) |

*Subscripts*

| | |
|---|---|
| 0 | reference |
| 1 | upstream |
| 2 | downstream |
| i | component |
| c | vena contracta |
| LBE | lead-bismuth eutectic |
| oil | secondary side thermal oil (Dowtherm© RP) |
| or | orifice |
| w | water |

thermal conductivity (11.8 W/m K at 573 K) for better heat transfer, and good neutron economy with small neutron absorption cross-section (0.0015 barn at 1 MeV) and high atomic mass (~208 g/mol) which leads to less neutron spectrum softening (OECD Nuclear Energy Agency, 2007). In this regard, several SMR designs which use LBE as coolant have been proposed, for instance, SVBR-100 by the Russian Federation (Zrodnikov et al., 2006) and G4M (also known as Hyperion) by the United States (Zhang et al., 2013).

Another application of LBE and lead can be found in research activities for accelerator-driven sub-critical systems (ADS) which are operated under subcritical conditions by compensating this off-criticality with a high-energy proton accelerator (Satyamurthy and Biswas, 2002). On account of its favorable features, LBE and/or pure lead can be used not only as spallation target for additional neutron generation but also as coolant at the same time. An example of this is EFIT reactor which is a pool-type 100-MWth ADS which uses pure lead as coolant (Cinotti, 2004). Within its design development, some thermal-hydraulic analyses on the system were carried out such as analysis on accidental transients (Bandini et al., 2008a,b) and pressure drop evaluation for helical tubes in heat exchanger (Castiglia et al., 2012). Furthermore, SCK-CEN in Belgium has developed MYRRHA which is based on the pool-type ADS concept and utilizes LBE as primary coolant (H. Ait Abderrahim et al., 2011). The design of MYRRHA has progressed and entered into the front end engineering phase (De Bruyn et al., 2014).

In addition to the potential coolant change, reactor coolant pumps are no more necessary to be installed if a simple and compact design can be achieved by being designed to be operated under natural circulation with main cooling mechanism. A research group in the Republic of Korea conceptualized a pool-type LBE-cooled SMR which solely relies on natural circulation for normal and accident cooling (Shin et al., 2015). Leaving aside the benefit from natural circulation in normal operation, the phenomenon is evaluated to be essential in accidents such as loss of flow accidents (LOFA) resulting from the failure of pumps and post-accident conditions where forced circulation cannot be made due to station blackout.

In order to overcome the conventional design limitations, there have been some activities worldwide on the characterization of LBE natural circulation not only by experiments with several loop facilities, but also by computational modeling. An experimental study on single-phase LBE natural circulation was performed by a research group in Japan in a test apparatus for water boiling tests from direct contact on LBE (Takahashi et al., 2005). Several experiments were carried out in ENEA-Brasimone Research Centre in Italy with NACIE facility for non-isothermal natural circulation given by various heater power ratings and gas-induced circulation by injecting argon bubbles into the loop (Coccoluto et al., 2011; Tarantino et al., 2011). The experiment results were used for the code benchmark of RELAP5/MOD3.3 by implementing the thermophysical properties of LBE. In Sweden, a medium-size facility TALL at KTH was utilized for the characterization of LBE in lead-cooled fast reactors and ADS (Ma et al., 2006, 2007). In those studies, various natural circulation phenomena were tested, such as natural circulation capability and stability, start-up from different initial conditions, and accident simulations. Similarly, the experiment 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 (Grishchenko et al., 2015). 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 900 W to 5000 W (Borgohain et al., 2016a). A house code called LeBENC was validated with the test results and the maximum temperature deviation was within 15% in transient simulations. A LBE test loop, KTL, was built to investigate natural circulation in a wide temperature range from 200 to 780 °C, which is higher than the maximum design temperature of most LBE test loops, 550 °C (Borgohain et al., 2016b).

We present the results of experiments on LBE non-isothermal natural circulation in a full-height scale test facility HELIOS (Heavy Eutectic liquid metal Loop for Integral test of Operability and Safety of PEACER) at Seoul National University (SNU) and the validation of a system thermal-hydraulics code MARS-LBE. As a precedent research, the investigation of hydraulic loss over each constituent component of the facility was performed in an