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Original Article

Experimental Investigation of the Thermal Hydraulics in Lead Bismuth Eutectic-helium Experimental Loop of an Accelerator-driven System

Wenxuan Xi [a,b], *Yongwei Wang* [a,*], *Xunfeng Li* [a], *Xiulan Huai* [a,*], *and Jun Cai* [a]

[a] *Institute of Engineering Thermophysics, Chinese Academy of Sciences, 11 Beisihuanxi Road, Beijing 100190, China*
[b] *University of Chinese Academy of Sciences, 19 A Yuquan Rd, Shijingshan District, Beijing 100049, China*

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ABSTRACT

The heat transfer characteristics between liquid lead bismuth eutectic (LBE) and helium are of great significance for the two-loop cooling system based on an accelerator-driven system (ADS). This paper presents an experimental study on the resistance characteristics and heat transfer performance in a LBE-helium experimental loop of ADS. Pressure drops in the LBE loop, the main heat transfer, and the coupled heat transfer characteristics between LBE and helium are investigated experimentally. The temperature of LBE has a significant effect on the LBE thermo-physical properties, and is therefore considered in the prediction of pressure drops. The results show that the overall heat transfer coefficient increases with the increasing helium flow rate and the decreasing inlet temperature of helium. Increasing the LBE Reynolds number and LBE inlet temperature promotes the heat transfer performance of main heat transfer and thus the overall heat transfer coefficient. The experimental results give an insight into the flow and heat transfer properties in a LBE-helium heat exchanger and are helpful for the optimization of an ADS system design.

1. Introduction

Liquid lead bismuth eutectic (LBE) is well suited as a spallation target, as well as being a good coolant for an accelerator-driven system (ADS). Therefore LBE has been proposed for the transmutation of nuclear waste [1–3]. LBE has many unique nuclear, thermo-physical, and chemical attributes such as a low melting point, high boiling point, certain chemical inertness to water and air, good neutron properties, as well as good antiradiation and heat transfer performance. Helium has the advantages of favorable security and a large specific heat capacity; therefore, it is the main coolant for some nuclear reactor systems [4]. But there are only a few experimental studies on heat transfer characteristics between LBE and helium at present, and that restricts the study about the optimized design of the heat exchanger. Therefore, it is of

* *Corresponding authors.*
E-mail addresses: mailwyw@163.com (Y. Wang), hxl@iet.cn (X. Huai).
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great significance to experimentally investigate the convective heat transfer characteristics between LBE and helium in the ADS two-loop cooling system.

Some scholars have studied the thermal-hydraulic characteristics of LBE in experimental and numerical simulation methods. Cheng and Tak [5] studied the heat transfer characteristics of LBE in a vertical tube with a constant heat flux. Using the k-ε and k-ω turbulence models in the simulations, they found the turbulent the Prandtl number of LBE was larger than conventional fluids, and it decreased with the increase of the Peclet number. Their conclusion was that the turbulent Prandtl number model of Lyon [6] is suitable for LBE. The LBE heat transfer model based on empirical formulas was submitted by Kirillov [7] and Stromquist [8].

In order to investigate the flow and heat transfer characteristics of LBE, many experimental loops were built. The thermal-hydraulic ADS lead-bismuth loop was designed and constructed at the Royal Institute of Technology (Roslagstullsbacken, Stockholm, Sweden) to perform thermal-hydraulic experiments for lead alloy cooled systems [9]. It is composed of a primary loop (LBE loop) and a secondary loop (glycerol loop). Ma et al. [10] presented a study on the resistance characteristics and heat transfer performance of LBE in a straight-tube heat exchanger and a U-tube heat exchanger. During their experiment, the LBE flowed in the inner tube and the secondary coolant flowed in the annulus. The heat exchangers of the straight-tube and U-tube had a counter-current flow arrangement. The experimental results show that the U-tube heat exchanger had a better heat transfer performance than the straight-tube heat exchanger. But the flow resistance of the U-tube heat exchanger is greater, and it is not easy to clean and replace the tubes.

In order to investigate the relevant technology of the liquid lead and LBE, the Technologies for Heavy metal SYStems (THESYS) were installed in KArlsruhe Lead Laboratory (Hermann-von-Helmholtz-Platz, Leopoldshafen, Germany) [11]. The activities of the THESYS concentrate on the development of fundamental heavy liquid metal technologies. Therein the main objectives of the THESYS are: (1) qualification of monitoring and conditioning systems for loop applications; (2) development of thermal-hydraulic measurement techniques for mean and local thermo-physical quantities; and (3) thermo-hydraulic benchmark experiments for validation of computational fluid dynamic codes.

In China, the fundamental research of ADS was carried out 10 years ago, supported by the Ministry of Science and Technology. From 2009, the Chinese Academy of Sciences (Beijing, China) carried out a project on ADS prophase research to develop key technologies of superconducting accelerators such as LBE loops and materials. In 2011, a large scaled ADS development program to transmute nuclear waste was launched by Chinese Academy of Sciences named “advanced nuclear fission energy” [12]. Based on this project, a LBE-helium heat exchanger was proposed and a LBE-helium experimental loop of ADS (LELA) was designed and constructed at the Institute of Engineering Thermophysics.

The project focuses on the thermal-hydraulic behavior and heat transfer performance between LBE and helium, to further improve the optimization design scheme of the main heat exchanger (MHX) and the regenerator. According to the design of LELA, LBE is heated by electrical heaters, and then it will exchange heat with helium in the MHX. The full-size model of MHX was established by Chen et al. [13]. Their investigation carried out the numerical simulation of three-dimensional fluid-solid coupled heat transfer between LBE and helium. The turbulent Prandtl number model proposed by Cheng and Tak [5] for the LBE flow in the tube side and the Reynolds analogy for helium in the shell side was used. The results show that the pressure drop, heat transfer coefficient, and the modified effectiveness of MHX are in good agreement with the theoretical calculation. The influences of flow rate and helium outlet temperature on the performance of MHX were further analyzed by Chen et al. [13]. A concept of modified effectiveness was introduced and correlated as the function of tube-side and shell-side heat capacities rate ratio.

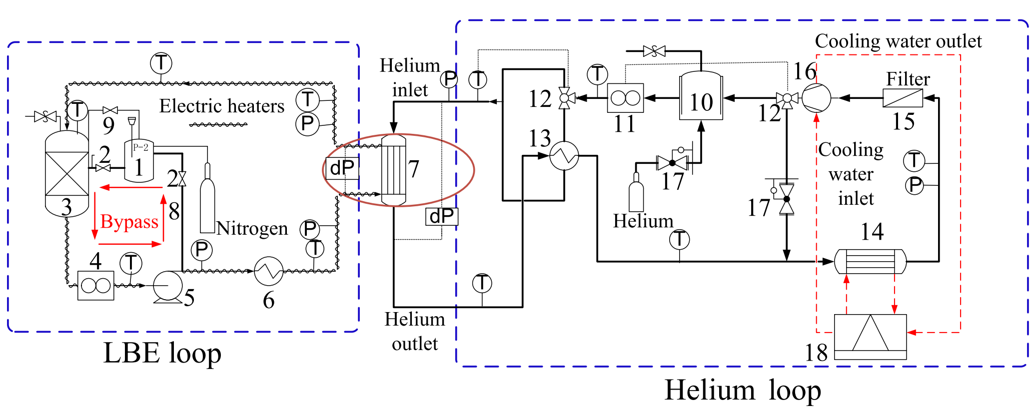

Fig. 1 – Schematic of the lead bismuth eutectic (LBE)-helium experimental loop of accelerator-driven system test facility. 1, lead bismuth eutectic melting tank; 2, value for lead bismuth eutectic; 3, lead bismuth eutectic transfer tank; 4, electromagnetic flow meter; 5, electromagnetic pump; 6, preheater; 7, lead bismuth eutectic-helium heat exchanger; 8, calibration loop of electromagnetic flow rate; 9, gas valve; 10, helium buffer tank; 11, helium mass flow meter; 12, three-way valve; 13, regenerator; 14, helium-water heat exchanger; 15, filter; 16, helium compressor; 17, pressure reducing valve; 18, water chiller.