Nuclear Engineering and Technology 48 (2016) 1154–1161

Available online at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Experimental Investigation of the Thermal Hydraulics in Lead Bismuth Eutectic-Helium Experimental Loop of an Accelerator-Driven System

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ARTICLE INFO

Article history:
Received 26 January 2016
Received in revised form
23 March 2016
Accepted 19 April 2016
Available online 10 May 2016

Keywords:
Convective Heat Transfer
Heat Transfer Coefficient
Helium
Lead Bismuth Eutectic

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

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http://dx.doi.org/10.1016/j.net.2016.04.008

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.

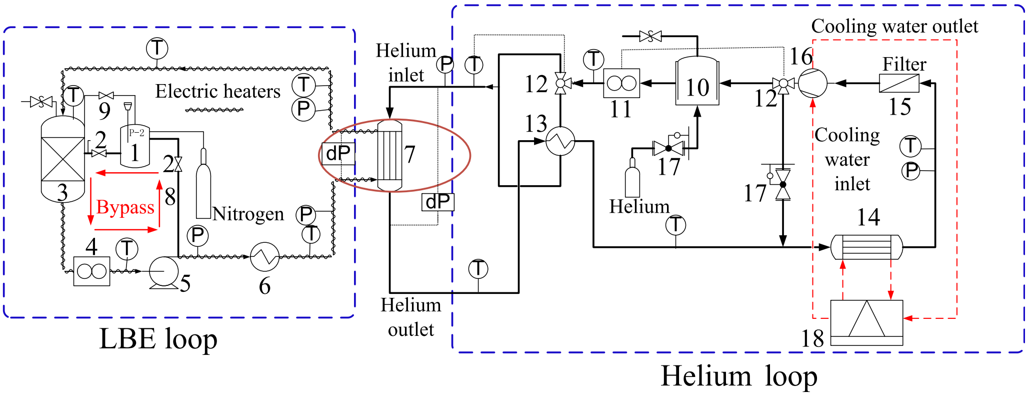

Fig. 1 – Schematic of the lead bismuth eutectic (LBE)-helium experimental loop of accelerator-driven system test facility. 1, lead bismuth eutectic melting tank; 2, value for lead bismuth eutectic; 3, lead bismuth eutectic transfer tank; 4, electromagnetic flow meter; 5, electromagnetic pump; 6, preheater; 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.

According to the current literature, there are few reports about the experimental investigation of heat transfer characteristics between LBE and helium, as well as the heat exchanger performance. In this paper, an experimental study of LBE and helium heat transfer in LELA is carried out. The influences of temperature and flow rate on the pressure drop and heat transfer are investigated.

2. Description of a LELA facility

A schematic of the LELA facility is presented in Fig. 1. It is composed of a LBE loop and a helium loop. The LBE loop consists of a melting tank, a transfer tank, an electromagnetic (EM) pump, an EM flowmeter, preheater, various electric heaters, and a LBE-helium heat exchanger. The melting tank is a metal cylinder, on which the outer surface is surrounded with a rope heater. The design power of the rope heater is 13 kW. All the pipelines are equipped with electrical heaters to be preheated to a power of 6 kW before the experiment. In order to protect the heating equipment, both loops are equipped with a proportional-integral-derivative (PID) temperature control system. At the same time, all the pipelines have 5° of inclination to ensure that the LBE can easily flow back into the melting tank after the experiments. Twenty-nine armored thermal resistance temperature sensors are installed to monitor the LBE temperatures. Based on the temperature signal which is fed back by the sensors, the PID temperature control system commands the heaters to heat the pipelines piecewise. In order to prevent damage due to the thermal expansion, elastic supports are installed on the LBE loop.

LBE is melted in the melting tank before the experiment, and then it is moved to the transfer tank by high pressure nitrogen. The valve between the two tanks is then closed and LBE is pressurized to fill the loop. During the experiment, LBE flows through the preheater, the MHX driven by the EM pump, and then goes back to the transfer tank. The preheater is installed in front of the MHX to adjust the LBE inlet temperature.

The helium loop is designed to realize the heat transfer from LBE to an intermediate fluid (helium), and finally to a helium-water heat exchanger. The helium loop is composed of a compressor, a buffer tank, a gas mass flowmeter, and a regenerator. The whole loop is filled with the helium gas (~3 MPa) including buffer tank, the shell side of MHX, and all pipelines. The buffer tank is placed in the outlet of the compressor to eliminate small pressure fluctuations. The low temperature helium, which is compressed, flows through the mass flow meter and regenerator, then the helium exchanges heat with the high temperature LBE in the MHX. The high temperature helium finally goes into the helium-water heat exchanger, and then its temperature reduces to about 50 °C. After that, the helium goes into the compressor through the filter to complete the circuit.

As a key equipment in LELA, the straight tube is used in the MHX (as shown in Fig. 2). Specifically, a tube-and-shell heat exchanger, with eight single segmental baffles and four spacer tubes is adopted. The MHX is composed of 57 straight tubes (12 mm of outer diameter and 9 mm of inner diameter). It has counter-current flow arrangement with LBE flowing in the tube side and the helium flowing in the shell-side. The straight tubes are arranged in regular triangular arrays. The distance between any two adjacent tubes is 19 mm. The spacer tubes are used to keep a fixed distance between adjacent baffles. The external diameter of the shell side is 219 mm, and the wall thickness is 6 mm. All of the pressure sensors are provided by SIEMENS (Siemens Ltd., Beijing, China). To ensure the accuracy of the experiment, all the pipes and the MHX are covered with aluminum silicate wool. The other geometry parameters and operating conditions of the facility are shown in Table 1.

However, the accuracy of the flow measurement of LBE has a very important impact on our experimental results. The LBE has high density, corrosivity, opaqueness, and the high temperatures at which the touch sensors are required to work presents problems [14]. Therefore, a noncontact method is adopted to measure the LBE flow rate in the present LBE experimental facilities, such as the thermal-hydraulic ADS lead-bismuth loop of the Royal Institute of Technology [15] and the THESYS loop of KArlsruhe Lead Laboratory [11]. The EM flowmeter is used in LELA, and its flowmeter is rechecked through the bypass (Fig. 1, item 8) before the experiment. At first, the LBE is melted and filled in the whole bypass. There is a magnetic level gauge in the melting tank, which can monitor the volume of the LBE as the calibration loop size is known. Then the relationship between the reading data of EM

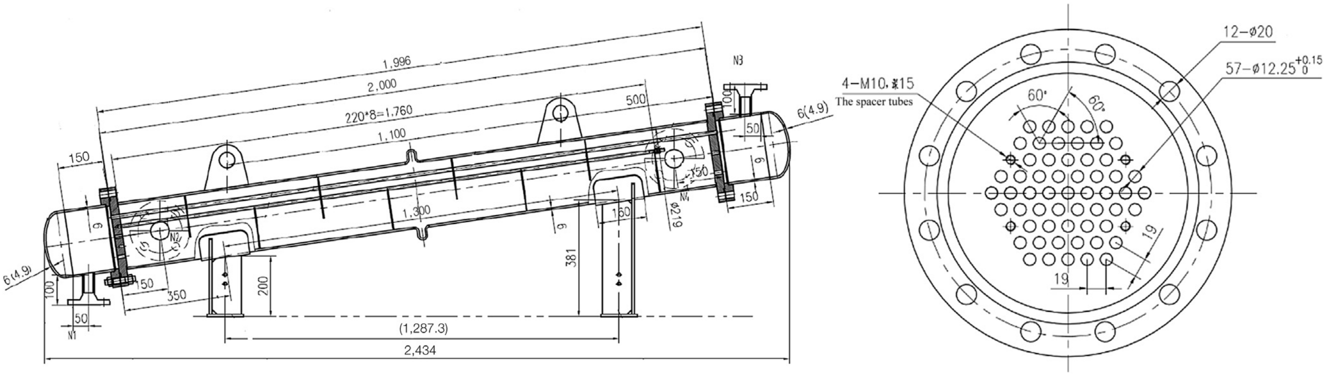

Fig. 2 – **The main heat exchanger of the lead bismuth eutectic (LBE)-helium experimental loop of accelerator-driven system test facility.**

Table 1 – The geometry parameters and operating conditions of facility.

LBE-helium experimental loop of ADS		
Parameters	LBE loop	Helium loop
Piping (mm O.D.)	42 & 32	57 & 47
Material	AISI 316 stainless steel	AISI 316 stainless steel
Working fluid	LBE	Helium
Max mass flow rate (kg/sec)	8.4	0.038–0.115
Operating pressure (MPa)	1.0	3.5
Inlet temperature (°C)	250–500	70–200
LBE-helium heat exchanger		
Parameters	Shell side	Tube side
Design pressure (MPa)	4.0	1.5
Working pressure (MPa)	3.5	1.2
Design temperature (°C)	480	520
Working temperature (°C)	450/300	500/350
Volume (m^3)	0.065	0.013
Working medium	Helium	LBE
No. of passes	1	1
Heat transfer area (m^2)	4.16	

ADS, accelerator-driven system; AISI, American Iron and Steel Institute; I.D., internal diameter; LBE, lead bismuth eutectic; O.D., outer diameter.

flowmeter and the LBE volume flowrate can be obtained at different EM pump electric voltages. According to our experiment results, the accuracy of the EM flowmeter is 1.7%.

3. Temperature control and data processing

In the LBE loop, the preheater is placed in the upstream of the MHX. The aim of installing the preheater is to control the LBE temperature before entering the MHX. When the LBE temperature reaches the set value, the preheater is shut down by the PID. When it decreases below the set value, the temperature control system turns on the preheater again. Due to the fluctuations of LBE inlet temperature, the outlet temperature of the tube side also changes periodically (Fig. 3A). In the helium loop, the PID temperature control system can adjust the aperture of the electric three-way valve according to the target temperature, and the helium flow rate that goes into the regenerator changes accordingly. This means that the flow rate of low temperature helium going into the regenerator will increase when the helium inlet temperature is lower than the target value, then the inlet temperature will gradually increase, and vice versa. So the periodical changes of the helium temperature resulting from variations of flow rate are the same in the inlet and outlet of MHX (Fig. 3B). In data processing, the actual temperature values of the tube and shell side of the MHX are obtained by taking the average of the multiple fluctuation periods in each case.

4. Results and discussion

4.1. *Pressure drop of the LBE loop*

Ma et al. [10] have investigated the LBE flow resistance characteristics through a straight-tube heat exchanger and a U-tube heat exchanger. The results show that the pressure drop calculated by the Moody correlationisin reasonable agreement with the experimental data, especially at temperature of 390 °C. The main reason is that the low kinematic viscosity of LBE leads to a thinner viscous sublayer than the roughness of the tube wall surface. However, lots of vortices are caused by the roughness result in the larger pressure drop, which finally contributes to a rise of flow resistance coefficient.

The two LBE temperature conditions of 264.8 °C and 289.3 °C were selected to investigate the pressure drop characteristics of LBE flow. Pressure sensors are installed in the pipeline between the EM pump outlet and the MHX inlet. The Moody and Techo correlations about pressure drops are referenced in Ma et al. [10]. The Reynolds number of LBE is defined by:

$$Re_{loop} = \frac{d_{loop} u_{loop} \rho}{\mu} \tag{1}$$

where d_{loop} is the pipe inner diameter of the LBE loop ($d_{loop} = 32$ mm), u_{loop} is the LBE velocity, ρ is the LBE density, and μ is the LBE viscosity. It is noteworthy that the Reynolds number Re_{loop} is based on the pipe diameter and the fluid velocity in the LBE loop. In the MHX, the Re_t is given based on the tube inner diameter ($d_t = 9$ mm) and the LBE velocity of the MHX tube side.

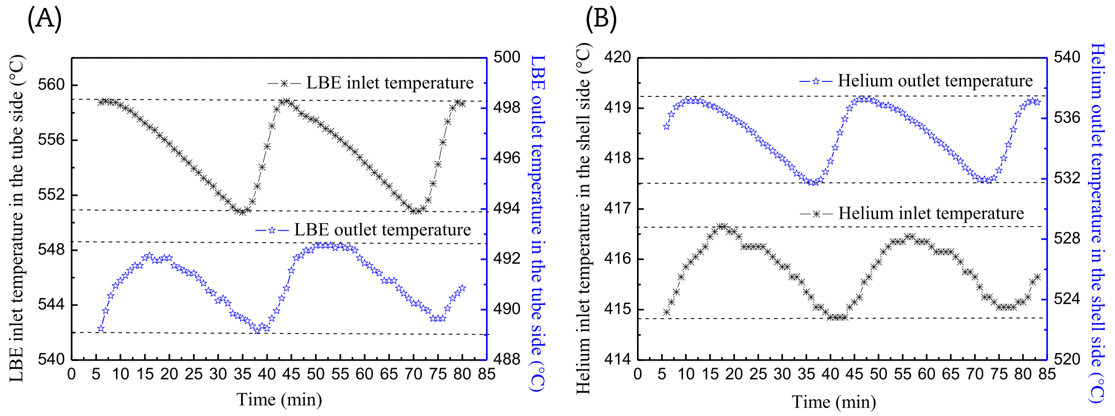

Fig. 3 – The inlet and outlet temperatures of main heat exchanger under the same case. (A) Lead bismuth eutectic (LBE) in the tube side. (B) Helium in the shell side.

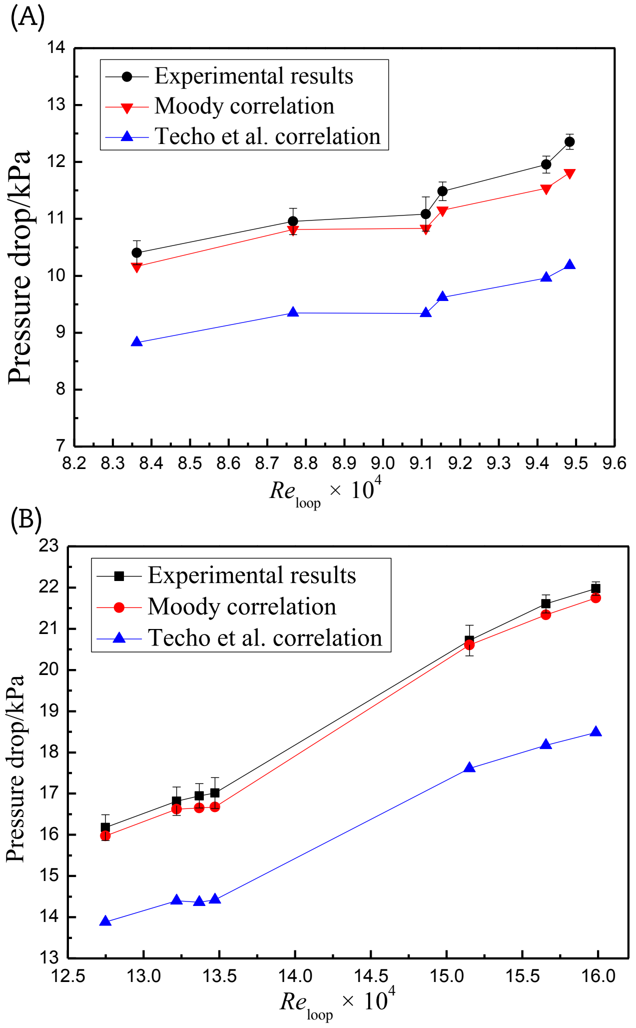

Fig. 4 – Pressure drop of the lead bismuth eutectic (LBE) loop. (A) The LBE temperature is 264.8 °C. (B) The LBE temperature is 289.3 °C.

As shown in Fig. 4, the Moody correlation is in better agreement with the experimental results compared with the Techo correlation, especially for high temperature levels. This conclusion is coincident with previous literature by Ma et al. [10]. Besides, the accuracy of the pressure drop measurement is further confirmed by the above experimental results.

4.2. *Pressure drop in the tube side of MHX*

The MHX is the most important component in the two loops cooling system of ADS. The pressure drop in the tube side is one of the main parameters to evaluate the performance of MHX. For the design and optimization of MHX, the experimental correlations are essential to accurately predict the pressure drop in the tube side. However, in the literature there is still few experimental investigations. The total pressure drop in the tube side of MHX consists of four parts, such as the gravity pressure drop, the frictional pressure drop, the local head loss, and the acceleration pressure drop. According to the heat exchanger design manual [16], the calculation method for the pressure drop excluding the gravity pressure drop is:

$$\varDelta P = (\varDelta P_L + \varDelta P_r)F_t N_p N_s + \varDelta P_n N_s \tag{2}$$

where $\varDelta P_L$ and $\varDelta P_r$ are the pressure drops caused by friction of the LBE flow in straight pipes and bends, respectively. Since the MHX is a one-way tube heat exchanger, with no bends, so $\varDelta P_r = 0$. $\varDelta P_n$ is the pressure drop when the LBE flows through the two heads. F_t is the dimensionless correction factor of structure, N_P is the number of tube side flow (for the MHX, $N_P = 1$), and N_S is the number of shells in series. The $\varDelta P_L$ and $\varDelta P_n$ can be calculated by:

$$\varDelta P_L = \lambda \frac{l}{d_t}\left(\frac{\rho u_t^2}{2}\right) \tag{3}$$

$$\varDelta P_n = 1.5\left(\frac{\rho u_t^2}{2}\right) \tag{4}$$

where u_t is the LBE velocity in the tube side of MHX, d_t is the tube inner diameter of 9 mm, and l is the tube length. In Eq. (4), the factor 1.5 is obtained after considering the channel structures of the MHX tube side. λ is the friction coefficient which can be calculated based on Reynolds number and the relative roughness ε/d_t (ε is the absolute roughness). If $Re_t < 2{,}000$, $\lambda = 64/Re_t$; for other cases, there are two calculation methods of Gu et al. correlation [16] and Nikuradse–Karman correlation.

For a steel or cast iron pipe, when Re_t changes from 3×10^3 to 3×10^6, Gu et al. correlation is written as:

$$\lambda = 0.01227 + \frac{0.7543}{Re_t^{0.38}} \tag{5}$$

When $(d_t/\varepsilon)/(Re_t \cdot \sqrt{\lambda}) > 0.005$, Nikuradse–Karman correlation is written by:

$$\frac{1}{\sqrt{\lambda}} = 2\lg\frac{d_t}{\varepsilon} + 1.14 \tag{6}$$

where $Re_t = (d_t u_t \rho)/\mu$ and ε is the roughness of the tubes. For the LBE loop, all the pipes are made of American Iron and Steel Institute 316 stainless steel and their roughness is equal to 0.015 mm.

As shown in Fig. 5, the deviation between experimental data and the pressure drop, calculated using Nikuradse–Karman, Moody, and Gu et al. correlations [16], are an average of 8.3%, 16.8%, and 17.9%, respectively. One of the reasons is that the gravity pressure drop takes a larger proportion in the total pressure drop in the present experiment. MHX is placed slantwise in the experimental loop (as shown in Fig. 2) and there is a meter vertical height difference between the inlet and outlet of the tube side. So the gravity pressure drop is notable in the MHX. The gravity pressure drop is related to the LBE density which is a function of the LBE temperature. Therefore, the temperature has a significant effect on the gravity pressure drop in the tube side of MHX. Besides, the roughness of the tube wall surface also causes the increase of pressure losses in the LBE loop. In the Nikuradse–Karman correlation, the roughness of the tube is 0.015 mm for the commercial stainless steel tubes,

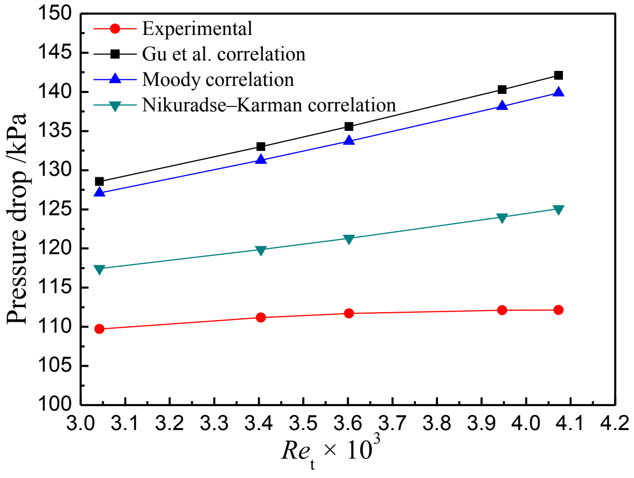

Fig. 5 – Pressure drop in the tube side of the main heat exchanger.

but the influences of the roughness on the pressure drop are not considered in the Gu et al. correlation [16]. This results in a larger deviation between the experimental data and the correlation.

At the same time, the LBE loop is a closed circuit and LBE is filled in the whole loop during the experiments, including the MHX. So the distribution of the mass flow rate in each tube is homogeneous, and there is no flow maldistribution.

4.3. *Heat transfer*

Alongside the resistance characteristics, heat transfer performance of the MHX is another important consideration in the heat exchanger design. In the present investigation, it is difficult to measure the convection heat transfer coefficients of the hot and cold fluids. The configuration of the MHX makes the determination of the internal temperature distribution impossible, and the operating conditions are neither under the constant wall temperature, nor the constant heat flux condition. Instead, the overall heat transfer coefficient can be obtained directly by measuring the thermal-hydraulic parameters, and then the convective heat transfer coefficients of fluids can be estimated. As a result, the present report focuses on the overall heat transfer coefficient K, which may be summarized by the following equation:

$$q = KA\varDelta T_{\mathrm{lm}} \tag{8}$$

where q is the total rate of heat transfer between the LBE and helium, K is the overall heat transfer coefficient, A is the heat

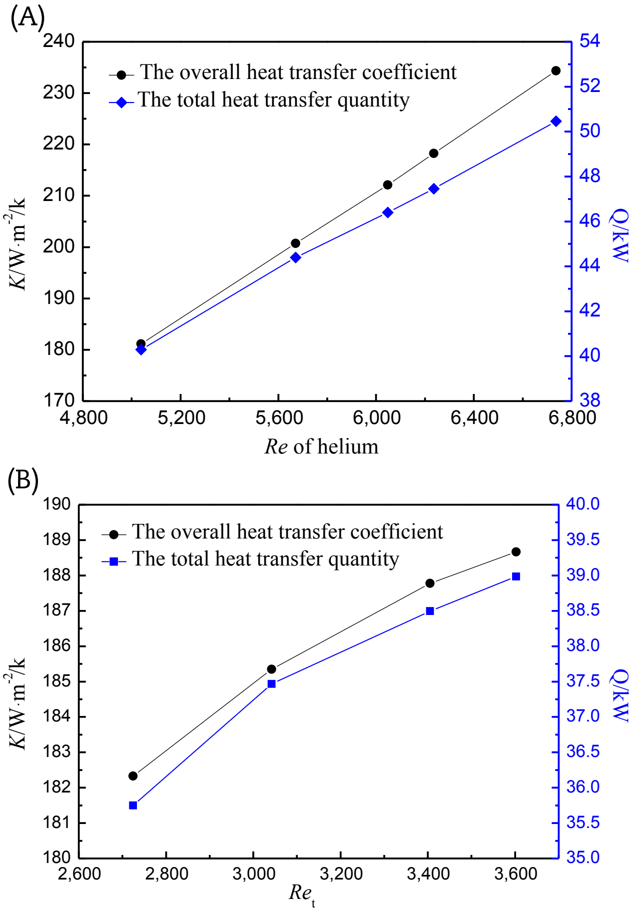

Fig. 6 – Effect of the helium and lead bismuth eutectic flowrate on the *K*. (A) *Re* of helium. (B) *Re* of lead bismuth eutectic.

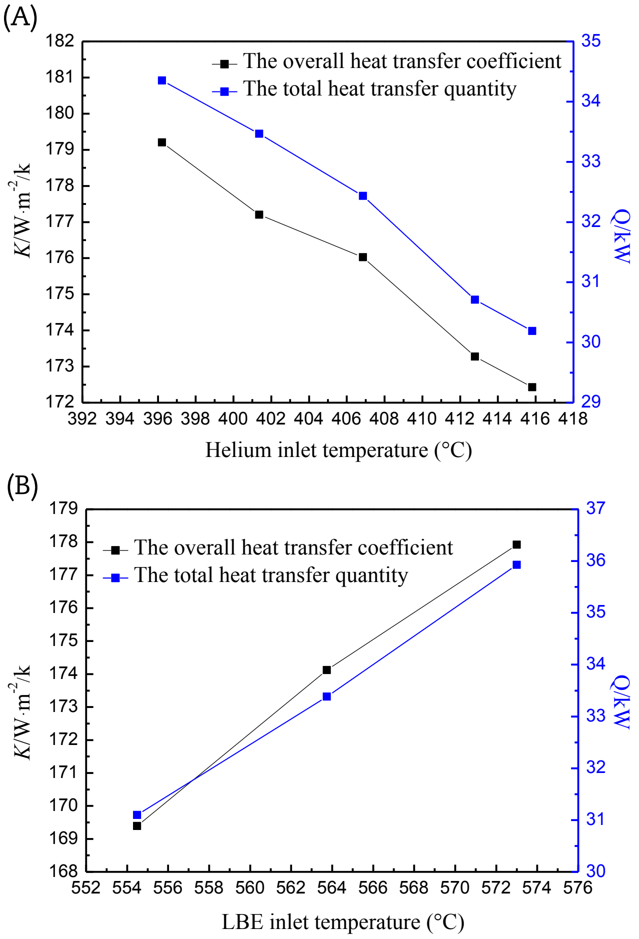

Fig. 7 – Effect of the helium and lead bismuth eutectic (LBE) inlet temperature on *K*. (A) Helium inlet temperature. (B) LBE inlet temperature.

Table 2 – Summary of the recommended correlations for main thermo-physical properties of lead bismuth eutectic.

Property	SI unit	Correlation	Uncertainty (%)
Density	$Kg\cdot m^{-3}$	$\rho = 11{,}096–1.3236T$	≤ 0.8
Heat capacity	$J\cdot kg^{-1}/°C$	$C_p = 159–2.72 \times 10^{-2}T + 7.12 \times 10^{-6}T^2$	≤ 7.0
Thermal conductivity	$W\cdot m^{-1}/°C$	$\lambda = 3.61 + 1.517 \times 10^{-2}T–1.741 \times 10^{-6}\cdot T^2$	≤ 5.0
Dynamic viscosity	$Pa\cdot s$	$\mu = 4.94 \times 10^{-4}\exp(754.1/T)$	≤ 5.0

SI, International system of units.

transfer area of the MHX, and ΔT_{lm} is the log mean temperature difference which is determined by:

$$\Delta T_{lm} = \frac{(T_h - T_c)_L - (T_h - T_c)_0}{\ln\left[(T_h - T_c)_L/(T_h - T_c)_0\right]} \quad (9)$$

where the subscripts of L and 0 designate the ends and the beginning of the MHX, respectively. Also, the helium properties are shown in the study by Petersen [17].

In the experiment, the inlet and outlet temperatures of the fluids in the heat exchanger are measured by thermal resistance sensors, i.e., T_h and T_c are measurable. The total rate of heat transfer q is obtained by a heat balance equation. Thus, the overall heat transfer coefficient is obtained by Eqs. (8) and (9). Obviously, the overall heat transfer coefficient depends on the geometrical and thermal hydraulic conditions of the MHX.

Based on the above analysis, the experiments are carried out in LELA with variable flow rates. The inlet temperatures of helium and LBE are constant. The operating conditions are as follows: helium inlet temperature is 134.8 °C, and the mass flow rate is in the range of 173.61–232.2 kg/h. While the LBE inlet temperature is 320 °C, the mass flow rate is in the range of 11,000.0–15,000.0 kg/h. Fig. 6 shows the effects of the helium and LBE Reynold number on the overall heat transfer coefficient. As can be seen in Fig. 6, the overall heat transfer coefficient is increased with the increasing Reynold number of helium and LBE, which means that the heat transfer performance of the MHX is improved at a higher Reynold number.

The inlet temperature is also an important factor in the performance of the MHX. Experimental investigations at variable temperature conditions are carried out. The mass flow rates of helium and LBE are constant. The helium inlet temperature is 127–147 °C; the mass flow rate is 178.0 kg/h. The LBE inlet temperature is 277–327 °C; the mass flow rate is 11,000.0 kg/h. Fig. 7 shows the effects of the helium and LBE inlet temperatures on the overall heat transfer coefficient. As shown in Fig. 7, the higher inlet temperature of helium leads to a smaller overall heat transfer coefficient. But when the inlet temperature of LBE increases, the overall heat transfer coefficient increases. That means increasing the inlet temperature of LBE can improve the heat transfer performance effectively.

4.4. *Measurement uncertainties*

Measurement uncertainty depends on the accuracy of the instruments used in the experiment, such as the thermal resistance sensors (an accuracy of 0.5%), the differential pressure transducer (made by Siemens, an accuracy of 0.15%), the helium mass flowmeter (Siemens Coriolis mass flow meter (Siemens Ltd., Beijing, China), an accuracy of 0.5%), EM flowmeter (an accuracy of 1.7%), and the data acquisition system. For the heat transfer characteristics, the uncertainties of q is less than 1.4%, while K is less than 1.2%. Meanwhile, the thermal physical properties of LBE, which are cited from Ref. [14], are also directly affected by temperature, and the uncertainties are shown in Table 2.

4.5. *Conclusion*

In this study, we successfully designed and constructed the LBE-helium experimental loop of ADS. Then, we made a detailed analysis on the flow resistance and heat transfer characteristics of the LBE-helium loop of ADS. The main conclusions are as follows. (1) Pressure drops of the pipeline predicted by Moody correlation are more accurate, especially under a higher temperature level. It is necessary to consider the roughness of the commercial pipeline when the pressure drops are calculated by correlations. (2) In MHX, the tube side pressure drop predicted by Nikuradse–Karman correlation is more accurate in contrast with Gu et al. correlation [16]. The deviations between the calculated results and experimental data are caused by the gravity pressure drop. The LBE temperature has a remarkable effect on the thermo-physical properties of LBE, such as viscosity, thermal conductivity, and density. The characteristic temperature must be selected carefully for the accuracy of measurements and calculations. (3) For the shell side of helium, the overall heat transfer coefficient of MHX increases with the increasing helium flow rate, and decreases with the inlet temperature increasing. For the tube side, the heat transfer coefficient of MHX is increased with the increasing of both the LBE Reynolds number and LBE inlet temperature.

Conflicts of interest

All authors have no conflicts of interest to declare.

Acknowledgments

This work is financially supported by the National Natural Science Foundation of China (Grant Number 51376177) and the “Strategic Priority Research Program” of the Chinese Academy of Sciences (Number XDA03010500).

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