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Buoyancy Impact on Heat Transfer of Lead-Bismuth Eutectic for Nuclear Applications

Jinghan Wang, Yangfan Ma, Min Zeng*, Qiuwang Wang

Key Laboratory of Thermo-Fluid Science and Engineering, Ministry of Education, Xi'an Jiaotong University, Xi'an, Shaanxi, 710049, China
zengmin@mail.xjtu.edu.cn

The liquid lead-bismuth eutectic (LBE) is an ideal primary coolant for the fourth-generation advanced nuclear systems. Due to its special physical properties, especially the low Prandtl number and high density, the natural convection phenomenon caused by buoyancy is significant. In this study, a circular tube is three-dimensionally modeled to predict the flow and heat transfer process of LBE. On the base of the model validation, simulations of the uniformly heated tube with/without buoyancy are performed. The different thermal-hydraulic performance obtained under different tube arrangements and operating parameters are compared, and the effects of buoyancy on the convective heat transfer of LBE are discussed. The results show that for LBE flow with smaller Reynolds numbers, convective heat transfer is significantly enhanced when gravity is opposite to the flow direction, while the same gravity and flow direction slightly weakens the convective heat transfer capacity. For the higher Reynolds number LBE flow, the buoyancy impact and the tube arrangement can be ignored. When the tube is placed horizontally, the heat transfer coefficient of the lower wall is about three times that of the upper wall. For different engineering applications, an appropriate arrangement is necessary to improve the efficiency of heat exchanger. This study may contribute to the development and application of LBE-cooled reactors.

1. Introduction

Nuclear energy has emerged as the largest low-carbon source of electricity for sustainable development and produces about 18 % of the electricity supply in advanced economies (IAEA, 2020). The problem of management and disposal of nuclear wastes have risen due to the rapid expansion of nuclear power industrial scale. Accelerator driven sub-critical system (ADS) has been widely recommended as a promising solution to proliferate and transmute spent nuclear materials since the 1990s (Chen et al., 2013). Heavy liquid metal (HLM), e.g. lead-bismuth eutectic (LBE), has been considered as the major coolant for sub-critical reactor like ADS (Zhang et al., 2020). LBE has many suitable properties for ADS, such as good neutron economy, physical properties, chemical inertness and strong buoyancy. The strong buoyancy, which provides more advanced natural circulation ability than sodium-cooled or gas-cooled systems (Wang et al., 2017), has an important impact on the flow field and temperature field. Mixed convection occurs in an ADS due to fluid gravity heterogeneity caused by the density variation, and the effects of natural convection on forced convection heat transfer cannot be ignored.

Many scholars have studied the buoyancy of liquid metals. Jackson (1983) proposed a theoretical model based on the study of buoyancy of liquid metals in a vertical tube, which provides a criterion for the condition of significant buoyancy. Niemann et al. (2018) pointed out that flow heat transfer and Reynolds stresses are strongly influenced by buoyancy, and the turbulent flow of low Pr number fluids at different Reynolds and Richardson numbers was investigated. Guo et al. (2020) used direct numerical simulations to study the mixed convection of liquid lead in a horizontal tube, and investigated the effects of different Richardson numbers on the mixed convection. Marocco et al. (2022) studied turbulent mixed convection of liquid metal flowing vertically in a uniformly heated tube with Reynolds numbers ranging from 2,650 to 7,500 using large eddy simulations.

In order to improve the thermal-hydraulic performance of LBE, it is necessary to study the related effects of buoyancy. In this study, a circular tube is three-dimensionally modelled to predict the flow and heat transfer

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process of LBE. On the base of the model validation, simulations of the uniformly heated tube with/without buoyancy are performed. The different thermal-hydraulic performance obtained under different tube arrangements and operating parameters are compared, and the effects of buoyancy on the convective heat transfer of LBE are discussed.

2. Physical model and numerical methods

2.1 Physical model and boundary conditions

The LBE is heated in a circular tube with an inner diameter of 10 mm and a length of 1.0 m by a constant heat flux on the wall. The velocity-inlet and outflow conditions are set on the inlet and outlet. The constant heat flux is applied on the wall surface. Detailed boundary parameters for the simulations are summarized in Table 1.

Table 1: Parameters for CFD simulation

Parameters	Values
Tube length/diameter (mm/mm)	1,000/10
Inlet temperature (K)	573.15
Inlet velocity (m/s)	0.02 – 2
Wall heat flux (W/m^2)	5×10^5
Gravitational acceleration (m/s^2)	9.81

2.2 Numerical method and mesh independence

The numerical study is executed by the commercial CFD software Fluent. The SIMPLE algorithm is used to deal with the pressure and velocity coupling. The shear stress transport (SST) k-ω model is selected to study the flow and heat transfer of LBE, and gravity effect is considered in the simulations. Since the Reynolds analogy theory is no longer suitable for the LBE due to its special thermal properties, an applicable turbulent Prandtl number (Pr_t) model should be constructed to better adapt to the flow and heat transfer characteristics of LBE. The Pr_t model for LBE turbulent flows proposed by Cheng and Tak (2006) is used, as shown below:

$$Pr_t = \begin{cases} 4.12 & Pe \le 1{,}000 \\ \dfrac{0.01Pe}{\left[0.018Pe^{0.8} - (7.0 - A)\right]^{1.25}} & 1{,}000 < Pe \le 6{,}000 \end{cases} \quad (1)$$

where

$$A = \begin{cases} 4.5 & Pe \le 1{,}000 \\ 5.4 - 9\times10^{-4} Pe & 1{,}000 \le Pe \le 2{,}000 \\ 3.6 & Pe \ge 2{,}000 \end{cases} \quad (2)$$

The thermal properties of lead-bismuth are estimated based on the Handbook on Lead-bismuth Eutectic of Nuclear Energy Agency (2015), as shown in Table 2.

Table 2: Thermal properties of LBE

Property	Symbol (Unit)	Correlation
Density	ρ (kg/m^3)	11,065-1.293T
Viscosity	μ (kg/m·s)	4.94×10^{-4}exp(754.1/T)
Thermal conductivity	λ (W/m·K)	3.284+1.617×10^{-2}T-2.305×10^{-6}T^2
Specific heat	c_p (J/kg·K)	164.8-3.94×10^{-2}T+1.25×10^{-5}T^2-4.56×10^{5}T^{-2}

2.3 Mesh independence and model validation

The computational domain is discretized by the structural mesh generated by ANSYS ICEM software, as shown in Figure 1. In order to capture the detailed flow and heat transfer in the near-wall region, the mesh refinement is adopted to ensure that the boundary layer wall function y+ for all the cases is smaller than 1. For the grid independence verification, five sets of grids are applied in the numerical solution to validate the grid independence. When the grid number is greater than 1,279,935, the relative deviation of the Nusselt number of the tube is less than 0.1 %, indicating that the numerical solutions are mesh-independent, as shown in Figure 2. The mesh number would be 1,279,935 considering the computational cost.

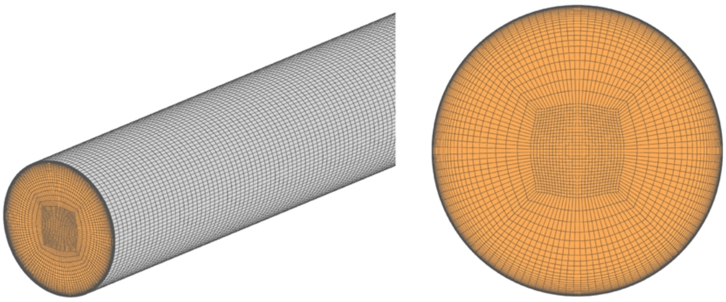


Figure 1: Mesh configuration

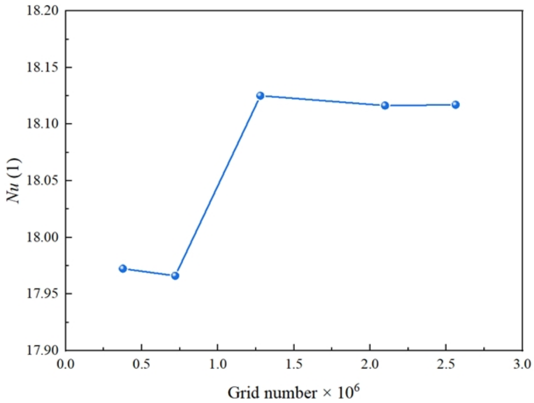


Figure 2: Grid independence test

The heat transfer correlation for LBE given by Cheng and Tak (2006), which agrees well with the experimental data of Johnson et al. (1953), is shown in Eq.(3). It is used for the verification of the feasibility and accuracy of present numerical model. It can be seen in Figure 3 that the present numerical model can provide a reasonable prediction of the flow and heat transfer process of LBE flow.

$$Nu = A + 0.018Pe^{0.8} \quad (3)$$

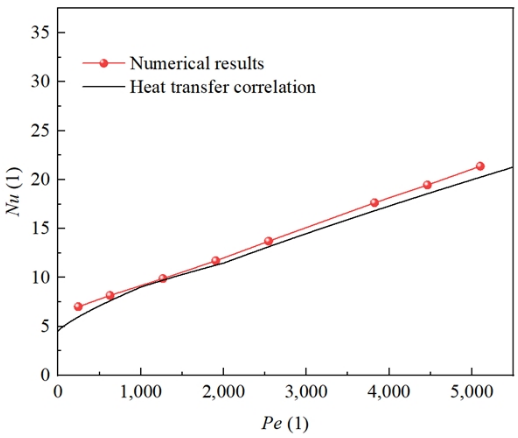
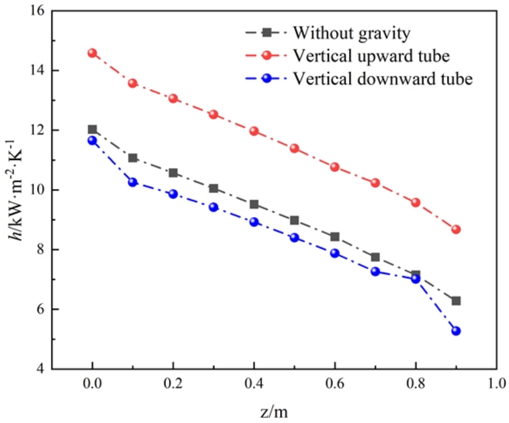


Figure 3: Comparison between simulation and heat transfer correlation

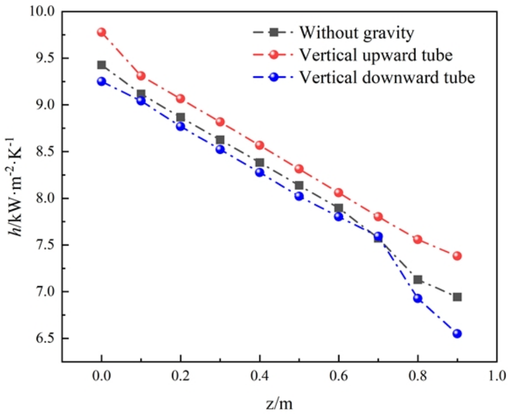
3. Results and discussion

The convective heat transfer coefficients of LBE, in vertical upward/downward arrangements of tubes with/without buoyancy for different inlet velocities, are given in Figure 4. It can be seen that when the gravity is considered, the LBE heat transfer coefficient of vertical upward pipe is the largest, while that of vertical downward pipe is the smallest. The convective heat transfer is more sensitive to buoyancy effects at smaller

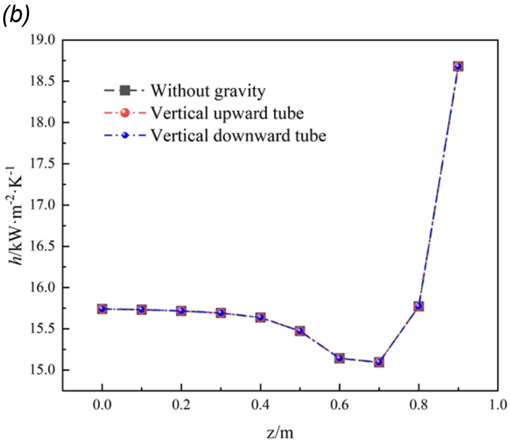
Reynolds numbers. At an inlet velocity of 0.02 m/s, the h_{LBE} can be increased by approximately 27.6 % overall by arranging the circular tube vertically upward, while the h_{LBE} can be reduced by 6.7 % when the tube is vertically downward. This buoyancy impact on convective heat transfer decreases with the increase of inlet velocity. When the inlet velocity increases to 2 m/s, buoyancy has little effect on the heat transfer. Turbulence is fully developed and the local convective heat transfer coefficients are high in the entrance region due to the thin thermal boundary layer. With the continuous development of the thermal boundary layer, the local convective heat transfer coefficients gradually decrease along the mainstream directions, and then tend to be stable. I.e., for LBE flow with smaller Reynolds numbers in a tube heated by constant heat flux, convective heat transfer is significantly enhanced when gravity is opposite to the flow direction, while the same gravity and flow direction slightly weakens the convective heat transfer capacity. The heat transfer can be improved by using the vertical upward tube arrangement. For the higher Reynolds number LBE flow, the buoyancy impact and the tube arrangement can be ignored.



(a)



(b)



(c)

Figure 4: Convective heat transfer coefficients of LBE: (a) vin = 0.02 m/s; (b) vin = 0.05 m/s; (c) vin = 2 m/s

Figure 5 illustrates the velocity distribution in the axial section z = 500 mm at different distances from the wall surface. In the region near the wall (y/*R*＞0.6), the LBE is accelerated in the upward tube and decelerated in the downward tube due to the buoyancy force. Accordingly, in the region far from the wall (y/*R*＜0.6), the LBE velocity is maximum in the downward tube and minimum in the upward tube to ensure a consistent total mass flow rate.

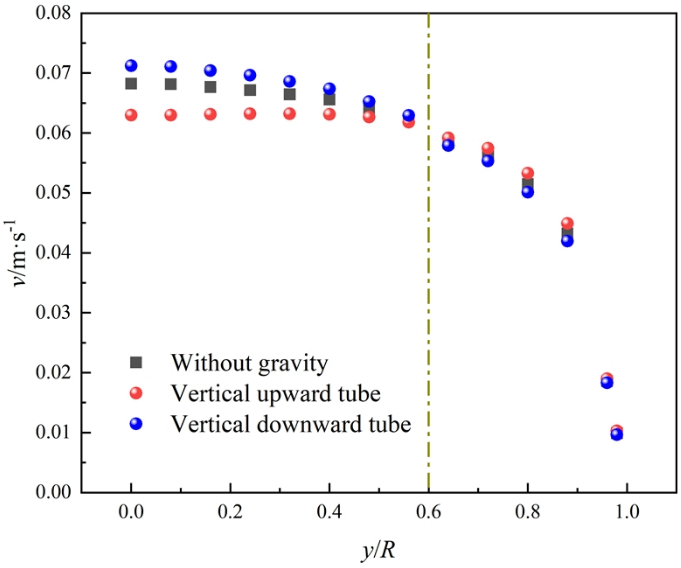


Figure 5: Velocity distribution at different distances from the wall (vin = 0.05 m/s, z = 500 mm)

Figure 6 compares the effects of buoyancy on LBE heat transfer horizontal and vertical tubes. Gravity is perpendicular to the flow direction in the horizontal tube, and the buoyancy force makes a big difference in the convective heat transfer level between the upper and lower walls. The heat transfer coefficient of the lower wall is about three times that of the upper wall. This phenomenon of large differences in heat transfer at different locations on the wall would not occur when gravity is parallel to the flow direction.

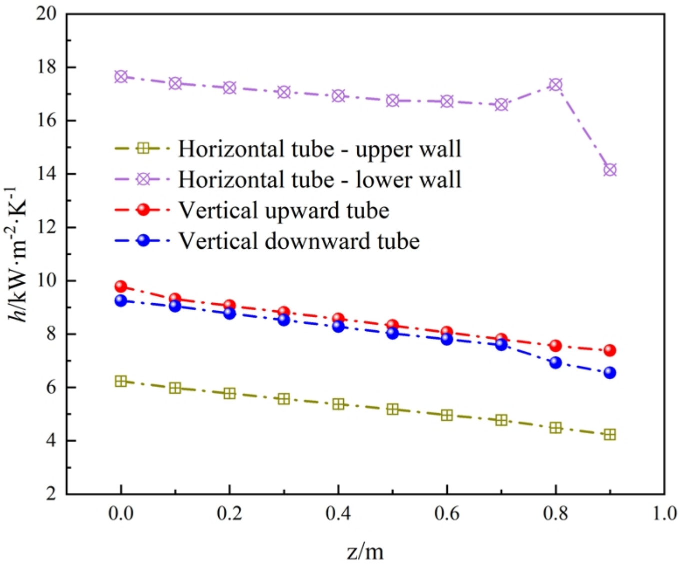


Figure 6: Convective heat transfer coefficients of LBE in horizontal and vertical tubes (vin = 0.05 m/s)

4. Conclusions

As an ideal candidate coolant for ADS, LBE has attracted lots of attention in both academia and industrial. In this paper, a circular tube is three-dimensionally modelled, simulations of the uniformly heated tube with/without buoyancy are performed. The different thermal-hydraulic performance obtained under different tube arrangements and operating parameters are compared, and the effects of buoyancy on the convective heat transfer of LBE are discussed. The results show that for LBE flow with smaller Reynolds numbers in a tube heated by constant heat flux, convective heat transfer is significantly enhanced when gravity is opposite to the flow direction, while the same gravity and flow direction slightly weakens the convective heat transfer capacity. At an inlet velocity of 0.02 m/s, the h_{LBE} can be increased by approximately 27.6 % overall by arranging the circular tube vertically upward. For the higher Reynolds number LBE flow, the buoyancy impact and the tube arrangement can be ignored. Gravity is perpendicular to the flow direction when the tube is placed horizontally, and the buoyancy force makes a big difference in the convective heat transfer level between the upper and lower walls. The heat transfer coefficient of the lower wall is about three times that of the upper wall. This phenomenon of large differences in heat transfer at different locations on the wall would not occur when gravity is parallel to the flow direction. For different engineering applications, careful consideration of the impact of buoyancy and tube arrangements is essential for the overall flow heat transfer performance of lead-bismuth based heat exchanger.

Nomenclature

c_p – specific heat at constant pressure, J/(kg·K)
h – heat transfer coefficient, W/(m^2·K)
Nu – Nusselt number, -
Pe – Peclet number, -
Pr – Prandtl number, -
Pr_t – turbulent Prandtl number, -
R – radius of the tube, m
T – temperature, K
u – velocity, m/s
x, y, z – cartesian coordinates
λ – thermal conductivity, W/(m·K)
μ – dynamic viscosity, Pa/s
ρ – density, kg/m^3

Acknowledgments

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