

Thermal-hydraulic Assessment of Seven Wire-wrapped rod Bundle

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Abstract: Lead bismuth eutectic (LBE) is one of the most potential materials for coolant and spallation target for Accelerator Driven Systems (ADS). Thermal-hydraulic behavior of LBE in fuel assembly is a key issue for development of the systems. To get a deeper understanding on the complex thermal-hydraulic features of wire-wrapped rod bundle cooled by upward LBE, an electrically bundle with 7 rods wrapped with helical wire was developed in KYLIN-II thermal-hydraulic forced circulation loop. The flow resistance, thermal entrance characteristic and heat transfer coefficient were investigated. As for the entrance characteristics, during the full heating length (exceeding 140 times the hydraulic diameter), the thermal field did not reach a fully developed and stable condition which is contrary to the ducted flows. The experimental heat transfer coefficient showed that the hexagonal shell has a great influence on the heat transfer coefficient in rod bundle geometry. For this reason the application of empirical correlation should be kept cautious in rod bundle analysis.

Key words: Accelerator Driven Systems; Thermal-hydraulics; Rod bundle; Lead-bismuth eutectic

1. Introduction

Accelerator Driven sub-critical Systems (ADS) are considered as one of the most potential options to incinerate long living fission products by transmutation (C. Rubbia,

1996; W. Gudowski, 2001). With respect to low melting temperature, high boiling temperature, outstanding heat transfer performance, chemical stability, and good neutron economy, Lead-Bismuth Eutectic (LBE) are currently attracting more and more attention word wildly to be both the coolant for sub-critical reactor core and spallation target in transmutation systems (T. Takizuka, 2002; N. Li, 2008). In 2011, the ADS project was launched in China by Chinese Academy of Sciences (CAS), and a 10MWth experimental reactor cooled by LBE named CLEAR-I (Y. Wu and Y. Bai) was designed by FDS team which has been strongly involved on advanced reactor concepts, advanced materials and nuclear code development. In the frame of this project, to support the design and construction of CLEAR-I, KYLIN-II multi-functional LBE facility, including material, thermal-hydraulic and safety loops has been established based on the former experience on lead-lithium experimental technology.

One of the most interesting topics in thermal-hydraulic fields is the turbulent heat transfer, especially for complex geometries, e.g. fuel assemblies and high power spallation target. Owing to the lower prandtl number, the heat transfer to heavy liquid metal is very different from the heat transfer to water or gas (X. Cheng, 2006). That is, compared to the contribution from convection, the contribution from thermal conductivity in low prandtl number fluid like lead-bismuth eutectic is much higher than water even through at the conditions with high Reynolds number. Thus existing heat transfer numerical models and experimental experience are not applicable to systems cooled with liquid metal directly.

Moreover, due to the compact arrangement of rod bundle and the difficulties of heavy liquid metal measurement, the experimental data on the rod bundle cooled by heavy liquid metal is scare. Several experimental studies were conducted in the sixties using mercury (Hg) and sodium–potassium alloy (NaK), which has the similar scale prandtl number with lead or lead bismuth. Unfortunately, as mentioned by W. Pfrang (2007), in most publications about these former experiments, no detailed description was given, whether spacer or what type of spacers have been used. Recently, with the increasing interesting in heavy liquid metal technology, a series of new bundle experiments (J. Pacio, 2014; M. Tarantino, 2013) were conducted to study the thermal-hydraulic characteristics of heavy liquid metal in rod bundle. Nevertheless, the rod bundle geometries have a lot of influencing factors, e.g. pitch to diameter, wire pitch, hexagonal shell and so on, only several experiments could not summarize the complex flow and heat transfer features. For the time being, it is well agreed that there still exists big deficiency in understanding and describing special thermal-hydraulic behavior in tight rod bundles, especially related to heat transfer behavior.

2 Experimental setup

The 7-heated rod bundle test section was installed in the vertical direction with upward flow at position 4 in Fig.1. The coolant LBE enters the rod bundle at the lower end and flows upward to move the thermal generated by heated pins. A general view of this test section is depicted in Fig.2. In the flow direction, upstream of test section, the flow developing length with 1.4 meters and a flow restrictor were placed to obtain a uniform inlet flow rate around each sub-channel.

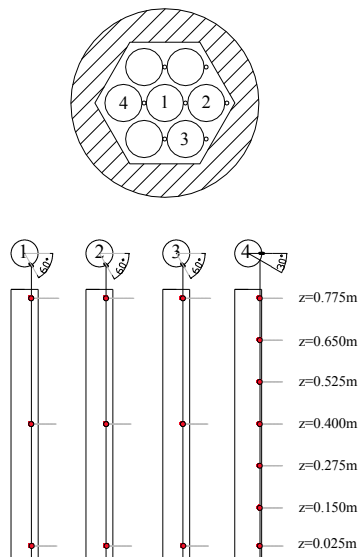


Fig.1. General view of the 7-rod bundle test section

The rod bundle were manufactured referring to the preliminary structure design of fuel assembly of CLEAR-I. Table 1 shows the main parameters of the experimental bundle. Each rod has a heated length of 800mm, and an unheated length of 1100mm. The nominal input voltage is 220V while the power of each pin is 5000W. To obtain the accurate power of experimental bundle, a direct-current power supply system consisting of a thristor rectifier and a power distribution system was employed.

To evaluate the thermal-hydraulic performance of the bundle, the wall temperature of heated rod and pressure drop of wire-wrapped bundle were measured in the test section. The bulk temperature in the bundle section was not measured. This parameter would be calculated from an energy balance throughout the test section (from inlet until axil position z). The wall thermocouples with 0.5mm diameter were embedded in the heated wall to measure the heated wall temperature which depicted in Fig.3. The number of the wall thermocouples is 16, and the detailed position is also depicted in Fig.2.

Table1 Main characteristics of the rod bundle

Parameters	Symbol	Value (mm)
Rod outer diameter	D	15
Pitch	P	16.74
Rod length	L	1900
Rod heated length	L _h	800
Apothem	a	48
Helical wire diameter	d _w	1.64
Helical pitch	H	375

3 Results and discussion

The friction factor of wire-wrapped rod bundle was calculated according to the following formula:

$$f = \frac{2 * \Delta P * d_h}{L_B * \rho * v^2} \tag{1}$$

Where ΔP is the pressure drop of flow resistance, d_h is the hydraulic diameter of rod assembly, L_B is the length of wire-wrapped bundle, and v is the average velocity.

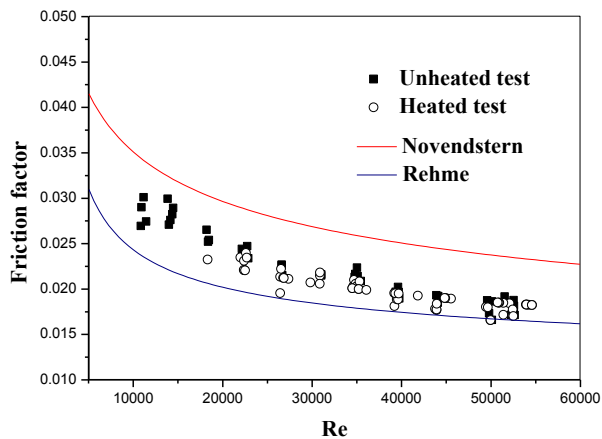


Fig.2. Evolution of the friction factor according to the Reynolds number

The experimental friction factor profiles as function of Reynolds number for the bundle are displayed in Fig.4. The unheated test was performed at $\sim 260^\circ\text{C}$ with adiabatic running, while the heated test was conducted at $\sim 260^\circ\text{C}$ of average inlet and outlet temperature with maximum temperature difference 40°C . From the experimental results depicted in Fig.2, there is no significant difference between the unheated and heated test due to their similar reference temperature. Furthermore, the experimental friction factor compared with empirical correlations (E.H. Novendstern, 1972; K. Rehme, 1972) which derived from the air or water experiments is also depicted in Fig.4. All the experimental values were located between the Novendstern and Rehme correlations. That could be seen that LBE has similar flow resistance characteristics of traditional fluid like water or air. In detailed the Rehme correlation presented a better agreement with the experimental results than Novendstern correlation. The probable reason is that the effect of the rod number is concluded in the Rehme correlation.

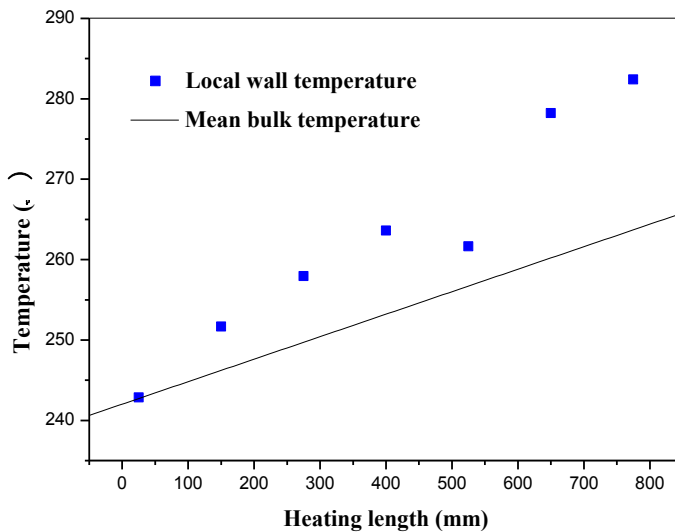


Fig.3. Thermal entrance characteristic of experimental bundle

The thermal entrance characteristic of experimental bundle is depicted in Fig.3. The blue squares are the wall temperature of PIN4 along the heating length, and the black line is the average bulk temperature derived from energy balance. It could be seen that along the flow direction the discrepancy between the wall temperature and bulk temperature became larger. This phenomenon could be concluded that the thermal field did not reach a fully developed and stable condition during the full heated bundle section, although the overall heating length reached to 140 times the hydraulic diameter. The conclusion was different with the ducted flows. This

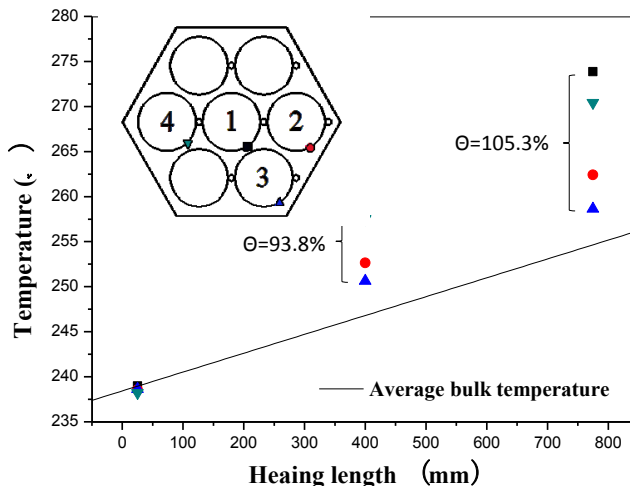
phenomenon was also predicted through CFD calculations by other publications (N. Govindha Rasu, 2013). They mentioned that the reason was the weak communication among the sub-channels in tightly packed bundle. In addition, the wall temperature at axial position $z=525\text{mm}$ was abnormal lower. The reason was that the thermocouple probably didn't embed well in the heated wall in this experiment.

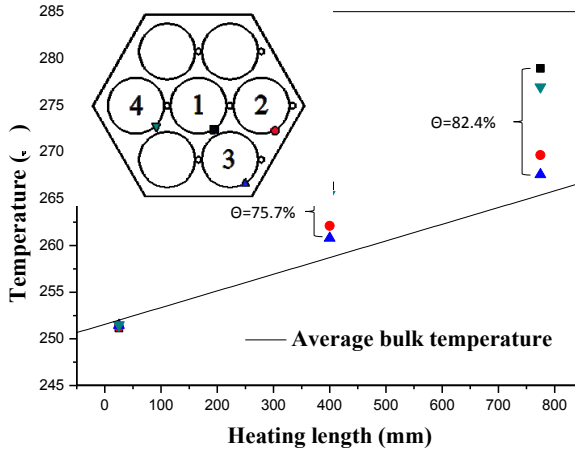
Fig.6 shows the temperature deviations in the cross section of the bundle, respectively for two different Peclet numbers. To characterize the temperature deviations, a non-dimensional parameter Θ (M. Berthoux, 2010) is defined as following:

$$\Theta = \frac{T_{w\max} - T_{w\min}}{T_{zf} - T_{in}} \tag{2}$$

Where $T_{w\max} - T_{w\min}$ is the measured maximum wall temperature deviation, $T_{zf} - T_{in}$ is the temperature difference between the local bulk temperature (calculated on heat balance) and inlet bulk temperature.

The wall temperature deviations between center rod and periphery rod could be detected obviously in Fig.6. The temperature deviations were caused by the adiabatic hexagonal shell and the different local hydraulic diameters between the inner and periphery sub-channels. Furthermore, the comparison between the Fig.6 (a) and (b) revealed that the temperature non-uniformity was more significant for lower Peclet number. That is because in the higher Peclet regimes, the coolant mixing is stronger, which can induce the temperature distribution more uniform.





(a) Pe=570

(b) Pe=1150

Fig.4. Temperature deviations in the cross section of bundle

The wall temperature of the center rod was used to evaluate the heat transfer coefficient. The local Nussult number (Nu) is defined as in Eq(3), where d_s is the hydraulic diameter of sub-channel, T_b is the average bulk temperture driven by energy balance, T_w is the measured wall temperature of center rod.

$$Nu = \frac{q'' * d_s}{(T_w - T_b) * \lambda} \tag{3}$$

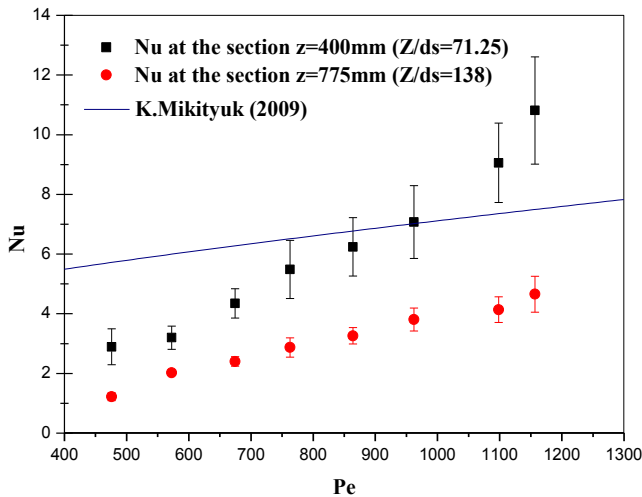


Fig.5. Evolution of the local Nussult number according to the Peclet number (The error bars were based on the standard deviation)

The Nu profiles as function of Peclet number (Pe) are depicted in Fig.7. At the given Pe, the Nu at axial position $z=400\text{mm}$ ($z/d_s \approx 71.25$) was remarkably larger than the value at axial position $z=775\text{mm}$ ($z/d_s \approx 138$). The phenomenon could be attributed to thermal developing condition which has discussed in Fig.3. Furthermore, the deviation became larger and larger along the flowing direction. The empirical correlation K. Mikityuk (2009) which is valid for full developed condition of infinite rod bundle is also depicted in Fig.7. It could be seen that the Nu at section $z=775\text{mm}$ had a similar rising slope of K. Mikityuk correlation, but the Nu at section $z=400\text{mm}$ had a relatively steep slope. Moreover, the magnitude of experimental Nu at section $z=775\text{mm}$ is smaller than K. Mikityuk correlation. That is because of the non-uniform distribution of wall temperature which discussed in Fig.6. Thus the local Nu which based on center rod wall temperature and average bulk temperature would be lower than the average Nu like K. Mikityuk. This indicates that the hexagonal shell has a great influence on the heat transfer coefficient of rod bundle geometry. For this reason the application of empirical correlation should be kept cautious.

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References

- C. Rubbia, 1996. Status of the Energy Amplifier Concept. Proceeding of the 2nd International Conference on Accelerator-driven Transmutation Technologies and Applications, Kalmar, Sweden, June 3-7.
- E.H. Novendstern, 1972. Turbulent flow pressure drop model for fuel rod assemblies utilizing a helical wire-wrap spacer system[J]. Nucl. Eng. Des. 22: 19-27
- J. Pacio, M. Daubner, F. Fellmoser, et al, 2014. Heavy-liquid metal heat transfer experiment in a 19-rod bundle with grid spacers. Nucl. Eng. Des. 273, 33–46.
- K. Rehme, 1972. Pressure drop performance of rod bundles in hexagonal arrangements. Int. J. Heat Mass Transfer 15 (12), 2499–2517.
- K. Mikityuk, 2009. Heat transfer to liquid metal: review of data and correlations for tube bundles. Nucl. Eng. Des. 239 (4), 680–687.
- L. Qiu, Y. Wu. B. Xiao, et al, 2000. A low Aspect Ratio Tokamak Transmutation System. Nucl Fusion. 40: 629-633.

- M. Berthoux, T. Cadiou, 2010. The Thermal Hydraulics in a Rod Bundle Representative of the Start-up Core of the ALLEGRO Gas Cooled Fast Reactor-Experimental and Numerical Approaches. *Nucl. Eng. Des.* 240, 3372–3386.
- M. Tarantino, I. Di Piazza, P. Agostini, et al, 2013. Thermal-hydraulic Assessment of HLM-cooled Pin Bundle in CIRCE Pool Facility. International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios FR13. Paris, France, March 4-7, 2013.
- N. Li, 2008. Lead-alloy Coolant Technology and Materials-technology Readiness Level Evaluation. *Progress in Nuclear Energy.* 50, 140-151.
- N. Govindha Rasu, K. Velusamy, T. Sundararajan, et al, 2013. Investigations of flow and temperature field development in bare and wire-wrapped reactor fuel pin bundles cooled by sodium.
- OECD/NEA, 2007. Handbook on Lead-Bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal–Hydraulics and Technologies. 2007 edition: 15-21.
- Q. Huang, S. Gao, Z. Zhu, et al. 2009. Progress in Compatibility Experiments on Lithium-Lead with Candidate Structural Materials for Fusion in China. [J]. *Fusion Eng. Des.* 84: 242-246.
- Q. Huang, C. Li, Y. Li, et al, 2007. Progress in Development of China Low Activation Martensitic Steel for Fusion Application. *J. Nucl. Mater.* 367-370:142-146.
- T. Takizuka, K. Tsujimoto, T. Sasa, et al, 2002. Design Study of Lead-bismuth Cooled ADS Dedicated to Nuclear Waste Transmutation. *Progress in Nuclear Energy.* 40,505-512.
- W. Gudowski, V. Arzhanov, C. Broeders, et al, 2001. Review of the European project — Impact of Accelerator-Based Technologies on nuclear fission safety (IABAT). *Progress in Nuclear Energy.* 38,135-151.
- W. Pfrang, D. Struwe, 2007. Assessment of correlations for heat transfer to the coolant for heavy liquid metal cooled core designs. Technical Report FZKA 7352, Forschungszentrum Karlsruhe GmbH.
- X. Cheng, N. Tak, 2006. Investigation on Turbulent Heat Transfer to Lead-bismuth Eutectic Flows in Circular Tubes for Nuclear Applications. *Nucl. Eng. Des.* 236, 385-393.