Experimental Study on Natural Circulation and Gas Injection Enhanced Circulation in KYLIN-II Mixed Circulation Loop

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Abstract

Pure lead and its alloys are foreseen to be used as coolant and/or spallation target in the advanced nuclear systems. To investigate the behavior of Lead Bismuth Eutectic (LBE) cooled nuclear systems, KYLIN-II Thermal-Hydraulic (KYLIN-II TH) mixed circulation test loop has been designed and built in HEFEI by FDS team. The loop is a multipurpose facility aimed to investigate natural circulation, forced circulation and gas enhanced circulation in HLM systems. In this context, experimental data and correlations for the design of nuclear systems cooled with heavy liquid metals will be gained. The work concerns the preliminary tests performed on KYLIN-II TH. During the experiments, the facility was operated at 200-350 ℃ with heating power from 16 kW to 70 kW. The natural circulation, transient circulation and preliminary Loss of Flow Accident (LOFA) was carried out in this work. The experiments show that the steady state of natural circulation is easy to be established in a few minute. The time duration of temperature transition state, during the foundation of natural circulation in start-up of natural circulation test and LOFA in this work, is less than 300 s, however, depended on the operation parameters of the facility.

Keywords: Lead-Bismuth eutectic coolant; Natural circulation; LOFA transient

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1. Introduction

Heavy Liquid Metals (HLMs) such as pure lead and its alloys broadly attract more and more attentions in the field of new generation nuclear systems. As candidate coolant materials for future advanced nuclear systems, its good neutronics and thermal-physical properties has been widely recognized. Lead-Bismuth Eutectic (LBE) is chosen as the spallation target and coolant material for Accelerator Driven Systems (ADS) **[1-3]**. In 2011, Chinese Academy of Sciences (CAS) has launched an ADS project and FDS team mainly in charge of the design, verification and manufacturing of China LEAd-alloy Reactor (CLEAR-I) **[2]** based on the experience in LBE , Pb-Li technology and also many years work of R&D on fusion/fission reactors **[4-12]**.

Due to the special characteristics of strong thermal expansion (buoyancy) of LBE, more and more attentions on safety considerations have been given to natural circulation in the advanced reactor designs. Natural circulation is driven by hydrostatic head due to a density variation caused by temperature difference. The development of natural circulation is foreseen to improve the passive safety and reliability for the reactor. To investigate the thermal-hydraulic behavior of lead bismuth eutectic (LBE) and support the technology and code validation and verification for heavy liquid metal cooled reactor, series loops around the world have been built in recent years, such as TALL[13, 14], HELIOS[15], NACIE[16], HANS[17] etc.. The height of TALL are 6.8m, 12m, and 8m respectively. The input power of TALL and HELIOS is 60 kW and 25 kW. For NACIE, the original input power was about 25 kW, after the updating the total input power has been reached up to 250 kW. HANS is a small loop with total circulation loop length 5.5m, the maximum main heater power during experiments is 2.5 kW. The main objective of these loops are focused on the thermal-hydraulic investigations on the heat transfer and flow characteristics of LBE fluid. In order to evaluate the thermal-hydraulic characteristics of CLEAR and establish its related technologies, a loop named KYLIN-II Thermal Hydraulic (KYLIN-II TH) mixed circulation test loop, has been designed and built in INEST. This loop allows performing experimental campaigns in the field of the thermal-hydraulics to obtain correlations essential for the design of nuclear plant cooled by heavy liquid metals. In the present paper, preliminary tests on natural Circulation, gas lift enhanced circulation and LOFA experiments were performed and presented.

2. KYLIN-II Thermal-hydraulic mixed circulation loop

2.1 The main loop

The KYLIN-II Thermal-Hydraulic mixed circulation loop (12 m height) is a rectangle loop mainly consisting of two vertical pipes (working as riser and downcomer) and two horizontal pipes. In the bottom of the riser a heat source, i.e. Fuel Pin bundle Simulator (FPS) with 61 pins (300 kW), was installed. A tube in tube heat exchanger is placed in the upper part of the downcomer. In order to provide higher flow rate for circulation, a mechanical pump is installed in the lower horizontal branch. The difference in height between the center of the heating section and the center of the heat exchanger is 2 m, which is very important for the intensity of the natural circulation. In the riser, an argon gas injection device ensures a driving force to enhance the natural circulation in this loop. The facility is sketched schematically in Fig. 1. Main parameters are listed in Table 1.

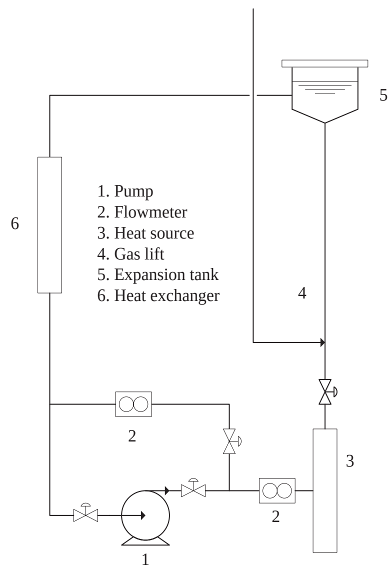


Fig.1 The general layout and drawing of KYLIN-II Thermal-hydraulic mixed circulation loop

Table 1 Main parameters of KYLIN-II Thermal-hydraulic mixed circulation loop

Fluid	LBE
Height	12 m
Pipe diameter	108 mm
Max.Design temperature	550 ℃
Design pressure	1.2 MPa
Material	316L
Max. Velocity	2 m/s (Forced Circulation)
	0.15 m/s (Natural Circulation)
	0.5 m/s (Gas Lift Enhanced Circulaiton)
Max.Thermal power	~300 kW
Second side fluid	H_2O (Pressurized water)
Max. Second side pressure	10 bar

2.2 Fuel Pin Simulator (FPS)

The fuel assembly of CLEAR-I consists of 61 fuel pins with diameter 15 mm of each fuel pin and the triangular pitch is 16.74 mm. Each pin is wrapped with helical wire spacer of 375 mm helical pitch, and the diameter of the helical wire is 1.64 mm. In the present paper, the structure of FPS is completely designed referring to the fuel assembly of CLEAR-I. Table 2 shows the main parameters of FPS. To simulate the nuclear heat, electric heating with direct current power is employed. The maximum power of each pin is reach to 5 kW which covers the maximum power of single fuel pin in CLEAR-I, and the total power of FPS is up to 300 kW.

Table 2 Main parameters of the 61-rod bundle

Parameters	Symbol	Value
Rod outer diameter	d_r	15mm
Pitch	P	16.74mm
Pitch-to-diameter ratio	P/d_r	1.116
Minimum distance to shell	w	1.79mm
Rod heated length	L_h	800mm
Apothem	a	67.30mm
Helical wire diameter	d_w	1.64mm
Helical pitch	H	375mm

3. Results and discussion

3.1 Establishment of natural circulation

The establishment of natural circulation in the primary LBE loop side is a dynamic procedure. It can be happened during the start-up of reactor from a cold zero power condition. Furthermore, when the main pump of the reactor lose its external driving head, it's extremely important that the natural circulation could be established as soon as possible. Thus in order to test this thermal-hydraulic phenomenon, the preliminary start-up test of natural circulation was carried out in KYLIN-II thermal-hydraulic mixed circulation loop. The natural convection foundation was observed by starting heating of the FPS with thermal power from 0 to 16 kW, shown in Fig. 2(b). Due to the heat loss of insulation around the surface of pipe and facilities, it was impossible to obtain a uniform temperature distribution. As seen in Fig. 1(a), the initial temperature of FPS and heat exchanger are different with each other. The inlet temperature of heat exchanger is slightly higher than that of outlet. And the outlet temperature of FPS is slightly higher than that of inlet. Such a temperature difference was accepted as the initial condition for the development of natural circulation in a closed LBE loop **[13, 14]**.

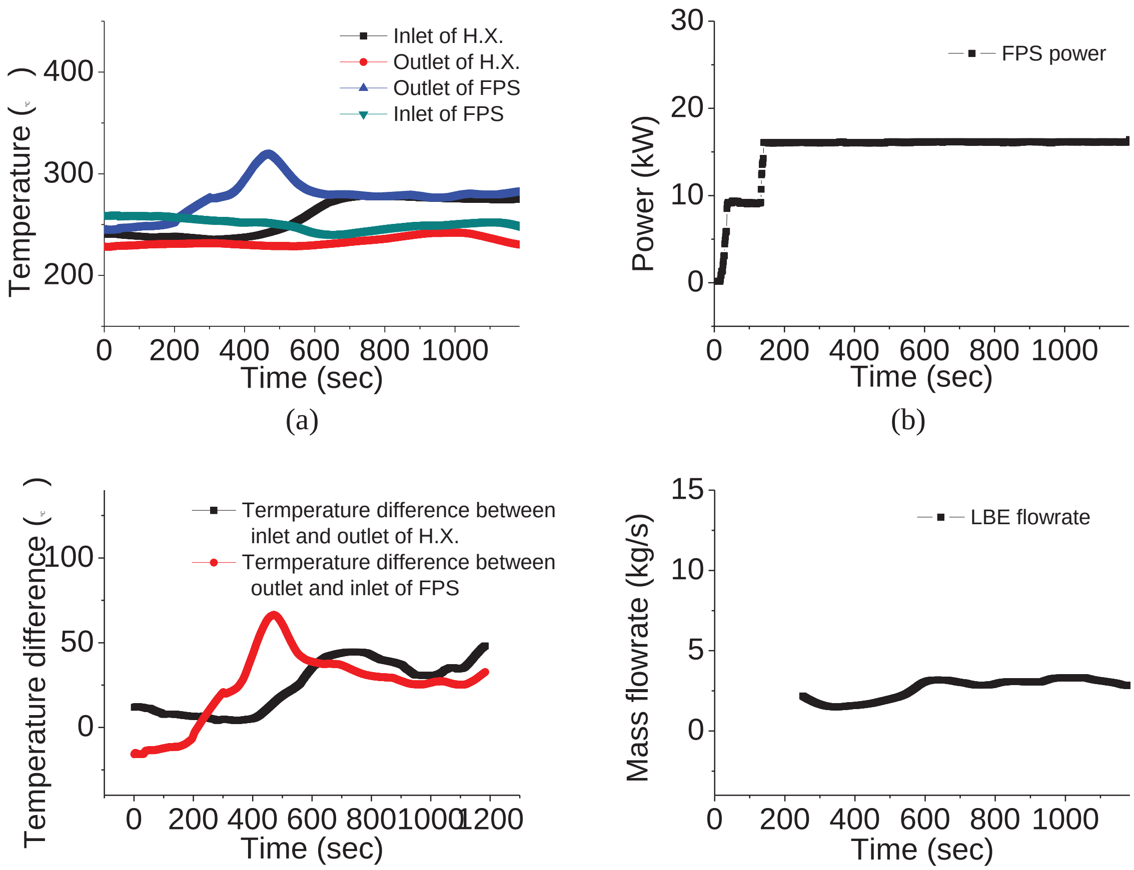


Fig. 2 Start-up of natural circulation from zero power condition, (a) Temperature, (b) power, (c) temperature difference, and (d) flow rate

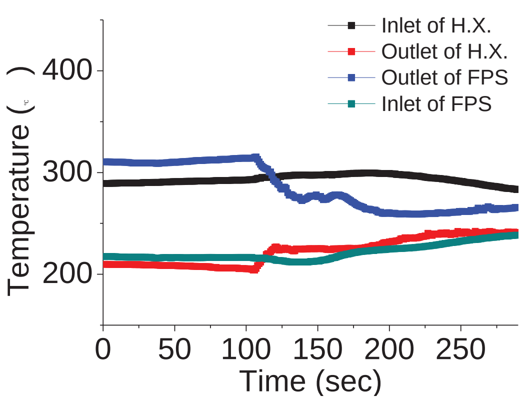
Fig. 2(a) shows the temperature variation during the natural circulation establishment. Because the start-up begins by gradually switching on the pump for secondary loop, thus no temperature decreasing of the outlet of heat exchanger is observed at the very beginning. The inlet temperature of FPS shows the same results due to the reason stated above. At the same time, the outlet temperature of the FPS and inlet of heat exchanger increases with the heating power input. Owing to the step power up effect, two peaks of FPS appear at ~300 s and ~500 s. Through the comparison between the Fig. 2(a) and Fig. 2(b), as can be seen that both of the temperature peaks stay at maximum level for around 200 s, and then decrease because of the cold LBE flowing into the FPS section. The maximum temperature is 325 ℃，about ~ 70 ℃ higher than the initial temperature and ~50 ℃ than the final temperatures during the start-up process. Although the temperature difference between the initial state and final state is about ~20 ℃, the FPS must overcome the first temperature barrier $\triangle T_1$ safely during the establishment of natural circulation.

The LBE goes further upwards to the heat exchanger, leading to the rising of the inlet temperature of the heat exchanger. However, the temperature peak appears at ~650 s, which is ~200 s postponed than that of FPS. Fig. 2(c) shows the temperature difference between inlet and outlet of heat exchanger and FPS. Fig. 2(d) depicts the flow rate of LBE in the primary loop. Due to part of the inlet and outlet temperature difference of FPS is less than zero. Only the flow rate after ~250 s is calculated according to the energy conservation equation. As can be seen, all the parameters, include the flow rate of LBE, become stable after ~650 s. Conclusion is given that the natural circulation of the loop is easy to be established by less than a quarter of an hour in this case.

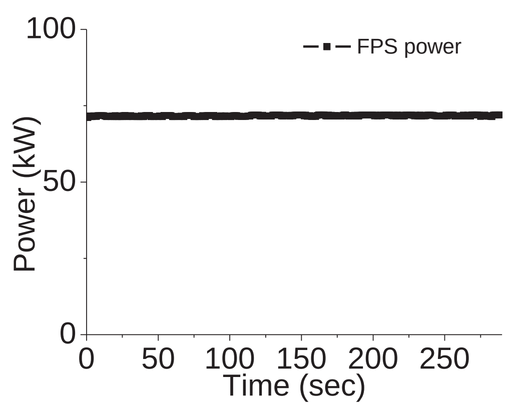
3.2 Gas lift enhanced circulation

LBE in the loop can be driven by the mechanical pump which could provide higher flow rate and pressure head for the circulation. In addition to this means, a gas lift pump is another effective way to promote the LBE not only in the loop but also in the reactor core. Two phase flow phenomenon between the gas and LBE can be explored to investigate the application probability of the gas lift technique in the ADS reactor. In this facility, a gas lift test section for obtaining the basic mechanisms involved in ADS reactor has been designed to promote the LBE circulation in the loop as an alternative way. A gas pipe is housed inside the riser, located just downstream the heating section. The argon gas is injected in the riser through a nozzle aiming to enhance the LBE circulation. In this case, the gas injection system provides an argon gas with flow rate of ~1 Nl/s to have a driving force based on the natural circulation during the transient test. The flow rate of argon gas is depicted in Fig. 3(c) and the input power adopted here is 70 kW shown Fig. 3(b).

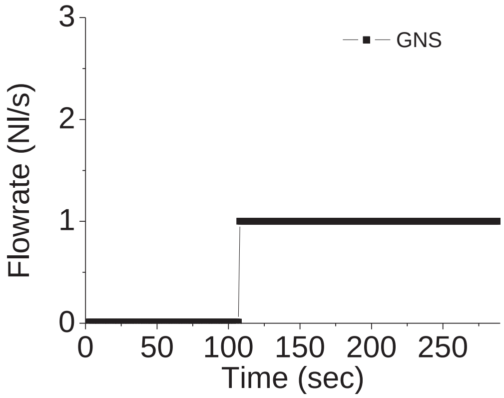
The development of gas lift circulation from a stable natural circulation is as shown in Fig. 3(a) and (d). The LBE flow rate in the pipe rise up very quickly when the gas injection is switched on at ~100 s. The outlet temperature of FPS decreases suddenly due to the cooler coolant from the cold leg moving through the FPS faster than natural circulation mode.



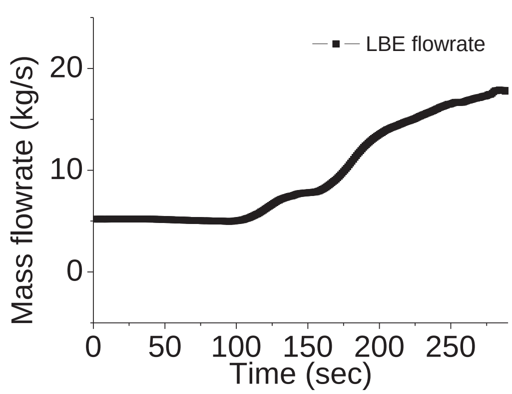
(a)



(b)



(c)



(d)

Fig.3. Transient experiment from natural circulation to gas lift enhanced circulation，(a) temperature, (b) power input, (c) flow rate of argon gas, and (d) flow rate of LBE

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The outlet temperature of heat exchanger increase quickly following the same trend as the inlet temperature of FPS. The temperature difference between inlet and outlet of FPS and heat exchanger shows decreasing trend. After about 170 s, the general trend of all the temperatures is stabilized gradually. The transient from natural circulation to gas lift enhanced circulation is determined by the gas flow rate injected into the riser. Obviously the more gas injection is provided, the faster flow balances is reached. In this circumstance, less than 3 min is required for the balance reconstruction.

3.3 Pretest of loss of flow accident

In recent years, much more attentions have been paid on the risk of loss of cooling capability for fuel assemblies in the primary loop of reactor, especially after the accident of Fukushima on March 11 of 2011**[18]**. The cooling capability of fuel assembly will be unavailable when the external driving force is switched off by accidents. Then the temperature in the reactor pool and in the sub-channel among fuel rods would increase continuously, eventually causing an accident due to the imbalance in heat generation and heat removal. Therefore, it is very important to identify the maximum temperature of the cladding when the loss of flow accident occurs in the ADS reactor. In order to demonstrate the passive safety ADS reactor during the loss of flow accident, the KYLIN-II thermal-hydraulic mixed circulation loop has been designed with the capabilities to conduct such transient experiments. In this experimental campaign, the gas lift system, acting as the external driving force, was kept on before the transient test being performed, as shown in Fig. 4(c). And the input power of FPS was kept at ~70 kW in the whole stage of test.

The development of LOFA from a gas lift enhanced convection mode is as shown in Fig. 4(a) and (d). When the gas lift is switched off, the LBE flow rate slows down very quickly due to the friction resistance of the loop. After about ~200 s，the flow rate decreases to a minimum value. The maximum temperature, appearing in approximate ~200 s, is about ~50 ℃ and ~15 ℃ higher than the temperature of initial and final state respectively during the start-up process. It is also clear that the highest temperature of this case has not exceeded the material restriction. The LBE flow rate of this test becomes stable after ~200 s, indicating the safety establishment of natural circulation.

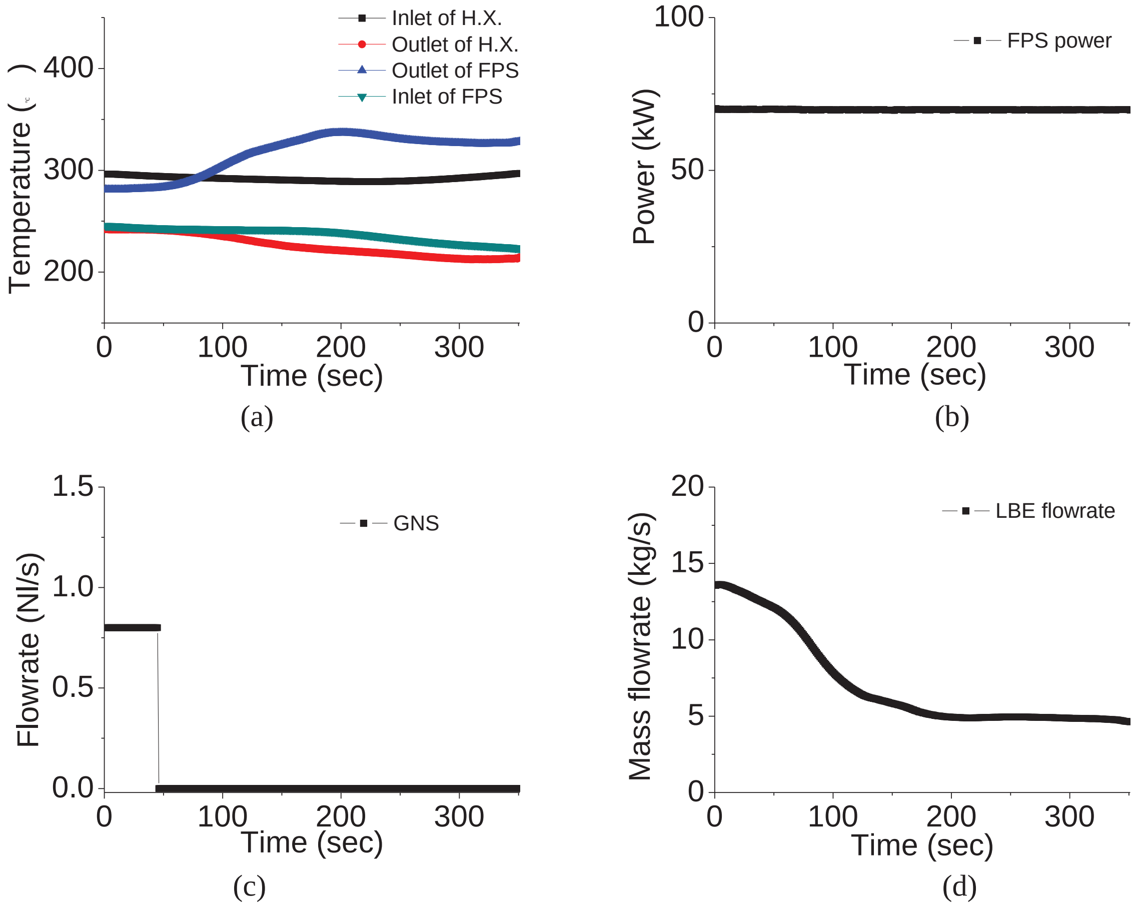

Fig. 4 Start-up of natural circulation from loss of gas lifting driving head, (a) temperature, (b) power input, (c) flow rate of argon gas, and (d) flow rate of LBE

4. Conclusion

The start-up of natural circulation and transient test from natural circulation to gas injection enhanced circulation was performed in KYLIN-II TH loop. Preliminary test on LOFA has also been carried out in this work. The natural circulation is easy to be established for the start-up process with less than a quarter of an hour under the operation parameters. The same manner is followed by the transient test from gas lift enhanced circulation to the foundation of natural circulation. The time duration of temperature transition state is less than 300 s, which is highly depended on the operation parameters of the experiment. The maximum LBE flow rate is reached up to 17 kg/s realized by gas lift. In order to achieve a comprehensive understanding of the thermal-hydraulic characteristics of LBE and support the validation and verification of CLEAR, much more experimental campaigns will be implemented in the near future.

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References

[1] C. Fazio, 2007. Handbook on lead-bismuth eutectic alloy and lead properties, materials compatibility, thermal-hydraulics and technologies. ISBN 978-92-64-99002-9. OECD/NEA (Organization for Economic Cooperation and Development/Nuclear Energy Association).

[2] Y. Wu, Y. Bai, Y. Song, et al., 2014. Conceptual Design of China Lead-based Research Reactor CLEAR-I. Nuclear Science and Engineering. 34(2), 201-208(in Chinese).

[3] 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.

[4] Y. Wu, Q. Huang, Y. Bai, S. Gao, Z. Zhu, Y. Chen, X. Lin, J. Liu, L. Zhu, G. Wang, L. Zhao, T. Zhou, H. Chen, FDS team, 2010. Preliminary Experimental Study on the Corrosion of Structural Steel in Liquid Lead Bismuth Loop. Chinese J. Nucl. Sci. Eng. 30, 238-243.

[5] Y. Wu, Q. Huang, Z. Zhu, et al., 2009. Progress in design and development of series liquid lithium-lead experimental loops in China. Nuclear Science and Engineering. 29(2), 161-169. (in Chinese)

[6] Y. Wu, FDS Team, 2006. Conceptual Design Activities of FDS Series Fusion Power Plants in China. Fusion Eng. Des. 81(23-24), 2713-2718.

[7] Y. Wu, FDS Team, 2008. Conceptual Design of the China Fusion Power Plant FDS-II. Fusion Eng. Des. 83(10-12), 1683-1689.

[8] Y. Wu, S. Zheng, X. Zhu, W. Wang, H. Wang, S. Liu, Y. Bai, H. Chen, L. Hu, M. Chen, Q. Huang, D. Huang, S. Zhang, J. Li, D. Chu, J. Jiang, Y. Song, FDS Team, 2006. Conceptual Design of the Fusion-Driven Subcritical System FDS-I. Fusion Eng. Des. 81, Part B, 1305-1311.

[9] Y. Wu, Q. Huang, Z. Zhu, et al., 2012. R&D of Dragon series lithium-lead loops for material and blanket technology testing. Fusion Eng. Des. 62-1, 272-275.

[10] Y. Wu, FDS Team, 2007. Conceptual Design and Testing Strategy of a Dual Functional Lithium-Lead Test Blanket Module in ITER and EAST. Nucl. Fusion. 47(11), 1533-1539.

[11] Q. Huang, S. Gao, Z. Zhu, M. Zhang, Y. Song, C. Li, Y. Chen, X. Ling, X. Zhou, FDS Team, 2009. Progress in Compatibility Experiments on Lithium-Lead with Candidate Structural Materials for Fusion in China. Fusion Eng. Des. 84, 242-246.

[12] Q. Huang, J. Li, Y. Chen, 2004. Study of Irradiation Effects in China Low Activation Martensitic Steel CLAM. J. Nucl. Mater. 329, 268-272.

[13] W. Ma, E. Bubelis, A. Karbojian, et al., 2006. Transient experiments from the thermal-hydraulic ADS lead bismuth loop (TALL) and comparative TRAC/AAA analysis. Nuclear engineering and design, 236(13), 1422-1444.

[14] W. Ma, A. Karbojian, B. R. Sehgal, 2007. Experimental Study on Natural Circulation and its Stability in a Heavy Liquid Metal Loop. Nucl. Eng. Des. 237, 1838-1847.

[15] J. H. Choa, A. Batta, 2011. Benchmarking of Thermal Hydraulic Loop Models for Lead-Alloy Cooled Advanced Nuclear Energy System (LACANES), Phase-I: Isothermal Steady State Forced Convection. J. Nucl. Mater. 415, 404-414.

[16] M. Tarantino, S. De Grandis, G. Benamati, et al., 2008. Natural circulation in a liquid metal one-dimensional loop. Journal of Nuclear Materials, 376(3), 409-414.

[17] A. Borgohain, B. K. Jaiswal, N. K. Maheshwari, et al., 2011. Natural circulation studies in a lead bismuth eutectic loop. Progress in nuclear energy, 53(4), 308-319.

[18] W. Ambrosini, G. Forasassi, N. Forgione, F. Oriolo, and M. Tarantino, 2005. Experimental study on combined natural and gas-injection enhanced circulation," Nucl. Eng. Des., vol. 235, no. 10-12, p. 1179–1188.