Performance test of electromagnetic pump on heavy liquid metal in PREKY-I facility

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Abstract: Pump is a key sub-system which drives the heavy liquid metal circulation in experimental loops. In the paper, the hydraulic and mechanical performances of an electromagnetic pump (EMP) were tested in the liquid metal test facility named PREKY-I. The test results showed that the EMP worked at good state when the working current was up to 170 ampere. In this condition, the flow rate was 5m³/h, and pressure head 7.5bar, when the outlet temperature was kept at 380°C during the test. The performance was close to the expected design parameters. The EMP had run continuously for 200 hours with stable performance. From the test results, the EMP could be used in KYLIN-II loop, which is the upgrade liquid metal test loop of PREKY-I.

1. Introduction

Fusion and fission energy are the important ways recognized so far to solve the energy crisis problems [1-7]. Fusion reactor liquid lithium lead blanket, because of its inherent characteristics and advantages, is widely recognized internationally as one of the fusion power cladding designs with most promising future [8-17]. Lead-based (lead, lead-bismuth, etc.) reactor, because of its good neutronics, thermal hydraulic and security features, has become one of the important options of the fourth generation advanced nuclear energy systems and one of the main reactor candidates for Accelerator Driven-subcritical Systems (ADS) [18-21].

KYLIN-II is a liquid lead-bismuth experimental loop. It is the important platforms to investigate the key technologies of liquid metal reactors. Pump is a key sub-system which drives the heavy liquid metal circulation in experimental loops. The three-phase cylindrical linear inductor ElectroMagnetic Pump (EMP) is chosen for the liquid metal experimental loop circulation. It has the advantages of absence of moving parts, low noise and vibration level, simplicity of flowrate regulation, easy maintenance and no leakage etc. [22-28]

The EMP for the liquid metal has been designed, produced and tested during the recent two years in the liquid Pb-Bi test facility named PREKY-I. Development of an EMP for operation under the liquid metal loop conditions is a difficult task because of the following reasons.

(1) The EMP is submerged in the lead-bismuth, whose temperature fluctuates depending on the proton beam trip in the range 300-400°C. A thin-walled austenitic steel 316L protective hull liable to
endure continuous thermal fatigue cycles is necessary to protect the EMP and flowmeters from direct contact with the Pb-Bi;

(2) The volume of the pump arrangement is very limited. Therefore, loads of electrical and magnetic circuits of the pumps leads to intensive heat release. Minimize the heat release and increase the thermal resistance between the pump inductors and the protective hull (minimal gaps filled with thermal conductive materials, etc.,) are ways for better cooling.

(3) Operating conditions of the EMP (high temperature, irradiation, magnetic field, mechanical stresses) impose strong restrictions to the structural material.

The problem required the development of an original procedure for the EMP calculation in order to optimize the design and technology as well as a comprehensive testing of the system.

2. Design of the EMP

2.1. Working principle of EMP
As shown in Figure 1, EMP consists a pump groove and two deflectors consisting of the excitation coil 1, the outer core 2, the inner core 3, and two guide grooves 4. Three-phase winding in the excitation coil annular groove produces traveling-wave electromagnetic field moving around the axis of the cylinder in the air gap. This magnetic field causes the induced current of in the liquid metal within the pump groove. Interaction between the induced current and the magnetic field generate pressure gradient and then liquid metal flow.

![Figure 1. The schematic diagram of EMP working principle](image)

2.2. Design parameters
According KYLIN-II experimental loop design parameters, the main input and design parameters of the EMP is given in Table 1 below:

| Table 1. The main parameters of EMP |
|-----------------------------------|
| Parameters                        | Values |
| Nominal Flow Rate, m³/h           | 5      |
| Pressure, MPa                     | 0.7    |
| Nominal Operating Temperature, °C | 300    |
| Line voltage, V                   | 370    |
| Line current, A                   | 140    |
| Input power, kW                   | 80     |
| Pb-Bi joule heat, kW              | 30     |
| Winding joule heat, kW            | 2      |
The PREKY-I loop was the pre-study platform of the large high-temperature liquid Pb-Bi loop KYLIN. It was applied to explore the key equipment performance (such as EMP, mechanical pump, heat exchanger etc.,) in liquid Pb-Bi loop, the reliability of measuring instruments and thermal hydraulic measurement technology in Pb-Bi environment. It could provide important experimental data for performance analysis and structural optimization of related measurement instrumentations, including temperature instruments, flow meter, liquid level meter and differential pressure transducers.

Figure 1. Scheme of PREKY-I

The scheme of PREKY-I was shown in Figure 2. The experimental loop PREKY-I was an isothermal, devious forced Pb-Bi loop, which was composed of main vessel (storage vessel and calibration vessel), EMP, flow meter, temperature sensor, level meter, pressure transducer, liquid metal valves, heaters, heat exchanger, data acquisition and control unit etc.. The main design parameters characterizing the facility were listed in Table 2.

Table 1. Main parameters of PREKY-I

| Name                      | Parameters     |
|---------------------------|----------------|
| Working temperature       | 200~500°C      |
| Working pressure          | 0.5~1.0MPa     |
| Velocity                  | 0.5~2.0m/s     |
| Size of flow channel      | Φ42(inner)×5mm  |
| Pb-Bi capacity            | ~1.0t          |

Several main testing sections were included in the loop under a wide range of operating conditions: (1) flow meter performance test; (2) the temperature comparative experiments both pipe and Pb-Bi; (3) equipment (such as EMP, mechanical pump, heat exchanger etc.,) hydraulic and mechanical performances test; (4) pressure drop testing of valve at different flow rates. Meanwhile, more useful technologies focused on the PREKY itself would provide technical supports for the construction and experiments of KYLIN.

4. Experimental results and discussion

Before test, the PREKY-I experimental needs to be preheated and then filled with liquid Pb-Bi. Flowmeter, thermocouple and pressure sensors which for test using for EMP had been calibrated, and their precisions met the test requirements. The arrangement of PREKY-I test rig are shown in Figure 3.
4.1. Static test
Static test of EMP is to obtain its static pressures with different phase currents. Firstly, the calibration vessel inlet valve (V2) should be turn off before the EMP was started. Secondly, start the EMP, and adjust the pump input current. Record the EMP inlet pressure (P1) and outlet pressure (P2) before each adjust the pump input current, and the EMP pressure head \(H = P2 - P1\). EMP currents relationship with the pressure heads are shown in Figure 4.

From Figure 4, the EMP head with phase current is linearly proportional relationship. With the increase of phase current, the pump head is gradually increased. The greater the phase current, the greater amplitude of pump head increases. The maximum pressure head of EMP is 9.06bar when the working current was up to 170A. When EMP working current is more than 170A, the pump excitation coil temperature is over 200°C, which exceeding the maximum limit of design temperature.

4.2. Dynamic test
Dynamic test is various hydraulic performances test of the EMP, including the relationship of current, pressure head, flow rate and efficiency, in dynamic testing, calibration tube inlet valve is fully opened. There are two ways to adjust the dynamic test. Firstly, with the EMP inlet valve fully opened, regulate EMP current to get various EMP hydraulic performances; Secondly, with the current of solenoid pump fixed at a certain value, get the hydraulic performance of the EMP by adjusting the EMP inlet valve opening. When the EMP current exceeds 170A, or EMP outlet temperature exceeds 400°C, the test should be stopped.

The following figure 5 (a) is relation curve between static and dynamic pressure head of EMP at different current conditions. From figure 5(a), with current of EMP increases, static and dynamic pressure head both increase. Dynamic pressure head is smaller than the static pressure head, because in the dynamic case, the frictional resistance within device flow path needs to be overcome. When
current is 170A, static and dynamic pressure head both reached the maximum value, with static pressure head at 9.06 bar, dynamic pressure head at 7.50 bar. As the current increases, the growth rate of the dynamic pressure is less than that of the static pressure head. Definition of difference between static and dynamic pressure head under the same current situation is $\Delta P$, the following figure 5(b) shown, as variation curve of $\Delta P$ at different currents. As figure 5(b) shows, as the current increases, $\Delta P$ gradually increases. The main reason is that, as the current increases, the driving ability of the electromagnetic pump increases. Liquid Pb-Bi flow rate increases in the loop, and circuit pressure loss increases. According to the pressure loss equation: 

$$\Delta P_h = \frac{1}{2} \rho \times v^2,$$

(Wherein, $\rho$- density of liquid Pb-Bi, $v$- average flow rate of liquid Pb-Bi in the loop) as can be seen, the loop pressure loss and flow rate is proportional to the quadratic relationship. The greater the flow rate, the greater the pressure loss in the loop, and the greater the magnitude of the dynamic pressure head of electromagnetic pump decreases.

![Figure 5. The pressure head (a) and $\Delta P$(b) curves in static and dynamic test](image)

Figure 6 is performance curve of pressure head of EMP and flow rate under different current conditions. As Figure 6 shows, with the increase of the current, the flow and the pressure head gradually increased; the amplitude of flow growth rate is greater than pressure head growth rate at the beginning. However, as the current increases, the pressure head growth rate is greater than the flow growth rate. When current is 170A, the dynamic pressure head is 8.82 bar, corresponding to the flow rate 5.21 m$^3$/h.

![Figure 6. The flow and pressure head curves under different currents](image)

Figure 7 is performance curve between the flow rate of EMP and efficiency under different current conditions. With increase of currents, flow rate and the efficiency gradually increase.
Figure 7. The flow and efficiency curves under different currents

Figure 8 is the relationship between the EMP flow and pressure head which is obtained by adjusting the electromagnetic pump inlet valve opening at fixed electromagnetic pump current. Since the flow is relatively small when the EMP current is <100A, four typical groups of current, respectively 100A, 120A, 150A and 170A, are tested for comparison.

As can be seen from Figure 8, when EMP current is fixed, as the EMP flow rate increases, the pressure head gradually decreases. The main reason is as follows: (1) Under certain current, it’s the heat loss fixes. When flow is small, the liquid Pb-Bi temperature within the EMP and the pump coil temperature quickly rise, the performance of the EMP reduced. With increase of flow, temperature of liquid Pb-Bi is gradually reduced, and the temperature of the coil is reduced, thereby the performance of the solenoid pump improves. (2) For EMP in the constant current case, as flow increases, pressure head only increases slightly, which is different from mechanical pump whose pressure head decreased rapidly.

Figure 8. The flow and head curves under different currents

EMP runs on PREKY-I test device for about 200h. During running time various hydraulic performance of the electromagnetic pump is tested. According to test results, the hydraulic performances of EMP are to meet the pre-designed requirements. As is shown in Figure 9, the EMP performance is relatively stable in the entire run-time.
5. Conclusion
In this paper, the EMP performance was tested in the LBE experimental loop. From the test results the following conclusions could be drawn.

(1) The designed EMP reaches a maximum flow of 5m³/h at 170A, maximum pressure head of 7.50bar, which meets the pre-design requirements;

(2) As EMP current increases, the flow rate increases, the circuit pressure loss increases, difference between the dynamic pressure of the pump head and the static pressure head becomes larger;

(3) In the same current, the effect of change of the EMP flow rate on the pressure head is relatively small, mainly because as the flow rate reduces, the pump temperature rises, and the performance degrades.

6. References

[1] Alejaldre C, Marco F, Finzi U et al. 2005 Status report on fusion research. *Nucl Fusion*, 45(10A):1-28.

[2] Ilhli T, Basu T, Giancarli L et al. 2008 Review of blanket designs for advanced fusion reactors. *Fusion Eng. Des*, 83(7-9):912-919.

[3] Wu Y, FDS Team 2006 Conceptual design activities of FDS series fusion power plants in China, *Fusion Eng. Des*, 81:2713-2718.

[4] Wu Y, Zheng S, Zhu X et al. 2006 Conceptual design of the fusion-driven subcritical system FDS-I. *Fusion Eng. Des*, 81, Part B: 1305-1311.

[5] Wu Y, FDS Team. 2008 Conceptual design of the China fusion power plant FDS-II. *Fusion Eng. Des*, 83:1683-1689.

[6] Wu Y, Jiang J, Wang M et al. 2011 A fusion-driven subcritical system concept based on viable technologies, *Nucl. Fusion*, 51 (10) 103036.

[7] Wang M, Huang H, Lian C et al. 2015 Conceptual design of lead cooled reactor for hydrogen production. *Int. J. Hydrogen Energy*, doi: 2015.10.1016/j.ijhydene.04.009.

[8] Antipenkov A, Butko A, Chepovski A et al. 1991 Fusion reactor blanket with Li17-Pb83 eutectic. *Fusion Eng. Des*, 14(3-4):427-444.

[9] Sardain P, Maisonnier D, Pac L et al. 2006 The European power plant conceptual study: helium-cooled lithium-lead reactor concept. *Fusion Eng. Des*, 81:2673-2678.

[10] Wu Y 2007 Design status and development strategy of China liquid lithium-lead blankets and related material technology. *Nucl Mater*, 367:1410-1415.

[11] Wu Y, 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.

[12] Wu Y, FDS Team. 2007 Design analysis of the China dual-functional lithium lead (DFLL) Test blanket module in ITER. *Fusion Eng. Des*, 82:1893-1903.
[13] Kumar E, Danan I C, Sandeep I et al. 2008 Preliminary design of Indian test blanket module for ITER. *Fusion Eng. Des.*, **83**:1169-1172.

[14] Morely N, Katoh Y, Malang S et al. 2008 Recent research and development for the dual-coolant blanket concept in the US. *Fusion Eng. Des.*, **83**:920-927.

[15] Wu Y, FDS Team 2009 Fusion-based hydrogen production reactor and its material selection. *Nucl Mater*, 386-388:122-126.

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

[17] Zhu Z, Huang Q, Gao S et al. 2011 Design analysis of DRAGON-IV Pb-Bi loop. *Fusion Eng. Des.*, **86**: 2666-2669.

[18] Wu Y, Bai Y, Song Y et al. 2014 Conceptual design of China lead-based research reactor for CLEAR-I. Nuclear Science and Engineering, **Vol. 34, No. 2**:201-208.

[19] Wang M, Huang H, Lian C et al. 2015 Conceptual design of lead cooled reactor for hydrogen production. *Int. J. Hydrogen production. Int. J. Hydrogen Energy*, doi:10.1016/j.ijhydene.2015.04.009.

[20] Wang M, Lian C, Li Y et al. 2015 Preliminary conceptual design of a lead-bismuth cooled small reactor (CLEAR-SR). *Int. J. Hydrogen Energy*, doi:10.1016/j.ijhydene.2015.03.097.

[21] Wu Y, Wang M, Huang Q et al. 2015 Development status and prospects of lead-based reactors. Nuclear Science and Engineering, **Vol.35 No.2**:213-221.

[22] Hideo A, Igor R, Gennady V et al. 2004 Magneto hydrodynamic instability in annular linear induction pump Part I. Experiment and numerical analysis. *Nucl Eng. Des.*, **227**:9-50.

[23] Hideo A, Igor R, Gennady V et al. 2006 Magneto hydrodynamic instability in annular linear induction pump Part II. Suppression of instability by phase shift. *Nucl Eng. Des.*, **236**,965-974.

[24] Ivanov S, Platacis E, Flerov A et al. 2006 Experience of calculation, design, fabrication and testing of the electromagnetic pump system for the megapie target. *Magneto hydrodynamics, Vol. 42, No. 2* - 3, pp. 275 - 280.

[25] Ivanov S, Flerov A 2009 Electromagnetic pump for a liquid metal spallation target: Calculation diagnostics, reliability. *Magneto hydrodynamics, Vol. 45, No.2*, pp.239-244.

[26] Dementjev S, Ivanov S, Wohlmuther M 2010 On a concept of electromagnetic pump for the liquid metal target for routine operation in the swish spallation neutron source. *Magneto hydrodynamics, Vol. 46, No. 1*, pp. 59 - 67.

[27] Prashant S, Sivakumar L, Rajendra R et al. 2011 Design, development and testing of a large capacity annular linear induction pump. *Science Direct, 7*:621-629.

[28] Reyoug H, Bum Y 2012 MHD stability analysis of a liquid sodium flow at the annular gap of an EM pump. *Annals of Nuclear Energy, 43*:8-12.

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