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Construction and initial operation of MHD PbLi facility at UCLA

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HIGHLIGHTS

- New MHD PbLi loop has been constructed and tested at UCLA.
- Pressure diagnostics system has been developed and successfully tested.
- Ultrasound Doppler velocimeter is tested as velocity diagnostics.
- Experiments on pressure drop reduction have been performed.
- Experiments on MHD flow in a duct with SiC flow channel insert are underway.

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ABSTRACT

A magnetohydrodynamic flow facility MaPLE (Magnetohydrodynamic PbLi Experiment) that utilizes molten eutectic alloy lead–lithium (PbLi) as working fluid has been constructed and tested at University of California, Los Angeles. The loop operation parameters are: maximum magnetic field 1.8 T, PbLi temperature up to 350 °C, maximum PbLi flow rate with/without a magnetic field 15/50 l/min, maximum pressure head 0.15 MPa. The paper describes the loop itself and its major components, basic operation procedures, experience of handling PbLi, initial loop testing, flow diagnostics and current and near-future experiments. The obtained test results of the loop and its components have demonstrated that the new facility is fully functioning and ready for experimental studies of magnetohydrodynamic, heat and mass transfer phenomena in PbLi flows and also can be used in mock up testing in conditions relevant to fusion applications.

1. Introduction

Because of its lower chemical reactivity with air, water and concrete compared to pure lithium, eutectic alloy lead–lithium PbLi (originally Pb17Li, and more recently Pb16Li) has been proposed as a tritium breeder and coolant fluid in several liquid metal blanket concepts for future fusion power plants, including self-cooled lead–lithium (SCLL) [1], dual-coolant lead–lithium (DCLL) [2], helium-cooled lead–lithium (HCLL) [3], and water-cooled lead–lithium (WCLL) [4] blankets. Starting from the 1980s, various studies, both experimental and theoretical, were performed focusing on various aspects of PbLi flows and associated heat and mass transfer phenomena with and without a magnetic field. For the last two decades of the 20th century, many experimental facilities utilizing PbLi as a working fluid were constructed and successfully operated all over the world, some of which are still in use. Among them are purely hydrodynamic loops (no magnetic field): PICOLO at KIT (former FZK) in Germany [5], ANAPURNA at CEA, France [6], a loop at the ENEA Research Center in Brasimone, Italy [7], and a loop at the Institute of Advanced Energy, Kyoto University, Japan [8]. There are only a few magnetohydrodynamic (MHD) PbLi facilities currently in operation: a loop at the Institute of Physics in Latvia [9], several MHD PbLi loops DRAGON I–IV at the Institute of Plasma Physics of the Chinese Academy of Sciences [10–12], and the ELLI loop at the Korea Atomic Energy Research Institute [13,14].

Using these facilities, many studies were conducted over the last two decades, focusing on various aspects of PbLi flows with and without a magnetic field, alloy manufacturing, its handling and interaction of PbLi with structural and functional materials. Among them are: compatibility and corrosion behavior of candidate steels for fusion reactor blankets [4,9,10,15–25], mechanical properties of structural materials exposed to PbLi flows [26], physical–chemical processes associated with the extended use of PbLi in blanket-relevant conditions [27], chemical interaction between liquid PbLi with oxygen-containing gases and water [28–30], online monitoring of liquid PbLi composition [31,32], PbLi impurity

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control and removal [33], and compatibility of silicon carbide (SiC) with high-temperature alloy [34]. Although a good understanding of PbLi behavior in blanket relevant conditions has been achieved, many practical problems vital to liquid metal blankets still remain open; thus, further studies are required.

In particular, many unresolved issues still remain in regards to potential use of SiC (either composite or foam) as a functional blanket material for electrical and thermal insulation or even as a structural material in some innovative blanket concepts. For example, in the DCLL blanket, which is currently the main US choice for further utilization in FNSF and DEMO reactors, a SiC flow channel insert (FCI) is proposed to decouple high-temperature PbLi from the ferritic steel wall, both thermally and electrically [35,36]. Although many blanket design studies [35–37] rely on good insulating properties of the SiC FCI, its effectiveness as electrical and thermal insulator in the flowing PbLi conditions has not been demonstrated yet. Another concern, which needs to be resolved, is corrosion behavior of reduced activation ferritic/martensitic (RAFM) steels exposed to a molten PbLi flow in the presence of a strong magnetic field followed by transport and deposition of corrosion products in the "cold" leg of the loop. The effect of a magnetic field on the corrosion rate seems to be strong, resulting in some cases in doubling of the mass loss [17,38], but the physical mechanisms associated with such a process are not well understood yet. Moreover, the existing experimental databases on corrosion are not full enough to extrapolate to blanket conditions. Also, further experimental progress in the case of PbLi flows can be seriously limited by lack of flow diagnostics tools, which need to be developed and tested to take into account special effects not pertinent to ordinary fluids or room-temperature liquid metals, due to high-temperature effects, presence of a magnetic field and high PbLi chemical reactivity.

The prime objective of the newly constructed (2011) MHD PbLi flow loop at University of California, Los Angeles (UCLA) called MaPLE (Magnetohydrodynamic PbLi Experiment) is to address the abovementioned issues via a series of experiments, first of all to take into account the effect of a magnetic field. Some results of the first runs of the loop were briefly reported in a conference paper [39] to highlight research progress achieved in the course of the so-called TITAN project between the US and Japan (see Ref. [39]). The present article introduces more details about the facility, its operation and flow diagnostics and also introduces details of current experiments and near-term experimental plans.

2. MHD PbLi loop at UCLA. Major construction steps and current state

The construction of the loop was started in 2010 under the base fusion program in the US and partly under the Task 1–3 "Flow Control and Thermofluid Modeling" of the US–Japan "TITAN" program. This program has been focusing on experimental studies and computer modeling of MHD flows and heat and mass transfer of electrically conducting fluids under conditions relevant to fusion blankets (see [39] and Refs. to [39]). A first working version of the loop was finished in July 2011. At that time the loop was run for 3 weeks continuously without a magnetic field. After that the loop was upgraded twice such that the magnetic field capabilities were added and the PbLi inventory was increased from 70 to 200 kg. Also two test-sections, a circular pipe and a rectangular duct, were fabricated and consecutively installed on the loop. The fourth version of the PbLi loop has also been designed for further corrosion studies at elevated temperatures up to 550 °C but these modifications have not been implemented yet.

The current (third) version of the facility is sketched in Fig. 1 and a photo, including a bare rectangular duct test-section, is shown in Fig. 2. The main components of this facility include a flow circuit, electromagnetic (EM) pump, EM flow meter, electromagnet and a glove box. The flow circuit, including a melting tank (also serves as a supply/drain tank) and pipelines, are made of stainless steel SUS304. The maximum inventory of PbLi in the loop is now about 200 kg. The style V EM conduction pump is made by Creative Engineers, Inc., USA. The pump tube is made of stainless steel SUS316. The loop is currently operated at 350 °C maximum as required by the temperature limit of the pump. The magnetic field is created by a water-cooled electromagnet with the maximum magnetic field of 1.8 T. The magnetic field is uniform within a space of 80 cm (axial) × 15 cm (horizontal) × 15 cm (vertical). The whole loop, except for the magnet, sits on a steel catch pan, which in turn is put on a four-wheel carrier, which can be moved forward or backward. This allows for all the maintenance work on the loop components to be done outside the magnet. The melting tank is heated by band-heaters and the piping and test section by rope-heaters. There are eight independent, individually controlled heater sections. The tubing part inside the EM pump is heated by its built-in heater and also due to parasitic Joule heating when the conduction pump is on. All loop components are thermally insulated.

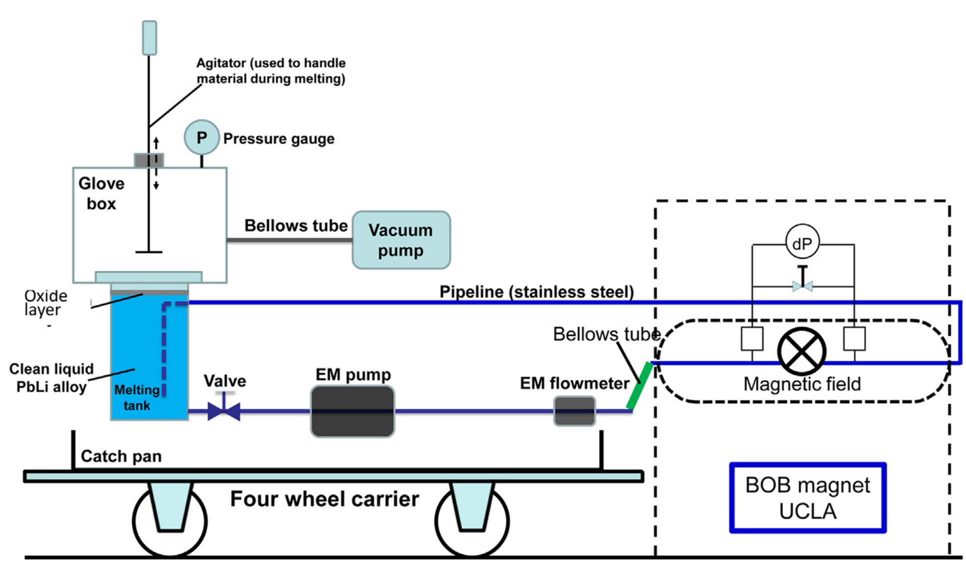

Fig. 1. Schematic diagram of the MHD PbLi loop at UCLA. Magnetic field is perpendicular to the plane of the sketch.

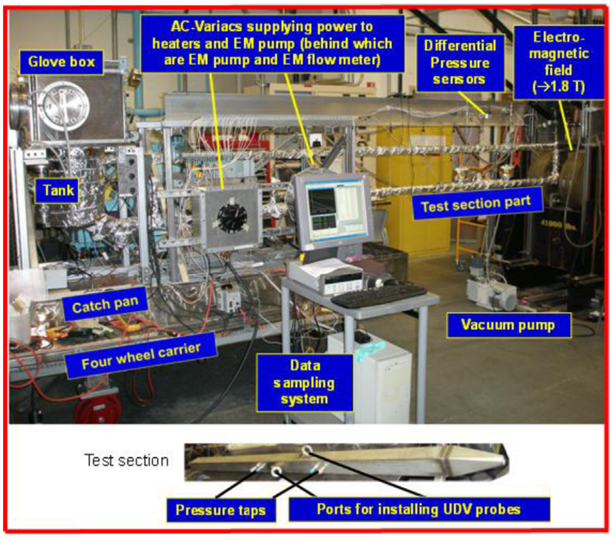

Fig. 2. Photograph of the MHD PbLi loop at UCLA, including the test-section.

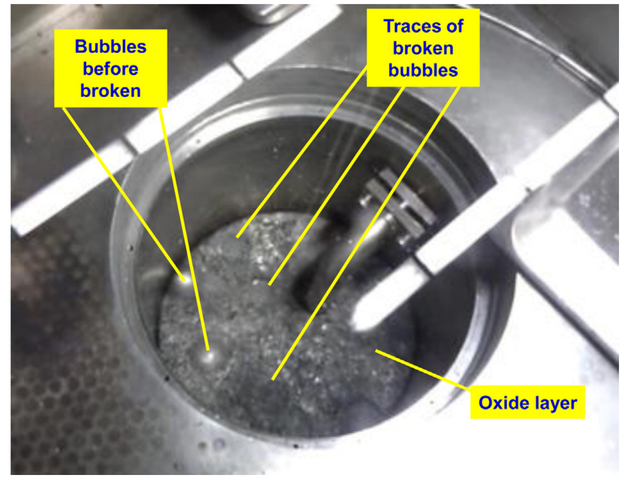

Fig. 3. Photograph showing emergence of gas bubbles at liquid surface during melting of PbLi ingots.

The glove box is designed to allow for a connection of a vacuum pump and/or a purification unit for circulation of high-purity argon gas through the loop in the initial loop operation stages to remove air and moisture.

3. Major loop operation procedures

3.1. Melting PbLi and oxygen removal

By now a detailed database of thermophysical properties of PbLi has been established [40] and many practical issues of handling the alloy, including its interaction with air and water, have been considered (see, e.g., Ref. [41]). The PbLi alloy used at present in MaPLE is supplied by Atlantic Metals & Alloys, Inc., USA in the form of 2-kg ingots. Based on information from the supplier, the manufacturing procedure starts with melting pure lead, which is brought to a temperature of about 380 °C, and then pure lithium is plunged into it and the melt is stirred to homogenize. In doing so, some minor composition adjustments are made to provide the desired content of the main components, and then the alloy is poured into molds. There is a release agent on the molds to prevent metal from sticking. Pouring the alloy in the molds is done in the air and thus significant air sorption is likely to occur. The alloy is nominally Pb17Li (17 atomic percent of Li), with the melting temperature of 235 °C, but some metallic impurities are present, which per the manufacture documentation comprise Ag, As, Bi, Cr, Fe, Mn, Si, Sn, Zn in small amounts varying from 2 to 150 wppm. The manufacturer has not provided any information about oxygen and nitrogen contents. However, independent XPS (X-ray photoelectron spectroscopy) analysis [42] has indicated that the bulk PbLi material contains oxygen in the free form as well as in the form of oxides Li_2O and PbO. Analysis of PbLi samples from another supplier also suggests significant amounts of free oxygen in the ingots [42,43].

Prior to running the EM pump, the PbLi melt is prepared by melting either the original ingots or, in some cases, of already used solidified alloy. When using the original ingots, the melting procedure is carried out in several steps inside the melting tank connected with a glove box as shown in Fig. 1. After loading the ingots into the tank, the heating power of the heater elements wrapped around the tank is gradually increased to achieve a temperature in the material of about 200 °C; the PbLi material in the tank is still solid. At the same time, the air from the tank, the glove box and all other parts of the loop is evacuated using a vacuum pump. The vacuum pump is kept running and heating continues for about 12 h until steady vacuum characteristics are achieved. After that the valve at the bottom of the melting tank is shut and the heating power is further increased to the level when melting starts and the melt reaches the desired operation temperature of about 350 °C, while vacuum pumping is continued. The heating process should not be too fast; otherwise the tank can be damaged due to thermal expansion of PbLi. Once PbLi is molten, emergence of many gas bubbles at the surface of the melt, as shown in Fig. 3, always occurs, which indicates that the gas bubbles (presumably of oxygen) are formed in the bulk liquid and then migrate upwards under the action of Archimedes force. This outgassing process resembles bubble formation in boiling but bears no relation to it as boiling happens at much higher temperatures. When melting is finished, the glove box and the melting tank are filled with argon at the pressure of about 1 atm. At this point, pumping of the liquid metal through the loop can be started. However, in many cases, vacuum pumping is alternated in addition with argon pumping to remove as much oxygen as possible. In such cases, circulation of argon gas is performed through the external purification unit (MG 20G, MBraun) to remove oxygen from argon to the level of tens of ppm. In the end of this procedure, some amount of oxygen in the melt is still remaining, but its concentration is obviously much less compared to that in the original ingots as indicated through continuous oxygen monitoring by the oxygen probe (MB OX-SE-1, MBraun) mounted on top of the glove box.

When working with the alloy, the gas-sorption ability of PbLi in either solid or liquid state has been indirectly confirmed in several ways. As already noted, the intensive release of gas bubbles, when melting PbLi, suggests the presence of a significant amount of oxygen in the original ingots. In addition to oxygen, argon-sorption processes seem to occur when the ingots are fully molten. Normally, the oxygen-removal procedure (including vacuum- and argon-pumping stages) is repeated several times to make sure that the oxygen content is minimal. When argon is evacuated, one can still observe emergence of gas bubbles but at this stage the bubbles are comprised of absorbed argon. The gas-adsorption/absorption ability has also been indicated when the alloy is in the solid state at a constant temperature. In particular, when the ingots are put in the inert atmosphere and left there for a few hours, gradual pressure decrease in argon can be seen, most likely due to the gas-sorption processes.

Another physical–chemical phenomenon that deserves consideration is the production of large amounts of mud-like, gray-color impurities in the form of a surface layer of about 1 cm thick during

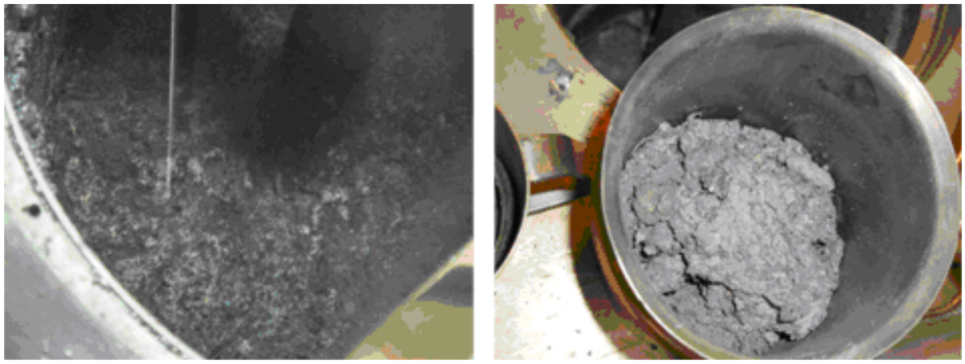

Fig. 4. Photographs showing (a) a layer of impurities on the surface of the PbLi alloy in the melting tank and (b) mud-like gray-color material removed from the surface when PbLi ingots are melted.

melting of the original ingots in the tank as demonstrated in Fig. 4. As spectral analysis shows, this layer is mostly made of various lead oxides with a melting temperature significantly higher than the alloy melting temperature and lighter than the pure alloy. Any significant presence of the gray material in other sections of the loop has not been detected as evidenced through visual testing of samples of solidified PbLi taken from various locations inside the loop, including connection pipes and the test article. These observations suggest that formation of impurities occurs mostly in the bulk liquid in the melting tank and then the impurities float up and remain at the free surface during all loop operations. Although it seems obvious that formation of impurities is mostly due to oxidation processes during melting, it is also possible that some impurities are formed earlier at the alloy manufacturing stage. Such impurities can include oxides, nitrides and even pieces of the anti-sticking agent.

To summarize, the procedure of melt preparation includes melting PbLi ingots and removal of oxygen and solid impurities. These consist of the following five steps.

(a) After putting PbLi ingots into melting tank, the whole loop is vacuum-pumped and pre-heated for about 12 h.
(b) While vacuum pumping is continued, electrical power of the heaters is gradually increased, until the PbLi ingots are all melted and the desired operation temperature of PbLi is achieved. During heating up and melting, the gases (mostly oxygen) contained in the original ingots are continuously released and pumped out via simultaneous vacuum pumping.
(c) Still under continuous vacuum pumping, the bulk of molten PbLi in the tank is agitated using a stirrer rod inserted through the upper cover of the glove-box in order to intensify gas release. This procedure can be repeated several times.
(d) As long as vacuum-pumping is continued, the impurities at the surface of the melt are periodically scraped with a spoon and removed using the glove box. If bubble formation is still visible and formation of the impurity layer at the surface continues, steps (c) and (d) are repeated.
(e) As soon as the gas release ceases, the melting tank and the glove box are filled with argon gas pressurized to 1 atm. At this point liquid metal pumping can be started. For more effective gas removal, however, further degassing can be performed via argon pumping, using a purification unit.

3.2. *Pumping PbLi*

To pump PbLi, a conduction-type EM series V pump manufactured by Creative Engineers, Inc., USA is used. The pump was originally calibrated by the manufacturer using sodium potassium eutectic alloy, NaK. The NaK data were then used by the manufacturer to project the obtained pump curve to the PbLi flow conditions using the electrical conductivity ratio between NaK and PbLi. It is thus necessary to build the actual pump curve using PbLi before starting experiments. The first run of PbLi flow in the loop was performed without a magnetic field. At that time the pump was continuously run for 4 days at fixed pump voltage and current at a temperature around 280 °C to assure good wettability of the internal pump pipe. Another run continued for 2 weeks; both runs did not reveal any changes in the measured flow rate during the tests, suggesting good wettability conditions. In these two runs, the air in the melting tank was evacuated but the tank was not filled with argon. In the following test runs, the melt was pumped in conditions when the melting tank was filled with pressurized argon. In these tests, the flow rate was measured at various argon pressures in the tank from 100 to 900 Torr for 3 temperatures of PbLi as shown in Fig. 5.

To build the characteristic curve of the EM pump, a special series of runs was performed with a magnetic field, which was varied from zero to the maximum one, such that the hydraulic resistance to the flow was significantly increased due to MHD effects. Fig. 6 shows the obtained pump curve (the developed pressure head as a function of the flow rate) versus the manufacturer's predictions. The pressure head was obtained by calculating and summing up all local hydraulic resistances along the flow path. As expected, the total pressure drop in the loop is mostly due to MHD effects associated with the liquid metal flow through the magnet. Good accuracy of such predictions was confirmed later by direct pressure drop measurements. The linearity of the plotted characteristic curve is excellent, though there is a discrepancy between the measured and estimated curves. To major degree this difference can be attributed to a higher pump voltage (240 V) used by the pump manufacturer compared to the present measurements (230 V).

From the pump performance tests, it has been confirmed that the maximum flow rate of 15 l/min can be achieved when a big

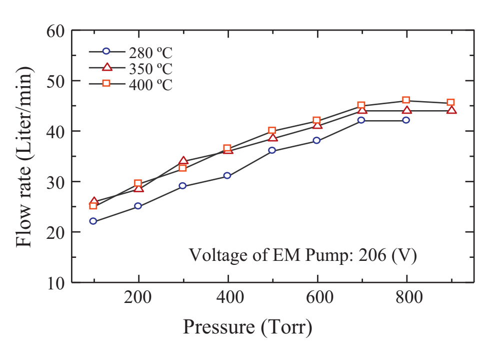

Fig. 5. Flow rate of PbLi as a function of temperature and argon-gas pressure.

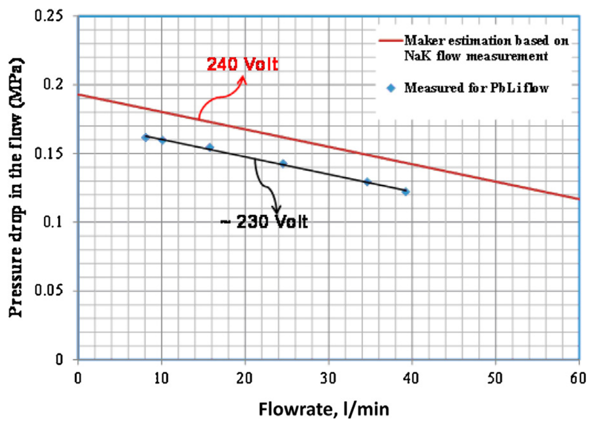

Fig. 6. The characteristic curve measured for the reference EM conduction pump.

stainless steel test section (2 m by 8 cm by 8 cm) with a wall thickness up to 3 mm is used while the magnetic field is maximal at 1.8 T. The estimated pressure drop in such a case does not exceed 0.15 MPa. It can be concluded that the facility has sufficient pumping capacity to perform various MHD experiments related to the DCLL blanket concept (see Section 5) such that a hydrodynamic Reynolds number of about 35,000 can be achieved. Significantly higher flow rates (up to 50 l/min), and higher Reynolds numbers (up to 110,000) can be achieved in a weaker magnetic field or when a magnetic field is not applied.

3.3. Draining and cleaning the loop

In the end of the operation cycle, which typically takes about 3 weeks, the liquid metal is drained back into the melting tank by gravity dumping and/or by argon gas pressure. After that the loop is cleaned. Complete drainage usually cannot be attained. First, there are some remains of the solidified liquid metal in the pipes, valves, etc. Second, at some small cross-sectional area locations in the loop, such as pressure sensor ports, a gray-color porous material was found after draining the loop (Fig. 7). This might be related to some solid impurities in the PbLi, such as already mentioned oxide particles and also lead–lithium intermetallic compounds, which have melting temperatures significantly higher than the loop operation temperature and densities different from the alloy itself. As a result, the impurities can flow with the alloy and accumulate in the "pockets" or "dead zones" in the loop, where the fluid is stagnant or forms recirculation zones. Third, there are a lot of impurities emerging on the surface of molten PbLi in the melting tank, which form residuals on the tank walls after complete removal of PbLi from the loop for disposal. Various cleaning procedures have been followed, and a typical one is described here.

Component sections are heated above the melting point of the liquid metal and drained as thoroughly as possible to reduce the amount of metal to be reacted with a special liquid solution. The

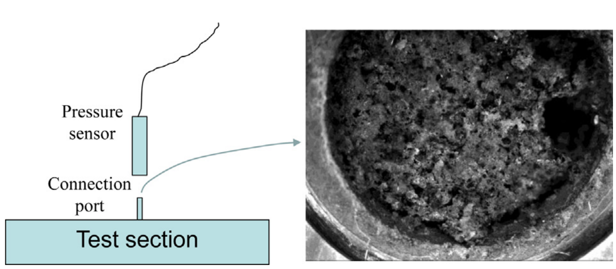

Fig. 7. Porous material: (right) found in the thin tubes; (left) connecting the pressure sensor with the test section after draining the loop.

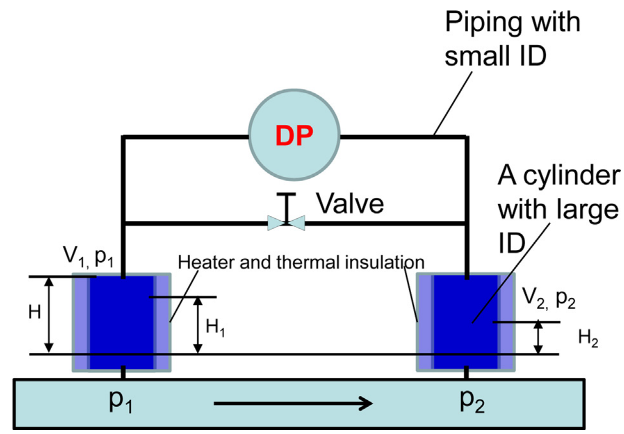

Fig. 8. Schematic of pressure difference measurement setup for high temperature liquid PbLi flow using a conventional gas flow DP sensor.

solution is made of equal volume measures of hydrogen peroxide, ethyl alcohol and acetic acid. This solution can chemically react with pure lead and lithium, and with the alloy itself and oxides. Since the reactions are all exothermic with generation of vapors, a gas-exhaust port must be setup in the loop components to be cleaned up. If the amount of solid residuals is large, the cleaning solution needs to be applied several times repeatedly until no reaction (indicated by no generation of bubbles and heat) happens any more. After applying the cleaning solution, hot water is used to flush out the reaction products. With this procedure, the remaining materials can be cleaned up effectively.

4. Development of PbLi flow diagnostics

4.1. Pressure measurements

Flow diagnostics in hot-temperature PbLi, including pressure or differential pressure (DP) measurements, is significantly limited because of the aggressive high-temperature environment, in particular because of corrosion. For example, commercially available high-temperature SERIES 35 X HTC pressure sensor manufactured by KELLER, Switzerland has an upper temperature limit of 300 °C, which is still lower than the present MaPLE operation temperature. Higher temperatures are not allowed since direct contact of PbLi with the diaphragm of a transducer will cause damage to the sensor.

An indirect approach has then been proposed for measurements of the differential pressure by utilizing a normal gas-pressure DP transducer (DP 15 transducer by Validyne Engineering Corp.). The key principle of this approach is illustrated in Fig. 8. The piping connection between the DP sensor and the flow passage is similar to that normally used, except for the setup of two large diameter cylinders filled with argon, which separates the membrane from the liquid metal. Before pumping PbLi, the whole loop, including the connecting thin tubes of the pressure measurement system, are filled with argon. When liquid PbLi flows in the loop, it also partially fills the cylinders causing pressurization of the argon. Then, the measured pressure difference between the two cylinders is fully equivalent to that in the liquid metal flow. In the proposed setup, the gas cylinders have the inner diameter (ID) of 70 mm and the height of 60 mm such that the volume of argon in each cylinder is much larger than its volume inside the connecting tubes (1.4 mm ID and 2 m total length).

The inaccuracy of the DP measurements associated with the difference in the liquid metal level between the two cylinders is therefore negligibly small. As estimated, the associated error in the DP measurements in the worst case scenario does not exceed 2%.

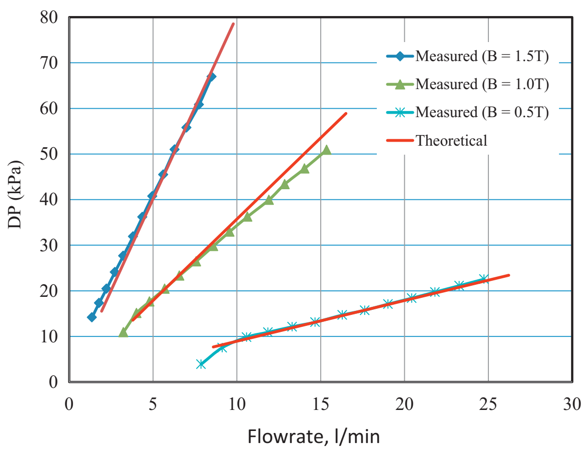

Fig. 9. Testing the proposed DP-measurement approach for pressure measurements in hot-temperature PbLi.

However, the proposed technique does not allow for instantaneous pressure measurements since any fast changes in the pressure will be damped. At present, this limitation is not important as the main experimental goal is to measure steady flow characteristics.

To test the proposed DP system, a round tube test section made of SUS304 steel of 22.1 mm ID and 24.5 mm OD was fabricated and installed, and the pressure difference was measured between the two locations, a distance $L = 0.5$ m from one another, within the uniform magnetic field region. Here, the flow is expected to be fully developed since the pressure taps are well distanced (tens of pipe diameters) from both the magnet edges and the edges of the test section. The results are shown in Fig. 9 for three values of the magnetic field 0.5, 1.0 and 1.5 T and flow rates from 2 to 25 l/min. In these tests the magnetic field is perpendicular to the main flow direction in the test-section. These results are compared with theoretical predictions obtained with an equation [44], which is known to demonstrate very good accuracy for fully developed flows in a thin-wall electrically conducting pipe:

$$dP = L\frac{c_w}{1+c_w}\sigma_f U_m B^2.$$

Here, c_w is the wall conduction ratio defined as $c_w = (\sigma_w/\sigma_f) \times [((d+2\delta_w)^2 - d^2)/((d+2\delta_w)^2 + d^2)]$ with σ_w being the wall conductivity, δ_w is the wall thickness, d is the ID of the pipe, σ_f is the electrical conductivity of liquid, U_m is the mean velocity, and B is the strength of applied magnetic field. The agreement with the theoretical predictions is very good; the discrepancy is within the 2% range.

Notice that the maximum transducer operation temperature as suggested by the manufacturer is limited to 121 °C, while the modified pressure measurements are in fact temperature unlimited. It is necessary to assure that the transducer operates within the recommended temperature range. This can be done easily by keeping the upper part of the DP-measurement system, including the DP sensor, exposed to air for natural cooling.

4.2. Flow rate measurements

Flow rate measurements are performed using a custom-made EM flowmeter (Fig. 10). The key element of the flowmeter is a permanent magnet with attached iron flux concentrator. The whole assembly is water cooled to keep the magnet at constant temperature of about 20 °C as the temperature increase may affect the measurements. The magnetic field is uniform (0.71 T) within the volume of 8 cm (axial direction) by 7 cm (vertical) by 4 cm (horizontal) such that the whole cross-section of the liquid-carrying tube is in the uniform magnetic field region. The tube is made of SUS304 steel and has ID d_{ID} of 0.0244 m and OD d_{OD} of 0.0254 m.

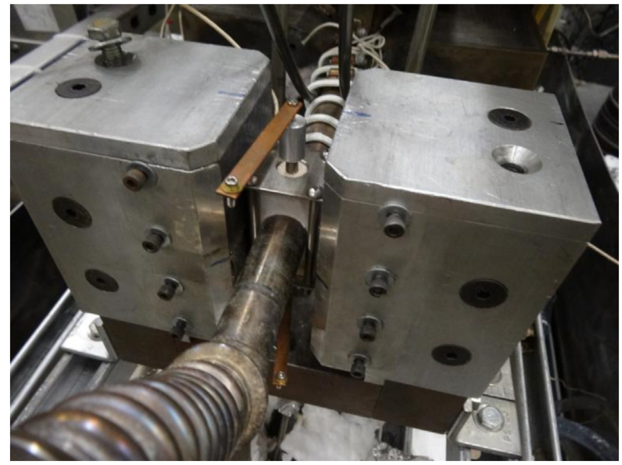

Fig. 10. EM flowmeter, including a permanent magnet with attached iron flux concentrator and liquid-carrying tube with two electrodes at the top and bottom.

Two pin electrodes are attached to the top and bottom of the tube. Once the flow-induced voltage S_{emf} (mV) between the electrodes is measured, the flow rate Q (l/min) is calculated using the following formula [45]:

$$Q = \frac{47.12 d_{ID} k_4}{B k_1 k_2 k_3} S_{emf}$$

Here, $k_1 - k_4$ are correction factors that take into account the effect of the electrical current closing through the conducting pipe wall, finite magnet dimensions, temperature effect on the magnetic field strength, and thermal expansion of the pipe, correspondingly, as suggested in Ref. [45]: $k_1 = 0.947$, $k_2 = 1.0$, $k_3 = 0.96$ and $k_4 = 1.0005$.

4.3. Ultrasound Doppler velocimetry

The ultrasonic Doppler velocimetry (UDV) technique is based on a pulsed ultrasonic echography together with instantaneous detection of the Doppler shift frequency [46]. The traveling time between the emission and reception of the ultrasound signal provides spatial information, while the Doppler frequency shift provides the velocity information. The UDV technique has been used for velocimetry in various room-temperature liquid metals, e.g., mercury, gallium and gallium–indium–tin alloy [47–49]. Moreover, it was also applied to several high-temperature melts, such as sodium [50], lead–bismuth, and bronze by using an acoustic waveguide [51].

In the present studies, a high-temperature UDV transducer developed by IHI Inspection & Instrumentation Co., Ltd., Japan (20 mm diameter and 89 mm length) was employed. To the best of our knowledge, this is the first time the UDV technique was applied to flowing PbLi. The employed transducer is more compact than waveguide sensors, and therefore can fit in a narrow magnet gap. Also, the tip of the transducer, which is exposed to PbLi, is made of titanium (TB340), a material that seems to be compatible with PbLi at high temperatures. Titanium also has a thermal expansion coefficient comparable with $LiNbO_3$, which is used as the piezoelectric element material. Based on the information from the manufacturer, the transducer is durable up to about 500 °C. Fig. 11 shows the photograph of the transducer and the schematic drawing of its interior structure.

The transducer was first tested in Japan by the 4th author in a small-scale rotating disk device [52] shown in Fig. 12 using PbLi alloy from the same supplier (Atlantic Metals & Alloys, Inc., USA). The measurements were performed in a commercial argon-filled

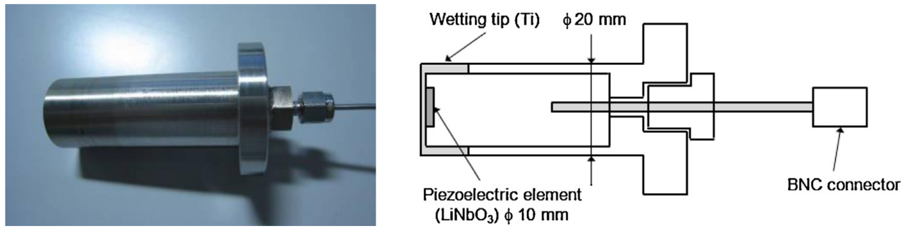

Fig. 11. Photograph (left) and schematic drawing (right) of the UDV transducer.

glove box, where the oxygen and the moisture concentrations were maintained at a level less than 1 ppm. In these conditions, no surface oxide layer was visually observed; the PbLi surface remained shiny. The tests have demonstrated that UDV is capable of measuring the swirl flow in high-temperature PbLi without adding any solid tracers as the naturally present lead-oxide particles in the bulk fluid can provide good signal reflection.

At UCLA, another series of UDV tests was carried out, first using a rectangular duct test-section shown at the bottom of Fig. 2. The test section is equipped with two UDV ports, one on the Hartmann wall and one on the side wall. Surprisingly, these tests had not indicated any reflection signal along the ultrasound beam. Further testing was then performed with a small amount of PbLi in a beaker. Similar to the experiments in the rotating disk device in Japan, these tests were done in a glove box filled with argon but the content of oxygen in argon above the melt surface remained high, a few tens of ppm, due to constructive limitations of the glove box and partly due to limited effectiveness of the purification unit. Such relatively high oxygen content still causes PbLi oxidation as described in Section 3 such that significant amounts of oxides are always present on the surface of the melt. In these conditions, the reflection signal was not detected again. Taking into account that the only difference between the UCLA small-scale experiment and that in Japan is the oxygen content, one can conclude that high concentration of oxygen in PbLi might be the main factor that indirectly prevents detection of the UDV signal.

It is clear that the ultrasound emitted by the transducer does not transmit to the molten PbLi because of some interfacial phenomena that involve interactions with oxygen. Special studies were than performed (also in the inert atmosphere in the glove box), in which the transducer tip was submerged in the melt and kept there for 290 h at 450 °C. These tests (Fig. 13) have revealed that no wetting in fact occurs during the first hours. After 290 h, some PbLi residuals can be observed on the tip indicating partial wetting. However, after washing the tip, gray-color spots are still observed on the surface suggesting that a chemical reaction, probably oxidation, might occur. These results suggest that removal of oxygen from the melt is the necessary condition to make the UDV technique in PbLi workable. On the other hand, the next studies should also address the effect of a finite-size electrically conducting tip on the flow. Ideally, the transducer should not cause any hydrodynamic or electromagnetic disturbances in the flow. This may imply further limitations on the transducer size and the choice of the tip material.

5. Current and near-future experiments

5.1. MHD pressure drop in flows in a sandwich-type rectangular duct

There are several approaches to reduction of the MHD pressure drop via electrical insulation. The concept of a sandwich-type (multi-layer) insulating flow channel insert was first proposed by Malang [53]. Another approach is based on utilization of laminated walls (see, e.g., Ref. [54]). A modification of this idea was proposed by Hashizume [55] as applied to a self-cooled liquid metal blanket design, where only three sides of the duct are electrically insulated, while the fourth one that faces the plasma does not carry any insulation. In this way, the MHD pressure drop can be significantly reduced by breaking the cross-sectional current circuit. At the same time, the non-insulated wall is made thinner compared to other three walls to reduce thermal resistance to the surface heat flux. This three-side multi-layer duct concept has recently been evaluated experimentally in MaPLE as a part of the already mentioned TITAN program. A test-section (Fig. 14) was fabricated in Japan at Tohoku University and brought to the US for testing. The host duct made of SUS316 steel has a length of 80 cm, a width of 2 cm and a height of 0.8 cm. In the experiments, the applied magnetic field is perpendicular to the short walls. The three insulated walls are 0.5 cm thick, while the fourth one, non-insulated, is 0.3 cm thick. The two short walls and one of the long walls are painted inside with liquid silica. After drying, a thin 0.1 mm insulating layer is formed on the walls. After that, a thin 0.1 mm insert of SUS316 steel is put inside the duct as shown in Fig. 14. As the last fabrication step, the forth wall, made of a 3 mm thick plate, is put on the top of the assembly and all parts are welded together.

Fig. 12. Schematic drawing (left) and photograph (right) of UDV tests in a PbLi swirl flow.

Fig. 13. Photographs of the titanium tip after submerging in PbLi at 450 °C: (left) after a few hours, (middle) after 290 h, (right) after removing PbLi residuals with a cleaning solution.

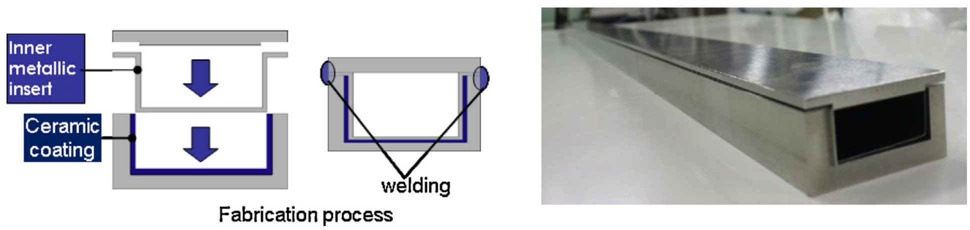

Fig. 14. A sandwich-type rectangular duct tested in MaPLE at UCLA: (left) fabrication process, (right) photograph.

This test section was installed on the loop and the differential pressure measurements taken over the duct section where the flow is expected to be fully developed. In the experiments, the magnetic field was varied from zero to 1.8 T, velocity from 0.1 to 2.0 m/s and the PbLi temperature from 270 to 350 °C. These parameters correspond to hydrodynamic Reynolds numbers up to 1.1×10^5 and Hartmann numbers up to 380.

Details of the experimental procedure and numerous experimental results are presented in Ref. [56]. Here, we summarize only the most important observations. It was demonstrated that the MHD pressure drop in the insulated duct is about 10 times smaller compared to the bare duct. In most cases, a good match has been found between the experimental pressure drop and that predicted with 2D numerical computations based on the fully developed laminar flow model (Fig. 15). In some cases, however, mostly when the magnetic field is lower and/or the flow velocity is higher, the discrepancy is significant (Fig. 16). Most likely this difference stems from turbulence or flow development effects, which become more important at higher velocities or smaller magnetic field due to increasing role of convection. These effects are so far not taken into account in the computational model. More discussions and comparison are given in Ref. [56].

5.2. Foam-based SiC flow channel insert

The main goal of the ongoing experiments with a flow channel insert (FCI) is to demonstrate the MHD pressure drop reduction in a PbLi conducting duct flow in the presence of a transverse magnetic field. FCI samples of foam-based SiC (Fig. 17) are fabricated by Ultramet, Inc., USA and delivered to UCLA for testing in PbLi.

Two experiments are planned to be done in the flowing PbLi conditions. In the first one, a 30-cm FCI segment will be put inside the host stainless steel duct and the pressure drop and electric potential distributions will be measured. The magnetic field will be varied from zero to 1.8 T (Hartmann number up to 1500) and the velocity up to 15–20 cm/s (Reynolds numbers above 5000). In the second experiment, two FCI segments will be put together with a small 1 mm gap between them. A holding scheme to restrict FCI displacements inside the host duct, which includes metallic springs and pins has already been developed. Also, another joint between two FCI segments, in the form of a T-bracket, as shown in Fig. 17, is considered for experimental testing. Along with the demonstration of MHD pressure drop reduction by the FCI another experimental goal is to evaluate the extra MHD pressure drop associated with the FCI joining. The experiments will be accompanied by 3D numerical

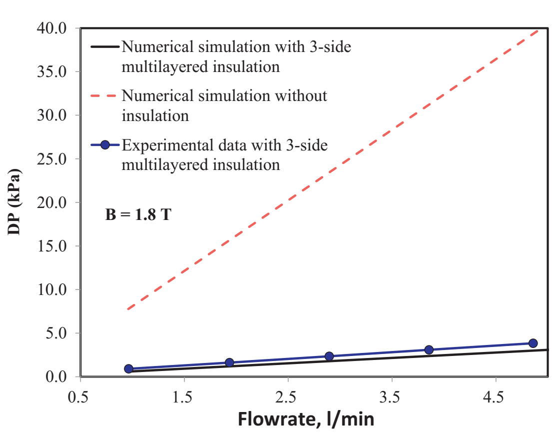

Fig. 15. High magnetic field pressure drop: experiment versus computations.

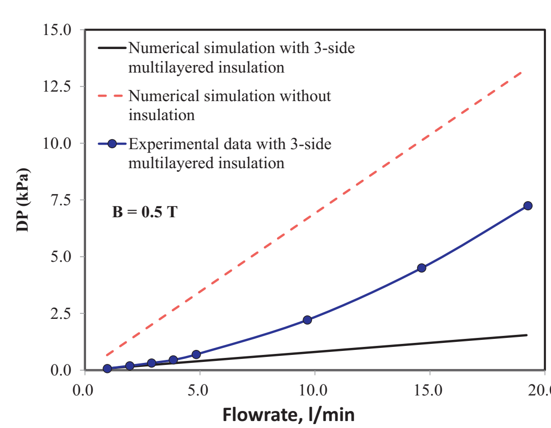

Fig. 16. Low magnetic field pressure drop: experiment versus computations.

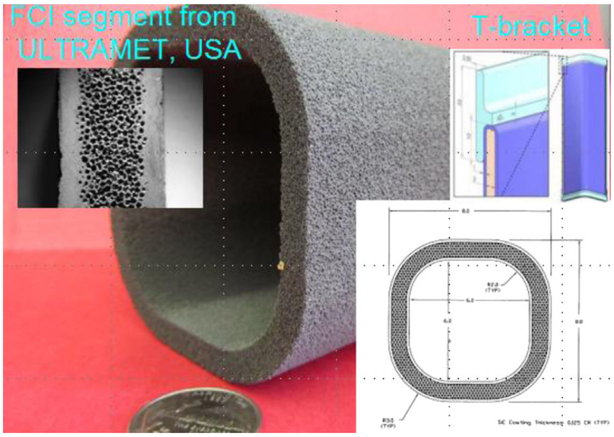

Fig. 17. SiC foam-based FCI for testing in the UCLA PbLi loop.

modeling. This will be the first experiment ever to test insulating properties of a SiC FCI, which is the key element of the DCLL concept.

6. Near-term loop upgrades

At present, the loop operation is limited to 350 °C (400 °C for short operations) to avoid severe corrosion problems, and also because of limitations on the maximum operation temperature of the EM pump. The corrosion experiments, which are planned in the near future, require much higher temperatures in the "hot leg". To upgrade the MaPLE facility to desired temperatures of up to 550 °C, a recuperator-type heat exchanger and additional heaters will be installed. Also, the major components of the loop transport system within the "hot leg", including the rectangular duct test-section, will be replaced with those made of advanced RAFM steel. Possible steel candidates are: EUROFER, CLAM and F82H. Discussions are underway with the EU, China and Japan, who expressed interest in upgrading the loop with their national RAFM steels as their contribution to the collaboration on these experiments. The specimens will be made of the same steel as the hot leg of the loop itself, such that possible multi-material effects are minimized. As a back-up option we also consider the whole loop, or at least its hot section, to be made of HT9 steel (a predecessor of advanced RAFM with about the same content of iron and chromium), while the specimens will be made of RAFM. Also, a so-called magnetic trap will be installed for continuous extraction of the ferrous precipitate to avoid any loop blockage.

7. Conclusions

A new MHD PbLi facility called MaPLE has been constructed and tested at UCLA. The loop is fully functioning and ready for experiments and mock up testing. The ongoing experimental work addresses the MHD pressure drop reduction via electrical insulation techniques and compatibility of blanket materials, such as silicon carbide, with the flowing lead–lithium alloy in the presence of a transverse magnetic field up to 1.8 T. First experiences handling the alloy suggest that PbLi contains significant amounts of free oxygen due to its high sorption ability. In a pure experiment, the amount of oxygen needs to be minimized. A degassing procedure that includes repeated vacuum pumping and argon gas purging has been developed and successfully applied, but the remaining amount of oxygen is still high. Although the presence of oxygen seems not to affect purely MHD flows, it may degrade the quality of measurements and also seems to play a significant role in corrosion processes. A significant effort is being made on instrumentation development since diagnostic tools for high-temperature liquid metals are still very limited. A new pressure diagnostics system was developed and successfully tested. As for velocity measurements, the ultrasound technique seems to be promising, but present efforts on implementation of the hot-temperature UDV system have not succeeded yet because of poor wetting of the UDV transducer tip. Future efforts will include loop upgrades, first of all to higher temperatures up to 550 °C, further instrumentation development for flow velocimetry, and SiC FCI flow and corrosion experiments.

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