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Status of "TITAN" Task 1–3 "Flow Control and Thermofluid Modeling"

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ABSTRACT

We review current accomplishments and ongoing work in Task 1–3 "Flow Control and Thermofluid Modeling" of the US-JAPAN "TITAN" Program. This encompasses construction of a new MHD lead–lithium loop at UCLA and planning, preparation and pre-experimental analysis for first experiments, including tests of high-temperature ultrasound Doppler velocimeter and studies of the behavior and electroinsulating properties of the foam-based silicon carbide flow channel insert in the flowing liquid metal in a magnetic field. First results of magnetohydrodynamic experiments on flow transitions from 3D to 2D are also presented and discussed.

1. Introduction

Task 1–3 "Flow Control and Thermofluid Modeling" of the US-JAPAN "TITAN" Program focuses on experimental activities and also on computer modeling of magnetohydrodynamic (MHD) flows and heat and mass transfer of electrically conducting fluids under conditions relevant to fusion blankets [1]. During the about two-year reference period (2009–2011), major efforts were taken to design, construct and test a new MHD lead–lithium (PbLi) loop at UCLA, including testing and calibration of its components (electromagnetic (EM) pump, EM flow-meter, high-temperature pressure sensor) as well as development and testing the most important loop operation procedures, such as: melting PbLi, removing trapped oxygen from the melt, filling and draining the loop, pumping the liquid metal throughout the loop, and temperature control. First experiments are underway to test a new high-temperature ultrasound Doppler velocimeter (HT-UDV) and also to address material compatibility issues and reduction of the MHD pressure drop by a foam-based silicon carbide (SiC) flow channel insert (FCI). Other ongoing experiments utilize the mercury loop at UCLA and deal with transitional phenomena from the 3D to 2D state in duct MHD flows. All experimental efforts are accompanied with numerical MHD/thermofluid computations in either 2D or 3D to address the most important flow phenomena related to a liquid metal blanket [2].

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2. Status of MHD PbLi facility at UCLA. Ongoing and near-term experiments

The MHD PbLi loop is shown in Fig. 1. There are a glove box with attached cylindrical melting tank at the bottom, electromagnetic conduction pump, custom-made electromagnetic flow meter, a vacuum pump and a gas purification system. All parts of the loop, including connecting pipes, are heated and thermally insulated to prevent PbLi from solidification. At the start of the loop operation cycle, about 70 kg of PbLi ingots (from Atlantic Metals, USA) are loaded into the melting tank (Fig. 2a), the air is evacuated and melting started. During melting and further melt heating, intensive bubble formation is observed on the surface of the melt due to air release, which is originally trapped in the ingots (Fig. 2b). This causes formation of oxide particles both in the bulk liquid and at the surface. The released gas is continuously removed by the vacuum pump until all bubble production stops. At the end of the melting/heating procedure, which takes about 24 h, all solid impurities (mostly oxides) come to the surface of the melt and remain there, while the melt beneath the oxide layer is visually clean (Fig. 2c). The free surface of the melt is far above of the EM pump level, so that no large oxide particles circulate throughout the loop.

After melting is done, the loop is filled with argon gas and then pumping liquid metal is started. The gas purification system can be used during the loop operation for continues removal of chemically active species, mostly oxygen and moisture, from argon. The electromagnetic pump (style V pump from Creative Engineers, USA) allows for the flow rate of PbLi up to 30 l/min at the maximum pressure drop of 0.15 MPa and even higher flow rates up to 50 l/min at lower pressure drops as confirmed by present measurements

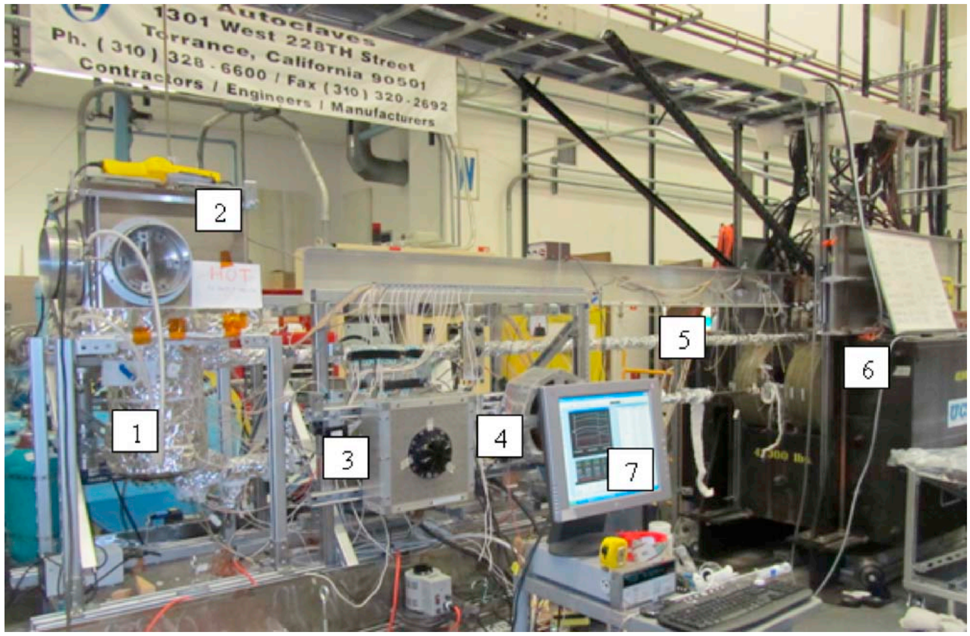

Fig. 1. Newly-constructed MHD PbLi loop at UCLA: 1 – PbLi melting tank with heaters, 2 – glove box, 3 – EM pump, 4 – EM flow-meter, 5 – pipes, 6 – electromagnet, and 7 – data acquisition system.

Fig. 2. Melting PbLi: (a) PbLi ingots before melting, (b) bubble formation during meting and further heating, and (c) oxide crust 0.5–1 cm thick with clean PbLi beneath.

(Fig. 3). These pump characteristics are close to those estimated by the pump manufacturer. The loop is currently operated at 350 °C to avoid severe corrosion losses by adjusting the heating power of three independent heater sections. The PbLi temperature is controlled with the set of thermocouples installed along the flow path. The major loop components are fabricated of stainless steel, which is resistant to the liquid metal attack, providing the PbLi is bellow 400 °C. The whole loop is installed on the wheeled platform and can be moved into the magnet space of the lab electromagnet, which provides up to 1.8 T uniform magnetic field (Hartmann number, Ha, up to 2000) in the work space of 80 cm × 15 cm × 15 cm.

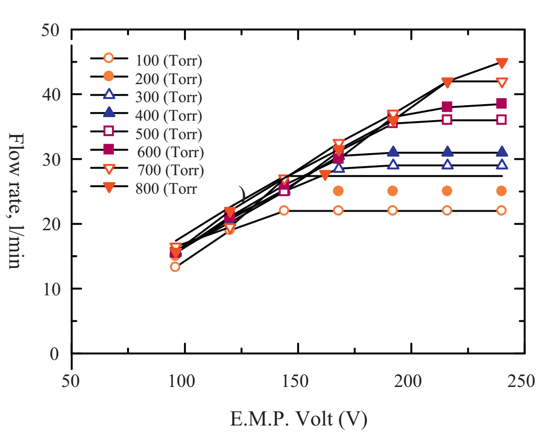

Fig. 3. Testing the EM pump. Flow rate is increased up to 50 l/min as the pump voltage is increased. Measurements are performed for the argon pressure from 100 to 800 Torr.

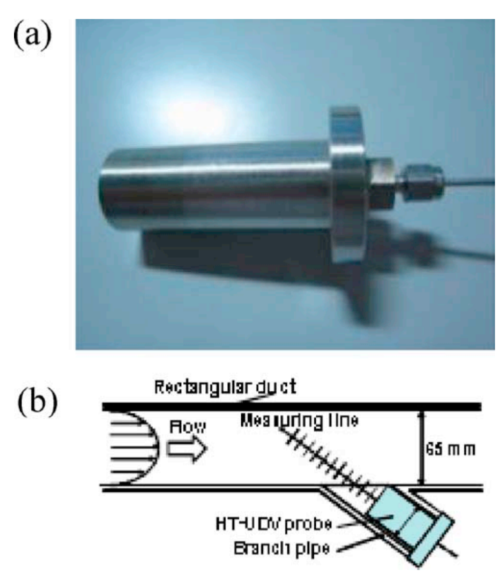

Fig. 4. (a) HT-UDV probe and (b) its location in the test-section.

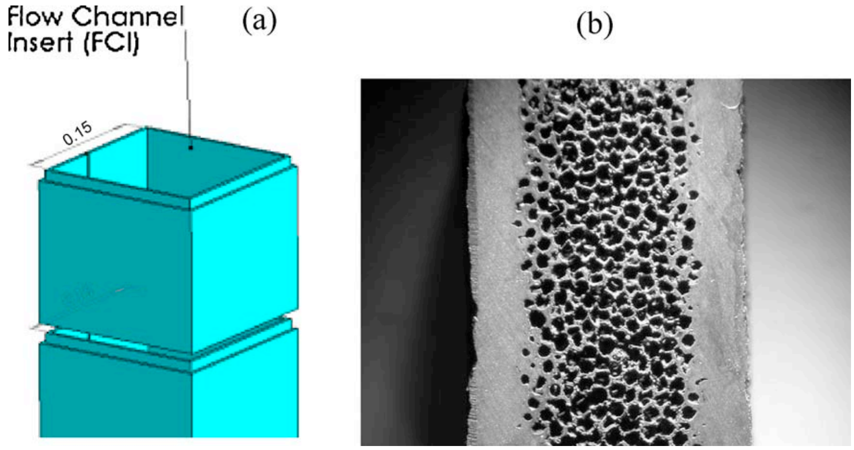

Fig. 5. SiC FCI: (a) schematic view of two overlapping FCI sections, and (b) foam-based SiC sample.

First experiments with the PbLi loop are underway, which mostly aim at testing and calibration of the HT-UDV (Fig. 4) system [3] with and without a magnetic field. This system is expected to become the basic diagnostics tool in the next MHD experiments to measure the velocity field in the flowing PbLi. Previous experiments were done in a PbLi swirl flow with the same HT-UDV probe but no magnetic field was applied [3]. In the present experiment, one HT-UDV probe is inserted through the test port in the Hartmann wall (perpendicular to the magnetic field) of a host stainless still rectangular duct test-section and the other through the side wall (parallel to the magnetic field). In these experiments, a fully developed MHD flow with the well-known "M-shaped" velocity profile is established over the middle section of a long (~1 m) duct, and then the two velocity measurements (by two HT-UDV probes) collected at different flow rates and magnetic field strengths are compared with the numerical data. The locations of the UDV probes and pressure transducers have been specified in the pre-experimental computations using a 3D MHD numerical code HIMAG [5]. In addition, the effect of the probe location on the flow is addressed via 2D modeling (see Section 4).

The main goal of the next experiment is the proof of the principal of the foam-based SiC FCI (Fig. 5), which in the real blanket design is envisaged as electrical and thermal insulator [4]. Such an FCI has never been tested before. The FCI is manufactured by ULTRAMET, USA. The FCI cross-sectional dimensions are 6 cm by 6 cm (internal) with the wall thickness of 1 cm; the corners are rounded. The foam-core is coated with a thin layer of crystalline SiC to seal the pores. Two SiC inserts will be tested consequently: one is 30 cm long and the other is 60 cm made of two shorter 30-cm sections.

The FCI box is centered in the outer stainless steel square duct to form a small gap of about 2 mm between the FCI and the steel wall, similarly to the real blanket design. FCI displacements in

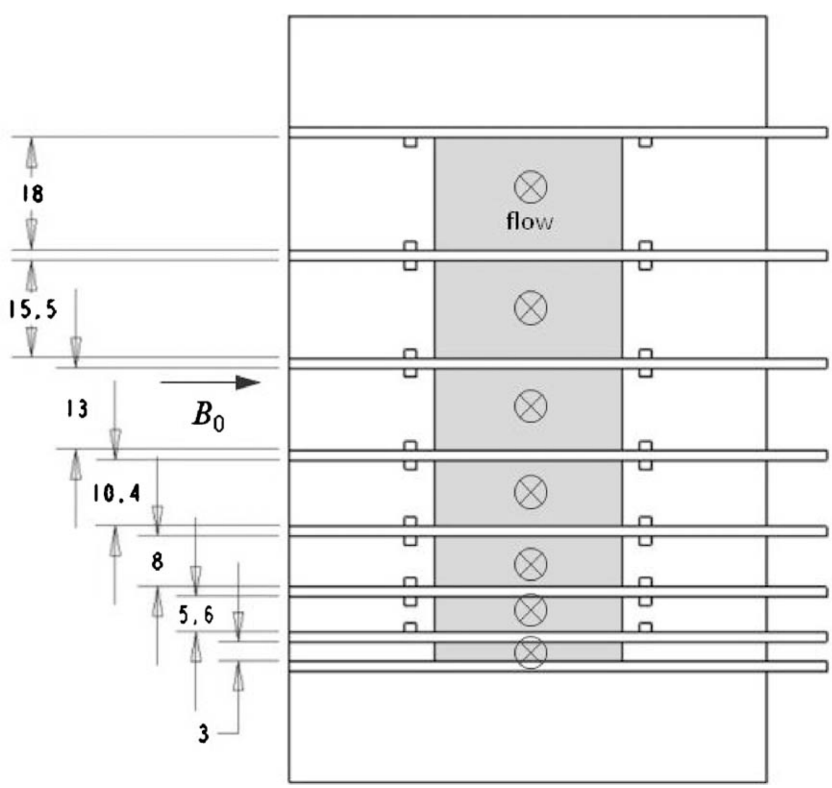

Fig. 6. Stack of 7 channels in the pre-qualification experiment.

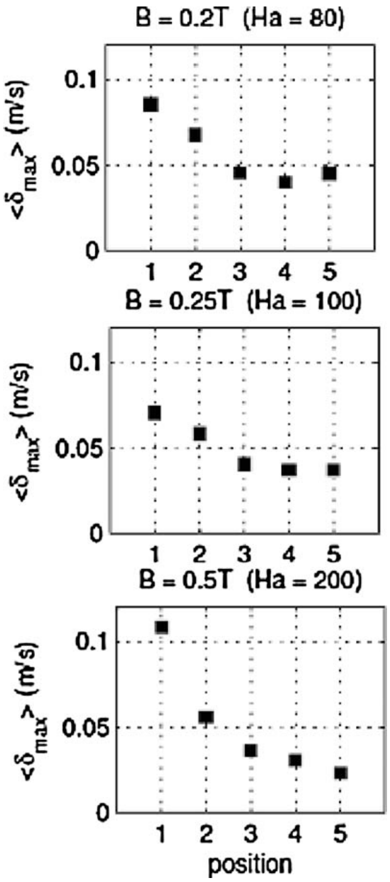

Fig. 7. Velocity fluctuations in the largest channel as a function of the axial position at Re = 54,000 (0.4 m/s).

the cross-sectional plane are prevented by putting stainless steel woven material in the gap at the FCI corners, while the axial motion is limited with the removable screws at the FCI edges. In doing so, the major section of the gap will remain open for the flow. We intend to demonstrate the pressure drop reduction by comparing the measured MHD pressure drop with and without the FCI and also by comparing the experimental data with the computational results. The FCI will be exposed to the flowing PbLi for about one week and then removed for visual observations and other testing to check for PbLi/SiC compatibility.

3. Pre-qualification experiment using Hg loop

This experiment, which plays a supplemental role to other MHD experiments in TITAN, addresses conditions when MHD flow in a non-conducting rectangular duct subject to a constant transverse magnetic field transitions from 3D to a quasi-2D (Q2D) state. The other purpose of this experiment is to test and calibrate the innovative instrumentation technique, where a Printed Circuit Board (PCB) populated with hundreds of potential probes is used, before a similar one is employed on further experiments. The test section consists of a stack of 7 non-conducting channels of different heights ranging from 3 mm to 18 mm, but with the same width and length (30.5 mm and 600 mm respectively, see Fig. 6). Turbulent pulsations formed in the upstream region, where the magnetic field is zero, enter the duct assembly through the feeding pipe and then experience a strong influence of the magnetic field, resulting in a Q2D flow at some distance from the inlet. Bulk velocities in each channel at different locations are derived from wall electric potential measurements using the Ohm's law. This technique is common in MHD and provides a good accuracy (see e.g. [6]). These bulk velocities demonstrate fluctuations, which are reduced with the axial position measured from the channel inlet (Fig. 7) to some level associated with a Q2D flow. Lower fluctuations are observed in a higher magnetic field at almost all locations. The main objective of these ongoing experiments is to construct a correlation for the transitional Reynolds number (Re) or/and transitional duct length. Current data suggests the interaction number $N = \mathrm{Ha}^2/\mathrm{Re}$, being the ratio of electromagnetic to inertia forces, to be the key dimensionless parameter.

4. Pre-experimental modeling for HT-UDV

The main objective of this pre-experimental analysis is to access possible effects of the location of the HT-UDV probe in the duct on the induced electric currents and velocity field via numerical computations. In MHD flows, the HT-UDV technique cannot be considered, in general, as a non-intrusive one because the induced electric currents can close through the probe and the attached conducting port structure. This additional circuit may cause significant disturbances of the flow field around the probe. Thus the location of the probe in the duct may be important, especially when the applied magnetic field is strong. These effects are analyzed using a 2D MHD code for the rectangular duct and two probe locations described in Section 2. For demonstration purposes, the duct walls are taken as non-conducting, while the probe is electrically conducting. The modeling results demonstrate almost no probe effect on the flow when the probe is located on the side wall (Fig. 8a). On the other

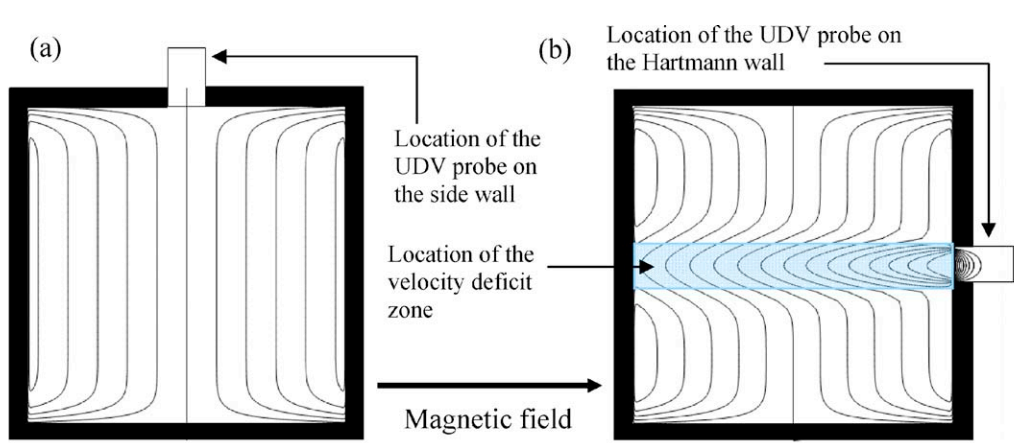

Fig. 8. Effect of the conducting HT-UDV probe on the induced electric current: (a) probe located on the side wall, and (b) on the Hartmann wall (b) of the host rectangular duct.

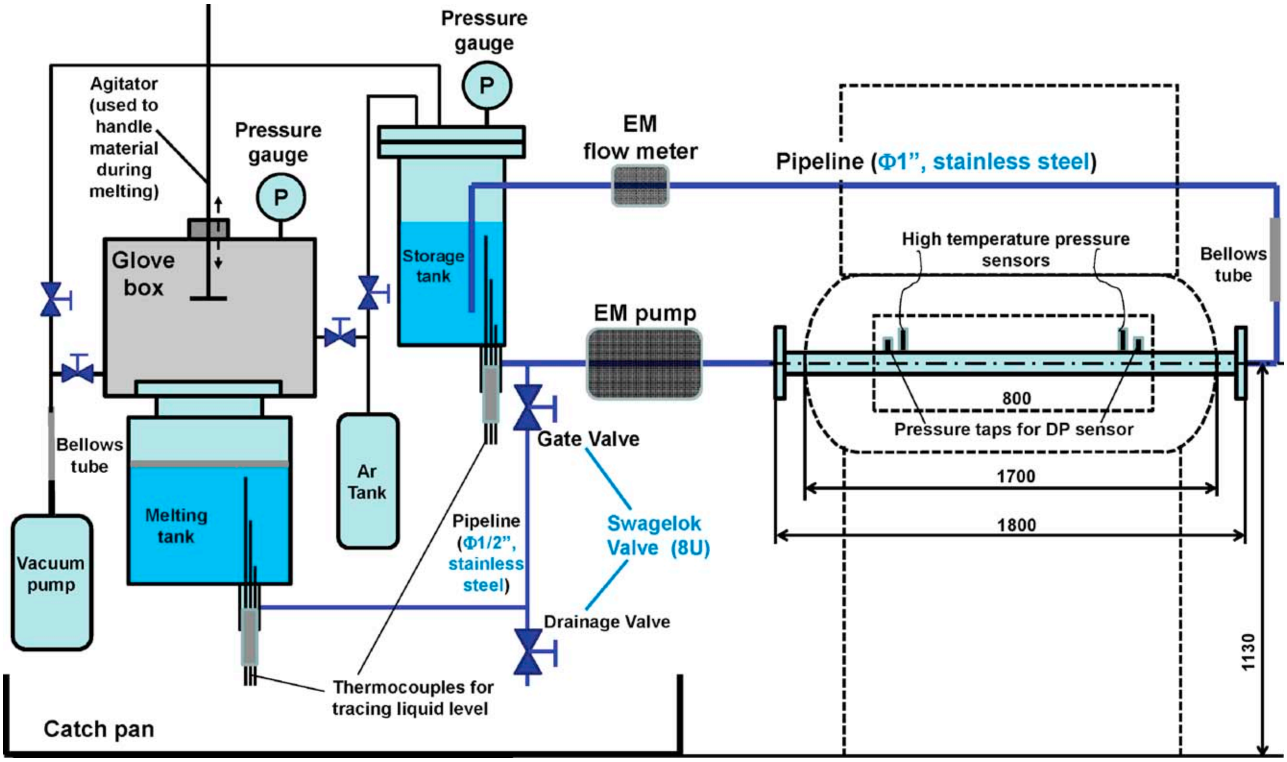

Fig. 9. Further PbLi loop modifications in 2011/2012.

hand, the probe located on the Hartmann wall causes significant changes in the electric current distribution and as a result leads to drastic changes in the velocity filed in the form of the velocity deficit zone (not shown here). The practical recommendation is therefore not to install the probe on the Hartmann wall. This and other effects associated with the electromagnetic flow disturbances due to electrically conducting HT-UDV probe will be further addressed in the experiments using the PbLi loop as described in Section 2.

5. Further PbLi loop upgrades

Near-future (2011/2012) loop upgrades will include an additional upper storage tank, new connecting tubes to accommodate a long 1-m rectangular duct test-section and a new higher capacity melting tank to have lager inventory of PbLi of about 100 kg. The melting tank will be positioned at the lowest point of the loop as shown in Fig. 9. These modifications will provide faster and more convenient loop operation, in particular when draining the loop.

6. Summary

During the reference period (2009–2011) of the US-JAPAN "TITAN" Program, Task 1–3 "Flow Control and Thermofluid Modeling" has focused on the construction and testing of a new MHD PbLi loop at UCLA, testing MHD flow diagnostics, experiments on transitions in MHD flows, and preparation to further experiments where an insulating flow channel insert made of foam-based silicon carbide will be tested.

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