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Data-acquisition, control & interlock system design for corrosion experiments of IN-RAFM steel with flowing Pb-Li in presence of magnetic field

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ABSTRACT

Indian Reduced Activation Ferritic Martensitic Steel (IN-RAFMS) has been selected as the reference structural material for Lead-Lithium Ceramic Breeder Test Blanket Module (LLCB TBM). Qualification requirements for the selected structural material include assessment of compatibility, in TBM-like conditions, against flowing eutectic lead-lithium (Pb-Li) liquid metal, which is primary coolant for TBM internal structures as well as a tritium breeder and neutron multiplier. In this view, corrosion experiments are planned to be conducted at relevant temperatures and flow conditions in a dedicated pump driven experimental loop fabricated at Institute for Plasma Research (IPR). Such an experimental facility requires continuous operation over long duration along with constant monitoring and control of critical process parameters like temperature, pressure and flow. In addition, to ensure occupational safety and investment protection of associated loop components, alarms and interlocks are required to notify any off-normal condition(s) arising during loop operation and to mitigate possible accidental scenarios. To perform the intended functions, a data-acquisition, control and interlock system is designed using PXI-express technology and LabVIEW software platform. Functionality of developed system has been successfully validated in an integrated manner. This paper discusses definitions and implementation methods of control and interlock logics. Detailed design of developed system including performance of pressure control system and electromagnet interlock module is presented.

1. Introduction

India is working towards development of LLCB TBM planned to be tested in equatorial port#2 of International Thermonuclear Experimental Reactor (ITER) [1–3]. LLCB TBM concept will be validated for tritium breeding and high-grade heat extraction feasibilities, which are necessary goals for DEMO reactor. LLCB blanket concept mainly consists of lithium titanate ceramic breeder in the form of packed pebble bed with liquid Pb-Li alloy eutectic acting as a tritium breeder, neutron multiplier and coolant. As shown in Fig. 1, LLCB TBM consists of a U-shaped first wall, ceramic breeder cassettes, Pb-Li flow channels, top plate, bottom plate and back plate arrangement [4]. Molten Pb-Li flows around ceramic breeder compartments to extract the volumetric heat from TBM internals as well as its self-generated neutronic heat. During normal operations, Pb-Li temperature varies between 300 °C and 460 °C at the inlet and outlet of TBM, respectively, while the velocity of Pb-Li inside TBM is approximately 10 cm/s. India specific steel IN-RAFMS (9Cr-1.4W-0.06Ta-0.25V) has been selected as the structural material for TBM due to its better mechanical properties and lower radiological impacts [5]. Due to highly corrosive nature of Pb-Li (especially at elevated temperatures), compatibility of structural material with flowing Pb-Li is of utmost concern for successful operation of TBM.

Worldwide, many facilities are operational to perform experimental studies (MHD and corrosion) related to high temperature liquid metals flowing in presence of high magnetic field [6–9]. Such critical experimental facilities demand measurement, automation & control to ensure an effective and safe operation. Associated occupational safety and investment protection of high-value components (like magnet, pumps etc.) must also be addressed through critical interlock functions.

As a process fluid, Pb-Li presents substantial challenges in terms of handling and operation at high-temperature [10]. In order to assess compatibility of IN-RAFMS for TBM-like conditions, a pump driven corrosion loop has been set-up at IPR to generate corrosion data for IN-RAFMS with flowing Pb-Li in presence of constant static magnetic field over long durations. Schematic diagram of the experimental facility and Pb-Li flow direction inside the loop is shown in Fig. 2. The complete facility is a complex assembly of electrical and mechanical components

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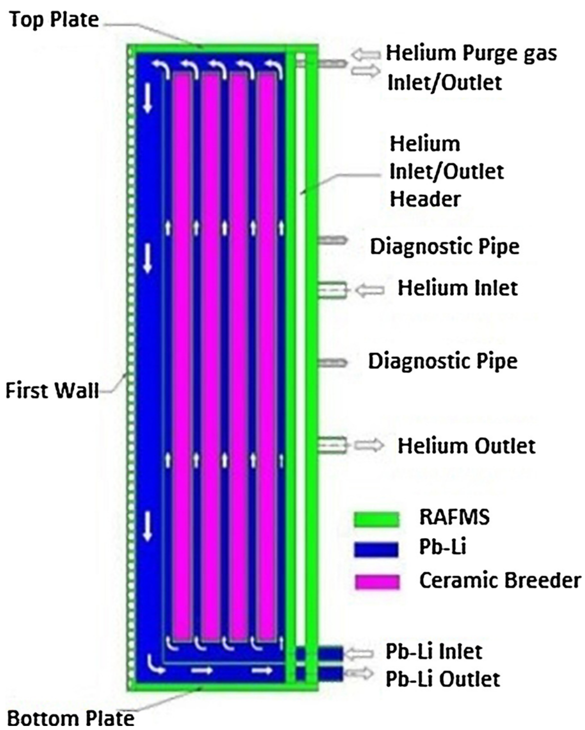

Fig. 1. Pb-Li flow configuration inside LLCB TBM.

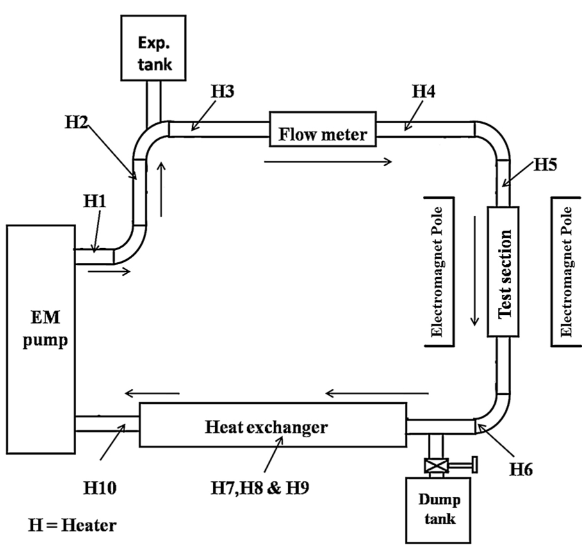

Fig. 2. Schematic diagram for pump driven corrosion loop.

including an electromagnet, test-section, electromagnetic pump (EMP) based on rotating permanent magnet disks, heat-exchanger section, dump tank, L-shape (between loop and dump tank), valves, magnetic flowmeter, expansion tank etc. Complete loop is fabricated from 1-in., 40 schedule pipe, while the test-section is a rectangular duct with flow channel dimensions of 18 mm (width) × 94 mm (height). Material of construction for the pipes and test-section is SS-316L. Test-section is placed between the poles of an electromagnet, with a pole-gap of 35 mm, capable of generating upto 1.4 T static magnetic field. Height of the test-section is maintained transversally to magnetic field direction. To study corrosion effects relevant to LLCB TBM operation in ITER, the test-section loaded with IN-RAFMS samples is required to be maintained at a temperature of 465 °C with Pb-Li flowing at a velocity of 10 cm/s. As compared to actual Pb-Li temperature limit of 460 °C in LLCB TBM, slightly higher temperature is selected for Pb-Li within test-section to estimate a conservative corrosion rate as well as to accommodate for possible variations in test-section temperature during long term operations. At the same time, critical components like EMP and magnetic flowmeter exert limits on process temperature due to deterioration of magnetic properties at elevated temperatures. To achieve required experimental parameters and to simultaneously address temperature constraints of critical components, a temperature gradient is necessary along loop pipeline. Ingress of air and other impurities from ambient should also be avoided to maintain Pb-Li composition for a correct estimation of IN-RAFMS corrosion rate.

The experimental facility is designed such that sections H1–H3 provide active heating where the Pb-Li temperature is increased from 300 °C to 450 °C. Sections H4 and H5, working as temperature conditioning sections, are maintained nearly at the same temperature as required within the test-section to provide a uniform fluid temperature without fluctuations. At test-section, temperature of Pb-Li is maintained at 465 °C over complete length where IN-RAFMS samples are exposed to Pb-Li flowing at a velocity of 10 cm/s in presence of static magnetic field. Pb-Li exiting from test-section loses heat through a forcedly cooled fin-structured heat-exchanger and enters EMP at a temperature of around 380 °C. Heaters at sections H6 to H10 remain off during steady state operation of the loop. Temperature of Pb-Li at the discharge of EMP falls down to 300 °C due to un-insulated EMP channel and the whole cycle is repeated. During normal operating conditions, Pb-Li mass flow-rate in the loop is 1.56 kg/s. In this configuration, pump driven corrosion loop provides required test conditions at test-section. Outer surface of test-section is thermally insulated (~6 mm on each side upto the magnet pole) to reduce temperature exposure to electromagnet structure. A total of 06 K-type thermocouple are spot-welded at centre locations of test-section surfaces to measure and maintain temperature of flowing Pb-Li. Expansion tank, located at highest point of the loop, is installed with discrete level switches to ensure that the loop pipeline and test-section are completely filled before Pb-Li circulation is performed. The top volume of expansion tank is filled with an inert cover gas maintained over liquid metal. The expansion tank also provides a means to accommodate temperature dependent volumetric fluctuations within loop inventory while inert cover gas provides a process seal against ingress of oxygen and other impurities into the test facility. This mandates continuous control of inert gas pressure over liquid metal within the expansion tank. To achieve above described operational objectives for pump driven corrosion test facility, loop automation and control is indispensable. In this view, to carry out uninterrupted loop operations for long durations, a data-acquisition, control and interlock system is designed using PXIe hardware technology with LabVIEW software development platform. Detailed functional requirements and configuration of designed system are presented in subsequent sections.

2. Functional requirements

Successful operation of a high-temperature integrated system demands monitoring and control of process variables to acquire relevant process data about present system state. Additionally, to provide investment protection of high-value items and to avoid system downtime due to malfunctioning of components, interlock logics must bring the facility to a known safe-state. For present pump driven corrosion experimental facility, following sections segregate the functional requirements:

2.1. Data-acquisition requirements

- To monitor and log temperature data with time-stamp for critical sections of the loop. Eight such critical sections are identified namely H4, H5, TS-mid (at test section), H10, EMP channel, expansion tank, dump tank and L-shape as shown in the schematic (shown in Fig. 2).

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