Construction of PREMUX and preliminary experimental results, as preparation for the HCPB breeder unit mock-up testing

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HIGHLIGHTS

• PREMUX has been constructed as preparation for a future out-of-pile thermo-mechanical qualification of a HCPB breeder unit mock-up.
• The rationale and constructive details of PREMUX are reported in this paper.
• PREMUX serves as a test rig for the new heater system developed for the HCPB-BU mock-up.
• PREMUX will be used as benchmark for the thermal and thermo-mechanical models developed in ANSYS for the pebble beds of the HCPB-BU.
• Preliminary results show the functionality of PREMUX and the good agreement of the measured temperatures with the thermal model developed in ANSYS.

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ABSTRACT

One of the European blanket designs for ITER is the Helium Cooled Pebble Bed (HCPB) blanket. The core of the HCPB-TBM consists of so-called breeder units (BUs), which encloses beryllium as neutron multiplier and lithium orthosilicate (Li2SiO4) as tritium breeder in form of pebble beds. After the design phase of the HCPB-BU, a non-nuclear thermal and thermo-mechanical qualification program for this device is running at the Karlsruhe Institute of Technology.

Before the complex full scale BU testing, a pre-test mock-up experiment (PREMUX) has been constructed, which consists of a slice of the BU containing the Li2SiO4 pebble bed. PREMUX is going to be operated under highly ITER-relevant conditions and has the following goals: (1) as a testing rig of new heater concept based on a matrix of wire heaters, (2) as benchmark for the existing finite element method (FEM) codes used for the thermo-mechanical assessment of the Li2SiO4 pebble bed, and (3) in situ measurement of thermal conductivity of the Li2SiO4 pebble bed during the tests.

This paper describes the construction of PREMUX, its rationale and the experimental campaign planned with the device. Preliminary results testing the algorithm used for the temperature reconstruction of the pebble bed are reported and compared qualitatively with first analyses completed with the FEM codes.

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1. Introduction

One of the mid-term goals projected at the Institute of Neutron Physics and Reactor Technology at the Karlsruhe Institute of Technology (KIT-INR) is to test a breeder unit mock-up (BU MU [1]) for the Helium Cooled Pebble Bed Test Blanket Module (HCPB-TBM [2,3]) in a dedicated helio loop named KATHELO [4]. This test will aim at the verification of the thermal and thermo-hydraulic performances of the BU under ITER relevant conditions, as well as to serve as an additional benchmark platform for the finite element (FE) code developed in KIT during the past years [5] for modeling the thermo-mechanics of pebble beds in the BU.

In order to reproduce the volumetric heating due to the neutron irradiation in an out-of-pile experiment with a BU MU, a heater system based on a matrix of wire heaters has been designed and developed [6]. As its implementation in a full scale BU MU is technically challenging, it is desired to check the performance of this heater system in a simplified yet relevant pre-test experiment (PREMUX) before its realization in a full scale BU MU. The main design characteristics of PREMUX have been presented in [6]. The
construction of this experiment, its rationale, the methods that are used and future steps are reported in this paper.

2. Experiment design, engineering and construction

2.1. PREMUX heater system and test box

The nuclear heating occurring in the HCPB BU has been discretized into volume cells of uniform power: 23 cells for the Li$_2$SiO$_4$ and 10 cells for the beryllium multiplier (Fig. 1, top). As it has been shown in [6], PREMUX reproduces two cells where the temperature will reach its maximum. Each cell contains a heater block that provides the corresponding discretized power. A central heater between both heater blocks is used for the determination of the thermal conductivity of the breeder material by hot wire method (HWM) [7].

These two cells reproduced in PREMUX are relevant in thickness (22 mm) and width (189.5 mm) to a BU MU. The length of the pebble bed corresponds to the length of two cells plus an extra length (118 mm) needed for purging the bed with helium gas.

The heater system composed by the two heater blocks and the central wire for HWM measurements has been designed in KIT-INR and developed by the company Thermocoox (Fig. 2). Each heater block can develop up to 700 W. The design details can be found in [6]. The positioning of thermocouples permits a temperature reconstruction of the section under study by means of biharmonic spline interpolation in a Control Tool program implemented with the software LabVIEW (explained in Section 2.4). The power of the heater blocks is regulated by two independent power supplies (EA PS8360-15 2U) with LabVIEW through Ethernet.

The pebble bed is enclosed in a box made out of P92 (X10CrWMoVNb9-2) ferritic steel grade (Fig. 3). This steel is currently used as substitution of EUROFER in many experimental and fabrication activities because of its similar composition and characteristics to EUROFER, yet more accessible and economic. In PREMUX is particularly important its similar thermal conductivity. The upper and lower walls in contact to the breeder material have 1.2 mm thickness (relevant to that in the cooling plates of a HCPB BU) and they are cooled by air at 0.2 MPa flowing through six squared channels of 25 mm side length. The air is coming from the air loop L-STAR Large Loop (L-STAR/LL) at the KIT-INR [8].

The geometry of the channels and its dimensions corresponds to a tradeoff between relevant thermal performance to a BU MU and manufacturability. First, it was decided to minimize the number of welds in the test box to reduce the distortion. Due to the small thickness of the pebble bed and the high thermal gradient in-between, a low tolerance (0.1 mm) is imposed for this dimension, thus the need for a reduced distortion. Therefore, the test box is fabricated by just welding together 2 quasi-symmetric parts (Fig. 3) with electron beam. Each half is fabricated out of a 50 mm thick P92 plate, where the 6 cooling channels and half of the volume of the pebble bed are cut off with spark erosion.

The length of the cooling channels is important for two reasons: (1) the longer, the more developed will be the flow and less pronounced the entrance region effects in the heat transfer region of the pebble bed and (2) the shorter, the easier the spark erosion process is. A spark erosion process around 300 mm long is standard in the industry. Several analyses performed with ANSYS CFX concerning the length of the channels showed that an airflow at 5 g/s (initial estimation for the cooling rate) needs a length of about 80 mm before it reattaches (Fig. 4, top). Therefore, the length of the test box has been set-up to 250 mm, which lets the flow to develop while keeping a standard spark erosion process.

Considering the 50 mm thick P92 plates, the height left for the cooling channels is about 25 mm. Past studies with just 5 cooling channels and rectangular shape (36 mm × 12 mm) show unsteady flow patterns due to the creation of a Karman vortex street at the considered flow regime (Fig. 4, bottom). This is due to the transition from the circular cross section of the interface pipes that connect the test box to the air loop to the rectangular one at the test box. What is more, a reduced number of channels make the structure less stiff against the secondary stresses coming from thermal expansion of the box, so it has been decided to keep the configuration with 6 + 6 cooling channels of 25 mm of side length.

A first guess of the coolant mass flow has been imposed to study the fluid dynamics of the air in the channels. However, a more precise value is needed in PREMUX so that the coolant is relevant (physically similar) to the helium cooling in the BU MU. The
similarity is found using the Buckingham Pi theorem [9]. Taking as variables the flow density $\rho$, flow velocity $u$, dynamic viscosity $\mu$ and the hydraulic diameter $D_h$, it is deduced from the theorem that the condition to impose is a similarity of Reynolds ($Re$) numbers:

$$\frac{\rho u D_h}{\mu} = \frac{\rho u D_h}{\mu}$$  \hspace{1cm} (1)

Taking into account that

$$\dot{m} = \rho u A$$  \hspace{1cm} (2)

where $A$ is the channel cross section and $\dot{m}$ the fluid mass flow, the relationship between $Re$ numbers reads:

$$\frac{\dot{m}}{\mu A} = \frac{\dot{m}_H}{\mu_H A_H}$$  \hspace{1cm} (3)

The air properties are taken at an average temperature of 40°C and 0.2 MPa, and 460°C and 8 MPa for the helium. The cooling channel of a BU MU is a rectangle of 2.6 mm $\times$ 4.5 mm and the average $\dot{m}_H$ is 0.84 g/s. This gives a $\dot{m}_{air} = 3$ g/s.

Custom interface pipes of ½ in. and P92 are welded to the test box by electron beam (Fig. 3). Due to the magnetism of the P92 steel, a demagnetization process is needed to avoid the deviation of the electron beam during the welding process. The length of these pipes (120 mm) is the minimum needed to have a developed flow at the entrance and to homogenize the temperature in the cross section of the pipe at the outlet. This last fact is important, as a temperature measurement is done at the end of each outlet pipe. In order to minimize this length, mixer plates have been designed and welded to the outlet interface pipes so as to promote turbulence and swirl of the air flow to accelerate the homogenization of the temperature at the outlet (Fig. 5).

### 2.2. PREMUX ancillary systems

The air coming from L-STAR/LL is collected in buffer tanks (Fig. 6, top), which damp out the eventual pressure peaks in the installation and distributes the air into the 6+6 cooling channels of the test box. The criteria for dimensioning of the buffer tanks and positioning of the piping connections has been to minimize material and space while keeping enough volume to obtain a steady flow regime during the distribution of the air to the test box (Fig. 6, bottom). Without any regulation, the calculated mass flow distribution in each channel is $(3.00 \pm 0.23)$ g/s. In order to compensate the differences of mass flow in each channel, the mass flow is measured at the inlet with flow sensors IFM SD6000 and it is controlled then with flow regulators. In order to make the regulation of the flow in each channel independent from each other, the pressure drop $\Delta p$ between the two buffer tanks is measured with a differential pressure sensor (ABB 26SDS) and it is used as the feedback signal in a PID controller, which keeps $\Delta p$ constant for better control of the mass flow in the cooling channels.

### 2.3. L-STAR/LL loop and PREMUX schematic diagram

PREMUX is integrated in the air loop L-STAR/LL (Fig. 7). It is formed by two parallel branches of three side channel blowers of 18 kW, which are able to give a mass flow up to 660 g/s. One of the branches is disabled nevertheless, as it is not needed for PREMUX, so only blowers LL-CP-1B to LL-CP-1B are used (Fig. 7). The air is cooled down after each blower with water cooled heat exchangers.

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**Fig. 4.** CFD analyses of the air coolant. Top: 25 mm $\times$ 25 mm channel; bottom: 36 mm $\times$ 12 mm channel.

**Fig. 5.** Thermo-hydraulic analysis of the air coolant at an outlet interface pipe: design of the mixer plates.

**Fig. 6.** Top: general picture of the ancillary. Bottom: CFD calculation of the air distribution at the inlet buffer tank.
(LL-HX-1B, LL-HX-2B and LL-HX-03). The air temperature is monitored (LL-TT sensors) before and after each blower, as well as the absolute pressure (LL-PA sensors). The water cooling is regulated through electrical control valves from the Control Tool.

A battery of frequency drives modulates the line voltage frequency of the blowers to adapt their velocity in order to reach the desired air mass flow.

However, the mass flow in the loop is not directly regulated from the Control Tool, but instead, \( \Delta p \) is controlled in the test section to ease the regulation of the air mass flow in each cooling channel of PREMUX, as described in Section 2.2.

The \( \Delta p \) control is executed by a PID controller, which has been included in the Control Tool. An option for controlling the frequency drives manually is also available. The schema of the \( \Delta p \) control loop in PREMUX is shown in Fig. 8.

### 2.4. PREMUX Control Tool in LabVIEW

A Control Tool program has been developed in LabVIEW for monitoring and acquisition of data in PREMUX. The program consists of three panels: the first for the heater control and data acquisition of the temperatures in the pebble bed and the second and third for the monitoring and control tasks of the ancillary and L-STAR/LL loop systems respectively. The first panel (Fig. 9) contains all controls for regulating the power in each heater block and the central wire heater for the thermal conductivity tests under a friendly user interface. The program allows as well controlling the heater blocks automatically performing power cycles reproducing the ITER pulses. In this panel, a thermal map reconstruction is performed by means of a two-dimensional biharmonic spline interpolation (BSI) [10] of the temperature measurements in the test section (Fig. 10, top).

The BSI is based on the biharmonic equation:

\[
\nabla^4 w(x) = \sum_{j=1}^{N} \alpha_j \delta(x - x_j) \tag{4}
\]

where \( x \) is an arbitrary position in \( \mathbb{R}^m \), \( x_j \) is the \( j \)-th of the \( N \) data points available (non-homogeneous spaced “point forces” where the \( m \)-dimensional spline has to pass through) and \( \alpha_j \) is a parameter representing the strength force at \( x_j \). The general solution for (4) is:

\[
w(x) = \sum_{j=1}^{N} \alpha_j \phi_m(x - x_j) \tag{5}
\]

Imposing that:

\[
w(x_j) = \sum_{j=1}^{N} \alpha_j \phi_m(x_j - x_j), \forall i : 1 \leq i \leq N \tag{6}
\]

the parameters \( \alpha_i \) can be then found by solving the resulting linear system of equations. For \( m = 2 \) dimensions, \( \phi_j \) takes the form of the following Green’s point force biharmonic function:

\[
\phi_2 = |x|^{1/2} \ln(|x|) - 1, \forall i : 1 \leq i \leq N \tag{7}
\]

The BSI procedure is enough stable and fast for running it in real time during the experiment, provided that the number of locations to interpolate is not too large. For example, the BSI works still fine interpolating a grid of 55 by 35 points at a sample rate of 500 ms.

### 3. Experimental campaign

There are three types of experiments are planned in PREMUX: (1) steady state power runs, (2) runs reproducing ITER power pulses and (3) runs for determination of the pebble bed thermal conductivity. Additional runs checking the robustness of the system toward...
variation of the purge gas pressure and the coolant mass flow are planned as well.

In the first type, a constant air coolant mass flow in each cooling channel \( (m_{\text{air}} = 3 \text{ g/s}) \) and test section pressure drop are kept constant. The power deployed in each heater block is increased progressively and temperature measurements in the pebble bed cross section under study in the steady state are taken. This test runs will be used as benchmark for the validation of two finite element models developed in ANSYS. The first is a pure thermal model, assuming negligible volumetric inelastic strains \( c^\text{el} = 0 \) in the Li4SiO4 as a conservative approach. The second is a coupled-thermo-mechanical model using the so-called Extended Drucker-Prager Cap plasticity model. Preliminary results (Figs. 10 and 11) show good agreement with the thermal model. The thermo-mechanical model is still under development and its validation with the experimental results from PREMUX will follow during 2014.

In the second type, ITER pulse runs will be reproduced in the heater block to check the performance of the heaters under cyclic loads and relatively fast transients. The pebble bed temperature will be measured as well.

The third type of run will be dedicated for determining the thermal conductivity of the Li4SiO4 by pulsed HWM \([7,11,12]\). At an instant \( t_0 = 0 \) the central wire heater is switched on, deploying a power \( q \) per unit length of the central heater. After a timespan of \( t_1 \) (enough to avoid initial transient effects in the heat transfer in the pebble bed), the closest thermocouple measures the temperature \( T \) of the Li4SiO4 at \( t_1 \) and \( \Delta T_1 = T(t_1) - T(t_0) \) is calculated. After some time \( t_2 \), \( \Delta T_2 = T(t_2) - T(t_0) \) is calculated again. With this data, the thermal conductivity of the pebble bed reads:

\[
k = \frac{q}{4\pi} \frac{\ln(t_2/t_1)}{\Delta T_2 - \Delta T_1}
\]  

(8)

Fig. 9. PREMUX Control Tool: main panel during operation.

Fig. 10. ANSYS thermal calculation (up) and thermal reconstruction of the measured cross section temperatures during operation (for a total heater power of 1437 W).

Fig. 11. Temperature profile in the symmetry plane (steady state, total heater power 1437 W).
4. Conclusion

The major design, rationale and constructive details of a pre-test mock-up experiment (PREMUX) as preparation for a future HCPB-BU test have been presented in this paper. For the first time, a heater concept aimed at reproducing the volumetric heating occurring in the HCPB-BU in a more realistic way than former plate heater concepts has been developed and its performance is being tested. As the thermocouple distribution in the pebble bed is non-uniformly distributed, the use of biharmonic spline interpolation (BSI) is very convenient to perform the thermal reconstruction of the pebble bed.

The experimental campaign with PREMUX is ongoing and complete results will follow in the first quarter of 2014. The validation of different pebble bed models developed for the HCPB-TBM BU in ANSYS is running using the experimental results of PREMUX as benchmark test.

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