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Critical heat flux experiments using a screw tube under DEMO divertor-relevant cooling conditions

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ABSTRACT

As part of the development of plasma-facing components (PFCs) for fusion machines, JAEA has been developing high-performance cooling tubes with pressurized water flow. Along this line, a cooling tube with a helical triangular fin on its inner surface has been recently proposed for application in a fusion DEMO to enhance heat removal. Since the fin can be machined via simple mechanical threading, this tube is called as a “screw tube”. The divertor cooling conditions for the JAEA DEMO design will be a pressure of 4 MPa and an outlet temperature of 200 °C, in order to improve the thermal efficiency of power generation. In the this study, the effect of subcooling on the critical heat flux (CHF) by the screw tube has been investigated under DEMO divertor-relevant conditions, with the local pressure of 4 MPa and the inlet coolant temperature up to 180 °C. A test sample of the screw tube is made of pure Cu instead of F82H, a candidate structural material for the DEMO divertor. The results show that the ICHF values of the screw tube are more than double the values of the smooth tube at the inlet coolant temperature of 180 °C, although the temperature rise of the cooling water by 140 K leads to a reduction in the ICHF by almost half as compared with those values at room temperature.

1. Introduction

In a design of a fusion DEMO reactor proposed by JAEA [1,2], a divertor must handle a high heat flux greater than 10 MW/m^2, as must the ITER divertor [3]. In the design, the divertor is to be cooled by pressurized water flowing within a cooling structure inside high-heat-flux components in order to be consistent with a DEMO blanket coolant. The accommodation of such high heat loads gives rise to several engineering issues, which affect the performance and lifetime of the divertor components. These issues include the heat removal capability of the cooling structure. From this viewpoint, the critical heat flux (CHF) in the flowing pressurized water, which corresponds to the burnout-leading melting of the cooling tube wall, is a key issue influencing the choice of the cooling channel geometry and the coolant conditions. Extensive research on high heat flux removal using pressurized water have been carried out as part of ITER R&Ds up to now [4]. In one of these projects, JAEA has developed a high-performance cooling tube with a helical triangular fin on its inner surface. Since the fin can be machined via simple mechanical threading, this tube is called as a “screw tube” [5]. In our previous experiments, it was reported that heat removal using a screw tube made of pure Cu is twice as high as that of a smooth tube for inlet coolant temperatures at room temperature [6] up to 100 °C [7].

In order to use the screw tube in the divertor of the next fusion machine, like DEMO, CHF tests have been carried out in the present study to examine its heat removal capability at higher cooling water temperatures as compared with the previous experiments. We have also upgraded our experimental facility to circulate cooling water at up to 200 °C at 4 MPa, which are the design values of the JAEA's DEMO [8]. In addition, output signals from accelerometric equipment attached to the test sample are compared with those from the thermocouples embedded in the test sample to examine the applicability of the accelerometric equipment for burnout detection. For this purpose, we used the screw tube made of pure copper instead of “Reduced Activation Ferritic Martensitic” (RAFM) steel, so-called F82H, which is a candidate structural material for a DEMO divertor. As the thermal conductivity of F82H is about 10% of that of pure copper, and the thickness of the tube wall must be reduced, the burnout detection method using thermocouples embedded in the tube wall cannot be applied [9]. Therefore, a new burnout detection method must be developed to replace the thermocouples.

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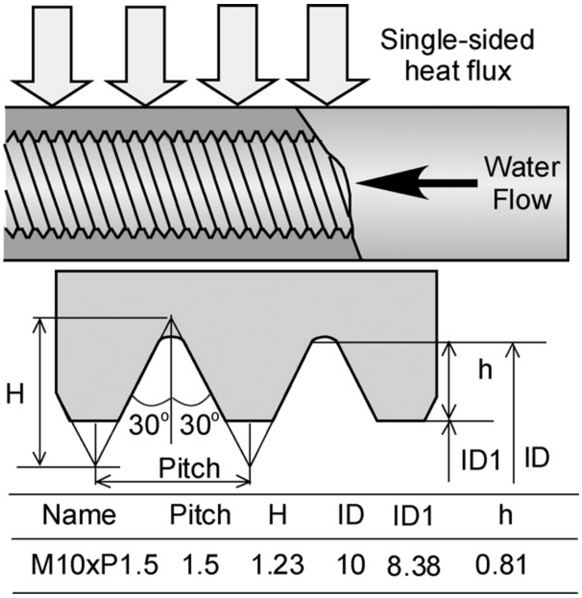

Fig. 1. Schematic view of the screw tube made of OFHC-Cu.

2. Experimental

2.1. Tube sample for CHF test

A sample for critical heat flux testing is shown in Fig. 1 The test sample is exposed to a heat flux from a single side by using hydrogen ion beam irradiation, and is cooled with pressurized water flowing inside the tube. The screw geometry is formed directly in a bare tube made of oxygen-free, high-conductivity copper (OFHC-Cu), using the ISO standardized metric screw thread of type M10 and 1.5-mm pitch. This geometry in the OFHC-Cu screw tube was confirmed to have the highest incident critical heat flux (ICHF) as compared to other screw geometries with various pitch sizes in the previous experiments [6]. The ICHF is defined locally on the outer surface using incident heat flux on the tube, although the CHF is usually defined on the cooling surface. As a reference, a smooth tube made of OFHC-Cu with outer and inner diameters of 14 and 10 mm, respectively, is also used in CHF testing.

Two kinds of burnout detection methods are applied to these test samples, as shown in Fig. 2. One is the usage of thermocouples embedded in the tube wall to measure the tube wall temperature. The other is the usage of accelerometric equipment to measure the vibration of the tube caused by the formation and collapse of the water vapor bubbles [10,11].

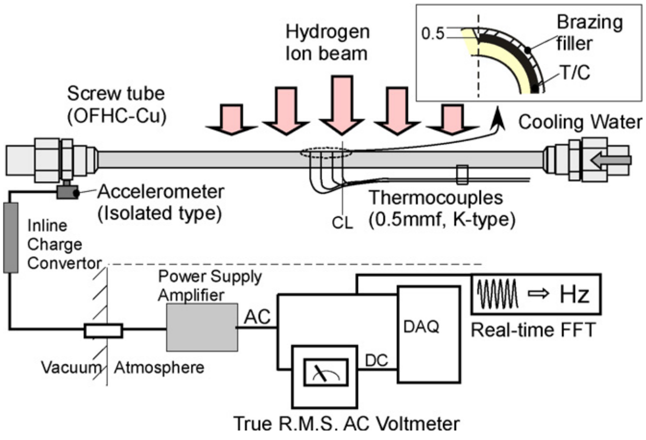

Fig. 2. Experimental setup of the CHF detection equipment.

The thermocouples (high-grade K-type, 0.5 mm OD), which have a response time of several milliseconds and an accuracy of ±4% for full scale, are brazed into the tube wall 0.7 mm below its surface with a filler material having a similar thermal conductivity to pure copper in order to minimize any obstacle to the heat flow in the tube wall. The tips of the thermocouples are located 0, 10, 20 and 30 mm downstream from the center of the test samples.

The accelerometer is directly mounted to the tube connector downstream of the test samples. This accelerometer is a charge-output type with a piezo-ceramic sensing element, which is connected to an inline-charge converter and a power supply with an amplifier. The output signal from the accelerometer is stored via a data-acquisition system by means of a true root mean square (RMS) AC voltmeter and a real-time fast Fourier transform (FFT) analyzer.

2.2. Experimental facility

The CHF testing is performed using the Divertor Acceptance Testing System (DATS), formerly known as the Particle Beam Engineering Facility (PBEF) [12]. DATS can generate an intense hydrogen ion beam up to 1.5 MW for durations lasting from 0.01 to 1000 s. DATS consists of a vacuum chamber, an ion source and a test bed with pressurized water circulation. The ion source is mounted as a heat source at the top of the vacuum chamber. The ion source consists of a source plasma generator and an acceleration grid system. In the source plasma generator, hydrogen plasma is produced by an arc discharge process using tungsten filaments. Only hydrogen ions are stably extracted by the acceleration grid system for beam energies ranging from 16 to 50 keV with a beam current up to 30 A. In the present experiment, the sample is placed in the test bed in the vacuum chamber to form a horizontal flow. The ion beam hits the center of the test sample. The cooling water system has recently been upgraded to simulate the DEMO divertor cooling conditions [8], in which the pressure and temperature of coolant are 4 MPa and 200 °C, respectively.

The incident heat flux profiles on the test sample are measured by a movable multichannel calorimeter mounted on the test bed. The multichannel calorimeter has an array of small copper chips parallel to the test sample and perpendicular to it. The incident heat flux is calculated from the temperature rise in the Cu chips

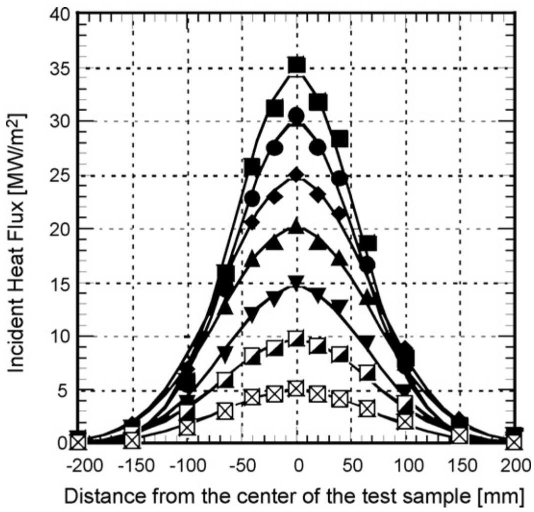

Fig. 3. Heat flux profiles at the sample position.