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High heat flux tests at divertor relevant conditions on water-cooled swirl tube targets

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High heat flux experiments were performed to provide a technology for heat flux removal under NET/ITER relevant conditions. The water-cooled rectangular test sections were made of hardened copper with a stainless steel twisted tape installed inside a circular channel and one-side heated. The tests aimed to investigate the heat transfer and the *critical* heat flux in the subcooled boiling regime. A CHF data base of 63 values was established. Test results have shown the thermalhydraulic ability of swirl tubes to sustain an incident heat flux up to a 30 $MW.m^{-2}$ range.

1. PERFORMED TESTS

Heat load experiments on several divertor test sections were performed by CEA in collaboration with NET. Seventeen test campaigns [1] were carried out using the 200 kW Electron Beam Facility (FE 200) of CEA/Framatome [2]. A wide range of water thermalhydraulic conditions (inlet temperature : 50 - 100 - 150 - 170°C, inlet velocity : 3 - 5 - 10 - 15 $m.s^{-1}$, pressure : 1.0 - 2.0 - 3.5 MPa) and various geometries (internal channel diameters : 10 - 14 - 18 mm) were tested. The mock-up was horizontally positioned in the facility vacuum chamber.

The facility is equipped with a CCD camera and an infrared camera from Inframetrics in order to view the mock-up surface behaviour during the tests. The required heat flux is established by computer controlled sweeping, of a power and a density depending on the power density required. The control system allows accurate adjustment of the power densities onto the exposed area. The beam sweeping was alternatively put 80 s on the mock-up and 5 s on the beam dump. The CHF was detected on infrared image. A normal image should have two hot lines on the mock-up edges. When increasing stepwise the incipient power, these two lines spread and reached each other in the middle of the mock-up producing a hot spot, the CHF was considered to start and the power increase was stopped in order to spare the mock-up.

2. HEAT TRANSFER IN THE SUBCOOLED BOILING REGIME

2.1. Finite element calculations and correlation agreement with tests

All the tests were accompanied by Finite Element (F.E.) calculations using the CASTEM 2000 code [3] developed by CEA. Special developments were made to take into account the variations of the heat transfer at the water wall : various correlations have been preinstalled in order to simulate the pure convective [4] (Dittus Boëlter, Sieder-Tate, Pethukov) and the subcooled boiling regime (Thom [5], Thom CEA, Jens and Lottes [6]). The Bergles and Rohsenow method [7] allows the two curves to be connected (Figure 1).

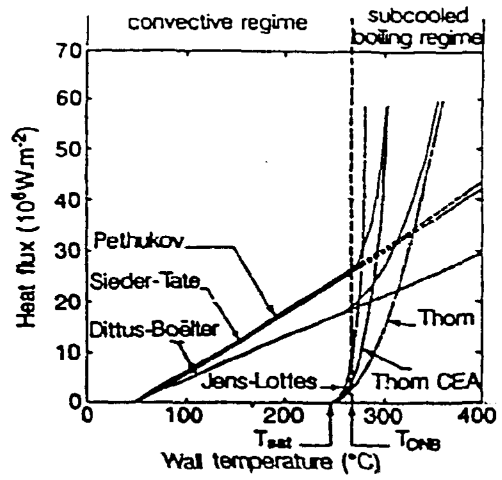


Figure 1. Preinstalled correlations in CEA-code

The heat transfer coefficient is evaluated by the code at the beginning of the calculation as a T_w function (in the subcooled boiling region $H = \Phi/(T_w - T_{bulk})$). During the calculation an iterative method is used because of the temperature dependency of the material properties and of the heat transfer coefficient [8].

The test section was equipped with 4 to 10 thermocouples to measure the temperature at various depths. The test thermocouple measurements are compared with the calculated temperatures for various correlations [1]. The best agreement was found using Sieder-Tate and Thom CEA correlations (Figure 2).

2.2. Heat flux concentration at the water wall

Two different approaches are proposed to evaluate the wall critical heat flux (WCHF). The WCHF is calculated by multiplying the IBHF by the peaking factor (p.f.). In an engineer approach (Eng. WCHF) the geometrical p.f. is defined as the ratio of the width upon the internal channel diameter of the mock-up. An another proposed approach (F.E. WCHF) is to take into account the maximum wall heat flux (WCHF max.) obtained by F.E. calculation (Figure 3), the F.E. p.f. being defined as the (WCHF max.) upon the IBHF.

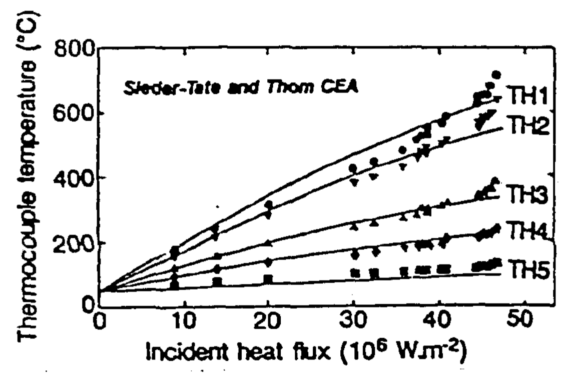


Figure 2. Test/calculation temperature comparison (Sieder-Tate and Thom CEA correlations)

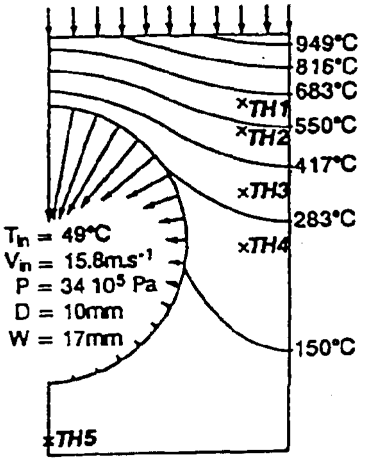


Figure 3. Example of F.E. calculation

The F.E. WCHF increases with outlet subcooling as the IBHF, higher the water inlet temperature, higher the F.E. WCHF (Figure 4).

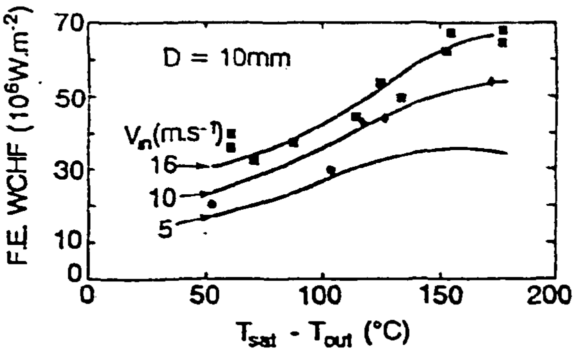


Figure 4. F.E. WCHF vs outlet subcooling (D = 10 mm)

3. CRITICAL HEAT FLUX CORRELATION

The CEA CHF data have been compared with Tong 75 correlation [1] [9] and Celata 94 model [10].

The Tong 75 correlation refers to a near wall bubble crowding model. As plotted in Figure 5, the ratio predicted WCHF using Tong 75 correlation upon F.E. WCHF is clearly 0.6 for a 10 mm internal channel diameter.

The Celata 94 model is a liquid sublayer dry-out model. As shown in Figure 6, the results are quite similar to the Tong 75 correlation.

The CHF can also be analysed in terms of adimensionnal numbers, for example, the Boiling number (Bo), the Jakob number (Ja) and the Reynolds number (Re_H) :

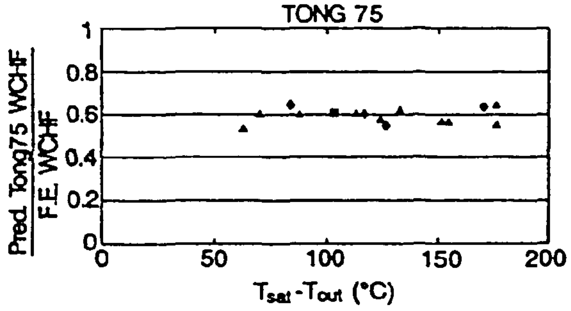
$$Bo_{crit} = \frac{\Phi_{crit}}{\rho_\ell V i_{fg}} \qquad (1)$$

$$Ja = \frac{\rho_\ell}{\rho_g} \frac{C_p (T_{sat} - T)}{i_{fg}} \qquad (2)$$

$$Re_H = \frac{V D_H}{\nu_\ell} \qquad (3)$$

In that case, Tong 75 correlation can be rewritten as :

$$Bo_{crit} = 1.84\left(\frac{D_H}{12.7\;10^{-3}}\right)^{0.32} Re_H^{-0.6} \qquad (4)$$
$$\left[1 + 0.00216\left(\frac{P}{221\;10^5}\right)^{1.8} Re_H^{0.5}\, Ja\right]$$



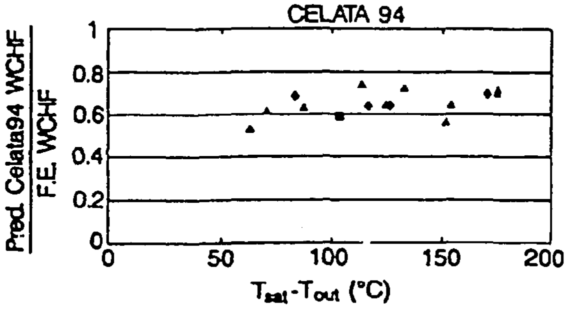


Figure 5. Comparison with Tong 75 correlation

Figure 6. Comparison with Celata 94 model

A comparison between test results and Tong 75 correlation divided by a 0.6 factor is given Figure 7.

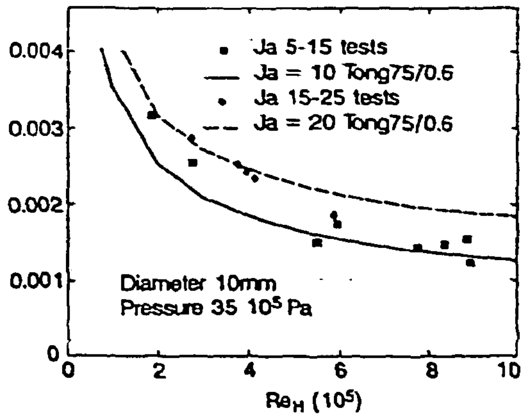


Figure 7. Adimensionnal analysis Bo_{crit} vs Re_H

4. CONCLUSION

A choice of correlation was made and incorporated in Finite Element (F.E.) calculations in order to simulate the heat transfer (pure convective and subcooled boiling regime). A good agreement was found between calculations and temperatures measured by side wall thermocouples during the tests.

An analysis methodology was chosen in order to estimate the critical heat flux (CHF) at the water wall : for the tested geometries the maximum heat transfer in the water channel was retained. CHF was analysed versus outlet subcooling. The Tong 75 correlation foresaw well these CHF variations but a corrective factor depending on the geometry was necessary for absolute prediction. Data were also compared with Celata 94 model which gave the same kind of agreement.

These results give a better knowledge of such high heat flux test sections and allow design of high heat flux elements to be done. They have confirmed the thermalhydraulic ability of these tubes to sustain an important incident heat flux up to a range of 30 MW m^{-2}.

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