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THERMAL-HYDRAULIC TESTS ON NET DIVERTOR TARGETS USING SWIRL TUBES

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1 - INTRODUCTION

Thermal-hydraulic tests have been carried out in collaboration between NET, CEA Cadarache and JET in order to find a cooling method capable of removing the high heat fluxes expected for the NET/ITER divertor.

The goal was to evaluate by experiments the critical heat flux (CHF) and heat transfer in the subcooled boiling regime using twisted tapes as turbulence promoters and testing them under relevant thermal-hydraulic conditions.

The CEA 200 kW Electron Beam (EB) facility and the 10 MW JET Neutral Beam (NB) test bed have been used to heat up the NET relevant test sections (TS) consisting of rectangular copper elements with circular internal channels. The TS have been exposed to the electron or ion beams under normal incidence.

This paper reports the results of the experiments and of thermal analyses performed in support of the tests. The experimental CHF values have been benchmarked with the Tong-75 correlation.

2 - TEST FACILITIES

2.1 - The CEA Electron Beam

The CEA test facility is a 200 kW electron gun. The required heat flux is established by computer controlled sweeping with a power and a frequency according to the required power density. The control system allows a good adjustment of the power densities onto the exposed area. The TS are positioned horizontally (Fig. 1). For the reported tests, an open cooling loop was used with an inlet pressure of 0.4 MPa. The coolant loop can supply water at pressures up to 4 MPa and temperatures up to 230°C with a mass flow of about 1.6 kg/s.

2.2 - The JET Neutral Beam Test Bed (NBTB)

The heat flux is produced by a high power hydrogen ion beam up to 1.5 MW and an energy up to 80 keV. The TS are positioned vertically. The maximum pressure and inlet temperature of the coolant are 0.9 MPa and 50°C respectively. Maximum mass flow is 1.24 kg/s. This facility has a closed water circuit with heat exchangers.

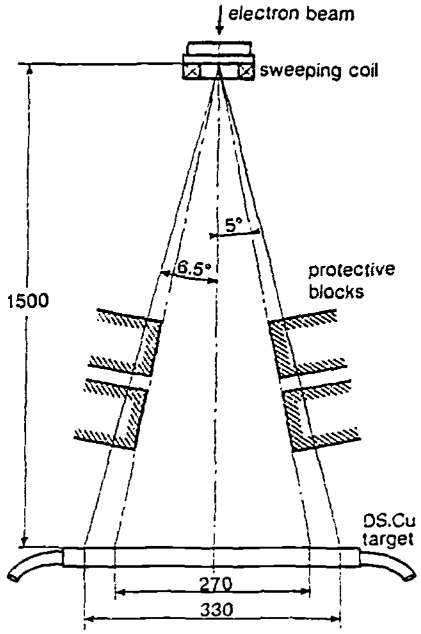


Figure 1 : CEA TEST ASSEMBLY

3 - TEST SECTIONS

Five different TS have been tested (1.a and 1 b at CEA ; 2.a, 2.b and 2.c at JET). They consist of rectangular sections with an internal circular channel in which a twisted tape is positioned. The cross-sections and geometrical data are shown in Table 1. The geometric parameters of interest from the thermal point of view are : the internal diameter D_i, the width l and the thickness t between the surface and the cooling channel.

All the TS except TS 2.a are made of dispersion strengthened copper (made by Outokumpu Copper, 28101 Pori, Finland). TS 2.a is made of a copper chromium zirconium alloy (made by Zollern Stahl & Metallfabrik. Sigmaringen, Germany). The twisted tape is made of stainless steel, twist ratios ranged from 2 to 2.5.

At JET two TS were mounted side by side for each test campaign in order to shield the support structures behind the exposed elements. A gap of nominally 2 mm was left to determine the power density with a vertical calorimeter array behind the elements (Fig. 2).

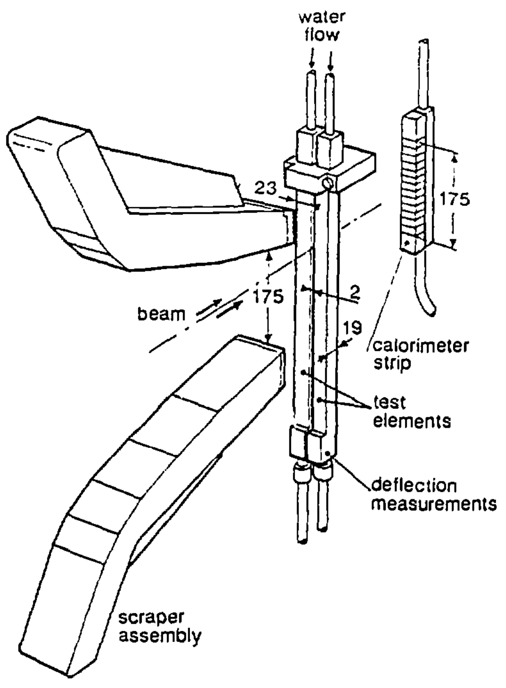


Figure 2 : JET TEST ASSEMBLY

4 - INSTRUMENTATION

For the tests at the CEA EB facility only thermocouples, pressures gauges and flow meters were used for monitoring and recording the test conditions.

The JET NBTB is equipped with vertical and horizontal Cu calorimeter blocks, infrared camera, pressure gauges and turbine flow meters. Thermocouples were also present in the TS and in the coolant loop for water calorimetry.

5 - DESCRIPTION OF THE TESTS AND MAIN RESULTS

The critical heat flux at the cooled wall (WCHF) can be approximated by multiplying the incident CHF (ICHF), defined as the impinging power per loaded element area, by a peaking factor defined as the ratio of element width over the diameter of the internal cooling tube, l/d. The resulting CHF value may not exactly coincide with the peak heat flux at the wall but takes into account both the maximum flux and the length of the circumference superheated. This engineering approach was used to obtain an estimated but immediate comparison between tests.

5.1 - Tests at CEA

TS type 1.a with 10 mm D_i and 1.b with 14 mm D_i were tested with the EB at CEA. For each TS the water velocity and the heated length were varied, keeping the average pressure constant. The power density was increased stepwise until the beginning of a burn out event was detected by the thermocouple response (Fig. 3) and by visual inspection. Due to the relatively long time constant of the TS physical melting was avoided in most cases by switching off the beam manually. During the stepwise ramp up of the EB power, data at steady state were collected to evaluate the heat transfer.

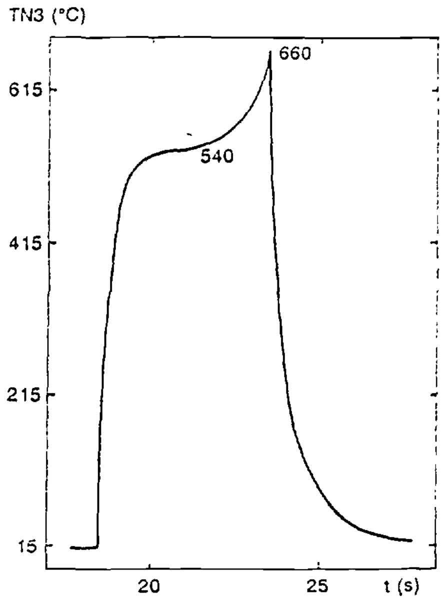


Figure 3 : THERMOCOUPLE RESPONSE AT CRITICAL HEAT FLUX

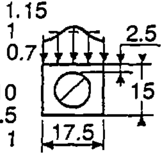
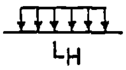
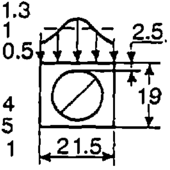
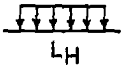
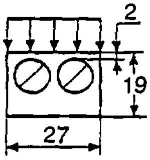
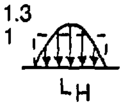
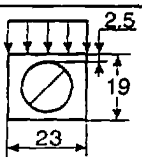
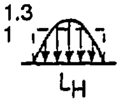
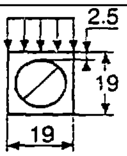
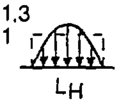
For one TS the EB power and the water velocity were kept constant and the heated length was varied parametrically.

The relevant test parameters and the results are summarized in Table 1. It was possible to remove more than 60 kW from tubes of 10 mm D_i, with a velocity of 8 m/s. The typical outlet subcooling was 50 to 70°C.

5.2 - Tests at JET

Three types of TS were tested in the JET NBTB : TS type 2.a with twin channels of 10 mm D_i, TS type 2.b and 2.c with a single channel of 14 mm D_i. Parameters varying during the tests were the water velocity and the inlet temperature. The length of the exposed zone (175 mm) was fixed by the beam scrapers. The longitudinal (vertical) profile is approximately gaussian with a 1/e half width between 140 and 170 mm. The vertical and horizontal beam profile were measured periodically by means of a retractable calorimeter array in front of the test elements. The total power was derived from water calorimetry. Knowing the total power, the ICHF was determined from the integral of the power density profile received by the vertical array of 13 calorimeters blocks behind the elements (Fig. 2).

Table 1 : Input data and main results

geometry and incident flux profile	longitudinal flux profile	main results								tested at
			T in (°C)	L_H (mm)	V (m/s)	Pmean (MPa)	W (kW)	ICHF (MW/m²)	WCHF (MW/m²)	
TS 1a ø10 twist ratio 2.5 tape thickness 1 		1)	20	89	6.8	0.2	31.7	22.2	39	CEA
		2)	20	89	3.5	0.2	30.8	21.6	38	
		3)	20	164	3.5	0.2	51.3	20.0	35	
		4)	20	164	8.1	0.2	64.1	>24.0	>42	
		5)	20	109	8.1	0.2	62.7	32.3	56.5	
		6)	20	114	8.1	0.2	63.3	32.5	57	
TS 1b ø14 twist ratio 2.5 tape thickness 1 		1)	20	114	4	0.2	56	29.3	45	CEA
TS 2a ø10 twist ratio 2 tape thickness 0.8 		1)	50	175	7	0.3	104	24	32.4	JET
		2)	15	175	7.2	0.55	100	27	36.5	
		3)	15	175	8.5	0.5	100	27	36.5	
TS 2b ø14 twist ratio 2 tape thickness 0.8 		1)	15	175	9	0.56	108	33	54	JET
		2)	15	175	5	0.85	80	26	43	
		3)	50	175	5	0.87	80	23	38	
TS 2c ø14 twist ratio 2 tape thickness 0.8 		1)	15	175	9	0.56	116	38	52	JET

The evaluation is as follows. The relation between the peak power density F_{max} and the total power, W, can be written as :

$$F_{max} = W / f_w \qquad (1)$$

where f_w is a factor determined by the vertical beam profile received by the blocks. Since the horizontal profile variation across the element width l is negligible the profile factor f_w can simply be determined from the integral (sum) of the vertical line power density profile on the blocks :

$$f_w = \frac{\left(l\, h \sum_{i=1}^{13} \Delta T_i \right)}{\Delta T_{max}} \qquad (2)$$

Here h is the height and ΔT_i the temperature rise of each individual block, ΔT_{max} is the maximum temperature rise measured. As W is measured independently by water calorimetry and f_w is determined at each shot, F_{max} is easily derived from eq. (1).

The advantage of the method is that it provides a power density measurement suited for long pulses and that it is valid also for non-gaussian profiles. It is also independent of the gap width which might change during the pulse due to thermal expansion.

The power density was stepwise increased until thermal burn out was approached. Destructive melting was avoided for TS 2.b and 2.c using thermal safety interlocks. Only a small local melted zone was observed showing that destruction was near. Destructive melting could not be avoided in the case of TS. 2.a.

The results are shown in Table 1. For TS 2.b and 2.c the ICHF was 33 and 38 MW/m² and the estimated WCHF 54 and 52 MW/m² respectively. For TS 2.b it was possible to remove 108 kW ; the result is even better, 116 kW, for the more favourable geometry of TS 2.c with a mean pressure of 0.56 MPa, an outlet temperature of 37°C and a water velocity of 9 m/s (See Fig. 4).

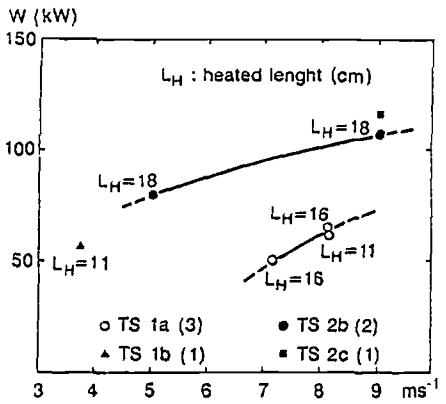


Figure 4 : POWER REMOVED PER TUBE AT CHF VERSUS WATER VELOCITY

The results obtained for the various tests are compared in Table 2. With the view of the NET/ITER divertor we have also included in Table 2 the power per meter which can be removed by an array of elements. The best power handling capability is obtained with the TS 2.c.

Table 2 : Comparison of power handling capability of the T.S.

TS N°	Int. tube diam. D_i mm	Width l mm	ICHF MW/m^2	Peaking factor l/D_i	Power/ meter MW/m
1.a	10	17	32	1.75	3.6
2.b	14	23	33	1.64	4.7
2.c	14	19	38	1.36	6.1

6 - FINITE ELEMENT CALCULATION

6.1 - Correlations used for heat transfer

In order to compute the temperature distribution in the TS cross-section, the heat transfer coefficient has been evaluated as a function of the wall temperature T_w. The following correlations have been used :

1. Dittus-Boelter[1,2] for $T_w < T_{onb}$

$$H_c = 0.023\ f\ R_e^{0.8}\ P_r^{0.33}\ \lambda/D_h$$

where
λ = conductivity of the water
D_h = hydraulic equivalent diameter 4 S / P
P_r = Prandtl number
R_e = Reynolds number, $R_e = \rho\ D_h\ V / \mu$
ρ being the density and μ the viscosity of water.

The effect of the twisted tape is taken into account by :

- using an equivalent diameter D_h
- increasing the velocity by :

$$V = V_L\ (1 + \pi^2 / 4\ y^2)^{0.5}$$

V_L being the longitudinal velocity and y the twist ratio (inside diameters /180° of tape twist).

- a fin effect factor f of 1.15.

T_{onb} (Onset of Nucleate Boiling Temperature) is calculated by the Bergles-Rohsenow[3] correlation.

2. Thom[4] correlation for $T > T_{onb}$

The heat flux transferred by nucleate boiling is :

$$F_B = 10^6\ (\ e^{P / 87E5}\ (T_w - T_{sat}) / 22.65\ )^2$$

and the total flux (boiling and convection combined) is written as :

$$F_w = \sqrt{F_c^2 + F_B^2\ (1 - F_0 / F_B)^2}$$

F_0 being F_B at $T_w = T_{onb}$ and
$F_c = H_c\ (T_w - T_{bulk})$.

A variable heat transfer coefficient can then be defined as :

$$H_w = F_w / (T_w - T_{bulk})\ .$$

An example of the wall heat flux as a function of T_w is given in Fig. 5.

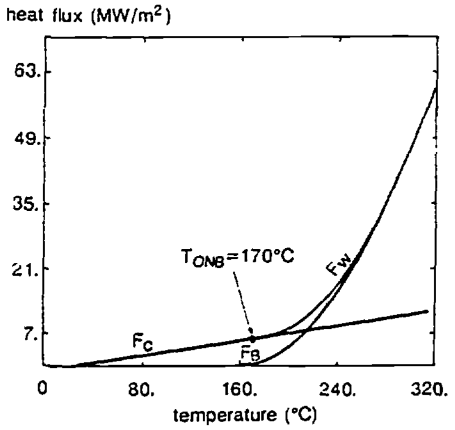


Figure 5 : WALL HEAT FLUXES VERSUS T_W

6.2 - Analysis

The FEM calculations are done with an iterative method, using the CASTEM 2000 code[5]. Starting with a predefined $T_w = T_{bulk}$ and correcting the wall heat flux gradually until the results converge. Material properties are taken temperature dependent.

The results are shown in Fig. 6 and 7 for the TS 2.c case 1. In Fig. 6 the isotherms are plotted and the vectors indicate the heat flux. In Fig. 7 the heat flux at the tube wall is plotted along the wetted perimeter.

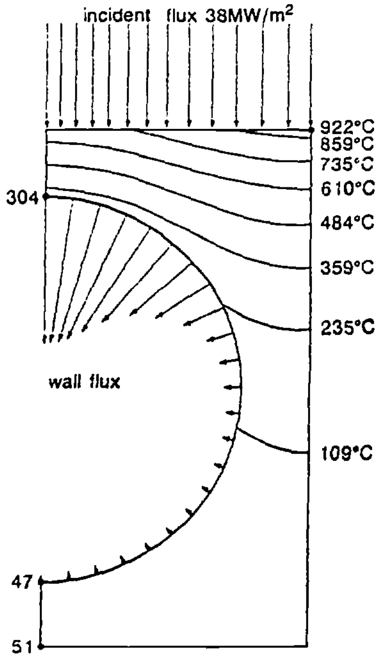


Figure 6 : TEMPERATURE ISOVALUES, TS 2c

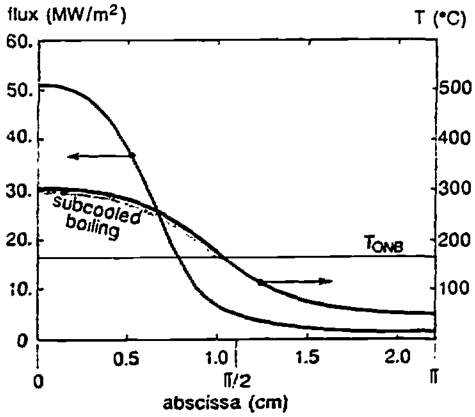


Figure 7 : FW AND TW VERSUS CIRCULAR WETTED PERIMETER, TS 2c - INCIDENT FLUX : 38 MW/m²

Calculated temperatures have been compared with the ones measured in the side wall in order to verify the correlations used. A typical example of this is given Fig. 8 for test 2b1.Good agreement has been found.

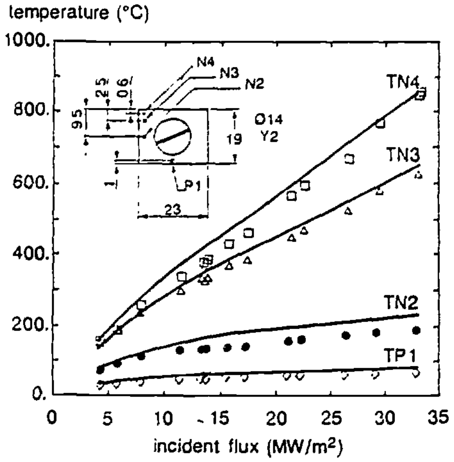


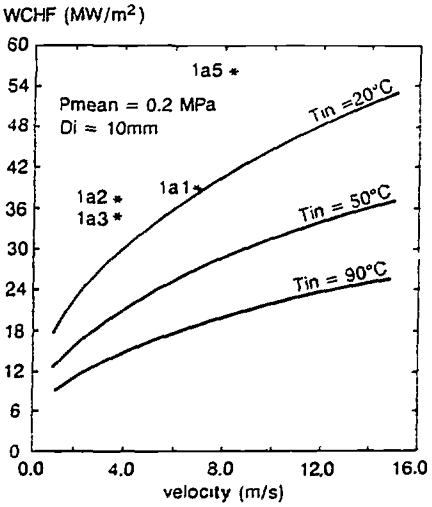
Figure 8 : TYPICAL COMPARISON BETWEEN MEASUREMENT (□ △ ● ◇) AND F.E. CALCULATIONS (——)

7 - PREDICTION OF CRITICAL HEAT FLUX

The correlation used is the Tong-75 correlation[6].

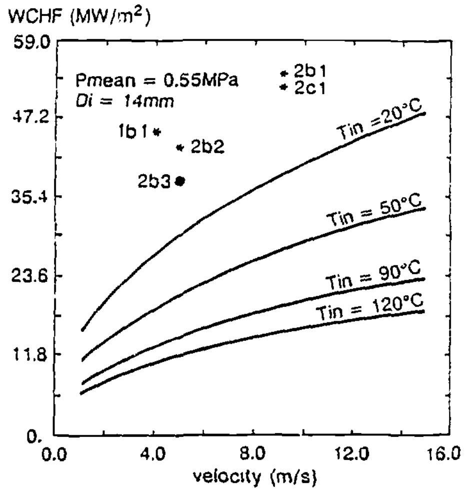
Reynolds number R_e, Velocity V and equivalent diameter D_h are used as defined in § 6.1. No additional friction factor was taken in account.

Until now this correlation was found to be correct in our tests at low pressure (see Figures 9 and 10, but note that the calculated curves are given at fixed outlet conditions which can be different from tests).



Each curve is calculated with water outlet conditions corresponding to W = 63 kW

Figure 9 : TONG 75 CORRELATION FOR 1a TESTS



Each curve is calculated with water outlet conditions corresponding to W = 108 kW

Figure 10: TONG 75
CORRELATION FOR 1b, 2b AND 2c TESTS

8 - CONCLUSIONS

Thermal-hydraulic tests on rectangular copper sections with internal circular bores equipped with swirl tapes have been performed using electron and ion beam facilities. A maximum incident CHF on the exposed surface of up to 38 MW/m^2 has been measured corresponding to a CHF at the wetted tube wall of over 50 MW/m^2. It has been shown that these TS are capable of handling high powers comparable to the values envisaged for the NET/ITER divertor.

The calculations are in good agreement with the test results. The Tong-75 correlation for the prediction of the CHF yields good results in the range of our test conditions. New tests are in preparation and variation of the CHF with pressure up to 4 MPa will be studied.

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