§ 13. Thermal Analysis on Mono-block Type Divertor Based on Subcooled Flow Boiling CHF Data against Inlet Subcooling in Short Vertical Tube

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Large Helical Device (LHD) has two types of divertor element. One is Mono-block type (Cylindrical one), the other is Flat-plate type (Rectangular one). It is important to clarify the relation between the uniform heating CHF data, $q_{cr,sub}$, on the test tube heated by a steadily increasing current and the one-side heating CHF data, $q_{cr,inc}$, on the divertor element heated by an electron beam facility with the effect of the cooling tube length. We make the thermal analysis of the Mono-block type divertor based on the CHFs and the HTCs data for the tube length, L, of 49, 99 and 149 mm with 9-mm inner diameter, give the ratio of the $q_{cr,inc}$ to the $q_{cr,sub}$ and establish the database for the high heat flux thermal management at the divertor [1].

Mono-block Type Divertor

The cross-sectional view of Mono-block type divertor is shown in Fig. 1. The divertor is made of the oxygen-free copper cooling tube with 10 mm inner diameter and 1.5 mm thickness, and the carbon armor (CX2002U) with 33 mm outer diameter and 10 mm thickness. The cooling tube is located in the center of the carbon armor. The carbon armor is brazed to the cooling tube. The heated lengths of the divertors are given as 49, 99 and 149 mm in this work. The high heat flux heat removal is achieved by the following way; the heat induced by collecting the high heat flux flow and the high energy particles on the carbon armor upper surface is transferred to the highly subcooled and pressurized water due to the forced convection and nucleate boiling heat transfer on the inner surface of the cooling tube. It was supposed that the lower surface is under the adiabatic conditions because the divertor are equipped in the vacuum chamber.

Numerical Analysis

The $(q_{wall})_i$ on the carbon armor upper surface are given as the values calculated from the incident heat flux, q_{inc}, at every $\pi/18$ for θ ranging from $\pi/2$ to π. The q_θ on the inner surface of the cooling tube are given with the aid of the relation between the heat flux, q, and the surface temperature, T_s, previously measured based on the surface temperature of the cooling tube numerically analyzed at every $\pi/18$ for θ ranging from 0 to π.

Influence of heated length

The numerical solutions of q_{inc} for the heated length, L, of 49, 99 and 149 mm are shown in Fig. 2 with the circle, triangle and rectangle symbols. The q_{inc} values with and without the transition to film boiling are shown as the solid and open symbols respectively. The incident critical heat flux, $q_{cr,inc}$, is defined as the maximum value of q_{inc} without the steep increase of T_{wall} due to the surface temperature on the cooling tube increasing to that of the film boiling regime (F-B). The $q_{cr,inc}$ value is around 14 MW/m^2 at the L/d of 4.9. They become lower with an increase in the L/d and finally arrive at the value of about 12 MW/m^2 at L/d of 14.9. The $q_{cr,inc}$ value becomes 14.3 % lower with an increase in L/d from 4.9 to 14.9. The critical heat fluxes, $q_{cr,sub}$, for uniformly heated tube are also shown in this figure for comparison. The $q_{cr,inc}$ values show nearly the same trend of dependence of q on L/d as $q_{cr,sub}$, although they are almost 38 % lower than the latter.

Comparison with uniform heating data

The ratios of the calculated q_{inc} for the Mono-block type divertor and the Flat-plate type one with the cooling tube diameter of 10 mm at the pressures of 594 kPa to 1 MPa to the experimental data of $q_{cr,sub}$ with the SUS304 tube of 9 mm inner diameter at the same pressure condition, $q_{inc}/q_{cr,sub}$, are shown versus A (=D/d or w/d) in Fig. 3. The calculated values of the $q_{cr,inc}$ for the heated length of 49 to 149 mm with the flow velocity of 6.9 to 13.3 m/s at the inlet pressure of 594 kPa to 1 MPa are approximately expressed by the following correlation.

$$\frac{q_{cr,inc}}{q_{cr,sub}} = 0.97\, e^{-\frac{A}{6.4}} \qquad (1)$$

where A=D/d for Mono-block type divertor and A=w/d for Flat-plate type one. The $q_{cr,sub}$ are expressed by the following equation.

$$Bo = 0.082\left\{\frac{d}{\sqrt{\sigma / g(\rho_l - \rho_g)}}\right\}^{-0.1} We^{-0.3}\left(\frac{L}{d}\right)^{-0.1} e^{-\frac{(L/d)}{0.53\,Re^{0.4}}} Sc^{*0.7}$$

for inlet subcooling ($\Delta T_{sub,in}$≥40 K) (2)

where Bo=q_{cr}/Gh_{fg}, Sc^*=$c_{pl}\Delta T_{sub,in}/h_{fg}$, We=$G^2 d/\rho_l\sigma$. Saturated thermo-physical properties were evaluated at the outlet pressure.

The $q_{cr,inc}$ value for higher pressures can be predicted by using Eqs. (1) and (2). The $q_{cr,inc}$ value thus derived for the inlet pressures of 0.5, 1 and 2 MPa at the flow velocity of 10 m/s with the inlet liquid temperature of 308.15 K are shown in Fig. 4 as a curve for each value of the pressure. The $q_{cr,inc}$ value for L=50 mm becomes higher than 20 MW/m^2 with the decrease in the A smaller than 2 for the pressure of 2 MPa. Those for L=100 and 150 mm becomes higher than 15 MW/m^2 with the decrease in the A smaller than 3.3 and 2.6 for the pressure of 2 MPa respectively.

References

1) Hata K. et al.: *Proc. of 11th International Conference on Nuclear Engineering*, Paper No. ICONE11-36118 (2003) 1.

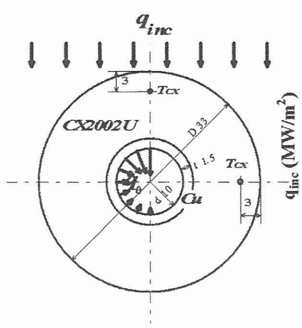

Fig. 1 Cross-sectional view of Mono-block type divertors.

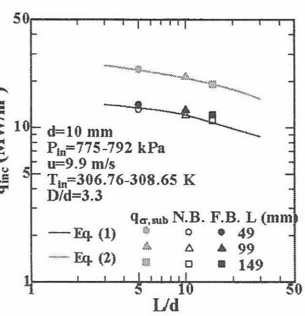

Fig. 2 Relationship between q_{inc} and L/d for D/d=3.3.

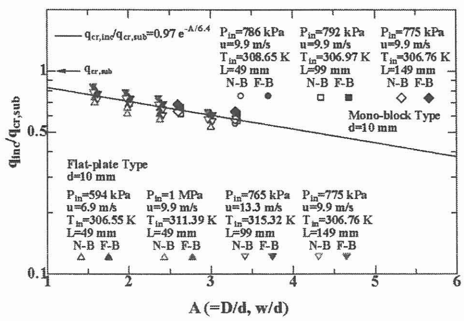

Fig. 3 Relationship between $q_{inc}/q_{cr,sub}$ and A (D/d, w/d) for L=49, 99 and 149 mm.

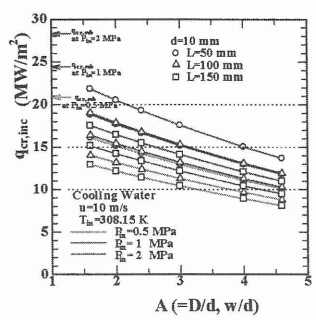

Fig. 4 Relationship between $q_{cr,inc}$ and A (D/d, w/d) at P_{in}=0.5, 1 and 2 MPa.