Porous Coating Influence on Heat Exchange Crisis in Circular Cooling Channels at One-Sided Loading

Investigation aims:

- Porous coating performing test data (obtained before on small-scale mock-ups at uniform one-sided heat loading) verification by test on medium-scale mock-ups.
- Research of heat loading non-uniform along channel influence on heat exchange crisis development at 3-D mock-up temperature distribution.
- Research of crisis development during process time.
- Test data base adding for correction calculated model at boiling on non-isothermal wall.

Porous coating effect (**accommodated test data base**)

Porous coating depositing technology is sintering between copper powder (coated on channel surface by special organic glue before) and base matter. This technology was well developed in Russia for different base matter and had good performance at all tests on small-scale mock-ups carried out by us.

The first initial investigations with PC were carried out on tubes at uniform heat loading. Steel and copper tubes with copper PC were tested (Previous coating of thin copper layer by galvanic method was used for steel tubes .)

The results of the test set mentioned before at uniform loading are shown on Fig.1. The tests were carried out at wide range of coolant flow rate and it's subcooling. It will be seen that using of PC at uniform heat loading increases CHF in 1.7-2 times at least.

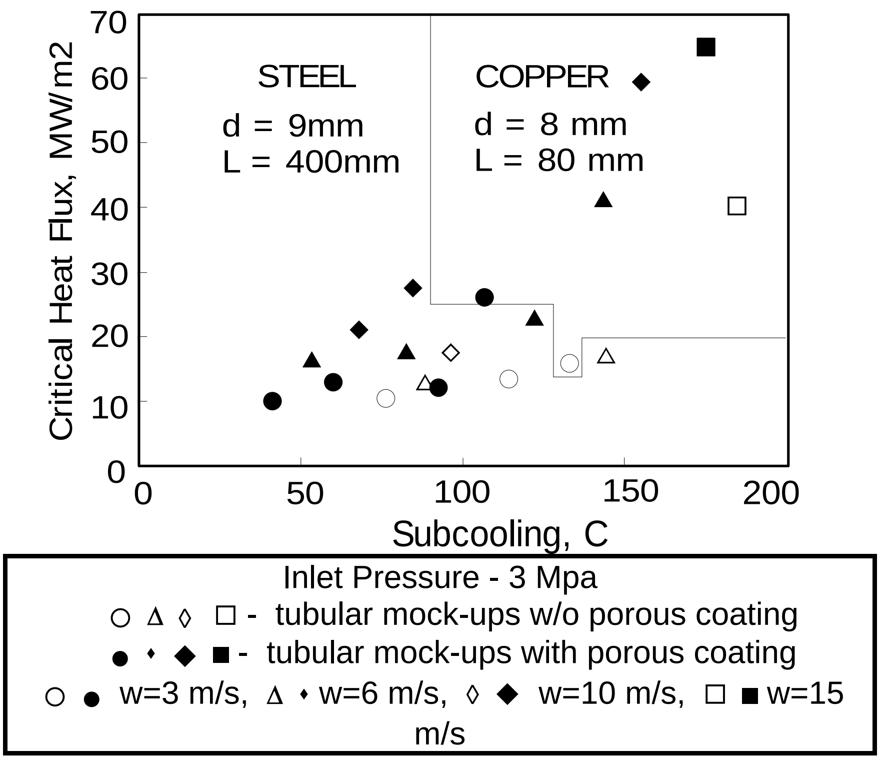
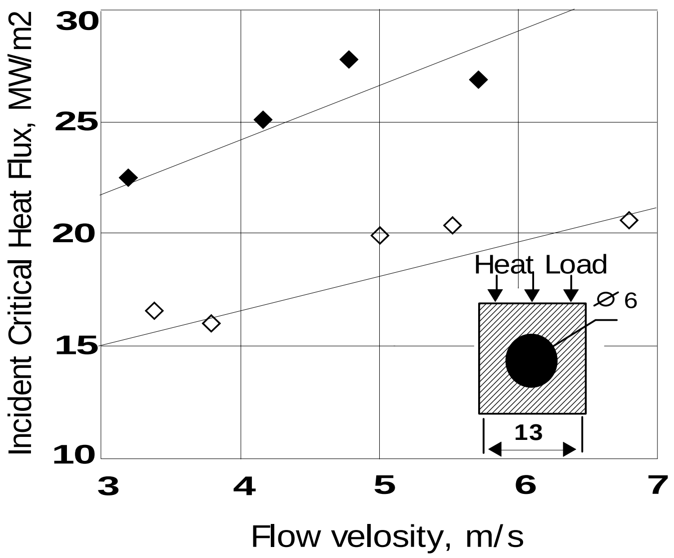


Fig.1. Porous Coating Impact on Critical Heat Flux at Uniform Heat Loading

Rectangular cross-section mock-ups with circular cooling channels were used in tests at one-sided heat loading. Mock-ups with width A=8.5, 10, 13 mm and channel diameter d=6 mm was investigated in Russia test sets. Mock-ups with width - A=20 mm and channel diameter - d=15 and 8 mm was investigated in SNLA test sets.

PC influence on Ultimate Heat Flux (UHF) value absorbed by mock-ups at pre-crisis mode is shown on Fig. 2. It will be seen that UHF for mock-ups with PC is more in 1.4-1.6 times at least than one for with smooth channels.

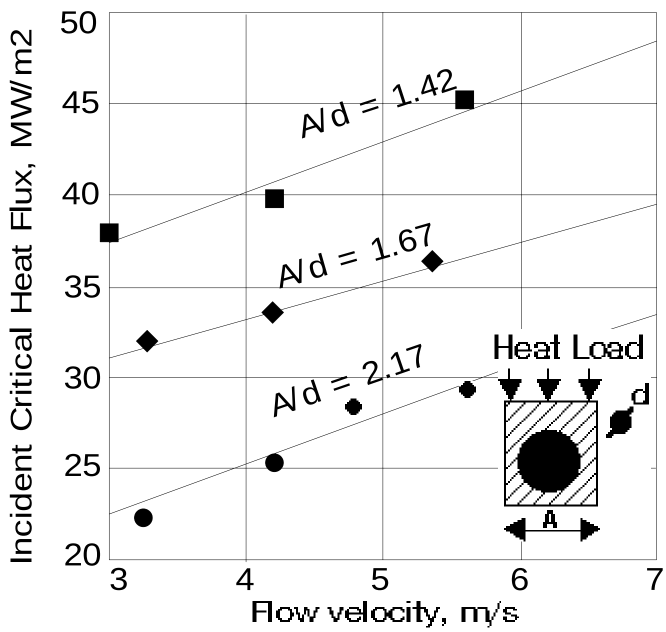


P = 2 MPa, Δt_{sub}=160 C

◆ - Channel with PC, ◊- Channel w/o PC

Fig.2. Porous Coating Impact on Incident Critical Heat Flux at the One-Side Loading.

Specific width A/d influence on ICHF value is shown on Fig. 3. Initial test just shown that A/d decreasing leads to drastically increasing of ICHF value.



P = 2 MPa, Δt_{sub} =160 C, with PC

Fig. 3. A/d Impact on Incident Critical Heat Flux at One-Side Loading.

However, all test set data treatment (including tests carried out on SNLA test set) shown that the maximal UHF could be obtained at just defined (optimal) specific width only. Test data treatment was carried out in per-unit co-ordinates. UCH value was related to CHF_{Shl} .

$$CHF_{Shl} = 4.12 \cdot 10^{-2} \cdot (\rho' w)^{1/2} \cdot \Delta T_{sub}^{\ 0.33} \cdot (1 - \rho''/\rho')$$

Here, CHF_{Shl} - Critical Heat Flux [MW/m^2] at uniform loading on circular channels w/o PC calculated by Shlykov correlation [1].

The function

$$UHF/\ CHF_{Shl} = f(\ A/\pi d\ )$$

has the well impressed maximum at $A/\pi d = 0.45$ [2]. This will be good seen on Fig.4.

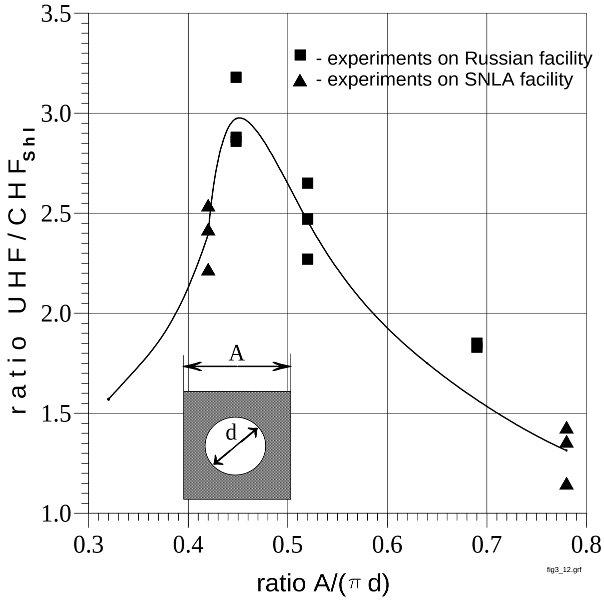
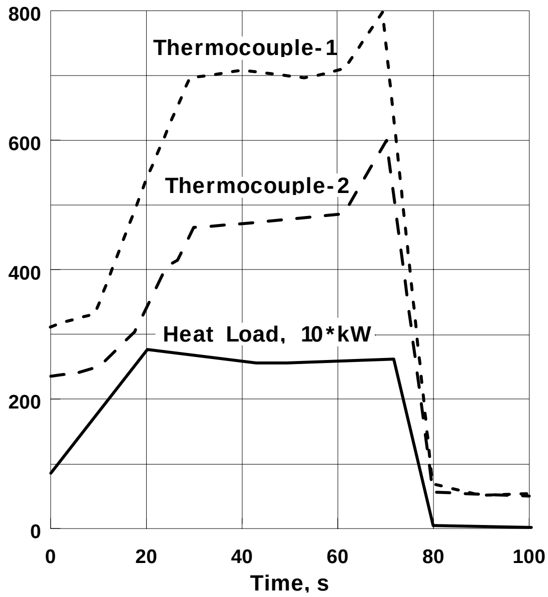


Fig. 4. Influence of geometric and operating parameters on UHF at one-side thermal loading of mock-ups with PC of circular channels.

The other typical feature of PC using is deceleration of crisis development during process time (up to several second tens).This process for A/d = 2.17 is shown on Fig. 5.



ICHF=25 MW/m^2, w=4.2 m/s, A/d=2.17, P=2 MPa, Δt_{sub} =160 C, with PC

Fig.5. Crisis time evolution on cooling channels with PC

Mock-ups prepared for future test

According Agreement with Mc Donnell Douglas Corporation, medium-scale mock-ups is fabricated from CuCrZr (Russian alloy) and Glidcop (USA alloy). Length of mock-ups is 900 mm, cross-section area - 33x40 mm, there are two cooling channels d = 10 mm per mock-up. Specific width $A/\pi d = 0.52$ approximately equals optimal value (see Fig. 4). Mock-ups is fabricated both with PC and w/o PC.

UHF investigation for these mock-ups will be carried out on SNLA (USA) e-beam at well impressed heat loading non-uniformity along mock-ups length (max at approx. 1/3 length). The local heat flux in each points along mock-up length will be measured by multy-points calorimeter method. Thermocouple matrix in mock-up body will be used to measure temperature distribution in 6 different cross-section along length of mock-ups.

Expected (calculated) results

Calculation modelling pre-crisis temperature state of mock-up (with non-isothermal cooling surface at one-sided heat loading) is not developed perfectly up to present. The main difficult for boundary condition setting is absent at present time authentic mathematical correlation for boiling curve $q = q(\Delta T_{sat}, \Delta T_{sub}, \rho\mathbf{O}, w, P, d)$ in after-crisis area (transient and film boiling). There are separate tests [3] for boiling curves (in this after-crisis area) for low-temperature boiling coolant (Freon-113, liquid N_2). Moreover, there is important fact that heat flux value in film boiling area increasing significantly in according with coolant velocity increasing and obtaining commensurable value heat flux value in point of first crisis (CHF_{ShI}).

For calculation of the expected results we use two alternative conceptions (because of there is not correct correlation of boiling curve for water in transient and film boiling area) in this non-predicted area:

conception A: $q = 0$ (i.e. $h = q/\Delta T_w = 0$) at $T_w > T_{CHF\ I}$

conception B: $q = CHF_I = const$ (i.e. $h = const/\Delta T_w$) at $T_w > T_{CHF\ I}$

Conception B does not leads to well impressed crisis (temperature avalanche-like increasing) at unlimited increasing of loading power. This conception is optimistic estimation. Conception A gives pessimistic estimation (moreover significant decreased). Reasonable result is between A and B conceptions.

Expected temperature of loaded by e-beam surface as a function of Incident Heat Flux calculated by these two conceptions for different inlet water temperature are shown on Fig. 6.

It will be seen that coolant subcooling significantly increases UHF value. Following correlation determined by previous test on small-scale mock-ups at one-sided loading was used for calculation medium-scale mock-ups temperature state:

$$h_{PC} = 1.4\, h_{smooth} \quad \text{and} \quad (CHF_{ShI})_{PC} = 1.4(CHF_{ShI})_{smooth}$$

Point of nucleate boiling appearing may be schematically determined as a cross point of the single-phase heat transfer curve

$$q_{conv} = h_{conv} (T_w - T_{inlet})$$

and nucleate boiling curve (Thom correlation).

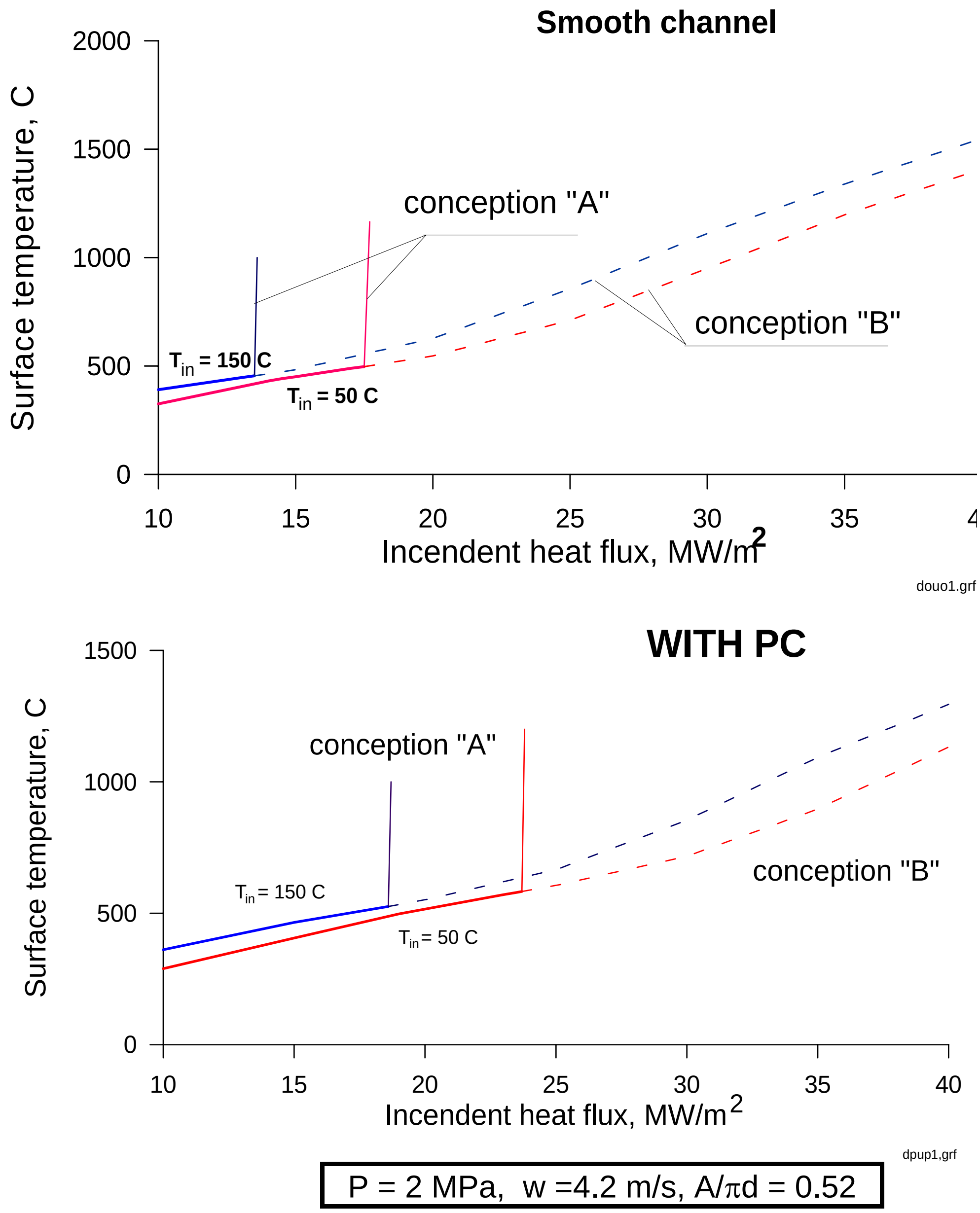


Fig.6. Mock-up loaded surface temperature dependence on Incident Heat Flux

Pre-crisis heat flux value for different coolant flow rate are given in Table. 1. In this Table for conception B it is taken conventionally as CHF value such magnitude at which $T_{surface}$= 1000 C. After that physical burnout and melting of mock-up will occur.

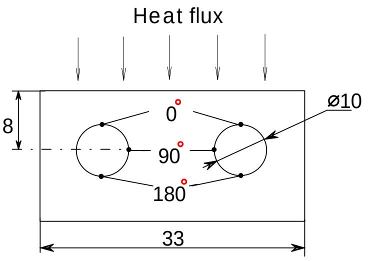
Table 1 Temperature state and pre-crisis of mock-ups

(P = 5.0 MPa, T_{inlet} = 100 C, d = 10 mm)

conception “A” - above line

conception “B” - under line

For “B” conception it is taken conventionally as CHF value such magnitude at which $T_{surface}$ = 1000C. After that physical burnout and melting of mock-up will occur.



	Flow velocity, m/s	Pre-crisis heat flux, MW/m^2	Surface temperature C	Wetted surface temperature, C		
				0°	90°	180°
W/O Porous Coating	5	$\frac{10.2}{22.8}$	$\frac{406}{1000}$	$\frac{304}{831}$	$\frac{207}{384}$	$\frac{151}{233}$
	7.5	$\frac{12.5}{25.7}$	$\frac{435}{1000}$	$\frac{309}{800}$	$\frac{196}{341}$	$\frac{137}{193}$
	10	$\frac{14.5}{28.0}$	$\frac{460}{1000}$	$\frac{313}{771}$	$\frac{189}{319}$	$\frac{128}{173}$
Porous Coating	5	$\frac{13.5}{27.2}$	$\frac{451}{1000}$	$\frac{311}{777}$	$\frac{198}{329}$	$\frac{137}{188}$
	7.5	$\frac{16.7}{31.0}$	$\frac{493}{1000}$	$\frac{317}{738}$	$\frac{189}{287}$	$\frac{125}{158}$
	10	$\frac{19.7}{34.0}$	$\frac{532}{1000}$	$\frac{333}{697}$	$\frac{182}{264}$	$\frac{119}{141}$