High Heat Removal by Evaporated Fluid in Porous Media

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Background

Study for thermal-hydraulics of fusion reactor

Fusion energy

20% ↙↙↙ ↘↘↘ 80%

Surface heat load	Volumetric heat generation
Plasma facing components (First wall·Divertor)	Blanket
	↓ ↓ ↓
Very high heat load several cooling systems are proposed	Coolant (Heat medium)
⇓	↓ ↓ ↓
Cooling with high performance	Generation of electricity
	⇓
↓↓	Extraction · conversion of energy with high efficiency

To realize a fusion reactor, high heat flux removal system will inevitably play an important role.

Conventional cooling system

Water cooling
- ○ good heat transport characteristics for small pumping power
- ○ good compatibility with material
- • Burnout heat flux decreases under high pressure condition
- • low outlet temperature → low thermal efficiency

advanced technique: forced convection in swirl tube

Gas cooling
- ○ inert
- ○ not affected by magnetic field
- • low heat transfer rate → poor cooling capacity
- • excessive driving force and heat-resistant materials are necessary

advanced technique: gas-solid impinging jet

Liquid metal cooling
- ○ high thermal conductivity, good thermal characteristics
- ○ treated as single phase flow with low pressure under high temperature condition
- • chemically active
- • MHD effect → excessive driving force

advanced technique: liquid metal mist cooling

Purpose

New concept of cooling system

Future power reactor

⇒ extraction · transport · conversion of energy with high efficiency and high power density

High heat flux component → { · generate high temperature heat medium (high power density) · remove very high heat flux }

New cooling system :
- Using metal porous media
- Based on heat removal by latent heat

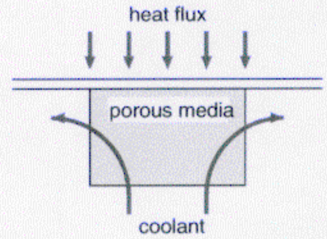


Fig. 1 Conceptual diagram

Merit of the cooling system using porous media

- Large thermal conductivity of metal material
  - ⇒ Thermal energy is transmitted into the inside of coolant
- Large contact surface between coolant and solid
  - ⇒ improvement of heat transfer
- Making coolant evaporate positively
  - ⇒ High temperature steam is available
- Boiling flow in porous media
  - ⇒ apparent thermal conductivity is enhanced by heat pipe effect

In this study

- Investigating the heat removal characteristics of this system
- Demonstrating high heat flux removal with high power density
- Analyzing heat transfer and fluid flow in porous media in detail

Fundamental experiment

Approach from high power density

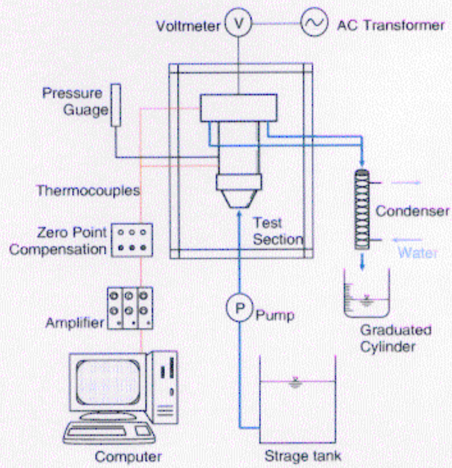


Fig. 2 Experimental apparatus

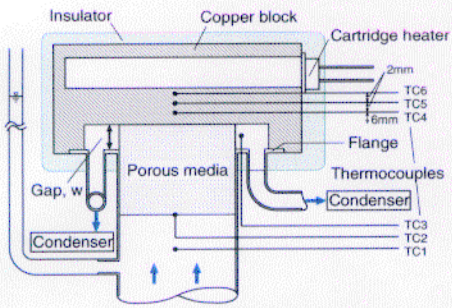


Fig. 3 Diagram of test section

Heaters: 650W(max) × 4

Porous media:

Sintered metal (SUS 316) composed of spherical particle with familiar characteristics with 5.0cm long diameter, 2.0cm long height

Table 1 Characteristics of porous media

Characteristics		Porous test sample #1	Porous test sample #2
average particle diameter	[μm]	500	160
average pore diameter	[μm]	25	9
porosity	[*vol.*%]	47	42

Experimental procedure

- Parameter

  P_{in} , T_{in} , q_{in}
- Water evaporates in porous media ($T_{out} > T_{sat}$)

  ⇓

  Start measurement (2 minutes) : T_{in} , T_{out} , $\dot{m}$
- Calculation of removed heat flux, $\overline{q}_{rmv}$

$$\overline{q}_{rmv} = \dot{m}\{c_l(T_{sat} - T_{in}) + h_{fg} + c_v(T_{out} - T_{sat})\} \quad (1)$$

$\overline{q}_{rmv}$	:	average removed heat flux
c_l, c_v	:	specific heat of water & steam
T_{sat}	:	saturation temp.
h_{fg}	:	latent heat
T_{in}	:	inlet temp.
T_{out}	:	outlet temp.
$\dot{m}$	:	mass flux

Experimental result

History of temperature

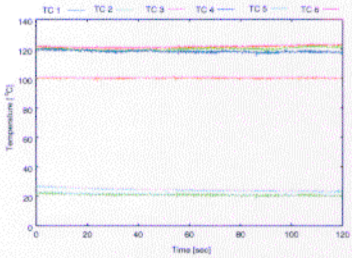


Fig. 4 q_{in}=0.73MW/m^2, $\dot{m}$=0.27kg/m^2/s, #2

Relation between $\dot{m}$ and P_{in}

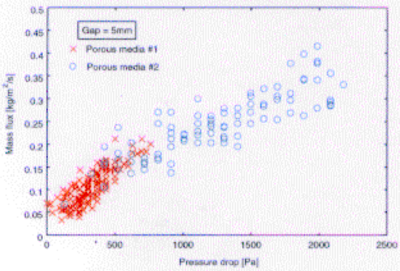


Fig. 5 Mass flux varying with pressure drop

Relation between $\dot{m}$ and $\overline{q}_{rmv}$

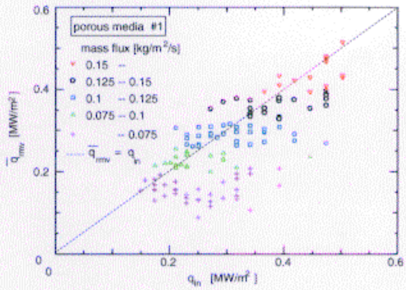


Fig. 6 $\overline{q}_{rmv}$ varying with $\dot{m}$: #1

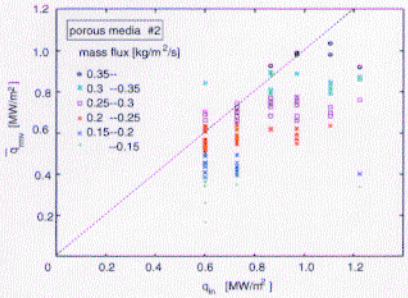


Fig. 7 $\overline{q}_{rmv}$ varying with $\dot{m}$: #2

Difference of heat removal characteristics

caused by different aspect of flow in porous media

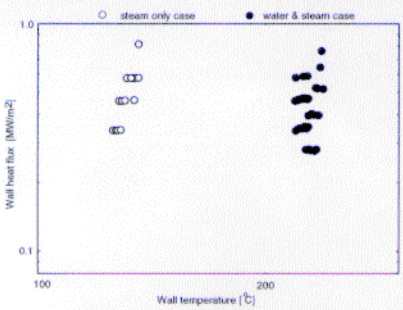
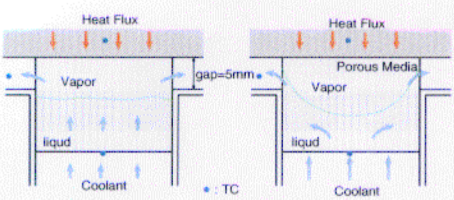


Fig. 8 Change of boiling curve



Steam only case　　Water & steam case

To enhance removed heat flux

Not all of water evaporates in porous media.

⇒ Water tends not to flow around the center of the heat transfer area.

⇒ Heat transfer decreases

↓ ↓ ↓

Undesirable feature for this cooling system

To enhance heat removal capacity:

Increasing mass flux with

- ○ Making water flow into the center of the heat transfer area, or
- ○ Making all of water evaporate in the porous media

↓ ↓ ↓

· Narrowing the **gap**'s width

· changing the shape of porous media

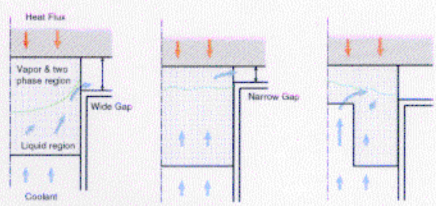


Fig. 9 Way to enhance heat removal capacity

Change of removed heat flux by the gap width

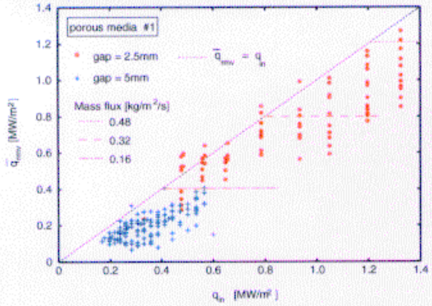


Fig. 10 $\overline{q}_{\rm rmv}$ varying with *gap* width: #1

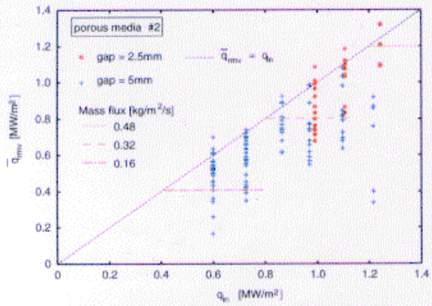


Fig. 11 $\overline{q}_{\rm rmv}$ varying with *gap* width: #2

Change of removed heat flux by the shape

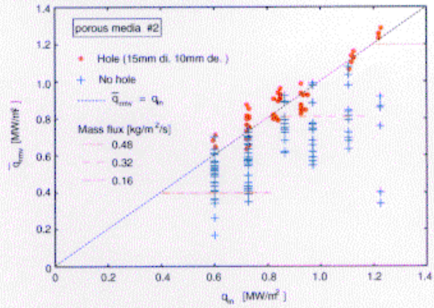


Fig. 12 $\overline{q}_{\rm rmv}$ varying with *shape*: 15di. 10de.

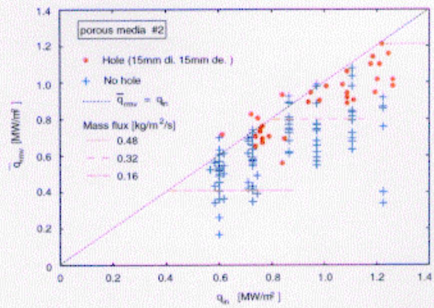


Fig. 13 $\overline{q}_{\rm rmv}$ varying with *shape*: 15di. 15de.

Summary of fundamental experiment

- Each mass flux had the upper limit of removed heat flux, and its value was nearly equal to the heat flux which is required to make all of the injected water evaporate in the porous media.
- Heat transfer between the heated wall and the porous media was rather better under the steam only condition than under the water & steam condition.
- Keeping the steam only case is effective for enhancement of the heat removal capacity with high outlet temperature of the cooling water.

High heat flux removal experiment

Approach from high heat load removal

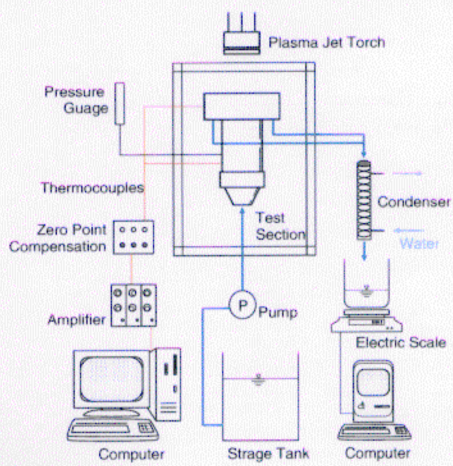


Fig. 14 Experimental apparatus

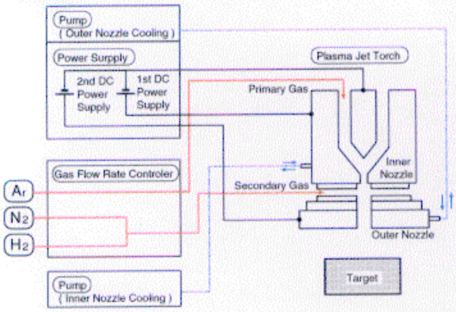


Fig. 15 Schematic view of Plasma Gun

Table 2 Experimental condition

Discharge current	300A	
Gas flow rate	Ar	30 l/min
	H_2	100 l/min
	N_2	25 l/min
Distance between plasma torch and target (H)	4.5, 7, 9.5, 12 cm	

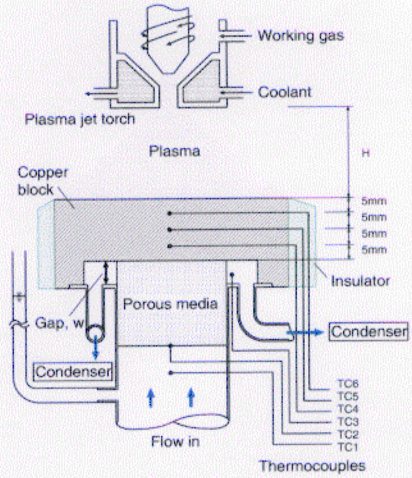


Fig. 16 Diagram of test section

Table 3 Characteristics and shape of porous media

Characteristics			Porous test sample No.			
			#1	#2	#3	#4
porosity	ε	[*vol.*%]	47	42	42	42
average particle diameter	d_p	[μm]	500	160	160	160
average pore diameter		[μm]	25	9	9	9
shape						
di		[mm]	0	0	15	15
de		[mm]	0	0	10	15

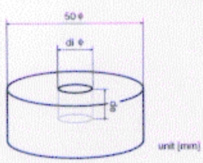


Fig. 17 Shape of porous media

Experimental procedure

- Parameter
  $P_{in}(u_{in})$, H(q_{in}), Porous test sample, *gap*
- Impose plasma jet (1 minute)
- Removed heat flux $\overline{q}_{rmv}$

⇒ evaluated by least square method using TC's data.

Adopted function : $f(x, \mathbf{a}) = a_0 \exp(a_1\, x) + a_2$

$$\overline{q}_{rmv} = k_{Cu}\, a_0\, a_1 \exp(a_1\, x_s) \tag{2}$$

x_s: Heat transfer surface position

Or

$$\overline{q}_{rmv} = \dot{m}\{c_l(\overline{T}_{out} - T_{in}) + \beta h_{fg}\} \tag{3}$$

$\dot{m}$	:	mass flux
c_l	:	specific heat of water
h_{fg}	:	latent heat
T_{in}	:	inlet temp.
$\overline{T}_{out}$	:	average outlet temp.
β	:	evaporation rate of cooling water

Flow characteristics

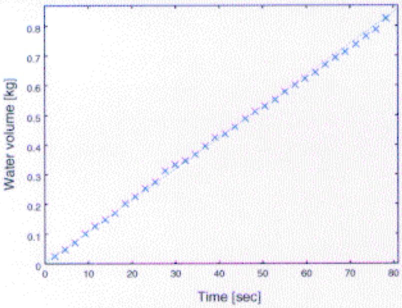


Fig. 18 History of water volume

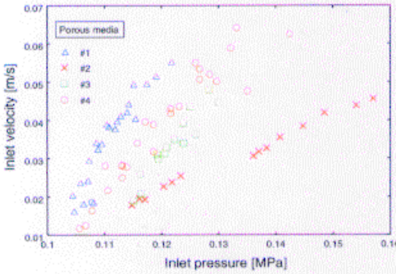


Fig. 19 $u_{\rm in}$ varying with $P_{\rm in}$: w=5mm

Heat removal characteristics

History of temp. & temperature profile

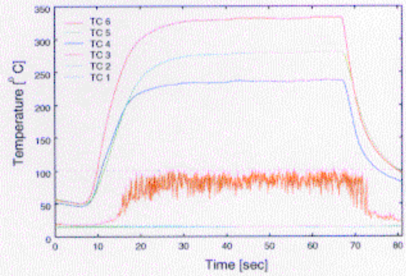


Fig. 20 History of temperature: H=7cm, #1, w=5mm

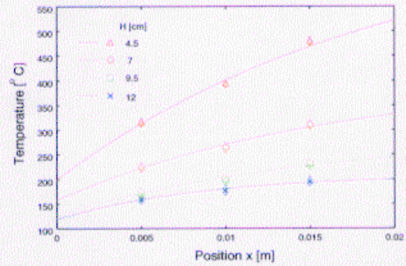


Fig. 21 Temperature profile varying with H: #2, w=2.5mm

Boiling curve & removed heat flux

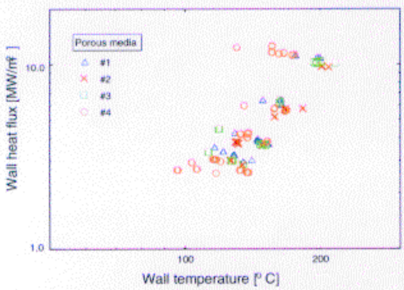


Fig. 22 $\overline{q}_{\rm rmv}$ varying with $T_{\rm w}$: w=5mm

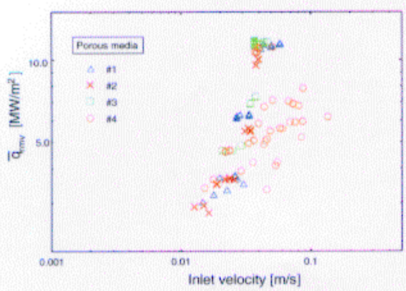


Fig. 23 $\overline{q}_{\rm rmv}$ varying with $u_{\rm in}$: w=2.5mm

Outlet temp. & evaporation rate

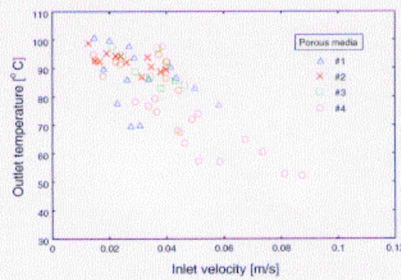


Fig. 24 $T_{\rm out}$ varying with $u_{\rm in}$: w=2.5mm

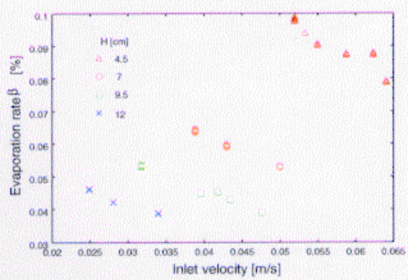


Fig. 25 Evaporation rate varying with $u_{\rm in}$, $q_{\rm in}$: #4, w=5mm

Critical heat flux

History of temp. & dependence on pressure

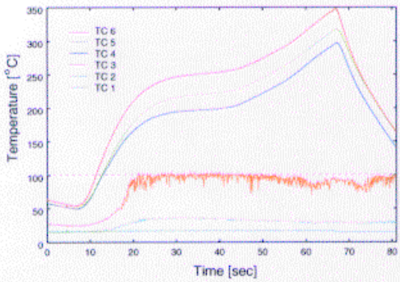


Fig. 26 History of temperature at CHF

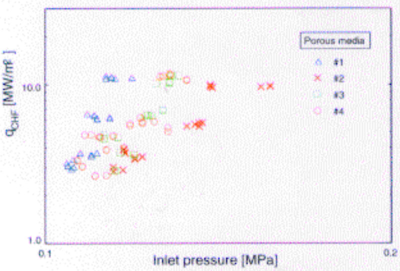


Fig. 27 $q_{\rm CHF}$ varying with $P_{\rm in}$

Change with $u_{\rm in}$ and *gap*

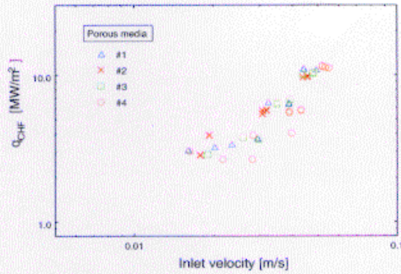


Fig. 28 $q_{\rm CHF}$ varying with $u_{\rm in}$: w=5mm

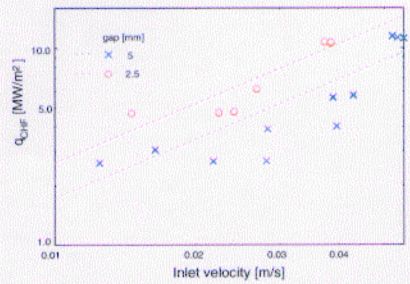


Fig. 29 $q_{\rm CHF}$ varying with *gap* width: #4

Summary of high heat removal experiment

- The evaporation rate has a negative correlation with the flow velocity and has a positive correlation with the incident heat flux.
- Outlet temp. of cooling water gets higher as flow velocity becomes slow. It is necessary for high heat removal with high power density that flow velocity is as small as possible.
- Critical heat flux increases proportionally to the flow velocity of cooling water.
- The narrow gap makes $q_{\rm CHF}$ higher and the evaporation rate bigger at the same flow velocity.
- It is feasible for the present cooling system to remove heat flux of 10MW/m^2 by the inlet velocity of the cooling water of 0.04m/s under the pressure of the order of 0.1MPa with making the cooling water of about 10% evaporate.

Numerical simulation for two-phase flow

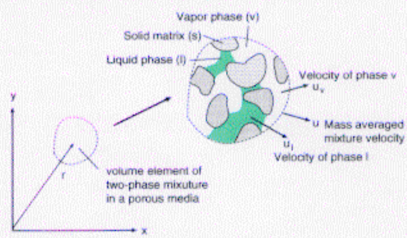


Fig. 30 Schematic illustration for a volume element containing a multiphase mixture

Treatment as continuum

○ Separate flow model (SFM)

  exact form but many equations to solve

○ Two-phase mixture model

  equivalent to SFM and small equations

Two-phase mixture model

Definition of a multiphase mixture

$$\rho \equiv \rho_l s + \rho_v (1-s)$$

$$\rho \mathbf{u} \equiv \rho_l \mathbf{u}_l + \rho_v \mathbf{u}_v$$

$$p \equiv \frac{p_l + p_v}{2} + \frac{1}{2}\int_0^{p_c} [\lambda_v(\xi) - \lambda_l(\xi)] \mathrm{d}\xi$$

$$\rho h \equiv \rho_l s h_l + \rho_v (1-s) h_v$$

Conservation equations

- for mass:

$$\varepsilon \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \qquad (4)$$

- for momentum:

$$\mathbf{u} = -\frac{K}{\mu(s)} [\nabla p - \rho_\kappa(s) \mathbf{g}]$$

- for energy:

$$\Omega \frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\gamma_h \rho \mathbf{u} h) = \nabla \cdot [\Gamma_h \nabla(\rho h)] - h_{vsat} \nabla \cdot (\Gamma_h \nabla \rho) + \nabla \cdot \left(f(s) \frac{K \Delta \rho h_{fg}}{\nu_v} \mathbf{g} \right) \qquad (5)$$

Velocity of each phase

$$\rho_l \mathbf{u}_l = \lambda \rho \mathbf{u} + \mathbf{j}, \quad \rho_v \mathbf{u}_v = (1-\lambda)\rho \mathbf{u} - \mathbf{j}$$

Diffusive mass flux by capillarity and gravity

$$\mathbf{j} = -D(s)\nabla s + f(s) \frac{K \Delta \rho}{\nu_v} \mathbf{g}$$

$$D(s) = \frac{K}{\nu_v} \lambda (1-\lambda)[-p_c'(s)]$$

	$h \le h_{lsat}$	$h_{lsat} \le h \le h_{vsat}$	$h \ge h_{vsat}$
T	$\frac{h - h_{in}}{c_l} + T_{in}$	T_{sat}	$\frac{h - h_{vsat}}{c_v} + T_{sat}$
s	1	$\frac{\rho}{\rho_l}\left(\frac{h_{vsat} - h}{h_{fg}}\right)$	0
Ω	$\varepsilon + \frac{\rho_s c_s (1-\varepsilon)}{\rho_l c_l}$	ε	$\varepsilon + \frac{\rho_s c_s (1-\varepsilon)}{\rho_v c_v}$
Γ_h	$k_{eff}/\rho_l c_l$	$D(s)/\rho_l$	$k_{eff}/\rho_v c_v$
γ_h	1	$\frac{\rho h_{lsat} + (1-\lambda)\rho h_{fg}}{\rho h_{lsat} + (1-s)\rho_v h_{fg}}$	1

Table 4 Variables in energy equation

Other variables

$$\nu(s) \equiv \left(\frac{k_{rl}(s)}{\nu_l} + \frac{k_{rv}(s)}{\nu_v} \right)^{-1}$$

$$\lambda(s) \equiv \nu(s) \cdot k_{rl}(s)/\nu_l$$

$$k_{rl} = s^3, \quad k_{rv} = (1-s)^3$$

$$f(s) = k_{rv}(s) \cdot \lambda(s)$$

$$\mu(s) = \rho(s) \cdot \nu(s)$$

$$\rho_\kappa(s) = \rho_l \lambda(s) + \rho_v (1 - \lambda(s))$$

$$p_c = p_v - p_l = \left(\frac{\varepsilon}{K}\right)^{1/2} \sigma J(s)$$

$$J(s) = 1.417(1-s) - 2.120(1-s)^2 + 1.263(1-s)^3$$

Numerical procedure

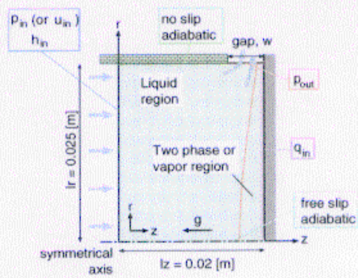


Fig. 31 Numerical system and BC.s

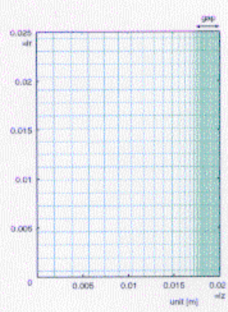


Fig. 32 Location of main grid

Numerical result

Heat transfer and fluid flow in porous media

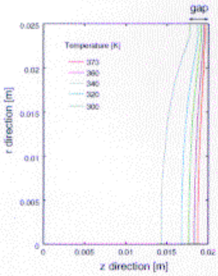


Fig. 33(a) Temperature

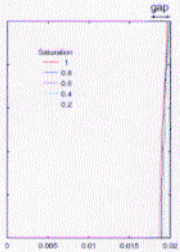


Fig. 33(b) Liquid saturation

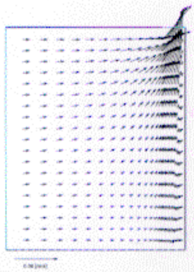


Fig. 33(c) Liquid velocity

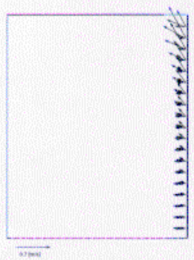


Fig. 33(d) Vapor velocity

Fig. 33 u_{in}=0.01m/s, q_{in}=2.0MW/m^2

Temperature distribution varying with u_{in}, q_{in}

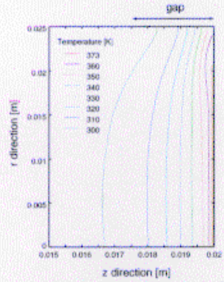


Fig. 34(a) q_{in}= 2MW/m^2

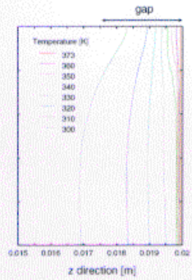


Fig. 34(b) q_{in}= 4MW/m^2

Fig. 34 Same u_{in}: 0.02m/s

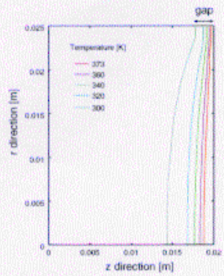


Fig. 35(a) u_{in}=0.01m/s

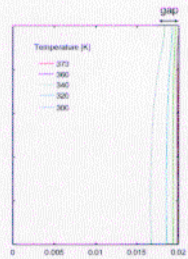


Fig. 35(b) u_{in}=0.02m/s

Fig. 35 Same q_{in}: 2MW/m^2

Temperature distribution varying with *gap*

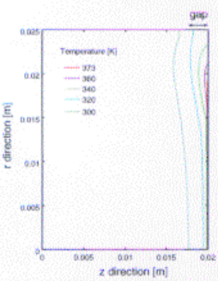


Fig. 36(a) w=2.5mm

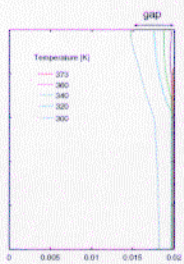


Fig. 36(b) w=5mm

Fig. 36 u_{in}=0.03m/s, q_{in}=5MW/m^2

Thermal diffusion near outlet

⇓

Effect of thermal dispersion

Comparison with experimental result

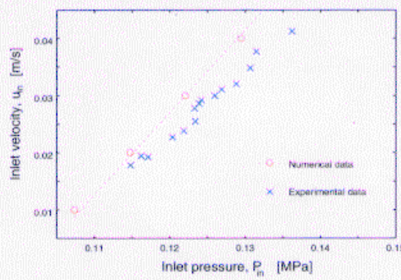


Fig. 37(a) w=5mm

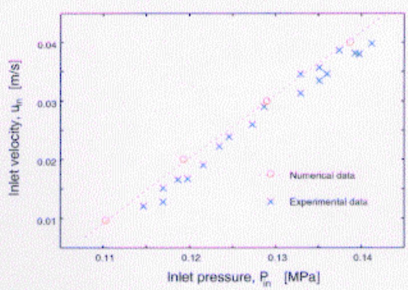


Fig. 37(b) w=2.5mm

Fig. 37 Relation between u_{in} and P_{in}

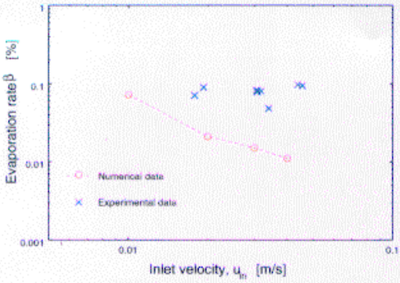


Fig. 38(a) w=5mm

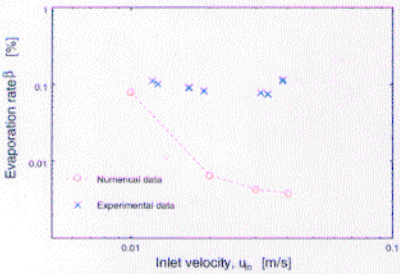


Fig. 38(b) w=2.5mm

Fig. 38 Relation between evaporation rate and u_{in}

Summary of numerical analysis

- There exists a counter current of vapor flow to liquid flow near the cooling surface.
- Thermal penetration depth becomes short when the flow velocity is fast, and when the incident heat flux is large, the heat doesn't penetrates into the porous media so much because the energy consumed by evaporation becomes large.
- The effect of thermal dispersion becomes noticeable in the outlet region as the flow velocity gets fast.

Application to fusion reactor

High heat removal by small flow velocity

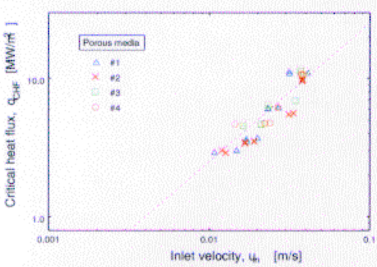


Fig. 39 $q_{CHF} \sim 2.5 \times 10^2 \cdot u_{in}$: w=2.5mm

Proposed system	:	10MW/m^2 by 0.04m/s
Swirl tube	:	38MW/m^2 by 10m/s
		under several MPa

High heat removal under low pressrue

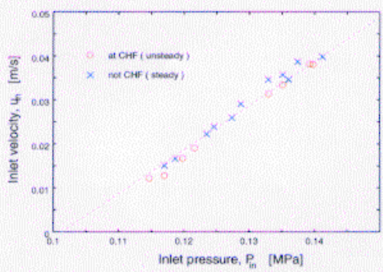


Fig. 40 $u_{in} \sim 1.0 \cdot (P_{in} - 1\text{atm})$: #2, w=2.5mm

∘ 10MW/m^2 by 0.05MPa pressure drop
∘ Not necessary to pressurize

↓↓↓

◇ Small pumping power
◇ Great room for materials and connections

∘ Porous media and high heat load material are not monolithic.

↓↓↓

◇ High flexibility

High heat removal with high power density

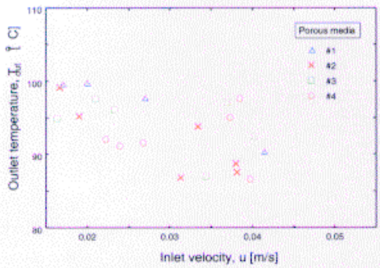


Fig. 41 Relation between u_{in} and T_{out} at CHF: w=2.5mm

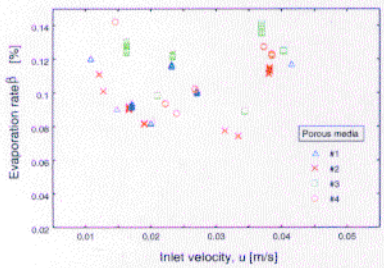


Fig. 42 Relation between β and u_{in} at CHF: w=2.5mm

Comparison with existing cooling system

Table 5 Comparison with swirl tube

	q_{CHF} [MW/m^2]	u_{in} [m/s]	ΔP [MPa]	exit subcooling [K]
experiment	10	0.04	0.04	10 ~ 15
extrapolation & calculation	30	0.12	0.12	51
swirl tube	30.7	12.0	0.52	110

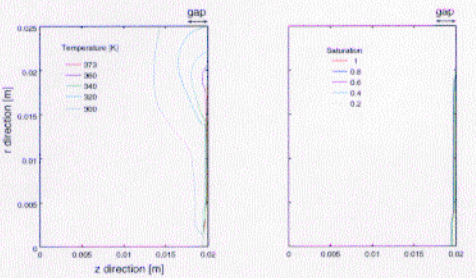


Fig. 43(a) Temperature Fig. 43(b) Liquid saturation

Fig. 43 u_{in}=0.12m/s, q_{in}=30MW/m^2

Summary of application to fusion reactor

- It is possible to remove high heat flux by slow flow velocity.
- The proposed system has the simple structure because the pressure drop is small and a pressurized water is not necessary.
- The proposed system has high flexibility at the time of its application because it is not monolithic but separable from the high heat load surface.
- It is feasible for the present system to transport energy with high density because outlet temp. of the cooling water can be high and 10% of water can be evaporated in the system.

Conclusion

A cooling system using porous media was proposed as a high heat flux removal system which can use energy effectively.
Following knowledges were obtained.

From experiment

- Each mass flux has the upper limit of removed heat flux, and its value is nearly equal to the heat flux which is required to make all of the injected water evaporate in the porous media.
- Heat transfer between the heated wall and the porous media is rather better under the steam only condition than under the water & steam condition.
- Keeping the steam only case is effective for the enhancement of the heat removal capacity with the high outlet temperature of the cooling water.
- The evaporation rate has a negative correlation with the flow velocity and has a positive correlation with the incident heat flux.
- Critical heat flux increases proportionally to the flow velocity of the cooling water.

- It is feasible for the present cooling system to remove the heat flux of 10MW/m^2 by the inlet velocity of the cooling water of 0.04m/s under the pressure of the order of 0.1MPa with making the cooling water of about 10% evaporate.

From numerical analysis

- There exists a counter current of vapor flow to liquid flow near the cooling surface.
- Thermal penetration depth becomes short when the flow velocity is fast, and when the incident heat flux is large, the heat doesn't penetrates into the porous media so much because the energy consumed by evaporation becomes large.
- The effect of thermal dispersion becomes noticeable in the outlet region as the flow velocity gets fast.

Application to fusion reactor

- It is possible to remove the high heat flux by the slow flow velocity under the low pressure condition.
- The proposed cooling system has high flexibility because of its simple structure.