

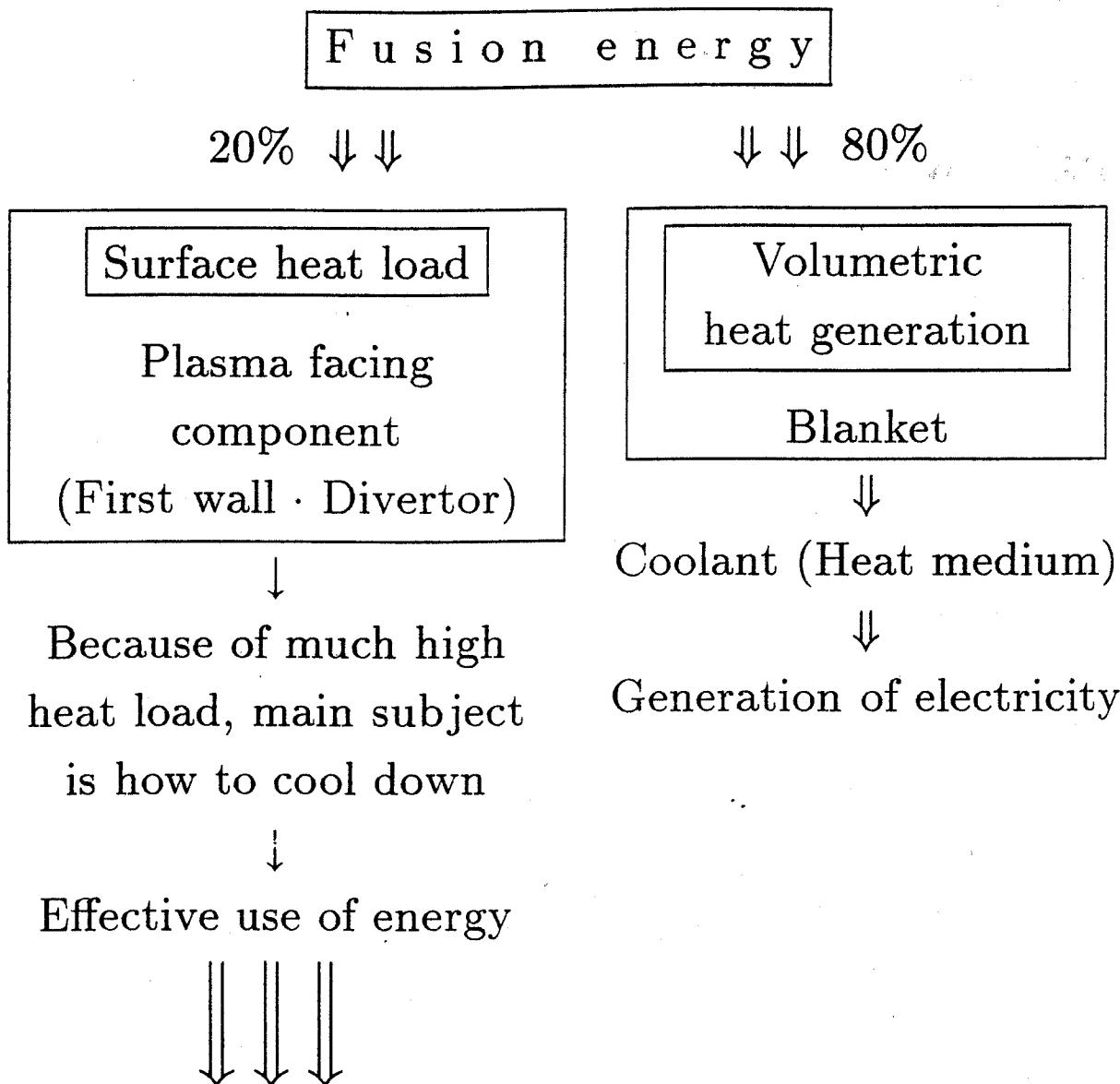
High-Heat-Flux Heat Removal by Evaporated Fluid in Porous Media

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Background

- Fusion power generating system



Development of new compact cooling system

- {
- generate high temperature heat medium
 - remove very high heat load

Concept

New concept of cooling system :

- Using metal porous media
- Based on heat removal system by latent heat of vaporization

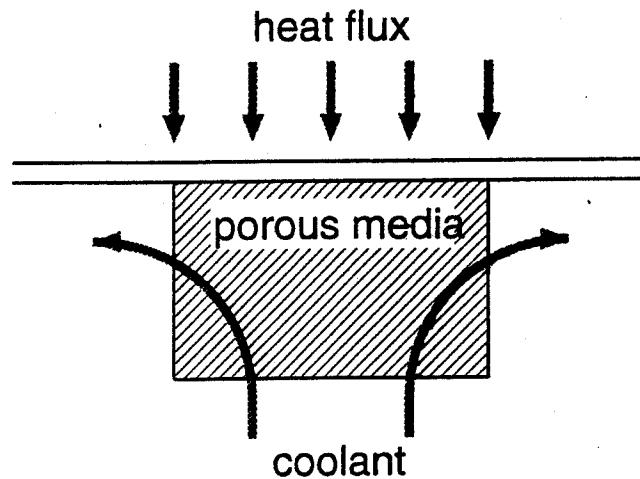


Fig. 1 Conceptual diagram

Merit

- Large thermal conductivity of metal material
 - ⇒ Thermal energy is transmitted into the inside of coolant
- Making coolant evaporate positively
 - ⇒ High temperature steam is available

In this study

- Demonstrating the utility of the cooling system using metal porous media
- Enhance the heat removal capacity of the system

Experiment

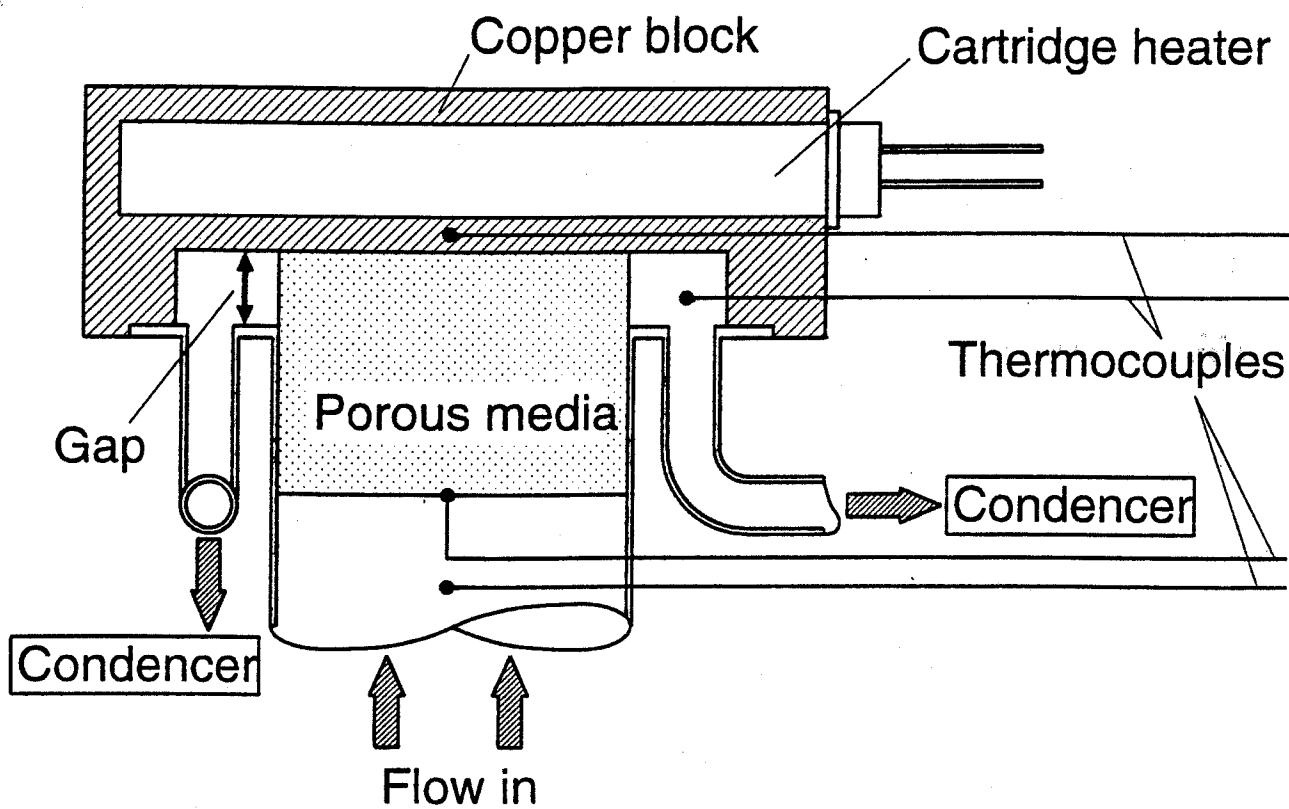


Fig. 2 Experimental apparatus

Heater : 650W(max) × 4

Porous media : Sintered metal (SUS 316L)
with 5.0cm long diameter

porous media #	#1	#2
porosity [vol.%]	47	42
average particle diameter [μm]	500	160
average pore diameter [μm]	25	9
viscous permeability [$\times 10^{-12}\text{m}^2$]	10	1
inertial permeability [$\times 10^{-6}\text{m}$]	3	0.8

Experimental result

Change of removed heat flux varying with gap width

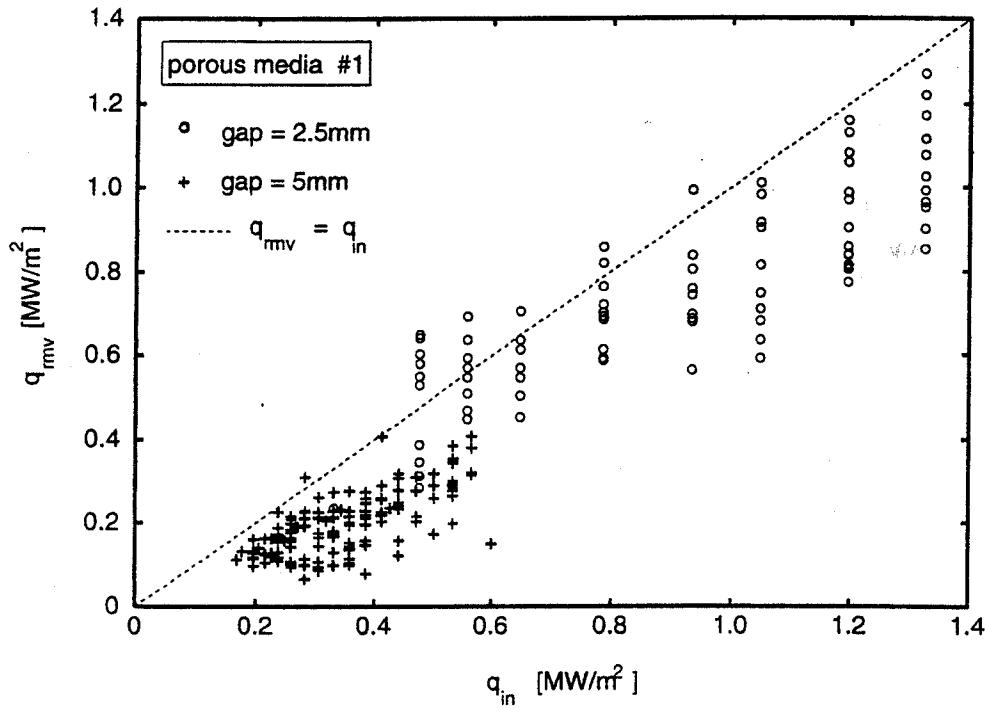


Fig. 3 q_{in} vs \bar{q}_{rmv} : porous media #1

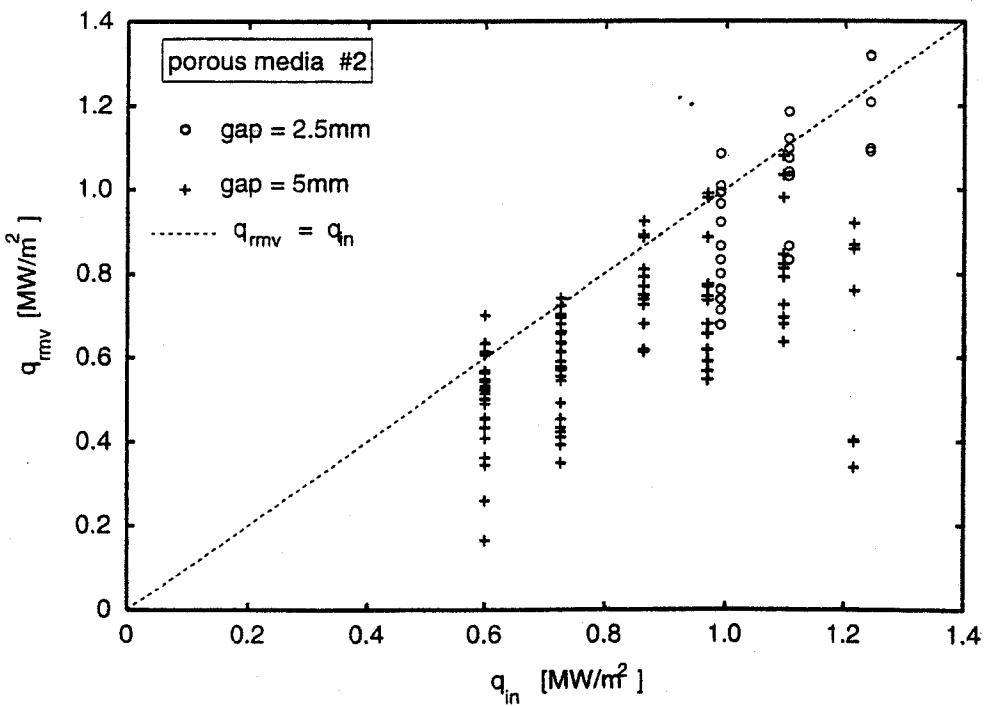


Fig. 4 q_{in} vs \bar{q}_{rmv} : porous media #2

Analysis

- 1-D analysis
 - The exact solutions are available.
 - But the boundary conditions on the heat transfer area are different from the experimental device.
- 2-D analysis
 - The boundary conditions on the heat transfer area are similar to the experimental device.

1-D numerical analysis

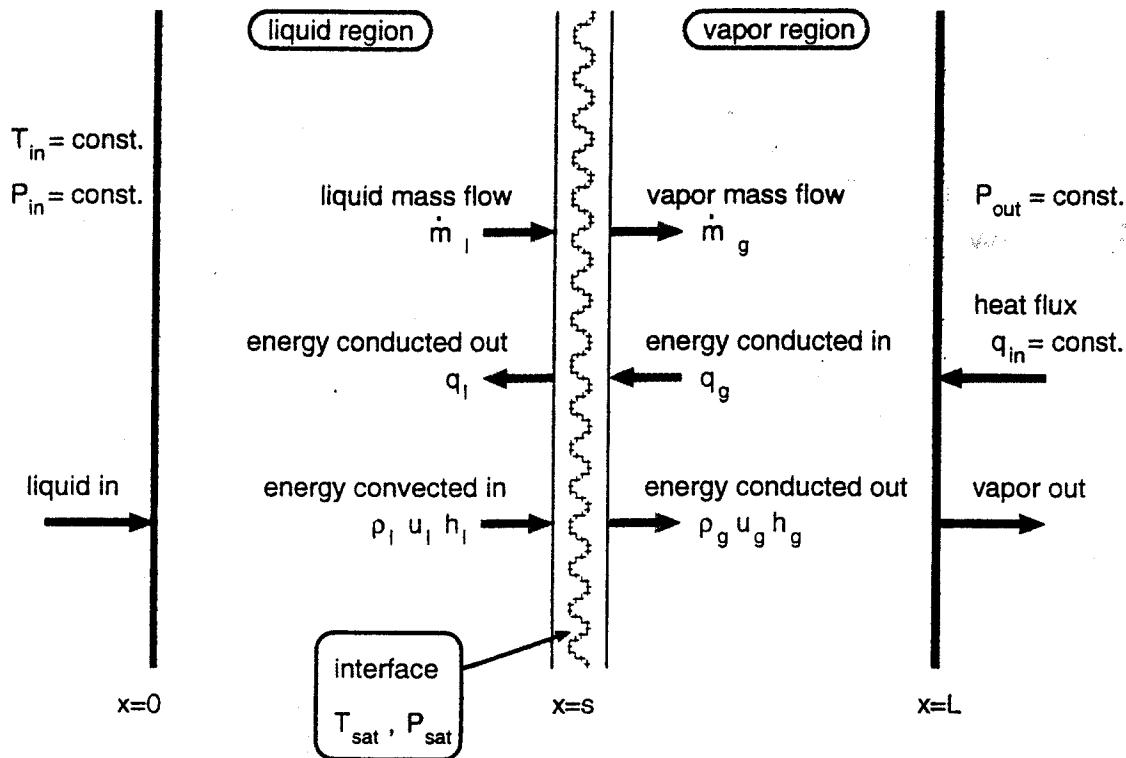


Fig. 5 Steady state 1-D model

Governing equations are :

$$\frac{d}{dx}(\rho_f u_f) = 0, \quad u_f = -\frac{K_\mu}{\mu} \frac{dP}{dx}, \quad \rho_f C_{pf} u_f \frac{dT}{dx} = k_{eff} \frac{d^2 T}{dx^2} \quad (1)$$

B.Cs. are :

$$(\dot{m}_l =) \rho_l u_l = \rho_g u_g (= \dot{m}_g), \quad k_{g,eff} \frac{dT_g}{dx} - k_{l,eff} \frac{dT_l}{dx} = \dot{m}_l \Delta H_{vap}$$

$$T_{in}, q_{in}, P_{in}, P_{out} = \text{const.}$$

Exact solutions are :

$$\dot{m}_l = \dot{m}_g = \frac{K_\mu}{\nu_l} \frac{R}{(Rs + L - s)} (P_{in} - P_{out}) \quad (2)$$

$$\theta_1 = \frac{\exp(f_S Pe_i X) - 1}{\exp(f_S Pe_i S) - 1} \quad (3)$$

$$\theta_g = 1 + \frac{q_{in} CL}{\kappa k_{g,\text{eff}} f_S Pe_i \Delta T_l} \cdot \\ \left\{ \exp\left(\frac{\kappa f_S Pe_i}{C}(X - 1)\right) - \exp\left(\frac{\kappa f_S Pe_i}{C}(S - 1)\right) \right\} \quad (4)$$

Interface position :

$$\left\{ \frac{q_{in} L}{\kappa k_{g,\text{eff}} \Delta T_l f_S Pe_i} \exp\left(\frac{\kappa f_S Pe_i}{C}(S - 1)\right) - H \right\} \cdot \\ \left(1 - \exp(-f_S Pe_i S) \right) = 1 \quad (5)$$

1-D results

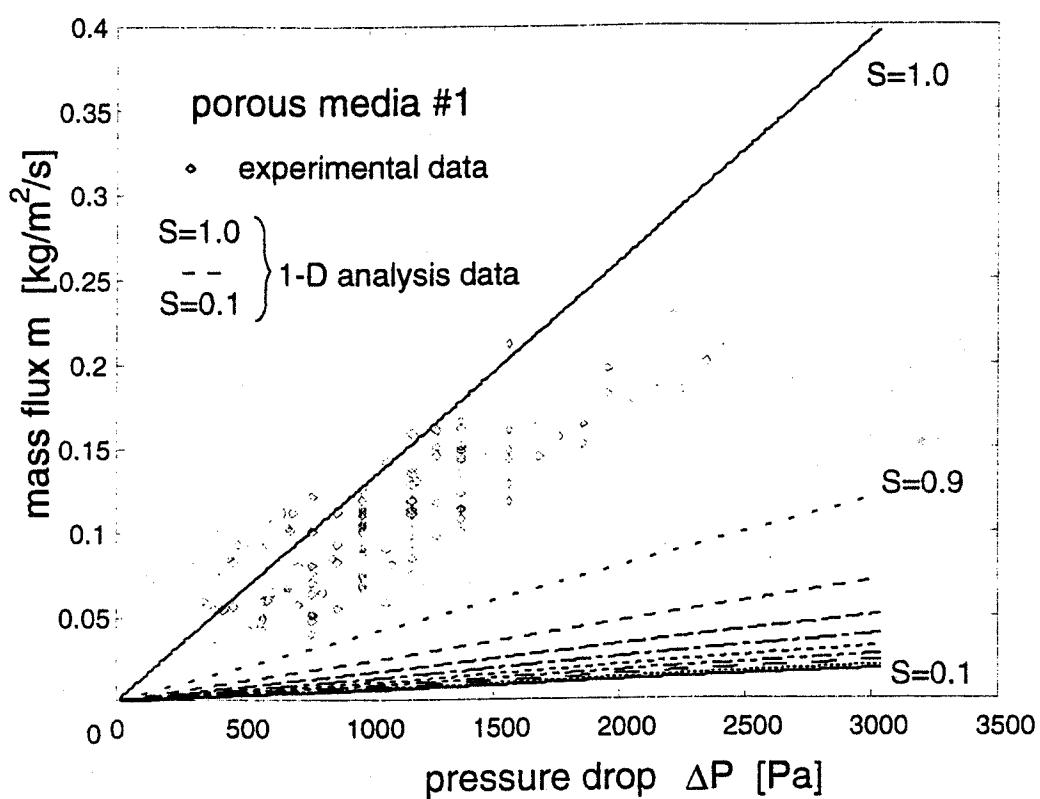


Fig. 6 Change of mass flux as parameter of S

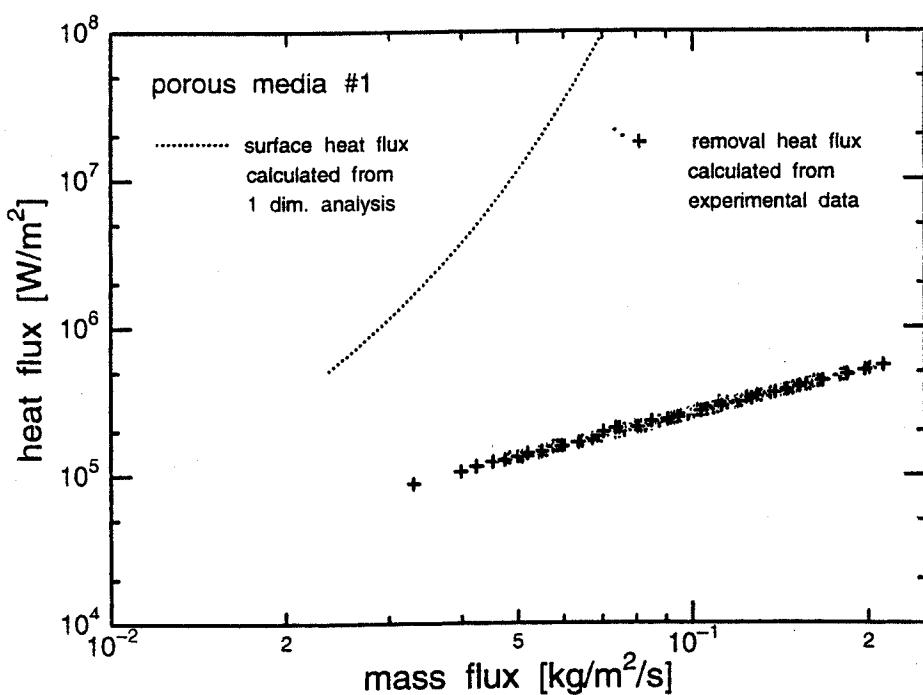


Fig. 7 Comparison of surface heat flux

Local volume averaging

$$\overline{W_f} = \frac{1}{V} \int_{V_f} W_f dV$$

W_f : local quantity associated with the fluid phase

Modified Gauss theorem

$$\nabla \overline{W_f} = \nabla \overline{W_f} + \frac{1}{V} \int_{A_{fs}} W_f \mathbf{n}_{fs} dS$$

$$\nabla \cdot \mathbf{W}_f = \nabla \cdot \overline{\mathbf{W}_f} + \frac{1}{V} \int_{A_{fs}} \mathbf{W}_f \cdot \mathbf{n}_{fs} dS$$

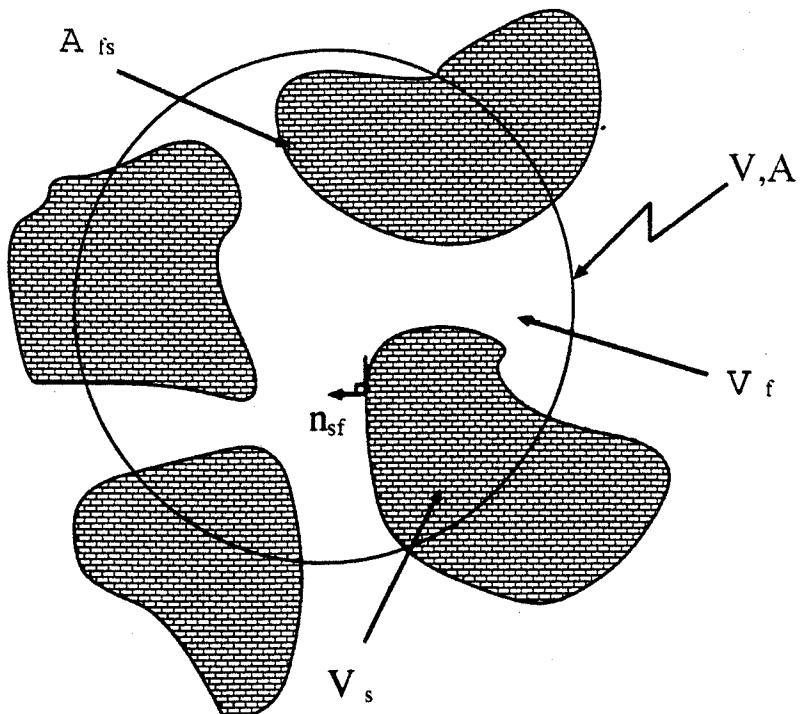


Fig. 8 Volume for local volume averaging

2-D numerical analysis

Mass momentum and energy balance equations :

$$\nabla \cdot \mathbf{v}_f = 0 \quad (6)$$

$$\rho_f \left[\frac{\partial \mathbf{v}_f}{\partial t} + \nabla \cdot (\mathbf{v}_f \mathbf{v}_f) \right] = -\nabla P_f + \mu_f \nabla^2 \mathbf{v}_f \quad (7)$$

$$\left\{ \begin{array}{l} \rho_f C_{pf} \left[\frac{\partial T_f}{\partial t} + \nabla \cdot (\mathbf{v}_f T_f) \right] = \nabla \cdot (k_f \nabla T_f) \\ \rho_s C_{ps} \frac{\partial T_s}{\partial t} = \nabla \cdot (k_s \nabla T_s) \end{array} \right. \quad (8)$$

B.Cs :

$$\text{on } A_{fs} \quad \mathbf{v}_f = 0, \quad T_f = T_s, \quad \mathbf{n}_{fs} \cdot k_f \nabla T_f = \mathbf{n}_{fs} \cdot k_s \nabla T_s$$

$\Downarrow \Downarrow \Downarrow$ Local volume averaging

$$\nabla \cdot \mathbf{v} = 0 \quad (10)$$

$$\rho_f \left[\frac{\partial \mathbf{v}}{\partial t} + \bar{\nabla} \cdot \left(\frac{\mathbf{v} \mathbf{v}}{\varepsilon} \right) \right] = -\bar{\nabla} P + \mu_f \bar{\nabla}^2 \mathbf{v} + B \quad (11)$$

$$\begin{aligned} \frac{\partial}{\partial t} [\varepsilon \rho_f C_{pf} + (1 - \varepsilon) \rho_s C_{ps}] \bar{T} + \rho_f C_{pf} \bar{\nabla} \cdot (\mathbf{v} \bar{T}) \\ = \bar{\nabla} \cdot (k_{stgn} \bar{\nabla} \bar{T} + \underline{\underline{k_d}} \cdot \bar{\nabla} \bar{T}) \end{aligned} \quad (12)$$

Where

$$\mathbf{v} = \varepsilon \bar{\mathbf{v}}_f \quad (\text{Darcy velocity vector})$$

$$B = - \left[\frac{\varepsilon \mu_f}{K_\mu} + \frac{\varepsilon \rho_f}{K_{inn}} |\mathbf{v}| \right] \mathbf{v} \quad (\text{Ergun's expression})$$

$$\underline{\underline{k_d}} = k_f \underline{\underline{D}} \frac{(1 - \varepsilon)}{\varepsilon^2} Pe^2 \quad (\text{Low Reynolds number flow})$$

Model for numerical analysis

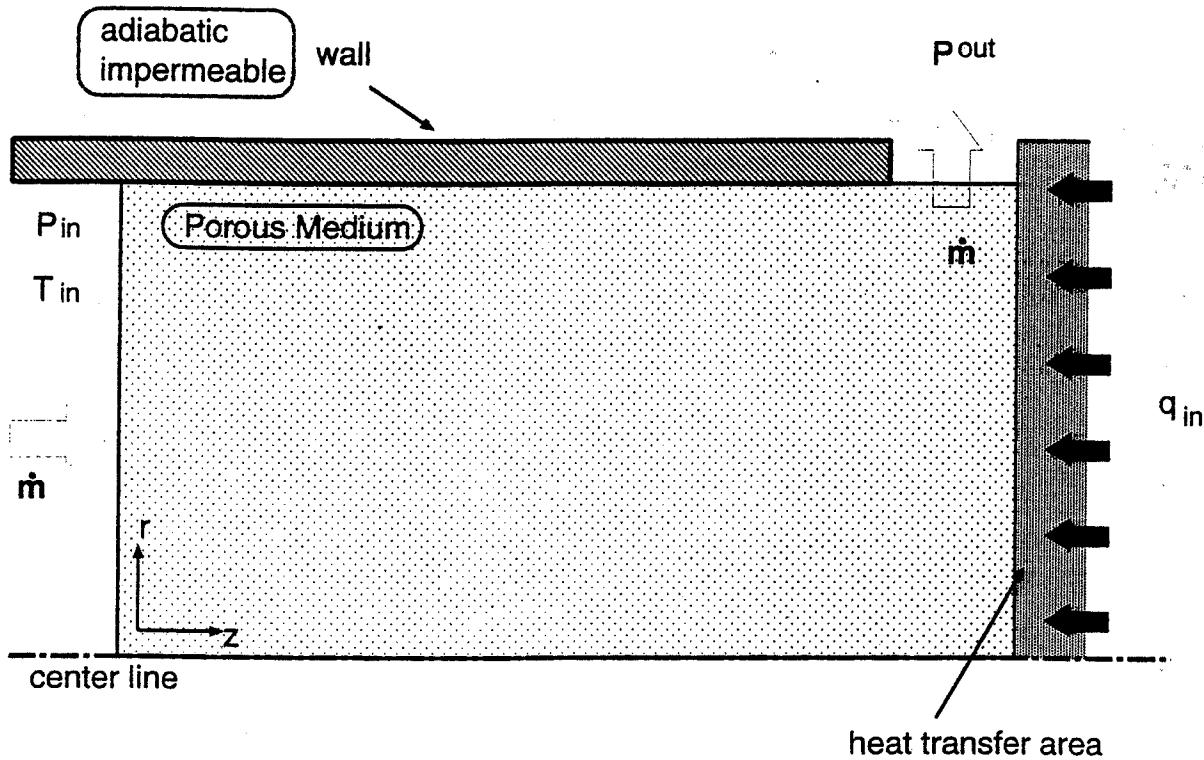


Fig. 9 2-D numerical model

Region : $8\text{cm} \times 2.5\text{cm}$

Porosity : # 1 , # 2

Parameter

P_{in} , T_{in} , P_{out} , q_{in}

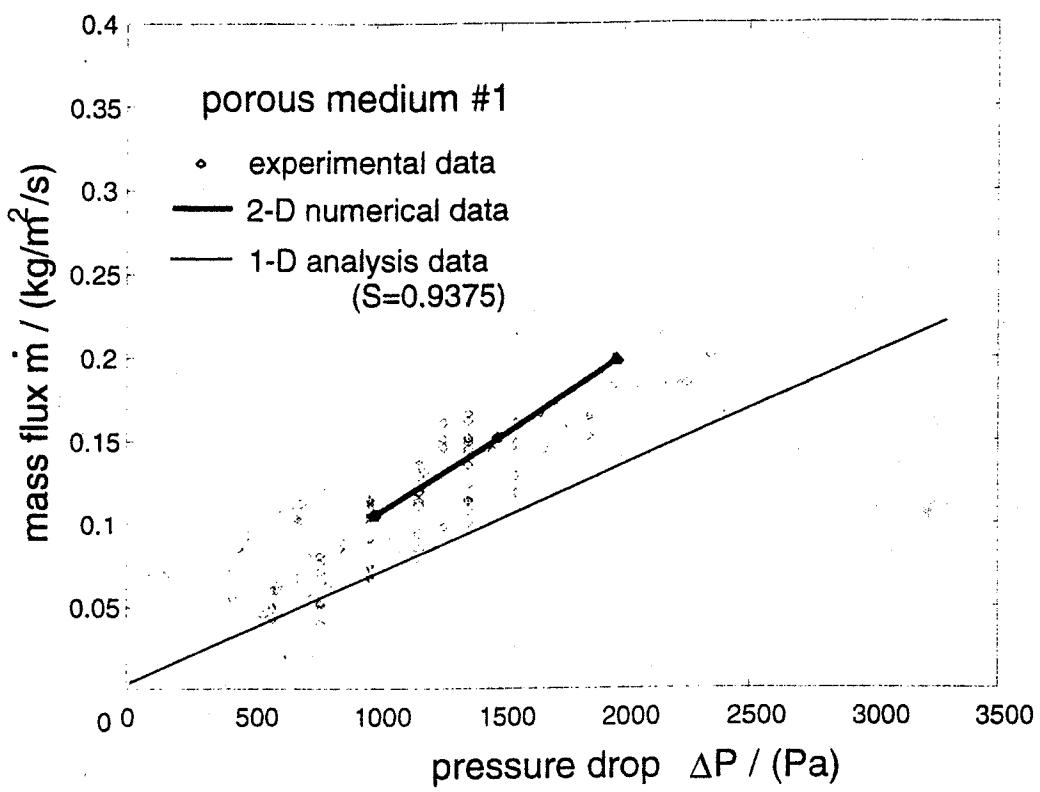


Fig. 12 Comparison of mass flux : porous media # 1

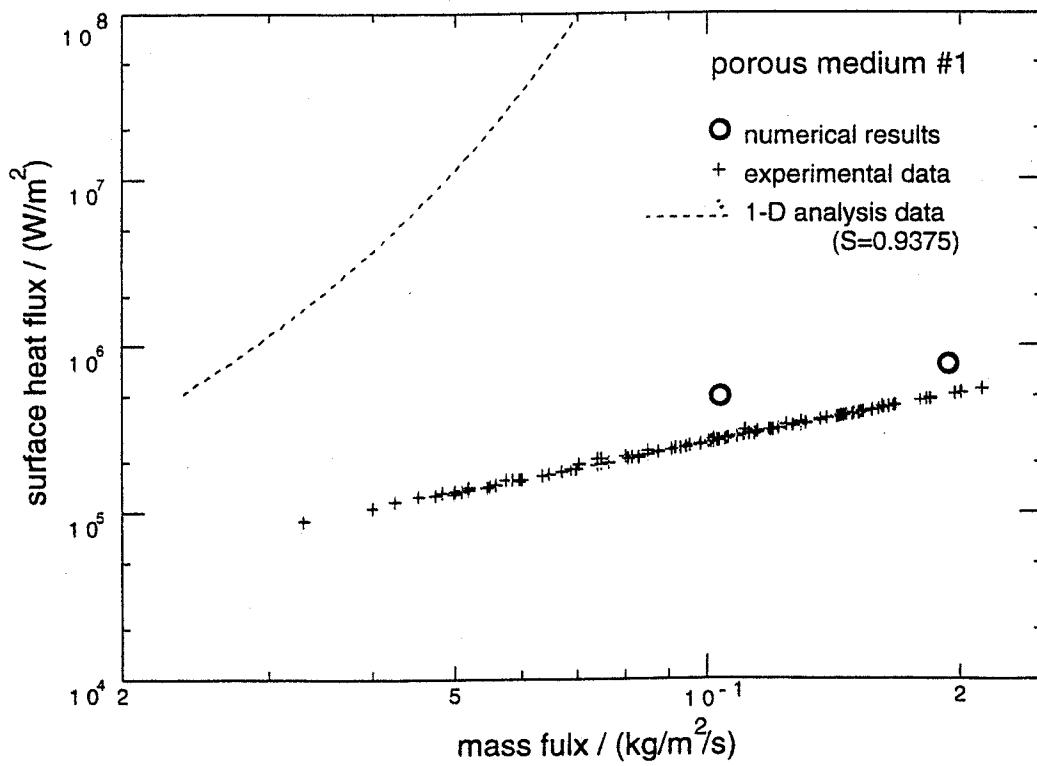


Fig. 13 Comparison of surface heat flux :porous media #1

Numerical results

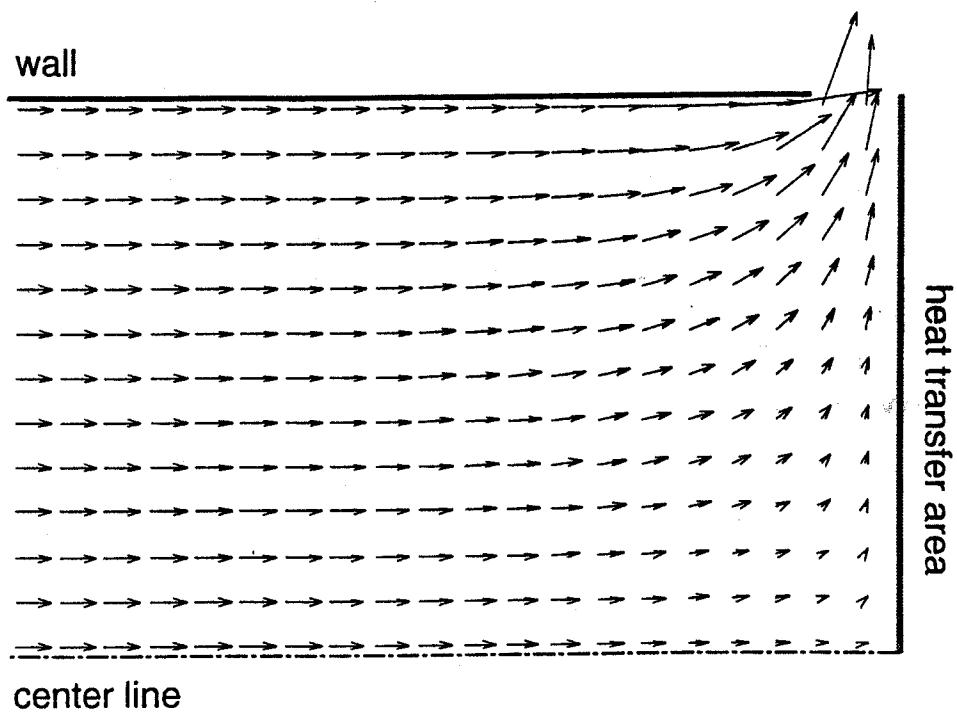


Fig. 10 Mass flux distribution ($\dot{m} = 0.1 \text{ kg/m}^2/\text{s}$)

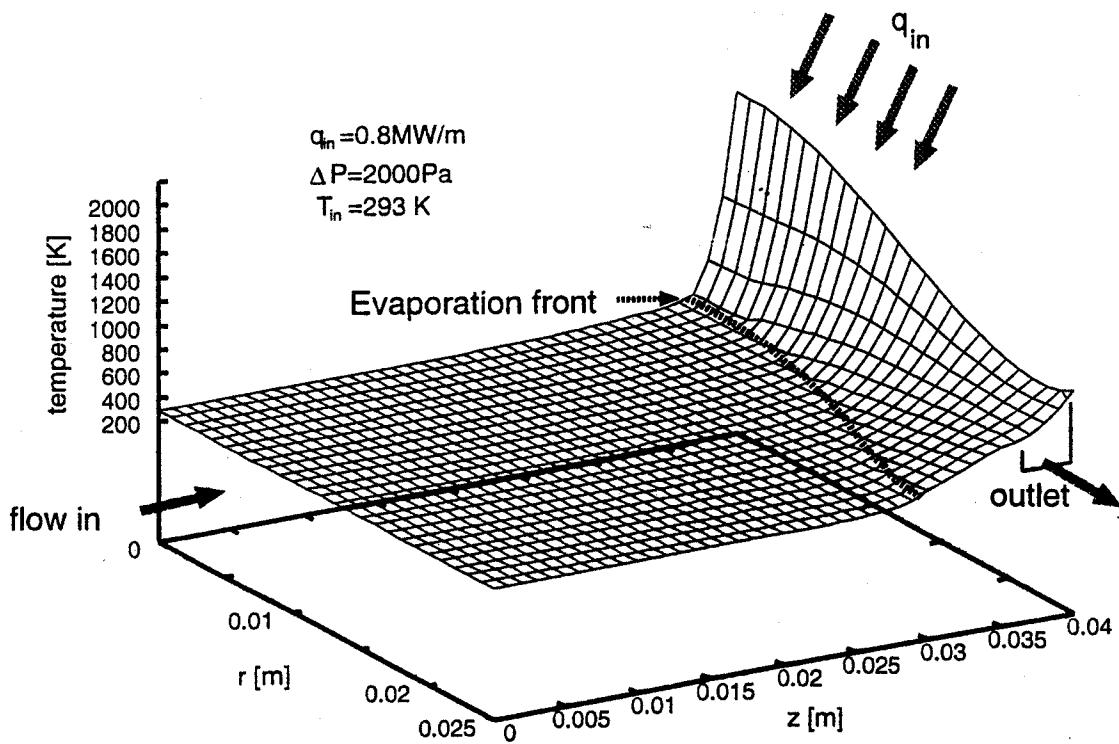
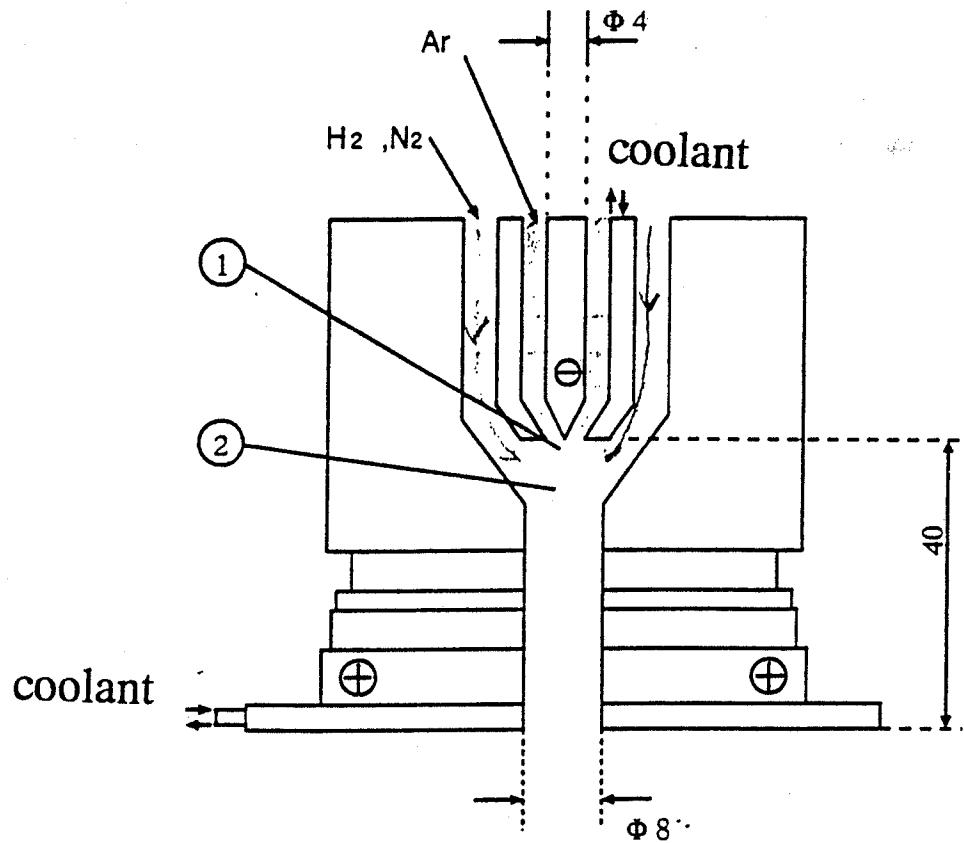


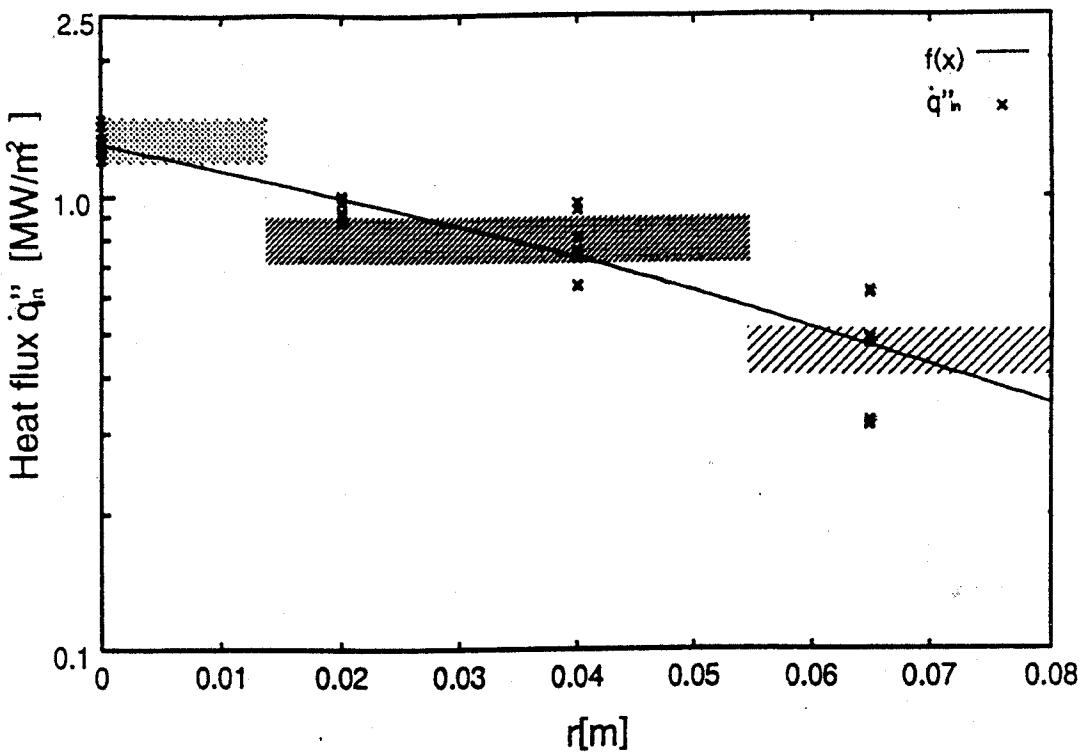
Fig. 11 Temperature distribution
($q_{in} = 0.8 \text{ MW/m}^2, \dot{m} = 0.2 \text{ kg/m}^2/\text{s}$)

High heat load source → Plasma arc jet

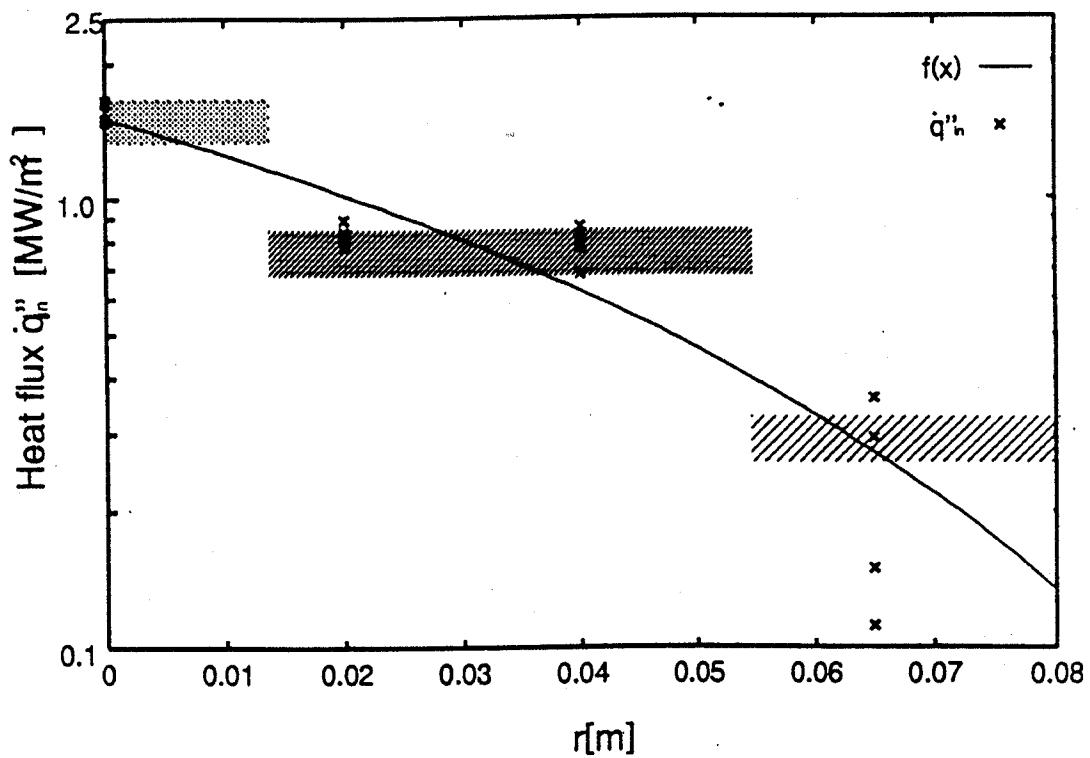
(11MW/m²)



Nozzle part of plasma arc jet facility



2.13: $Ar=40.0\ell/\text{min}$, $H_2=50.0\ell/\text{min}$, $Zl=10.2\text{cm}$



2.14: $Ar=30.0\ell/\text{min}$, $N_2=40.0\ell/\text{min}$, $H_2=20.0\ell/\text{min}$, $Zl=8.4\text{cm}$

Conclusion

- From experiment:
 - the removed heat flux could be enhanced up to the value that corresponded to the maximum power of heaters used in this experiment.
 - It is feasible for the proposed cooling system to remove heat flux up to 1.3MW/m^2 at the present step, and there seems to be a great possibility of the enhancement of the heat removal capacity of this cooling system.
- From the analyses:
 - 1-D analysis could predict the relation between the pressure drop and the mass flux, while it couldn't predict the relation between the mass flux and the removed heat flux.
 - 2-D numerical simulation can predict above both relations.