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THERMOFLUID DYNAMICS OF THE SINQ TARGET

- A Natural Circulation Loop as a Target -

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1. Introduction

The target of the spallation neutron source at SIN (SINQ) is a liquid lead bismuth eutectic (LBE) in a vertical cylindrical container with the proton beam entering from below. The thermofluid behaviour of the liquid LBE was investigated based on the natural convection in an enclosure. It has been shown that the natural convection mechanism is effective for transporting energy deposited at the bottom to the heat exchanger located at the top of the target [1].

However, simulation experiments with water showed some instabilities in the total flow. The corresponding bifurcation and axial asymmetry lead to a swaying motion of the rising flow. These would result in difficulties of monitoring the thermofluid behaviour and reduce the controlability of the target.

Therefore, the system was modified by introducing a guide tube, which is a simple coaxial tube, into the container. This new concept leads to advantages, described in the following points;

1) The flow configuration is converted from pure natural convection in a simple enclosure to a natural circulation loop. This simplifies the prediction of overall behaviour of the system.
2) A higher flow rate of the target liquid can be expected. Hence the maximum temperature will be lower and the transient shortened. Furthermore, the effect of local flow disturbances might become smaller.
3) Since the cooled liquid is guided right down to the bottom of the target, increased cooling of the window by target liquid will result.

In this paper are presented the results of the analysis on the thermofluid characteristics of the target system with guide tube, based on the one dimensional natural circulation loop [2]. This analysis is compared with the NACOSPANS experiments.

2. Analytical

2.1 Analytical method

The calculational model is illustrated in Fig.1. The loop consists of two long vertical legs of the same diameter as the guide tube and of the height of the target. One leg corresponds to the inner flow channel of the guide tube and the other to the outer. An internally heated region is located at the bottom of one leg and the heat exchanger at the top of the other. The heat exchanger is simulated by a volumetric heat sink. By assuming a constant flow area over the loop and by neglecting the effects arising from turns at the both ends, the problem becomes one dimensional. Details of the derivation of the equations and solutions are described in [3].

The governing equations in nondimensional form are ;

(1) $$\partial\Theta/\partial\tau + w(\partial\Theta/\partial Z) = \alpha/(2DL^2)\partial^2\Theta/\partial Z^2 + q'$$

where
$$q' = \begin{cases} 1 & : 0 < Z < \delta \\ 0 & : \delta < Z < 1/2 \\ -\Theta & : 1/2 < Z < 1/2+\gamma \\ 0 & : 1/2+\gamma < Z < 1 \end{cases}$$

(2) $$dw/d\tau = -\lambda Lw^2/d + Qg\beta/2D^3L \int_0^1 \Theta\, dZ$$

In the above equations, the Bousinesque approximation has been used. The momentum equation has been integrated over the loop to eliminate the static pressure.

The normalized variables are as follows :

(3)
$$\Theta = (T-Ts)D/Q$$
$$\tau = tVs/2L$$
$$w = v/Vs$$
$$Z = z/2L$$
$$\delta = h/2L$$
$$\gamma = 1/2L$$

where Vs (= 2DL) is the characteristic velocity.

λ is the friction coefficient in a smooth tube and given by :

(4)
$$\lambda = 64/Re \quad : Re<2000 \text{ (Laminar)}$$
$$\lambda = 0.3164/Re^{1/4} \quad : Re>2000 \text{ (Turbulent)}$$

A closed form solution for the steady state can be obtained when axial heat conduction in Eq.(1) is neglected. They are :

(5) $\Theta = Z/w + C1 = Z/w + \delta\exp(-\gamma/w)/w[1-\exp(-\gamma/w)]$

$: 0 < Z < \delta$

$C2 = \delta/w[1-\exp(-\gamma/w)] \qquad : \delta < Z < 1/2$

$C3\exp(-Z/w) = \delta\exp(-Z/w)/w\exp(-1/2w)[1-\exp(-\gamma/w)]$

$: 1/2 < Z < 1/2+\gamma$

$C4 = \delta\exp(-\gamma/w)/w[1-\exp(-\gamma/w)] \qquad : 1/2+\gamma < Z < 1$

Fig.2 illustrates the temperature distribution given by (5).

Substituting these temperature results into Eq.(2), one obtains

(6) $-\lambda Lw^2/d = Qg\beta/2D^3L\{\delta(1-\delta)/2w - \delta + \delta\gamma\exp(-\gamma/w)/w[1-\exp(-\gamma/w)]\}$

A steady state velocity value can be obtained by solving this nonlinear equation.

2.2 Analytical Results

Extreme examples can be examined. If $\gamma/w<1$, the following relationship is obtained for the steady state velocity ;

(7) $w^3 \rightarrow Qg\beta\delta(1-\gamma)/4D^3L \; ; \; v \rightarrow Q^{1/3}$

Therefore, the steady state velocity is proportional to the cube root of beam power. The maximum temperature is

(8) $\Theta max = C2 \rightarrow \delta/\gamma \; ; \; Tmax \rightarrow Qh/DL$

It is linearly proportional to the input power but inversely to D and L.
The temperature difference is

(9) $\Delta\Theta max = C2 - C4 \rightarrow Q^{-1/3} \; ; \; \Delta Tmax \rightarrow Q^{2/3}$

This agrees with the results in [4].

A volumetric heat sink rate is obtained from the heat exchanger characteristics based on the total amount of heat transfer.

(10) $UST/\rho CpV = DT$

where U is an average overall heat transfer coefficient, S the total heat transfer area, ρ the density of LBE, Cp the specific heat of LBE, V the volume of the shell of the heat exchanger. Then, D can be estimated from

(11) $D = 2Urn/\rho CpRb^2$

where r is the radius of the heat exchanger tube, n the number of tubes, Rb the radius of the loop.

For the representative numerical values of the real target, U=0.1 W/cm^2K, r=1.5 cm, Rb=5.5 cm, n=30, ρ=10.5 g/cm^3, Cp=0.15 Wsec/gK,

$$D = 0.19 \text{ /sec.}$$

The solution of Eq.(6) is shown in Fig.3 with dimensions of L=350 cm, h=30 cm, l=200 cm. The maximum temperature was calculated like C2 (Eq.5) with the corresponding velocity values (Fig.3). It shows the 1/3 power law for velocity variation as Eq.(7) and a linear proportionality for the maximum temperature as Eqs.(7) and (8) with respect to the input power.

2.3 Numerical Calculations

2.3.1 Simple tube loop

Equations (1) and (2) were solved numerically in order to study the time dependent behaviour of the loop and the effect of axial heat conduction. Details of the numerical methods and most of the results on the time dependent temperature distributions are given in [3].

The effect of input power on the maximum temperature and velocity is shown in Fig.4. The maximum temperature depends roughly linearly on the input power and the velocity shows approximately cubic root of the input power. This agrees with the simplified prediction. However, the velocity value is smaller by factor 2. This is due to the effect of the axial heat conduction.

Fig.5 shows the effect of the volumetric heat sink rate D on the maximum temperature and velocity. The velocity is only slightly affected by D. However, Tmax decreases inversely with increasing D, which also agrees with Formula (8).

2.3.2 The effect of pressure loss at the bottom turn

One might expect that the pressure drop from the U turn bend at the bottom of the target will have a large effect on the flow. In order to investigate this, the governing equation (2) was slightly modified as :

$$(12) \qquad dw/d\tau = -(K+2\lambda L/d)w^2/2 + 2Qg\beta/D^3L \int_0^1 \Theta \, dZ$$

where K is an empirical coefficient of the pressure loss produced by geometry variations such as sudden enlargement, contraction, bends and turning bend [5]. For the present case, it is taken as 2.86. This value is a few times larger than that for the smooth tube pressure loss (the second term in the parentheses) for the

dimensions of real target.
Similar behaviour of the time variation of the maximum temperature and velocity was obtained [3]. However, the stationary value of the velocity is lower, which results in a higher maximum temperature at the steady state. For the case of a representative SINQ-target at 1MW power input and compared with the results without turning loss, the velocity is reduced by about 44 cm/sec and the temperature increased by about 11 °C.

3 Water Experiments (NACOSPANS)

NACOSPANS is a test rig for water flow experiments in a 2m high cylinder. The apparatus is described in [6]. Flow visualization was made by using ink as a tracer. Movie films were taken for two different input powers of 500 and 800 W. By analysing those films, stationary velocity values were obtained which are plotted in Fig.6. A good agreement is obtained, although those values are slightly lower than predictions.

4. Conclusion

The thermal and fluid dynamic characteristics of the SINQ-target have been investigated analytically and numerically. The Model used is based on a natural circulation loop with uniform heat deposition at the bottom and a volumetric heat sink for the heat exchanger at the top. The analytical method is supported by the water experiments. The following conclusions are drawn.

1) The steady state velocity is proportional to cubic root of the beam power, and the maximum temperature is linearly proportional to the input power. Both analytical and numerical calculations show the same behaviour.
2) The effect of the axial heat conduction on the steady state velocity is large. For a representative SINQ-target a factor of 2 reduction is obtained.
3) The flow is well established with higher velocity level. For a representative SINQ-target it is approximately 160 cm/sec.
4) The maximum temperature increase at the steady state is about 206 °C. Hence the maximum temperatures will be below 400 °C and therefore below a level where fast corrosion effects might occur.
5) The effect of the pressure loss due to the U turn bend at the bottom of the loop shows a large effect.

Acknowldegement

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Nomenclature

D	:	Volumetric heat sink rate
g	:	Gravity
h	:	Height of the heated region
l	:	Length of the heat exchanger
L	:	Target height
p	:	Pressure
q,Q	:	Uniform Volumetric heat deposition
Re	:	Reynolds number
t	:	Time
T	:	Temperature
Ts	:	Initial temperature
v,V	:	Velocity
Vs	:	Characteristic velocity
w	:	Dimensionless velocity
z,Z	:	Space coordinate
α	:	Thermal diffusivity
β	:	Thermal expansion coefficient
λ	:	Pressure loss friction coefficient
ν	:	Dynamic viscosity
ρ	:	Density
τ	:	Dimensionless time
θ	:	Dimensionless temperature

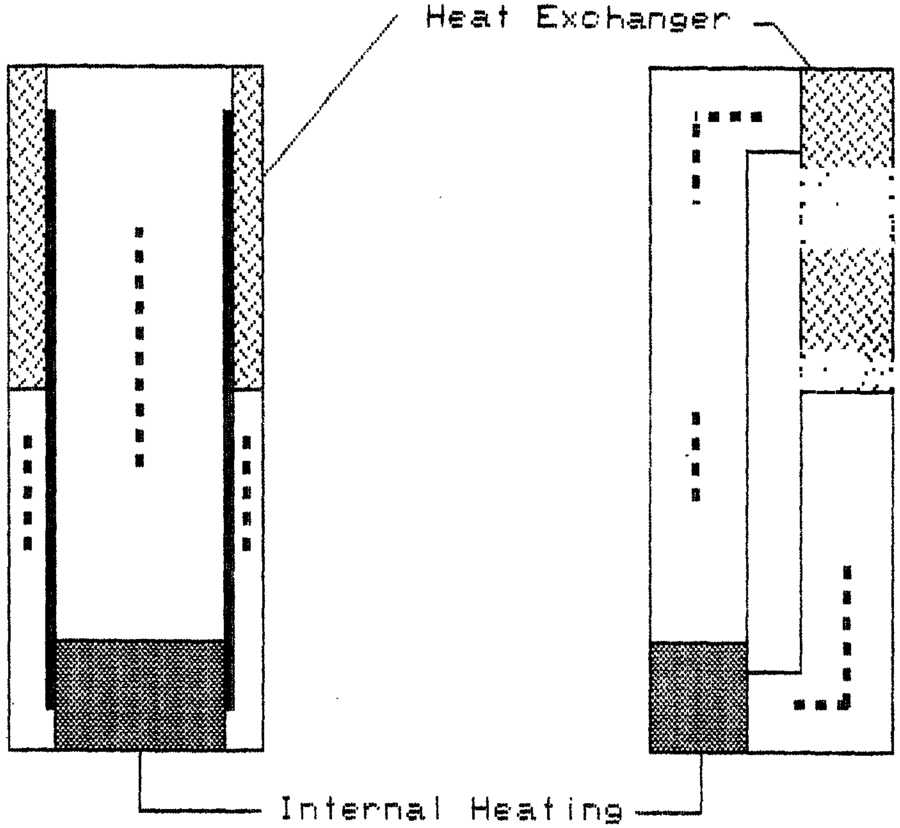

Fig.1 SINQ Target and Calculational Model

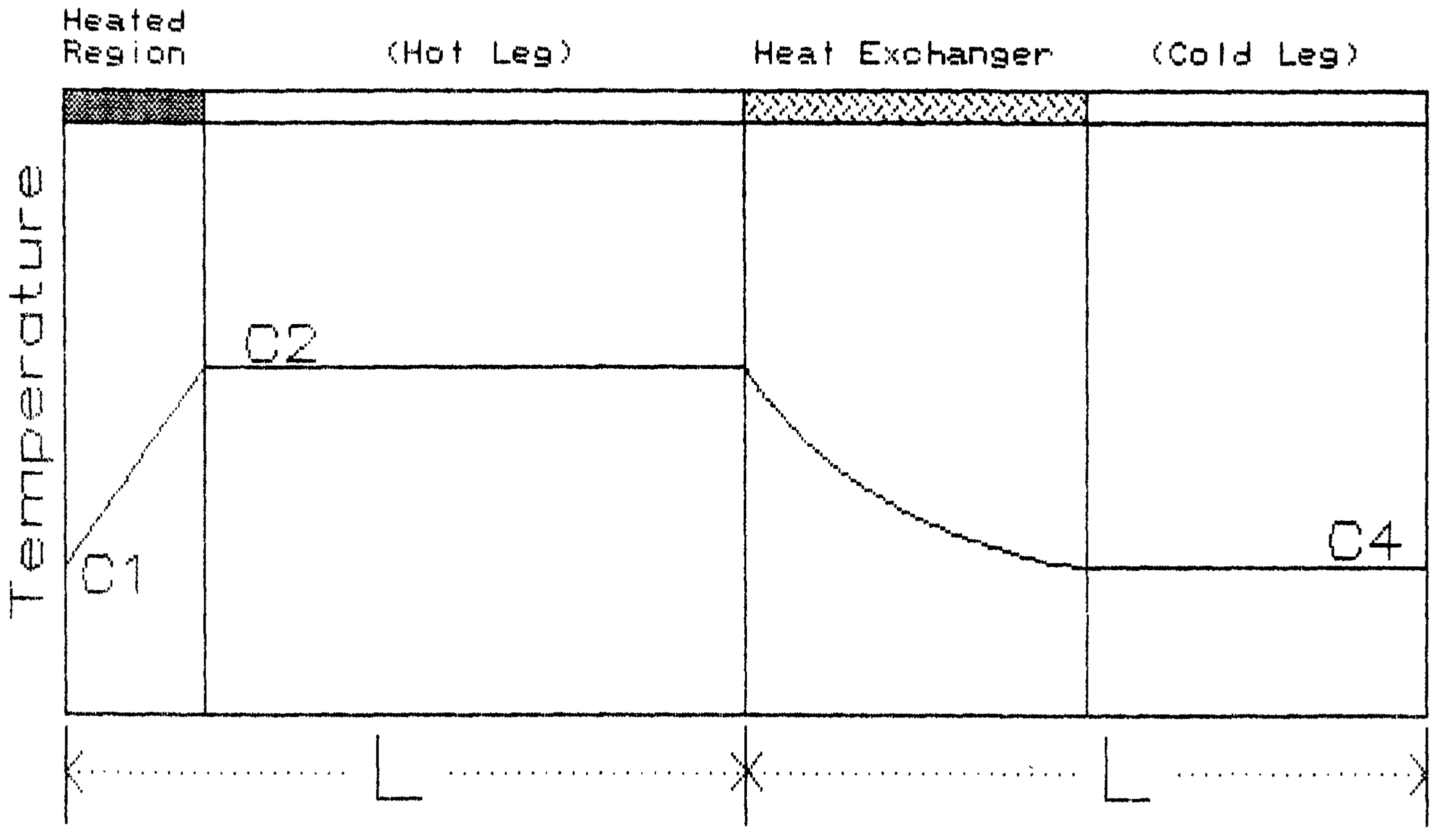

Fig.2 Schematic Temperature Distribution for Steady State without Heat Conduction

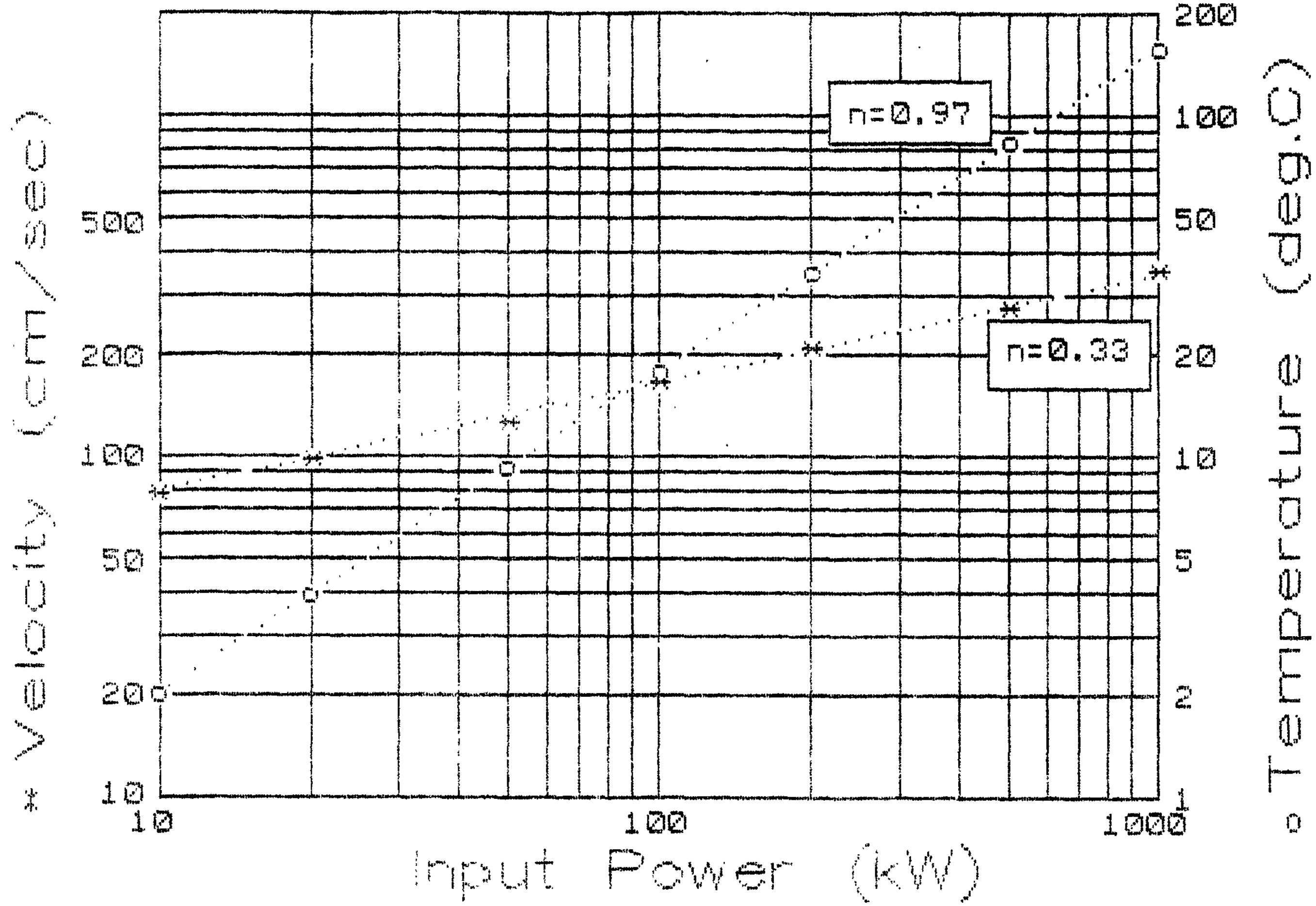

Fig.3 Analytical Results for Steady State Velocity and the Maximum Temperature

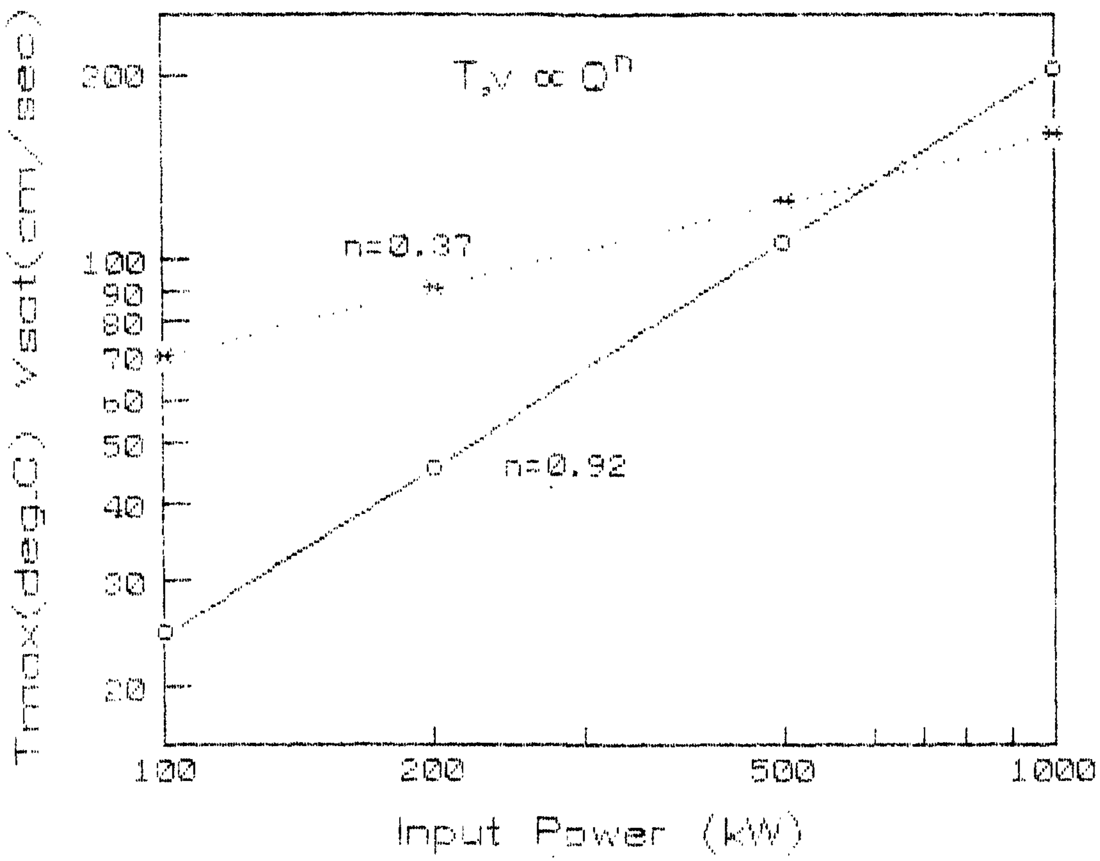

Fig.4 Dependence of the Steady State Maximum Temperature and Velocity on Input Power

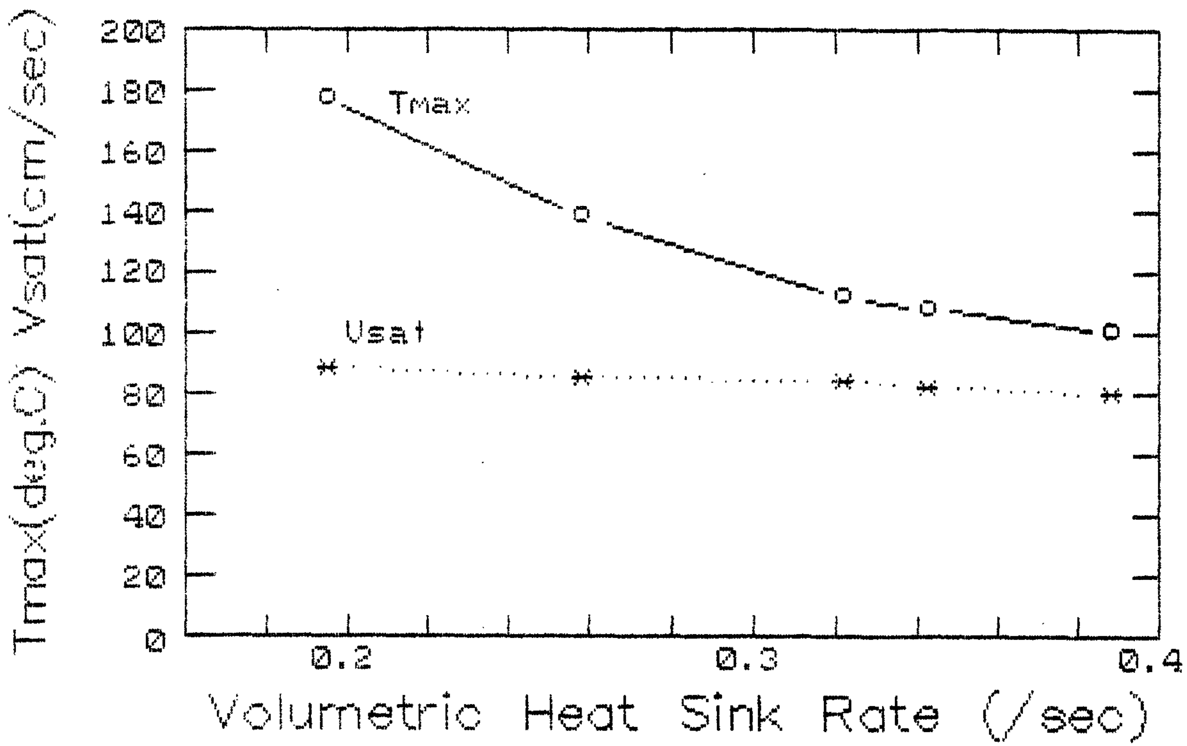

Fig.5 Dependence of the Steady State Maximum Temperature and Velocity on Volumetric Heat Sink

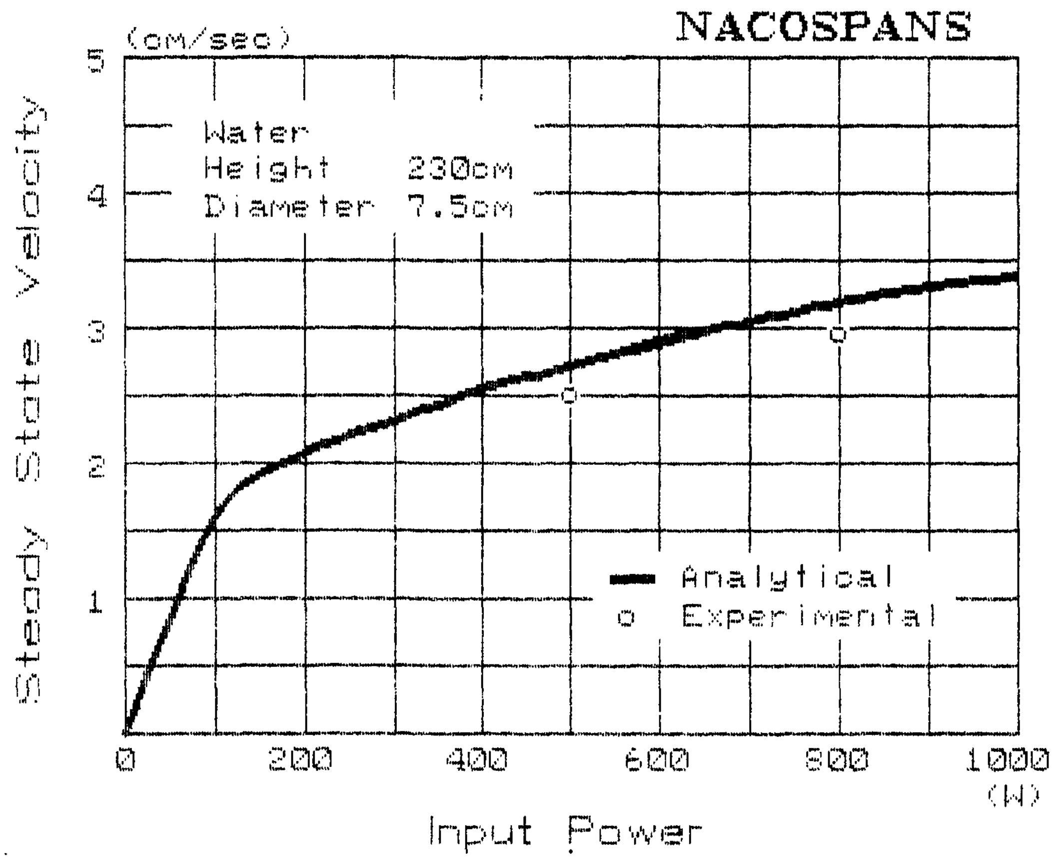

Fig.6 Comparison of Analytical and Experimental Steady State Velocity