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Thermal and Hydraulic Design of Mercury Target - Cross Flow Type -

Masanori KAMINAGA, Ryutaro HINO and Akira SUSUKI
Japan Atomic Energy Research Institute (JAERI), JAPAN
Motoaki SAKASHITA
Hitachi Engineering Co., Ltd., JAPAN
Fumito NAKAMURA and Hisato TAGAWA
Hitachi, Ltd., JAPAN

ABSTRACT

For the design of the 5MW mercury target system at JAERI, sufficient heat removal with a slow mercury flow is necessary to prevent corrosion and erosion. In this paper, the conceptual design for the target container of the Cross Flow Type was performed and thermo-hydraulics in the target was numerically investigated with the STAR-CD Code.

It was effective that distribution plates were positioned near the inlet and the outlet in the container and the openings on the distribution plates were made larger near the beam window. As a result, the maximum temperature of mercury was less than 220 C and the maximum flow velocity was less than 1.5 m/s. Simulations with some parameter changes showed that maximum temperature could be reduced further.

1. Introduction

For a target system using a high power proton beam, mercury is the most promising material as spallation target. However, mercury has two undesirable properties: first, it is corrosive at high temperature, and second, it causes erosion when it flows fast. Mercury in the target container can be kept at low temperature if the mercury flow rate is increased, but the mercury flow rate is also restricted by the size of the mercury cooling system and the target container. The size of the target container especially requires the mercury flow rate to be small, because the efficiency of neutron utilization will drop if the target container becomes larger. Therefore, the design of the target container must meet these requirements, that is, it must realize a slow and effective mercury flow that can remove the nuclear heat and keep mercury at low temperature.

Target container can be categorized into the Return Flow Type and the Cross Flow Type according to the mercury flow patterns. In the Return Flow Type target, mercury flows along the proton beam, while in the Cross Flow Type target, mercury flows across the proton beam. Comparing these types, the Cross Flow Type target has more possibility of achieving low temperature with a slow mercury flow, while the appropriate distribution of the mercury flow rate in the target is a difficult problem.

For the development of the 5MW mercury target project at JAERI, in this paper, the conceptual design and elemental specifications of the mercury cooling system was investigated and a prototype model of the Cross Flow Type target was presented. The mercury flow distribution in the target container and its improvements was investigated with the STAR-CD Code.

2. The Conceptual Design of a Mercury Cooling System

Fig. 1 illustrates the conceptual design of a mercury cooling system. As shown in Fig. 1, the mercury cooling system consists of two mercury circulating pumps, two heat exchangers, a surge tank, and two drain tanks, etc. Mercury is driven by the mercury circulating pumps and circulates through the target system. Hot mercury heated in the target is transferred into the surge tank and moved into the heat exchangers. Mercury is cooled below 50 C in the heat exchangers and returns to the target again. The mercury flow rate is set at 50 m^3/h to suppress the temperature rise in the target below 100 C on average. As shown in Fig. 2, the mercury cooling system is installed on a target train. A protective cover encloses all equipment to seal mercury vapor for the accident of mercury leakage from the equipment.

3. The Conceptual Design of a Target Container

3.1 Comparison of Target container type

Target container can be categorized into the Return Flow Type and the Cross Flow Type according to the mercury flow patterns. Table 1 shows the comparison of these two types.

The mercury temperature rise in a target depends on the total heat generated along the mercury flow path. That is, in the Cross Flow Type target, the temperature rise is determined by the total heat integrated along the direction perpendicular to proton beam, while in the Return Flow Type target, the temperature rise is determined by the total heat integrated along the same direction as proton beam. In the case of our beam profile, the total heat generated along the direction perpendicular to proton beam is smaller than that generated along proton beam direction. Therefore, the temperature rise is smaller in the Cross Flow Type target than in the Return Flow Type for the same mercury flow velocity.

The mercury flow velocity in a target depends on the cross sectional area of the channel in the target container. The channel area in the Cross Flow Type target is larger than that in the Return Flow Type target, because the length of the target in the proton beam direction is generally longer than the length across the beam line. Therefore, the mercury flow velocity is smaller in the Cross Flow Type target than in the Return Flow Type target for the same mercury flow rate.

The size of the Cross Flow Type target is generally larger than the size of the Return Flow Type target, because both an inlet channel and an outlet channel are necessary for the Cross Flow Type target, while the outlet channel is not necessary for the Return Flow Type target.

The technical issue with the Cross Flow Type target is the method of realizing the necessary mercury flow distribution, because the appropriate mercury flow distribution can remove the intense heat and suppresses the temperature rise. In the case of the Return Flow Type target, it is only required for mercury to flow smoothly near the beam window, therefore the flow pattern is simple and the flow distribution is not important.

3.2 The Conceptual Design of a Target Container

Considering advantages and disadvantages discussed above, we selected the Cross Flow Type target and investigated the method to realize the appropriate mercury flow distribution. Fig. 3 shows the illustration of the conceptual design of a mercury target container. The target container is cooled by coolant that flows between the outer and inner containers. Helium gas, light water and heavy water were considered as a candidate. We selected heavy water as a coolant material by following reasons.

(1) In order to remove the generated heat, water coolant is more preferable than helium gas.

(2) Water was not recommended because of vapor explosion possibility in case of inner container failure. This was the reason why helium gas was normally used. However, this possibility is avoidable by keeping mercury at low temperature.

(3) Neutron absorption cross section of heavy water is lower than light water. Therefore, heavy water is better material from the view point of neutron utilization.

The mercury flow crosses the central part of the target, where the pulsed proton beam is injected across the mercury flow and causes heat generation. In order to remove the intense heat near the beam window, the openings on distribution plates near the beam window are designed to be larger than other position. Moreover, the openings on the inlet plate are aligned in the lower part and openings on the outlet plate are aligned in the upper part, so that the heated mercury can flow smoothly with the natural convection.

4. Thermo-Hydraulic Analysis

4.1 Model for Thermo-Hydraulic Analysis

Thermo-hydraulic analysis was carried out with the STAR-CD Code. Computational region was divided into 39,960 cells (X=74, Y=45, Z=12) as shown in Fig. 4. The axial distribution of power density is given in Fig. 5, which is obtained by the averaging the power density calculated by the NMTC/JAERI Code. The mercury flow rate was set at 50 m^3/h and the cross sectional areas of the inlet and the outlet were determined to suppress the mercury flow velocity under 1 m/s. In order to remove the intense heat near the beam window, the openings on distribution plates near the beam window are designed to be larger than other position. The openings on the inlet plate are aligned in the lower part, while the openings on the outlet plate are aligned in the upper part.

4.2 Results of Thermo-Hydraulic Analysis

Fig. 6 shows the temperature and the velocity distributions of mercury on the middle surface of the target. The maximum temperature of 220 C was observed near the beam window, where the heat generation was relatively large and the mercury flow rate was also relatively small. The maximum flow velocity of 1.5 m/s was observed near the outlet distribution plate. The following two methods for improvement were expected to reduce the maximum temperature:

1st Method Enlarging the cross sectional area of the front part of the target compared to that of the rear part of the target.

2nd Method Increasing the radius of side corner roundness at the front end of the target.

4.3 Effect of Improvements

Simulations with the target containers shown in Fig. 7 were also carried out to prove the effects of 1st & 2nd method on the reduction of temperature. The results are listed in Table 2.

By the 1st method, the maximum temperature could be reduced to about 213 C. On the other hand, the maximum flow velocity increased to about 2.2 m/s, because the cross sectional areas of the inlet and the outlet were decreased. However, the ratio of the maximum velocity relative to the inflow velocity was the same as the base case. Therefore, enlargement of the cross sectional area of the front part in the target container can reduce the mercury temperature without increasing flow velocity. By the 2nd method, the maximum temperature could be reduced to about 211 C, and the maximum velocity was the same as the base case.

These results showed the fact that the maximum temperature could be reduced further by optimizing the shape of the target container.

5. Summary

For the design of the 5MW mercury target system at JAERI, sufficient heat removal with a slow mercury flow is necessary to prevent corrosion and erosion. In this paper, the conceptual design for the target container of the Cross Flow Type was performed and thermo-hydraulics in the target was numerically investigated with the STAR-CD Code.

It was effective that distribution plates were positioned near the inlet and the outlet in the container and the openings on the distribution plates were made larger near the beam window. As a result, the maximum temperature of mercury was less than 220 C and the maximum flow velocity was less than 1.5 m/s. Simulations with some parameter changes showed that maximum temperature could be reduced further.

References

(1) H.TAKADA, N.YOSHIZAWA, K.KOSAKA, K.ISHIBASHI, “An Upgraded Version of Nucleon Meson Transport Code : NMTC/JAERI97”, JAERI-Date/Code 98-005, February 1998.

(2) R.HINO, M.KAMINAGA, T.ASO, H.KOGAWA, S.ISHIKURA, A.SUSUKI, A.TERADA, H.KINOSHITA and K.HAGA, "Spallation Target Development at JAERI", June,1998,

(3) R.HINO, K.KAMINAGA, S.ISHIKURA, I.YANAGISAWA, M.UZAWA, K.KUROSAWA, K.IKEDA and S.UCHIDA, "Preliminary Design of Mercury Target -Return Flow Type-", June, 1998.

Table 1 Comparison of Mercury Flow Type between Cross Flow Type and Return Flow Type

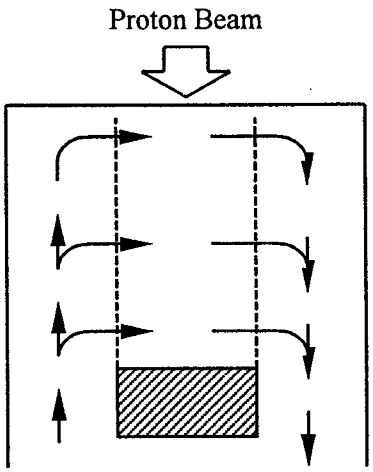
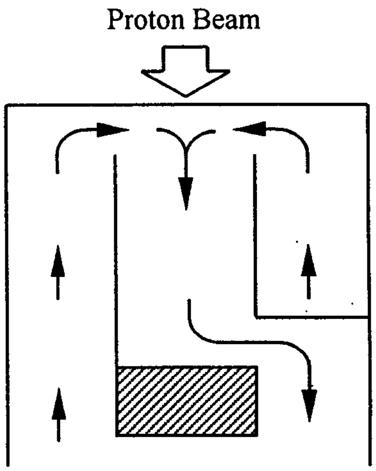
Flow Type	Cross Flow Type	Return Flow Type
		
Max. Temperature	Low O	High
Mercury Velocity	Low O	High
Container Size	Large	Small O
Flow Distribution	Complicated	Simple O

Table 2 Result of Parameter Survey Analysis

Item	Inlet & Outlet Channel Size (mm)	Max. Temp. (C)	Max. Velocity (m/s)	$\left[\frac{\text{Max. Vel.}}{\text{Inflow Vel.}}\right]$ (%)
Base case	W145×H98	220	1.5	149
1st method	W 98×H98	213	2.2	148
2nd method	W145×H98	211	1.5	149

Note : Mercury flow rate : 50m^3/h

Mercury inlet temperature : 50C

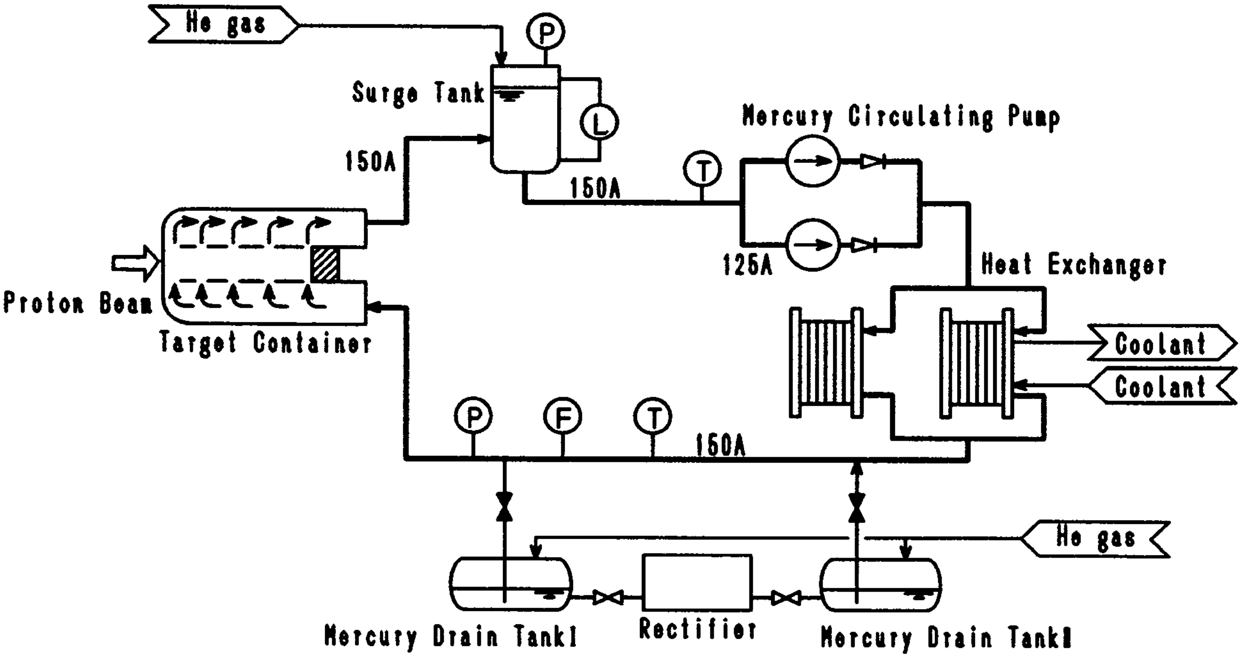


Fig. 1 Conceptual Diagram of Mercury Cooling System

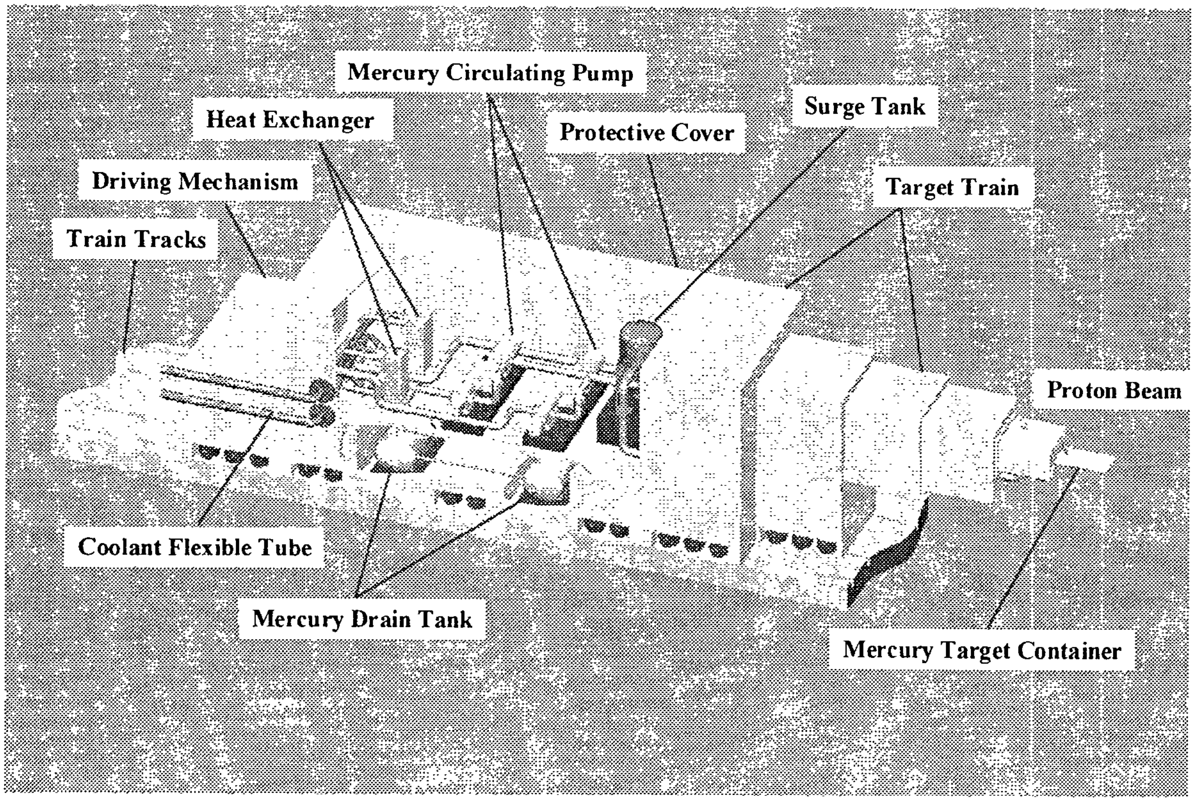


Fig. 2 Bird-eye View of Mercury Cooling System

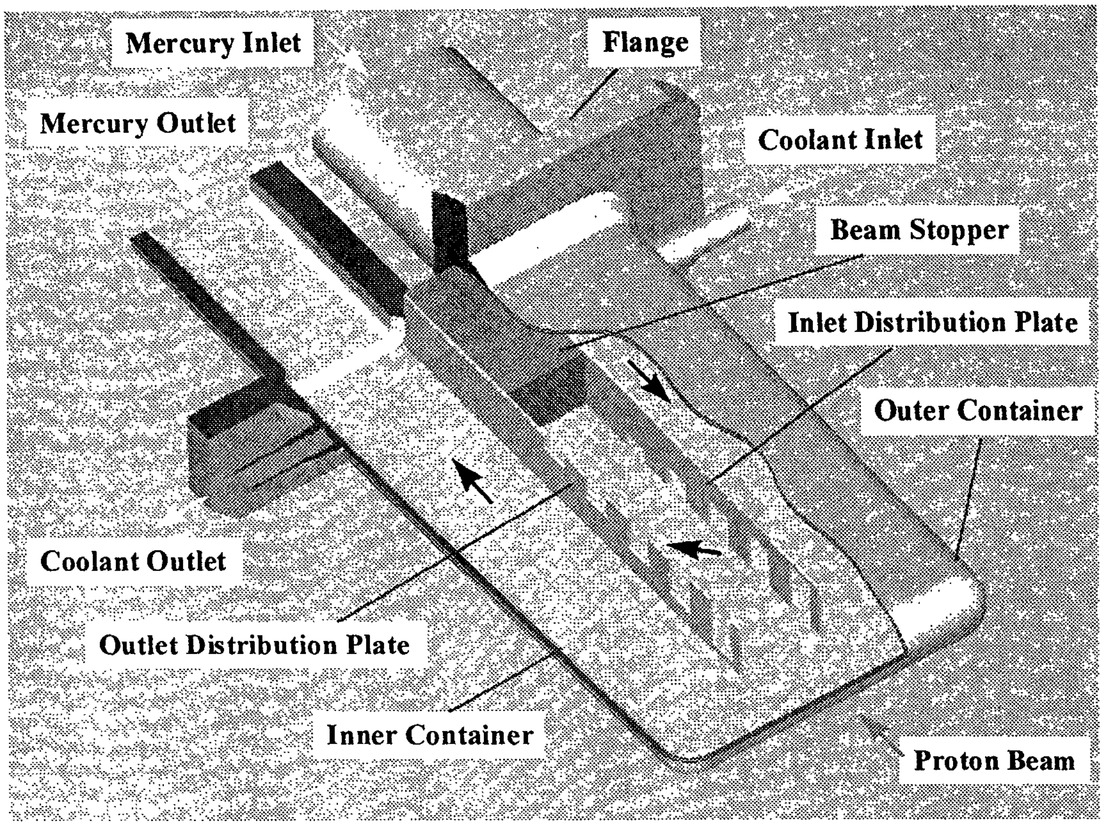
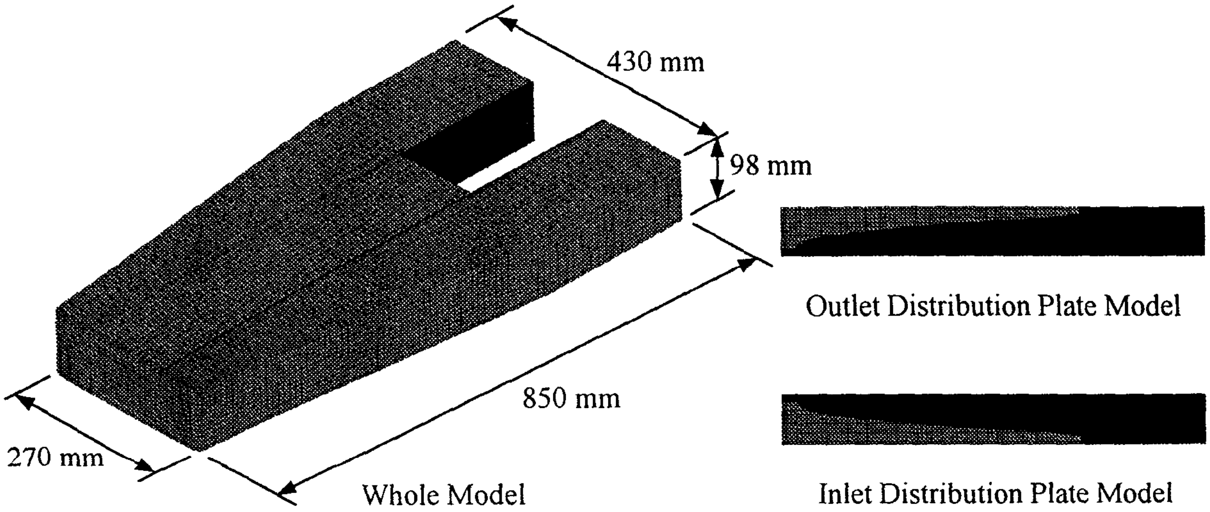


Fig. 3 Illustration of Mercury Target Container of Cross Flow Type

Using Code : STAR-CD
Number of Cell : 39,960
(X , Y , Z) = (74 , 45 , 12)



Whole Model

Outlet Distribution Plate Model

Inlet Distribution Plate Model

Fig. 4 Model for Thermo-Hydraulic analysis

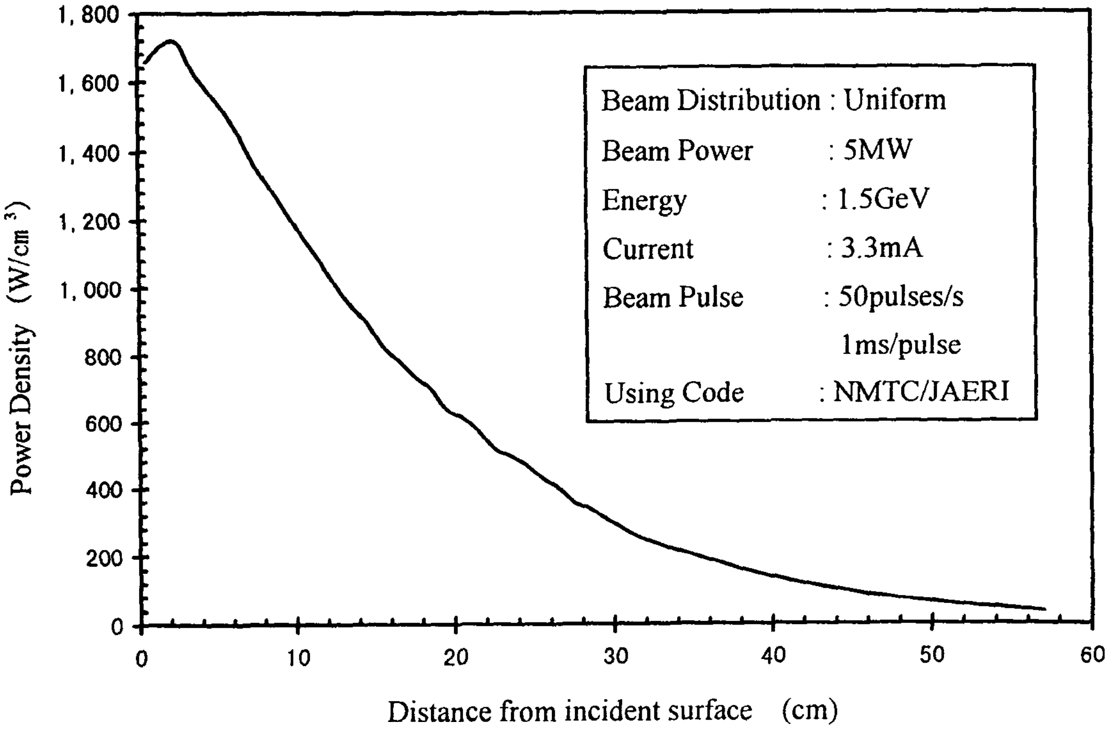
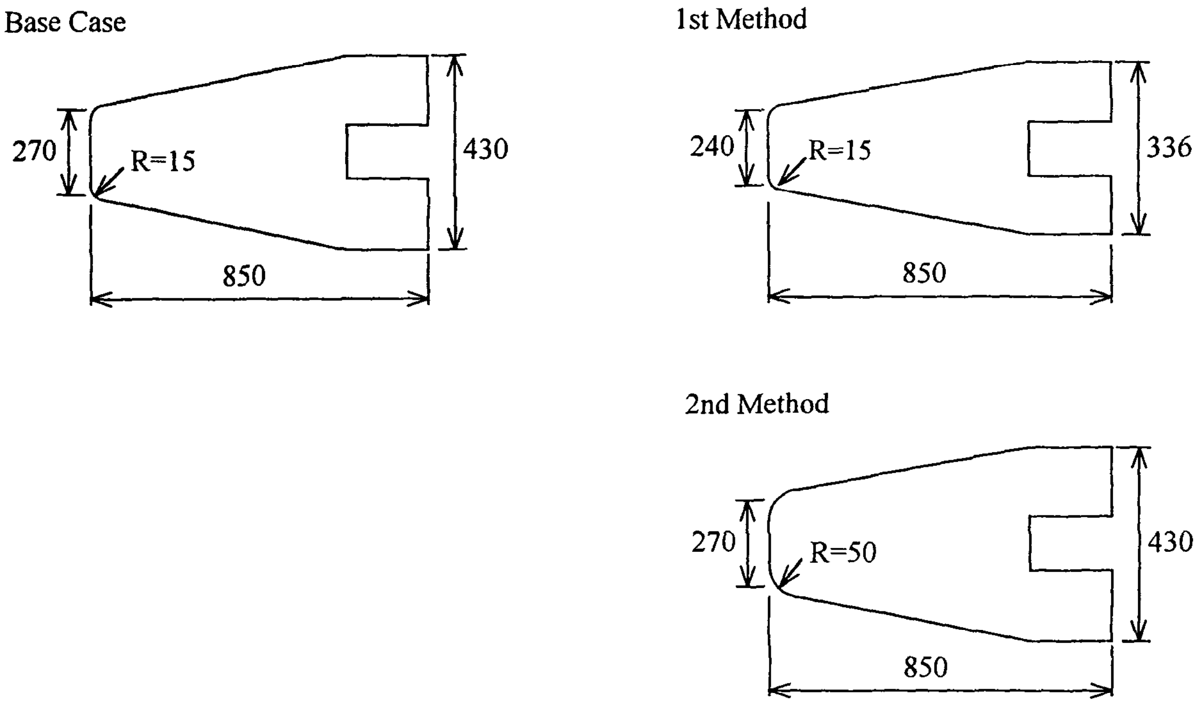


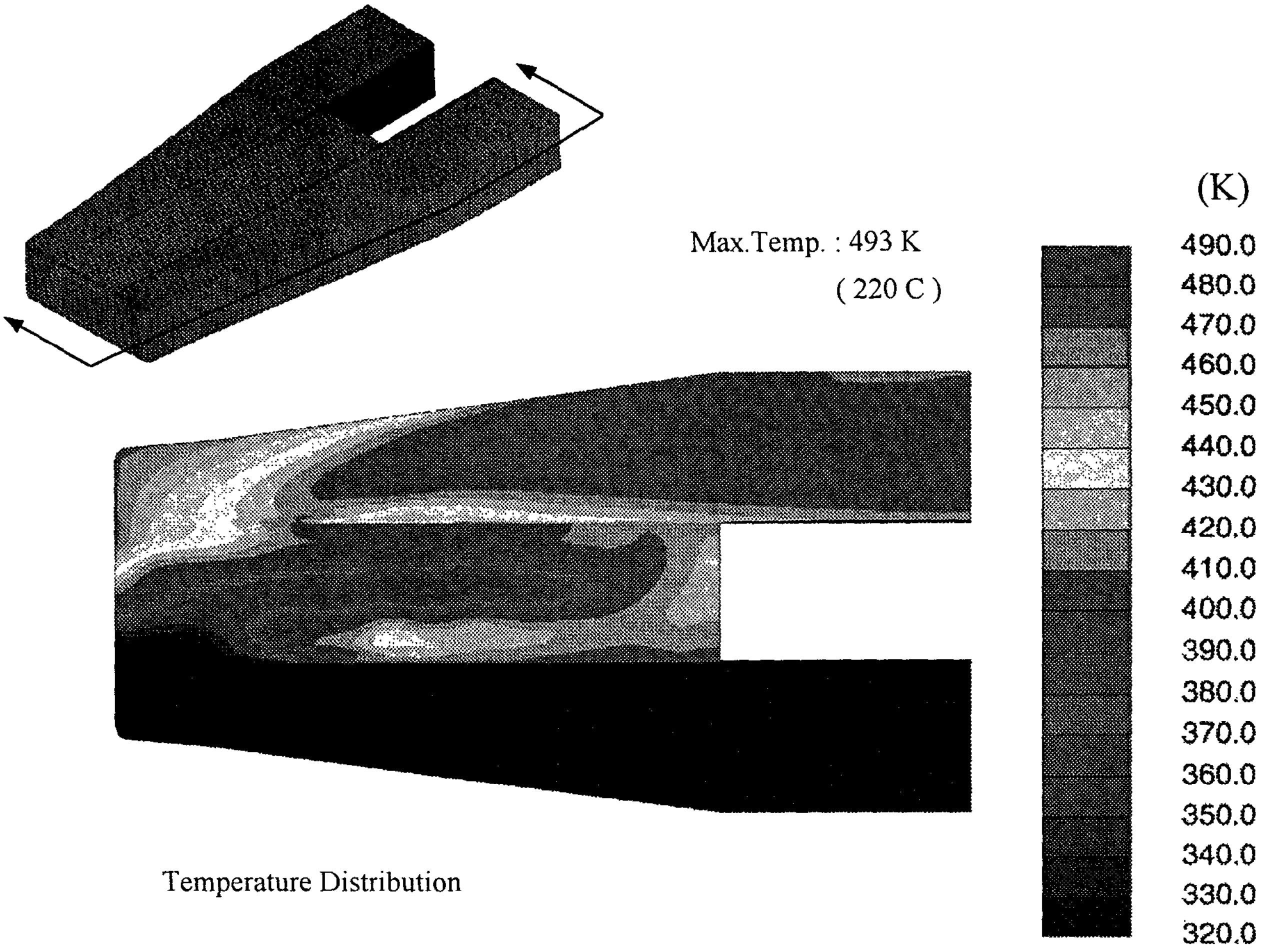
Fig. 5 Axial Distribution of Power Density in Mercury Target


Base Case

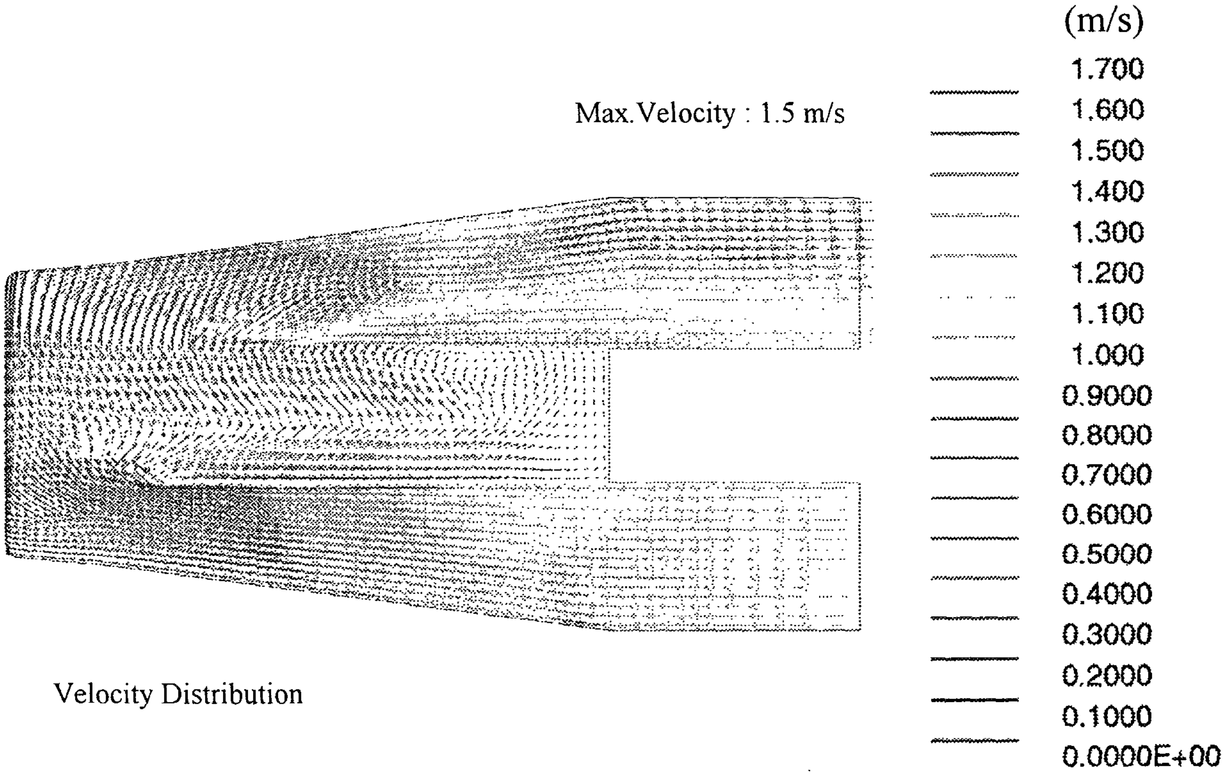
1st Method

2nd Method

Fig. 7 Mercury Container Shape for Parameter Survey Analysis



Temperature Distribution



Velocity Distribution

Fig. 6 Result of Thermo-Hydraulic Analysis in Mercury Target of Cross Flow Type