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Thermal-hydraulic Analyses on Simplified Cross-flow Mercury Target

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Abstract

A cross-flow type mercury target, which controls mercury flow rate distribution in the target channel using perforated plates, is proposed to simplify the target structure for the JAERI/KEK spallation neutron source (JSNS). Computational fluid dynamics (CFD) is being used to assess feasibility of this target structure for 2 MW beam power spallation sources. The high Reynolds number form k-ε turbulence model with turbulent Prandtl number (Prt) of 1.5 is used with turbulent boundary conditions calculated by wall functions. The CFD simulations show that the proposed target structure can realize high cooling performance with allowable flow rate using simple perforated plates when its open area distribution is optimized.

1. Introduction

A next generation spallation neutron source (proton beam power of MW order) is being planned in Japan as a joint project between JAERI and KEK [1]. High-energy (3 GeV) protons are injected into a target material with a beam power of 1 MW (at the first stage) to produce a high-density neutron flux by spallation reactions. Because of the high heat density caused from spallation reactions in the target, mercury is to be used as target material to resolve the heat removal problem.

A cross-flow type target, named because of the mercury flow direction which is lateral to the proton beam incident direction, is being considered because of its better cooling performance for the beam incident surface of the target (target window), compared to that for a return-flow type. A problem arises in how to realize a suitable flow rate distribution in the irradiation region, according to the heat generation profile, which avoids hot spots generation that may cause flow instability by mercury boiling and accelerate corrosion of structural materials, within an acceptable pressure loss. To resolve this problem, a simple target structure with perforated plates, which allows easy target manufacture, was considered to control mercury flow rate by an open area distribution.

To assess thermal-hydraulic performance of this target concept, steady state, three-dimensional CFD simulations are performed using k-ε turbulence model with time averaged heat generation rate. Beam pulsation effect, such as pressure wave generation caused from rapid thermal expansion, will be investigated separately.

2. Target models

The heat generation profile for the mercury target is calculated by the hadron transport code NMTC/JAERI and MCNP-4A [2]. Figure 1 shows the heat generation profile at 2 MW beam power used in this study, which involved a 30 % margin in the data from nuclei calculations. A rectangular footprint of the beam on the target window of 50 × 130 mm^2 and flat power distribution normal to the beam incident direction were assumed. Heat density is high near the window, takes its maximum value of 744 MW/m^3 20 mm downstream and decreases exponentially. The energy conversion rate to heat in the target is 55 % (1.1 MW) to the total beam power.

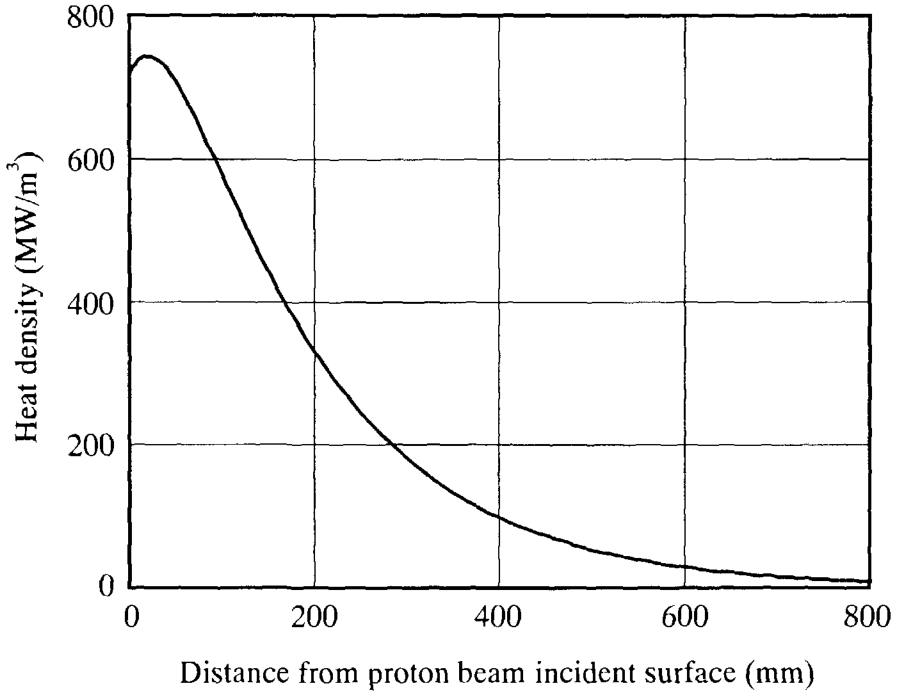

Fig. 1. Calculated heat generation profile along proton beam incident direction for JSNS mercury target (2 MW)

As shown in Fig. 2, the target is horizontal relative to the beam direction, and consists of beam irradiation region (target channel), one inlet channel and one outlet channel separated by two perforated plates. The cross-sectional dimensions of the target channel are 80 x 200 mm^2 decided by the proton beam cross section and some margins that satisfy the maximum height of the target vessel when coupling with moderators is considered. The length of the target channel is 800 mm decided by flight pass of 3 GeV protons. The target beam window is hemicylindrical so that the design pressure can be realized using as thin as possible vessel wall thickness. The inlet and outlet channels have the same dimensions (80 x 150 mm^2) and their outer surface are hemicylindrical for the same reason as the window is. The width of the inlet/outlet channels is tapered towards the target nose to reduce the mercury inventory in the target vessel because of reduction of neutron absorption.

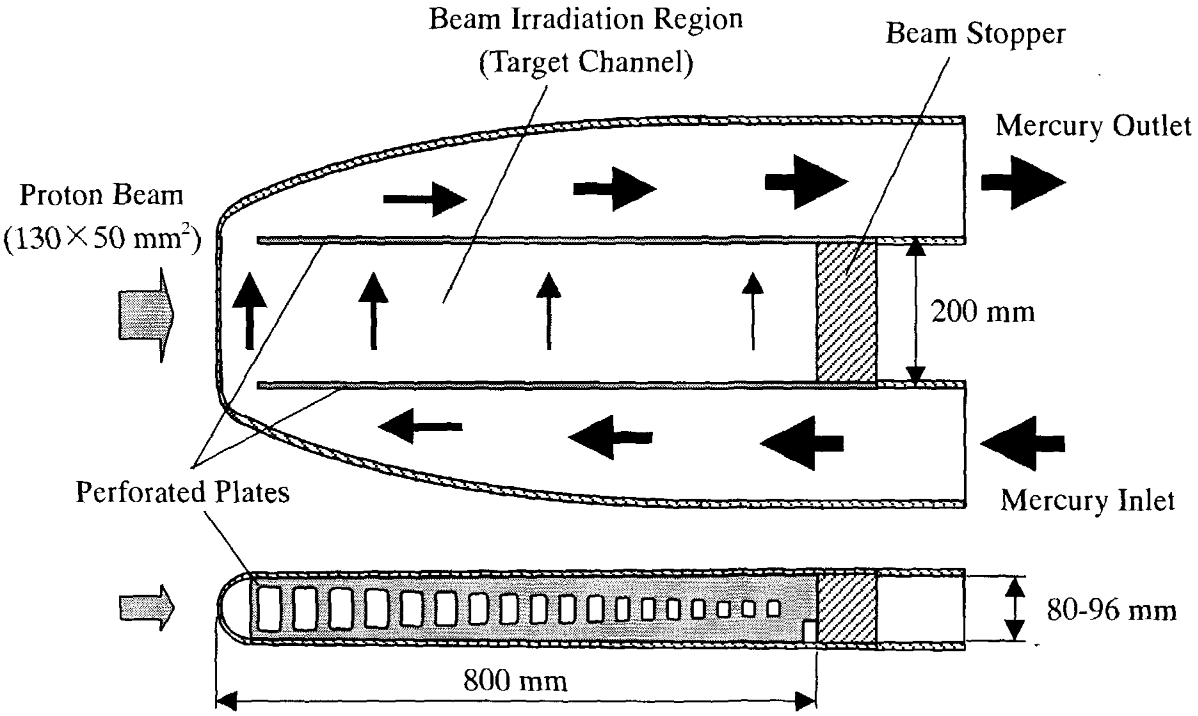

Fig. 2. Simplified cross-flow type mercury target with perforated plates

The flow rate distribution of mercury in the target channel is controlled by the open area distribution of the perforated plates. To realize a mercury flow pattern, which can suppress the hot spot generation, thermal-hydraulic calculations are needed to optimize the open area distribution of the perforated plates. For a base case, the plate is subdivided into 20 sections and open area fractions are decided in each section. The first section toward the target window is fully opened and open area fractions for other sections are proportional to relative heat density to the peak value. The result for the base case is used to modify the open area distribution to suppress maximum mercury temperature.

The flow rate of mercury is set to 50.9 m^3/h which corresponds to mean velocity of 1.25 m/s at the inlet channel and its Reynolds number is 1.67×10^6. Mean temperature increase of mercury is 44 K which means a 70 % margin to the design maximum temperature, 473 K, when inlet temperature is 323 K.

3. Numerical

The calculation code used in this study is STAR-CD [3] (Simulation of Turbulent flow in Arbitrary Regions) which is used extensively to compute many types of flow phenomena in various applications. The high Reynolds number form k-ε turbulence model is used with the standard model coefficients [4] and turbulent Prandtl number (Prt) of 1.5 in combination with the wall functions.

The differential equations governing the conservation of mass, momentum, energy and turbulence variables are discretised by the finite volume method using the QUICK (Quadratic Upstream Interpolation of Convective Kinematics) scheme. QUICK is a third order scheme that fits a parabola through two points upstream and one point downstream to get an interpolated value at a cell surface. The discretised equations are solved by an iteration technique using the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm [5]. All variables are under-relaxed in every iteration to obtain converged solutions that satisfy a maximum residual for each variable less than 0.1 %.

The computational model of the target is shown in Fig. 3. Total mesh number for the target model is 177,240 and fine meshes are used near the wall and near the separation plates to get better resolution. Inlet flow velocity is assumed to be uniformly 1.25 m/s, perpendicular to the inlet channel boundary and inlet mercury temperature is assumed to be 323 K. The distributions of variables on the outlet boundary are evaluated by extrapolation from upstream

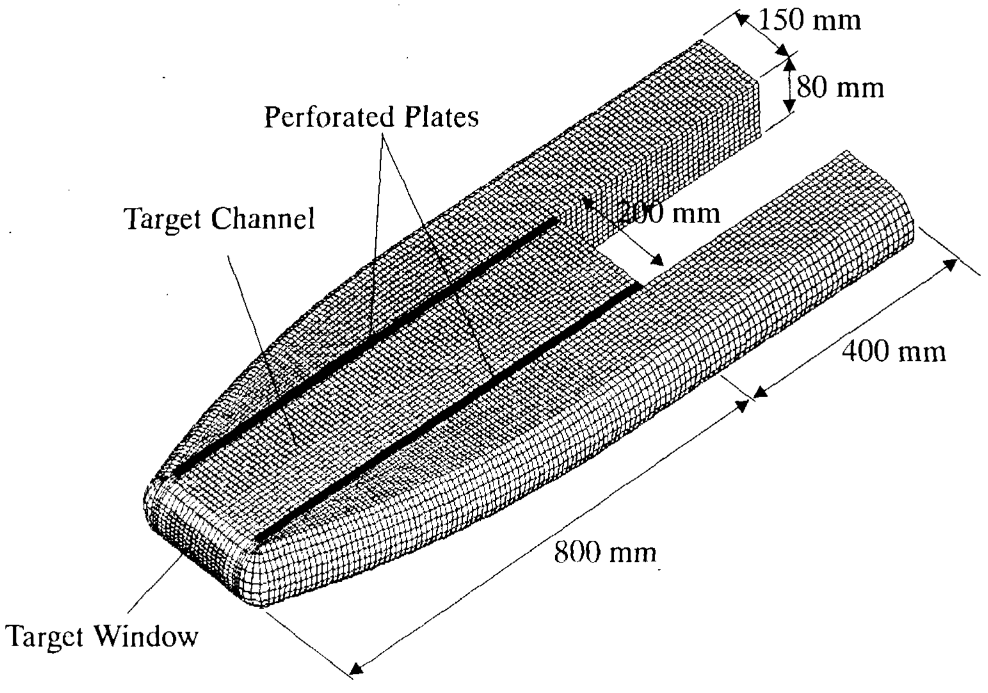

Fig. 3. Computational model of simplified cross-flow type target

on the assumption of zero gradient, and the velocities are adjusted to give the required outlet flow rate. The mercury outer surface contacted to the target vessel wall, except for the target window, and separation plate surfaces are insulated. Heat generation in the target window is considered by heat flux of 1.1MW/m^2 at the beam incident region. The heat generation profile in mercury is applied by a user subroutine program.

4. Results and discussion

4.1 Base case

A calculated distribution of velocity magnitude for the base case in the horizontal cross section at the midpoint of the target height is shown in Fig. 4. In the front half of the target channel, mercury flows across the beam incident direction, but a large recirculation flow is generated backwards in the target channel because of the small open area of the perforated plates. Bulk velocity near the target window is 1.7 m/s which is too fast to remove heat, even if there is a peak heat generation region. The maximum velocity, 2.3 m/s, is observed at the outside of the outlet channel and velocity gradually becomes uniform toward the outlet boundary of the target.

A calculated temperature distribution in the same cross section as for the velocity vectors is shown in Fig. 5. The maximum temperature, 463 K, is observed at the center of the recirculation region. This is rather critical for thermal stress of the target vessel if no cooling measures is considered outside it. On the other hand, in the front half region of the target channel, mercury is well cooled down, especially near the target window, and the maximum temperature increase of mercury around there is just 50 K. Optimization of the open area distribution of the perforated plates should be made to suppress this recirculation flow and decrease the flow rate in the front half of the target channel.

4.2 Modified case

Optimization of the open area distribution of the perforated plates is carried out by try and error. The calculated results of the base case are used to modify the open area distribution of the perforated plates. Figure 6 shows the velocity component across the beam incident direction at the center of the target as a function of the location from the target window. Calculated result for the modified case in which the open fraction is proportional to the square root of the heat density is compared to that for the base case. In the modified case, mercury velocity near the target window is decreased and the recirculation flow in the backward region of the target channel is moved downstream in the target channel.

A calculated distribution of velocity magnitude for the modified model in the horizontal cross section at the midpoint of the target height is shown in Fig. 7. Due to the increased open area of the perforated plates in the backward target channel, flow velocity is

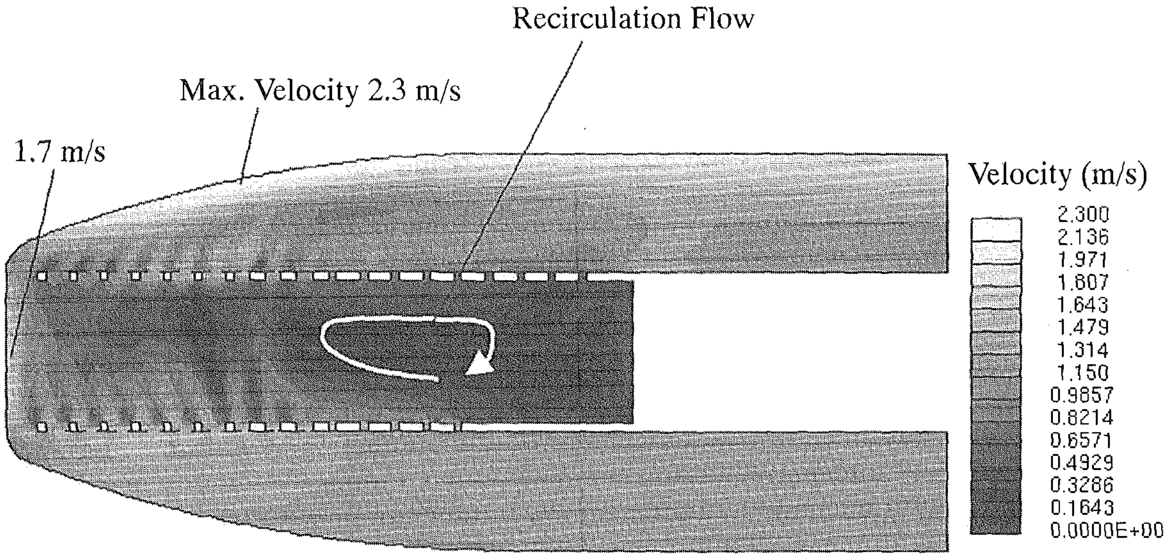

Fig. 4. Calculated velocity magnitude for base case in the horizontal cross section at the midpoint of the target height

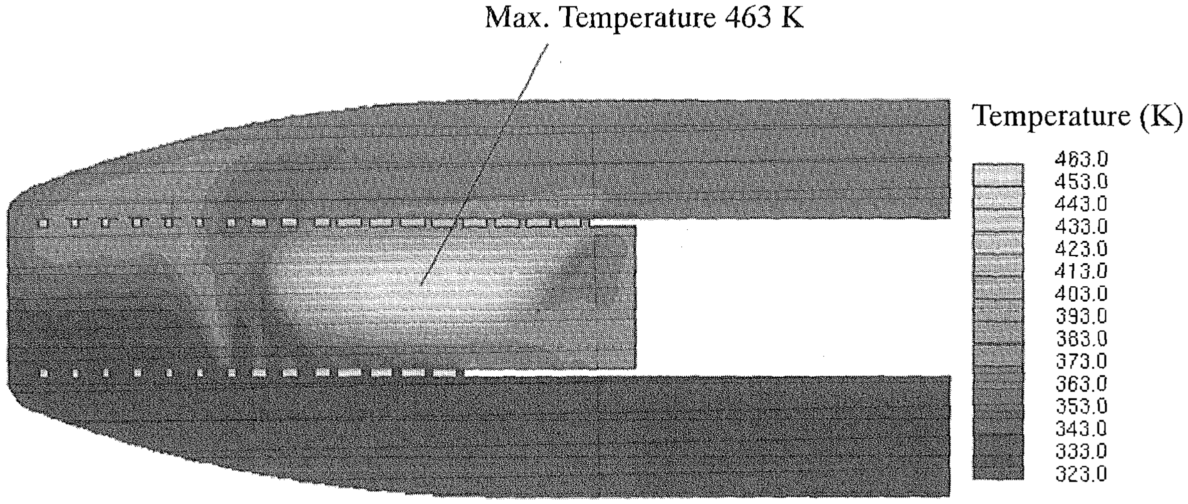

Fig. 5. Calculated temperature distribution for base case in the horizontal cross section at the midpoint of the target height

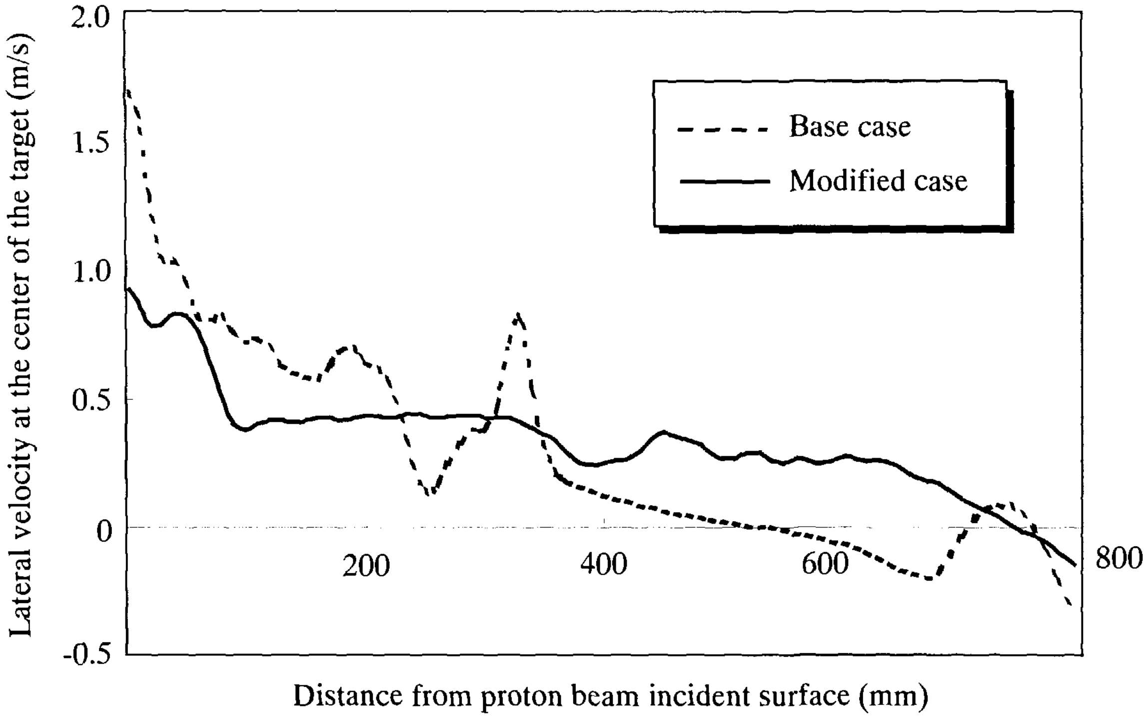

Fig. 6. Calculated profile of velocity components across the beam incident direction at the center of the target

increased in that region and the large recirculation flow, seen in the base case, is not observed. There is a small recirculation flow near the end of the target channel, but the heat density in this region is small so that mercury temperature will not increase so much. Mercury bulk velocity near the target window decreases to 0.9 m/s, as a result, maximum velocity outside the outlet channel is decreased to 1.8 m/s which is favorable for decreasing vessel erosion.

A calculated temperature distribution in the same cross section as for the velocity vectors is shown in Fig. 8. The hot spot at the center of the recirculation flow, seen for the base case, is not observed. The maximum temperature is 417 K near the front corner of the target channel, which fully satisfies the design temperature, 473 K. Because the distribution profile of mercury flow rates in the target channel is similar to the heat density profile, there are no hot spots in the target channel and the mercury temperature is almost uniform.

From the calculated results shown above, the simplified cross-flow type target with perforated plates is judged to be a candidate for the 2 MW target configuration. Further optimization of the open area distribution is needed to take into account vessel cooling by mercury, especially for the target window. To evaluate temperature distribution of the target vessel which is needed to assess thermal stress, calculations for the conjugate heat transfer problem, that is coupled heat transfer within a fluid and the target vessel, should be carried out in the future.

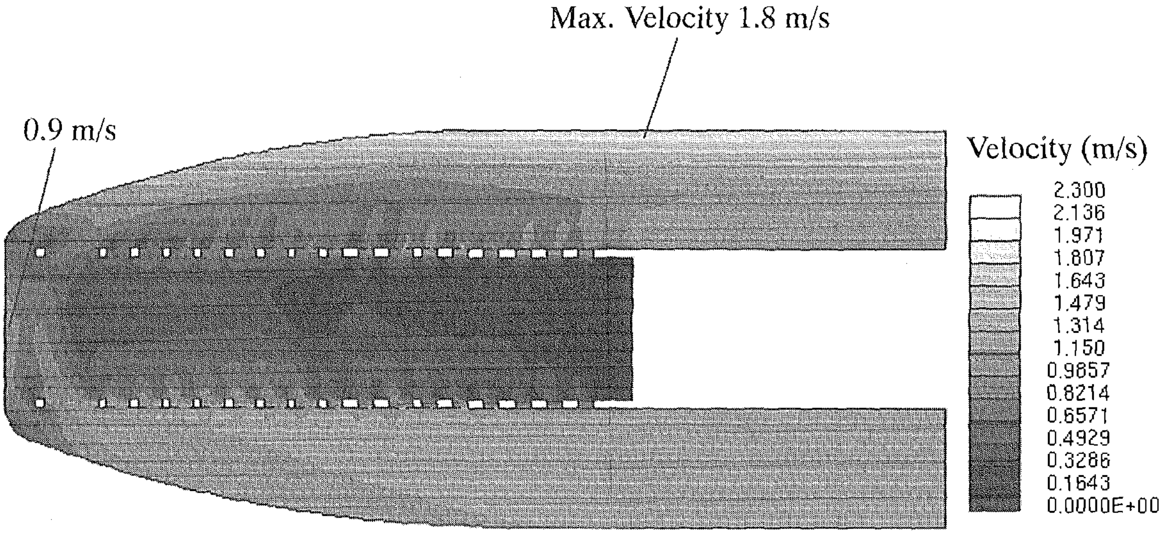

Fig. 7. Calculated velocity magnitude for modified case in the horizontal cross section at the midpoint of the target height

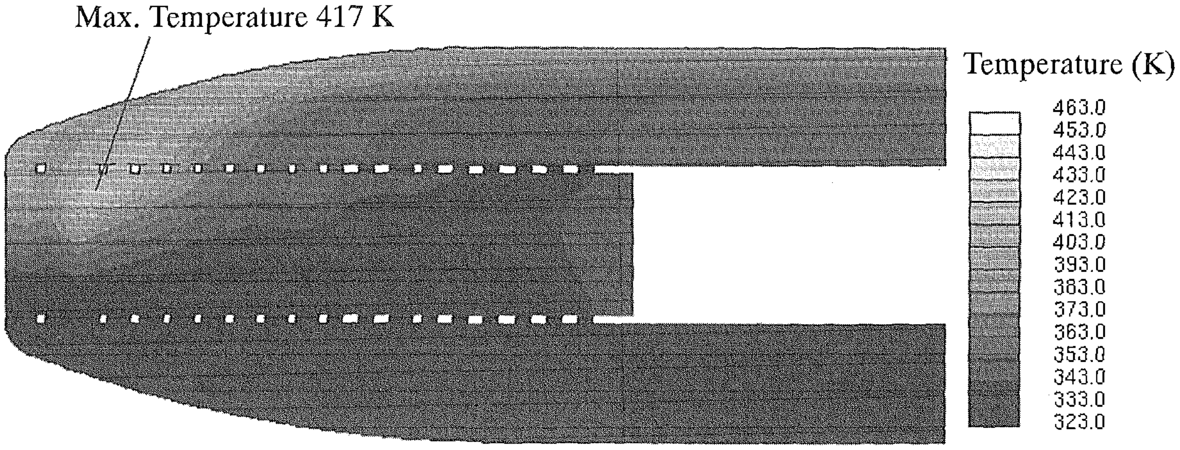

Fig. 8. Calculated temperature distribution for modified case in the horizontal cross section at the midpoint of the target height

5. Conclusions

Three-dimensional thermal-hydraulic analyses were carried out to evaluate feasibility of a simplified cross-flow type mercury target, which controls mercury flow rate distribution in the target channel using perforated plates. The high Reynolds number form k-ε turbulence model with Prt of 1.5 was used in combination with the wall functions. Optimization of the open area distribution of the perforated plates was carried out to get better cooling performance. The results were as follows.

(1) Calculated results for the base case in which the open area fraction was proportional to the heat density profile showed the large recirculation flow in the target channel. The maximum mercury temperature of 463 K was observed in the center of the recirculation region which would be rather critical for the thermal stress of the target vessel if no cooling measures were considered outside it.

(2) Calculated results for the modified case in which the open area fraction was proportional to the square root of the heat density showed the maximum temperature of 417 K near the front corner of the target channel which fully satisfied the design temperature (473 K). This type of target was judged to be a candidate for the 2 MW target configuration. Thermal-hydraulic analyses in conjunction with heat transfer to the vessel wall should be carried out to assess thermal stress in the target vessel in the future.

References

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