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Thermal Hydraulic Design of the Active Part of the MEGAPIE Target

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Abstract

Thermal hydraulic analyses and design of the active part of the MEGAPIE target have been performed using the CFX 4.3 code in the present work. Three types of geometric configurations, i.e. with a flat guide tube, with a slanted guide tube and with an injection bypass are investigated with the main emphasis on the coolability of the beam window and the heat removal from the active part of the target. In the target with a flat guide tube flow stagnation occurs in the region near the window center. This leads to an excessive hot spot on the window surface. To improve the coolability of the window, two methods are proposed. By the first method the lower end of the inner cylinder is cut with an inclined cross section. In this way, the axial-symmetry of the flow is destroyed and the flow stagnation zone near the window center is reduced. However, the improvement of heat transfer is insufficient to keep the window temperature below the design value. The second method is to introduce a bypass injection to remove the flow stagnation zone from the window center region. The CFX results show that with a bypass injection, the beam window can be sufficiently cooled down and the heat deposited in the target can be safely removed from the active part of the target. More optimization studies are required for designing a target with a bypass injection to obtain an optimum thermal-hydraulic performance.

1. Introduction

The nuclear waste problem has strongly affected the public acceptance of nuclear power. For many decades, efforts were made to reduce the amount of nuclear waste. Incineration of long-lived radioactive nuclides, in particular in an accelerator driven system (ADS) [1], is considered to be one of the most favorable solutions. Worldwide many ADS related projects have been initiated. The U.S. Congress directed the DOE to study the accelerator transmutation of nuclear waste (ATW) and to prepare a “roadmap” for developing this technology. In response to the congressional mandate, DOE reported the Congress a six-year science based

R&D program to assess the technical feasibility of the ATW technology in 1999 [2]. Similar projects are now launched in Japan (the OMEGA project) and Korea (the HYPER project) [3].

In Europe intensive research and development programs are now underway relating to the ADS technology. One of the main components in an ADS is the spallation target where a large amount of neutrons are produced. Heavy liquid metal, e.g. lead or lead-bismuth eutectic, is preferred to be used as target material and as coolant as well, due to its high production rate of neutrons and efficient heat removal properties. In a liquid metal target the beam window is exposed to a high radiation and thermal field. Thus, cooling of the beam window is considered as one of the most critical items in designing a spallation target. To gather practical experience relating to liquid metal targets, the pilot target MEGAPIE (MEGAwatt Pilot Experiment) will be designed and fabricated in Western Europe [4-6]. It is planned that conceptual and engineering designs are finished by 2001 and the target starts to be irradiated from 2004. The Forschungszentrum Karlsruhe (FZK) is actively involved in this project, especially in thermal-hydraulic design of the target and Korea Atomic Energy Research Institute (KAERI) is going to join in the project.

A three steps strategy is being proposed for the research activities accompanying the target design [7]. In the *first step*, numerical analysis is carried out with available CFD codes, to provide the first knowledge about the thermal-hydraulic behavior in a spallation target. Based on numerical studies a preliminary design of a target can be achieved. The second and third steps are experimental works to provide data base for final target design and for validation of computer codes.

The present work is dealing with the numerical design study of the active part of the MEGAPIE target. For this purpose the CFD code CFX-4.3 was used. In the present paper, numerical results obtained up to now are presented and discussed.

2. MEGAPIE Target

A sketch of the MEGAPIE target is given in Fig. 1. The proton beam from the accelerator is injected from below. Spallation reactions and a large heat deposition rate occur in the lower part of the target, the so-called "active part" which is the main concern of the present work. Lead-bismuth eutectic is used as spallation material and as coolant to remove the heat released in the target. Liquid lead-bismuth is circulated with electromagnetic pumps downward through the annular gap between both cylinders. It makes a U-turn at the bottom and flows upwards through the inner cylinder, called guide tube. The lower part of the target consists of a thin hemisphere shell called "beam window" which is the physical boundary to separate the spallation region from its vacuum environment. The beam window is exposed to high radiation and thermal load. A high heat flux on the window surface is expected. Cooling of the window is, therefore, the key task of the present study.

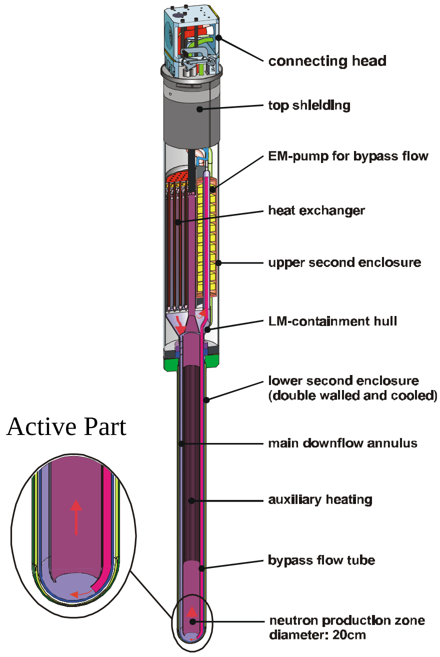


Fig. 1 Sketch of the MEGAPIE target [5].

The main technical data of the MEGAPIE are summarized as follows:

- beam power: 1.0 MW
- proton energy: 0.6 GeV
- beam shape: 2-dimensional Gaussian distribution
- diameter of the active part (window): ~18 cm
- target material/coolant: Pb-Bi eutectic
- inlet temperature of coolant: ~200 ^{o}C

The outer dimensions of the MEGAPIE target are identical to ones presently in use at the accelerator SINQ of the Paul Scherrer Institut (PSI). Very thin window (~2 mm) is considered to minimize the heat deposition in the window. It is known that about 60% of the beam energy is released as heat in the active part of the target. Because of the small window thickness, the heat deposition in the window can be approximated as [8]:

$$q''' = 1.3\times10^{9}\exp[-(\frac{x}{s_x})^2-(\frac{y}{s_y})^2]\ ,\quad (\sigma_x = 0.019m,\ \sigma_y = 0.033m)$$

(1)

By neglecting the thermal radiation heat transfer and the azimuthal heat conduction inside the window, the heat flux on the window surface can be expressed by

$$q'' = q'''\times\delta \qquad (2)$$

where δ is the window thickness. The local heat deposition in the target is determined by

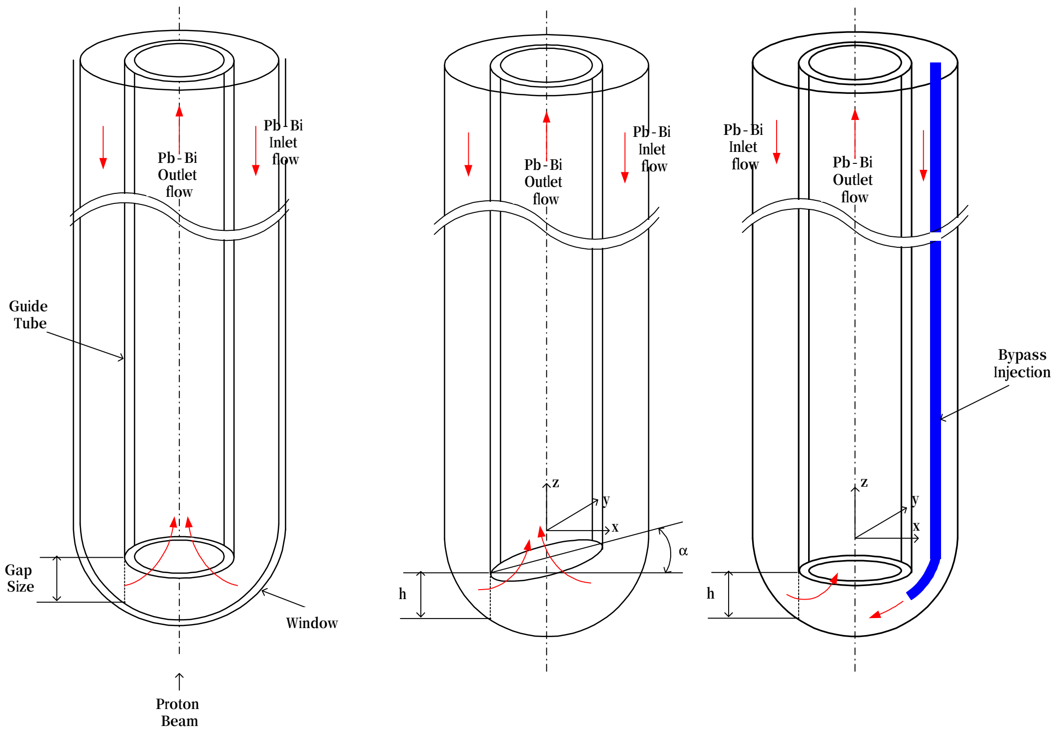
$$q''' = 1.58\times10^{9}\exp[-(\frac{x}{\sigma_x})^2-(\frac{y}{\sigma_y})^2]\exp[-\frac{(z-z_o)}{L}],\quad L = 0.21 \qquad (3)$$

where $z-z_0$ is the z coordinate distance from the window at given point. According to Eq. (3) about

650 kW heat is released in the active part of the target.

According to Eq. (1) the maximum heat flux on the window surface is about 2.6 MW/m². This requires a special care to ensure a proper cooling. Thus, design of the active part is one of the main tasks in the design phase of the MEGAPIE target. In the thermal-hydraulic point of view, many design criteria have to be defined. Two of them are crucial for the present study, i.e. the maximum temperature of the window surface T_{max}, and the maximum velocity of Pb-Bi U_{max}. The maximum velocity of Pb-Bi should not exceed the value about 1.5 m/s and the maximum temperature of the window surface should be kept below about 400°C. The main reasons for these design limits are due to structural material problems, such as corrosion and erosion.

Three types of geometry are considered in the present study, as indicated in Fig. 2. In the first configuration (Fig. 2 (a)) a flat guide tube is used. For this type of design it is expected that a large flow stagnation zone occurs near the window center because of axis-symmetry of the flow. This leads to a poor cooling of the beam window and, subsequently, to an excessive hot spot on the window center. To improve the cooling performance, two methods have been proposed and investigated in the present study. The first method (Fig. 2 (b)) is to cut the lower end of the guide tube with an inclined cross section. In this way the axis-symmetry of the flow is destroyed and the flow stagnation zone near the window center can be reduced. The second method (Fig. 2 (c)) is to introduce a bypass injection to remove the flow stagnation zone near the window center. In the present paper, numerical studies relating to these three types of configurations are presented and discussed.



(a) With a flat guide tube *(b) With a slanted guide tube* *(c) With a bypass injection*

Fig. 2 Three types of active parts of the target considered.

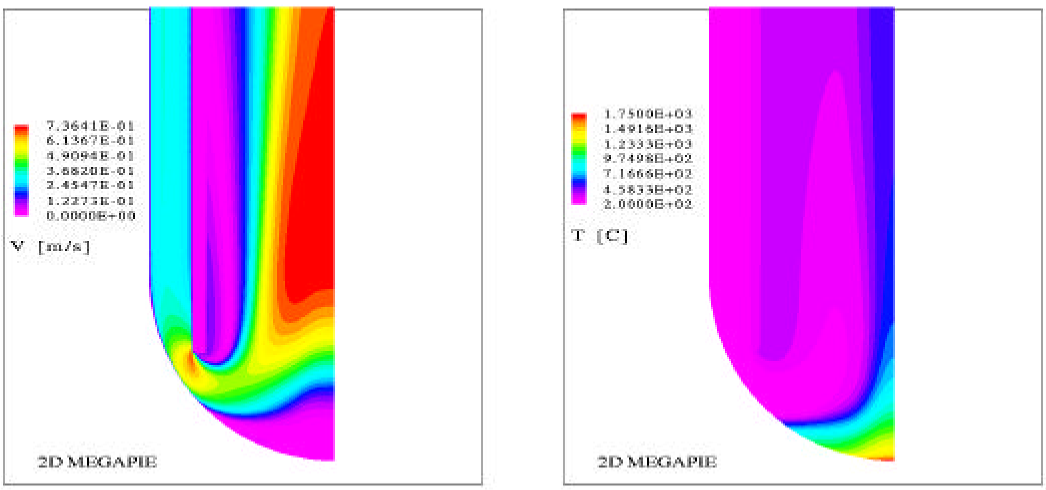
3. Numerical Analysis

In the present study numerical analysis of the target has been performed using the CFX 4.3 code [9], which is a general purpose thermal-hydraulic code developed by AEA Technology. For turbulence modeling, the standard k-ε model with logarithmic wall function is adopted. Heat generation in the window is considered as boundary heat flux using Eq. (2). This treatment is reasonable because the window thickness is small. Conducting or adiabatic condition is considered for the guide tube. Adiabatic boundary is used for the outer surface of the outer cylinder. Inlet temperature and velocity of lead-bismuth are set to 200 ^{o}C and 0.3 m/s, respectively. With this velocity and geometry, the mass flow rate of lead-bismuth without bypass injection becomes ~ 30 kg/s.

3.1 Target with a Flat Guide Tube

As can be seen in Fig. 2 (a), 2D calculations are possible for the target with a flat guide tube. To perform 2-D calculation, heat deposition in the window and in the target material is simplified as an axis-symmetric distribution. The only geometric parameter which can be varied is the gap size for the target with a flat guide tube. Although the target is about 3 m high, the height of the computational domain is reduced to 1180 mm to avoid unnecessary computing expenditure. In the present work, the hottest plane (i.e., x = 0) is chosen to reflect worst results of 2D analyses. Heat deposition is computed using Eqs. (1) & (3) with x = 0.

Figure 3 shows the results for a gap size of 20 mm. Near the gap and in the central region, a high velocity flow is obtained. A large flow stagnation region occurs around the window center and flow recirculation exists in the spallation region. An excessive high temperature near the window center is observed. The highest temperature exceeds 1000 ^{o}C.



(a) Velocity *(b) Temperature*

Fig. 3 Velocity and temperature distribution in the target with a flat guide tube and a gap size of 20 mm.

Numerical calculations are performed for different gap sizes changing from 5 to 50 mm. Figures 4 and 5 summarize the results achieved. Figure 4 shows the velocity profiles along the center line of the target (x=0, y=0) with different gap sizes. Obviously, a smaller gap size results in a higher velocity and a lower window temperature. However, the pressure drop is higher. Even for an extremely small gap size (5 mm), the cooling of the beam window remains insufficient. Therefore, the target design with a flat guide tube is not acceptable and needs further modification.

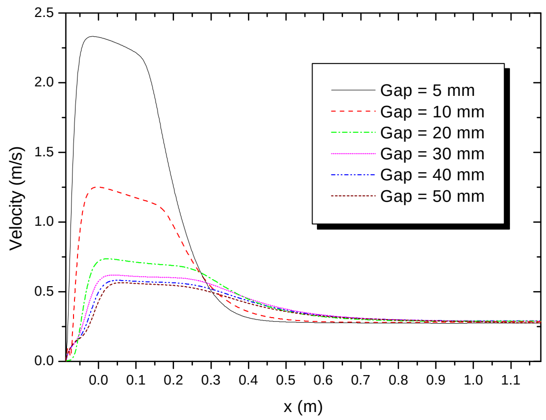


Fig. 4 Effects of the gap size on the velocity profile along *the center line.*

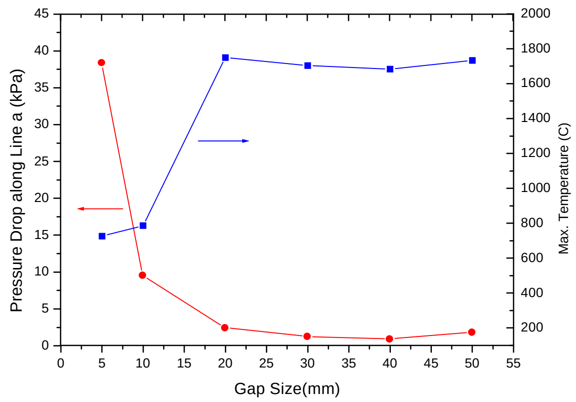


Fig. 5 Effects of the gap size on the pressure drop and the maximum window temperature.

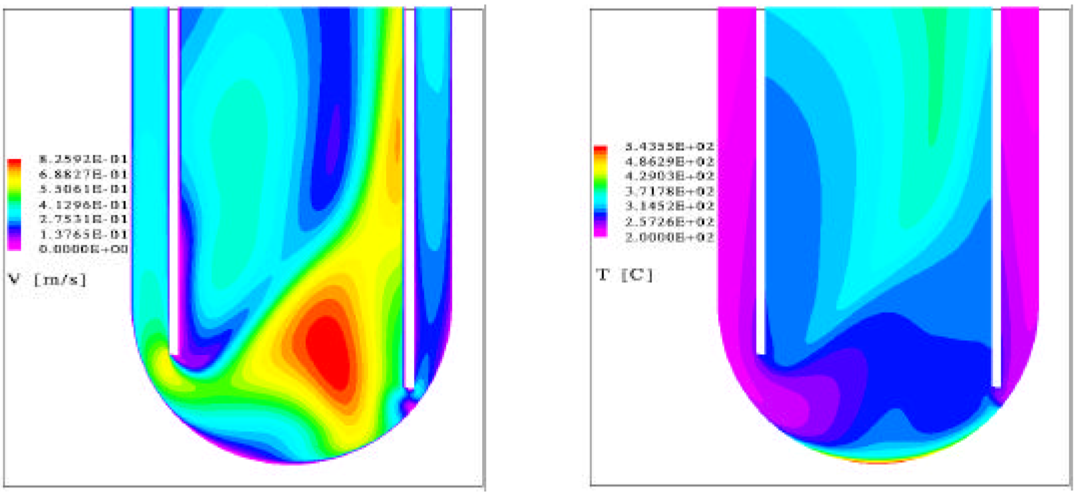
3.2 Target with a Slanted Guide Tube

For this configuration 3-D calculation is required. To avoid an excessive large number of volume cells and some numerical difficulties, the height of the computation domain is reduced to 30 cm. The gap size, cutting angle and direction are the main design parameters. The reference design parameters are chosen as follows (See Fig 2(b)):

- gap size (h) :10 mm
- cutting angle (α) : 8 °
- direction of the cutting surface: normal vector perpendicular to y-axis

Heat deposition rate in the window and in the target was determined by Eqs. (1) & (3). The guide tube has a thermally insulating wall.

Figure 6 shows the distribution of the velocity and the temperature in the target. It is seen that the flow stagnation zone around the window center is significantly reduced compared to that in the target with a flat guide tube. The Pb-Bi flow from the larger gap passes through the center region and meets the flow from the smaller gap. A high flow velocity region is observed near the guide tube wall which forms the small gap. A small flow recirculation zone occurs around the small gap and near the larger gap, respectively. Compared to the case with a flat guide tube, the hot spot location is shifted towards to the larger gap. In spite of a strong reduction in the maximum temperature, the coolability of the window remains insufficient. The maximum window surface temperature is about 550°C, far beyond the design limit (400ºC). Therefore, it is decided to consider another design, i.e., the target with an injection bypass.



(a) Velocity *(b) Temperature*

Fig. 6 Velocity and temperature distribution in the target with a slanted guide tube.

3.3 Target with an Injection Bypass

As for the shape of injection bypass of the target, rectangular bypass tube may be preferred due to the flexibility in varying the bypass flow area. However, in terms of fabrication and thermal stress, circular tube is more advantagable. Major design parameters of the rectangular bypass jet are illustrated in Fig. 7.

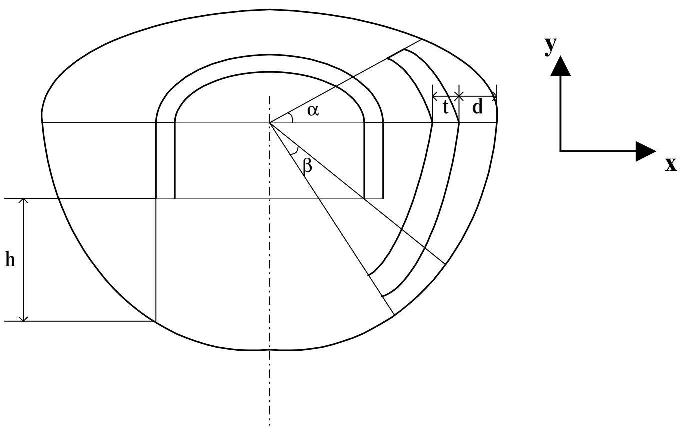


Fig. 7 Main design parameters of the target with a rectangular bypass.

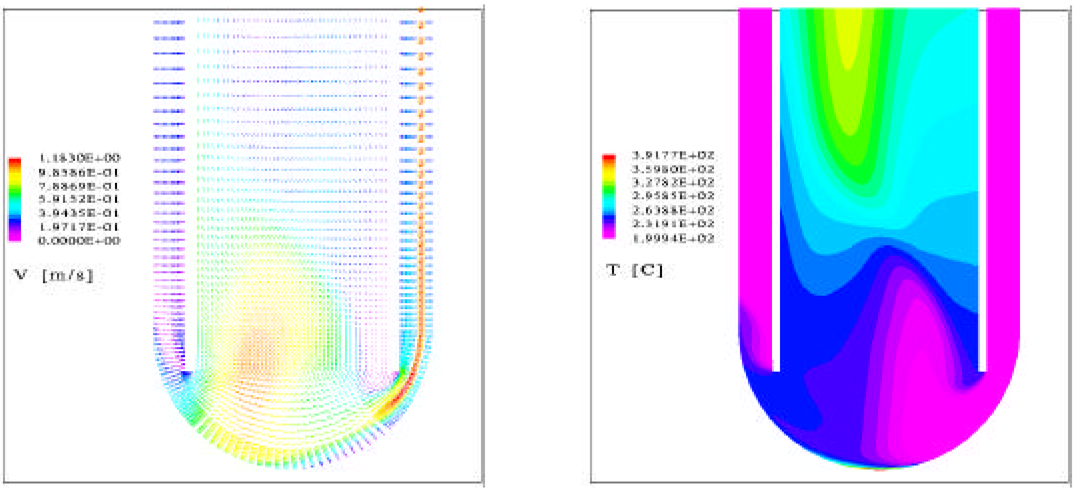
The reference values of the design parameters are chosen as follows:

- gap size (h): 30 mm

- injection velocity (V_b) : 1.0 m/s
- position of nozzle end (β) : 0 ^{o}
- distance from the wall (d) : 5 mm
- bypass depth (t) : 5 mm
- bypass width (α) : 20 ^{o}
- location of bypass injection: on x-axis

With the reference values, the flow rate of the injection bypass is about 10% of the total flow rate. The height for the computation domain is about 30 cm, to avoid an excessive large expenditure in computation. The guide tube wall is considered as thermally insulating. For the simplicity the thickness of the bypass tube wall is neglected.

Figure 8 shows the velocity and temperature distribution for the reference parameters using Eqs. (1) & (3) for the heat deposition. A high injection velocity from the bypass nozzle is obtained. Flow stagnation zone disappears around the window center. Bypass flow penetrates into the central region and affects strongly the flow in the opposite side of the annular gap. The maximum temperature is about 390ºC. Compared to the previous designs, i.e., the targets with a flat or a slanted guide tube, the coolability of this design is improved significantly. Further reduction in the maximum window temperature can be achieved by optimising the design parameters.



(a) Velocity *(b) Temperature*

Fig. 8 Velocity and temperature distribution in the target with an injection bypass.

4. Conclusions

Thermal-hydraulic analyses of the active part of the MEGAPIE target have been performed in the present study using the CFX 4.3 code. Three different geometric configurations are considered, i.e. with a flat guide tube; with a slanted guide tube; with a bypass injection. From the numerical results achieved the following conclusions are made:

- In a target with a flat guide tube an excessive hot spot on the window surface occurs. The maximum temperature on the window surface is far beyond 1000°C.
- By using a slanted guide tube instead of a flat guide tube the flow stagnation region near the window center is strongly reduced. The coolability of the beam window is improved significantly. Nevertheless, the maximum temperature on the window center is still far beyond the design limit.
- With a bypass injection, the beam window can be sufficiently cooled down and the heat deposited in the target can be safely removed from the active part of the target.

More optimization studies are required for the target with a bypass injection to obtain an optimum thermal-hydraulic performance.

Acknowledgement

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