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Numerical Design of the Active Part of the MEGAPIE Target

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Abstract

Numerical Design of the Active Part of the MEGAPIE Target

Thermal-hydraulic analysis of the active part of the MEGAPIE target has been performed using the CFX 4.3 code. 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 axis-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. Two different kinds of bypass tubes are considered, i.e. a rectangular tube and a circular tube. A systematic parameter study has been performed for the configuration with a rectangular bypass tube. Based on the numerical results, optimum values of some geometric parameters (i.e. position and size of the bypass tube) as well as of flow rate can be obtained. Preliminary calculations for the target with a circular bypass tube show very promising results. With a simple circular bypass tube, the beam window can be cooled sufficiently. Nevertheless, further detailed numerical studies are necessary to optimize the design parameters. The numerical calculations have to be backed up by model experiments, using both water and lead-bismuth as fluids.

Kurzfassung

Nummerische Auslegung des aktiven Teils des MEGAPIE Spallationstargets

Nummerische Untersuchungen zum thermohydraulischen Verhalten des aktiven Teils des MEGAPIE Targets wurden durchgeführt. Dabei wurde der CFD Code CFX4.3 eingesetzt. Drei verschiedene geometrische Konfigurationen des Targets wurden untersucht, nämlich mit einem flachen Führungsrohr, mit einem schräg geschnittenen Führungsrohr und mit einer Bypass-Strömung. Die Kühlbarkeit des Strahlfensters sowie die Wärmeabfuhr aus dem Spallationstarget wurde analysiert. Die Ergebnisse zeigen, dass in einem Spallationstarget mit einem flachen Führungsrohr ein großer stagnierender Bereich nahe des Fensterzentrums entsteht. Dies führt zu einer extrem hohen lokalen Temperatur an der Fensteroberfläche. Bei der zweiten Konfiguration wird das untere Ende des Führungsrohrs schräg geschnitten, um die Symmetrie der Strömung zu zerstören und die stagnierende Zone zu reduzieren. Trotz einer Verbesserung des Wärmeübergangs bleibt die Kühlung des Fensters nach wie vor ungenügend. Die maximale Temperatur an der Fensteroberfläche überschreitet weiterhin den Auslegungswert. Bei der dritten Konfiguration wird eine Bypass-Strömung eingeführt, die direkt auf die Umgebung des Fensterzentrums gerichtet wird, um die stagnierende Zone nahe des Fensterzentrums vollständig zu entfernen. Zwei verschiedene Typen von Einspeisungsrohren wurden untersucht, nämlich ein rechteckiges Rohr und ein kreisförmiges Rohr. Für das rechteckige Einspeisungsrohr wurde eine systematische Untersuchung durchgeführt. Die Ergebnisse zeigen, dass das Konzept mit einer Bypass-Strömung vielversprechend ist. Damit kann das Fenster ausreichend gekühlt und die Wärme aus dem Spallationstarget abgeführt werden. Es bedarf jedoch weitere nummerische Untersuchungen, um die geometrischen Parameter und den Massenstrom der Bypass-Strömung zu optimieren. Die nummerischen Untersuchungen müssen durch Modellexperimente begleitet werden, die sowohl Wasser als auch Blei-Wismut als Fluide verwenden.

CONTENTS

1. Introduction

The problem of nuclear waste has strongly affected the public acceptance of nuclear electricity production. Since many decades, efforts have been made to reduce the nuclear waste. Incineration of long lived radioactive nuclides, in particular in an accelerator driven system (ADS) [1-6], is considered to be one of the most favorable solutions. Many ADS related projects have been initiated worldwide, e.g. the AAA project in USA [4], the OMEGA project in Japan [5] and the HYPER project in Korea [6].

In Europe intensive research and development programs are now underway relating to the ADS technology [7, 8]. 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 both as target material and as coolant, 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 a high thermal field. Thus, cooling of the beam window is considered as one of the most critical issues in designing a spallation target [9]. To gather practical experience relating to liquid metal targets, the pilot target MEGAPIE will be designed and fabricated in Western Europe [10]. This target will be put into test in the accelerator SINQ of Paul Scherrer Institut (PSI) in Switzerland. The Forschungszentrum Karlsruhe FZK is actively involved in the MEGAPIE project, especially in thermal-hydraulic design of the target.

A three steps strategy is being proposed for the research activities accompanying the target design [11]. 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 the third steps are experimental studies to provide a data base for the final target design and for the 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 [13] is used. In this report numerical results obtained up to now are presented and discussed.

2 MEGAPIE Target

A sketch of the MEGAPIE target is given in Fig. 2.1. The proton beam from the accelerator is injected from below. Spallation reaction and a large heat deposition rate occurs in the lower part of the target, the so-called “active part”. Lead-bismuth eutectic is used both as spallation material and as coolant to remove the heat released in the spallation area of the target. Liquid lead-bismuth is circulated with an electromagnetic pump 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 a high 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.

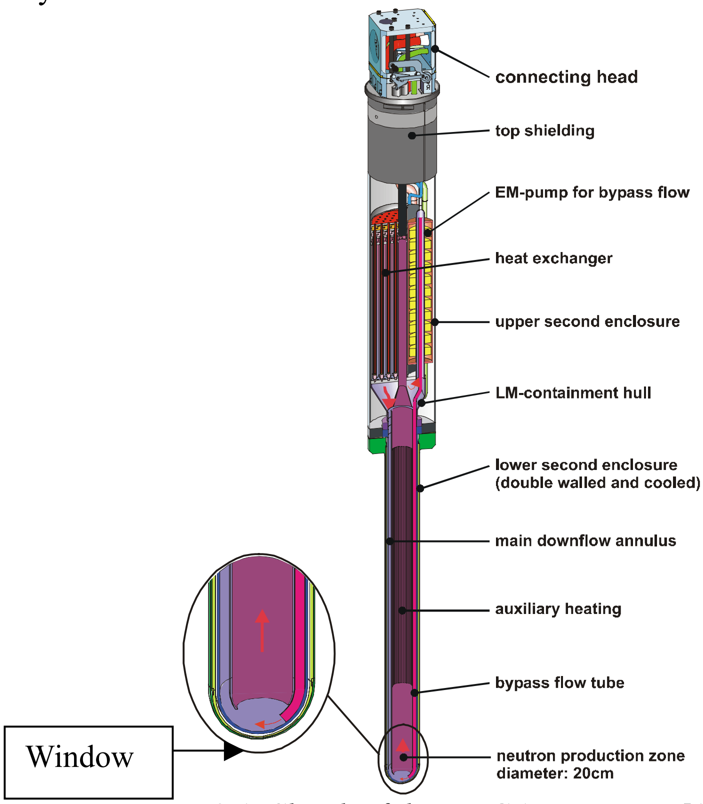


Fig. 2.1: Sketch of the MEGAPIE Target [10]

The main technical data of the MEGAPIE target 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
- window thickness: ~2 mm

It is known that about 60% of the beam energy is released as heat in the active part of the target. Because of a small window thickness, the heat deposition in the window can be approximated by the following Gaussian distribution [12]:

$$q''' = 1.3 \times 10^9 \exp[-(\frac{x}{\sigma_x})^2 - (\frac{y}{\sigma_y})^2] \text{ W/m}^3 \quad (2.1)$$

with $\sigma_x = 0.019 m$, $\sigma_y = 0.033\ m$.

The coordinate used for the present work is shown in Fig. 2.2.

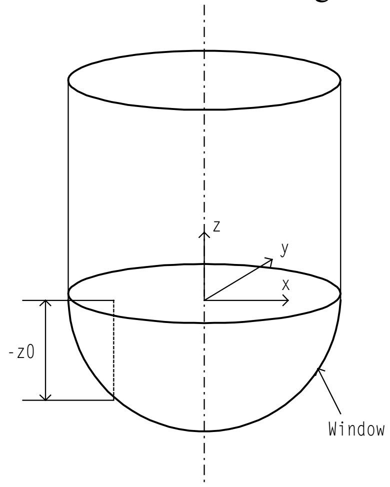


Fig. 2.2: Coordinate system used in the present work.

According to eq. (2.1) about ~5.44 kW heat is generated in the window. 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

$$q'' = q''' \times \delta \quad (2.2)$$

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

$$q''' = 1.58 \times 10^9 \exp[-(\frac{x}{\sigma_x})^2 - (\frac{y}{\sigma_y})^2] \exp[-\frac{(z - z_o)}{L}] \text{ W/m}^3 \quad (2.3)$$

with $L = 0.21$ m. Here $z - z_0$ is the z axial distance from the window for a given point. According to equation (2.3) about 650 kW heat is released in the active part of the target.

According to equations (2.1) and (2.2) 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. From 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 of about 1.5 m/s and the maximum temperature of the window surface should be kept below about ~400°C. The main reason for these design limits is due to structure material problems, such as corrosion and erosion.

Three types of configurations are considered in the present study, as indicated in Fig. 2.5. In the first configuration 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, indicated as (1) in figure 2.5, is to cut the lower end of the guide tube. 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, indicated as (2) in figure 2.5, is to introduce a bypass injection to remove the flow stagnation zone near the window center.

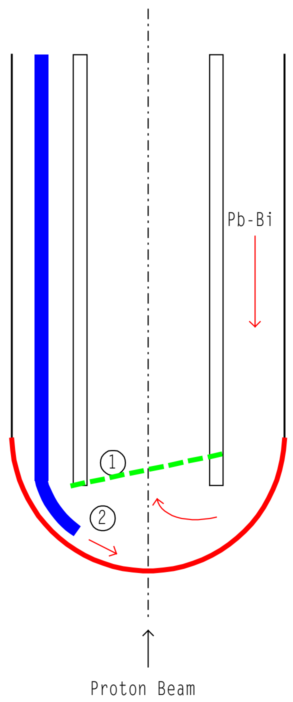


Fig. 2.5: Active part of the target considered in the present work

3 Numerical analysis

In the present study numerical analysis of the target has been performed using the CFX 4.3 code [13], which is a general purpose thermal-hydraulic code developed by AEA Technology. It has been widely applied to study fluid dynamics and heat transfer. The solution method of CFX is based on the finite volume method (FVM). The geometry is spilt into small volume cells. The partial differential equations governing mass, momentum and energy balance are replaced by algebraic equations for each volume cell. The system of these equations is solved by specified numerical techniques using appropriate boundary conditions. For the present analysis the following assumptions are made:

- Fluid is incompressible.
- Flow is highly turbulent and steady-state.
- Boussinesq approximation is valid.The standard k-ε model with logarithmic wall functions was used. Attention was paid to keep the first mesh size close to a solid wall in the range of $30 \le y^+ \le 100$. Here y^+ is the dimensionless distance from the wall.

The mesh generation in the CFX 4.3 code is based on the "body-fitted" and "multi-block" approach. "Body-fitted" means that the grid boundaries fit the geometry boundary considered. This feature of CFX4 is of crucial importance for the present work because of the curved window surface. "Multi-block" means blocks are joined together to form the geometry. Each block is subdivided into volume cells in a structured way.

The database of the thermal-physical properties of Pb-Bi is still not complete. There exists deviation between different sources. In Europe [14] many institutions have agreed on using a unique database. Table 3.1 summarizes the thermal-physical properties of Pb-Bi used in the present study. The user subroutines USRCND (for conductivity) and USRVIS (for viscosity) are supplied and incorporated into the CFX-4.3 calculation.

3.1 Target with a flat guide tube

3.1.1 Geometry and boundary conditions

The target with a flat guide tube, as shown in Fig. 3.1, is the first geometric configuration of this study. Flow inside this configuration is considered as axis-symmetric. The only geometric parameter which can be varied is the gap size.

Table 3.1 Pb-Bi properties used in the present work (T in °C)

Property	Unit	Value
Density	kg/m^3	10255.75
Viscosity	kg/m s	$3.26\times10^{-3} - 6.26\times10^{-6}T + 4.63\times10^{-9}T^2$
Conductivity	W/m K	9.7 + 0.01 T
Thermal expansion coefficient	1/K	1.2×10^{-4}

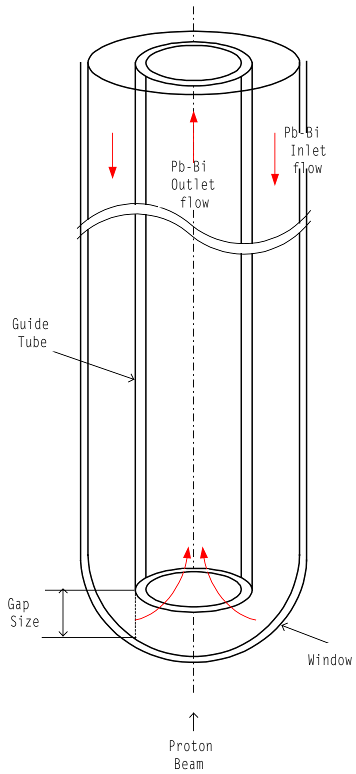


Fig. 3.1: MEGAPIE target with a flat guide tube

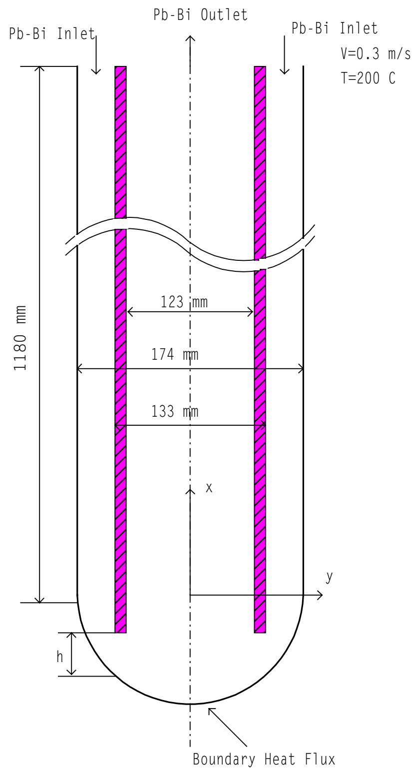


Fig. 3.2: Dimensions and boundary conditions considered

The dimensions and the coordinate system used in this chapter are shown in Fig. 3.2. The x-axis is in the axial direction and the y-axis in the radial direction. The outer diameter of the target is 174 mm and the inner diameter of the guide tube is 123 mm. The guide tube thickness is 5 mm. Although the target is about 3 m high, the height of the computational domain is reduced to 1180 mm to avoid unnecessary computing expenditure. The thickness of the window is 2 mm. Inlet temperature and velocity of Pb-Bi are set to 200°C and 0.3 m/s, respectively. This corresponds a mass flow rate of about 30 kg/s.

To perform the 2-D calculation, heat deposition in the window and in the target material is simplified as an axis-symmetric distribution. In the present study, the hottest plane (i.e., x = 0) is chosen. Heat generation in the window is expressed by a boundary heat flux using equation (2.2). This is reasonable because the window thickness is small. The thermal conductivity of the guide tube is varied from 0 up to 20 W/m K, to study its effect on the coolability of the beam window. Adiabatic boundary is used for the outer surface of the outer cylinder.

The axis-symmetric 2D meshes are generated using CFX-Build 4. Figure 3.3 shows the meshes in the lower part of the computation domain. The distance of the first line of fluid node from the wall is about 1.5 mm. Heat deposition is computed using eqs. (2.1) & (2.3) with x = 0. The standard k-ε model with logarithmic wall functions is adopted for turbulence modeling.

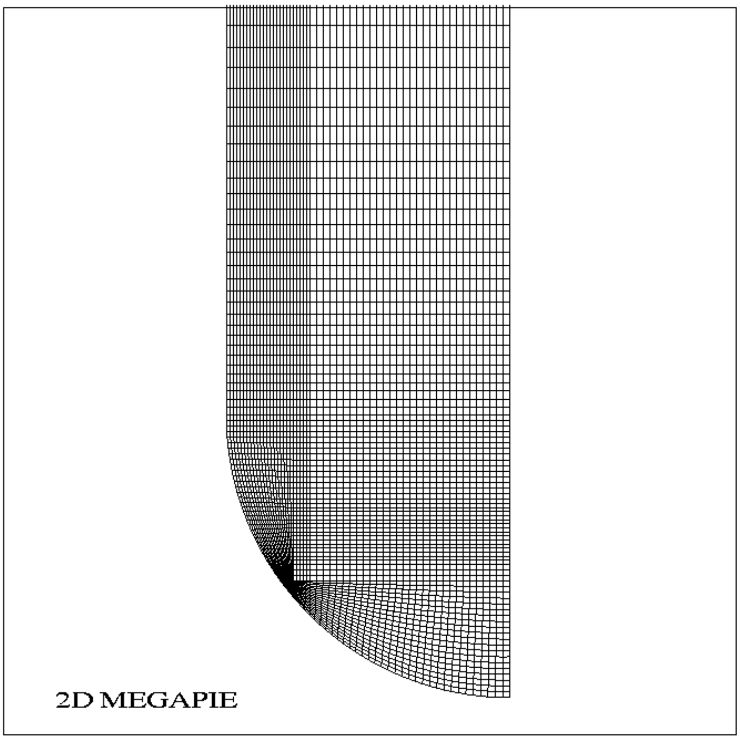
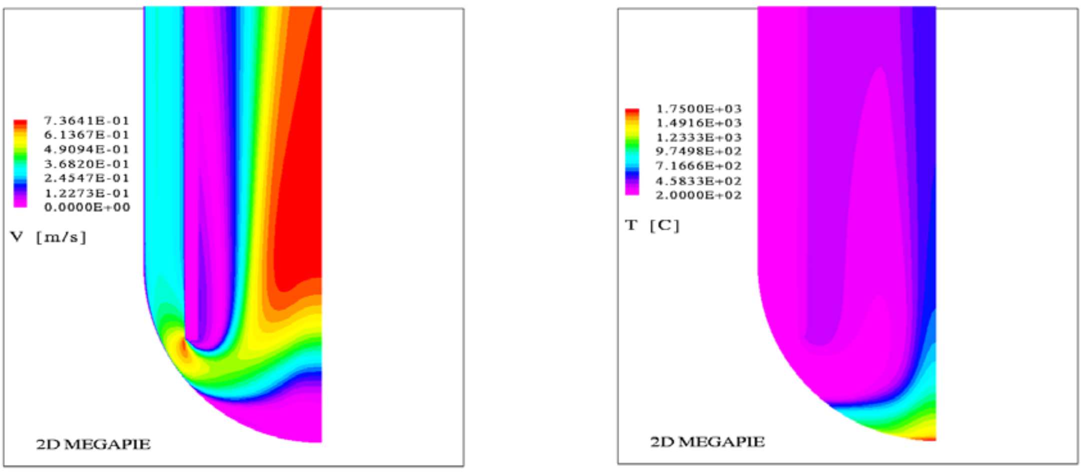


Fig. 3.3: Generated meshes for the 2D analysis

3.1.2 Results and discussion

Figures 3.4 and 3.5 show the velocity and temperature distribution 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.



(a) Velocity *(b) Temperature*

Fig. 3.5: Results for the target with a flat guide tube and a gap size of 20 mm

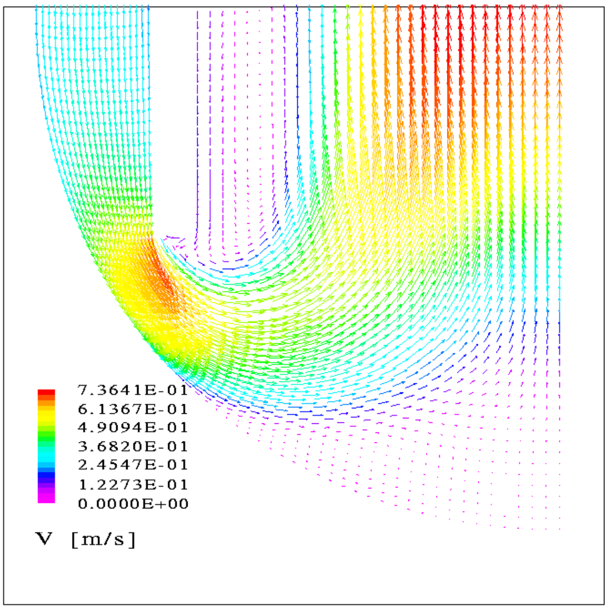


Fig. 3.5: Velocity vector in the target with a flat guide tube and a gap size of 20 mm

Effect of gap size

The gap size *(h)* is one of the main design parameters to be optimized. Numerical calculations are performed for different gap size changing from 5 to 50 mm. Figures 3.6 to 3.8 summarize the results achieved. A smaller gap size results in a higher velocity and a lower window temperature. However, the pressure drop is higher. The pressure drop in figure 3.8 is defined as the pressure difference between the reference point (*x=0 ,y=0*) and the point (*x=0, y=80 mm*). Even for an extremely small gap size (5 mm), the cooling of the beam window remains insufficient. Therefore, modification of this configuration is necessary.

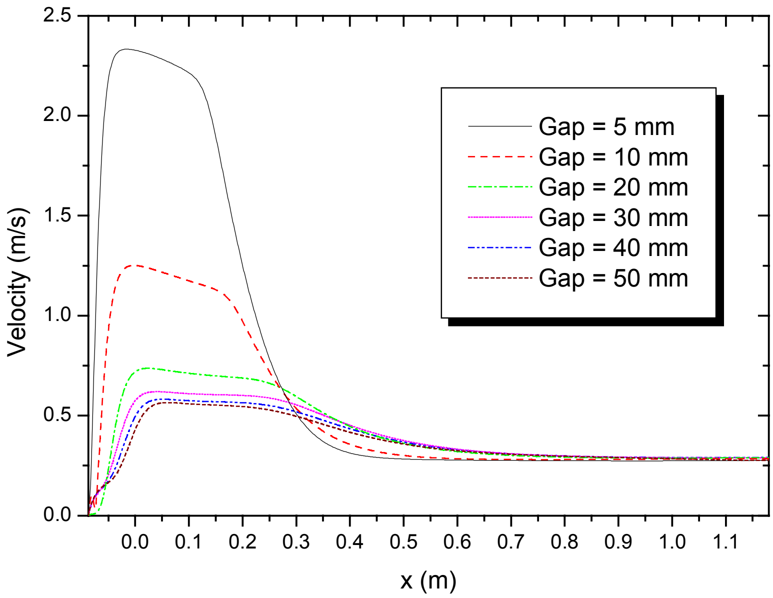


Fig. 3.6: Effect of the gap size on the velocity profile along the center line (y=0)

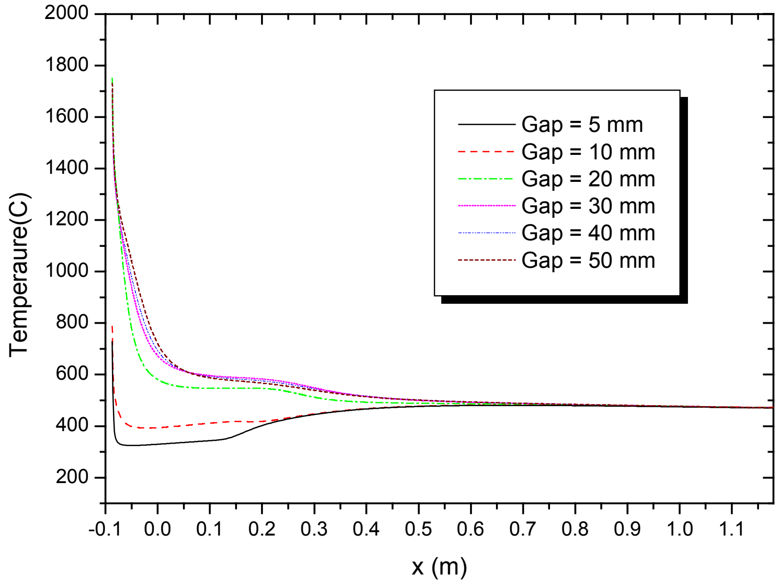


Fig. 3.7: Effect of the gap size on the temperature profile along the center line (y=0)

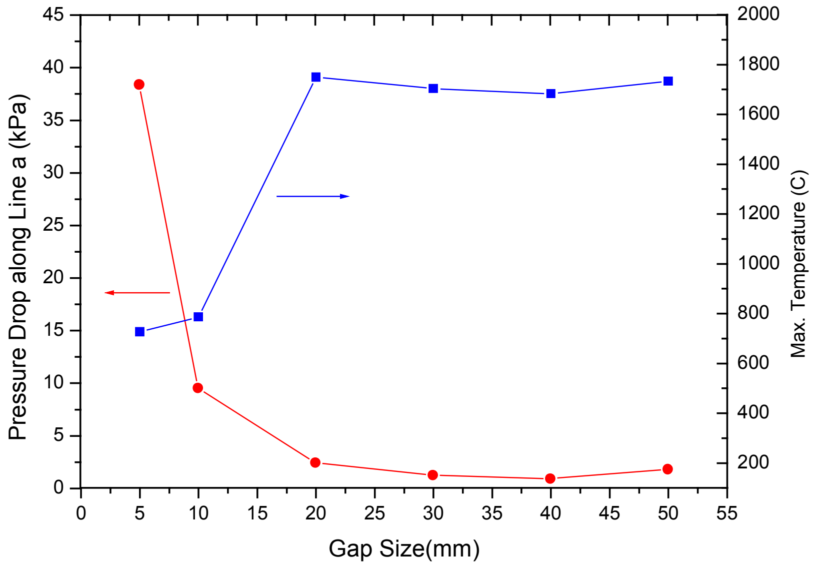


Fig. 3.8: Effect of the gap size on the pressure drop and the maximum temperature

Effect of buoyancy

In order to examine the effect of buoyancy, calculations are performed by excluding the buoyancy effect. Figure 3.9 compares the results for both the cases with and without buoyancy. A strong effect of buoyancy is obtained at high level of temperature.

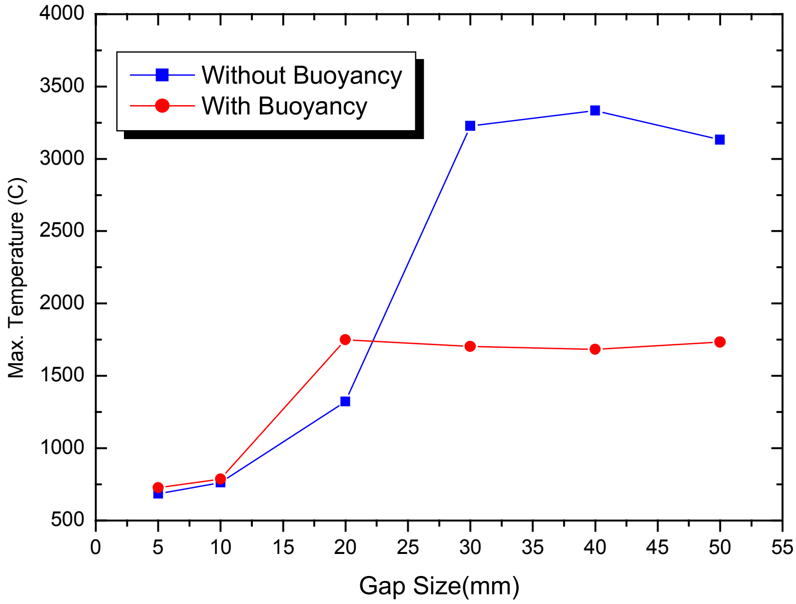


Fig. 3.9: Effect of buoyancy on the maximum temperature for different gap size

Effect of the thermal conductivity of the guide tube wall

In order to study the effect of the thermal conductivity of the guide tube wall, calculations with the entire target height are necessary. 3-D calculations with a full height (about 3 m) need a large number of meshes. Therefore, the effect of the thermal conductivity is investigated only in the 2-D configuration. The results can be, however, extrapolated to a 3-D configuration. Three values of thermal conductivity are taken, i.e. 20, 2.0 and 0.2 W/m K. Table 3.2 and Figure 3.10 summarize the results. It can be seen that a reduction in the temperature on the window surface of about 50°C is achieved, when the thermal conductivity of the guide tube wall is reduced from 20 down to 0.2 W/m K.

Table 3.2: Effect of the thermal conductivity of the guide tube wall on the maximum window temperature

Thermal conductivity	T_{max}
20 W/m K	1829.48°C
2 W/m K	1786.25°C
0.2 W/m K	1773.78°C

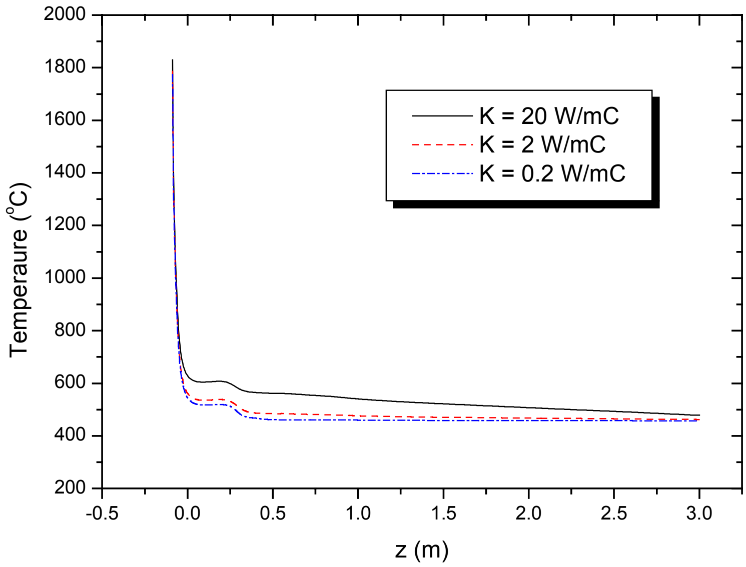


Fig. 3.10: Effect of the thermal conductivity of the guide tube wall on the temperature profile along the center line of the target

3.2 Target with a slanted guide tube

3.2.1 Geometry and boundary condition

It has been found that in the target with a flat guide tube, a large flow stagnation region occurs near the window center and leads to an excessive high temperature in the window center. One method to destroy the axis-symmetric flow, to reduce the flow stagnation region and, subsequently, to improve the coolability of the window is to introduce a slanted guide tube. In this case the lower end of the inner cylinder is cut with an inclined cross section, as shown in Fig. 3.11.

It was agreed among the partners of the MEGAPIE project that the effect of the gap size h, the inclination angle α and the direction of the cutting cross section on the coolability of the beam window has to be investigated. A detailed analysis will be carried out by PSI. In the present study, one calculation was carried out with the following conditions:

- gap size (h) : 10 mm
- cutting angle (α) : 8 °
- direction of the cutting surface: normal vector parallel to the x-z plane.

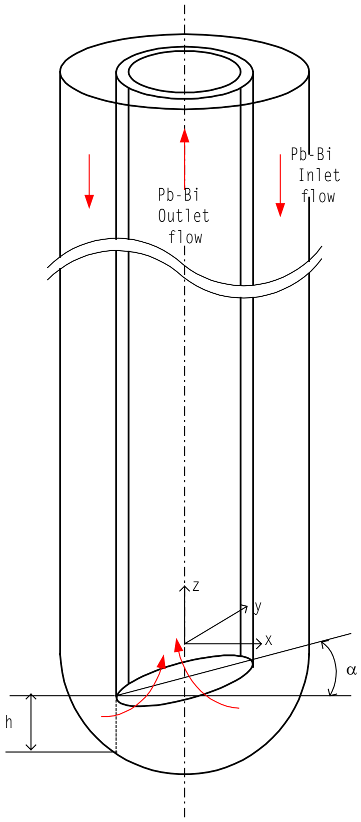
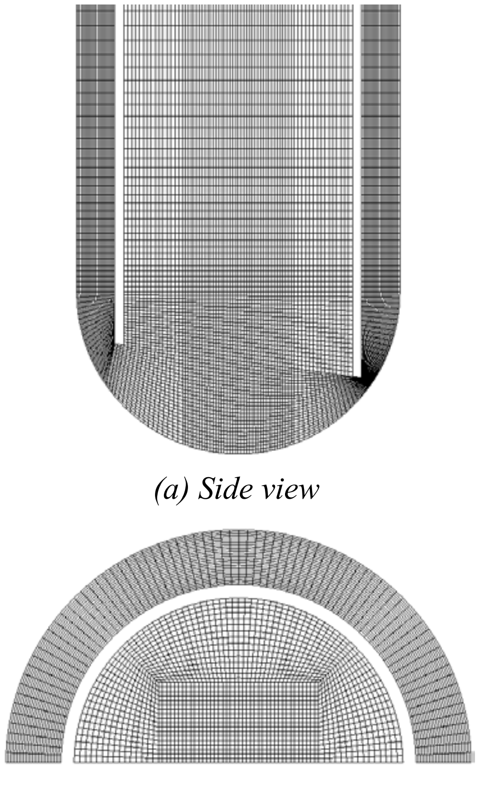


Fig. 3.11: *Target with a slanted guide tube*



(a) Side view

(b) Top view

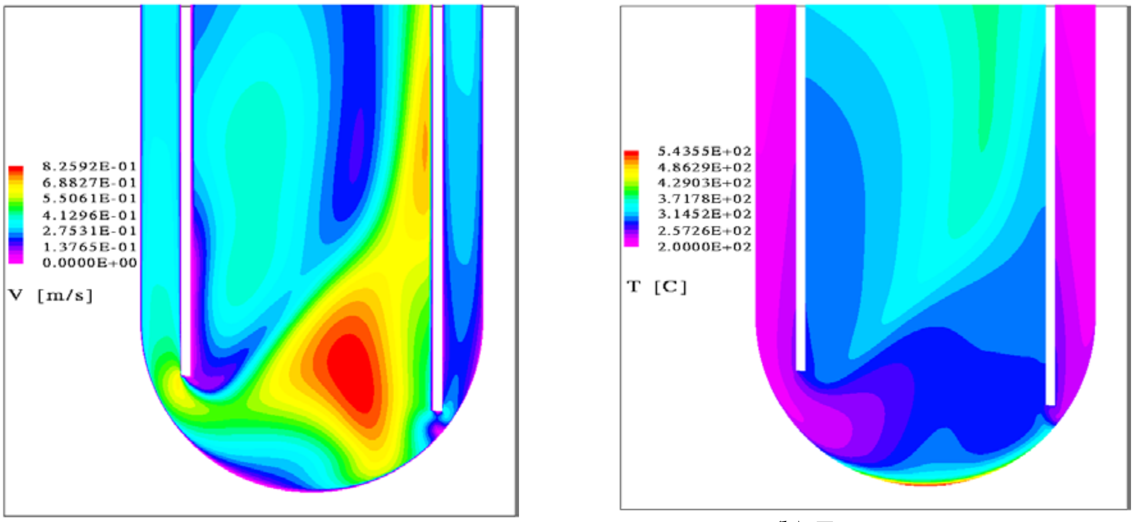
Fig. 3.12: Meshes for the target with a slanted guide tube

The main purpose of this calculation is to show in general the coolablity of the window in the target with a slanted guide tube. For this configuration, 3-D calculations are 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. In this case about 300,000 volume cells are generated. Figure 3.12 shows the grid cells generated for the target with a slanted guide tube.

3.2.2 Results and discussion

For this calculation the boundary condition is the same as for the target with a flat guide tube. Heat deposition rate in the window and in the target was determined by eqs. (2.1) & (2.3). The guide tube has a thermally insulating wall.

Figure 3.13 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. 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 of 400°C.



(a) Velocity *(b) Temperature*

Fig. 3.13: Results for the target with a slanted guide tube

3.3 Target with a rectangular bypass tube

3.3.1 Geometry and boundary conditions

In this chapter a bypass injection is adopted to improve the coolabilty of the beam window, as shown in Fig. 3.14.

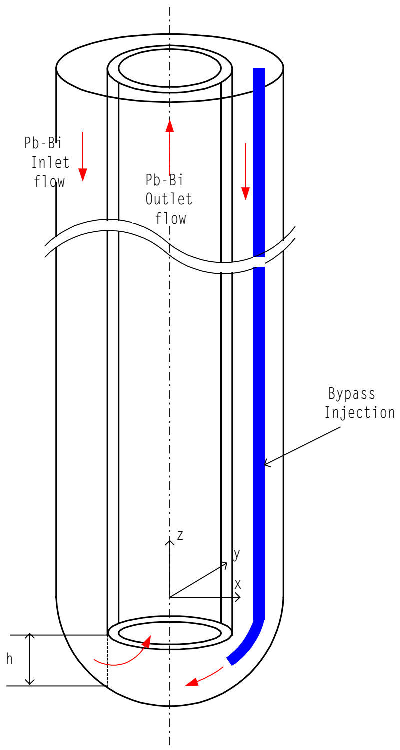


Fig. 3.14: Target with an injection bypass

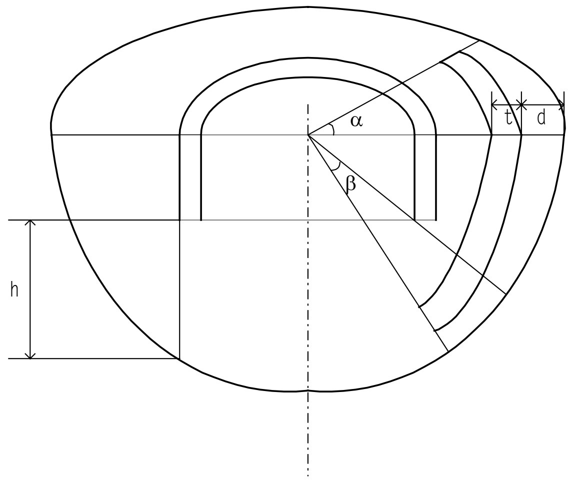


Fig. 3.15: Main design parameters of the target with a rectangular bypass injection

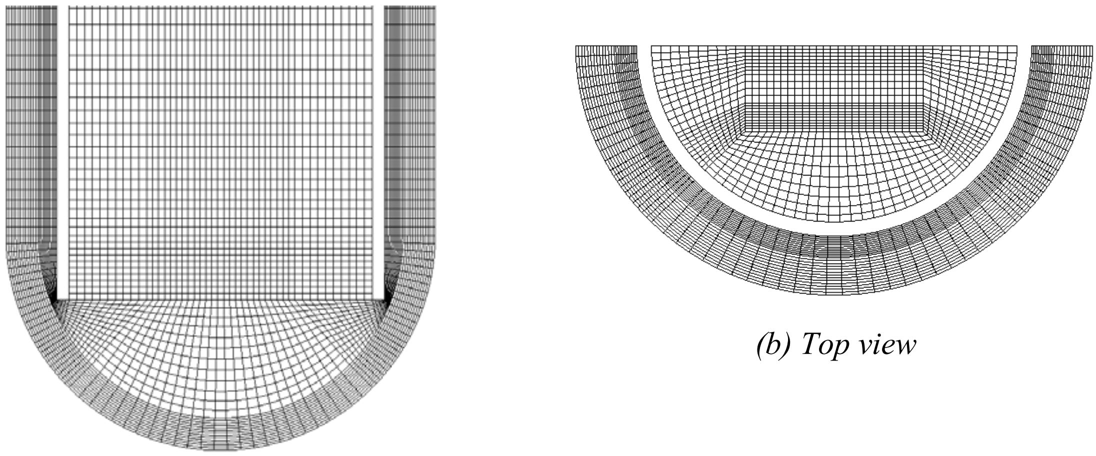
Two different types of injection bypass tubes are considered, i.e. rectangular and circular tube. With a rectangular bypass tube a large injection flow area can be achieved. However, a circular shape is easier to fabricate and to install in the target.

Major design parameters of the rectangular bypass jet are illustrated in Figure 3.15. The reference line for the angle α is the x-axis. The reference line of the angle β is the line connecting the sphere central and the lower end of the guide tube. To achieve an optimum performance of the target, the effects of the geometric parameters of the bypass tube are investigated to provide a first information for the design optimisation. The parameters considered in the present study are: the injection velocity (V_b), the position of the nozzle end (β), the distance from the wall (d), the depth of the bypass tube (t), the bypass width (α),the injection direction and the gap size (h). The reference values are summarized as below:

• gap size:	h = 30 mm
• injection velocity:	$V_b = 1.0$ m/s
• position of nozzle end:	$\beta = 0^o$
• distance from the wall d:	d = 5 mm
• depth of the bypass tube t:	t = 5 mm
• bypass width:	$\alpha = 20^o$
• location of the bypass injection:	on y-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.

About 200,000 meshes are generated for this 3-D calculation, as shown in Figure 3.16. The distance of the first fluid node from solid walls is about 1 mm.



(a) Side view *(b) Top view*

Fig. 3.16: Meshes for the target with a rectangular bypass tube

More recently, the following equations for the heat deposition have been provided [15], i.e.

$$q''' = 0.696 \times 10^9 \exp[-\frac{1}{2}\{(\frac{x}{\sigma_x})^2 + (\frac{y}{\sigma_y})^2\}] \tag{3.1}$$

for the heat deposition in the window and

$$q''' = 1.1136 \times 10^9 e^{-\frac{z-z_0}{B}} \times \left[1 - e^{-\frac{z-z_0-Z_a}{\lambda}}\right] \times e^{-\frac{1}{2}\left\{\left(\frac{x}{\sigma_x^*(z)}\right)^2 + \left(\frac{y}{\sigma_y^*(z)}\right)^2\right\}} \tag{3.2}$$

for the heat density in the target material. The parameters in equations (3.1) and (3.2) are summarized as below:

$\sigma_x = 0.020188\, m$

$\sigma_y = 0.033505\, m$

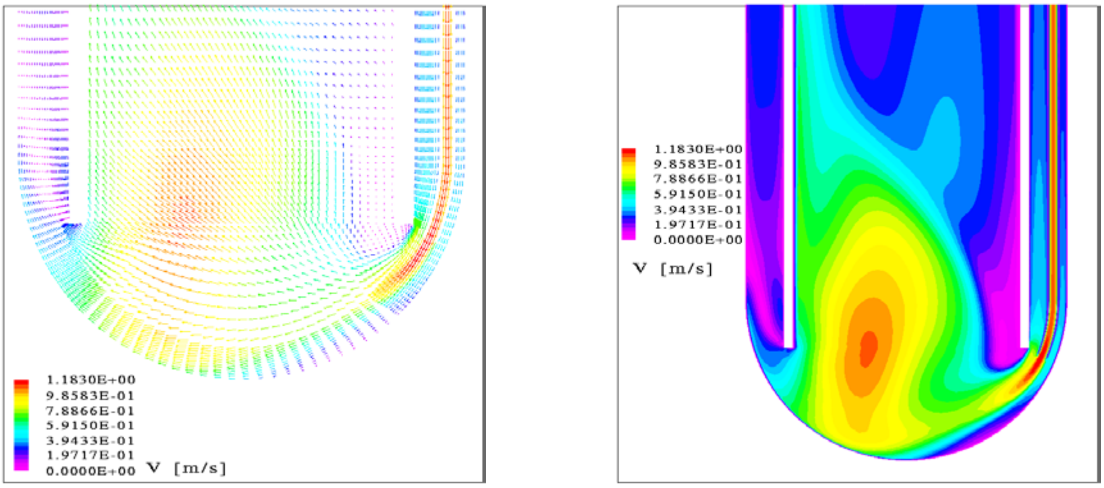
$\sigma_x^* = 0.019 + 0.00035 \times (z - z_0),\ m$

$\sigma_y^* = 0.0331 + 0.00035 \times (z - z_0),\ m\ B = 0.15\, m, \quad Z_a = -0.018\, m, \ \lambda = 0.018\, m$

For the numerical calculations in chapters 3.3 and 3.4, equations (3.1) and (3.2) are used to calculate the heat deposition rate.

3.3.2 Results and discussion

Figure 3.17 shows the velocity distribution for the reference case. 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 the flow in the opposite side of the annular gap. Figure 3.18 shows the temperature distribution. The maximum temperature is about 400°C. Compared to the previous designs, i.e., the targets with flat or slanted guide tube, the coolability of this design is improved significantly. Further reduction in the maximum window temperature can be achieved by optimizing the design parameters.



(a) vector plot *contour plot*

Fig. 3.17: Velocity distribution for the reference design

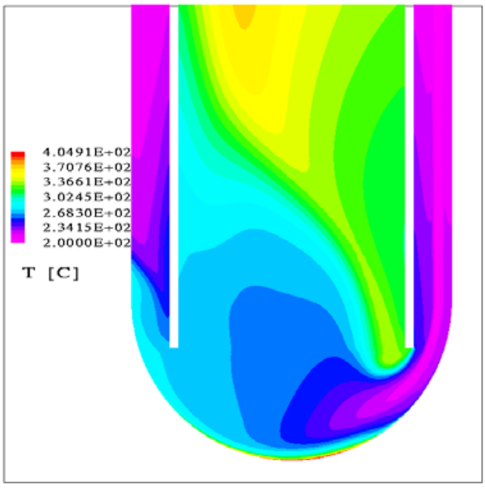
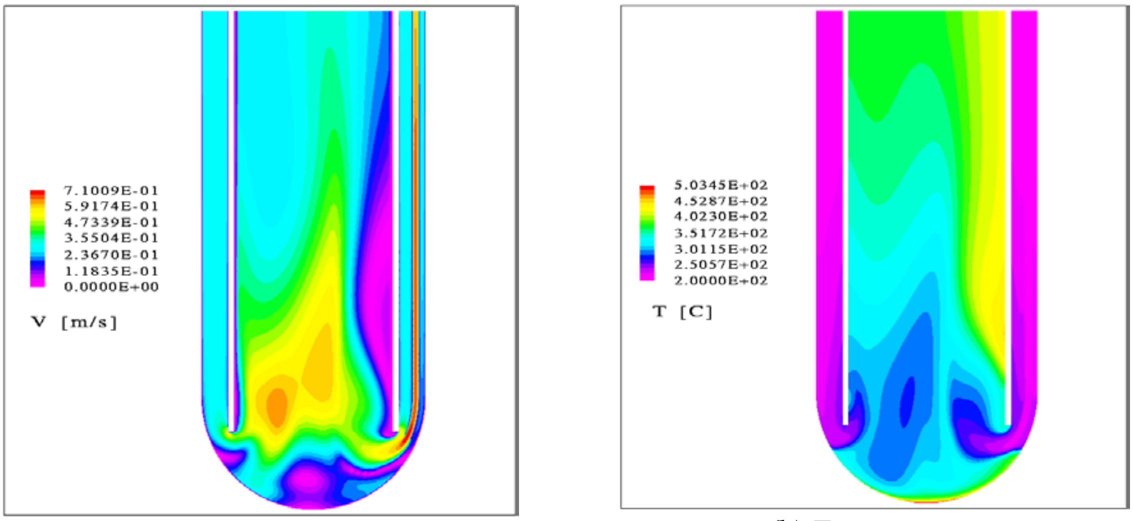


Figure 3.18: temperature distribution for the reference design

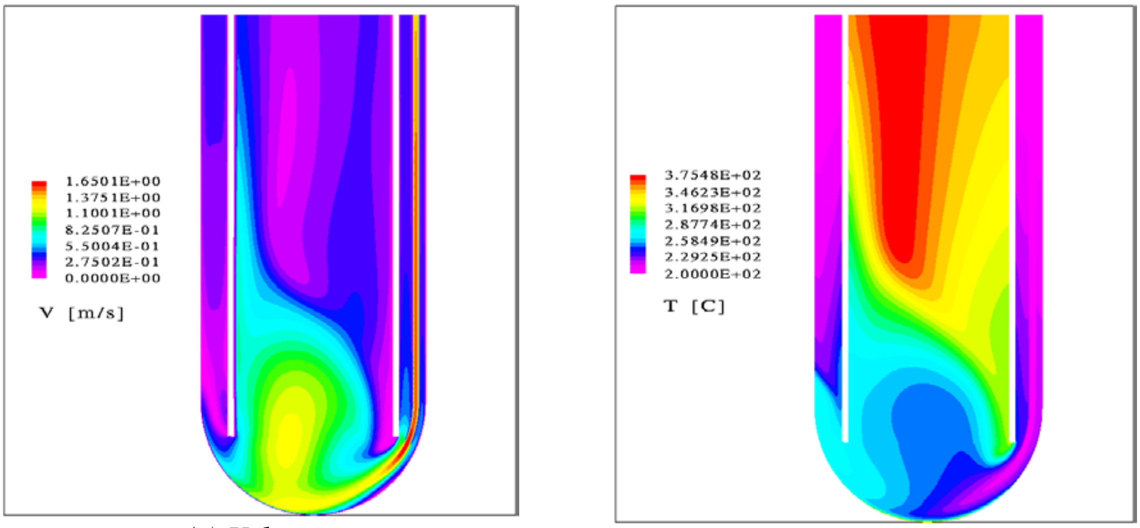
Effect of injection velocity (V_b)

The injection velocity of the bypass is changed to 0.6 and 1.4 m/s, respectively. Figure 3.19 shows the velocity and temperature profiles for the case with an injection velocity of 0.6 m/s. Obviously, the bypass injection is not high enough to eliminate the flow stagnation zone completely. The maximum window temperature exceeds 500°C. Figure 3.20 shows the velocity and temperature profiles for the case with a higher the injection velocity 1.4 m/s. In this case the high injection velocity removes completely the stagnation region near the window center. However, it creates a large flow recirculation in the riser. Thus, the position of the maximum temperature is moved to the riser, apart from the window. The maximum temperature of the window surface is reduced to about 330°C. The maximum temperature of Pb-Bi increases slightly, and the maximum velocity of Pb-Bi is about 1.65 m/s, slightly exceeds the design limit 1.5 m/s. More optimization studies are thus required. Figures 3.21 and 3.22 present the velocity and temperature profiles along the center line for the cases with different injection velocities.



(a) Velocity *(b) Temperature*

Fig. 3.19: Results for V_b = 0.6 m/s



(a) Velocity *(b) Temperature*

Fig. 3.20: Results for V_b = 1.4 m/s

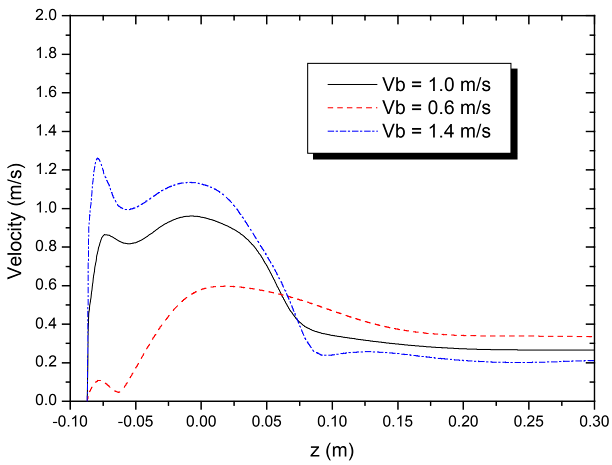


Fig. 3.21: Effect of the injection velocity on the velocity profile along the center line.

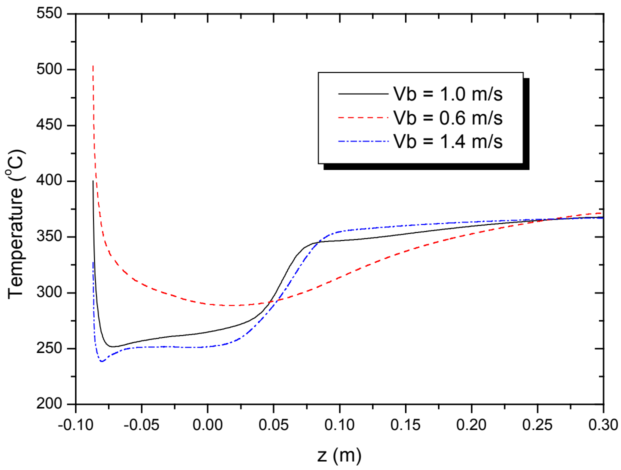


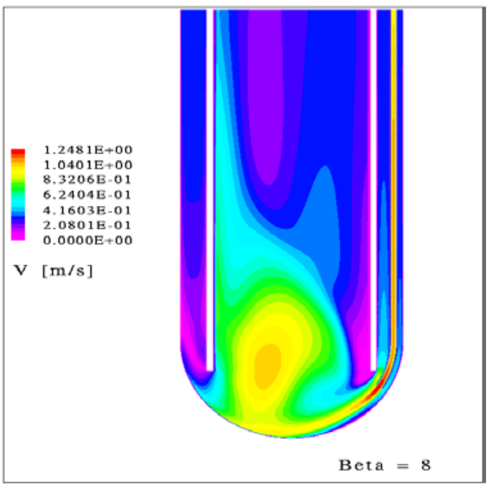
Fig. 3.22: Effect of the injection velocity on the temperature profile along the center line.

Effect of the position of the nozzle end (β)

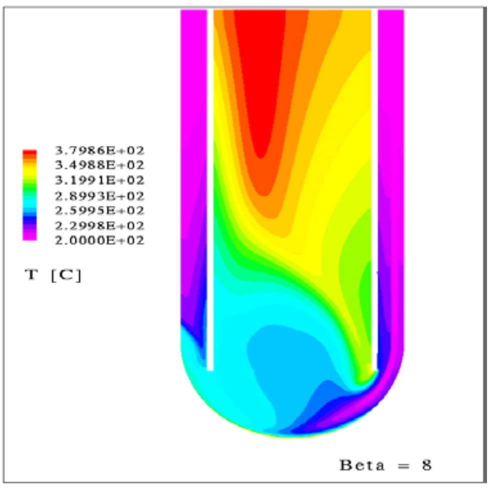
Three different β values of were taken, i.e. 0°, 8° and 23°. Table 3.3 summarizes the results. An increase in β improves the coolability of the beam window. The maximum window temperature decreases. However, in the target design the β value is limited, to avoid an excessive exposure of the bypass tube to the irradiation field. Figures 3.23 to 3.26 show the velocity and temperature distribution for different β values.

Table 3.4 Effect of β values on T_{max} and U_{max}

β	T_{max}	U_{max}
0 °	404.91 °C	1.1830 m/s
8 °	342.21 °C	1.2481 m/s
23 °	319.20 °C	1.4983 m/s

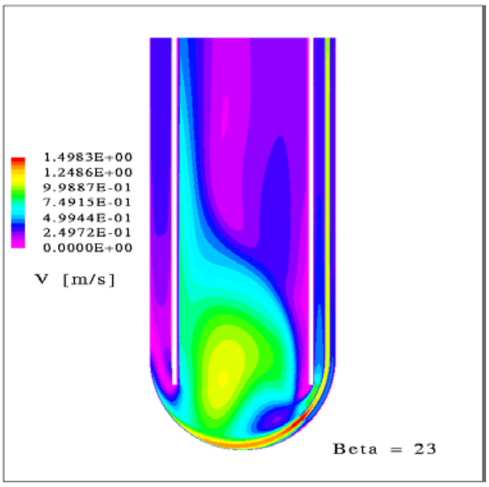


(a) Velocity

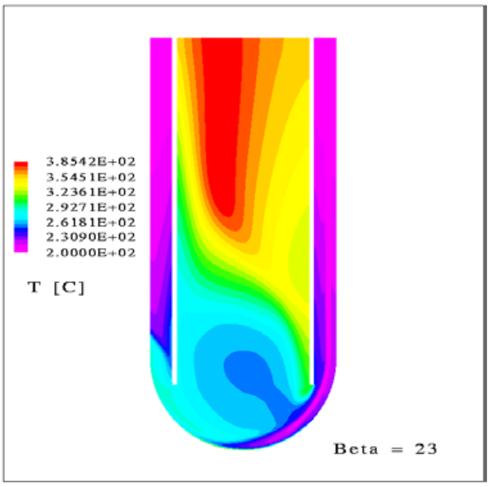


(b) Temperature

Fig. 3.23: Results for β=8°.



(a) Velocity



(b) Temperature

Fig. 3.24: Results for β=23°

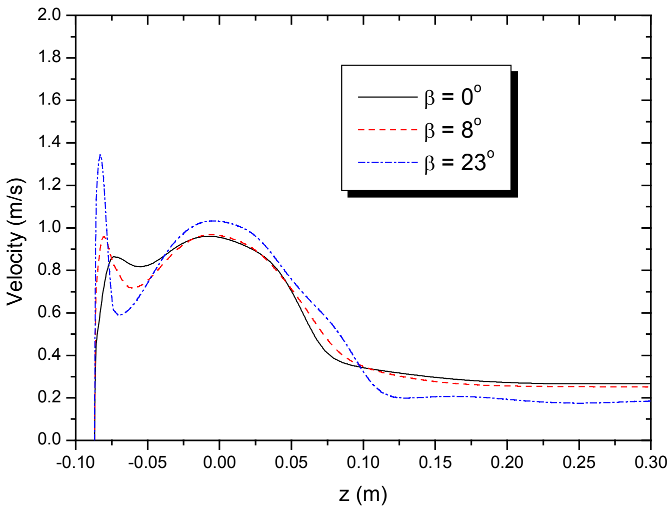


Fig. 3.25: Effect of β on the velocity profile along the center line.

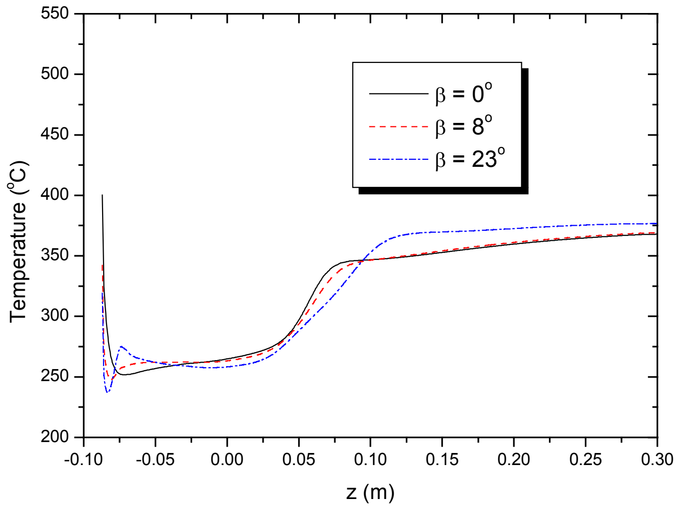


Fig. 3.26: Effect of β on the temperature profile along the center line.

Effect of the distance from the wall (d)

The distance from the wall (d) is reduced from 5 mm to 3 mm. Figures 3.27 and 3.28 show the effect of the distance *d* on the velocity and the temperature profiles along the center line. In the case with a smaller distance, the hot spot is located at the window center and the maximum temperature is increased from 405°C up to 486°C. The results indicate that a slight movement of the bypass tube would cause a large change in the window coolability.

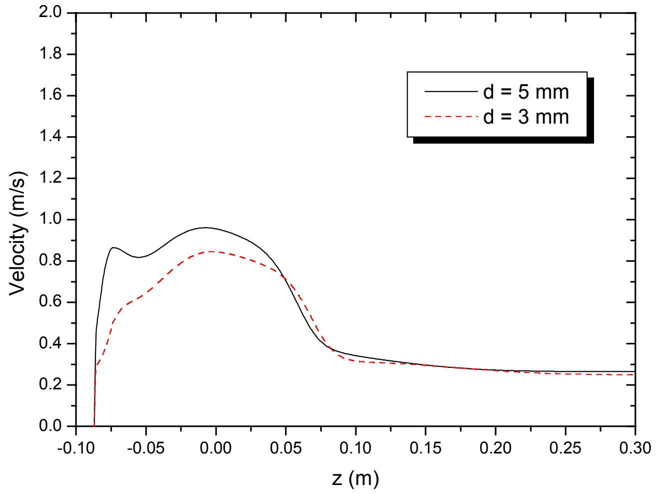


Fig. 3.27: Effect of d on the velocity profile along the center line

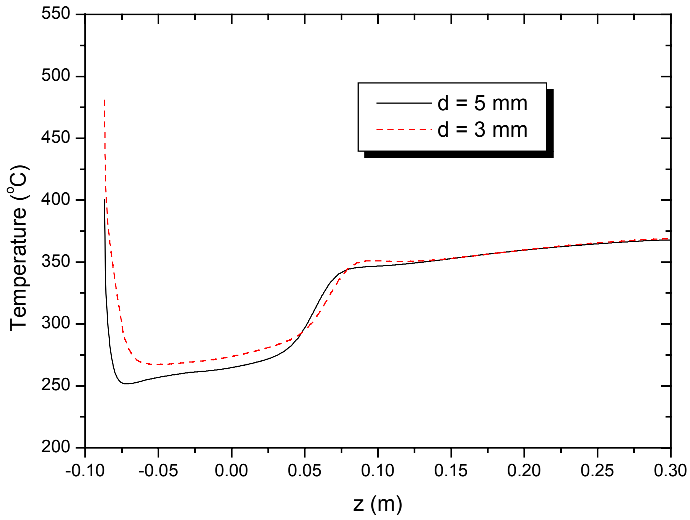


Fig. 3.28: Effect of d on the temperature profile along the center line

Effect of the depth of the bypass tube (t)

The depth of the bypass tube (t) is changed from 5 mm to 3 mm and 8 mm, respectively. A injection velocity of V_b = 0.6 was used for these three calculations. Figures 3.29 and 3.30 show the effect of the depth on the velocity and the temperature profiles along the center line. The velocity peak as well as the temperature peak show their minimum values at a tube depth of 5 mm. Increase in the tube depth from 5 mm up to 8 mm leads to an increase in the maximum window temperature of about 80°C, although a larger t value results in a higher mass flow rate of the bypass injection. The results emphasize the strong dependence of the window temperature on the local flow condition close to the window surface.

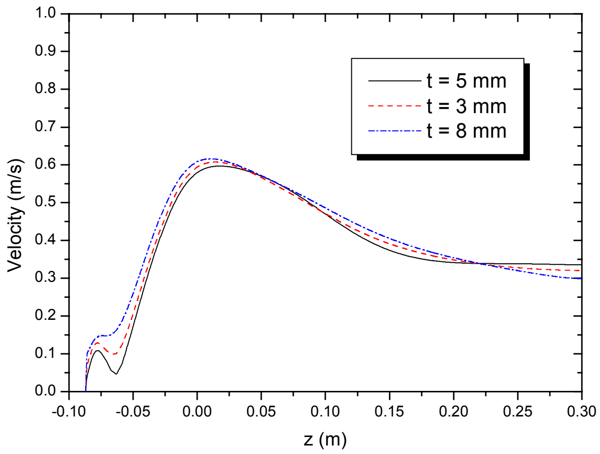


Fig. 3.29: Effect of t on the velocity profile along the center line

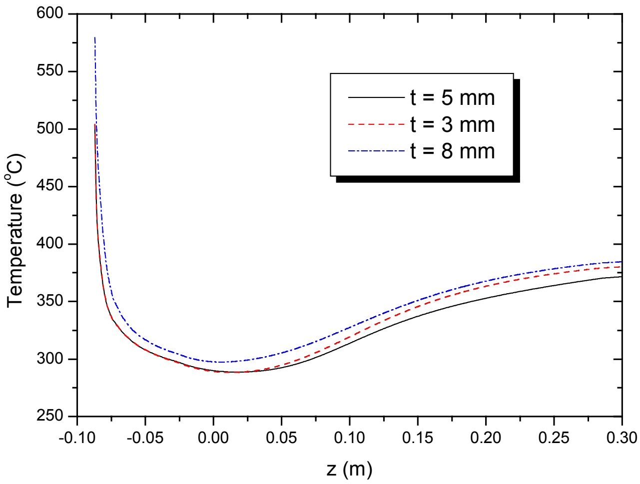


Fig. 3.30: Effect of t on the temperature profile along the center line

Effect of the width of the bypass tube (α)

The bypass width represented by the angle α is varied from 20° (reference value) to 30°. Table 3.4 summarizes the effect of α on the maximum temperature and the maximum velocity. The maximum window temperature increases significantly by increasing the bypass width from 20° to 30°. The main reason is the formation of a flow recirculation generated by the bypass flow itself. This flow recirculation is enhanced by increasing the tube width. More studies are necessary to optimize the tube width. Figure 3.31 shows the effect of the bypass width on the temperature profile along the center line.

Table 3.4: Effect of α on the maximum window temperature and the maximum velocity

α	T_{max}	U_{max}
20°	404.91 °C	1.1830 m/s
30 °	573.77 °C	1.0168 m/s

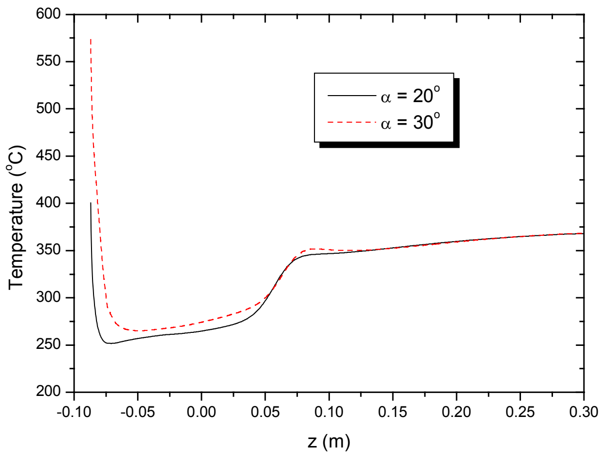


Fig. 3.31: Effect of α on the temperature profile along the center line

Effect of the Bypass Injection Direction

Since heat deposition in the target is not axis-symmetric, direction of the bypass injection, i.e. location of the bypass tube against the hottest plane of the heat deposition, plays also an important role. In the present study, two different directions are considered, i.e. bypass tube lying on the y-axis (reference case) and on the x-axis, respectively. Table 3.5 and figure 3.32 summarize the results showing the effect of the injection direction. It is seen that the velocity profile is hardly affected by the injection velocity, whereas the maximum window temperature reduces significantly, if the bypass tube lies on the x-axis. The maximum window temperature is reduced down to 325°C.

Table 3.5: Effect of the injection direction

Location	T_{max}	U_{max}
y-axis	405°C	1.183 m/s
x-axis	325°C	1.183 m/s

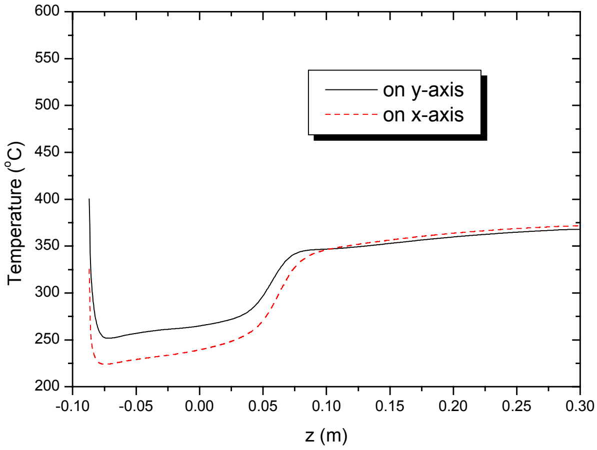
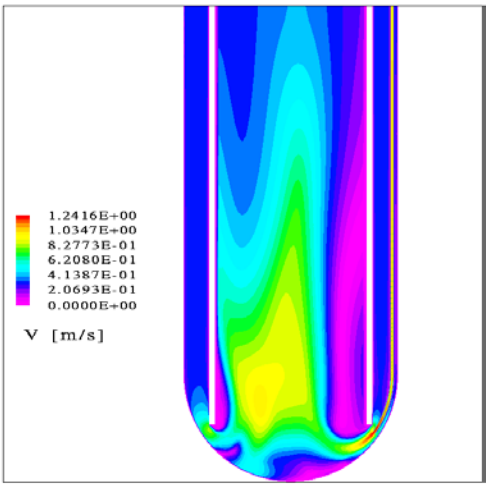


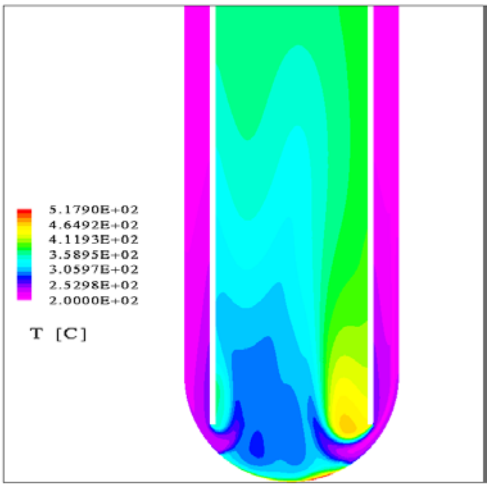
Fig. 3.32: Effect of the injection direction on the temperature profile along the center line

Effect of gap size (h)

To examine the effect of the gap size, calculations with a gap size of 15 mm were also carried out. Figure 3.33 shows the result for the small gap size. In this calculation, both *t* and *d* are 3 mm. As can be seen in figure 3.33, a flow stagnation region exists near the window center. This results in a high window temperature. Obviously, there exists an optimum value of the gap size relating to the coolability of the beam window. Further studies are needed to obtain the optimum value.



(a) Velocity



(b) Temperature

Fig. 3.33: Velocity and temperature profiles for the case with a small gap size (h=15 mm)

3.4 Target with a circular bypass jet

3.4.1 Geometry and boundary conditions

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. In order to check the coolability óf the beam window in case of a circular bypass injection tube, one calculation was carried out for the target with a circular bypass tube. The parameters used in this calculation are indicated in figure 3.34 and summarized below:

- gap size (h): h = 40 mm
- injection velocity: V_b = 1.0 m/s
- position of nozzle end: $\beta = 0^o$
- bypass diameter: D = 10 mm
- distance from the wall: δ = 5 mm
- direction of the bypass injection: on x-axis

In this case the bypass mass flow rate is only 2.7 % of the total mass flow, about 20% of that in case with a rectangular bypass tube. For simplicity the thickness of the bypass tube is neglected in this calculation.

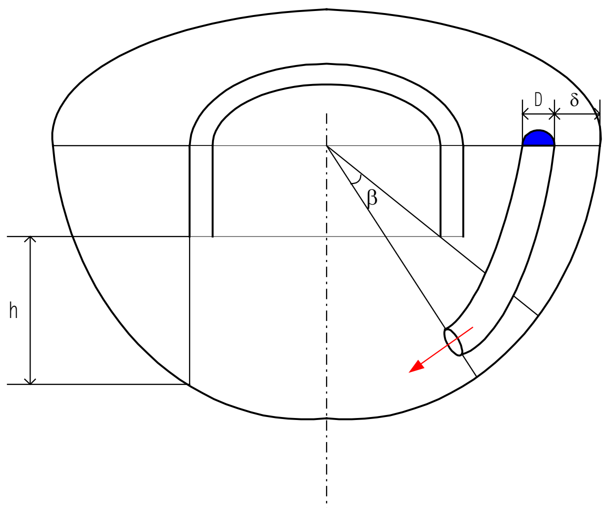
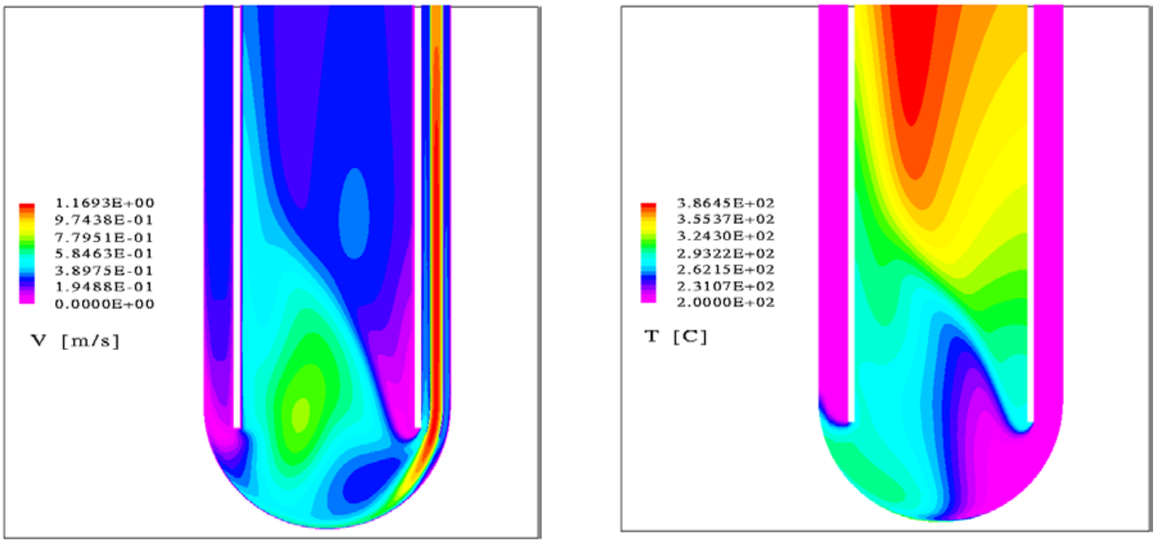


Fig. 3.34: Main parameters of the target with a circular bypass injection tube

3.4.2 Results and discussion

Figure 3.35 shows the temperature and the velocity profiles in the target with a circular bypass tube. The maximum velocity is less than 1.2 m/s, well below the design limit. The maximum window surface temperature is 387 °C, at the same level as in the case with a rectangular bypass tube, although the mass flow rate is much lower. Obviously, with a circular bypass tube the beam window can be sufficiently cooled down and the spallation heat can be safely removed from the active part of the target. The design with a circular bypass tube is proven to be a promising design concept which has to be further investigated in the future.



(a) Velocity *(b) Temperature*

Fig. 3.44: Velocity and temperature profiles in the target with a circular bypass tube

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. Four different geometric configurations are considered, i.e. with a flat guide tube; with a slanted guide tube; with a rectangular bypass tube and with a circular bypass tube. From the numerical results achieved so far 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 the design limit (≈ 400°C).
- By using a slanted guide tube instead of a flat guide tube the flow stagnation region near the window center is reduced significantly. 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 either a rectangular or a circular bypass tube, 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.
- Compared to a thermally insulating wall, a thermally conducting wall of the guide tube results in an increase in the window surface temperature of about 50°C. This should be taken into consideration in the design of the MEGAPIE target.
- A higher injection velocity of the bypass reduces the window temperature. However it causes a large recirculation region in the spallation zone and leads, subsequently, to a higher temperature of the Pb-Bi in the spallation zone.
- The present study indicates clearly that for the configuration with a rectangular bypass tube there exist optimum values for the tube end position, the distance to the wall, the depth and the width of the bypass tube. Additional numerical analysis is necessary to find out these optimum values for the target design.
- Due to the asymmetric distribution of the heat deposition in the window as well as in the target, it is recommended to install the bypass tube on the axis with the smallest spreading length of the proton beam.
- In the configuration with a circular bypass tube, a much smaller bypass flow rate is required. However, the coolability of the beam window is comparable to the case with a rectangular bypass tube. A further systematical study is necessary to optimize the geometrical parameters of such a circular bypass tube.

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