THERMAL-HYDRAULIC DESIGN ANALYSIS OF A 5 MW SODIUM-COOLED TUNGSTEN TARGET

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Abstract

One of the main objectives of the ADTF (Accelerator-Driven Test Facility) is the demonstration of the feasibility of the accelerator-based transmutation of nuclear waste. A pre-conceptual design of an accelerator-driven, sodium-cooled sub-critical multiplier assembly has been developed with a thermal power of 100 MW. A high-energy proton beam (600 MeV/5 MW) is fed to the spallation target for neutron production. In the design configuration with a solid target with tungsten plates, the sub-critical assembly core and the target form two parallel flow paths cooled with sodium. The present thermal-hydraulic analysis focuses on the following aspects:

- Cooling capability of the beam window.
- Cooling capability of the tungsten plates.
- Passive decay heat removal.

The effect of important design parameters on the thermal-hydraulic behaviour of the target has been investigated. Based on the results achieved, reference thermal-hydraulic designs of the sodium-cooled tungsten target are proposed. Measures are recommended and assessed to enhance the thermal-hydraulic performance of the target under both normal operating conditions and passive decay heat removal conditions.

1. Introduction

The proposed Accelerator-driven Test Facility (ADTF) within the Advanced Accelerator Application Program of the US Department of Energy is envisioned as a major nuclear research facility with multiple testing and production capabilities. [1] One of the main objectives of the ADTF is the demonstration of the feasibility of the accelerator-based transmutation of nuclear waste. For this purpose, an accelerator-driven sub-critical multiplier (SCM) is being designed with a thermal power of 100 MW. [2] A high-energy proton beam (600 MeV/5 MW) is fed to the spallation target for the neutron production. Two different designs of the spallation target have been considered, i.e. a heavy liquid metal (HLM) target or a sodium-cooled tungsten target. In the HLM target, liquid lead-bismuth eutectic (LBE) is used as the spallation material and the coolant as well. One of the major concerns of a LBE target is the big deficiency in reliable technology of operating a lead-bismuth cooled facility.

Although solid tungsten targets have been constructed for some other purposes, the heat deposition density in the present application is much higher than in the cases studied in the past. In the ADTF test facility with a solid target, the sub-critical reactor core and the target form two parallel flow paths with common circulating pumps. The thermal-hydraulic behaviour of the target under normal operating conditions as well as under passive decay heat removal conditions need to be investigated. The present analysis focuses on the following aspects:

- Cooling capability of the beam window. The beam window is made of steel and separates the accelerator-related devices from the reactor island. A high heat deposition density in the beam window makes the cooling capability of the window one of the most challenging tasks of the target design.
- Cooling capability of the tungsten plates. Thin tungsten plates are used as the spallation material, which are covered with steel cladding. A sufficient cooling capability has to be provided to both the tungsten plate and the cladding.
- Passive decay heat removal. In a solid target, decay heat is released in the solid materials located in the spallation zone. A safe removal of the decay heat under natural convection conditions is one of the design requirements.

This paper summarises the thermal-hydraulic analysis carried out to date. Based on the results achieved, a reference design of a sodium-cooled tungsten target is proposed. The effect of important design parameters on the thermal-hydraulic behaviour of the target has been investigated. Measures are recommended and assessed to enhance the thermal-hydraulic performance of the target under both the normal operating condition and the passive decay heat removal condition. To complete the design of the solid target, structural analyses should be performed and integrated with the thermal-hydraulic analyses.

2. Boundary conditions

The main characteristics and requirements of the solid tungsten target are summarised as follows: [2]

Beam power:	5 MW
Beam diameter:	16.2 cm
Coolant:	Sodium

Spallation material:	tungsten
Radial beam power distribution:	uniform
Sodium inlet temperature:	360°C
Maximum coolant velocity:	5 m/s
Maximum window temperature:	600°C
Maximum cladding temperature:	600°C
Window and structural material:	stainless steel (HT9)

The heat released in the active part of the solid tungsten target is about 3.7 MW. For the present analysis, the heat deposition rate in the beam window and in the structure material is assumed to be 50% of that in tungsten at the same location. Sodium is assumed to be transparent to the proton beam. Based on the experience available, the maximum velocity of sodium should be lower than 5.0 m/s. From thermal stress consideration the maximum temperature of the beam window, as well as the cladding material, has to be kept below 600°C. The sodium inlet temperature is the same as the temperature at the core inlet (about 360°C). The four centre rings of the SCM core are left open to accommodate the spallation target, which has an outer diameter of 34 cm. At the conceptual design phase, many options are still open related to the design of the reactor core. In general, it was agreed that the existing sodium systems technology gained at EBR-II should be applied to ADTF as far as possible. [2] In the reference proposal, a fuel pin of EBR-II type (MK-III) has been proposed. The fuelled length of the EBR-II fuel pin is about 36 cm. Therefore, the length of the spallation zone should be smaller than 36 cm.

3. Target proposals

Two design configurations were proposed, as shown in Figures 1 and 2. Table 1 summarises some reference parameters of both configurations.

Table 1. **Reference parameters of both configurations**

Configurations	Horizontal plates	Vertical plates
Number of tungsten plate [-]	55	6×28
Thickness of the tungsten plates [mm]	3.0	4.0
Cladding thickness [mm]	0.15	0.15
Flow channel width [mm]	2.5	3.0
Diameter of beam window [mm]	200	200
Thickness of beam window [mm]	2.5	2.5
Effective heat transfer coefficient across the gap [kW/m^{2}K]	5.0	5.0

In the first design, the tungsten plates are placed horizontally in the spallation zone, whereas in the second design the tungsten plates are arranged vertically. Both designs have a single flow path, i.e. the coolant cools at first the tungsten plates and then the beam window. In the reference proposal of the horizontal configuration, the total number of tungsten plates is 55. The thickness of each tungsten plate is 3 mm. This gives a total tungsten thickness of 165 mm for beam damping. The flow channels between two tungsten plates have a height of 2.5 mm. This gives a total height of the channels of

135 mm. In this case, the total height of the spallation zone is about 320 mm. The tungsten plate has a circular shape with two extended wings. The diameter of the circle is 200 mm, and the outer diameter of the wings is 330 mm, which is identical to the inner diameter of the guard tube. The wall thickness of the guard tube is 5 mm. The diameter of the vacuum beam tube is 200 mm. The beam window has a hemispherical shape with a thickness of 2.5 mm. A cladding is required for the tungsten plates for structural purpose and to retain spallation products. The thickness of the cladding should be as small as possible. A thickness of about 0.15 mm is used for the reference proposals. The effect of the cladding thickness on the cooling capability has to be assessed. In the wing region, the thickness of the tungsten plates could be reduced, to provide sufficient space for a gas plenum accommodating spallation gas.

Figure 1. **Horizontal configuration**

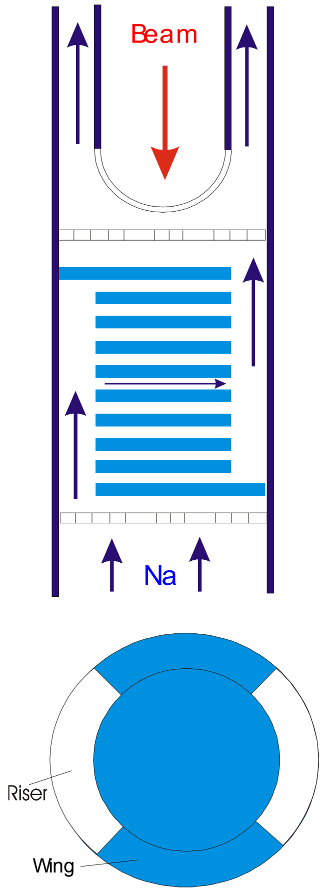
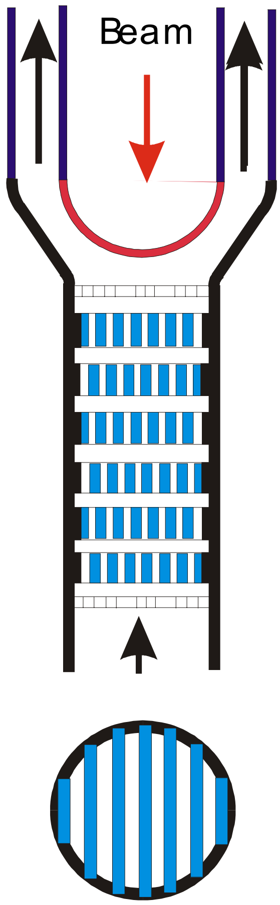


Figure 2. **Vertical configuration**



A perforated plate is located close to the beam window, to achieve a desirable flow distribution close to the window and to provide a sufficient cooling capability of the beam window. The porosity distribution of the perforated plate should be optimised. If required, a perforated plate is put at the target inlet, to guide the inlet flow smoothly to the riser annuli and to minimise flow re-circulation in the inlet region. The pressure drop through the target assembly should match the pressure drop through the multiplier fuel assemblies.

The mass flow rate of sodium into the target is 40 kg/s. This gives an average sodium temperature rise of 70°C. The average sodium velocity in the riser and in the channels is 3.4 m/s and 2.2 m/s, respectively, below the maximum acceptable velocity of 5 m/s.

In the second proposal, the tungsten plates are placed vertically in the spallation zone. The thickness of the plates is 4 mm, and the height of the plates is 55 mm. The channels between plates have a width of 3 mm. The entire spallation zone is axially divided into six sub-zones. Each sub-zone contains a tungsten plate bundle with 28 plates. The six tungsten plate bundles are staggered, so that for each proton there is at least 165 mm of beam damping depth of tungsten. The gap between each sub-zone is about 5 mm. The total height of the spallation zone is 355 mm. The lower part of the guard tube has an inner diameter of 200 mm. The total flow area is about 0.018 m^2. This gives an average velocity of about 2.6 m/s, also below acceptable limits. The flow area in the beam region is about 0.012 cm^2. The temperature increase in the beam region might be about 30% higher than the average value.

4. Results and discussion

This study analyses the thermal-hydraulic behaviour of the target under both normal operating conditions and passive decay heat removal conditions. The effect of the following parameters has been studied:

- Thickness of the Tungsten plate.
- Thickness of the cladding.
- Thermal resistance of the gap between the cladding and the tungsten plate.
- Width of the flow channels.
- Porosity distribution of the perforated plates.

4.1 Horizontal configuration under normal operating conditions

Under normal operating conditions, the flow behaviour in the target and the cooling capability of both the spallation zone (tungsten plate and cladding) and the beam window are investigated.

4.1.1 Spallation zone

The spallation zone consists of an inlet riser, an outlet riser and 55 flow channels. Thermal-hydraulic behaviour in the spallation zone has been analysed using a one-dimensional approach. Figure 3 shows the coolant velocity in different channels for the reference parameters. The channel number is ordered from the top down to the bottom, i.e. channel 1 is the channel closer to the beam window. It is seen that the coolant velocity both in the upper part and in the lower part is higher than in the middle region. However, this velocity difference is small, less than 1%.

Figure 3. **Flow velocity in different channels**

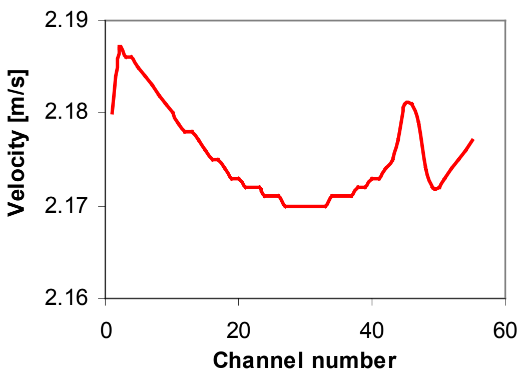


Figure 4. **Maximum temperature in different flow channel**

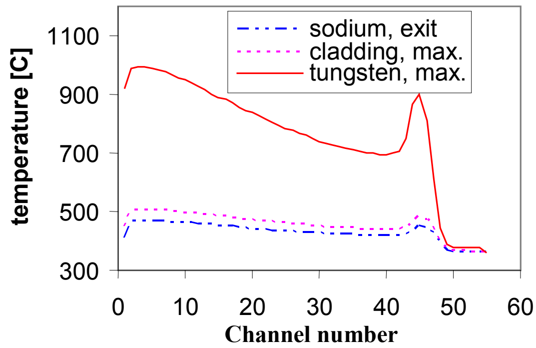


Figure 5. **Effect of the tungsten plate thickness on the maximum temperatures**

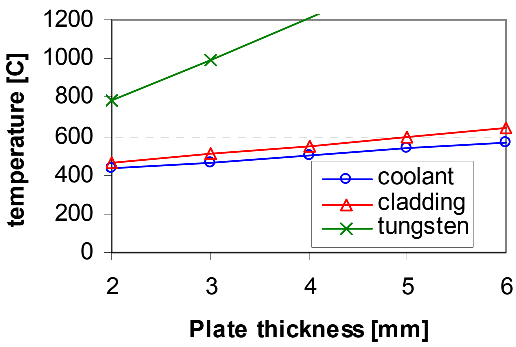


Figure 6. **Effect of the cladding thickness on the maximum temperatures**

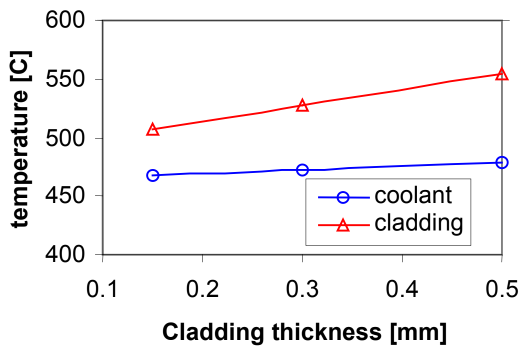


Figure 4 shows the maximum temperature of the coolant, the cladding and the tungsten plate in different flow channels. The results show that the maximum cladding temperature in the entire spallation zone is about 520°C, well below the design limit (600°C). A large temperature drop (about 500°C) across the gap between the cladding and the tungsten plate is obtained. In this analysis, the effective heat transfer coefficient of the gap was 5.0 kW/m^{2}K, corresponding to a helium gas layer with a thickness of about 20 µm.

Thickness of the tungsten plate

The upper limit of the thickness of the tungsten plate is determined by the maximum temperatures in the spallation zone. Figure 5 shows the maximum temperature of the coolant, the cladding and the tungsten plate versus the plate thickness. At a thickness of 5 mm, the cladding temperature exceeds the design upper limit (600°C). The selection of the lower limit of the plate thickness is mainly based on the consideration related to the target construction and to the total beam damping length. A smaller plate thickness leads to a larger number of plates, to provide sufficiently large beam damping length. At the same time, the flow channel width has to be reduced accordingly, to keep the total height of the spallation zone within the fuel pin length (36 cm). A plate thickness of 2 mm requires a channel width of about 1.5-2.0 mm. The construction of both the thin tungsten plate and the narrow flow channels would be a challenging task. Furthermore, the thermal expansion and deformation of the plates have to be taken into account, to avoid local flow reductions and excessive local temperature peaks. Based on the above considerations, a plate thickness of 3.0 mm and a channel width of 2.5 mm have been proposed for the horizontal configuration.

Thickness of the cladding

The thickness of the cladding affects mainly the cladding temperature. Figure 6 shows the maximum coolant temperature and the maximum cladding temperature versus the cladding thickness. The cladding material (HT-9) used in this study has a high thermal conductivity. Even with a cladding thickness of 0.5 mm, the cladding temperature is still below 600°C. If another material, e.g. SS316, is used as the cladding material, the thermal conductivity is reduced by about 35%. In this case, a cladding thickness of 0.5 mm would be the upper design limit.

The selection of the cladding thickness is also dependent on the tungsten plate thickness. For a larger plate thickness, the upper limit of the cladding thickness will be reduced. A combined design optimisation of all the geometric parameters is necessary for the final design of the target.

4.1.2 Beam window

For the analysis of the cooling capability of the beam window, only the upper part of the target is considered, i.e. the region above the uppermost tungsten plate, as indicated in Figure 7. Due to the non-symmetric arrangement, flow modelling must be three-dimensional in this region. However, for this preliminary analysis, this region is simplified to an axis-symmetric 2-dimensional domain, as shown in Figure 8. Coolant is assumed to enter the domain in the annular gap. Some geometric parameters are summarised as follows:

- Inner radius of the beam tube (R1): 100 mm
- Thickness of the beam window (D4): 2.5 mm
- Inner radius of the guard tube (R2): 165 mm
- Distance between the tungsten plate and the perforated plate (D1): 100 mm
- Distance between the perforated plate and the beam window (D2): 30 mm
- Thickness of the perforated plate (D3): 5.0 mm

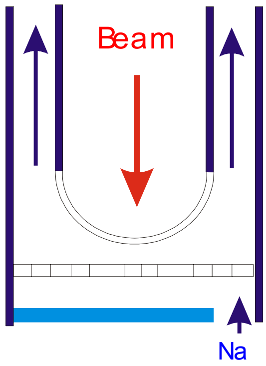
The diameter of the tungsten plate is identical to the diameter of the beam window, i.e. 200 mm. The perforated plate is divided into three zones, as shown in Figure 9. In the central region there is a single hole with a diameter of D5. In the middle range, $D5 \leq D \leq D6$, and in the outer region, $D6 \leq D$, two different porosity values are assumed, ε_1 and ε_2.

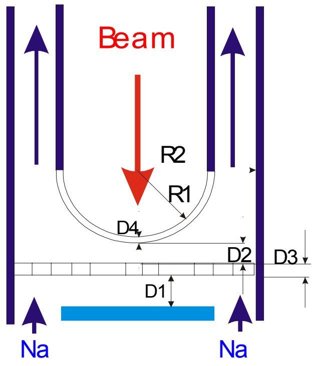
A thickness of 2.5 mm for the beam window is selected based on the previous experience gained in the design of both the ISTC target [4] and the MEGAPIE target. [5] As window material, HT9 is selected due to its high thermal conductivity and favourable corrosion resistance properties. Assuming that the sodium coolant temperature at the inlet of the target is 360°C and the heat released in the spallation zone is 3.7 MW, a temperature rise of 70°C is obtained through the spallation zone. The sodium temperature at the inlet of the computation domain is 430°C. The inlet velocity of sodium is 1.0 m/s. For this numeric analysis, the CFD code CFX-4.4, has been used.

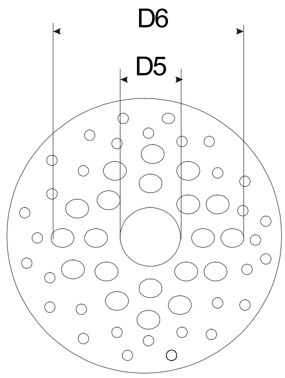
Figure 7. **3-D Flow domain close to the beam window**

Figure 8. **Simplified computational domain for the 2-D CFX calculation**

Figure 9. **Perforated plate**







Five different cases have been analysed, as summarised in Table 2. The effect of the distribution of perforated plate porosity is investigated with the first four cases, whereas in the fifth case, the gravitation acceleration (g) is set to be zero, to analyse its effect on the heat transfer behaviour. The diameter of the central hole (D5) is 60 mm. The outer diameter of the middle region (D6) is 200 mm.

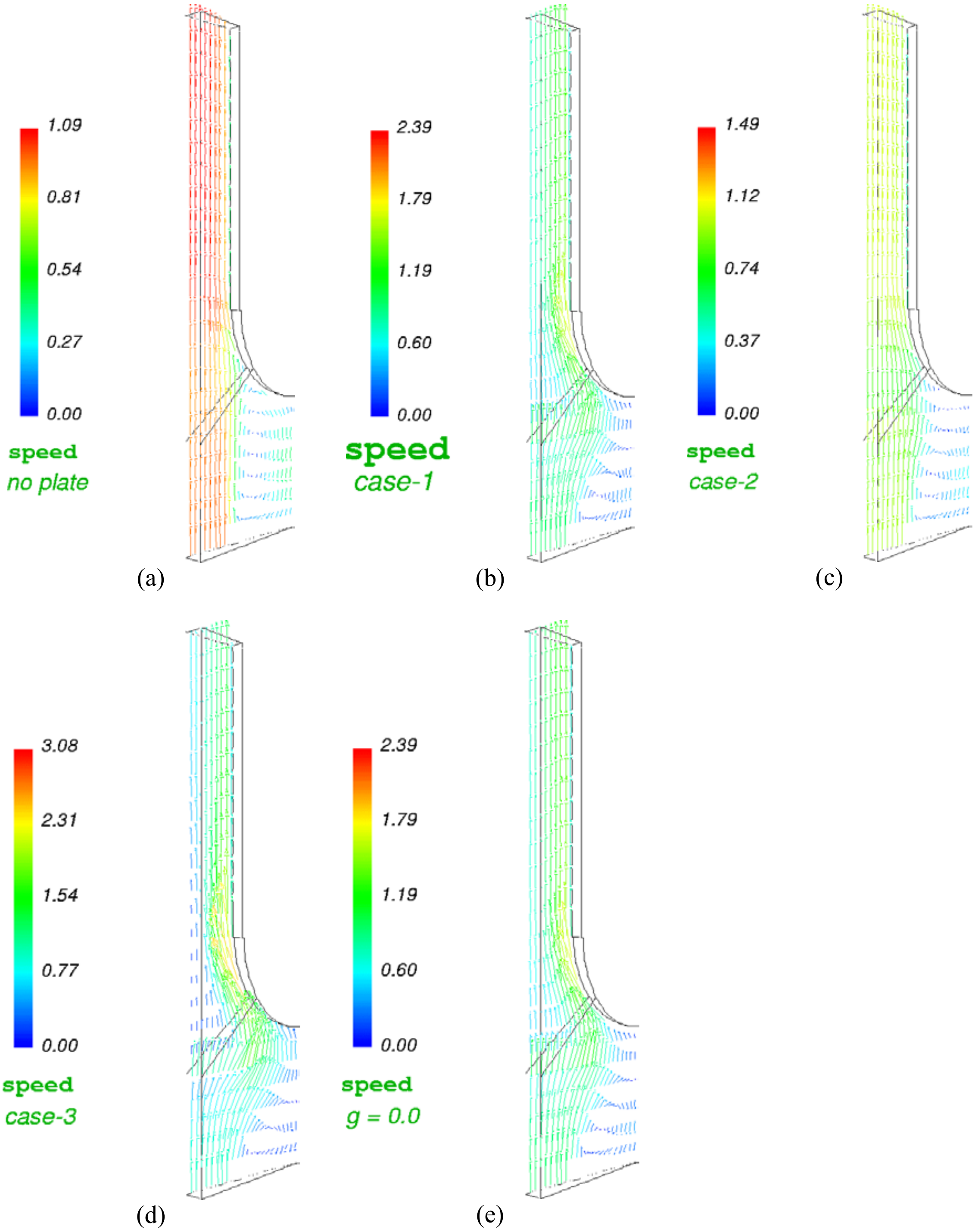
Table 2. **2-D CFD results**

	Input data			**Results**			
	ε_1	ε_2	g	V_{max} [m/s]	U_{rev} [m/s]	T_{max} [C]	ΔP [Pa]
Case 1	0.5	0.2	9.8	2.39	-0.37	549.87	1145
Case 2	0.5	0.5	9.8	1.49	-0.38	647.32	290
Case 3	0.5	0.1	9.8	3.08	-0.30	545.40	2286
Case 4	no perforated plate		9.8	1.09	-0.46	648.71	115
Case 5	0.5	0.2	0.0	2.39	-0.37	549.87	1145

Figure 10 shows the velocity fields in the five different cases. The main results are summarised in Table 2. For all cases a flow re-circulation zone occurs in the region below the perforated plate and close to the symmetry axis. In the case without a perforated plate, coolant entering the annular gap flows mostly straight ahead. In the cases with perforated plates, coolant is partially forced to flow towards the central region. The smaller the porosity ε_2, the stronger the coolant flow towards the window centre, and the higher the maximum sodium velocity in the computational domain. However, both the size of the flow re-circulation zone and the maximum reversal flow velocity are reduced with the reduction of porosity in the outer region.

In the case without a perforated plate, there is a large hot zone close to the window centre. The maximum window temperature is about 650°C. A significant reduction in this hot zone is achieved for the cases with a porosity of the outer region smaller than 20%. The maximum temperature of the window is reduced to about 545°C. It is seen in Table 2 that the gravity acceleration has no effect on either the velocity field and the temperature field.

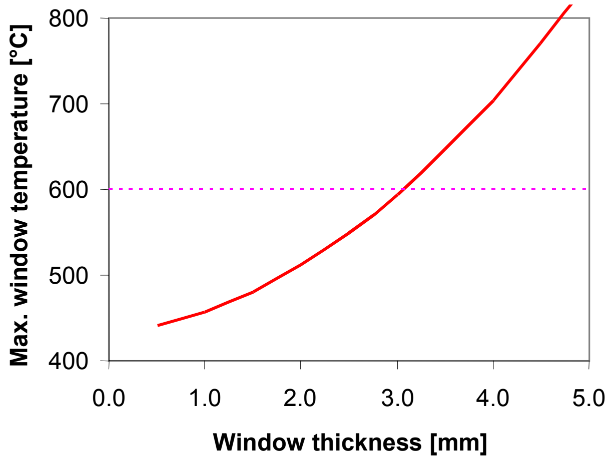
Figure 10. **Velocity field in five different cases**



Window thickness

The thickness of the beam window is one of the key parameters affecting the maximum window temperature. By neglecting the heat conduction in the circumference direction, the estimated maximum window temperature is shown in Figure 11 for the case 1 versus the beam window thickness.

Figure 11. **Effect of the window thickness on the maximum window temperature**



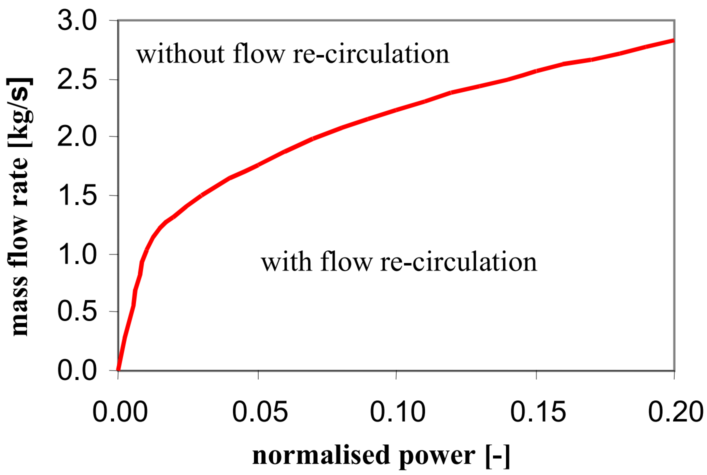
It is seen that the window temperature reaches the design criteria (600°C) at a window thickness of about 3.0 mm. Thus, the proposed reference design assumes a window thickness of 2.5 mm. According to the experience gained during the design of the ISTC target and the MEGAPIE target, a window thickness of about 2.5 mm should be sufficient to withstand thermal and mechanical stress load. Nevertheless, structural analysis will be needed to assess the safety margin.

4.2 Horizontal configuration under passive decay heat removal conditions

4.2.1 Spallation zone

One of the important design criteria of the solid target is the feasibility of passive decay heat removal, i.e. the decay heat has to be safely removed by natural convection of sodium. Under natural convection conditions, the coolant velocity in the upper part of the target will be lower than that in the lower part of the target. Under some conditions, flow reversal in the upper part may occur. For the reference proposal, the boundary line (critical line) for the onset of flow re-circulation has been derived, as illustrated in Figure 12. In this figure, the heat generation rate is normalised to the nominal value (3.7 MW). The design of the spallation target has to provide sodium flow rate above the critical line under natural convection conditions.

Figure 12. **Critical line for the onset of flow re-circulation**



The mass flow rate through the target under passive decay heat removal conditions depends on the design of the reactor core, the primary loop and the target itself. For the present analysis, the following data are taken (pressure drops are similar to that of EBR-II [2]):

- Thermal power of SCM: 100 MW
- Thermal power of the target: 3.7 MW
- Pressure drop over the reactor core: 0.27 MPa
- Pressure drop over the primary loop (no core): 0.07 MPa
- Mass flow through the target: 40 kg/s
- Mass flow through the active core: 720 kg/s
- Mass flow through the entire primary loop: 810 kg/s
- Elevation difference between the active core and the upper plenum: 1.0 m
- Elevation difference between the active core and the heat exchanger: 3.7 m

The decay heat fraction in the spallation zone (tungsten plate), which is defined as the ratio of the decay heat to the nominal power, should be lower (to approximately 25%) than in the reactor core. [3] Due to the lack of reliable data, two different values of the decay heat fraction are studied for the target, i.e. 100% and 25% of the decay heat fraction in the reactor core.

Figure 13 shows the mass flow rate through the target versus the decay heat fraction. For comparison, the critical mass flow rate is also indicated in this figure. For a decay heat fraction of 25% of that in the core, the mass flow rate is well above the critical value. A nearly uniform distribution of the velocity is obtained (see Figure 14). In this case, a sufficient cooling capability of the spallation zone is provided. For a 100% decay heat ratio, the mass flow rate through the target is close to, but smaller than, the critical value. Flow re-circulation in the upper part of the spallation target takes place (Figure 14). Coolant and cladding temperature will exceed acceptable values.

Figure 13. **Mass flow rate into the target under natural convection conditions** (Fq : decay heat ratio)

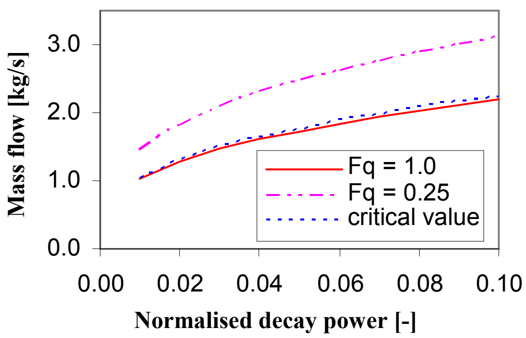
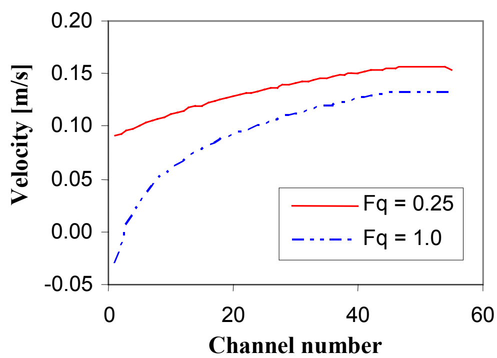


Figure 14. **Velocity in different flow channels under natural convection conditions** (core decay heat fraction = 5%)



A possibility to achieve a more uniform distribution of the coolant flow in the spallation zone, is the introduction of additional hydraulic resistance at the inlet of each flow channel. Figure 15 shows the velocity distribution in the flow channels for a flow restriction with a hydraulic resistance of 10 inserted into each flow channel. In this case the assumed ratio of the decay heat fraction is 100%. Compared to the case without an additional hydraulic resistance (Figure 14), the velocity distribution is much more uniform. A sufficient cooling capability for the spallaton zone is obtained (Figure 16).

Figure 15. **Velocity in each flow channel with additional hydraulic resistance** (core decay heat fraction = 5%)

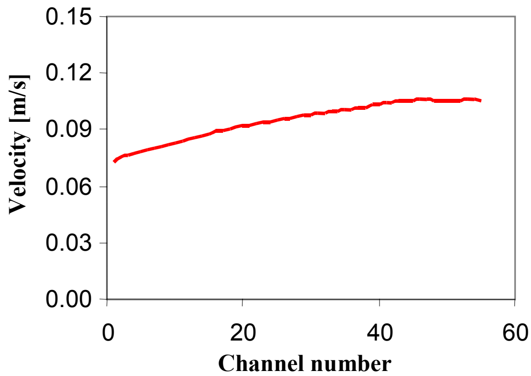
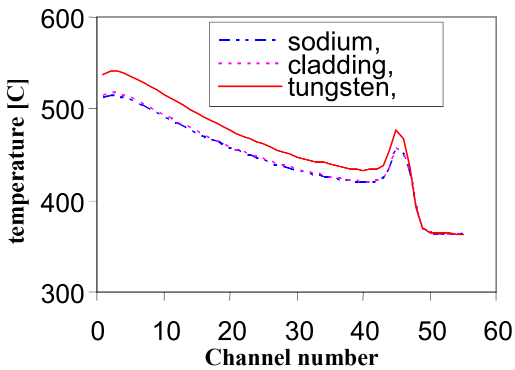


Figure 16. **Temperatures in each flow channel with additional hydraulic resistance** (core decay heat fraction = 5%)



4.2.1 Beam window

The total mass flow rate into the spallation target under natural convection conditions (see Figure 13) is supplied to cool down the beam window. This mass flow rate is sufficient to safely remove the decay heat from the beam window.

4.3 Vertical configuration

For the time being, no detailed analysis has been carried out for the vertical configuration. The main challenge of this design is to provide sufficient large beam damping depth (at least 16 cm), and at the same time to keep the total height of the spallation zone below 36 cm. To cope with this boundary condition, the gap between the plate bundles is small, i.e. 5 mm in the reference proposal. This would cause a high pressure drop over the spallation zone. It is worth mentioning that this restriction will disappear if the target is used in a sub-critical reactor with fuel pin with a larger fuelled region.

A similar cooling capability for both the spallation zone and the beam window is expected in the vertical configuration as in the horizontal configuration. A perforated plate located close to the beam window is recommended, to enhance the coolant mixing and to achieve a more uniform temperature distribution of the coolant before it cools down the beam window. Detailed analysis of the cooling behaviour and the design optimisation of the perforated plate should be carried out in the next phase.

In the vertical configuration, passive decay heat removal is not a serious concern. No local flow re-circulation is expected under passive decay heat removal conditions. The mass flow rate established under natural convection conditions will be sufficient to cool down both the spallation zone as well as the beam window.

5. Summary

In this study, two different configurations have been proposed for a sodium cooled tungsten target for the accelerator-driven test facility (ADTF). Detailed thermal-hydraulic design analysis has been carried out for the horizontal configuration. The effect of important design parameters has been investigated.

Under normal operating conditions, a sufficient cooling capability has been achieved for both the cladding and the tungsten plate, if the cladding thickness is less than 0.5 mm. The cooling capability of the spallation zone under passive decay heat removal conditions is one of the key limitations of this design. A significant improvement can be achieved by inserting additional hydraulic resistance into the flow channels. The CFD calculations performed so far indicates a sufficient cooling capability of the beam window if the perforated plate for flow distribution is properly designed.

Detailed 3-D CFD analysis is required in the future to optimise the geometrical arrangement of the upper part of the target, including the perforated plate. The feasibility of the proposed target designs needs to be assessed related to neutron-physics, thermal-mechanics and material consideration.

A similar cooling capability of both the spallation zone and the beam window is expected in the vertical configuration as in the horizontal configuration. A safe decay heat removal under natural convection conditions is easily realised in the vertical configuration.

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