# EXPERIMENTAL STUDIES SUPPORTING THE DESIGN OF A 1 MW LBE TARGET

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## Abstract

A 1 MW LBE-target has been designed and constructed in the framework of the ISTC-559 project. Experimental studies have been performed at the Forschungszentrum Karlsruhe to support the target design. Tests were carried out at the HYTAS test facility with water as the working fluid. The main objectives of this study are to investigate the flow behaviour in the target, especially around the beam window, to make contribution to the design optimisation of the target systems, and to validate numerical analysis. Flow patterns around the beam window were visualised by the laser light sheet technique, and velocity distribution was measured by a 2-D Laser-Doppler Anemometry. This paper summarises the main test results obtained to date, which give a better understanding of the flow behaviour in the target geometry and an important database for code validation.

## 1. Introduction

Heavy liquid metals such as lead or lead-bismuth eutectic (LBE), are preferred to be used as spallation material, due to the high production rate of neutrons and the efficient heat removal properties. However, the experience in heavy liquid metal thermal hydraulics is somehow limited. Extensive research activities are needed towards a more comprehensive knowledge of the basic thermal-hydraulic phenomena involved in the complex geometry of a LBE-target. This is especially true in the case of Computational Fluid Dynamics (CFD) codes which are a unique tool for the design of such spallation targets with a high power density. [1]

In the framework of the ISTC-559 project, [2] a 1 MW LBE spallation target was designed and constructed. The Forschungszentrum Karlsruhe performed comprehensive thermal-hydraulics studies, to support the target design. The activities at the Forschungszentrum Karlsruhe consist of two parts, i.e. numerical design optimisation and experimental verification. Numerical analysis was carried out with commercial CFD codes, to provide basic information about the thermal-hydraulic behaviour in the target and to achieve an optimum configuration of the target.

Due to the deficiency in the modeling of turbulent flow in the complex geometrical configuration, experimental studies are inevitable, to provide a database for verification of the numerical studies. Therefore, at the Forschungszentrum Karlsruhe experimental studies were performed at the HYTAS (HYdraulics of TArget Systems) test facility, which uses water as the working fluid. Such a model experiment enables a systematical study into the physical phenomena involved and a much more sophisticated measurement than in the case with the original fluid (LBE). These experiments provide not only information for design optimisation, but also an important database for validating CFD codes. The test data are well suited for assessing the performance of turbulence models in the generic geometry of an ADS target.

Numerical studies related to the thermal-hydraulic behaviour of various target designs, including the ISTC target, have been reported in the previous publications. [3,4] This paper gives a summary on the experimental study on the hydraulic behaviour in the ISTC target.

## 2. Experimental facility

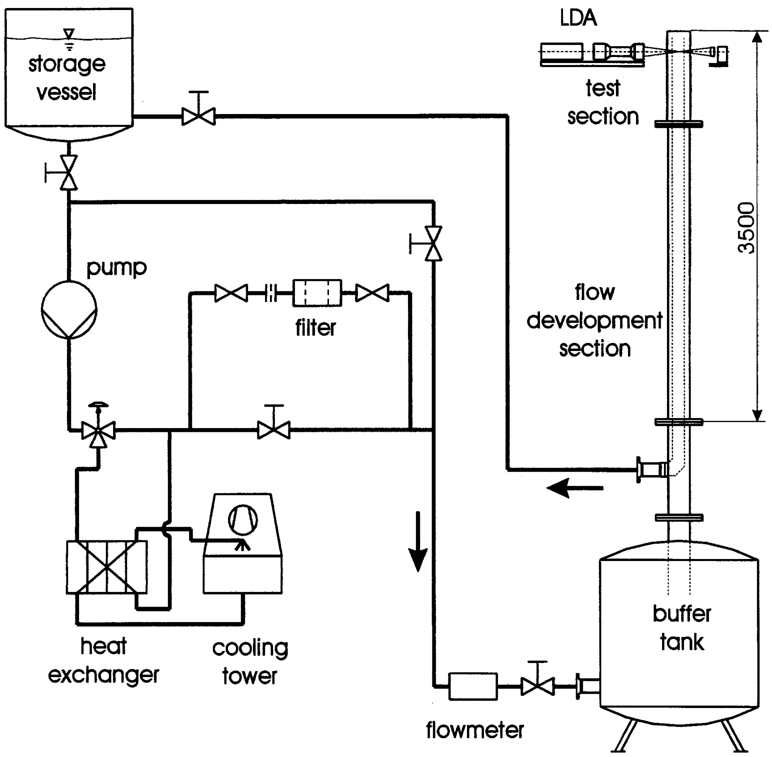
Figure 1 shows schematically the HYTAS test facility. The loop is operated under an atmospheric pressure without heating, and is capable of circulating a maximum volumetric flow rate of 100 $m^3/h$. It consists mainly of a water storage vessel, a pump, a heat exchanger, a purification device, a buffer tank and the test section. The flow rate was measured by a flow-meter located upstream the buffer tank. The heat generated by the pump is removed via the heat exchanger, so that the water temperature in the test section is kept constant

Figure 2 shows the geometric configuration of the test section. The outer square channel has a dimension of 200 mm×200 mm. The inner channel has a square outer surface with a dimension of 150 mm×150 mm and a circular inner surface with a diameter of 130 mm. The channel wall is made of optical glass and suitable for a high accuracy LDA measurement. The total height of the test section is 860 mm. The connection between the loop and the test section is designed in such a way, that the flow in the test section can be bi-directional, i.e. either flowing upwards through the peripheral channel and downwards through the central channel, or upwards through the central channel and downwards through the peripheral channel. Figure 3 is a photographic view of the test section mounted at the HYTAS test facility.

For both the upward and the downward cases, flow stagnation and flow re-circulation zone are expected in the vicinity of the window centre. To eliminate flow stagnation and to reduce the flow re-circulation zone, a perforated plate with distributed holes is installed close to the window. Figure 4 shows the perforated plate used in this experimental study. The plate is located 14 mm below the window surface centre. The thickness of the plate is 5 mm. Tests were carried out for both cases, i.e. with and without the perforated plate, to study the effect of the plate on flow pattern.

The volume flow rate was varied from 5 m³/h to 20 m³/h. This corresponds to a Reynolds number in the central flow channel from 6 500 to 27 000. Two velocity components, i.e. axial velocity and azimuth velocity, were measured with a 2-D Laser-Doppler Anemometry (LDA).

Figure 1. **Scheme of the test loop HYTAS**




## 3. Results

In this section, two terms, i.e. upward flow and downward flow, are introduced to identify the main flow direction in the central flow channel. The origin of the co-ordinate system used to present the test results is located at the centre of the window surface. The positive y-axis is directed upwards. The axial velocity is defined as positive, if it is in the same direction as the main flow in the central flow channel, e.g. in the case of downward flow, the axial velocity is positive, if it is directed downwards. The x-axis presents the radial distance from the window centre. Velocity measurement was carried out on the x-y plane with the azimuth angle $\theta = 0$ (see Figure 2).

Figure 2. **Scheme of the test section**

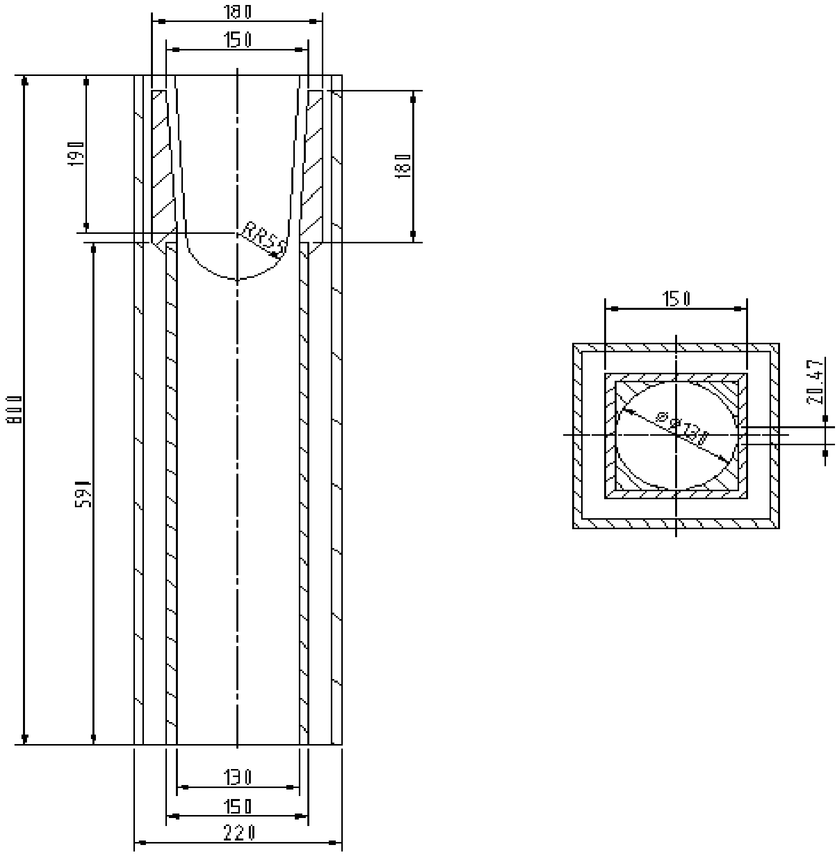



Figure 3. **Photography of the test section**

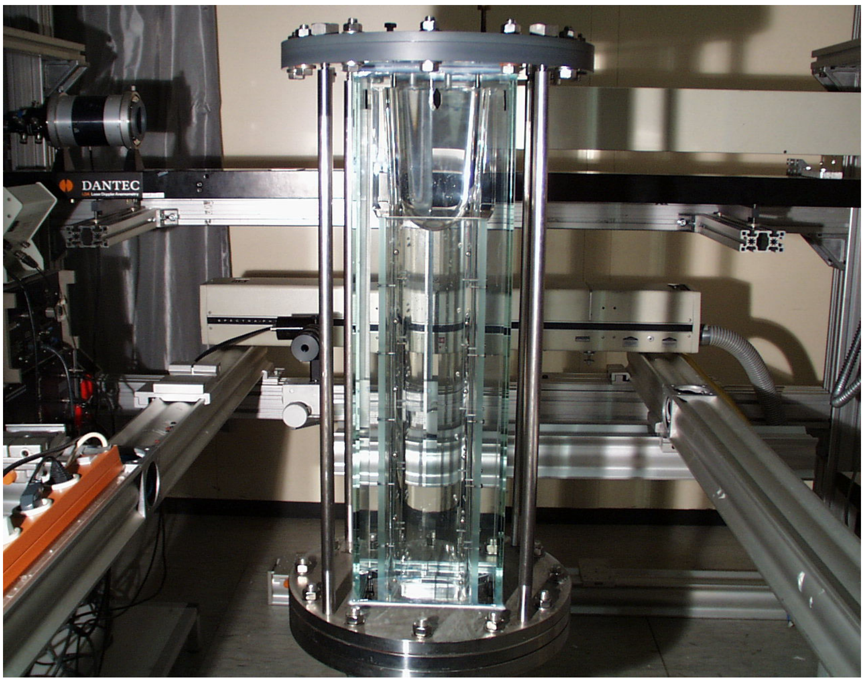
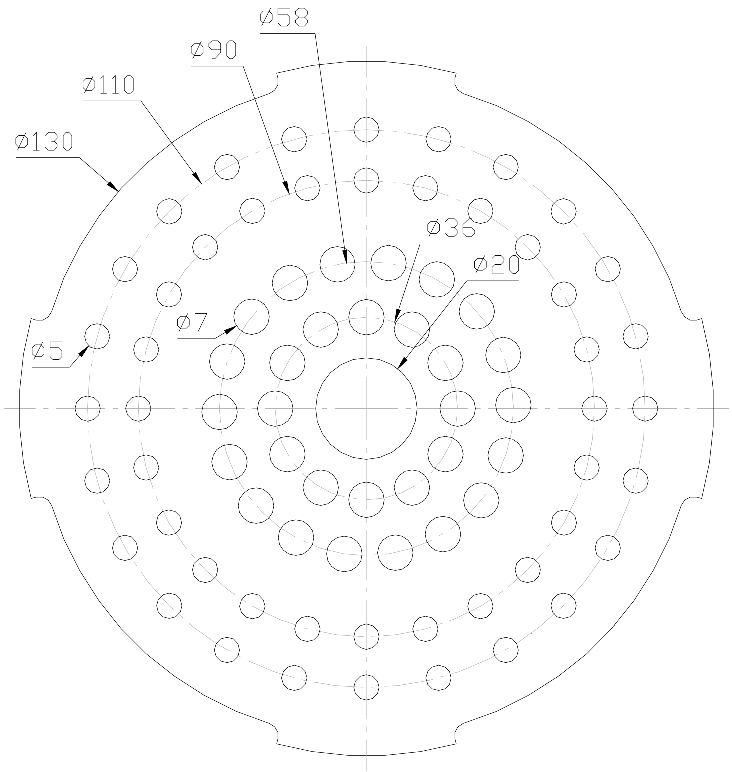


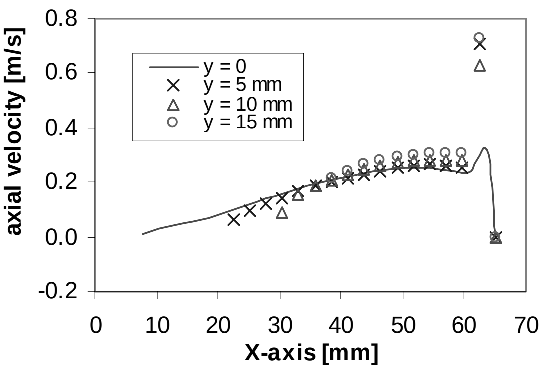
Figure 4. **Scheme of the perforated plate**



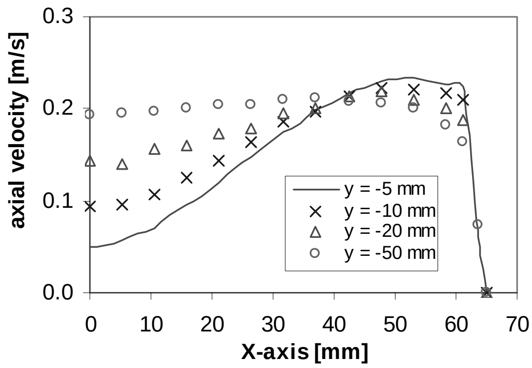

### *Upward flow without perforated plate*

Figure 5 shows the profile of the axial velocity at different elevations in the case of upward flow without perforated plate. The volume flow rate is 10 m³/h. The velocity drops to zero by approaching both solid walls. At the elevation with positive y values, a high velocity peak is observed about 5 mm apart from the central flow channel wall. In the region below the window centre (negative y values) the velocity profile changes from N-shape far way from the window to M-shape by approaching the window. In the channel centre, the axial velocity decreases by approaching the window, while it increases in the region close to the channel wall.

Figure 5. **Axial velocity profile for upward flow without perforated plate**




(A)




(B)

***Downward flow without perforated plate***

Figure 6 shows the profiles of the axial velocity for the case of downward flow without perforated plate. The mass flow rate is 10 $m^3$/h. A downward velocity peak is observed about 5 mm to 10 mm from the flow channel wall. Negative axial velocity appears in the central region at an axial distance from the window centre less than 90 mm. This indicates the presence of a flow re-circulation zone. The maximum upward flow velocity in the inner flow channel is about 0.2 m/s and located on the central line (x=0) and at a distance of about 30 mm from the window centre. Furthermore, it is found that the flow re-circulation zone becomes larger in the axial direction, when the volume flow rate is reduced. The size of the flow re-circulation zone in the radial direction is hardly affected by the volume flow rate.

Figure 6. **Axial velocity profile for downward flow without perforated plate**

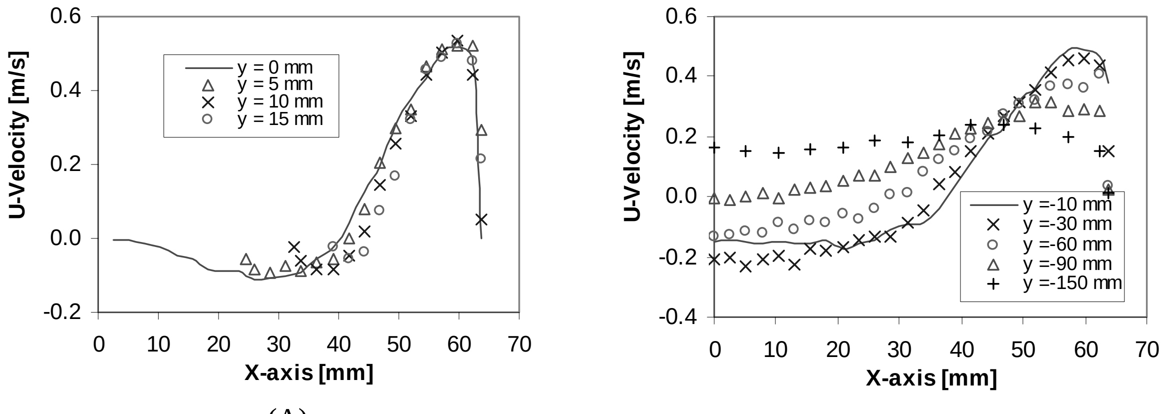



Figure 7 shows the RMS value of both velocity components along two different lines, i.e. y=5 mm and y=-5 mm. It is seen that over a large range, the RMS value is well constant. Both velocity components show a similar strength of fluctuation. Close to the channel wall and on the central symmetric line, large velocity fluctuation is obtained. This is caused by the larger velocity gradient close to the channel wall as well as on the symmetric line. Figure 8 compares the velocity profiles at y=0 for three different volume flow rates. The profiles are very similar to each other. The velocity amplitude is approximately proportional to the volume flow rate.

***Upward flow with perforated plate***

Figure 9 shows the profile of the axial velocity at different elevations in the case of upward flow with the perforated plate. The volume flow rate is 10 $m^3$/h. At an elevation far away from the perforated plate (large negative y-values), the velocity profile is similar to that of a developed turbulent flow in a pipe. The velocity profile changes by approaching the perforated plate. The velocity in the channel centre increases, while it decreases in the outer region. Very close to the perforated plate, a wavy profile is formed with several velocity peaks due to the holes on the perforated plate. Downstream and close to the perforated plate (y=-10.5), a strong wavy profile of the axial velocity is obtained. The maximum velocity in the centre is about 1.2 m/s, four times larger than the average value. Between the holes negative axial velocity appears. This indicates the presence of flow re-circulation between the holes. The results show a well symmetric distribution of the axial velocity and confirm the high accuracy of the applied LDA measurement technique. The strength of the velocity wave declines with the distance from the perforated plate and disappears at elevation y ≥10 mm.

Figure 7. **Velocity fluctuation of downward flow without perforated plate U': fluctuation of axial velocity V': fluctuation of azimuth velocity**

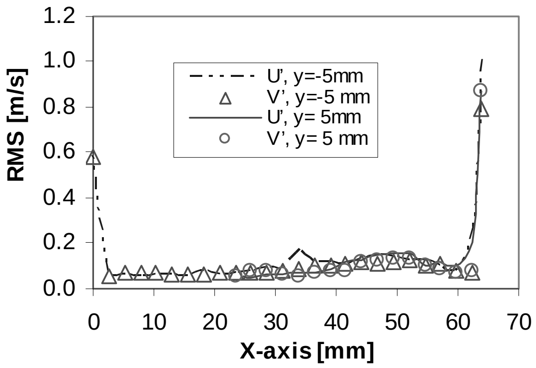



Figure 8. **Effect of volume flow rate on the axial velocity profile V: volume flow rate**

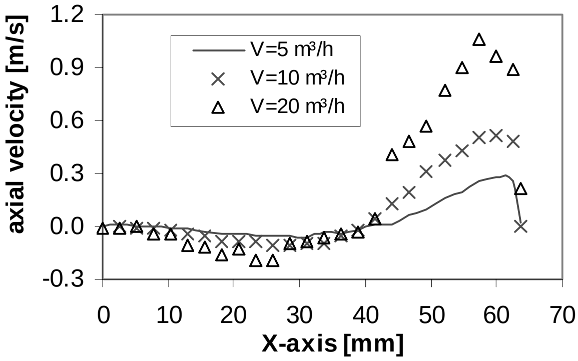



Figure 9. **Axial velocity profile of upward flow with perforated plate**

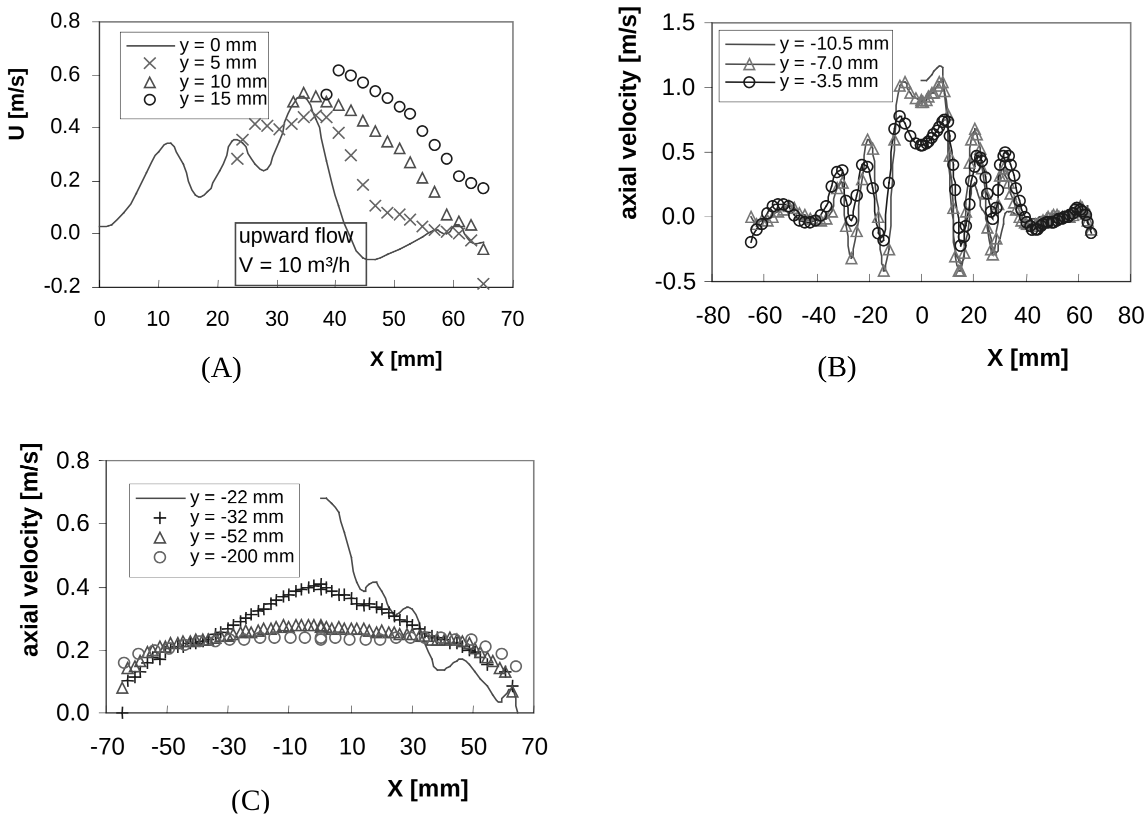
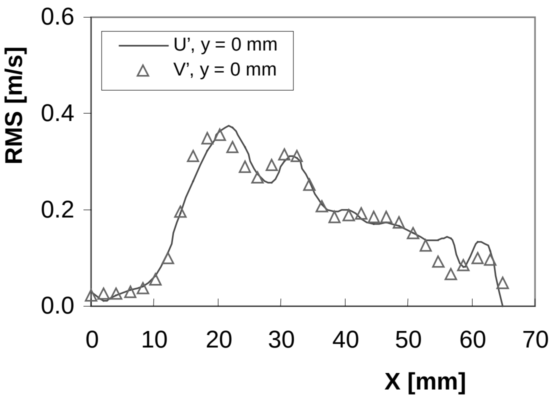
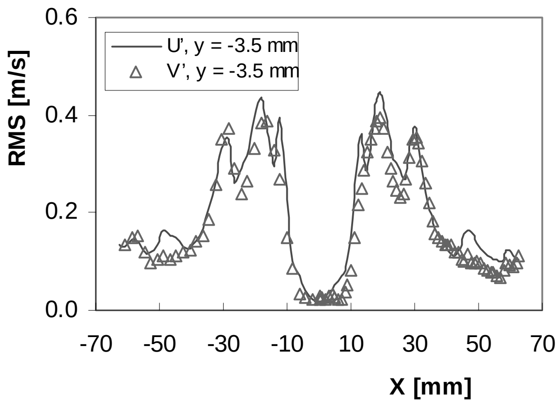



Figure 10 shows the RMS value of both velocity components at two different elevations close to the window, i.e. y=0 mm and y=-3.5 mm. Very similar profiles of the fluctuation of both velocity components are obtained. This indicates a well isotropic behaviour of the velocity fluctuation. In the vicinity of the window surface, the velocity fluctuation is low. A high velocity fluctuation is obtained in the range 15 mm $<\times<$35 mm. The location of the peaks of velocity fluctuation corresponds to the location of sharp variation in the velocity.

Figure 10. **Velocity fluctuation of upward flow with perforated plate**
**U': fluctuation of axial velocity**
**V': fluctuation of azimuth velocity**




(A)

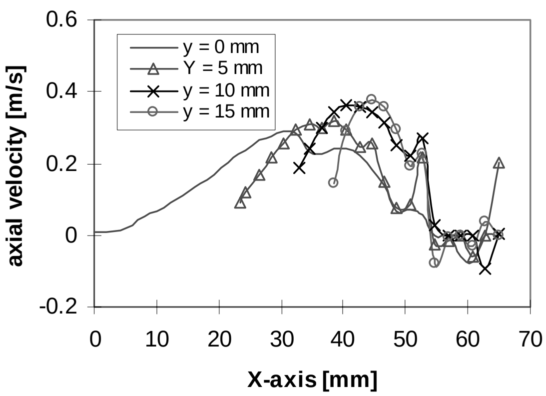



(B)

***Downward flow with perforated plate***

Figure 11 shows the profile of the axial velocity in the case of downward flow with the perforated plate. The volume flow rate is 10 m³/h. The flow upstream the perforated late is strongly affected by the presence of the perforated plate. Flow becomes wavy, and flow re-circulation occurs in the gap between the window surface and the inner flow channel wall. Obviously, the perforated plate forces the fluid flowing towards to the window region. This causes a slightly upward flow in the region close to the channel wall. Close to the perforated plate, velocity in the centre region increase. At the elevation closest to the perforated plate (y=-10.5 mm), the axial velocity in the centre is as high as 0.8 m/s. At the closest elevation downstream the perforated plate (y=22 mm), the axial velocity in the centre increases to about 1.6 m/s. The velocity profile changes rapidly with the distance from the perforated plate. At a distance of 40 mm downstream the perforated plate, the wavy velocity profile diminishes. However, the flow profile deviate still far from a developed turbulent flow, even at the elevation y=200 mm, where the velocity in the centre is still significantly higher than the average value.

Figure 11. **Velocity profile of downward flow with perforated plate**



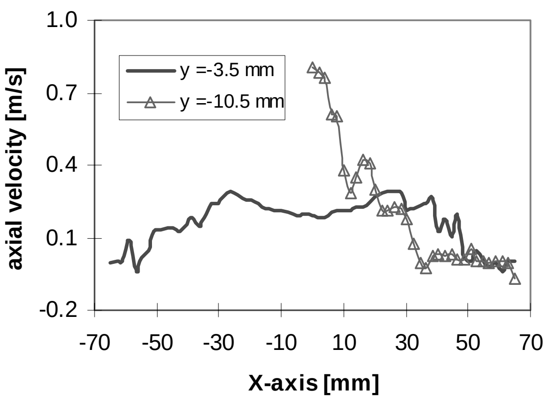
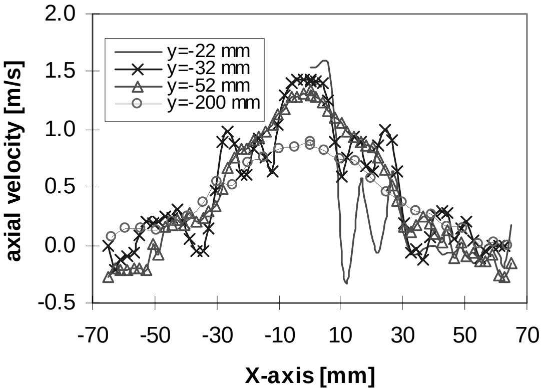



Figure 11. **Velocity profile of downward flow with perforated plate** (contd.)

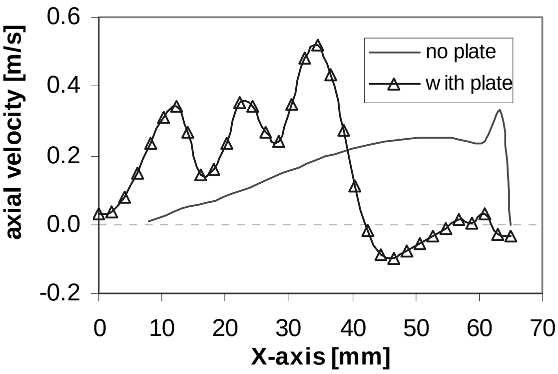



(C)

***Effect of perforated plate***

Figure 12 compares the axial velocity profile of upward flow with the perforated plate with that without perforated plate. It is seen that the introduction of the perforated plate leads to a strong increase in the axial velocity near the window. The stagnation zone close to the window is reduced significantly. However, flow re-circulation occurs in the outer region, i.e. $x \geq 40$ *mm*. Therefore, an optimisation of the distribution of the holes on the perforated plate is required to reduce or to eliminate flow re-circulation.

Figure 12. **Effect of the perforated plate on the velocity profile at y=0 mm**




**Summary**

Experimental studies on the hydraulic behaviour in a 1 MW LBE target have been performed at the Forschungszentrum Karlsruhe to support the target design. Water was used as working fluid to enable the visualisation of flow pattern and an accurate measurement of local flow velocity. The effect of flow direction, flow rate and perforated plate on the flow behaviour was investigated. Based on the main results presented in this paper, the following conclusions can be drawn:

- An experimental database is provided to a better understanding of the hydraulic behaviour in complex target geometries. This database is well suitable for validating CFD codes.

- In the case without perforated plate, flow velocity is low near the window surface centre. A large flow re-circulation zone occurs in the region close to the beam window in the case of downward flow. Therefore, a target design with downward flow without perforated plate should not be taken into consideration in the future.
- The introduction of a perforated plate enhances the flow velocity near the window significantly. Design optimisation of the distribution of holes on the plate is required to minimise flow re-circulation in the vicinity of the plate.
- A well isotropic behaviour of velocity fluctuation is obtained. This encourages the application of the k-ε turbulence model to the complex target geometry.

## REFERENCES


[1] Benchmark Working Group, edited by S. Buono.

[2] Proceedings of the First Meeting of the Benchmark Working Group on Heavy Liquid Metal Thermal-hydraulics, June, 1999, CERN, Geneva.

[3] E. Yefimov.

[4] The main results of feasibility study of liquid metal targets and the working plan on the project #559.

[5] Kick-off meeting on the ISTC project #559, February 1998, Obninsk, Russia.

[6] X. Cheng, I. Slessarev.

[7] Thermal-hydraulic Investigations on Liquid Metal Target Systems.

[8] Nuclear Engineering & Design 202 (2000), pp.297-310.

[9] X. Cheng, C. Pettan, J.U. Knebel, T. Schulenberg, G. Heusener.

[10] Experimental and Numerical Studies on Thermal-hydraulics of Spallation Targets.

[11] Proceedings of International Conference on Accelerator Application 2000, Washington DC, November 2000.