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THERMO-HYDRAULICS, COLOUR AND ART

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ABSTRACT
This paper describes a thermo-hydraulics experiment performed on the mock-up of the liquid-metal cooled steel target container of a spallation neutron source. The beam of the Paul Scherrer Institute 600 MeV proton accelerator is used to obtain a high-neutron flux. This bombards a target under realistic experimental conditions, hence, becoming a probe for scientific experiments. The goal was to analyse and visualise the cooling of the target proton entrance window. In the mock-up, heat removal is realised by forced convection of a mercury coolant. A description of the test set-up is given and qualitative as well as quantitative results from the cooling process are presented visually. In addition, an improvement in interpretation of data is shown by using colours. In the final section, an artistic output entitled 'The Collection' is presented; this consists of artificially-coloured infrared thermograms resembling, and compared with, butterflies.
Keywords: thermo-hydraulics of liquid metals, IR Thermography measurements, visualization of internal flow within convection boundary layer, heat transfer visualization, art in science

1 INTRODUCTION

As part of the development programme of the Swiss Intense Neutron Source (SINQ) at the Paul Scherrer Institute (PSI) and the European Spallation Source (ESS), neutron spallation sources experimental concepts with liquid-metal (LM) targets have been proposed [1].

One concept using a high-power neutron spallation source with a circulated LM target is shown in Fig. 1. The 600 MeV proton beam of the PSI accelerator penetrates into the target of the SINQ facility through a beam entry window. This window is strongly heated by the proton beam, the heat deposition in the steel wall resulting in a heat flux q^* of up to 140 W/cm^2 at the inner surface of the window. The LM, in this case, mercury, is simultaneously used as target material and coolant. It is contained in an approximately 4-m long structure made of concentric pipes and vessels. The neutron-producing part of the target consists of two concentric steel pipes filled with mercury and placed in the centre of the SINQ moderator tank. The lower part of the outer pipe is closed off with a hemispherical shell, i.e. LM container (LMC), causing the LM flowing down the annulus to perform a U-turn and to return upwards through the inner riser pipe (RP) to the electro-magnetic pump and the target heat exchanger.

The experiments on the cooling of the proton beam entry window are part of the development programme for neutron spallation sources with LM targets at PSI. A two-dimensional and dynamic (2DD) method of using infrared thermography (IRT) techniques is applied for visualising the cooling efficiency of the heated window wall. This 2DD IRT methodology developed at PSI was around 2000 [2], and constantly improved upon subsequently [3, 4]. It allows the elaboration of heat transfer coefficient (HTC) charts. The 2DD IRT methodology is based on the emissivity-corrected measurement of the thermal radiation field emitted from the outer surface and arithmetical constructions of the temperature fields on outer and inner surfaces of the LMC window. Finally, the field of the differential temperature, i.e. the difference between the inner-surface temperature and the bulk LM coolant temperature, is worked out. In this way, the differential temperature thermograms obtained, together with known values of the applied heat flux, allow both qualitative and quantitative HTC characteristics of the cooling to be determined. The patterns of the flow in the boundary layer on the inner surface of the window wall are made visible. Finally, animated IR differential thermogram sequences can be generated, allowing

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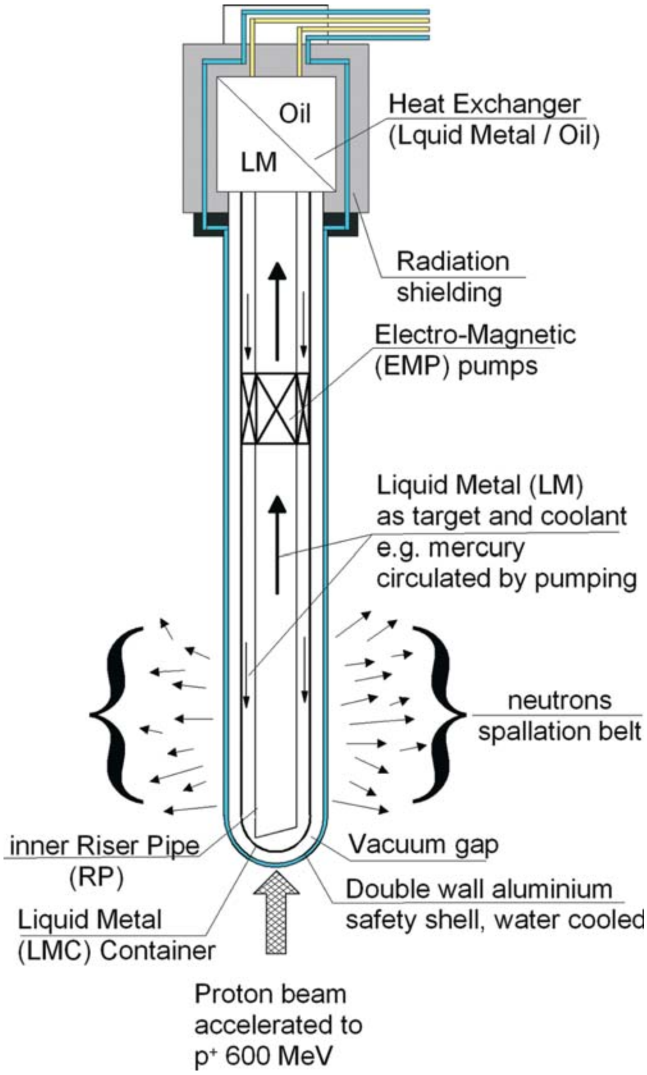

Figure 1: Schematic representation of a liquid-metal based concept for a spallation neutron source target in vertical configuration at the PSI SINQ facility.

observation to be made of the spatial and temporal behaviour of the flow and cooling behind the steel wall (http://asq.web.psi.ch/ASQ/projects/liquid/liquid.html).

During these experimental activities in the field of thermo-hydraulics using LM coolants, many different patterns of flow have been observed by using IRT techniques. Basically, the grey-scale thermograms need data processing leading to quantitative colourisation, in order to display or enhance what would otherwise be ‘hidden’ phenomena. An example of the influence of a colourisation on a readability of data is given in [5]. The results in many cases have shown surprising and inspiring visual records. The temptation is strong to add more colours than necessary or to make combinations of scientific thermograms to create an artistic collage. In this Special Issue, results of thermo-hydraulics experiments are presented which, whilst fulfilling their scientific objective, also lay claim to artistic character. 'The Collection' which resulted has been rewarded at the IR Image Gallery of THERMOSENSE XXII and is now shown for the first time in a printed publication as an additional 'artistic' aspect of this experiment. The hope is that more experimentalists may be inspired with similar ideas to make scientific investigations appealing to the general public by visualising them in an artistic form.

2 EXPERIMENTS

2.1 Goals

Because of the importance of target integrity, cooling of the proton beam entry window should be experimentally investigated in great detail. In reality, the Gaussian-distributed density of power deposition by the SINQ proton beam in the target window will result in a peak heat flux of 140 W/cm^2 in the centre of the inside window surface and an average value, taken over the proton beam 'foot print' area, of about 70 W/cm^2. Therefore, the goal of this test was to show that the proposed cooling concept of the target is able to avoid local overheating of the window and to guarantee the integrity of the target. The basic idea of the test was to observe the cooling effect of the flowing heavy LM on the heated hemispherical shell of the target mock-up. An important condition of the test was to use the same materials as foreseen for the concept of the real target (steel DIN 1.4057) with mercury as the spallation material and coolant.

2.2 Set-up and instrumentation

Figure 2 shows the set-up of the skin effect heating (SEH) experiments with the IR scanner (IR thermography camera) in a central axial position. The instrumentation of the test made it possible to observe the cooling effects with high spatial and temporal resolution. The 2DD IRT methodology was developed and applied for the first time in this test [2]. Two different geometrical flow configurations with flat-cut und slanted-cut ending of the RP, respectively, and different pump flow rates were examined with the goal of finding out whether window cooling was adequate and if a slanted edge of the RP had a positive influence on heat removal. The geometry adopted was that of the existing vertical target of the SINQ facility (window diameter 212.8 mm). The window wall thickness of 2.88 mm was chosen to achieve an optimum for the high-frequency electrical heating in the wall, without depositing heat in the fluid. A suitable volume heating mechanism for the window, the so-called SEH, was chosen in order to optimise the conditions for IR thermography measurements. More details are given in the technical descriptions [2]. Forced mercury flow is established by electromagnetic pumping at different flow rates (from 0.6 l/s, 1.2 l/s, 2.4 l/s up to 3.6 l/s). At low flow rates, convection may be additionally influenced by the weak buoyancy effects caused by the SEH. The latter produces a power deposition resulting in a heat flux of 2-11 W/cm^2 in the central region of the inside window surface. This value is much smaller than the average heat flux of 70 W/cm^2 produced in the real SINQ target by the proton beam, but it is high enough to study the characteristics of the heat transfer process from the window to the LM.

The experiments were carried out at the Institute of Physics of the University of Latvia (IPUL) in Riga-Salaspils, using a test loop with a capacity of about 6 tons of mercury. The temperature measurements on the window surface were made both with the 2D non-contact IR thermography device FLIR-AGEMA Thermovision THV900 SWTE and with thermocouples. More details of THV900 can be found in [6].

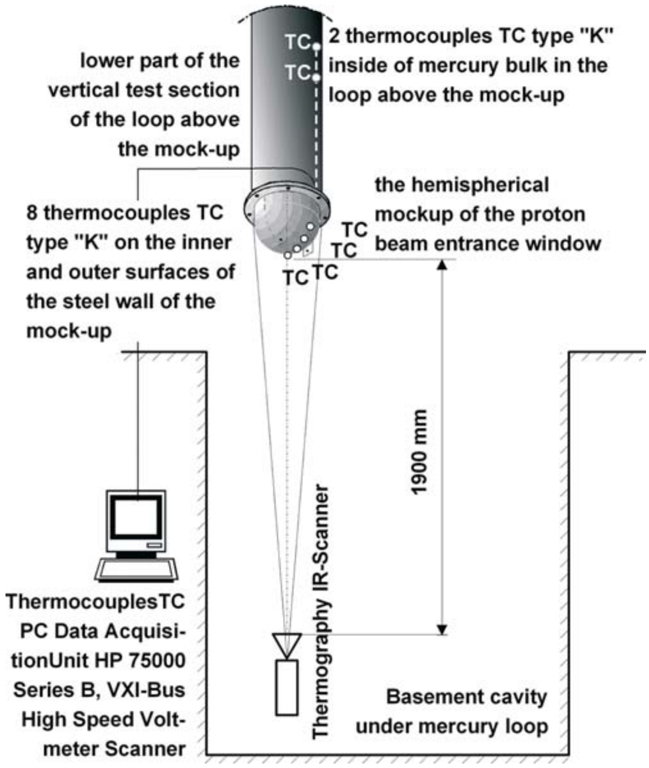

Figure 2: Set-up and instrumentation of the SEH test.

3 RESULTS

3.1 Estimation of HTC

The fine 2D geometrical resolution of the IR thermograms (the size of the pixels on which the thermograms are built is 1.5 × 1.5 mm), the high digital (12-bit) resolution and the high sensitivity (0.1°C) of the IR thermography for the outer surface temperature T_o measurement, allow the field $\Delta T_{o.bulk} = T_o - T_{bulk}$ of temperature differences between the bulk temperature of the mercury and the temperature distribution on the window outer surface to be defined with sufficient precision to estimate the cooling effectiveness of the mercury flow. If the heating conditions are stable for different flow configurations, then by simply calculating $\Delta T_{o.bulk}$ temperature-fields the cooling efficiency on the whole surface may be precisely assessed.

Additionally, it has been shown [2] that if the values of the local heat flux q^* can be correctly ascertained, a quantitative estimation of the cooling efficiency is possible. The value of the local HTC obtained from a measurement of the differential outer surface temperature $\Delta T_{o.bulk} = T_o - T_{bulk}$ must be amended to satisfy the requirement $\Delta T_{i.bulk} = T_i - T_{bulk}$ in which the temperature T_i must be determined on an invisible inner wall surface. Hence, the formula must be supplemented by a term representing the thermal resistance of the window, which, for a power density constant in the direction normal to the wall amounts to $\delta/2k$. Thus:

$$h = 1/\mathrm{HTC} = \frac{\Delta T_{\mathrm{i.bulk}}}{q*} = \frac{\Delta T_{\mathrm{o.bulk}}}{q*} - \frac{\delta}{2k},$$

where h is the local thermal resistivity of the boundary layer, k is the thermal conductivity (for DIN 1.4057 k = 25 W/m°K), $q*$ is the local heat flux, δ is the wall thickness, T_i is the temperature on the inner surface, T_o is the temperature on the outer surface of the window wall, and T_{bulk} is the mercury bulk temperature.

3.2 Estimation and visualisation of cooling efficiency

In addition to visualisation of the cooling efficiency with HTC-charts, thermograms allow some deductions to be made regarding the characteristics of the flow itself. In particular, the flow pattern (e.g. detection of dead zones) can be studied especially within the conductive boundary layer on the inner surface of the window.

The basic geometrical configuration of the inner guide pipe with a circumferentially uniform 'flat' gap of 2 cm to the window (horizontal flat edge of the RP) is shown in elevation (cross section) in Fig. 3a and in plan view (vertical axial projection) in Fig. 3b. In the case of forced convection with a pump flow rate of 1.2 l/s, the grey-scale thermogram obtained prior to final data treatment is shown in Fig. 3c. In such 'raw' grey-scale thermograms, the effects of boundary layer flow patterns on values of $\Delta T_{\mathrm{o.bulk}}$ are insufficiently visible. This problem is overcome by the use of coloured isotherms, as shown in Fig. 3d. The advantage gained by using colour in visualisation of fluid flows.

The isotherm lines, marked yellow and green for values $\Delta T_{\mathrm{o.bulk}}$ = 3.6°C and $\Delta T_{\mathrm{o.bulk}}$ = 7.2°C, respectively, help to visualise the cooling effect of the flow. The isotherm line at 7.2°C can be clearly

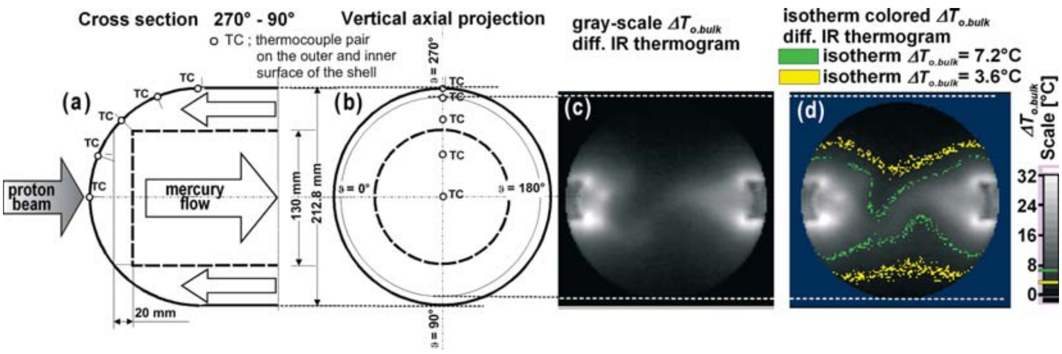

Figure 3: Typical thermograms obtained for experiments with uniform or 'flat' gap of 2 cm. (a) Elevation (cross section). (b) Plan view (vertical axial projection), for geometrical configuration of the inner guide pipe. (c) Grey-scale 'raw' $\Delta T_{\mathrm{o.bulk}}$ differential IR thermogram, the pattern of the dead zone caused by the swirl in the central region is difficult to recognise. (d) Coloured $\Delta T_{\mathrm{o.bulk}}$ – isotherm differential IR thermograms render the central swirl pattern of the flow more visible.

attributed to a vortex and a characteristic insufficiently-cooled dead zone appears in the middle of the target window.

The two hot spots on the left and right of the IR-thermogram were caused by the SEH electrodes, which were placed outside the important central region of the target window.

For the uniform 'flat' gap an estimation of the HTC for the central point, based on [2] with an average heat flux value of $q^* = 20{,}000\ \mathrm{W/m^2}$, yields:

$$
\begin{aligned}
\mathrm{HTC} &= q^* / \left(\Delta T_{\mathrm{o.bulk}} - q^* \cdot \delta / 2k\right) \\
&= 20{,}000\ \mathrm{W/m^2} / (7.2°\mathrm{K} - 20{,}000\ \mathrm{W/m^2} \cdot 0.00288\ \mathrm{m} / 2 \cdot 25\ \mathrm{W/m°K}) \\
&= 3{,}306\ \mathrm{W/m^2 °K}.
\end{aligned}
$$

The basic geometrical configuration was adopted to have a non-uniform 'skew' or 'slant' gap of 2 cm (slanted edge of the RP). This is shown in elevation (cross section) in Fig. 4a and in plan view (vertical axial projection) in Fig. 4b. The resulting grey-scaled thermogram and the corresponding thermogram with coloured isotherms are shown in Fig. 4c and d, respectively.

A comparison of the thermograms of Figs 3d and 4d, obtained with the same pump flow rate of 1.2 l/s, shows that the cooling pattern has changed in an essential way: in particular the dead zone and the vortex in central domain have disappeared, and the value $\Delta T_{\mathrm{o.bulk}} = 3.6°\mathrm{C}$ is considerably smaller than the value $\Delta T_{\mathrm{o.bulk}} > 7.2°\mathrm{C}$ for the uniform 'flat' gap.

For the non-uniform 'skew' or 'slant' gap an estimation of the HTC for the windows centre, based on [2] with an average heat flux value of $q^* = 20{,}000\ \mathrm{W/m^2}$, yields:

$$
\begin{aligned}
\mathrm{HTC} &= q^* / \left(\Delta T_{\mathrm{o.bulk}} - q^* \cdot \delta / 2k\right) \\
&= 20{,}000\ \mathrm{W/m^2} / (3.6°\mathrm{K} - 20{,}000\ \mathrm{W/m^2} \cdot 0.00288\ \mathrm{m} / 2 \cdot 25\ \mathrm{W/m°K}) \\
&= 8{,}064\ \mathrm{W/m^2 °K}.
\end{aligned}
$$

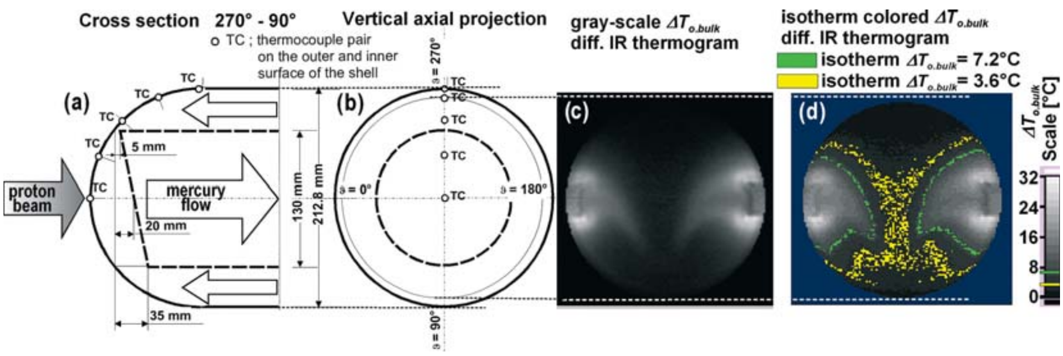

Figure 4: Typical thermograms obtained for experiments with non-uniform ('slanted' or 'skewed') gap of 2 cm. (a) Elevation (cross section). (b) Plan view (vertical axial projection), for geometrical configuration of the inner guide pipe. (c) Grey-scale 'raw' ΔT_{o}.bulk differential IR thermogram. (d) Coloured ΔT_{o}.bulk – isotherm differential IR thermograms, which makes the central washing-out pattern of the flow better visible. The thermogram displays the typical 'butterfly' pattern of the ΔT_{o}.bulk temperature field, which always appears in this case. This pattern is also more stable than the one shown in Fig. 3d, which results for a suction swirl.

The comparison of the estimated HTC values shows the advantage of the RP with slanted cut-off; it is more than twice as effective in the case of forced convection with a 1.2 l/s flow rate.

The dynamic behaviour of the temperature flow patterns on the steel window can be viewed on the web page (http://asq.web.psi.ch/ASQ/projects/liquid/liquid.html) or in the animation inserted as a supplement to the electronic issue of this paper. Clicking on the IR-thermograms initialises the appertaining hyperlink to a movie sequence of thermograms. The 1 Hz 'live' visualisations have been prepared by averaging, emissivity correction and subtraction of IR-thermography sequences originally recorded with a time resolution of 20 Hz.

More details concerning SEH experiments on the cooling of the SINQ target entry window can be found in [2].

4 ART

The pattern of differential thermograms in Fig. 4d has led to a science–art association, by comparing them with butterflies in Fig. 5. More specifically some artificially coloured scaling, an entire collection of 'infrared butterflies' was created and compared with photos of 'organic' butterflies.

Figure 5: 'The Collection' brings together the beauty of natural and infrared butterflies. The round thermograms show the convex surface of a heated hemispherical steel container, in which a thin wall is cooled from inside by flowing mercury. The picture was awarded first prize at the SPIE XXII Thermosense IR Image Gallery.

5 CONCLUSIONS

The use of only two colours for isotherms of grey-scale IR-thermography in the SEH test series with currently available time-, space- and temperature-resolution of the AGEMA THV900 equipment gives satisfactory results for:

- the visualisation of the temperature fields with his characteristic pattern, produced by the mercury flow behind the proton beam entry window of the mock-up for the LM spallation neutron source target concept with the SINQ conditions, and
- the comparison of the local convective HTCs for different steady-state flow conditions and geometrical cooling configurations. For this, more qualitative comparison, the precise absolute value of the local heat flux q^* need not be known, but it is imperative to ensure that the distribution of the local heat flux q^* remains the same for all configurations compared and that the mercury bulk temperature is simultaneously controlled.

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