Confined single- and multiple-jet impingement heat transfer in helium-cooled beam window assemblies at a cyclotron facility

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Abstract. The thermal modelling of the helium-cooled beam-window assemblies on the radionuclide production bombardment stations at iThemba LABS is described based on a dimensional analysis description of convection heat transfer utilizing turbulent submerged jets. It is concluded that these windows remain relatively cool even when bombarded with proton beams having the maximum design intensity. The reasons why helium is the preferred coolant are also discussed, partly based on a comparison with the cooling properties of other gasses.

1. Introduction

At iThemba LABS, radionuclide production targets are irradiated outside the beamline vacuum in order to facilitate rapid target transfers after bombardment and to preserve the cyclotron vacuum. This approach is followed by several other such facilities in the world. The relevant beamlines are provided with beam exit windows consisting of two closely-spaced thin metal foils cooled by a suitable gas flowing between them. These gas-cooled double-foil windows are thin enough to cause minimal beam energy degradation but provide a strong enough barrier to maintain the vacuum behind it for extended periods of time. They do have a finite life-time due to radiation damage, however, but a window typically lasts many months and sometimes even several years.

Figure 1 shows the vertical beam target station (VBTS) at iThemba LABS as well as its helium-cooled beam window assembly. This bombardment station is used for the production of long-lived radionuclides with beams of the highest intensity delivered by the separated sector cyclotron (SSC). Circularly swept proton beams of 66 MeV with intensities up to 300 µA are delivered to this facility. The sweep frequency is 3 kHz. A typical beam profile is shown in figure 2, obtained by analysing an autoradiogram made on radiochromic film [1] with an open source version of the software package DoseLab. The beam profile is very well represented by a rotating Gaussian function truncated at twice the full width at half maximum (FWHM) value. Such Gaussian functions are therefore used to model the beam.

The thermal modelling of such windows is the topic of this presentation. The calculation of temperature profiles for a window foil under bombardment is relatively straightforward and is based in this work on the finite difference approach described in Ref. [2]. For such calculations to be meaningful, however, the input data provided should be trustworthy. Convection heat-transfer coefficients, for example, are sometimes problematic to determine accurately. Values deduced from measurements as well as calculations based on dimensional analysis [3] are often inconsistent and differences by up to an order of magnitude are not uncommon [4,5].

Recently Gagnon et al. [6] obtained good agreement between measurements and calculations of the thermal behaviour of water-cooled metal targets, using forced convection heat-transfer coefficients predicted from the equations derived in a dimensional analysis study of heat transfer by means of submerged liquid jets. The original study [4] employed Freon (R-113) as cooling medium. Gagnon et al. applied – with brute force – the derived formalism of Ref. [4] to water-cooled targets and obtained surprisingly good results. This prompted us to investigate the same approach for helium-cooled beam windows, in particular because some experimental values for the convection heat-transfer coefficient obtained from a simulated window assembly [2] are available, which would permit a direct comparison. Furthermore, there was a need to have a fresh look at the thermal behaviour of beam windows on all the bombardment stations for radionuclide production at iThemba LABS in view of a programme to increase production capacity by increasing the beam intensity. Two bombardment stations for horizontal beams are shown in figure 3: The "Elephant" is used for the production of short-lived medical radionuclides (such as ^{67}Ga, ^{81}Rb and ^{123}I) using batch targetry, while "Babe" is dedicated to semi-permanent targetry (currently housing an enriched [^{18}O]H_2O target for ^{18}F production). As for the VBTS, circularly swept beams (but with a smaller sweep radius) are also delivered to the Elephant but the beam to the Babe station is not swept. Thus, the beam characteristics at the three bombardment stations are different and it would be interesting to compare the thermal behaviour of the beam windows under maximum bombardment conditions as it pertains to each station. Some of the properties of the beam and window assemblies are summarized in Table 1.

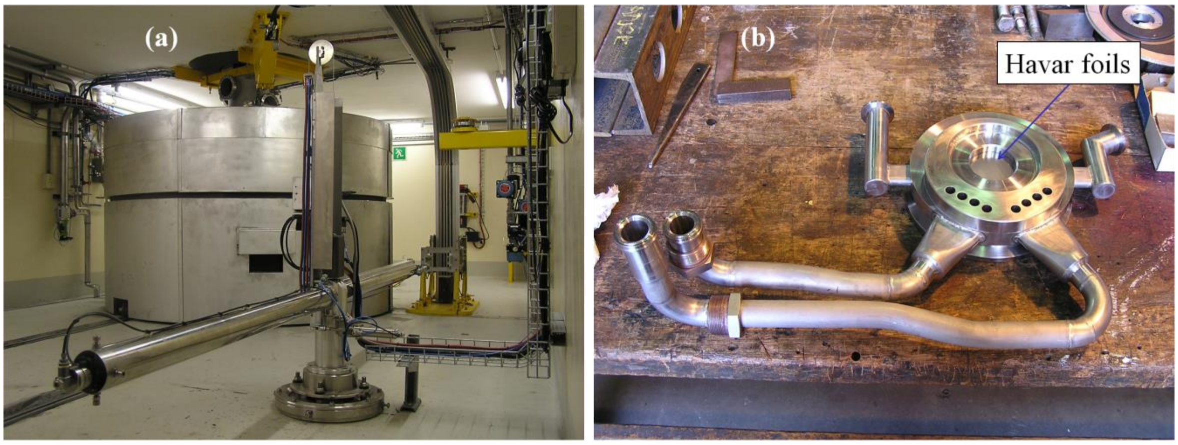

Figure 1. (a) The vertical beam target station (VBTS) at iThemba LABS for the production of long-lived radionuclides such as ^{22}Na, ^{68}Ge and ^{82}Sr. **(b)** A beam window assembly of the VBTS.

2. Jet impingement heat transfer

The methods of dimensional analysis are most often employed to derive expressions for the convection heat-transfer coefficient by searching for correlations between an appropriate set of dimensionless quantities such that it reproduces the measured data. Generally, the dependent variable is expressed as a power-law monomial function of the independent variables in dimensionless form, as this guarantees dimensional homogeneity [3]:

$$Q = \alpha A^{a}_{therm} \cdot B^{b}_{therm} \cdots X^{x}_{geom} \cdot Y^{y}_{geom} \cdots, \tag{1}$$

where A_{therm}, B_{therm}, X_{geom}, Y_{geom}, etc., are thermal and geometrical quantities in dimensionless form, respectively, while α, a, b, x, y, etc., are real numbers. First, we will consider the case of a single jet.

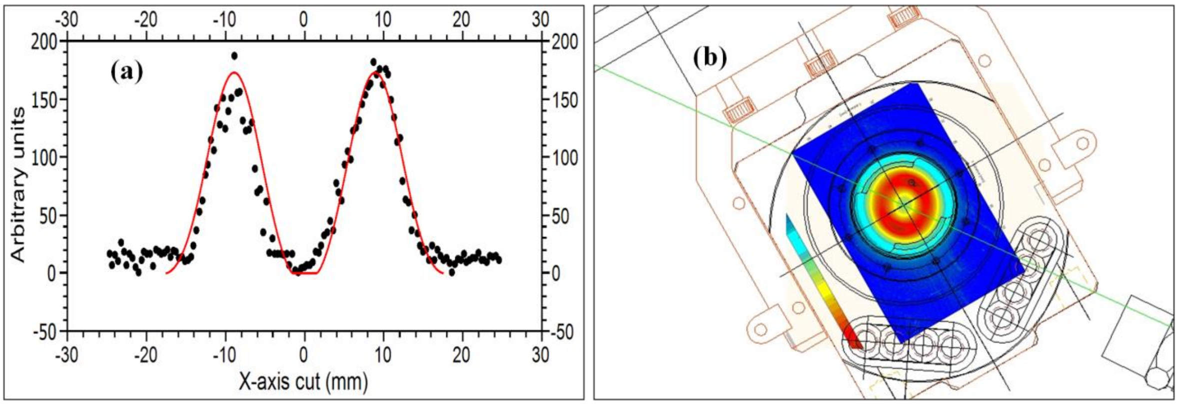

Figure 2. (a) Measured VBTS beam profile (symbols) obtained from an autoradiogram analysed with the DoseLab software (see text). The curve is a cross section through a rotating Gaussian function truncated at 2 x FWHM. **(b)** The autoradiogram overlayed on a VBTS target holder.

In this work, all jets are assumed to have circular orifices. Chang et al. [4] obtained the following expression for the stagnation point Nusselt number, $Nu(0)$, a dimensionless form of the convection heat-transfer coefficient which will be explained below:

$$Nu(0) = 0.660 Re_j^{0.574} Pr^{0.4} (z/d_j)^{-0.106}, \tag{2}$$

where Re_j is a Reynolds number evaluated with the characteristic length taken (by convention) as the exit nozzle diameter, Pr is the Prandtl number, z is the distance between the nozzle exit and the point of impact on the heated surface, and d_j is the nozzle exit diameter. The dimensionless groups are given by

$$Nu = \frac{hx}{k}; \qquad Re = \frac{\rho v x}{\mu}; \qquad Pr = \frac{c_p \mu}{k}; \tag{3}$$

where h is the convection heat-transfer coefficient, k is the thermal conductivity of the coolant, x is a characteristic length (which is taken here as the nozzle exit diameter d_j , as already mentioned), ρ is the density of the coolant, v is its bulk flow velocity, μ is its dynamic viscosity and c_p is its specific heat. The Reynolds number is a measure of the ratio of inertial forces to viscous forces in the coolant medium – the higher the Reynolds number the more turbulent the flow. The Prandtl number is a ratio of the magnitudes of the diffusion of momentum and diffusion of heat in the coolant medium. Thus, the heat-transfer coefficient can be evaluated as it is the only unknown quantity. Note that this applies only to the stagnation point (i.e. the point of impact). There is a radial decrease in the value of the Nusselt number away from the stagnation point. A local average Nusselt number for a region within a radius r from the stagnation point is given by

$$\begin{aligned} \overline{Nu}(r)/Nu(0) &= [1 + 0.1147 (r/d_j)^{1.81}]^{-1} \quad \text{for} \quad r/d_j \leq 1.25; \\ \overline{Nu}(r)/Nu(0) &= 1.0632 (r/d_j)^{-0.62} \quad \text{for} \quad r/d_j > 1.25. \end{aligned} \tag{4}$$

A local average heat-transfer coefficient is then given by

$$\bar{h} = \frac{\overline{Nu}(r) k}{d_j}. \tag{5}$$

The data of Ref. [4] were not extensive enough to find a general description for multi-jet heat transfer. In that study, results from a 25 jet set-up arranged in a 5 x 5 matrix was extensively compared to the single-jet results and some interesting conclusions drawn. No significant additional dependence on the pitch-to-jet diameter ratio, *p*/*d*, was found, however, an inclusive dependence already exists in equation 4. A weak dependence was found on the z/d_j ratio from plots of $\overline{Nu}(r)_{multi-jet} / \overline{Nu}(r)_{single-jet}$ versus z/d_j, leading to an overall expression as follows:

$$\overline{Nu}(r)_{multi-jet} = C(z/d_j)^{-0.116}\,\overline{Nu}(r)_{single-jet}, \tag{6}$$

where C is a constant found to have a value of $C = 1.667$ for that particular case.

In our study, we followed a slightly different approach which gave quite similar results. Assuming that N equispaced jets have mass flow rates of $1/N$ of the total flow rate, a local radial region for each jet can be defined by partitioning the surface to be cooled accordingly:

$$r_l = \sqrt{\frac{A_h}{\pi N}}, \tag{7}$$

where A_h is the area of the heated surface. Average local Nusselt numbers using this radius can then be obtained from equation 4. The combined effect of reducing the jet diameter, which naturally follows if we increase their number while keeping the total flow rate constant, as well as reducing the effective radius in equation [4] leads to an increase of the heat-transfer coefficient.

The approach outlined above is believed to be conservative as it essentially assumes individual jets to act independently of neighbouring impinging jets. In real situations, however, there is interference between the jets due to the viscosity of the coolant medium. According to Ref. [4], this reduces the strength of the jet potential cores and the values of the heat-transfer coefficient at the stagnation points. Nevertheless, the interaction of the jets with each other leads to increased turbulence, hence increased effective Reynolds numbers, which leads to an overall increase in convection heat transfer.

Table 1. Typical properties of the beam and He-cooled window assemblies.

	VBTS	**Elephant**	**Babe**
Beam direction	vertical	horizontal	horizontal
Beam sweep radius	10 mm	3 mm	nil (no sweeping)
Beam sweep frequency	3 kHz	450 Hz	450 Hz
Beam diameter (2 x FWHM)[a]	10 mm	8 mm	8 mm
Maximum design beam current	300 µA	100 µA	50 µA
Window collimator diameter	36 mm	16 mm	16 mm
Target collimator diameter[b]	none	none	9 mm
Window diameter	50 mm	20 mm	20 mm
Inner window foil thickness	75 µm	25 µm	25 µm
Outer window foil thickness	50 µm	25 µm	25 µm
He bulk pressure (temperature)	1.25 bar (25 ºC)	1.25 bar (25 ºC)	1.25 bar (25 ºC)
He bulk volume flow rate[c]	125 m^3/h	125 m^3/h	125 m^3/h
He jet flow velocity	138 m/s	217 m/s	217 m/s
Number of jets	20	1	1
Effective jet exit diameter	4 mm	14.27 mm	14.27 mm

[a] Diameter of the unswept beam, assuming a Gaussian shape of width twice the full width at half maximum.

[b] Not required on the Elephant and VBTS. Necessary to reshape the degraded beam for the $H_2{}^{18}O$ target.

[c] Delivered by a positive displacement rotary compressor.

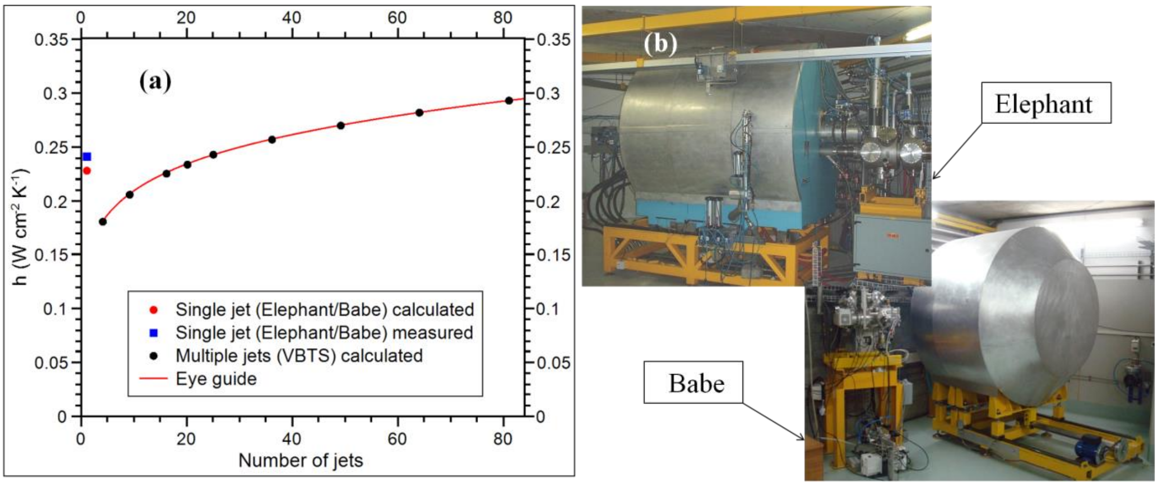

Figure 3. (a) Measured and calculated convection heat-transfer coefficients (see text). (b) The two horizontal beam target stations for radionuclide production at iThemba LABS.

3. Results and conclusions

Calculated and measured convection heat-transfer coefficients for single-jet helium cooling of the beam windows of the two horizontal-beam stations (the Elephant and Babe window assemblies are similar) are shown in figure 3. The calculated value of 0.228 W cm^{-2} K^{-1} is quite close to the measured value of 0.24 W cm^{-2} K^{-1}. For the VBTS, which has 4 times larger windows, a multi-jet configuration was chosen to achieve similar cooling with the same helium flow rate. With the same flow rate but by increasing the number of jets, the cooling becomes more efficient, as shown in figure 3. The final VBTS window design employs 20 jets. In all cases, the helium flow rate is nominally 125 m^3/h at a pressure of 1.25 bar at room temperature (25 ºC assumed in all calculations – see Table 1). This gives a linear gas velocity of about 217 m/s for Babe/Elephant windows and 138 m/s for VBTS windows. Figure 3 (a) shows that very similar values of the convection heat-transfer coefficient are obtained for the Elephant/Babe windows and the VBTS if 20 jets are employed, even though the He flow rate is lower in the latter case. It was also found that the two approaches outlined for calculating multi-jet heat transfer coefficients give values not differing by more than 10% for the case of Ref. [4].

Figure 4 (a) shows calculated temperature profiles for the Havar beam windows of all stations using typical beam profiles and maximum design beam intensities (50 μA for Babe, 100 μA for the Elephant and 300 μA for the VBTS). A conservative, slightly lower value of h = 0.2 W cm^{-2} K^{-1} has been adopted for all the calculations. Havar is a Co-Cr-Ni-based super alloy which can be used safely up to temperatures of 700 ºC (its melting point is 1480 ºC) thus one can conclude that these windows are operating at relatively cool temperatures. The windows of Babe become the hottest as that beam is not swept but the maximum temperature is still below 250 ºC. All windows will rapidly melt if the helium cooling fails (i.e. when $h \rightarrow 0$) while the bombardment continues. If the beam sweeping falls away, Elephant windows will survive but VBTS windows will melt.

Finally, figure 4 (b) compares different gasses as coolant. It is evident that the lighter gasses are better for this application. While hydrogen has the best cooling properties, it will be too dangerous to use for window cooling due to its highly flammable properties, thus helium is the cooling gas of choice. An additional advantage of helium is that its interactions with the energetic protons of the beam do not lead to a build-up of radioactive activation products in the cooling system, something which would have been unavoidable if e.g. R22 Freon in the gas phase was used.

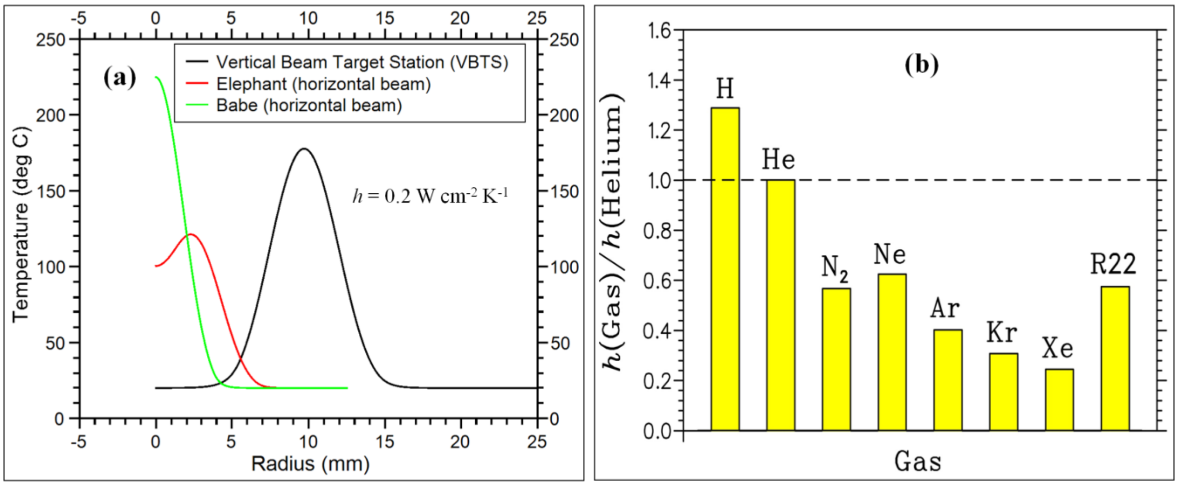

Figure 4. (a) Calculated temperature profiles for beam window foils under bombardment with maximum design beam intensity. **(b)** Ratios of convection heat-transfer coefficients for various gasses as coolants (relative to helium).

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