Saturation Conditions in Elongated Single-Cavity Boiling Water Targets

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Introduction

It is shown that a very simple model reproduces the pressure versus beam current characteristics of elongated single-cavity boiling water targets for ^{18}F production surprisingly well. By fitting the model calculations to measured data, values for a single free parameter, namely an overall heat-transfer coefficient, have been extracted for several IBA Nirta $H_2{}^{18}O$ targets.

IBA recently released details on their new Nirta targets that have a conical shape, which constitutes an improvement over the original design that has a cylindrical shape [1,2]. These shapes are shown schematically in Figure 1.

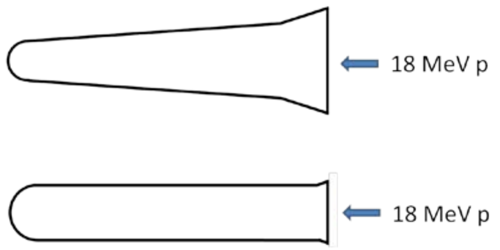

FIGURE 1. Shapes of the new conical and old cylindrical IBA Nirta water-target cavities.

A study by Alvord et al. [3] pointed out that elevated pressures and temperatures in excess of the saturation conditions may exist in a water target during bombardment. However, as long as the rate of condensation matches the rate of vaporization, the bulk of the system should remain at saturation conditions. Superheated regions are therefore likely to form but also likely to disappear rapidly, typically on the scale of a few milliseconds. Even though the boiling process is generally quite complex, enhanced by radiation-induced nucleation, the presence of fast mixing mechanisms in the water volume justifies some simplifications to be made.

Materials and Methods

The simplified model assumes that the bulk of the target water has a constant temperature, which is the same as the inner wall temperature of the cavity, T_w. A second simplification is to neglect the temperature difference across the target chamber wall, which is only justified if the wall is thin. The boiling is not explicitly taken into consideration, including the rather complex boiling behaviour at the Havar window, except to acknowledge that it is the main mixing mechanism. Large temperature gradients can briefly exist in the water but they also rapidly disappear [3]. A further assumption is that a single, overall convective heat-transfer coefficient can be applied, which is considered to be constant over the entire water-cooled surface. As the wall thickness is neglected, the heat-transfer surface is taken to be the inner surface of the cavity, excluding the surface of the Havar window. The energy balance between the beam heating and the convection heat transfer (Newton's law of cooling) is given by

$$I_b \Delta E = hA(T_w - T_0), \quad (1)$$

where I_b is the beam intensity, ΔE is the energy windows of the target (taken as 18 MeV), h is the convective heat-transfer coefficient, A is the inner cavity surface through which the heat has to be transferred from the target-water volume to the cooling water, and T_0 is the cooling-water temperature.

The saturated vapour pressure versus temperature of water is a characteristic curve, given by the steam tables [4]. It can be written as

$$P = f(T) \quad \text{or} \quad T = f^{-1}(P). \quad (2)$$

Assuming the bulk of the system at saturation conditions, one gets from (1) and (2)

$$P = f(T_w) = f\left[\left(\frac{\Delta E}{hA}\right)I_b + T_0\right]. \quad (3)$$

The function f is represented by a polynomial. The only unknown in Equation (3) is the overall convective heat-transfer coefficient h. Our approach was to adjust h until a good fit with a set of measured data was obtained. It also has to be mentioned that subtle differences in the physical properties between ^{18}O-water and natural water have been neglected.

Admittedly, the real target is more complex than reflected by Equation (3). Nevertheless, the results obtained from Equation (3) provide interesting and useful insight.

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Results and Conclusion

Measured data and corresponding calculations are shown in Figure 2 for three different conical targets and one cylindrical target. The extracted convective heat-transfer coefficients are presented in Table 1 for the four cavities.

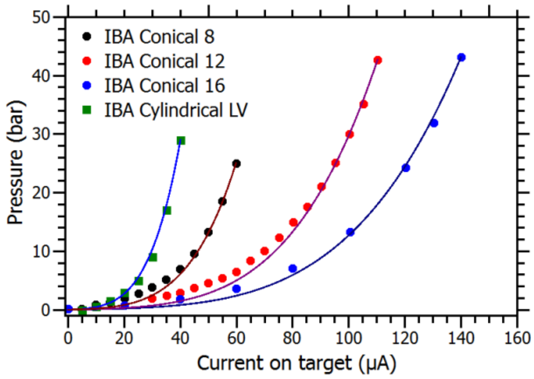

FIGURE 2. Pressure versus beam current for several Nb inserts. Square symbols: Measured at iThemba LABS. Round symbols: Devillet et al. [1]. The curves are calculations using Equation (3) with T_0 = 30 °C for the mean cooling-water temperature.

Target	Cavity volume (cm^3)	h ($W\ cm^{-2}\ °C^{-1}$)
Nirta Conical 8	3.7	0.44
Nirta Conical 12	5.0	0.48
Nirta Conical 16	7.0	0.44
Nirta Cylindrical LV	2.4	0.41

TABLE 1. Inside volumes of the investigated target cavities and values extracted for the overall heat-transfer coefficient.

As can be seen in Figure 2, while there are some differences between the data and calculated curves, especially towards lower beam currents, the overall agreement is remarkably good. It is possible that the better agreement towards higher beam intensities is related to more ebullient boiling and more rapid mixing, i.e. a closer agreement with to the conditions that the model assumes.

The values obtained for the overall convective heat-transfer coefficient are also remarkably similar. This tells us that, by and large, all the cavities perform in a similar way and the performance in terms of maximum operational beam current depends largely on the available surface to effectively remove the heat from. The values of h increase marginally if a smaller value is adopted for the cooling-water temperature. Note that the choice of T_0 = 30 °C used to obtain the results in Table 1 is typical for the room temperature, closed-loop cooling system used at iThemba LABS, under stable operational conditions.

A study by Buckley [5] on a different target design reports a value of h = 0.49 W cm^{-2} °C^{-1}, which is reassuringly similar. That study describes a cylindrical target cavity with a volume of 0.9 cm^3, 8 mm deep, cooled with 25 °C water from the back, operated with a 15 MeV proton beam with an intensity of 30 μA.

The Nb Nirta targets are typically filled with ^{18}O-water to about 60% of the cavity volume (see refs. [1,2] for the recommended values). The elongated shape, in combination with the ebullient properties of the boiling water, prevents burn-through. All the targets deliver production yields in agreement with the expected saturation yield. The targets are self-regulating – no external gas pressure is required.

While the thermosyphon targets seemingly take advantage of a superior concept, we are now questioning whether this is really so in practice? It is not clear to us that the much more complex thermosyphon targets deliver any operational and/or performance advantages compared to the simple elegance of these elongated, single-cavity boiling target designs.

References

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Acknowledgements

The authors would like to thank F. Devillet for making the detailed dimensions of the conical targets available to us. This work is based on research supported by the National Research Foundation of South Africa (UID 85507). The grant holder acknowledges that opinions, findings and conclusions or recommendations expressed in any publication generated with NRF supported research are that of the authors, and that the NRF accepts no liability whatsoever in this regard.

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