RECENT DEVELOPMENTS ON THE IFMIF/EVEDA BEAM DUMP COOLING CIRCUIT*

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Abstract

During the IFMIF/EVEDA activities a conical dump made of copper has been designed to stop the 125 mA, 9 MeV, D+ beam. This element will receive a total power of 1.125 MW. It is cooled by a high velocity water flow that circulates through an annular channel along the outer surface of the cone. The coolant composition must be defined taking into account corrosion and erosion phenomena. This work will present the influence of copper corrosion on the cone cooling parameters.

INTRODUCTION

The IFMIF-EVEDA beam dump design [1, 2] is based on a 2.5 m long copper cone (30 cm of aperture diameter, 5-6.5 mm thickness) whose inner surface absorbs the beam, being the maximum power density deposited in nominal conditions of around 2.3 MW/m^2. This piece is cooled by water (31 °C inlet temperature) flowing in counter-beam direction at high velocity through the annular channel formed between it and a second piece (shroud) made of four truncated cones of slightly different slopes.

Deionized water is employed to extract the 1.125 MW along the variable width cooling channel. Deionized water is eager for ions in an attempt to achieve equilibrium by combining with any surronding element. Besides the high velocity water flow, ranging from 8.5 m/s to 4.5 m/s, and the steep inner cone temperatures achieved (93°C), make corrosion an issue to consider in the beam dump [3].

Theoretical Background

Corrosion phenomena modelling begins by considering the convective diffusion equation (1), where c_i denotes the ion concentration, D_i is the diffusion coefficient and $\vec{v_i}$ is the flow velocity.

$$\frac{\partial c_i}{\partial t} + (\vec{v_i}\nabla)\, c_i = \nabla\left(D_i \nabla c_i\right) \tag{1}$$

Equation (1) is brought into a non-dimensional form, showing that it depends on the Reynolds and Schmidt numbers. Next step is taking profit of the principles of convective mass transfer which specify that under forced convection flow conditions, mass transfer is determined by the Sherwood number (dimensionless) and therefore advantage between the analogy of heat and mass transfer can be taken.
Therefore Sherwood (Sh) number must also depend of Reynolds and Schmidt numbers [4].

The mass flux defined as shown in equation (2), where c_i^w and c_i^b are the wall and bulk copper concentrations and K_i^{fl} (equation 3) the mass transfer coefficient, together with equation (1) show the heat and mass transfer analogy in equation (4).

$$j_i = K_i^{fl} \cdot \left(c_i^w - c_i^b\right) \tag{2}$$

$$K_i^{fl} = \frac{D_i}{d_{hyd}} Sh \tag{3}$$

$$\frac{\partial c_i^b(t,x)}{\partial t} + \vec{v_i} \cdot \frac{\partial c_i^b(t,x)}{\partial x} = \frac{U_{ch,i}}{A_{ch,i}} \cdot j_i(t,x) \tag{4}$$

Where U_{ch} is the flow channel perimeter and A_{ch} is the flowing water cross section area.

In the solution of equation (4) the following assumptions have been considered:

- The transport equation for copper dissolved in water is solved.
- A 1D approximation is employed.
- No diffusion across radial or azimuthal direction.
- Mass transfer coefficient correlation for annular channel employed.
- Boundary condition at the entrance: c^b(x=0,t=0) = 0. Neumann boundary condition at the exit ($\nabla c^b = 0$).
- No extraction is considered.
- Copper wall solubility data in acid medium (pH = 6) taken from [5].

RESULTS

In order to solve and validate equation 4, three different resolution methods have been used:

a. A finite volume partial differential equation solver using Python, FiPy [6], for the solution of equation(4).

The transient solution is confronted when it reaches equilibrium with:

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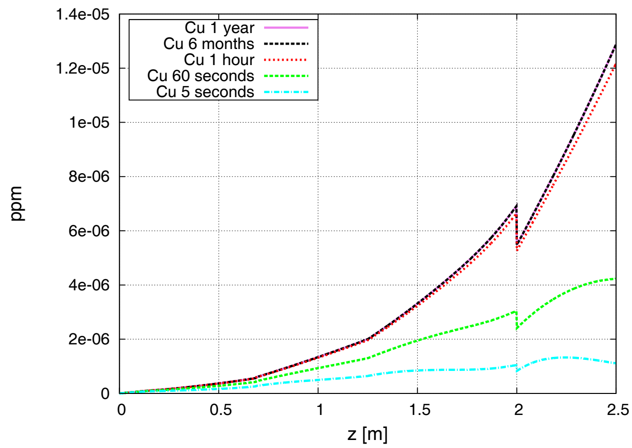

Figure 1: Transient evolution of the copper concentration.

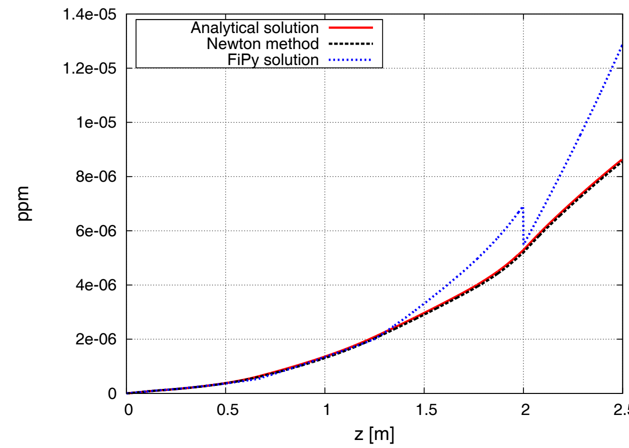

Figure 2: Comparison between the different solution methods.

b. The analytical solution of the stationary equation.

c. The solution obtained by applying Newton method.

In Figure 1, the transient evolution of copper concentration (in ppm) is shown. It is seen that the transport process is close to equilibrium values after 1 hour. Nevertheless equilibrium is reached after one year.

Validation of the results obtained simulating with FiPy, have been performed by two different ways. Firstly by obtaining the analytical solution (equation (6)) of the stationary transport equation (5).

$$\vec{v_i}(x) \cdot \frac{\partial c_i^b(x)}{\partial x} = \frac{U_{ch,i}(x)}{A_{ch,i}(x)} \cdot j_i(x) = \frac{f_i(x)}{\vec{v_i}(x)} \qquad (5)$$

$$c(x) = \exp\left(\int -a(x)dx\right) \cdot \left[\int b(x) \exp\left(\int a(x)dx\right) dx\right] \qquad (6)$$

$$a(x) = \frac{U_{ch}(x) K^{fl}(x)}{A_{ch}(x) \vec{v}(x)} \qquad (7)$$

$$b(x) = \frac{U_{ch}(x) K^{fl}(x)}{A_{ch}(x) \vec{v}(x)} c^w(x) \qquad (8)$$

Secondly by solving the transport equation applying the Newton method (equation (9)) with a step h of 1 mm.

$$c_{i+1}^b(x) = c_i^b(x) + h f_i(x) \qquad (9)$$

On Figure 2, a comparison of the three methods is shown. It can be seen that FiPy module over predicts the solution from the mid part of the cooling channel until the end of it. Instead, Newton method and the analytical solution predict lower concentration values.
The high concentration values obtained from FiPy solver deal with quick velocity shifts along the beam dump cooling channel.

Another case scenario was simulated in order to verify this last point. Considering a constant velocity of 6.88 m/s which is an average value along the cooling channel, the results show a higher degree of concordance with the analytical solution. Although as seen in Figure 3, it is still influenced by the changes in the cooling channel geometry caused by the four truncated cones that conform the outer cone (shroud).

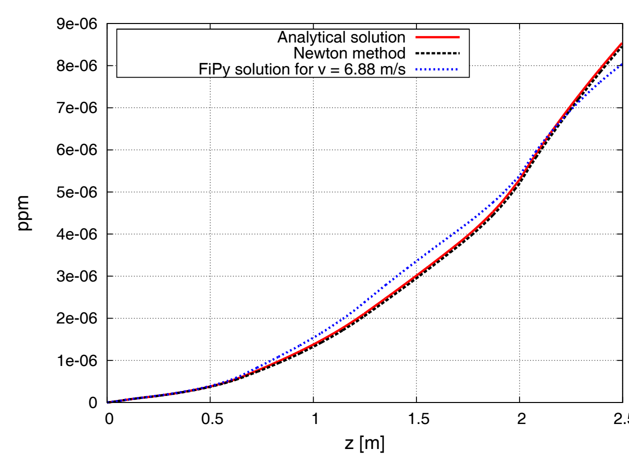

Figure 3: Solution for a velocity of 6.88 m/s.

DISCUSSION OF THE RESULTS

The corrosion analysis yields a decrease of the inner cone thickness a maximum of 0.53 mm. This result means that the overall thickness (Figure 4) is reduced in a 10%, corresponding to an annual corrosion rate of 3.63 kg/m^2.

As a consequence, the cooling channel gap increases causing a decrease of the velocity field and hence of the heat transfer coefficient (HTC).

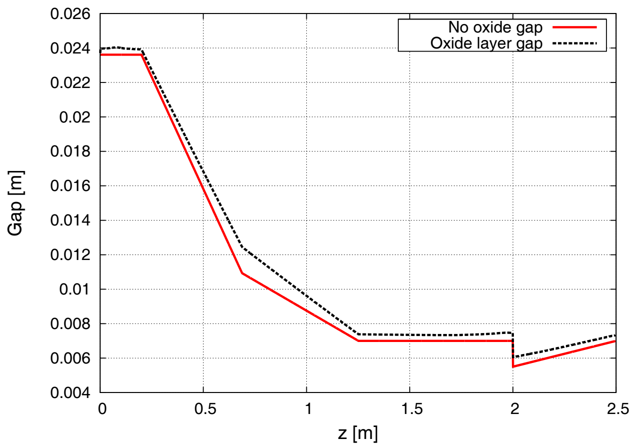

Figure 4: Cooling water gap.

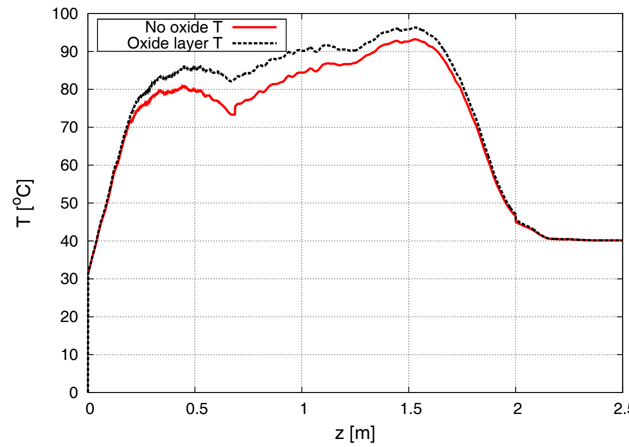

Figure 6: Inner cone temperature profile.

The increase in channel width is specially significant in terms of influence over velocity at the inlet of the beam dump. As seen in Figure 5, the decrease in velocity produces a variation of the HTC between 2.000 - 6.000 W/m^2°C.
Although the heat transfer coefficient varies significantly, its effect over the innner cone temperature is not so significant (Figure 6) because heat deposition in that section of the cone is low compared with the middle sections of the beam dump.

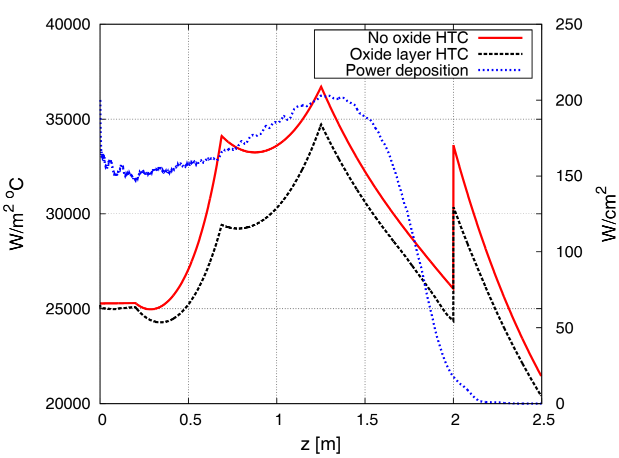

Figure 5: Heat transfer coefficient (HTC) and power deposition profile.

On Figure 6 the inner cone temperature profile for non oxidizing and corroding conditions are plotted. The maximum temperature increases up to 95.6°C when corrosion is taken into account, while in non oxidizing conditions the maximum temperature is 93°C.

CONCLUSION

A corrosion analysis of the IFMIF-EVEDA beam dump has been performed relying on the convective diffusion equation and the heat and mass transfer analogy. The problem at first instance was approached by means of a partial differential equation solver based on python (FiPy). When comparing the results, it was observed that a variable velocity profile was leading to inaccurate results. Therefore the stationary solution solved either analytically or by Newton method was taken to do all the post process analysis.

The post process shows a decrease in some sections of the inner cone thickness of the order of 10%. Nonetheless it does not affect the beam dump from the thermohydraulical point of view. It has to be taken into account that this result deems a whole full power year operation, while in reality there will be an initial commissioning period. Lower power duty cycles and therefore lower water flows will be employed, meaning a decrease in the mass transfer coefficient and also in the corrosion activity.

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