CALCULATION OF AIR SPEEDS FOR COOLING TITANIUM FOILS OF HIGH POWER ELECTRON ACCELERATOR

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Abstract

The 100kW, 2.5 MeV electron accelerator being developed at RRCAT requires the electron beam to be scanned and transported from the accelerator on to the product through a 1500 mm x 60 mm x 50μ thick titanium foil. As electrons pass through the foil, they generate heat ~2.5 kW in the foil. The maximum foil temperature must be kept below 600K to guard against foil failure due to low rupture strength at high temperature or a burn out. The titanium foil must be cooled by forced air convection only as other cooling media such as water would severely attenuate the electron beam and may even absorb it completely for any practical water cooling design. The foil sees a very steep temperature gradient of 300K within a span of 60 mm and concept of average heat transfer coefficient cannot be used and use of local temperature dependent heat transfer coefficient is imperative. The calculation has been done using the programming language of ANSYS with each finite element being flagged with one temperature dependent local heat transfer coefficient. This paper discusses the methodology of calculation and presents the results in terms of required air speed for cooling the foil.

MATERIAL

A 1500 mm x 60 mm x 0.050 mm titanium foil acts as a vacuum barrier between the vacuum envelope of electron accelerator and the atmosphere due to their ability to allow a large transmission of electrons without much attenuation, its mechanical strength at higher temperature and the possibility of making thin foils. Another important property of titanium is total hemispherical emissivity (ε) which helps in the heat transfer by radiation. ε can be assumed to have a constant value of 0.54 at the radiation temperature of 600K. Figure-1 gives the variation of total hemispherical emissivity with absolute temperature[1]. The total hemispherical emissivity of titanium may increase with time on the atmospheric side due to thickening of oxide layer. However, in totality, this effect may be ignored. The thermal conductivity of titanium is low and is at its minimum (~ 18 W/m.K) around 600 K.

The foil thickness is decided based on the designed sag, pressure difference (1 atm), allowable stress and foil width [2]. Since the allowable stress is a strong function of temperature and shows sharp degradation with increasing temperature, it is necessary to keep a limit of maximum temperature for the foil. Owing to this consideration, titanium temperature has been limited to 600K while evaluating the cooling requirement of the foil.

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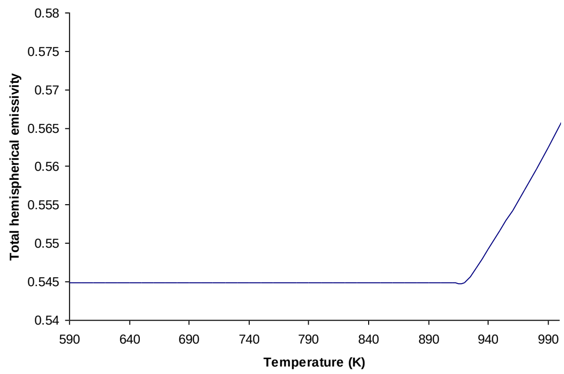

Figure-1: Total hemispherical emissivity of titanium.

HEAT TRANSFER CALCULATIONS

Heat Load

Maximum transmission loss occurs with 1 MeV, 50 kW beam interacting with titanium foil. The total loss figure comes out to be 1.8 kW. For thermal evaluation, the value has been increased by 10% and a value to 2 kW has been used for the calculations.

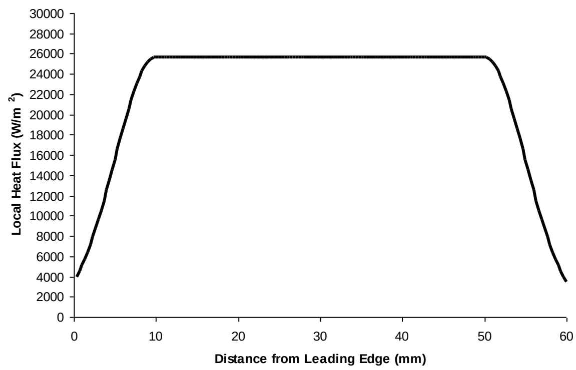

Figure 2: Average heat flux across the width.

The lateral scanning across the 60 mm width of the foil is done at a high frequency (typically at 1 kHz) and the scanning across the length (1500 mm) is done at a lower frequency (typically at 60 Hz. Due to a Gaussian distribution of electrons in an unscanned beam, the heat generation in the foil will follow a Gaussian distribution at the edges and a flat top in the middle (fig-2) for a scanned beam.

In FE modelling, the heat generated has been modelled by imposing heat flux boundary conditions. Since, the descritization is uniform and the element area is same for all the elements; the heat flux can be calculated by dividing the heat generated by the element area.

$$Heat\ Flux = 25675.6\ \ Exp[-20000(x-x')^2]\ \frac{W}{m^2} \qquad (1)$$

where

x = distance from the leading edge

x'= 0.01 m for 0<x<0.01 & 0.05 for 0.05<x<0.06

Modelling of Heat Transfer

A continuously varying foil temperature can be interpreted as a succession of infinitesimally small temperature steps occurring at infinitesimally closed spaced locations. Presence of a steep temperature gradient of 300 K in a span of less than 60 mm in the foil, necessitate that the heat transfer coefficient calculation is based on local conditions like the distance from the leading edge as well as the film temperature.

From these considerations, the heat flow Q at any location x having temperature Tx, ambient temperature T∞ and width w can be obtained by the following integral:

$$Q = \int h(x, T_x)(T_x - T_\infty) w dx ....(2)$$

and the heat transfer coefficient is given by:

$$h_{total} = 0.332 * \frac{k}{x} * \sqrt{\text{Re}} * \sqrt[3]{\text{Pr}}$$

$$+ 2\sigma\varepsilon(T_w^2 + T_\infty^2)(T_w + T_\infty)................(3)$$

Equation (3) is modified for a turbulent flow if the Reynolds Number exceeds 5 x 105. At a particular location and for a particular air speed, the equation becomes a function of temperature only.

We adopted a calculation methodology in which the length in the flow direction was descritized in 180 elements thus keeping the element size as one third of a millimetre. Depending upon the distance of centriod of each element from the leading edge, the total heat transfer coefficient is calculated for a particular air speed. Therefore, if we associate each element with a location specific but temperature dependent heat transfer coefficient then the problem is reduced and an iterative procedure (such as Newton-Raphson or modified Newton Raphson) will give a converged solution. For one particular solution step, the entire heat transfer problem is solved by assuming that the air speed is constant. Then, the air speed is varied in successive solution runs so that a suitable air speed can be found out that limits the maximum temperature in the foil to 600K.

RESULTS

The thermal boundary layer as well as the hydrodynamic boundary layer start from the leading edge. The viscosity of air increases as the same gets hotter during the flow from leading edge to the trailing edge. Secondly, as the air gets hotter, the available temperature difference for convection and radiation decreases. These two effects reduce the heat transfer as the flow progresses. Also, the heat generation is symmetric and Gaussian near the leading (rising) and the trailing edges (falling) with a flat top in the middle (Fig-2). This indicates that the maximum temperature is expected to lie slightly before the trailing edge.

Temperature Distribution over the foil

Figure-3 shows the temperature distribution along the flow length of the foil for an air speed of 48.5 m/s. The peak occurs 15 mm before the trailing edge.

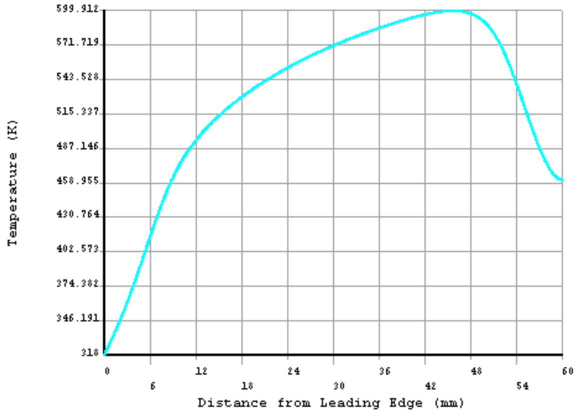

Figure 3: Variation of temperature along the foil.

CONCLUSION

This work has been done by Finite Element Method using the parametric design language of ANSYS™. The calculation shows that the required air speeds obtained from this rigorous approach is almost four times the value obtained from the conventional average heat transfer coefficient approach. The calculated air speed is close to but on the slightly higher side of the air speeds normally used in similar accelerators used in countries like Russia. This is due to the hotter conditions prevailing at Indore which not only reduces the temperature difference with the foil and but also increases the dynamic viscosity. We recommend a blower and air channels capable of delivering an air speed of 60 m/s to ensure a 20% margin over the calculated air speed. The boundary layers are very small (<0.5 mm) and therefore there is no need of providing high volume flow rate.

The developed ANSYS programme can be used for cases where the temperature rise is very steep and average heat transfer coefficient cannot be used. The program has the capability of judging laminar to turbulent transition and changing the value of convective heat transfer coefficient based on the value of Reynold's number.

REFERENCES

[1] W.R. Wade, Langley Aeronaut. Lab. NASA, Technical note 4206 (1958) [AD 153 191]

[2] Siegfried Schiller, Electron Beam Technology, John Wiley &Sons, p491, 1982