HEAT TRANSFER AND THERMAL STRESS ANALYSIS OF RF STRUCTURES OPERATED IN BOILING REGIME

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Abstract

RF structures operating in the boiling heat transfer regime can achieve high average power levels at reduced coolant flow rates. The attainable power is limited by the detuning of the rf structure and thermal stresses. A three-dimensional finite-element model has been developed to study the dynamic behaviour, temperature distribution, deformations and stress pattern of an 805 MHz on-axis-coupled structure operated in the boiling heat transfer regime.

Introduction

A high power 1.5 MeV electron beam injector has been designed at the Chalk River Nuclear Laboratories. The injector linac will be driven by two 100 kW cw (100% duty factor) klystrons and is designed to operate at an average energy gradient of 3.25 MeV/m and a beam loading of about 50%. One of the design requirements of the linac structure is high power handling capability with low cooling water flow rate. As demonstrated in an earlier report[1], this can be achieved from a thermohydraulic view point by using the boiling heat transfer process; nevertheless, the limit imposed by the yield strength of the structure material is still a major concern.

This paper investigates the problems of heat transfer, thermal stress and operational stability of a compact 805 MHz injector linac cooled by the boiling heat transfer process. A numerical analysis was performed using a 3-dimensional finite element model similar to the one developed earlier for the study of structures operated in the single phase flow regime[2].

Description of the 805 MHz Linac Structure

The 805 MHz on-axis-coupled graded-beta structure consists of 3 accelerating cavities and 2 coupling cavities. Figure 1 shows the OFHC copper cavity profile and the dimensions for each of the 6 segments of the structure. The segments are brazed together to form a 0.4619 metre long structure. The cooling circuits are composed of 8 circumferential cooling channels (diam = 9.52 mm) running from one end of the structure to the other, and 8 web headers that feed water to a series of 4.76 mm diameter web channels. Each cavity segment has 2 web channels that traverse the web wall between the beam aperture and the coupling slots. These channels are oriented 45° upward with the water flow directed from a lower inlet header to an upper outlet header to avoid the formation of water vapour pockets. The header and circumferential cooling channels are arranged in counterflow to minimize temperature differences in the structure.

The length of each cavity, the calculated shunt impedance and average on-axis field are shown in Table 1. The dimensions of the coupling slots are the same for all cavities. The first neighbour coupling constant is the largest for the lowest beta cavity and consequently there is a field drop in the structure.

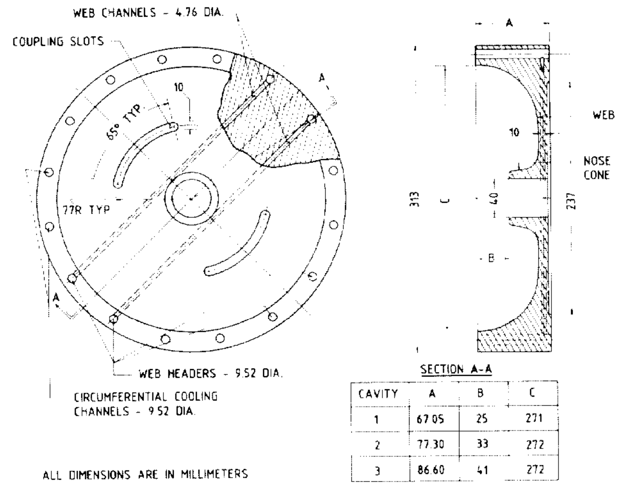

Fig. 1 Layout of one segment (one-half cavity) of the 805 MHz on-axis-coupled structure.

Table 1

Length and RF Parameters of Cavities

Cavity	Length (m)	β	Power (kW)	Power kW/m	Shunt Impedance (MΩ/m)	Average On-axis Field (MV/m)
1	0.1341	0.72	31.54	235.3	42.1	3.23
2	0.1546	0.83	34.89	225.7	39.4	3.93
3	0.1732	0.93	38.53	222.5	34.4	3.57

Thermohydraulic Analysis

The average power dissipation in the structure per unit length is 227 kW/m. The heat fluxes on the surface of the accelerating cavities are calculated with the computer code SUPERFISH[3]. The surface power density varies from about 39 W/cm^2 at the nose cones to 15 W/cm^2 at the outer accelerating cavity radius. There is no power dissipated in the coupling cavities. The analytical model assumes that:

1. Coolant flow rate is equal in web cooling channels connected to the same header.

2. Heat transfer film coefficients are constant in each type of cooling channel.

In web headers, web channels and circumferential cooling channels the calculated heat fluxes are 28.9 W/cm^2, 79.6 W/cm^2 and 27.7 W/cm^2 respectively. In the web headers, the flow rate at the inlet/outlet end is 0.033 kg/s. At this flow rate, the cooling regime is below the point of fully developed boiling (FDB), therefore, undesirable transient flow problems that may be caused by liquid/vapour separation are avoided. The point of onset nucleate boiling (ONB) in the channel is determined by a minimum wall superheat (T_W-T_{SAT}) of about 3°C. On the average, the wall superheat in header channels is found to be around 8°C.

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The fl rate in each web channel is 0.011 kg/s. Here boiling is more vigorous and the cooling regime ranges from fully developed sub-cooled boiling to saturated boiling with vapour fraction at the exit end of the web channel of -0.005.

To minimize the temperature differences around the outer circumferential area, the heat removal capacity of the circumferential cooling channels, with a flow rate of 0.022 kg/s, is made equal to that of the web headers. Accordingly boiling also occurs in these channels at an average wall superheat of 9°C.

The Dittus-Boelter equation is used to evaluate the heat transfer coefficient in the single phase flow regime.

$$h = 0.023 \left(\frac{GD}{\mu}\right)^{0.8} Pr^{0.4} \frac{k}{D}$$

For the partial boiling condition that exists in the headers and circumferential cooling channels (i.e., transition from single phase convection to fully developed nucleate boiling) the correction method proposed by Bergles Rohsenow[4] was used to account for both the convective heat flux (ϕ_c) and the nucleate boiling heat flux (ϕ_{nb}):

$$\frac{\phi}{\phi_c} = \sqrt{1 + \left\{\frac{\phi_{nb}}{\phi_c}\left(1 - \frac{\phi(nb)_{ONB}}{\phi_{nb}}\right)\right\}^2}$$

where ϕ = total heat flux
ϕ_c = $h\,(T_w - T_b)$
ϕ_{nb} = $h_{nb}(T_w - T_{SAT})$
$\phi(nb)_{ONB}$ = nucleate boiling heat flux at $T_w - T_{SAT}$ corresponding to onset of nucleate boiling.

In the sub-cooled boiling region ranging from fully developed boiling to saturated boiling the Thom et al. relation[5] is used:

$$\phi = h_{nb}(T_w - T_{SAT});\ \text{where } h_{nb} = 44.4 \exp\left(\frac{p}{8.7}\right) \phi^{1/2}.$$

The resulting average heat transfer coefficient calculated for each type of cooling channel is:

- web headers and circumferential channels, $h = 4000\ W/m^2{}^\circ C$
- web channels, $h = 40890\ W/m^2{}^\circ C$.

Heat Transfer and Thermal Stress Analysis

Figure 2 shows the three-dimensional finite element model. Due to symmetry, only one quarter of a full segment needs to be modeled. A total of 1258 elements and 1824 nodes are used. First order isoparametric 8 node elements are used, with 1 and 3 degrees of freedom per node for the heat transfer and thermal stress analyses respectively. The cooling channels are approximated by quadrilateral holes with the same total heat transfer surface area, and the rounded ends of the coupling slots are modeled with squared corners.

The isotherm contours are given in Fig. 3. These show an average temperature in the outer circumferential area of 130°C. Near the beam aperture, due to the higher heat flux and the discontinuity of the conduction heat path at the coupling slots, a higher web wall temperature is predicted (T = 180°C). The highest temperature is at the nose cone (T = 230°C). Along the web cooling channel the surface temperature is also higher at the central area indicating that this is a local hot spot where the critical heat flux may be reached first in the web cooling circuits. About 40% of the total heat load is removed by the web channels alone (16% in the case of convective cooling in single phase flow). The rest is carried away in approximately equal portions by the circumferential cooling channels and web headers.

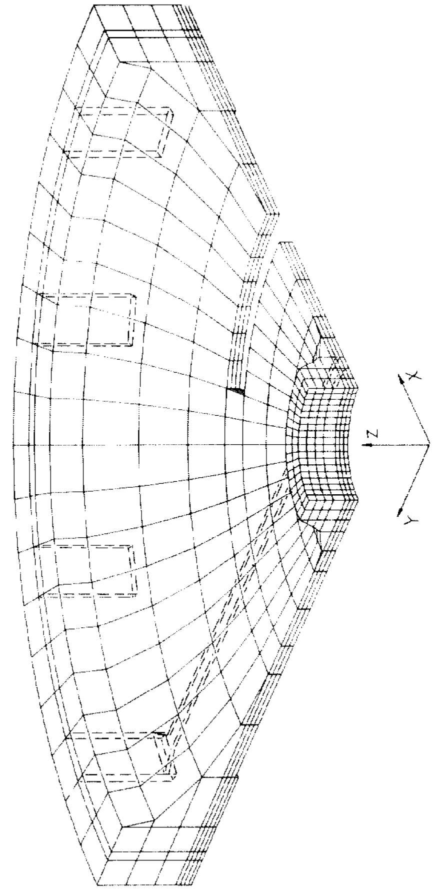

Fig. 2 The three-dimensional finite element model.

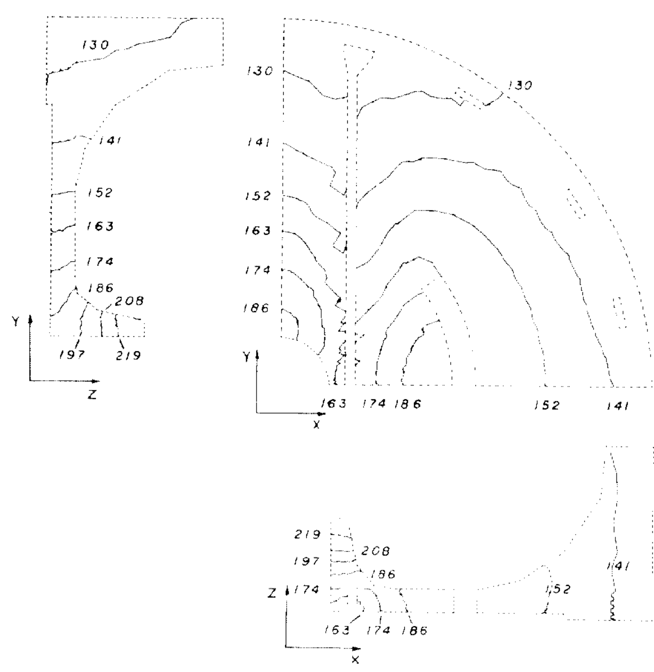

Fig. 3 Isotherms on the cavity wall (temperature in °C).

The high heat transport efficiency of the web channel helps reduce the temperature gradients and lower the thermal stress in the structure. Figure 4 shows the calculated Von Mises stress pattern in the structure with a peak stress of 78 MPa predicted on the surface of the beam aperture on the coupling cavity side. This is higher than the yield strength of the cavity material (σ_y = 69 MPa for annealed OFHC copper) so some initial plastic deformation is to be expected during the first thermal loading cycle. However, since this is lower than $2\sigma_y$, the structure should come to a predictable elastic response during the subsequent cycles[2]. Stress concentration is also predicted at the ends of the coupling slot. The stress intensity here is higher than expected because of the squared corners on the model.

In general, similar structure deformation as reported in Reference 2 is observed. The corresponding changes in frequency and stopband frequency gap are reported in Table 2 for each of the 3 accelerating cavities of the injector. The calculated change in field distribution is negligible (less than 0.01%).

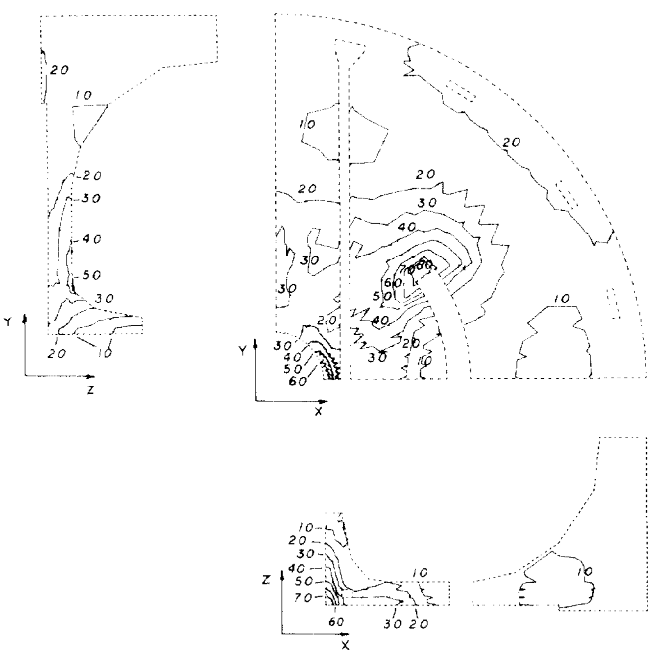

Fig. 4 Von Mises stress contours in the cavity wall (stresses in MPa).

Conclusions

Thermohydraulic, heat transfer and thermal stress analyses have been performed for the 805 MHz on-axis coupled structure with cooling channels operated in the boiling heat transfer regime. The results show that:

- At a power level of 227 kW/m only a flow rate of 0.011 kg/s is required in the web channels.

- The web channels remove heat more effectively than when operated in the single phase flow cooling regime and thus the resulting maximum stresses stay at an acceptable level.

- The structure behaviour is stable and predictable after some initial permanent detuning due to plastic deformation at the beam aperture surface.

Table 2

Frequency Shifts per Unit Displacement and Change in RF Parameters of the Structure

(from an initial state uniform temperature of 40°C)

Cavity	$\Delta f/\Delta G_A$ (MHz/mm)	$\Delta f/\Delta R_A$ (MHz/mm)	$\Delta f/\Delta G_C$ (MHz/mm)	$\Delta f/\Delta R_C$ (MHz/mm)	Frequency Shift (MHz)	Change of Stop-band Freq. Gap (MHz)
1	8.2807	-5.1917	25.677	-11.5503	-1.0984	-0.2974
2	6.0293	-5.2477	25.677	-11.5503	-1.2296	-0.3139
3	5.4331	-5.2404	25.677	-11.5503	-1.3663	-0.3384
Average for the structure					-1.23143	-0.3166

Nomenclature

C_p = specific heat at constant pressure (J/kg°C)
D = cooling channel diameter (m)
G = mass flux (kg/m^{2}s)
h = heat transfer coefficient (W/m^2°C)
k = thermal conductivity (W/m°C)
p = pressure (MPa)
Pr = $\mu \cdot C_p/k$), Prandtl number
T = temperature (°C)
W = mass flow rate (kg/s)
β = 2 x cavity length/wavelength
ϕ = heat flux (W/m^2)
μ = dynamic viscosity (kg/m·s)
σ = stress intensity (MPa)
$\Delta f/\Delta G$ = frequency change per unit displacement of the accelerating/coupling gap MHz/mm
$\Delta f/\Delta R$ = frequency change per unit displacement of cavity radius MHz/mm
ΔT_{SAT} = $T_w - T_{SAT}$

Subscripts

A = Accelerating cavity
C = Coupling cavity
b = bulk property of water
nb = nucleate boiling
SAT = saturation
w = wall

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