BOILING HEAT TRANSFER PROCESS IN THE DESIGN OF HIGH POWER LINAC STRUCTURES

T. Tran Ngoc and J.-P. Labrie
Atomic Energy of Canada Limited, Research Company
Chalk River Nuclear Laboratories, Chalk River, Ontario, Canada KOJ 1J0

Abstract

The heat removal efficiency of the boiling heat transfer process is very high. This process has been applied in the design of a high power 1350 MHz on-axis coupled structure. The operating limits of such a design and its advantages compared to a more conventional scheme with single phase flow forced convection are discussed.

Introduction

The power handling capability of room temperature linac structures is limited by the temperature gradient between the beam aperture and the outer wall of the cavities and by the water velocity in the cooling channels. The temperature gradient is responsible for thermal stresses in the beam aperture region of the cavities and permanent detuning of a structure occurs when these stresses exceed the material's yield strength. The cooling water velocity is usually kept below 3 m/s to prevent excessive erosion of the channels, thus limiting the heat transfer coefficient.

Stable operation limits have been measured with a 2450 MHz on-axis coupled structure using single phase flow cooling regime[1]. In order to increase the power handling capability and reduce the coolant flow rate in high power linac structures, better ways of removing the inherent rf heat losses are required. Table 1 gives a comparison of heat transfer coefficients for different conventional cooling techniques[2]. The higher heat removing capability of the boiling heat transfer process (one order of magnitude greater than single phase flow) is an attractive option for the cooling of high power linac structures.

Table 1

Order of Magnitude of Convective Heat Transfer Coefficients

Heat Transfer Process	Typical Heat Transfer Coefficient ($W/m^2 °C$)
Air free convection	6-30
Water, forced convection	300-12000
Water, boiling	3000-60000

This paper describes an analytical method to calculate the different cooling parameters (e.g., cavity wall temperature, heat flux and flow rate) and the results of a study of the application of the boiling heat transfer process to linac structure design. A comparison is made between a 1350 MHz on-axis coupled structure operated in single phase forced convection and in the boiling heat transfer regime. The operating characteristics as well as the maximum power handling capability are discussed along with the criteria that set limits for the design of high power structures.

Description of the Linac Structure and the Analytical Model

Figure 1 shows the cavity profile and the water cooling circuits of a 1350 MHz on-axis coupled structure made of OFHC copper. The shunt impedance is 55 MΩ/m with a first neighbour coupling coefficient of 7.5%. The following analysis was based on a 1.5 m long accelerator made up of 27 segments brazed together.

Each sub-structure has its own independent cooling circuits; web cooling plus circumferential cooling are used to obtain stable operating conditions at high power[1,3]. The circumferential cooling channels are a series of 20 holes (9.5 mm diameter) located in the outer perimeter area of the cavities and permit a through flow from one end to the other of the sub-structure. Each web cooling circuit is an inlet/outlet header system that cools alternate cavity webs. The web cooling channels (3.2 mm diameter) are oriented 45° upward with the water flow directed from a lower inlet header to an upper outlet header. The circuits are arranged in counterflow to minimize temperature differences in the structure.

Based on the above linac structure design an analytical model was developed using the following assumptions:

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

(2) Heat fluxes are uniform in web channels, headers and in circumferential cooling channels.

(3) Total heat loss distribution to different parts of the structure was ascalculated with the computer code SUPERFISH[4] and from measurements with a similar structure[1].

The heat flux is higher in the web holes than in the circumferential cooling channels or web headers. Therefore the web cooling circuits are of particular interest and are the focus of the present study.

Heat Transfer Analysis

Boiling heat transfer has been extensively studied in recent years and many excellent reviews are available[5-7]. For a uniformly heated tube fed with sub-cooled liquid, the heat transfer regime changes as shown in Fig. 2. Forced convection to single phase liquid exists between inlet and the point of onset of sub-cooled nucleate boiling (ONB) given by:

$$Z_{ONB} = \frac{W\ Cp}{\pi\ D}\left[\frac{(\Delta T_{SUB})_i + (\Delta T_{SAT})_{ONB}}{\phi} - \frac{1}{h_f}\right] \qquad (1)$$

where[8]

$$(\Delta T_{SAT})_{ONB} = \sqrt{\frac{8\ \sigma\ T_{SAT}\ v_g\ \phi}{k\ H_{fg}}} \qquad (2)$$

From this point on, the formation of vapour occurs at the surface of the tube with bubbles growing and collapsing whilst still attached to or sliding along the tube surface.

As the temperature of the liquid near the tube wall increases, bubbles start to detach from the

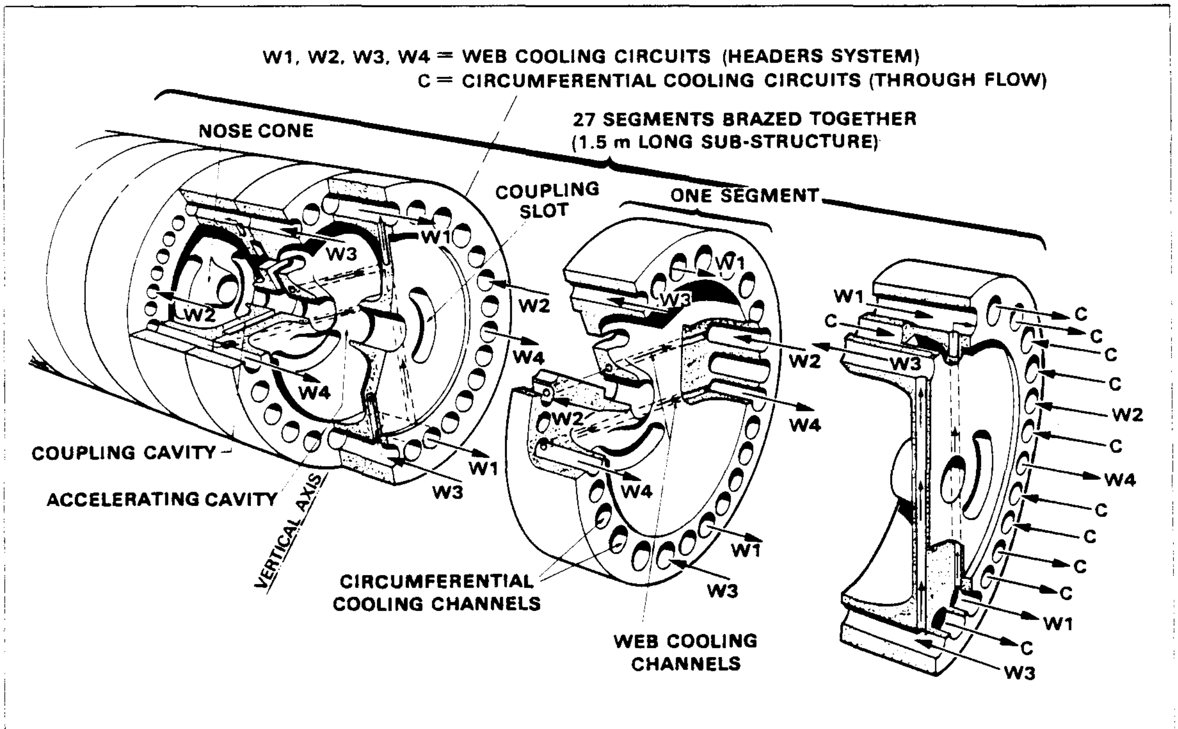

Fig. 1 Cooling circuit arrangement for the 1350 MHz on-axis coupled structure.

heated surface and condense in the colder liquid in the inner core area of the tube. This is known as the condition of fully developed sub-cooled boiling (FDB) and the point of bubble detachment is given by:

$$Z_{FDB} = \frac{W\,C_p}{\phi\,\pi\,D}\left[(\Delta T_{SUB_i}) - (\Delta T_{SUB})_{FDB}\right] \qquad (3)$$

where $(\Delta T_{SUB})_{FDB}$ is[9]:

$$(\Delta T_{SUB})_{FDB} = 0.0022\left[\frac{\phi D}{k_f}\right] \text{ for Pe} < 70\ 000 \qquad (4)$$

and

$$(\Delta T_{SUB})_{FDB} = 153.8\left[\frac{\phi}{G\,C_{p_f}}\right] \text{ for Pe} > 70\ 000. \qquad (5)$$

As the fluid temperature approaches saturation temperature, the transition between sub-cooled boiling and saturated boiling could be thermodynamically determined from a heat balance calculation (x=0, where x is the vapour fraction or fluid quality). The liquid core temperature only reaches saturation at a further distance downstream (at z=z*, see Fig. 2). The process of saturated nucleate boiling is later on replaced by the "evaporation" process as we moved into the two phase forced convection region where heat is carried away from the tube wall by forced convection through a thin liquid film then by evaporation into the vapour core. As the fluid quality increases a critical value is reached where we have complete evaporation of the liquid film. This is known as the "dryout" condition and can be estimated using the Groeneveld table method[10]. The vapour fraction at a distance Z from inlet is given by:

$$x(z) = \frac{4\,\phi\,Z}{G D\,H_{fg}} - \frac{\Delta H_i}{H_{fg}} \qquad (6)$$

The heat transfer coefficient in fully developed sub-cooled boiling and saturated boiling regime is evaluated from the following relationship[11]

$$\phi = h_{nb}\,(T_w - T_{SAT}) \qquad (7)$$

where

$$h_{nb} = 44.4\,\exp\left(\frac{P}{8.7}\right)\,\phi^{1/2} \qquad (8)$$

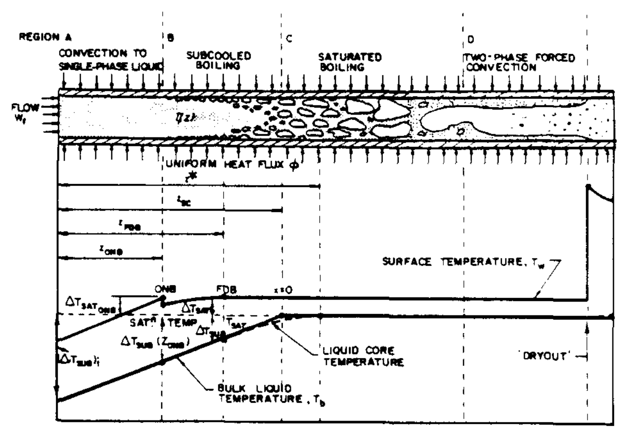

Fig. 2 Wall and liquid temperature in a uniformly heated tube[2].

Figure 3 summarizes the results of the above analytical analysis for an inlet water temperature of 40°C and a system pressure of 0.2 MPa. For a total rf heat loss of 50 kW/m in the 1350 MHz structure, the heat flux in the web cooling channels and in the web headers are 31.2 W/cm^2 and 3.2 W/cm^2 respectively. In the single phase flow heat transfer regime and for a maximum water velocity in the web cooling circuit of 3 m/s, the mass flow rate through each web hole is 0.014 kg/s and the heat transfer coefficient is 15 000 $W/m^2{}^\circ C$. The wall temperature varies between 70°C and 76°C from the first to the last web hole of the same circuit, which represent the 2 extreme cases of the heat transfer problem. The same structure, operated in boiling heat transfer regime, only requires a flow rate of 0.001 kg/s (less than 1/10 of that required in the single phase flow regime) if boiling is allowed to go up to FDB at the far end of the inlet header. At the exit end of the last web hole boiling is in saturated regime with $x = 0.21$. Here the critical heat flux (CHF) is 264 W/cm^2. In the first web hole boiling starts very soon after entrance and reaches saturation at the exit end. Therefore the heat transfer coefficient and the wall temperature remain very uniform in every web hole and are estimated to be 25 500 $W/m^2{}^\circ C$ and 133°C respectively. This higher wall temperature means a decrease in the structure shunt impedance of about 20% from room temperature condition[1].

In the boiling heat transfer regime, the operating limit for the present design is determined by the following criteria:

(1) Water velocity everywhere in the system should be below 3 m/s.

(2) Maximum heat flux should stay well below the CHF value to avoid dryout condition.

(3) Boiling in the inlet header should be limited to below FDB to avoid undesirable transient flow problems that may be caused by liquid/vapour separation.

The calculated power handling limit is 320 kW/m of rf heat losses; this corresponds to a heat flux of 200 W/cm^2 in the web cooling channels. The web hole wall temperature goes up to about 151°C and the decrease in shunt impedance is 24%. In the last web hole, the water exit quality is $x = 0.029$ (saturated boiling) and CHF value is 439 W/cm^2. Figure 3 also shows some trends of the heat transfer curve. It indicates that, for a constant heat flux system like a linac structure, any operation beyond the CHF value will drive the wall temperature almost instantly from T_A to T_B which is well above the melting point of OFHC copper. Therefore the CHF value is a very important design criterion in the boiling heat transfer process. Although the pressure drop associated with two phase flow is much higher than in the single phase flow regime, in the present design, it remains well below the limit of 30% of the initial pressure. This indicates that no choking of the flow is occuring[12] and allows the cooling circuit to be operated at a low system pressure (0.2 MPa).

Discussion and Conclusion

Boiling heat transfer could be effectively used to increase the power handling capability of room temperature linac structures. Application of this process to the design of a 1350 MHz on-axis coupled structure decreases considerably the coolant flow rate requirements and results indicate that power levels of 320 kW/m can be achieved. Despite the fact that the process is accompanied by an increase in wall temperature ($T = 151^\circ C$) and therefore a loss in shunt impedance ($\Delta ZT^2 = 24\%$), the temperature distribution remains very uniform ensuring the operating stability of the system. Experimental work is planned to verify the limitations of this cooling process. Further investigation is underway for high power linac

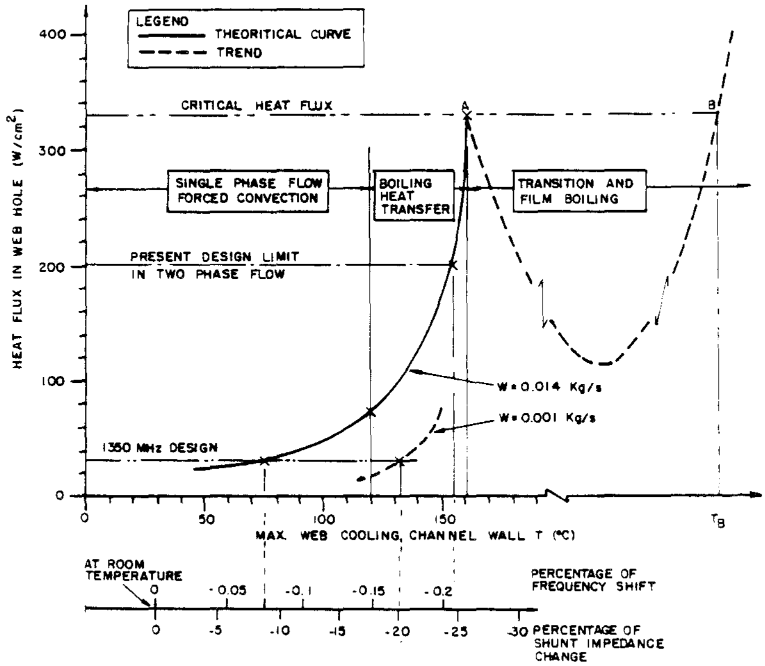

Fig. 3 Heat flux versus wall temperature in a web cooling channel (estimated frequency shift and shunt impedance change for the structure).

structure cooling designs in which boiling water is circulated by means of natural convection. Such designs are more reliable than forced convection because failure prone mechanical components such as pumps are eliminated and the cooling system is unpressurized.

Nomenclature

C_p = specific heat at constant pressure (J/kg°C)
D = cooling channel diameter (m)
G = mass flux (kg/m^2s)
h = heat transfer coefficient ($W/m^2{}^\circ C$)
H = enthalpy (J/kg)
k = thermal conductivity (W/m°C)
p = pressure (MPa)
Pe = $GD(C_p/k)$, Peclet number
T = temperature (°C)
v = specific volume (m^3/kg)
W = mass flow rate (kg/s)
x = $(H-H_f)/H_{fg}$, thermodynamic equilibrium quality
Z = distance from inlet (m)
ϕ = heat flux (W/m^2)
σ = surface tension (N/m)
$\Delta T_{SUB} = T_{SAT} - T_b$
$\Delta T_{SAT} = T_w - T_{SAT}$

Subscripts

b = bulk
f = liquid phase
g = gas or vapour phase
fg = difference between liquid and gas phase
i = inlet
nb = nucleate boiling
SAT = saturation
w = wall

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