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NEW CONCEPT FOR A HIGH-POWER BEAM DUMP

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ABSTRACT

A new concept for a dump for the ion and neutral beams used in the controlled nuclear fusion program uses thin sheets of a refractory metal such as tungsten formed into troughs having semi-circular cross sections. High-velocity water flowing circumferentially removes heat by subcooled nucleate boiling. Possible advantages are modular construction, lower water-pumping power, and a lower pressure drop than in conventional beam dumps. An example design calculation is shown for a dump capable of absorbing an incident flux of 10 kW/cm^2 .

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NOTATION

L	thickness of water channel, cm
L_{water}	channel thickness of water channel, or thickness of film
L	distance from water flow path, cm
P	water pressure, psi
q	heat flux, kW/cm ²
q_{crit}	critical heat flux at "burnout," kW/cm ²
r	radius of curvature of the water flow path, cm
T	temperature, °C
T_{exit}	water temperature at channel exit, °C
T_{inlet}	water temperature at channel inlet, °C
V	water velocity, m/s
V_{max}	maximum water velocity, m/s
ΔT_{film}	temperature difference between the cool- film surface and the water temperature, °C
ΔT	temperature difference due to heat conduction in the sheet, °C
θ	angular measurement of water flow path, degrees
ρ	mass density
μ	viscosity

INTRODUCTION

Recent technological developments in the program to produce energy from controlled nuclear fusion have resulted in the production of particle beams of unusually high intensity. These intense beams, which consist of deuterium atoms, are being used to bring magnetically confined plasmas to unprecedentedly high densities, temperatures, and

confinement times, leading many in the field to predict the establishment of scientific feasibility¹ in the experimental apparatus now under construction. The neutral atom beams developed for this new generation of experiments have energies up to 120 keV and are capable of a power density on the plasma target of up to 30 kW/cm², with the total power being over 1 MW (2). Further development should make these beams operate in steady state.

Although the intention is that these intense beams be absorbed in magnetically confined plasmas, beam dumps are necessary during beam conditioning and during startup because at these times the plasma may not be dense enough to fully stop the beam. Also, beam dumps are needed to absorb the energy of the accelerated deuterium ions after they have passed through the neutralizer in a beam line. That is, those ions not converted to neutrals must be magnetically deflected into a beam dump. Thus, there are three positions where beam dumps are needed: in the beam path used to tune up the beam system; on the opposite side of the plasma from the beam source where the penetrating beam is dumped; and after the neutralizer, where the ionized portion of the beam is dumped.

Conventionally, beam dumps are built of copper that is either tubular or that has etched passages covered with a thin copper sheet; high-velocity water is then passed through these passages or tubes. Up to several kW/cm² can be absorbed this way before the water makes the often catastrophic transition from nucleate boiling to film boiling ("burnout"). Several approaches are used to absorb high-power-density beams by spreading the heat over a large area. One common method is to incline the beam dump at a small angle to the beam so that the beam is spread over a larger area. This is satisfactory unless the resulting large size of the inclined dump is too compromising of other system

¹Defined as the production of fusion power equal to the heating power absorbed by the plasma.

requirements. Another approach is to rotate the beam dump as is done in x-ray tubes and in rotating-target neutron sources. However, these dumps usually do not accommodate themselves well to large-area beams having a typical dimension up to 1 m. In a design recently suggested by Yoshikawa (2), rotating, cooled, hollow tubes are used. In another suggested approach, Wells (3) and Yoshikawa (4) provide a number of design details for a dump in which the beam impinges directly on a stream of liquid metal.

Two major problems associated with high-heat-flux beam dumps are the very high power required for pumping the cooling water and the fabrication of the thin-walled refractory metal surfaces that are needed for maximum performance. An array of thin-walled tubes containing high-velocity water is a straightforward way to build a beam dump and is predicted to give high performance. For example, Hoffman et al. (5) describe 2-m-long, 10-mm-diam Ta-10W tubes with a structural factor of safety of 4 and a pumping power of 400 kW/m² of normal surface that can absorb a heat flux of 1.3 kW/cm²; however, for higher heat fluxes, pumping power increases rapidly and structural safety factor decreases.

Very high heat fluxes (greater than 10 kW/cm²) have been absorbed using short test sections and a very high pressure drop; for example, Gambill and Green provide data for a 11-kW/cm² flux inside a 0.62-cm I.D. by 2.3-cm-long tube with 300-psi differential pressure and a swirl generator (6). However, this performance cannot be achieved in long tubes (about 1 to 2 m) because of excessive pressure drop and, for most applications, excessive pumping power.

For some applications, there may be advantages to another design approach, one in which water flows in a curved path normal to the axis of the cylindrical surface rather than parallel to the axis as in a tube with axial flow: pumping power may be less because high water velocity can be established selectively, where it is needed for high heat flux, rather than being established over the entire perimeter of a tube; and refractory metal alloys may be more easily available in sheets than tubes. We have designed an example beam dump which our calculations show has the potential to achieve high heat-transfer performance with reasonable pumping power. Whether these advantages can be realized in a practical design is not clear.

THE CONFIGURATION

Figure 1 shows the beam-dump configuration relative to the incident beam. The x- and y-axes are in the plane of the dump surface. The z-axis is normal to the plane of the dump surface. The dump is oriented so the incident beam is in the y-z plane. A cross section of the dump in the x-z plane is shown in Fig. 2. A thin metal sheet is bent into a cylindrical shape as shown with water flowing on the concave surface in the gap between the sheet and a backing surface. In the figure, the sheet is shaped as a portion of a circular cylinder. For the example case, the bending stresses caused by the pressure drop will cause a slight departure from the circular shape; however, the stresses are small and the deflection is negligible. The width of the beam dump in the x-direction can be made any size by adding the basic modular units. Likewise, repairs can be made

Fig. 1. Configuration of beam dumps relative to the incident beam.

Fig. 2. Cross section of the beam dumps, showing the water-flow paths and the modular construction.

by replacing only one module. This dump can also be made as long as desired in the y-direction, an advantage over tubular dumps because the pressure drop and the temperature rise with length make the long tubes impractical for very high heat fluxes.

The individual module is shown in cross section in Fig. 3. Note that the water channel thickness or gap, d , is thinner at the front of the module and thicker at the inlet and outlet. Since the incident power density is maximum at the front, the water velocity is increased at the front so that the variation in heat transfer will match the variation in power density. Thus, the maximum water velocity occurs only where needed, and pressure drop is minimized.

EXAMPLE CALCULATION

Maximum Critical Heat Flux

Data are not available for the conditions of this design. However, we can estimate by extrapolating from experiments in which very high heat

Fig. 3. Module cross section showing a variable water-channel thickness. Channel is thinnest, producing the highest velocity where the incident beam is most intense.

Thin-sheet subcooled flow-boiling water have been demonstrated on small areas. Shafer and Jack achieved 13 kW/cm^2 in tests on a simulated arc-jet nozzle (7) and we have estimated the maximum critical heat flux q_{crit} for "burnout" conditions using their results as presented in an empirical correlation developed by Roussar (8):

$$q_{crit} = 0.85 \left(1 + \frac{V \Delta T_{sub}}{1906} \right) \Delta H / \text{cm}^2 \quad (1)$$

where V = average water velocity in m/s, and ΔT_{sub} is the temperature in °C below saturation temperature at the local water pressure. Thus, we assume that q_{crit} depends only on ΔT_{sub} and V ; this assumption, however, is not established experimentally for our assumed geometry.

Let the gap l vary a factor of two as given by

$$l = d_0 (2 - \cos \theta) \quad (2)$$

where $\theta = 0$ at the point of maximum heat flux and $\theta = \pm 90$ at the water inlet and exit and where d_0 is the minimum gap size shown (see Fig. 3). For $q_{max} = q_{crit}$, and for a given ΔT_{sub} , we determine V_m from Eq. (1). The pressure drop is therefore

$$P = \int_{-\pi/2}^{\pi/2} \left(\frac{\Delta P}{\Delta l} \right)_r r d\theta$$

where l is the distance along the water-flow path and r is the radius of curvature of the water-flow path.

Assuming established single-phase flow, we estimate the drop in water pressure from the friction factor relationship for nonboiling flow in tubes:

$$\left(\frac{\Delta P}{\Delta l} \right)_r = \frac{1}{2d} \frac{V^2}{f}$$

where $f = 0.316 \text{ Re}^{-0.25}$ and $\text{Re} = \rho V 2d / \mu$. Thus, using Eq. (2) for d , we can determine the pressure drop:

$$\Delta P = \left(\frac{\Delta P}{\Delta l} \right)_{max} \int_{-\pi/2}^{\pi/2} \frac{d\theta}{(2 - \cos \theta)^3}$$

where

$$\left(\frac{\Delta P}{\Delta l} \right)_{max} = \frac{\ell_0}{2d_0} \frac{V_m^2}{f}$$

If we evaluate the integral, we obtain

$$\Delta P = \left(\frac{\Delta P}{\Delta l} \right)_{max} 1.5 r$$

[Note: For a constant gap d_0 , the pressure drop would be $\Delta P_0 = (\Delta P / \Delta l)_{max} r$. Therefore, varying the gap this way reduces the pressure drop by a factor of

$$\frac{\Delta P}{\Delta P_0} = \frac{1.5}{1} = 0.48]$$

Using Eq. (1) for determining V_m and assuming $d_0 = 1 \text{ mm}$, at $\Delta T_{sub} = 200^\circ \text{C}$ we calculate pumping power for various values of q_{max} as shown in Fig. 4. For an incident flux of 10 kW/cm^2 , the example design parameters then are:

$$\begin{aligned} r &= 1 \text{ cm} \\ d_0 &= 0.1 \text{ cm} \\ V_m &= 55 \text{ m/s} \\ \Delta P &= 25 \text{ psi (0.17 MPa)} \\ P_{inlet} &= 450 \text{ psi (3.1 MPa)} \\ P_{exit} &= 425 \text{ psi (2.9 MPa)} \\ \text{Pumping power} &= 0.48 \text{ MW/m}^2 \\ t_{inlet} &= 30^\circ \text{C} \\ t_{exit} &= 39^\circ \text{C} \end{aligned}$$

If we assume the thermal conductivity of tungsten, the stresses in the sheet are:

$$\begin{aligned} \text{Thermal stress} &= 26 \text{ kpsi (179 MPa)} \\ \text{Hoop stress} &= 25 \text{ kpsi (173 MPa)} \\ \text{Total stress} &= 51 \text{ kpsi (352 MPa)} \end{aligned}$$

At the location of maximum heat flux,

$$\begin{aligned} t_{water} &= 35^\circ \text{C} \\ \Delta t_{film} &\approx 200^\circ \text{C (5)} \\ \Delta t_{conduction} &= 160^\circ \text{C} \end{aligned}$$

Therefore, the maximum surface temperature of the tungsten would be about 400°C .

This design has some apparent problems, such as the difficulty of shaping the sheets into a curve with the small radius ($r \approx 1 \text{ cm}$) required to limit hoop stress while still providing a practical water manifold design. Also, other materials may be superior to tungsten; nevertheless, it is sug-

²Note that we use $2d$ in place of tube diameter for the flow in a gap.

Fig. 4. Pumping power versus incident power.

gested that this design be considered for high-heat-flux applications where simple tubing arrays also have serious limitations. For example, we can compare the pumping power required for this design (0.05 MW/m^2) with that for a circular tube with the same water velocity (and, therefore, the same ΔT_{sub} , assuming that the same ΔT_{sub} can be maintained). For a 1-cm-diam tube (as used in the study of Ref. 6), for $q = 10 \text{ kW/cm}^2$ and $V = 55.2 \text{ m/s}$, the required pumping power would be 1.5 MW/m^2 . Therefore, the tube design requires about 3 times more pumping power than the curved-sheet design described here, and tube length would be limited because of high pressure drop ($\Delta P \approx 300 \text{ psi/ft}$).

FABRICATION

There may be several ways to build this type of beam dump, two possibilities are suggested here. One, shown schematically in Fig. 5, is to fasten curved sheets, that are approximately half-cylinders in shape, to a backing block. The critical fabrication step is the brazing of the sheet to the block. The braze joint must be leak tight because there will be high-pressure water on one side and vacuum on the other. The beam must not be allowed to hit the sheet at the ends where, because of the end cap, the cooling is poor. Because of support from the adjacent cells, the braze joints will be under only shear stress, except at the end cap where special design care will be necessary.

Inlet and outlet manifolding is a formidable design problem because of the very high-volume flow rates ($2.6 \text{ m}^3/\text{s}$ for 1 m^2 of normal surface for the 10-kW/cm^2 case described above).

Another way to build the beam dump is to use tubes. As illustrated in Fig. 6, thin sheet is formed into a tube and brazed to a curved backing plate. The seam could be a lap joint and need not be absolutely leak tight. An inner tube or rod of smaller diameter is located so as to form the vary-

ing width channel. This design may have structural advantages.

Fig. 5. Alternate module design, showing the inlet and outlet of the ends.

Fig. 6. "Tubular" module. The tube is self-supporting and therefore does not need its neighboring modules to take up the static pressure.

CONCLUSION

For large-area beam dumps capable of absorbing heat fluxes greater than 5 kW/cm^2 , there may be advantages to using this concept of water flowing in a curved path of short length rather than axially through tubes. Major advantages are that less water pumping power is needed, and a reasonable pressure drop is possible for large-area beam dumps. We have made an approximate calculation of