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ELECTRODE COOLING FOR LONG PULSE HIGH CURRENT ION SOURCES

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Summary

The need for cooling of electrode surface in ion sources for neutral beam line applications is summarized. The properties of possible cooling fluids are discussed and the decision to use water as a cooling fluid of choice is explained. The influence of source geometry on the design of a cooling canal is examined and two possible designs are presented. The need for model testing and the results of the tests on a model cathode are also discussed. Some remarks are also made on a method of predicting burnout failure of a cooled electrode.

MASTER

Introduction

The next generation of fusion reactor experimental facilities will require neutral beam heating system with significantly increased power levels. Neutral beam currents of 20 Amperes (equivalent) beam pulses of 5 to 100 seconds and injection energies of from 150 to 400 KeV have been quoted. Sources designed to meet these beam line specifications must incorporate cooling systems for the various electrode surfaces. The extraction and acceleration grid structures of positive ion sources and the cathode structures of surface plasma negative ion sources present particularly difficult problem of cooling.

At Brookhaven National Laboratory the Neutral Beam Group is currently developing surface plasma sources of the Penning and Magnetron type. Fig. 1 shows the B.N.L. MK IV Penning source. The objective is to design and construct a source module to deliver 10 Amperes of H^- with a pulse length of up to 100 seconds. Sources will be stacked to meet the beam line requirements. It has been estimated[1] that a source capable of meeting the above requirements will require an arc power of 200 kw and that this power is distributed 70% to the cathode structure and 30% to the anode. Assuming a power efficiency of 50 MA/kW this results in a heat load to the cathode of 3 kW/cm^2. In addition, it is necessary that the surface temperature of the cathode be maintained at between 300°C and 600°C during the power pulse.

Cooling of surface plasma sources of the Penning and Magnetron type present particularly difficult problems at high heat fluxes. Cooling takes place at or close to the nucleated boiling regime and thus allows only a small margin of error. This paper will discuss the relative merits of the various cooling fluids available and the type of cooling process used. Due to limitations conditioned by the geometry of the source, the cooling fluid starting length becomes a dominant factor in the heat removal process. The most satisfactory method of design is by model testing. Brookhaven National Laboratory and Westinghouse Electric Corporation I.G.T.D. have constructed test stands to carry out model testing experiments. Results will be presented on the cooling of a possible cathode design for the BNL MK IV Penning source.

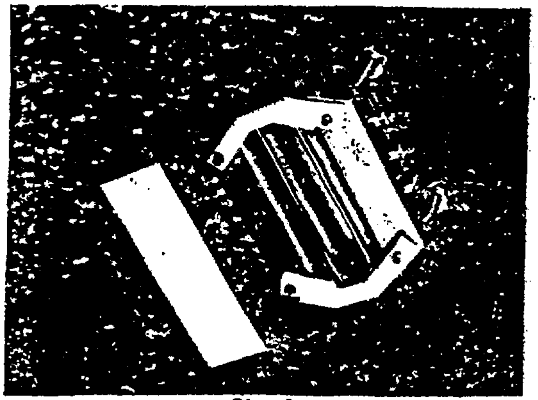

Fig. 1
MK IV Penning Source

The importance of the ability to predict the onset of cooling failure leading to burnout is examined and a method is proposed which may be useful to predict burnout.

Choice of a Cooling Fluid

The primary objective of the Brookhaven program is to develop a source module capable of delivering 10 Amperes of H^- with a pulse length of up to 100 seconds. From thermodynamic considerations the heat load may be considered continuous with temperatures becoming stable, other than total system enertia, within a few milliseconds. The electrode cooling system will consist of three major assemblies which are connected.

a. Heat abstraction.
b. Fluid transportation, including pumping.
c. Heat rejection.

The system should use reliable, well tested techniques and should not be a development program in itself. The heat abstraction system is very strongly related to the design of the source and to a lesser degree to the choice of fluid. The fluid transportation, other than pressure and temperature considerations, is dictated by the choice of fluid, as is the heat rejection system.

A cooling fluid should have the following properties.

a. Able to remove the required amount of heat within the temperature limitations.

b. Be safe to use and have no undue hazard during source operation.

c. Easy to handle when changing sources and carrying out other modifications to the source system.

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d. Able to insulate the electrode voltage during operation.

e. Be compatible with all source materials.

f. Have a low pumping horsepower.

Possible cooling fluids are:

a. Liquid metals and heat transfer salts.

b. Hydrocarbon and silicone-based heat transfer fluids.

c. Demineralized water (pressurized).

Many of the liquid metals and heat transfer salts may be disregarded due to temperature considerations. The melting point needs to be 100°C or less in order to allow for a reasonable temperature drop through the electrode wall when operating at 300°C. It would be advantageous if the melting point is below room temperature. Mercury, cesium and two of the NaK alloys meet the ideal conditions. The disadvantages of these possible liquid metals is that they are either very toxic or highly reactive. In addition, they are also very good electrical conductors. The major advantage is that they are good conductors of heat with film coefficients ranging from 1.7 to 3.69 W/cm² °C.

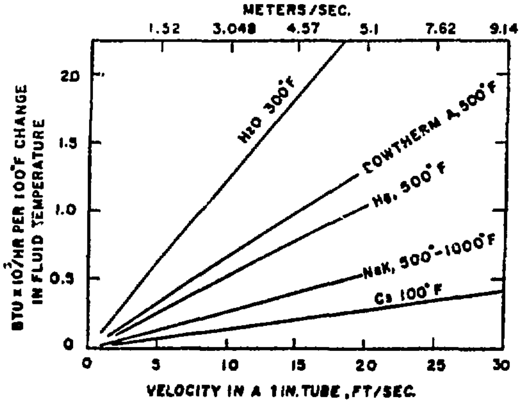

Fig. 2
Comparison of Heat Transporation Properties of Various Cooling Fluids

The hydrocarbon and silicone based heat transfer fluids are generally suitable for use in the required temperature range and have good electrical insulating properties. The major disadvantage is that most have some form of environmental hazard problem and also have rather low heat transfer properties. Dowtherm "A" film coefficients range from 0.17 to 0.284 W/cm² °C.

Cooling systems using water can be shown to have heat transfer film coefficients comparable to the liquid metals. By demineralization and pressurization, the fluid can be made essentially nonconducting and also able to operate in the required temperature range.

The major advantages of water cooling are that the techniques are fully developed and are in everyday use. When work is done on the source, no toxic or hazard problems exist. There are no environmental problems and water is compatible with all the materials used within the source.

Fig. 2 & 3 compare the properties of the fluids considered.

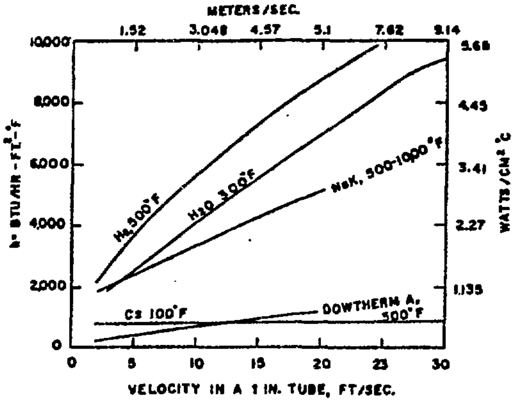

Fig. 3
Comparison of Film Coefficient of Various Cooling Fluids

It is clear from the foregoing that demineralized pressurized water has considerable advantage over the other possible heat transfer fluids and is the fluid of choice for the source development program. At some future date, other considerations may require a re-evaluation of this question. For example, it is necessary to supply cesium to the interior of the source and it may be possible to combine a closed loop cesium liquid metal cooling system with a cesium supply system.

<u>Demineralized Pressurized Water as a Cooling Fluid</u>

Water is in everyday use as an energy transfer fluid; the following are typical design heat flux values for commercial equipment.

a. Utility Boilers	47.3 - 63 W cm^{-2}
b. Current Solar Boilers	70 - 100 W cm^{-2}
c. Marine Boilers	47.3 - 50 W cm^{-2}
d. Naval boilers (high rated)	95 - 100 W cm^{-2}

These figures should be compared to the required value of 1000 to 3000 W/cm².

The variation of heat flux with ΔT is assumed to follow the well-known Nukiyama curve. As $\Delta T = T_w - T_s$ increases so the influence of the fluid velocity on the heat flux transmited decreases. For a very large ΔT the heat flux seems to be almost totally independent of fluid velocity within very large velocity variations. The fluid velocity and, hence, the mass flow are the controlling factors in the value of the burnout heat flux.

A correlation developed by Engelberg-Foster and Grief[2] for application in the nucleated boiling regime, i.e. large ΔT, yields

$$\overline{q} = 4.3\cdot10^{-5}\,\frac{a c \rho_l\ T_s}{\sigma^{1/2}(L\rho_v)^{3/2}}\left(c T_s a^{1/2}\right)^{1/2}\left(\frac{\rho_l}{\mu}\right)^{5/8}\left(\frac{\mu c}{k}\right)^{1/3}\Delta P^2 \qquad (1)$$

Where:

D = Diameter ft.
G = Mass velocity lbs/ft.^{2}
h_1 = Film coefficient btu/hr. ft.^{2} °F
$\overline{q}$ = Heat flux btu/hr. ft.^{2}
T_1 = Temperature degree °F
P = Pressure lb./ft.^{2}
T_s = Saturation temperature °F
T_w = Temperature of heating surface °F
$T_w - T_s$ = T_1 = superheat temperature °F
$T_s - T_1$ = T_2 = subcooling temperature °F
$T_w - T_1$ = $T_1 + T_2$ Overall temperature difference °F
ΔP = Pressure difference corresponding to super-heat temperature T_1 lb./ft.^{2}
L = Latent heat of vaporization of fluid btu/lb.
ρ = Density lb./ft^3
c = Specific heat at constant pressure btu/lb. °F
k = Thermal conductivity btu/hr.ft.^{2} °F/ft.

σ = Surface tension lb./ft.
μ = Viscosity lb./hr.ft.
a = Thermal diffusivity ft.^{2}/hr.

Subscripts: 1 = liquid, w = wall, v = vapor

Note that there is no velocity term and that the dominant terms are T_s and ΔP. This correlation has shown close agreement with experimental results for nucleated boiling in pressurized water and mercury.

For the twisted tape configurations, shown in Fig. 5, the expression, developed by J Kim et al[8] is applicable.

$$\overline{q} = 1.46 \times 10^{-2} \, \Delta T_1^{\,2.854} \qquad (2)$$

where the tap twist ratio y = 2.48.

At moderate values of ΔT, the velocity term becomes more significant in the energy transfer process and the following correlation developed by Sieder and Tate[3] appears to agree with experimental results.

$$\frac{h_1}{G\,c_1}\left(\frac{c\,\mu}{k}\right)_1^{2/3}\left(\frac{\mu_w}{\mu_1}\right)^{0.14} = \frac{0.023}{(DG/\mu_1)^{0.2}} \qquad (3)$$

In order to maintain the required cesium layer on the operating face of the cathode, the surface temperature must be maintained between 300 °C and 600°C. System pressures of between 250 and 500 psi are required to supress boiling and maintain the surface temperatures at the required value.

Cooling Canal Design

The source geometry is very often an overriding factor in the space allowed for water cooling canals. The entrance and exit region of a canal presents difficulties in that sharp turns cannot be avoided in most cases. Fig. 4 is a cooled cathode design for the BNL MK IV Penning source shown in Fig. 1.

Here there are many variations in cross section and direction of fluid flow. The starting length is defined as that distance over which the fluid velocity profile continues to change due to a change of canal cross section or flow direction. This distance may vary between 10 and 60 diameters depending upon the fluid velocity and type of entry. A modification of equation (2) may be used to calculate these effects[4], clearly a better solution is to avoid the problems by design wherever possible. Fig. 5 shows the component parts of a cathode designed by the Westinghouse Electric Corp. I.G.T.D. for the B.N.L. MK V source shown in Fig. 6.

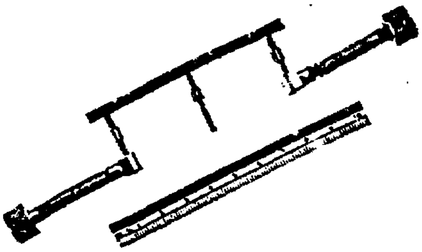

Fig. 4
MK IV Penning Ion Source
Cathode Assembly

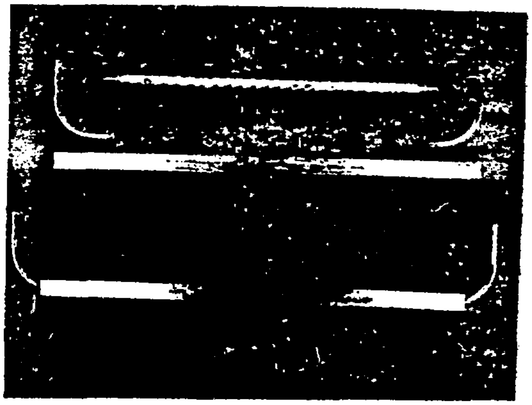

Fig. 5
Component Parts of MK V
Penning Ion Source

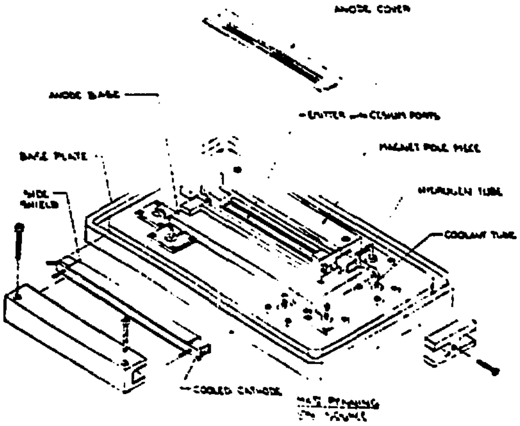

Fig. 6
MK V Penning Ion Source

As an example, consider the structure shown in Fig. 7. This represents a possible cathode design for low power cw operation in the BNL MK IV Magnetron source. Because of source test stand limitations it is intended that the water system be a once through to drain with no pressurization using domestic water. Water will be supplied to the cathode and returned to ground through water chokes. The water flow passage involves two right angle bends at entrance and exit and a central divider to reproduce two separate water circuits. Equation (3), or any modification of this equation, is not applicable due to the short length of the heated section of the canal. Application of equation (1) with an internal pressure of 15PSIG and a T_w of 350°F, (all other fluid properties obtained from standard references) yields

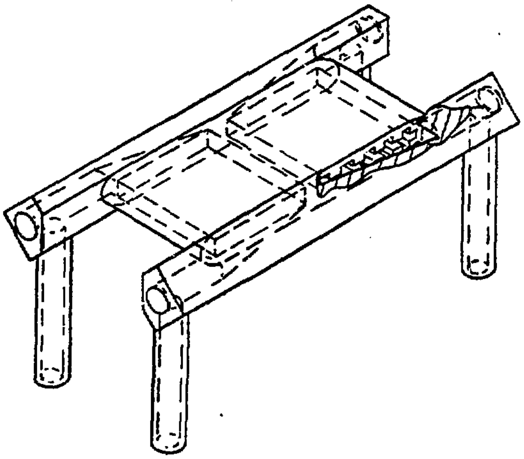

Fig. 7
MK IV Magnetron Ion Source
Cathode Assembly

$$\bar{q}\ 4.3\cdot10^{-5}\cdot\frac{0.0065\cdot59.8\cdot250}{0.044^{1/2}(945\cdot0.073)^{3/2}}\left(250\cdot0.0065^{1/4}\right)\left(\frac{59.8}{0.702}\right)^{5/8}$$

$$\left(\frac{0.702}{0.383}\right)^{1/3}2.286\cdot10^{8} \qquad (4)$$

$$\bar{q} = 3.225\cdot10^{5}\ \text{btu/hr.ft.}^{2} = 102\ \text{watts/cm}^{2}$$

By slotting the cooled surface to give a surface enhancement ratio of 2.5 yields a cathode operating surface heat flux

$$Q = 250\ \text{W/cm}^{2}\ \text{cw}$$

Making reasonable assumptions on the rest of the water system and allowing for a 20°F temperature rise of the water, a flow rate of 511 lbs./hr. results, giving a velocity of 6.8 ft./sec. and a Renolds number Re = 44318. Applying Fannings equation results in a rather modest pressure drop of 4 PSI.

A computer run using the DOT[7] computer code yields a mean surface temperature of approximately 250°C under this heat flux. It is anticipated that the actual heat flux may be higher due to the Hypervaportron effect.[9]

The maximum thermal stress is induced under startup conditions when the temperature across the Molybdenum wall will reach approximately 230°C.

Local bending stress $P = 1/2\ \Delta T\ \alpha E$

which yields P = 24500 lbs.

The U.T.S. for Molybdenum at 250°C is listed at 10^5 lbs./in.^{2} giving a factor of safety of 4. Under normal operation this stress will be reduced. The method of location for the cathode within the anode will allow for thermal expansion.

The use of domestic water as a cooling fluid is not recommended except as an expedience to facilitate a testing program. The usable life of cathodes with small dimension cooling canals and using domestic water is not expected to be very great.

Deposition of metal salts etc. on to the cooling passage walls in the boiling zone will cause localized blockages leading to failure. Deionization of the water removes these metal salts, thus providing insulation of the cathode voltage with respect to ground, also preventing the deposition of these salts in the cooling space.

One version of the Penning type cathode shown in Fig. 5 contains a twisted ribbon to provide enhanced heat transfer properties to the fluid. The starting length is reduced by use of shaped fluid entry sections and a mask is used to shield the starting length from the applied heat load. Assuming a system pressure of 15PSIG and T_w = 325°F application of equation (2) yields

$$\bar{q} = 1.46\cdot10^{-2}(325-250)^{2.854}$$

$$\bar{q} = 3.28\ \text{kW cm}^{-2}$$

Again if reasonable assumptions are made on the rest of the system and a fluid temperature rise of approximately 100°F is allowed, then a flow rate of 480 lbs./hr. results in giving a velocity of 9.55 ft./sec and a Renolds number Re = 61500. A twisted slot version of this cathode has also been fabricated.

At high T with nucleated boiling, two phase flow in the cooling fluid takes place. Under these conditions, even minor changes in cross section, with associated pressure changes, can cause a vapor lock and burnout conditions. The most satisfactory method of design is a calculated first pass followed by model testing. Computer studies have been made of various cathode cross sections suitable for the MK IV and MK V Penning sources.[5,6] Film coefficients were computed from Equations 1, 2, and 3.

Cathode Testing Program

Test stands suitable for testing possible cathode designs have been constructed at BNL and at Westinghouse Electric Corporation R & D Center. The Westinghouse test stand is capable of simulating cathode heat loads of up to 5 kW/cm^2. This test stand is more fully described in paper 20-07 of this symposium. The BNL test stand is similar, but has lower power capability.

The Penning cathode shown in Fig. 5 was tested in the BNL test stand at a power level of 600 W/cm^2. Figure 8 shows the variation of surface temperature with input power for two points along the length of the canal, and also contains a calculated curve of the mid point temperature. The influence of the change of cross section at the exit passage is clearly indicated. The Penning cathode shown in Fig. 6 will be tested at the Westinghouse R & D Center.

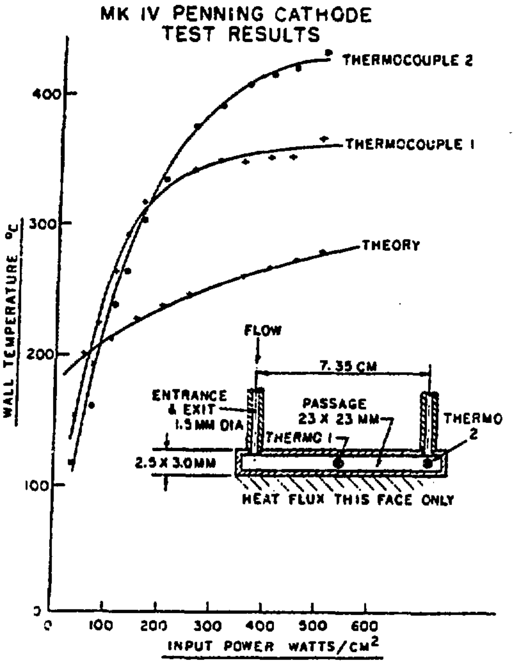

Fig. 8
MK IV Penning Cathode Test Results

Prediction of Burn Out

The failure of a cooled electrode under test or service conditions will lead to the discharge of substantial quantities of fluid into a vacuum system. This type of failure can mean a major interruption of a testing program or, even worse, the shutdown of a neutral beam line. The failure of a water cooled surface results from the formation of a steam sheath between the cooling fluid and the surface. Heat transfer takes place by gas convection and radiation only leading to a rapid rise in temperature. For the design shown in Fig. 5, this temperature will exceed the melting point of the material within approximately 100 m secs. It is, therefore, essential to provide a method of predicting the onset of failure of a cooled surface.

One approach to this problem is to use the change of sound "signature" with power level increases as a prediction of burnout failure. The design shown in Fig. 5. is a twisted ribbon inserted into a bore. Heat is supplied at one side only, therefore, steam bubble nucleation sites will be at this side only. The size and frequency of steam bubble formation will depend upon the power level. After a bubble leaves the surface, the distance travelled around the twisted helix before condensing will depend upon the power level. If suitable detectors are mounted into the water system at locations close enough, the sound signature of the growth and collapse of these steam bubbles may be detected. As the power level is increased, steam bubbles will travel such a distance that they again reach the heated surface before condensing and may no longer undergo collapse. At this point, a significant change in the sound signature may be detected. Buoyancy forces associated with the centrifugal forces imparted by the helix twist cause bubbles to migrate towards the center of bore. It is, therefore, probable that some long lived steam bubbles will collapse leading to difficulties in understanding what a particular sound signature means.

The collapse of a steam bubble can be associated with pressure changes and it is, therefore proposed to insert quartz piezo pressure transducers into the water system. These transducers will be mounted as close as possible to the cooled surface and the frequency spectrum will be recorded on magnetic tape. Electrodes will be tested to burnout and the frequency spectrum characteristics will be analyzed for significant events. Once the failure characteristics have been established, it will be a relatively simple matter to make real time electronic comparisons with the frequency spectrum of an operating system. At the point that a frequency match occurs with the failure frequency spectrum, a shutdown signal can be provided.

Conclusion

The BNL cooled electrode development program is aimed at the production of electrode structures capable of sustained operation under an incident heat flux of 1.0 to 3.0 kW/cm². The properties of the various cooling fluids available have been examined and the decision has been made that demineralized pressurized water will be the fluid of choice. The temperature of the electrode operating surface will be controlled by variations in the system pressure. Two possible cooling canal geometries have been examined and calculations show that a heat flux up to 3kW/cm² can be removed from a cathode suitable for use in a BNL MK V Penning source. Progress has been made on the construction of test stands and some electrode models have been tested at power levels of 0.6 kW/cm². There is indication that a method of predicting the onset of burnout failure will work.

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