AN ULTRA-THIN SEPTUM MAGNET

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Introduction

Beam extraction efficiency can be improved by using an extraction magnet with the thinnest possible septum and the highest possible magnetic field. This improvement in performance is applicable equally for magnets used for extraction from a machine as for momentum separation in a beam transport system.

The extent to which a thin current-carrying septum reduces the fringe magnetic field depends, among other things, on the thinness of the septum. As the magnetic field obtained in the gap is dependent on the current-carrying capacity of the magnet, it follows that the best results obtain with a high current density in the septum thickness.

The lower the septum temperature the higher the current-carrying capacity. This necessitates turbulent cooling water flow to obtain good heat transfer, something difficult to sustain with longitudinal cooling passages of long length relative to the cross-sectional area. Transverse cooling passages allow full generation of turbulent flow with minimal pressure drop for the range of apertures being considered. They also reduce transverse current variations in the septum thus minimising transverse field perturbations.

This type of construction allows, within limits set by the installational environment, septum magnets of any length, straight or curved to suit the particular beam dynamics. Further, the thin septum of this construction reduces beam lost due to nuclear interactions.

The range in which it is necessary to operate is outside normal practice for heat transfer and fluid flow. A search of the literature has revealed little relevant work reported.[1]

Fluid Dynamics

The need for turbulent flow within the cooling pipes necessitated trials to check the validity of the Darcy equation and of the value of the critical Reynolds Number.

Trials were first done to ascertain if the Darcy equation for calculating pressure drop in pipes is valid when applied to extremely small bore pipes.

The Darcy equation is of the form

$$V = Kx \propto y\beta$$

If the diameter of pipe is constant then $X = K_2$ hence $\log V = \beta \log y + \log K_3$.

From this equation the relevant constants were found by plotting flow against pressure drop. With velocities up to 80 ft/sec the validity of the Darcy equation was confirmed, using small bore pipes.

The importance of the intake configuration and the likelihood that a practical design would embody a Borda mouthpiece led to an investigation into the effect of such an intake on flow, and into the influence of bell mouthed intakes and intakes with the inlet edges carefully deburred. The latter is important since particles torn from edges could block the pipes and also, because of the adverse ratio of edge surface to cross-sectional area of small diameter pipes creating relatively larger pressure loss at inlet.

Deburring and bell mouthing were done with suitably sized needles. A well deburred pipe entry improved flow by about 10%. Further improvement in performance due to bell mouthing was not significant.

Trials showed that a Reynolds Number of between 3000 and 6000 was necessary to ensure turbulent flow. Attempts to establish the transition point were made by accoustic means using a stethoscope, by vibration measurement using an accelerometer with its output transduced to give a voltage readout, and finally by simple observance of the jet of water issuing from the free end of the pipe under test. A change in flow pattern was clearly observed over a Reynolds Number band of 200 - 300. Fig. 1.

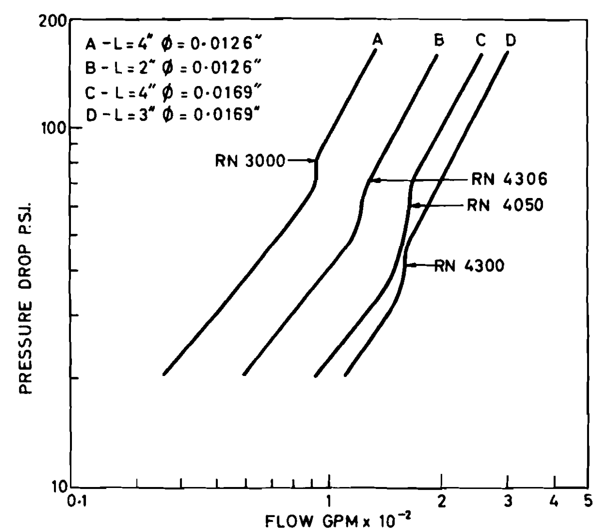

Fig. 1. Transition Laminar/Turbulent Flow.

Further investigation was made into the influence of length/diameter on the critical Reynolds Number, since it was thought the relatively high value observed may be due to the existence of two critical velocities — first reported by Osborne Reynolds in 1913. Trials on a 0.0169 in. internal diameter pipe showed that the transition occurred with a flow of 0.162 cubic inches per second (2.66 cc/sec) at a length of 2.5 in. (6.4 cm), i.e. about 150 diameters. The mass flow is equivalent to a mean velocity of 61 ft/sec (18.6 m/sec), corresponding to a Reynolds Number of 9700. Fig. 2.

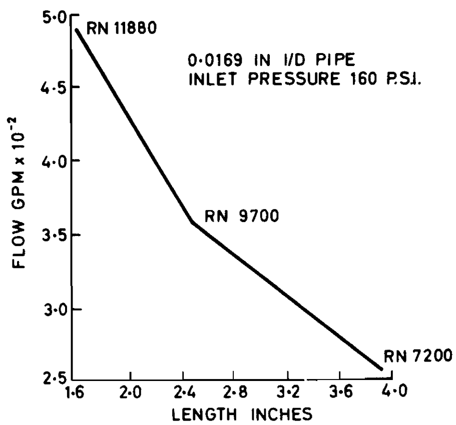

Fig. 2. Influence of L/D on Transition Point.

Heat Transfer

Basically a high rate of heat transfer is required between the septum and the cooling water if a high current is to be sustained. This can be effected by increasing the ratio of surface area to volume of cooling channel and by using a high water velocity.

If the classic formulae

$$\frac{hD}{k} = 0.023 \frac{(DG)^{0.8}}{(\mu)} \frac{(Cp\ \mu)^{0.4}}{(K)} \qquad (1)$$

is reduced in terms of the variables then

$$h \propto \frac{V^{0.8}}{d^{0.2}} \qquad (2)$$

assuming K and μ to be constant over the temperature range considered.

But $q = hA\Delta t$ and as $A = \pi dL$

$$q \propto V^{0.8}\, d^{0.8}\, L\Delta t$$

Hence the heat transfer coefficient (h) will increase with an increase in velocity, but decrease with an increase in diameter. The heat transfer will increase in velocity and increase in diameter. With the case of small bore pipes, to redress the loss of heat flux with the small diameter, the coolant velocity and Δt must be high. The heat transfer per unit length of septum is marginally better with the thinner septum using the smaller tube diameter.

Trials were carried out to determine heat transfer rates and to confirm the classical empirical formula for forced convection conditions. A series of measurements were made using stainless-steel pipes since these were readily available. Heating was by the resistance to the passage of current along the length of pipe, temperatures being recorded at each end and in the middle. The current was increased until burnout occurred. The interesting feature of these results was that the curves of heat flux vs Δt go straight to burnout without exhibiting the classic shape of the nucleate — film boiling curve.[2] This situation is analogous to the burnout condition possible with heat-flux controlled systems with forced convection boiling.[3] The burnout flux was sufficiently high to give confidence that a high heat transfer was to be expected with small bore pipes.

Quite high electrical current densities were obtained before burnout occurred — 330 A/mm^2 in the stainless-steel tube, equivalent to about 2000 A/mm^2 in copper.

The desired design of septum will use copper pipes, and more exhaustive trials were conducted with these. With the electrical power available at the time of test, it was difficult to achieve sufficient heating in the copper pipe to make such a method worthwhile. Considerable experimentation produced a somewhat crude, but simple and adequate rig to feed into the pipe a variable and measurable heat flux. Figure 3 shows this rig where two acetylene burners heat a copper block through which the pipe has been brazed. Thermocouples were attached to the pipe at inlet and outlet and in positions in the copper block that would enable an assessment to be made of the total heat flux into the pipe.

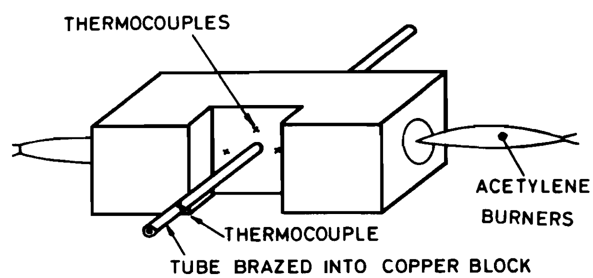

Fig. 3. Experimental Rig.

Figure 4 shows q/A vs Δt (water/wall differential temperature) for a 0.0245 (0.62 mm) inch internal diameter copper pipe for a range of coolant velocities. In the non-boiling region the heat flux is what is to be expected from the classic equations for single phase forced convection. The curves for the boiling regions are steeper and can be compared with results published by McAdams.[4] These curves set the limit to the heat flux that can be transferred safely for this size of pipe at these velocities. The trial magnet reported herein transferred 760,000 Btu/sq ft/hr (240 W/cm^2) thus a high factor of safety is possible with this design.

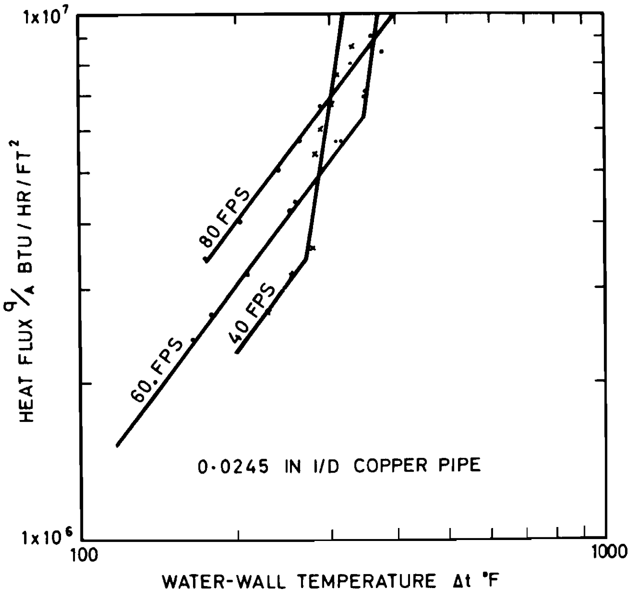

Fig. 4. Heat Transfer Characteristics.

Separate calculations of the Nusselt, Prandtt, and Reynolds Numbers led to the determination of the constant in Eq. (1) at a mean value of 0.022 for non-boiling regimes rising to 0.037 when in the boiling region.

Construction

Figure 5 shows a general section of a trial magnet designed to give a magnetic field of 3 kG across a 20 mm gap with a current of 5000 A. This magnet was designed cheaply for developmental use.

The septum is made from two high conductivity copper plates, silver brazed together in a vacuum oven. Each mating face was machined to receive the small diameter stainless-steel water pipes which are brazed between the two copper plates. The components were silver plated before assembly. The outer faces of the septum were then machined to the required thickness of 1.5 mm. The current flowing outside the septum is reduced to approximately 0.02% of the septum current by using sub-water manifolds holding 4 tubes, the sub-manifolds being connected to the main flow and return manifolds via ceramic insulated connections. The back throat winding is of conventional rectangular section water cooled copper conductor.

An alternative method of producing the septum is to electrolytically deposit copper onto pre-positioned pipe assemblies. This was tried, and has the disadvantage that because of the difficulty in ensuring that all pipes are taut and straight during the plating process, it was not known precisely where the pipes lay within the final copper deposition. This made it impossible to consider machining the septum down to the pipe diameters: the random variation in position resulted in an unnecessary thick septum.

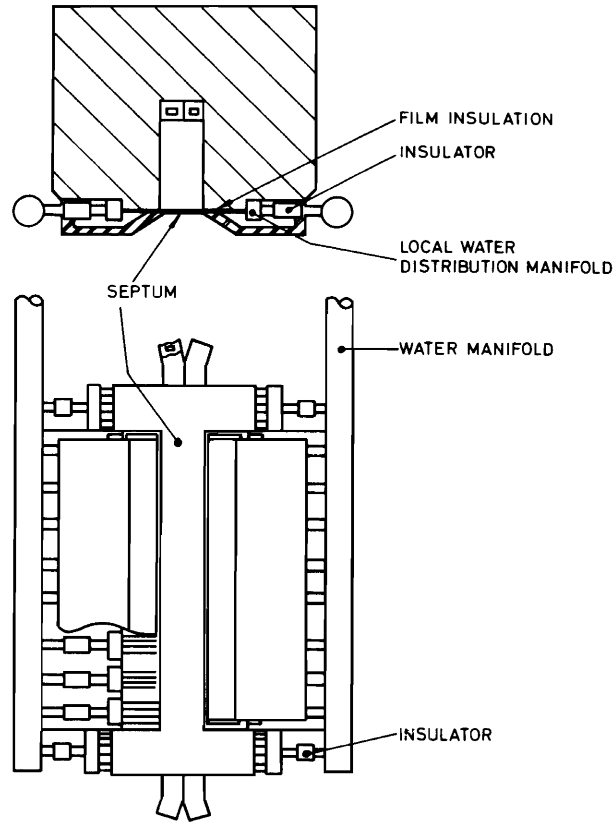

Fig. 5. Thin Septum Magnet.

Magnetic Field Measurements

The trial septum was designed to the following specifications:-

Septum thickness	1.5	mm
Aperture	20	mm
Length of yoke	150	mm
Current	5000	A
Ampere turns	5000	
Field	3	kG

The current was applied in easy stages up to a maximum of 5000 A, so that a check could be made of the progressive increase in water and wall temperature. At 5000 A the water temperature rise was 5^{o}F at a water flow velocity of 80 ft per second (24.4 m/sec).

Magnetic field measurements were obtained using a Hall probe. Figure 6 shows a plot of magnetic field with a current of 5000 A. The fringe field can be attributed to the fact that with this experimental design of magnet a small current leaks along the septum water manifolds, thus creating the effect of an anti-reluctance winding. This effect can be designed out of an operational magnet.

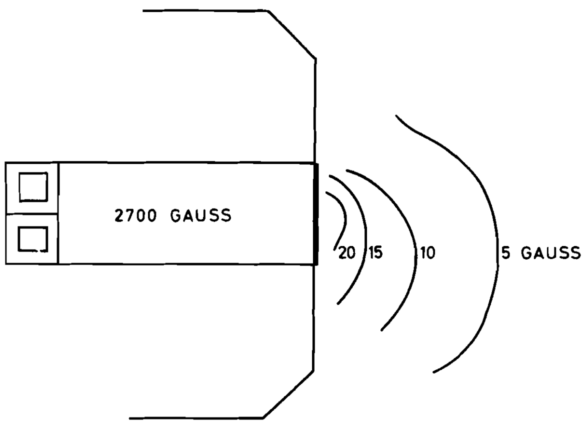

Fig. 6. Internal and External Magnetic Field at 5000 A

Preferred Design

Figure 7 shows a section of a thin septum magnet of a design suitable for operational use. The septum plates are machined as described. To simplify design and to remove the current leak inherent in the experimental design, each pipe is to be individually insulated. The ends of the copper pipes may be coated with ceramic to the necessary thickness using Glow Discharge Beam Techniques.[5,6] The pipes are then silver brazed into the septum, after which the assembly is given a protective rhodium flash plating. The ceramic coated ends are dipped in a silver-glass colloidal suspension — care taken not to block the internal bores — which after heating bonds a silver coating to the ceramic.

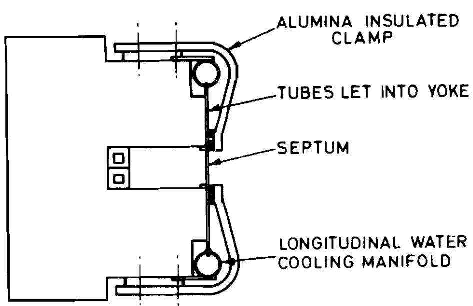

Fig. 7. A Design of Operational Magnet

The pipe ends are then silver soldered into the water manifolds. The outer faces of the plates are machined until a witness of braze material shows. The septum is then essentially as thick as the pipe diameters. The resulting section can then be considered homogeneous for heat conduction and electrical resistance. Load on the septum due to the magnetic field is carried by the whole section, Fig. 8 refers.

Fig. 8. Construction of Septum

The assembly will be located and secured against magnetic load by alumina coated clamps.

Conclusions

A method has evolved where magnets of any practical length can be made with septums as thin as 0.5 mm (0.0195 in.). Work on water flow and heat transfer has revealed interesting results and has shown the safe limits to which the septum can be designed. A design of an operational magnet is proposed using electron beam techniques to provide a thin ceramic insulation to the water cooling pipes.

For a given septum thickness the field in the magnet gap with transverse cooling can be at least twice the field which can be obtained with longitudinal cooling.

References

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