ACCELERATOR MAGNET PLUGGING BY METAL OXIDES: A THEORETICAL INVESTIGATION, REMEDIATION AND PRELIMINARY RESULTS*

W.W. Rust, Ph.D., P.E., TJNAF, Newport News, VA 23606, USA

Abstract

The Thomas Jefferson National Accelerator Facility has experienced magnet overheating at high power. Overheating is caused by cooling water passages becoming plugged and is a direct result of the Dean Effect deposition of corrosion products suspended in the water. Solving simplified dynamic model equations of the flow in the magnet tubing bends yielded a relationship for plugging rate as a function of particle size, concentration, velocity, channel width and bend radius. Calculated deposition rates using data from a previous study are promising. Remediation has consisted of submicron filtration, magnet cleaning, and dissolved oxygen removal. Preliminary results are good: no accelerator outages have been attributed to magnet plugging since the remediation has been completed.

BACKGROUND

The Thomas Jefferson National Accelerator Facility (Jefferson Lab) Continuous Electron Beam Accelerator (CEBA) is a race track configured, multi-pass superconducting linear electron accelerator with magnets in the arc sections that recirculate the beam. The magnets, klystrons and power supplies are cooled with low conductivity water (LCW), which is supplied by four LCW systems.

All of the LCW systems are similar in design and construction. Circulating pumps move cooling water through headers and cooling passages associated with each system. The water returns to heat exchangers equipped with PID controllers that actuate three-way valves to maintain the desired temperature. Side stream mixed bed resin systems are used to polish the water. Each system is protected by pre and post filter arrays, sized for the appropriate flow through the resin bottles. All of the systems are equipped with combination head and make-up feed tanks that are maintained under positive nitrogen pressure.

The piping system is made of stainless steel, fibre cast pipe, copper pipe and tubing, plastic or rubber connection hoses, and brass hardware. Some magnets have capillary-like, sub-millimeter cooling passages.

Near pure water flowing through metallic piping tends to accumulate oxide particles. Over time, the particles will form a residue on the conductor walls. The residue is less thermally conductive than copper and interferes with heat transfer. Moreover, the residue noticeably affects the small passages by gradually blocking the flow of water, which further reduces heat transfer. Eventually, these magnets shut down due to overheating.

System improvements have been ongoing since the construction was completed. Nevertheless, corrosion related plugging problems emerged as beam energy increased and maintenance intervals decreased. A literature search revealed that the Fermi National Accelerator Laboratory (FNAL) had experienced similar problems and had solved them using mechanical oxygen removal and full flow filtration [1]. The Jefferson Lab began a trial program that emulated the equipment installed at FNAL, and hopefully will achieve comparable results.

ANALYTICAL ANALYSIS

Fluid flowing through a curved tube has a dynamically induced, secondary circulation that is normal to the main stream [2]. This effect was first investigated by Dean. [3]. Knowledge of the behavior of the induced flow field in terms of relevant fluid properties and design parameters could be used to predict the plugging rate. It can be shown that the average deposition rate for film of particles on a tube wall is:

$$\frac{dh}{dt} = c\Delta R\left[\frac{1}{A}\int\frac{\partial V_r}{\partial r}dA\right] \qquad (1)$$

Where h is the film thickness, c is the particle concentration, ΔR is the particle diameter, A is the deposition area along the radius of curvature, and V_r the radial component of the flow. Determining the value of the integral, even for a simplified case, could serve as guide for experimental verification and as a point of departure for future work.

Sandeep and Palazoglu [4] present an overview of the current work in secondary flow in coiled tubes, particularly with respect to heat transfer. The Dean number is defined as the product of the Reynolds' Number and the square root of the ratio of the tube diameter to the radius of curvature. The Dean number is modified by using the hydraulic radius non-circular channels. Although square and round passages are used in magnets, only square channels are analyzed here. To further minimize complications, the modelling for this problem will neglect second order effects to the extent necessary as discussed below.

The continuity equation, Eq. (2), and the momentum equation, Eq. (3), for incompressible flow are shown below.

$$\nabla \cdot V = 0 \qquad (2)$$

$$\boldsymbol{\rho}\frac{\mathbf{DV}}{\mathbf{D}t} = \boldsymbol{\rho}\mathbf{g} - \nabla\mathbf{p} + \boldsymbol{\mu}\nabla^2\mathbf{V} \qquad (3)$$

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A rectangular cylindrical co-ordinate system (r, θ, z) best describes a square passage flow channel. The inside radius (r_0) is measured from the origin. The dimension of the channel is w by w, and the inside lower corner is located at (r_0, 0, -w/2).

The momentum equation can be modified for pipe flow by realizing that gradients along the flow direction are small. [5] For a magnet flow passage, the tubing is usually wound with 90-degree bends with a section of straight tube between bends. The flow is assumed to be fully developed, and the velocity profile across the channel does not change appreciably in the time needed to pass through the bend. Also, the cross channel pressure gradient and flow velocity is small compared to its second derivatives. Applying these assumptions to continuity and momentum equation, one obtains the following set of equations governing the flow field, Ω:

$$\frac{\partial V_r}{\partial r} + \frac{\partial V_z}{\partial z} = 0$$

$$-\frac{\rho}{\mu}\frac{V_\theta^{\,2}}{r} = \frac{1}{r}\left(\frac{\partial}{\partial r}\left(r\frac{\partial V_r}{\partial r}\right)\right) + \frac{\partial^2 V_r}{\partial z^2}$$

$$0 = \frac{1}{r}\left(\frac{\partial}{\partial r}\left(r\frac{\partial V_z}{\partial r}\right)\right) + \frac{\partial^2 V_z}{\partial z^2}$$

And on the boundary walls, Γ:

$$V_r = 0$$

$$V_z = 0$$

Where the subscripts indicate the coordinate directions.

These assumptions have basically turned the problem into a two dimensional one. By doing so, a function can be defined that will identically satisfy the continuity equation. Namely:

$$\frac{\partial \phi}{\partial z} = V_r$$

$$\frac{\partial \phi}{\partial r} = -V_z$$

The procedure used to solve the momentum equation was to first normalize the dependent and independent variables. The resulting Poisson equation was solved iteratively using the method of lines for a second order accurate, centered difference scheme over 2500 points. The velocities were then back calculated from the solution set. A parametric study of the integral in equation (1) was performed for various ratios of width (w) to inside radius of curvature (r_0). The result is:

$$\frac{dh}{dt} = 0.0277\left(\frac{w}{r_0}\right)\frac{c\Delta R V^2}{\nu} \qquad (4)$$

Where w is the width of the square channel, ν is the kinematic viscosity, and V is average fluid velocity. It should be noted that the integral term had both positive and negative deposition rates at various points across the deposition surface. Only the positive rate was considered because the negative rate would remove material. This could not occur because there would be no material to remove from a clean surface. This approximation should work well provided the deposition surface does not significantly disturb the flow. The long-term growth of the deposits will require more computational research.

SYSTEM IMPROVEMENT CHRONOLOGY

Plugging of LCW from iron oxide in cooling circuits first became a problem in 1993, soon after power supplies and magnets were installed. Unfortunately, iron body pumps with brass impellers were selected to circulate LCW. For ordinary treated system water, this is not a problem; however, the LCW system was designed to operate at full purity, 18 MΩ-cm. LCW with dissolved oxygen aggressively attacked the iron pumps, thus becoming a corrosion particle source. The pumps were replaced with stainless steel.

The aggressive nature of high purity water on metal was a concern for our aluminum beam dump. In 1995 and 1996, a conductivity control system was developed to reduce the water purity. The system worked so well it was installed in all LCW systems at the Jefferson Laboratory. The accelerator operating point was selected to be 2.0 MΩ-cm.

Also during the 1996 period, plugging of magnets had again become problematic. Henkel [6] found that plugging was caused by iron oxide (magnetite), which is caused by a "single electrode corrosion of iron particulates immersed in oxygenated water." Tubing bends were analysed and the inside radius surfaces were found generally to be coated with deposits. The amount varied from light and streaked to uniform and heavy. A fifteen-micron thickness (or about 3μ/yr) was typical of the average layer of magnetite deposits. Free stream header concentrations were found to be 10 ppb for iron and a diameter of 5 - 10 μ. To lower the dissolved oxygen concentration, oxygen scavenging resin bottles were added to the mixed bed array. A year before the study, filter porosity was decreased from 5μ to 0.5μ in the side stream to help clean the water. Local filtration was also installed near the most critical magnets. Improvements made to the system seemed to ameliorate the plugging problems.

In late 1999 and 2000, however, magnet trips due to heat excursions again manifested themselves. Additional testing showed a new character to the composition: particles were now mostly copper oxide with a ratio of 9 parts copper to 1 part iron.

Seeking other expert opinion, contact was made with other National Laboratories in the LCW production facility departments. Chris Ader of FNAL [7] sent us information on FNAL's solution to the problem. We immediately began work on a prototype system to emulate the FNAL system. Further knowledge on general process of copper corrosion was found [8,9].

DISSOLVED OXYGEN REMOVAL

Following FNAL, a dissolved oxygen removal system was installed. The primary element is a device called a contactor, which was placed in the side stream purification and feed system.

A contactor is basically a molecular sieve. System water with dissolved oxygen at a given partial pressure flows past one side of the sieve. The other side of the sieve is maintained at a lower oxygen partial pressure by using a vacuum pump, sweep gas, or both. The dissolved oxygen, carbon dioxide and other gasses diffuse through the sieve membrane and are carried away by the vacuum pump.

Also, full flow filters with 0.5 μ media were placed in the return side of the magnet LCW loop. This is in addition to the other filters already in place.

The pH is a key factor in the corrosion process. In general, pH over 7.0 minimizes both copper and iron corrosion, while a pH below 7.0 increases corrosion and adversely reduces the solubility of the copper oxides in hot wall passages. The contactor system removes dissolved carbon dioxide and increases LCW pH, while chemical removal of oxygen with scavenging resin lowers LCW pH. Since lower LCW pH is undesirable, the scavenging resin has been removed from the polishing system.

There are several general principles that should be observed when using an oxygen contactor:

1. No sub-atmospheric system pressure should be allowed to develop anywhere in the piping system.
2. The feed water must be degassed before being injected into the system.
3. Contactors are sensitive to excess temperature and pressure. Excessive pressure will destroy the contactor.
4. The system should be isolated from the atmosphere by using nitrogen to pressurize head tanks.
5. Magnet passages must eventually be chemically cleaned to remove oxide film. Film build-up is a natural consequence of flow dynamics. It is also directly related to thermal effects on copper oxide solubility.

CALCULATED DEPOSITION RATE COMPARED WITH MEASURED DATA

Although Eq. (4) was derived for a square channel, it could be tested by using the available data for circular specimens above. The inside radius of the analyzed bends is not stated, but judging from the magnet plans, the inside radius is probably between 25 and 35 mm. Moreover, the particle diameter is important to the rate of deposition. Henkel [6] observes that the size composition of the deposits varies greatly, even after local filtering. He notes that the "coating is being formed by mechanical adhesion of thousands of these particulates." This is very likely since magnetite particles will bond together magnetically. The main flow stream was filtered to 0.5 μ; one would expect the larger particles to form from an aggregate of smaller particles. This will result in two cases: Case I is a homogeneous fluid with 0.5μ particles suspended therein, and Case II is non-homogeneous fluid with 5μ particles formed from the smaller particles with the same total particle mass as Case I. One could surmise that the numerical concentration will vary accordingly, but there is not enough data available to show this. The tube forms a 90 degree bend with a 35 mm radius. Water flows through the channel with an average velocity of 0.06 m/s, a particle concentration of 10 parts per billion (ppb) for 0.5μ for Case I and 5μ for Case II. The kinematic viscosity of 300K water is 8.57E-7 m^2/s. For a circular channel, the diameter is substituted for the width of the square channel.

For Case I, the deposition rate is 3.1 μ/year and 31 μ/year for Case II with the same concentration. Case I agrees with the 3 μ/year mentioned above.

CONCLUSIONS

The plausibility of the deposition rate analysis presented here seems to agree with previous experience. The deposition rates for square and circular channels, which were not analyzed, are expected to be approximately the same.

Although our oxygen removal system has not been in service long enough to draw ironclad conclusions, we have not had any plugging problems as of this writing. We are optimistic that the system will improve the accelerator reliability.

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