TN0016

Cooling water requirements for magnet coils

Scan magnets

Electromagnets that are designed to deflect high rigidity ion beams and change field quickly generally require their coils to be water-cooled as many kilowatts of power must be removed at high field settings. Pyramid scan magnet coils are wound with high conductivity copper conductor where the cooling water flows in the hollow core of the copper. This provides a very efficient heat transfer for the whole coil assembly.

Cooling systems

Permanent installations will require a closed circuit cooling system. The coolant must be delivered to the magnet distribution manifold with sufficient pressure head to provide the required flow rate so that the magnet is thermally stable at maximum excitation. The system should have sufficient heat removal capacity for the expected maximum load, sufficient pressure head to drive the required flows through all the magnets and water chemistry that doesn't degrade operation over a span of several years.

Water chemistry

The use of wetted copper components is unavoidable. The management of corrosion and deposition of materials in the water circuit is a complex issue with no single best practice suited to all situations. An in-depth study of cooling electrical generator stators, which is also valid for consideration of cooling electromagnet coils, is reported by Duffeau et al [1]. Further information is available in Zickler [2] and Dortwegt [3]. The formation and deposition of copper oxides is inevitable over time. According to the strategy for control of pH and dissolved oxygen levels, you can attempt to minimise deposition or minimize the release of deposited materials that could then accumulate at a blockage point. The reference [1] describes the options.

The most convenient water chemistry for water systems where air cannot be excluded is to run deliberately at relatively high dissolved oxygen (> 2 ppm) by having water surfaces open to air and pH between 7.5 and 9 (alkaline). In this environment copper oxides will deposit on copper surfaces, but they tend to stabilise and thus form a protective coating. The oxides are inhibited from spreading around the system. The pH can be established and maintained using added alkali such as sodium hydroxide. The oxygen level must be maintained or the copper oxide layers will be eroded.

The alternative low oxygen water chemistry minimises the formation of oxides. It is generally more complicated to maintain. Further details are available in reference [1].

If biocides are used, their compatibility with the cooling circuit materials & the effect on pH must be taken into account. The water/working fluid then needs to be maintained/changed periodically, a lot like an automotive cooling system.

The scan magnet application does not require particularly low conductivity coolant in order to stand off electrical potential. Low conductivity may however be a result of the water chemistry strategy employed, and conductivity is available as a measure of coolant condition.

Wetted materials

Generally copper and brass components and plastic hoses can be used together. Copper and stainless steel components and plastic hoses can be used together. Brass and stainless steel components should not be in close proximity to each other in the same system due to the potential for galvanic corrosion. The wetted areas of the Pyramid D2-650 scan magnet system are primarily copper and polythene, with small areas of brass. Total wetted area of materials in contact with water (both magnets combined) are as follows:

OFHC copper (hollow conductor coils)	2.98 m^2.
Brass (coil terminations and fittings)	0.04 m^2
Polyethylene (connecting hoses)	0.35 m^2

Industry report [4] provides information on galvanic corrosion effects, and specifically the use of stainless steel, and reference [5] provides a comprehensive list of materials and their mutual galvanic potentials. Materials with a large mutual galvanic potential should not be combined in a water circuit.

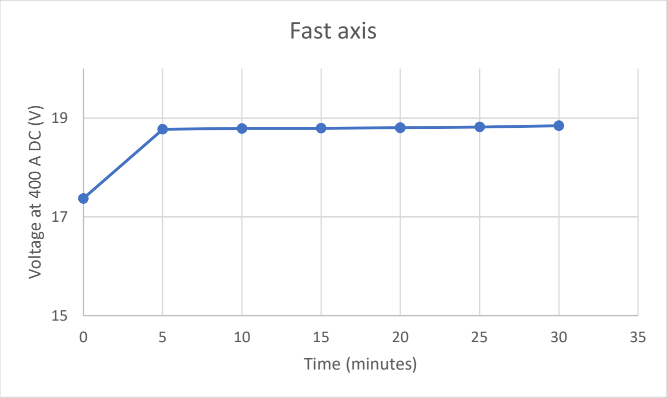
Inspection and preventative maintenance

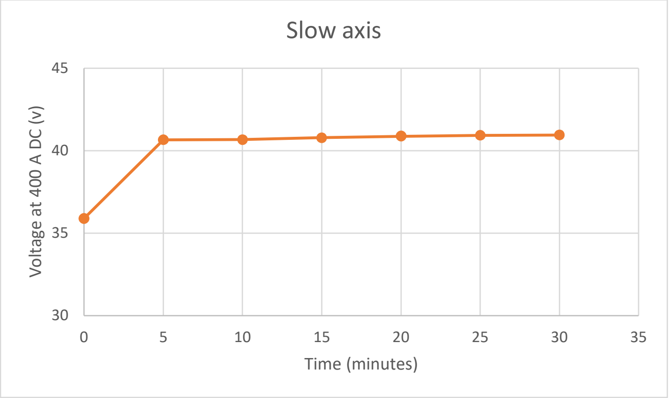
Over a period of years of continual operation, there will be some removal and deposition of solids in the water circuits. Information about methods of monitoring, maintaining and filtering the coolant is given in reference [1]. A routine visual inspection of hoses and joints and recording of any monitored parameters such as pressure drops, water conductivity and pH will allow replacement of components to be planned. Cast fittings such as valves will generally degrade faster than machined or extruded parts due to their relative roughness and/or porosity.

The most challenging components to replace would be the magnet coils. The narrow bore makes them more prone to blockage. The result would be reduced cooling efficiency, thus the coils would heat up more at high DC current settings and the resistance would increase due to the positive temperature coefficient of resistance of copper. The cooling efficiency can be monitored as part of the regular machine QA. If the system allows the pressure drop or flow rate to be measured, this should be logged for evidence of reduced flow.

Information is also provided by the scan magnet power supply because it reports the voltage V_{mon} and current I_{mon} it is providing. For the IECO MPS400-350-PY supply used in the D2-650 magnet system, the readback voltages should be multiplied by 50 to give the actual values. If a magnet is operated at a fixed known current and the inlet water pressure and temperature are at controlled values, then no voltage is being used to drive the inductance of the coils. The monitored voltage therefore indicates the only ohmic resistance. At high current settings the coils will warm up to an equilibrium temperature. If the coil heats up excessively due to blockage, the resistance will increase more, and in the case of extreme blockage the resistance will carry on increasing until the overtemperature causes the thermal switches to interlock the power supply. Keeping a record of the way the voltage increases with time at high current setting will reveal reduction in cooling effectiveness. The test will be most sensitive at high current settings.

When the coils of the D2-650 magnets are new, the equilibrium voltage is reached in about 5 minutes at the maximum DC rating of 400 A DC as shown in the following plots. An equivalent test for the D2-640R scan magnets should use no more than 360 A.


Fast axis


Slow axis

On the other hand if the cooling core in the coils is increasing in diameter due to erosion of copper this would be revealed initially in reduced pressure drop, and eventually in increased resistance as the copper cross section is reduced. It is unlikely that this would happen during the lifetime of the system, and is far less likely than copper oxide blockages.

Water velocity

The coolant tube diameters should be chosen so that the water velocity nowhere exceeds 3 m sec^{-1} to reduce erosion and transport of deposits to blockage points. The Pyramid D2-650 magnet set has a specified coolant flow rate of 12 litres per minute. The minimum pipe internal diameter d required to limit the velocity to 3 m sec^{-1} is:

$$d = \sqrt{(4F/(\pi V))} = \sqrt{(800/921)} = 0.93 \text{ cm}$$

where d is in cm, V is velocity in cm sec^{-1} = 300, F is the flow in cm^3 sec^{-1} = 12*1000/60 = 200. A larger diameter is recommended to reduce the speed to well below the limit.

The bore of the magnet coils is relatively small, but the velocity and pressure drop across the coils is reduced by the use of parallel circuits.

As an example, the D2-650 slow axis magnet divides the incoming flow into N = eight parallel circuits, four per coil pack. The recommended flow rate is F = 8 litres per minute = 133.3 cm^3 sec^{-1}. The conductor has bore diameter d = 0.363 cm. Thus the flow velocity in each circuit is:

$$V = (F/N) / (100(\pi . d^2/4)) = 1.6 \text{ m sec}^{-1}$$

References

[1] GUIDE ON STATOR WATER CHEMISTRY MANAGEMENT (April 2010) François Duffeau, Denis Aspden, Gert Coetzee, Robert Svoboda, Wolf-Dietrich Blecken, Uwe Eickelbeck, Robert E Fenton, David Wallis, Jan Stein (available at https://theunfamousseries.com/guide-on-stator-water-chemistry-management.html and other sites).

[2] "Basic design and engineering of normal-conducting, iron-dominated electromagnets" (section 4.42), Th. Zickler, CERN lectures on magnet design. (https://cds.cern.ch/record/1334336/files/65.pdf?version=1)

[3] "Low-conductivity water systems for accelerators", R.Dortwegt, Proceedings of 2003 Particle Accelerator Conference. (https://accelconf.web.cern.ch/p03/PAPERS/ROPB008.PDF)

[4] "Stainless Steel in Contact with Other Metallic Materials", The European Stainless Steel Development Association, Materials and Applications Series, vol 10. (https://www.worldstainless.org/Files/issf/non-image-files/PDF/Euro_Inox/Contact_with_Other_EN.pdf)

[5] "Galvanic Corrosion Chart", Zyology Ltd. (https://www.zygology.com/store/pc/catalog/Zygology%20Anodic%20Index.pdf)