Modeling and evaluation of resistive magnet thermal performance in field-cycled MRI

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Introduction: In conventional MRI, a single superconducting magnet is used to polarize and subsequently image an object. In field-cycled MRI, the superconducting magnet is replaced by two resistive magnets: a high-field magnet to polarize the sample and a low-field magnet under which to acquire the image [1,2]. The polarizing and readout magnets, as they are called, are pulsed on and off during each TR. However, thermal heating becomes a potential limitation when using resistive magnets. Magnet heating can cause damage to the system, as well as cause field inhomogeneity and center frequency drift. Two theoretical heat transfer models were developed, called the Lumped Parameter (LP) [3,4] and Equilibrium models [4,5]. The combination of these two models can predict the spatially and temporally dependent temperature evolution of a water-cooled magnet. The two theoretical models were compared to experimental heating measurements taken from the field-cycled MRI scanner built by the authors. A photograph of the scanner is shown in figure 1. Reasonable agreement was found between the experimental temperatures and those predicted by the theoretical models.

Theory: The LP model is a thermal analogy to an electrical circuit, which assigns a lumped resistance and capacitance to the entire magnet system, and thus the transient temperature can be predicted. However, the conductor temperature is assumed to be uniform in the LP model, and thus cannot be determined as a function of position within the coil. The Equilibrium model assumes a steady-state temperature has been attained inside the magnet; heat transfer is then modeled along its path from the conducting wires to the water-cooling system. This model can determine the equilibrium temperature at any location inside the magnet and the cooling system itself; it cannot, however, predict the temperature dependence on time.

Methods: A field-cycled MRI scanner was designed using the method described by Gilbert *et al.* [1]. The scanner and cooling system were built using the method described by Gilbert *et al.* [6]. The low-field readout magnet consists of six coils and ten cooling plates. The high-field polarizing magnet consists of eight coils and ten cooling plates. All coils were constructed in-house. The forced-water cooling system is described by Gilbert *et al.* [4,6]. Flow rates of 9 l/min were used to cool both the polarizing and readout magnets.

The LP and Equilibrium models were used to predict the equilibrium temperatures and the thermal time constants of the polarizing and readout magnets. These values were then determined experimentally. A DC power supply drove each magnet, in constant current mode, for 30 min, during which time the voltage was recorded at 30 s intervals. The average temperature of the magnet was determined by the temporal change in resistance. This process was repeated for five current magnitudes. The resistance of the magnet during cooling was measured directly with a multi-meter. Once data had been acquired, the heating and cooling portions of the temperature curves were fit to an exponential to determine the equilibrium temperature and the thermal time constants. The experimental values were then compared to the theoretical values predicted by the LP and Equilibrium models.

Results and Discussion: Figure 2 shows the experimental and theoretical equilibrium temperatures for the polarizing magnet. The equilibrium temperatures for the readout magnet are similar. Both magnets can be driven continuously at 100 A without the risk of damage to the system. The time constants for the two magnet systems are shown in figure 3. Both magnet systems were designed to operate at 100 A. At this current, each magnet's temperature will rise less than 20 °C during a typical 5 min scan-time. Allowing the scanner to reach thermal equilibrium prior to data acquisition significantly reduces this temperature rise and the associated drift in center frequency. Thermal expansion of the copper wires was found to have negligible effect on the inhomogeneity.

Thermal modeling is a vital component in the design of any resistive magnet system. The thermal models discussed here will be used in the design of future field-cycled MRI scanners, and can be applied to any resistive magnet system. They also allow for the determination of safe operation modes for the scanner, as the temperature of the magnets can be determined as a function of time for any pulse sequence.

References:
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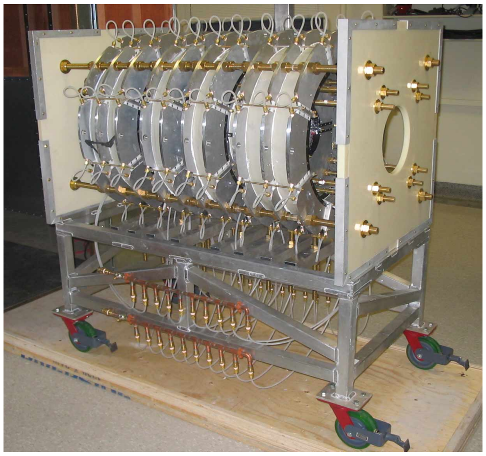

Figure 1: The field-cycled MRI scanner developed by the authors.

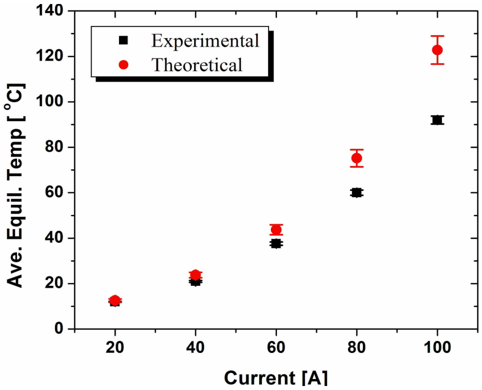

Figure 2: The experimental and theoretical average temperatures of the polarizing magnet.

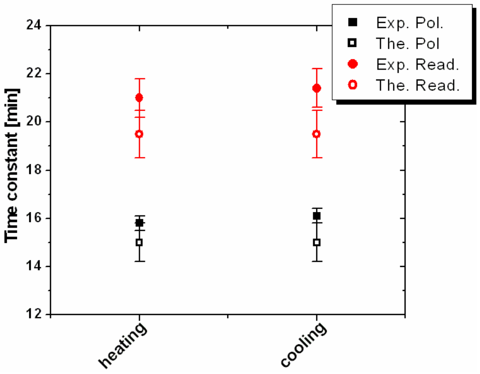

Figure 3: The experimental and theoretical thermal time constants for the polarizing and readout magnets.