PULSED CRYOGENICALLY COOLED COILS FOR MAGLEV EXPERIMENTS

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As a less costly alternative to the use of a superconducting coil in the experimental testing of the split-track maglev system for high speed transport, pulse-operated copper coils, cooled with liquid nitrogen, have been successfully used for the force measurements. Calculations have been carried out for constant current conditions to establish the conductor specific heat, resistance and voltage time relationships during the pulse, together with an experimental investigation of coil heat transfer in restricted open pool boiling. The result has been an increased sensitivity and the ability to examine a variety of configurations at a reduced cost.

INTRODUCTION

For small scale levitation experiments based on the electrodynamic principle, superconducting magnets with their relatively small power supplies have been used for extended running and, at Warwick, tests have been carried out with a superconducting coil mounted in a force balance above a 3-m diameter test wheel, operating up to 45 m/s. However, it was found that the superconducting coil with its mechanical supports within the helium cryostat and vacuum assembly tended to make design changes relatively expensive and experimentally difficult. For prototype design configurations, therefore, it would be advantageous to use conventional copper coils to investigate the effect of coil shapes on the strength and distribution of the forces generated. This would enable an optimised coil geometry to be developed as the initial stage before constructing the superconducting coil.

The design of the coils requires a minimal cross-section conductor area in order to model the geometric relationship with the superconducting equivalent. To match the constant flux condition of the superconducting coil the high current density is accommodated by pulse operation of the coils under constant current excitation. More normal operation of pulse coils is with a constant voltage and so a previous analysis is re-examined for constant current conditions. The calculations establish the conductor specific heat, resistance and voltage time relationships during the pulse and these are supplemented with an experimental investigation of coil heat transfer in restricted openpool boiling. This investigation has allowed pulse-operated copper coils with a liquid nitrogen cryogen to be used as an alternative to superconducting coils over the 3-metre test wheel. Levitation force measure ments have established parameter dependence for the split-track system and the results compare with predictions.

In the following analysis the voltage and temperature rise in a cryogenically-cooled copper coil, pulsed with uniform current density, are established (the ampere-turns are kept constant under current control).

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ANALYSIS FOR PRECOOLED COILS

The analysis has been carried out on the basis that the resistivity of the copper coil is reduced by a factor of 8 at the temperature of liquid nitrogen. Likewise, the specific heat, c_p, is also temperature dependent. The fundamental equations governing the current and temperature rise in a uniform current density, pulsed coil are given by,

$$v(t) = L\, di(t)/dt + i(t)(Re + R(t)) \tag{1}$$

and

$$dT(t)/dt = i^2(t)R(t)/\gamma V c_p(t) \tag{2}$$

where $v(t)$, $i(t)$, $R(t)$ are the terminal voltage, coil current and coil resistance at time t, respectively, and L = coil inductance, Re = external (current lead) resistance, γ = conductor density (kg/m^3), V = conductor volume (m^3), $c_p(t)$ = conductor specific heat (J/kgK), and $T(t)$ = conductor temperature (K). If we assume that both $v(t)$ and $T(t)$ can be represented by a power series expansion [1] then equations (1) and (2) can be satisfied for all the coefficients sequentially, thus

$$v(t) = v_o + v_1 t + v_2 t^2 + v_3 t^3 + \ldots + v_n t^n + \ldots = \sum_{n=o}^{\infty} v_n t^n \tag{3}$$

and since the current will be kept constant, then $di(t)/dt = 0$ and $i(t) = I$ so that (1) becomes

$$v(t) = I(R_e + R(t)) \tag{4}$$

The way that the coil resistance $R(t)$ and $R(t)/c_p(t)$ varies with time is not known, but can be deduced from the temperature at time t by the relationships:

$$R(t) = R_o[1 + \alpha\ (T(t) - T_o)] \tag{5}$$

$$R(t)/\gamma V c_p(t) = c_o[1 + \beta\ (T(t) - T_o)] \tag{6}$$

and
$$T(t) = b_o + b_1 t + b_2 t^2 + b_3 t^3 + \ldots + b_n t^n + \ldots = \sum_{n=o}^{\infty} b_n t^n. \tag{7}$$

so that
$$R(t) = R_o[1 + \alpha \sum_{n=1}^{\infty} b_n t^n] \tag{8}$$

and
$$R(t)\gamma V c_p(t) = c_o[1 + \beta \sum_{n=1}^{\infty} b_n t^n] \tag{9}$$

and from (7),
$$dT(t)/dt = \sum_{n=1}^{\infty} n b_n t^{n-1} \tag{10}$$

Substituting (3), (8), (9) and (10) into (4) and (2) and equating coefficients, it can be shown that:

$$(v(t) - v_o)/IR_o = I^2\alpha[c_o t + \tfrac{1}{2} I^2 \beta c_o^{\,2} t^2 + \tfrac{1}{6} I^4 \beta c_o^{\,3} t^3 + \ldots] \tag{11}$$

Now if the specific heat of the conductor at t = 0 (and $T = T_o$) is $c_p^{\,*}$ then from (9) $c_o = R_o/\gamma V c_p^{\,*}$ and introducing another non-dimensional constant χ, the ratio of coil power input to coil heat capacity normalised by the coil time constant, $L/R_o (=\tau_o)$, i.e. $\chi = I^2 c_o L/R_o$, (12)

So, if equation (11) is normalised by the coil time constant, then by substituting (12) and, by using the Maclaurin expansion for $e^{\beta\chi\tau}$ to give a closed solution, it can be shown that

$$v(\tau) - v_o)/IR_o = \alpha/\beta\ [e^{\beta\chi\tau} - 1] \tag{13}$$

and for the conductor temperature rise,

$$T\ (\tau) - T_o = \frac{1}{\beta}\ [e^{\beta\chi\tau} - 1] = \frac{1}{\alpha}\left[\frac{v(\tau)}{v_o} - 1\right] \tag{14}$$

The constants α and β relate to copper conductors at liquid nitrogen temperatures, and have values of 0.031 and 0.014 respectively [3]. Equation (13) is plotted in Fig. 1 for a range of values of $\chi\tau$. For low values of $\chi\tau$, the relationship is linear, decade for decade.

Fig. 2 shows the normalised voltage rise for a family of χ and τ. The values of χ in parenthesis refer to the higher values of τ, where τ has an expanded range. For other values of χ or τ, the abscissa or χ value can be scaled appropriately.

CONCLUSIONS

This investigation has shown that pulse-operated copper coils with liquid nitrogen cooling can be used as a cheaper and more versatile alternative to superconducting coils for scaled experiments. It is also suggested from this work that copper or aluminium coils with liquid nitrogen, pool boiling could provide an acceptable and cost effective alternative to superconductors for the field coils of a linear synchronous motor drive for a wheeled suspension, transport system.

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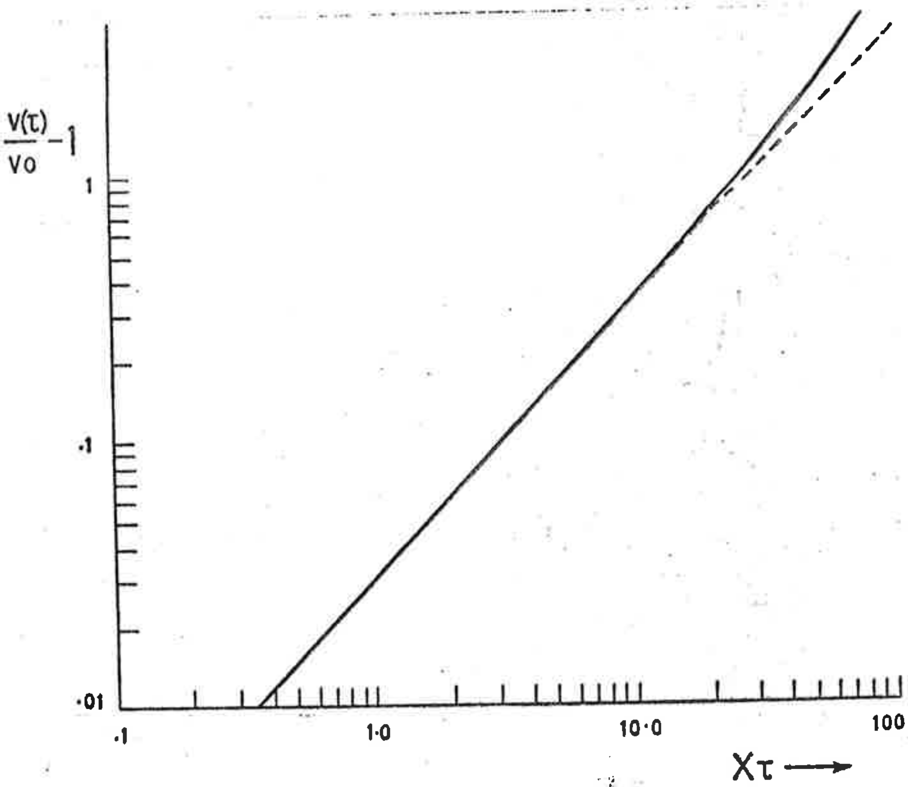

Fig. 1. Normalized voltage rise for constant current coil.

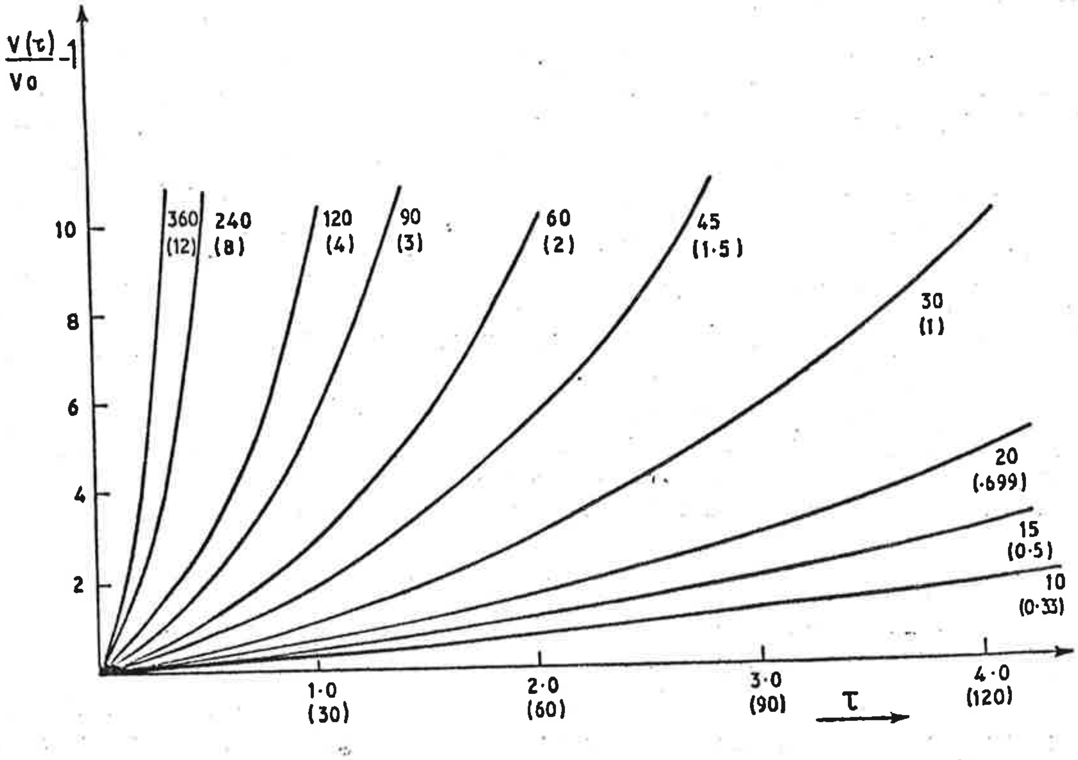

Fig. 2. Normalized voltage rise for constant current coil.