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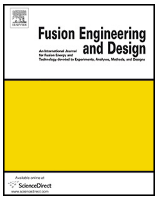

Free or confined arc model relevant to the quench hazard of large superconducting coils

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HIGHLIGHTS

- A numerical model of free or confined arcs is presented.
- The model solves the fundamental equations describing the arc column physics.
- Model solution is quick and suitable for use in FEA and computational simulation.
- Calculations of arc column radius are consistent with experimental measurements.

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ABSTRACT

This arc model was motivated by the need to model arcs during the failure of a large superconducting magnet following an unmitigated quench. During a quench, resistive heating raises the conductor and insulator temperature. Electrical and mechanical properties change and inline and bypass arcs can form. The arcs are sustained by the massive (gigaJoule) stored magnetic energy. As windings are bypassed by shorts, the inline arc current and hence, arc diameter, increases. Cable-in-conduit conductors limit the maximum arc column diameter and when limited, the arc properties change rapidly as the arc changes from a free arc to a confined arc. For arc current 10–100 kA we calculate the arc column electrical properties and temperature, by solving a set of equations describing the arc physics. The equations describe the arc column heating, gas ionisation, heat loss and electrical properties. By constraining the maximum arc column diameter in the solution, the transition between free and confined arc can be calculated.

1. Introduction

It is conceivable that electrical arcs will occur during the failure of a large superconducting magnet following an unmitigated quench accident. To assess such accidents numerical simulations are done [1–3] and it is necessary to use an appropriate arc model to calculate the voltage–current characteristics and heating.

During an unmitigated quench, resistive heating raises the conductor temperature. Electrical and mechanical properties change leading to dielectric breakdown of insulators and arc formation. Inline and bypass arcs can form that are sustained by the stored magnetic energy (gigaJoules for the ITER magnets).

An arc model was required that had sufficient inclusion of physics and coverage of conditions for the model to be used in safety analysis simulations of the ITER magnets. The model presented, is based on the high pressure arc theory described by Cobine [4, p. 326]. A numerical solution was not realistic at that time and Cobine made the assumption that at constant pressure the arc temperature can be considered independent of the arc current. We have developed the model without these assumptions. Additionally, since cable-in-conduit conductors limit the maximum arc column radius we developed the model to give a confined arc solution.

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2. Electrical conduction

The arc is represented as a column of ionised gas with a temperature T_a, measured in K in a background gas of temperature T_g. The gas molecular behaviour is ignored.

An ionised gas has a neutral particle density N and an ionised particle density n measured in m^{-3}. When an electric field E, measured in V/m is present, ions and electrons achieve an average drift velocity v_i and v_e respectively. In the calculation of the current density J measured in A/m^{-2} the contribution from v_i is ignored because the electron mobility greatly exceeds the ion mobility.

$$J = \rho_q v_e, \tag{1}$$

where ρ_q is the electron charge density. The electron charge density ρ_q is,

$$\rho_q = ne, \tag{2}$$

where e is the elementary positive charge. The drift velocity v_e is a function of the *reduced electric field*, E/N. In this model, we use the approximation that v_e is proportional to E/N at low values of reduced electric field so we can write,

$$v_e = \frac{\mu E}{N}, \tag{3}$$

where μ is a constant. Values for μ can be obtained from the electron mobility tables for common gasses [5]

The arc current I carried by an arc of radius R is,

$$I = \pi R^2 J. \tag{4}$$

3. Ionisation

The gas pressure P measured in Pa and the gas temperature T_g measured in K are known quantities. The gas equation is,

$$P = N k_B T_g, \tag{5}$$

where k_B is the Boltzmann constant.

To calculate the ionised particle density n for the arc column, the Saha equation is used. The familiar form of the Saha equation with pressure P_{atm} given in *atm* ($P_{atm} = P/101,325$) is,

$$\log\left(\frac{x^2 P_{atm}}{1-x^2}\right) = \frac{5\log T_a}{2} - \frac{5040 V_i}{T_a} - 6.5, \tag{6}$$

where x is the ionisation ratio,

$$x = \frac{n}{N} \tag{7}$$

and the first ionisation potential is V_i measured in V. For helium, which is relevant to superconducting magnets, $V_i = 24.59$ V.

4. Arc column heating

The arc column heating is due to the arc current and this can be related to the energy transferred in ion-neutral collisions. We can ignore the electron collisions because of the large mass difference between ions and electrons. We will consider the arc column to be in local thermal equilibrium and the electron, ion and gas temperatures are equal. We can ignore v_e and v_i in the calculation of the number of ion-neutral collisions per second and consider only the ion thermal speed v_{th}. A standard relation is,

$$v_{th} = \sqrt{\frac{8 k_B T_a}{\pi M_g}}, \tag{8}$$

where M_g is the mass of the gas particle. If the ion-neutral collision cross-section is σ and the ion mean free path is δ, then the number of collisions per second in arc section of length δ is,

$$Z_\delta = nN\sigma v_{th}\delta\pi R^2. \tag{9}$$

There are two contributions to the electric field; the applied arc voltage along the arc channel and a radial potential drop $k_B T_a/2e$ across the plasma pre-sheath of the arc column. Therefore, the average radial field $\bar{E}_r$ is,

$$\bar{E}_r = \frac{k_B T_a}{2eR}. \tag{10}$$

The ions and neutrals have equal mass. The ions gain energy from the electric field between collisions and transfer half that energy to neutrals during collisions. Equating the arc current heating power to the collisional power transfer for a length δ of arc column we get,

$$EI\delta = \left(\frac{1}{2}\right) Z_\delta \frac{e(E+\bar{E}_r)}{N\sigma}. \tag{11}$$

5. Arc column cooling

For the cooling, we ignore radiation cooling and use the same method as Suits and Poritsky [6] where the arc column is treated as a hot cylinder and the heat dissipation is according to the result by Nusselt [7]. The coefficient of heat transfer for the arc column measured in W/(m^2 K) is h. The Nusselt number for the arc column boundary is,

$$Nu = \frac{hR}{k}, \tag{12}$$

where k is the thermal conductivity in W/(m K). The cooling equation used by Suits and Poritsky [6] is,

$$Nu = C(GrPr)^\alpha \quad 0.04 \le \alpha \le 0.25, \tag{13}$$

where Gr and Pr are the Grashof and Prandtl numbers respectively. C and α are constants. The range given for α is based on experimental observations but not for arcs. Suits and Poritsky do not suggest a value or range for C. For the examples in this paper $C = 1$ and $\alpha = 0.08$. Using these values the model is consistent with the classic arc model by Ayrton [8]. The parameters C and α can be used to *fit* the arc model to any particular experimental measurements or to other algebraic models.

The Grashof number Gr is,

$$Gr = \frac{g\beta\rho^2(T_a - T_g)(2R)^3}{\eta^2}, \tag{14}$$

where η is the dynamic gas viscosity measured in Ns/m^2, g is the standard acceleration due to gravity, and β is the coefficient of thermal expansion ($\beta \approx 1/T$ for an ideal gas).

The gas density ρ, which depends on the gas particle mass M_g is,

$$\rho = M_g N. \tag{15}$$

The Prandtl number Pr is,

$$Pr = \frac{C_P \eta}{k}, \tag{16}$$

where C_P is the heat capacity measured in J/(kg K). For gases Pr is approximately constant for a wide range of temperatures and therefore a single value, depending on the background gas, is used.

The coefficient of heat transfer h appearing in Eq. (12) is evaluated from the electrical power dissipated in an column of radius R, which gives,

$$h = \frac{EI}{2\pi R(T_a - T_g)}. \tag{17}$$

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