The Effect on Stability and Thermal Hydraulic Quenchback of Perforating the Jacket of a Cable-in-Conduit Conductor

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Abstract—This paper continues earlier work on the reduction of the quench pressure in a double-jacketed cable-in-conduit conductor achieved by perforating the inner jacket. The present study examines the effect of the perforations on the stability margin and on the onset of thermal hydraulic quenchback.

I. INTRODUCTION

In an earlier paper [1], I investigated how much the quench pressure could be reduced by perforating the jacket of a cable-in-conduit conductor. The conceptual arrangement in [1] is a double-jacketed conductor. The inner jacket, which is perforated by small, regularly spaced holes, contains a cable and supercritical helium. The outer jacket, which encompasses a volume substantially larger than that of the inner jacket, contains supercritical helium. The perforations relieve the pressure in the inner jacket during a quench. In the quenches considered in [1], an entire hydraulic path goes normal all at once. This is the situation originally considered by Miller et al. [2], on whose work [1] is based.

I noted in [1] that the perforations might diminish the stability of the cable against thermal perturbation by reducing the heating-induced flow of the helium. When a normal zone appears in a cable-in-conduit conductor, the helium wetting the normal part of the cable is heated and expands, creating a strong flow through the interstices of the cable [3]. This flow greatly enhances the transfer of heat from the cable to the helium, thereby making all of the helium available for recovery. As a result, the stability margin approximates the enthalpy of the helium between the ambient temperature and the current-sharing threshold [4]. The perforations bleed off some of this induced flow and thus diminish the stability margin.

If the thermal perturbation exceeds the stability margin, the initial normal zone does not recover and instead propagates. In [5], a theory is given of propagation in cable-in-conduit conductors based on the idea that the expansion of the heated helium in contact with the normal conductor causes the normal zone to grow. The pressure in the normal zone is diminished by the perforations, so we anticipate a reduction in the velocity of propagation as well as a delay in the onset of thermal hydraulic quenchback [6].

II. MODIFIED HYDRODYNAMIC EQUATIONS

In [1], the hydrodynamic equations originally used by Miller et al. [2] were modified to include a distributed sink q [$\text{kg m}^{-3} \text{s}^{-1}$] that describes the loss of helium from the inner volume by percolation through the inner jacket. The presence of the sink changes the equation of continuity by the inclusion of the term $-q$ on its right-hand side:

$$\partial \rho / \partial t + \rho (\partial v / \partial z) = -q \quad (1a)$$

But the momentum equation

$$\rho (dv/dt) = -\partial p / \partial z - (2f/D)\rho v^2 \quad (1b)$$

and the energy equation

$$\rho T (ds/dt) = Q + (2f/D)\rho v^3 \quad (1c)$$

remain unchanged. The derivation of these equations is given in [1] and will not be repeated here.

In [1] and [2], the emphasis was on flow conditions seconds after the conductor went normal, that being the order of the elapsed time at which the pressure peaks. In this late stage of flow, the pressure gradient is mainly expended against friction and not in accelerating the helium. Then the left-hand side of (1b), the inertial force, is much smaller than either of the two terms on the right. Neglect of the inertial force provides the basis for an approximate analytic treatment of quench pressure, propagation velocity, and thermal expulsion in quenching cable-in-conduit conductors, all of which are late-stage phenomena [7].

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Stability, on the other hand, is decided in tens of milliseconds, and for such a time and even shorter times, the inertial force cannot be neglected. But now the frictional force can. So very early on, a quenching cable-in-conduit conductor resembles a shock tube. This is the notion employed in [3], where the early flow induced by the Joule power of the normal conductor was calculated by the method of characteristics commonly used to describe flow in shock tubes. What we do here is to follow the approach of [3] to see what difference the sink term $-q$ on the right-hand side of (1a) makes to the induced flow.

III. HEATING-INDUCED FLOW

In [3], (1a) and (1b) were linearized and the frictional terms were dropped. These equations then become

$$\partial \rho / \partial t + \rho (\partial v / \partial z) = -q \quad (2a)$$

$$\rho (\partial v / \partial t) + \partial p / \partial z = 0 \quad (2b)$$

$$T(ds/dt) = Q/\rho \quad (2c)$$

Now by using the thermodynamic identity

$$d\rho = dp/c^2 - (\rho \beta T / c_p) ds \quad (3)$$

we can eliminate ρ in favor of p and obtain the equations

$$(\partial p / \partial t) / c^2 + \rho (\partial v / \partial z) = \beta Q / c_p - q \quad (4a)$$

$$\rho (\partial v / \partial t) + \partial p / \partial z = 0 \quad (4b)$$

Equations (4a) and (4b) were solved in [3] by the method of characteristics, but we need not repeat this work here. Rather we can employ the results given in [3] merely by correcting the Joule power density Q by the factor $1 - c_p q / \beta Q$.

IV. EXAMPLE

We now work in detail a numerical example based on the configuration of the Westinghouse coil of the Large Coil Task [8]. The data describing the coil and conductor are given in Table I.

From this data we find that the Joule power density in the helium is 13.1 MW/m^3 , from which it immediately follows that is $211 \text{ kg m}^{-3} \text{ s}^{-1}$.

To estimate the sink strength q , we need to assume a factor, CF , by which the peak pressure is to be reduced by the perforations. We choose $CF = 0.6$ and guess the Fanning friction factor f in the cable to be about 0.01. Using (6b) and (11) of [1], we find $q = 2.14 \text{ kg m}^{-3} \text{ s}^{-1}$. Then the factor in (5) is 0.990, i.e., the effective value of Q is only about 1%

TABLE I.
DATA DESCRIBING THE WESTINGHOUSE COIL

Ambient temperature	3.8 K
Ambient pressure	1.25 MPa
Helium density	156 kg/m^3
Helium specific heat	$2690 \text{ J kg}^{-1} \text{ K}^{-1}$
Volume coefficient of thermal expansion of helium	0.0431 K^{-1}
Ambient magnetic field	8.0 T
Area of the cable space	275 mm^2
Area of copper in the cable space	120 mm^2
Area of helium in the cable space	88 mm^2
Area of Nb_3Sn /bronze in the cable space	67 mm^2
Hydraulic diameter of the cable space	0.4 mm
Length of a hydraulic path	120 m
Cable construction	486 0.7-mm strands
Resistivity of the copper (4.2 K, 8.0 T)	$4.4 \times 10^{-10} \text{ ohm-m}$
Operating current	18 kA

lower than the value without perforations. According to the results in [3], this means that in this example the perforations cause a 1% reduction in the induced flow velocity. Such a small reduction has a negligible effect on stability.

V. THE PISTON PROBLEM

The theories of [5] and [6] are both based on the solution of the so-called piston problem, namely, the problem of the flow induced in cold helium in a long, slender pipe by the motion of an externally driven piston whose displacement Z is proportional to a power n of the elapsed time t : $Z = Xt^n$. The solution used in [5] and [6] is derived by a method described in detail in [6]. It refers to the case $q = 0$ and is based on the neglect, mentioned earlier, of the inertial term in (1b). When $q > 0$, the same procedure leads to the equations

$$\partial p / \partial t + \partial v / \partial \xi = -q \quad (5a)$$

$$\partial p / \partial \xi = -v^2/2 \quad (5b)$$

where we have introduced (as in [6]) special units in which $\rho = c = D/4f = 1$. Here $\xi = z - Z(t)$ is the distance coordinate in a frame of reference moving with the piston. Equations (5a) and (5b) are subject to the boundary and initial conditions

$$v(0, t) = Z'(t) = nXt^{n-1} \quad (6a)$$

$$p(z, 0) = v(z, 0) = 0 \quad (6b)$$

$$p(\infty, t) = v(\infty, t) = 0 \quad (6c)$$

where now p is the pressure rise.

In a tube with an impervious wall, there is no sink and $q = 0$. Equations (5) and (6) then have the solution for the pressure rise $p(0, t)$ at the piston

$$p(0,t) = AZ^{3/2}t^{-1} \quad (7)$$

where A is a constant that depends on n and is given fairly accurately by $A = 0.473n + 0.208$. For small enough times, when the action of the perforations can still be neglected, we expect that (7) gives the pressure rise at the piston correctly even when q is not zero.

When $n = 1$, (5a) and (5b) have a steady solutions in which p and v depend only on ξ . In a frame of reference fixed with respect to the walls of the tube, this solution represents a traveling wave. Now (5a) and (5b) become

$$dv/d\xi = -q; \quad dp/d\xi = -v^2/2 \quad (8)$$

In [1], q has been shown to have the form $q = Cp^{1/2}$, where the value of the constant C depends (as shown in [1]) on the size and spacing of the perforations. If we now divide the first equation of (8) by the second and integrate, we find

$$v^3 = 4Cp^{3/2} \quad (9)$$

The constant of integration has been set equal to zero in order to satisfy boundary condition (6c). Since $v(0) = X$, we find

$$p(0,t) = X^2(4C)^{-2/3} \quad (10)$$

We expect (7) to hold for short times and (10) to hold for long times. The time t_* at which they cross is given by

$$t_* = XA^{-2}(4C)^{-4/3} \quad (11)$$

For the sake of illustration we continue an example given in [1] in which the perforations are used to reduce the maximum quench pressure by 40%. The illustrative parameters are given in Table II.

TABLE II.
ILLUSTRATIVE PARAMETERS FROM [1]

Hydraulic diameter	1 mm
Half-length of a hydraulic path	100 m
Ambient temperature	4.2 K
Ambient pressure	1 MPa
Helium density	151 kg m ⁻³
Sonic speed in helium	283 m/s
γ (porosity parameter of [1]; $C = \gamma\rho^{1/2}/D$)	2.25×10^{-7}
Fanning friction factor	0.01

In special units, $C = \gamma/4f = 5.63 \times 10^{-6}$; since $A = 0.681$ when $n = 1$, the product of the last two factors in (11) is 2.95×10^{-7} . If $X \sim 1$ m/s in mks units, it equals 3.54×10^{-3} in special units. Thus $t_* = 1.20 \times 10^4$ in special units. Since the unit of time in special units is $D/4fc = 8.84 \times 10^{-5}$, $t_* = 1.06$ s.

If the onset time for thermal hydraulic quenchback calculated by the method of [6] is $\ll t_*$, then the calculation is self-consistent, and the perforations make little difference to the onset. But if the calculated onset time is $\gg t_*$, the calculation based on [6] is no longer self-consistent and the perforations affect the onset of thermal hydraulic quenchback. Then (10) must be used in the onset formula of [6], and threshold behavior may be observed: if compression to the pressure $p(0,t)$ heats the cold helium to the current-sharing threshold temperature, thermal hydraulic quenchback will occur; otherwise, it will not, no matter how long we wait.

CONCLUSIONS

The most important conclusion that we can draw from this work is that it seems possible to reduce substantially the quench pressure in a double-jacketed cable-in-conduit conductor without seriously affecting its stability by suitably perforating the inner jacket. The perforations should not affect the onset of thermal hydraulic quenchback when the onset is rapid, as is the case in high-current-density conductors. But when the onset would otherwise take a relatively long time, the presence of perforations may suppress it altogether.

SYMBOLS

c	Sonic speed in helium [m/s]
c_p	Specific heat of helium [J kg ⁻¹ K ⁻¹]
C	$C = \gamma\rho^{1/2}/D$; see [1]
D	Hydraulic diameter [m]
f	Fanning friction factor [dimensionless]
n	Exponent in the power law $Z = Xt^n$ for the piston displacement
p	Pressure [Pa]
q	Distributed sink strength [kg m ⁻³ s ⁻¹]
s	Specific entropy of helium [J kg ⁻¹ K ⁻¹]
t	Time [s]
T	Temperature [K]
v	Flow velocity [m/s]
X	Proportionality constant in the power law $Z = Xt^n$ for the piston displacement
z	Distance along the conductor [m]
Z	Piston displacement [m]
β	Volume coefficient of thermal expansion of helium [K ⁻¹]
γ	Dimensionless porosity parameter of [1]
ξ	$z - Z(t)$; distance along the conductor in a coordinate system moving with the piston [m]
ρ	Density of helium [kg m ⁻³]

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