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EFFECT OF SUBCHANNEL FLOW VELOCITIES ON THE STABILITY OF HOLLOW CABLE CONDUCTORS*

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INTROUDCTION

The hollow cable conductor adopted by Westinghouse for the Large Coil Program (LCP) model coil consists of a bundle of triplex conductor strands which are initially encased in a circular pipe, but the pipe is subsequently compacted into a square shape. The void, void size, and helium flow distributions among the interstices and subchannels of the conductor affect the conductor cooling, the helium pump work and the refrigeration load. However, there does not exist any experimental or theoretical work that deals with this problem. An analysis was therefore carried out to study the effect of void sizes on the stability of the conductor and the helium pump work required. This work is reported in this paper.

TRIPLEX HOLLOW CABLE CONDUCTORS

Forced flow cooled triplex hollow cable conductors have been proposed for use in a number of toroidal field coils. However, the conceptual designs were generally based on idealized, uniform flow models. A forced flow supercritical helium cooled cable conductor was also proposed by Westinghouse for the Large Coil Program[1]. The reference conductor consists of 7×3^4 or 567 strands that is initially encased in a stainless steel jacket. The cable is subsequently compacted into a square configuration. The fabrication of the conductor has been described elsewhere[2]. A cross-section of a sample 567 strand conductor is shown in Figure 1.

Examination of Figure 1 clearly showed that the helium void size and the void distributions are non-uniform. It may be anticipated that the helium mass velocities in the subchannels with the small void sizes are smaller than the nominal helium mass velocity (flow through the entire conductor). Consequently, the rates of heat transfer are expected to vary with the subchannel size.

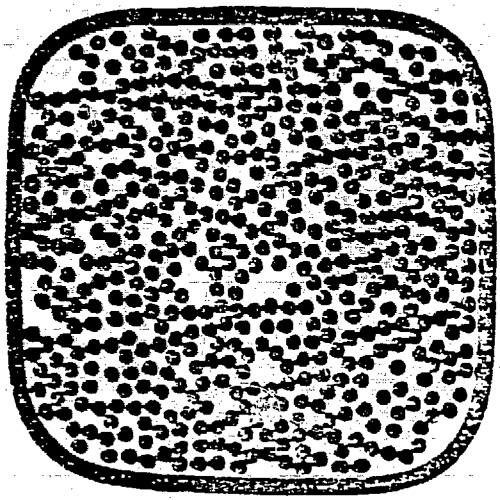

Figure 1. Cross Section of a Typical LCP Conductor Sample.

Given the non-uniform sizes of the subchannels, it was postulated that the strands in contact with the largest subchannels and hence the highest helium flow velocities would recover first. If the transport current is designed to be less than the critical current, then the first recovering strands could carry a higher current then the average. There results a "cascaded recovery" phenomenom where the strands in contact with the minimum flow velocities recover last. Accordingly, for the design of the LCP conductor, it was necessary to determine the relation between subchannel mass velocity and the nominal mass velocity. The first determines the stability of the conductor while the latter determines the pressure drop across the conductor circuit and the helium pump work required. It was evident that such a relation can be developed from the relation of the friction factors with helium flow in the conductor and in the subchannels.

FRICTION FACTORS IN HOLLOW CABLE CONDUCTORS

Hoenig et al.,[3] measured the friction factors of a 57 strand (19 triplex) round pipe cable conductor. The friction factors were calculated from the equation:

$$\Delta P = - \frac{2 L f G^2}{\rho d_H g_c} \qquad (1)$$

where f is the friction factor, G the mass velocity, ρ the helium density, L the conductor length and d_H is the hydraulic diameter, four times the helium flow area divided by the wetted perimeter. Their experimental data showed the following important phenomena: 1) The friction factors are higher than those for smooth tubes and; 2) There is no transition in the friction factor between laminar and turbulent flows. The first observation is as anticipated if one compares the friction factors for flow through tube banks, packed beds, etc., with flow through smooth tubes. The 57 strand triplex conductor tested actually had a relatively uniform void distribution. Therefore, one might expect that, to a certain extent, a conductor with a less uniform void distribution but having the same void fraction could have different friction factors for the same Reynolds number. The second observation is again consistent with flow through tube banks and packed beds which are similar to flow through conductor strands.

Correlation of Friction Factor Data

The lack of a discontinuity in the friction factor curve in the transitional regime suggested that the apparent friction factor, f, may be correlated by the sum of a laminar term and a turbulent term, similar to a generalized correlation developed for packed beds:

$$f = \frac{\alpha}{Re} + \beta \qquad (2)$$

where α and β are empirical constants.

R_e is the nominal or "apparent" Reynolds number, determined from the nominal hydraulic diameter (d_H) and the nominal mass velocity (G):

$$Re = \frac{d_H G}{\mu} \qquad (3)$$

It can be shown that the hydraulic diameter can be given in terms of the strand diameter (d_s) and the helium void fraction (ε) such that:

$$d_H = \frac{d_s \varepsilon}{(1 - \varepsilon)} \qquad (4)$$

Correlation of Hoenig's friction factor data for the round pipe triplex cable conductor by the above equation was obtained with $\alpha = 46.67$ and $\beta = 0.0233$. The correlation is illustrated in Figure 2. It can be seen that the empirical equation fits the data well within the scatter of the experimental measurements.

RELATION BETWEEN SUBCHANNEL AND NOMINAL MASS VELOCITIES

In principal, the total flow cross-sectional area may be divided into a number of sub-channels. Although the twisting of the conductor strands relocates subchannels along the length of the conductor, [redacted]. It should be noted that for very short lengths of the conductor, continuous sub-channels can be approached.

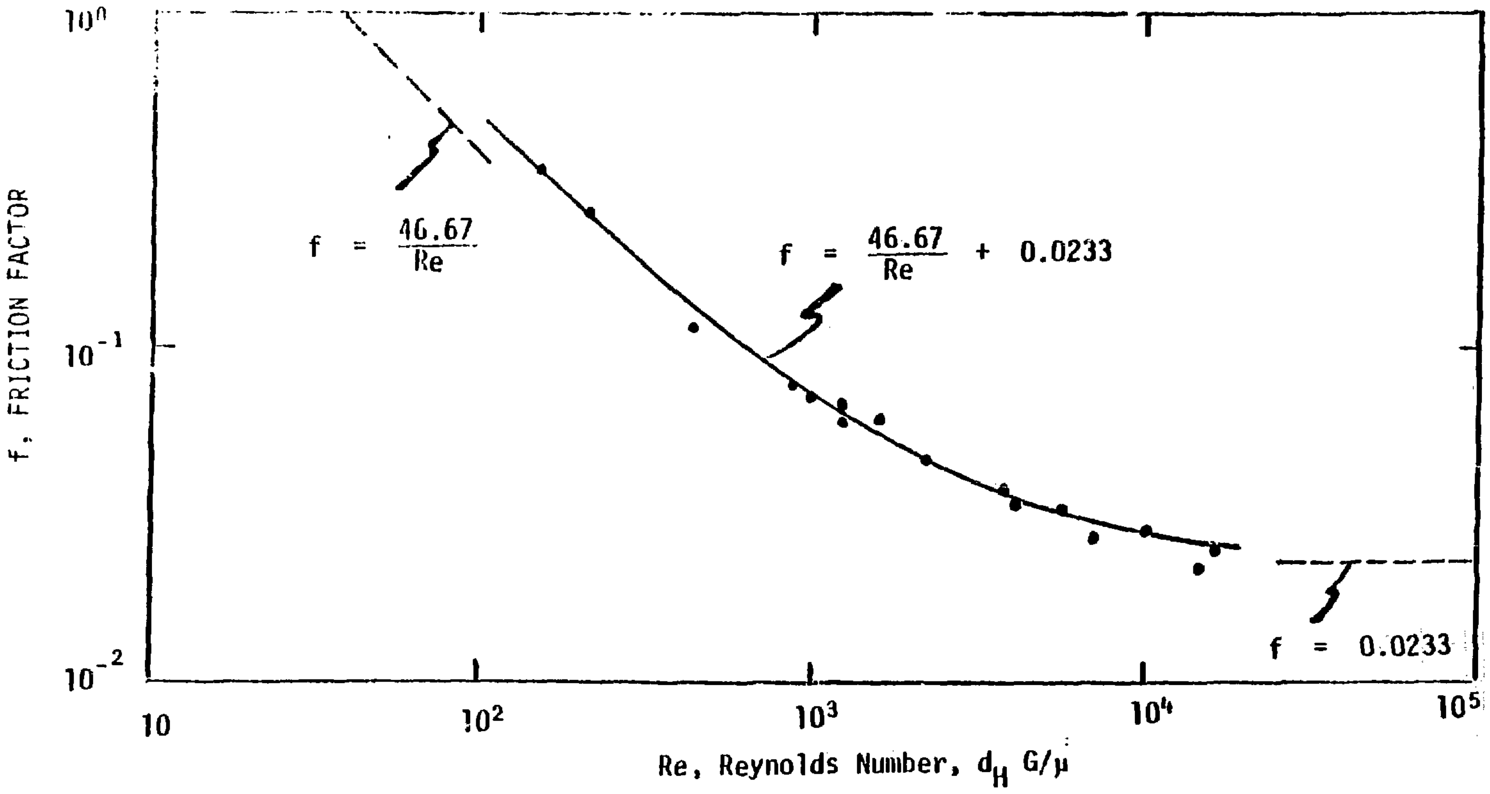

Figure 2. Friction Factor Correlation for Round Pipe Triplex Cable Conductors. Data from Hoenig et al.[3]

The pressure drop across all the sub-channels must be the same. Moreover, it must be equal to that determined from the nominal friction factor, the nominal hydraulic diameter and the nominal mass velocity. For the smallest sub-channels, the friction factor is expected to be dominated by the laminar term so that for an approximation, $f = 46.67/Re_{min}$ can be assumed to apply to the minimum size subchannel.

For a given conductor design where the total conductor cross-sectional area, the void fraction and the strand diameter are specified, the nominal hydraulic diameter becomes fixed and the nominal mass velocity G can be calculated for any mass flowrate. G is therefore related to G_{min} if the minimum sub-channel hydraulic diameter, d_{min}, can be established. Examination of the cross-sections of a number of conductor samples showed that many types of sub-channels can be found. Clearly the case of six strands surrounding one in a closest-packed triangular pitch array forms the minimum size subchannel where the void fraction is 0.093. The relations between G and G_{min} were calculated for two sub-channel models to provide an illustration. The results are shown in Figure 3. It is noted that with increased sub-channel hydraulic diameters, the mass velocity in the sub-channel approaches the nominal value.

CONCLUSIONS AND RECOMMENDATIONS

The experimental data obtained by Hoenig was based on an idealized conductor with a specific void fraction of 0.35. Therefore, for the compacted LCP conductors with a different void fraction, deviations from the correlations may be anticipated. Therefore, there is need for more experimental data, specifically for compacted hollow cable conductors.

Although the existence of continuous, parallel subchannels is not expected because of the twisted strands, the relation between subchannel flow and nominal flow developed here is expected to be fairly good from a statistical viewpoint.

In an analyses on the transient recovery of conductors, it is recommended that the minimum mass velocity to be used to determine the heat transfer coefficient and the mass flowrate with the latter based on the total flow cross-sectional area. In this way, some advantage is taken of coolant mixing among subchannels. The use of minimum subchannel flow area would be overly pessimistic, while the use of the nominal mass flowrate is expected to be overly optimistic.

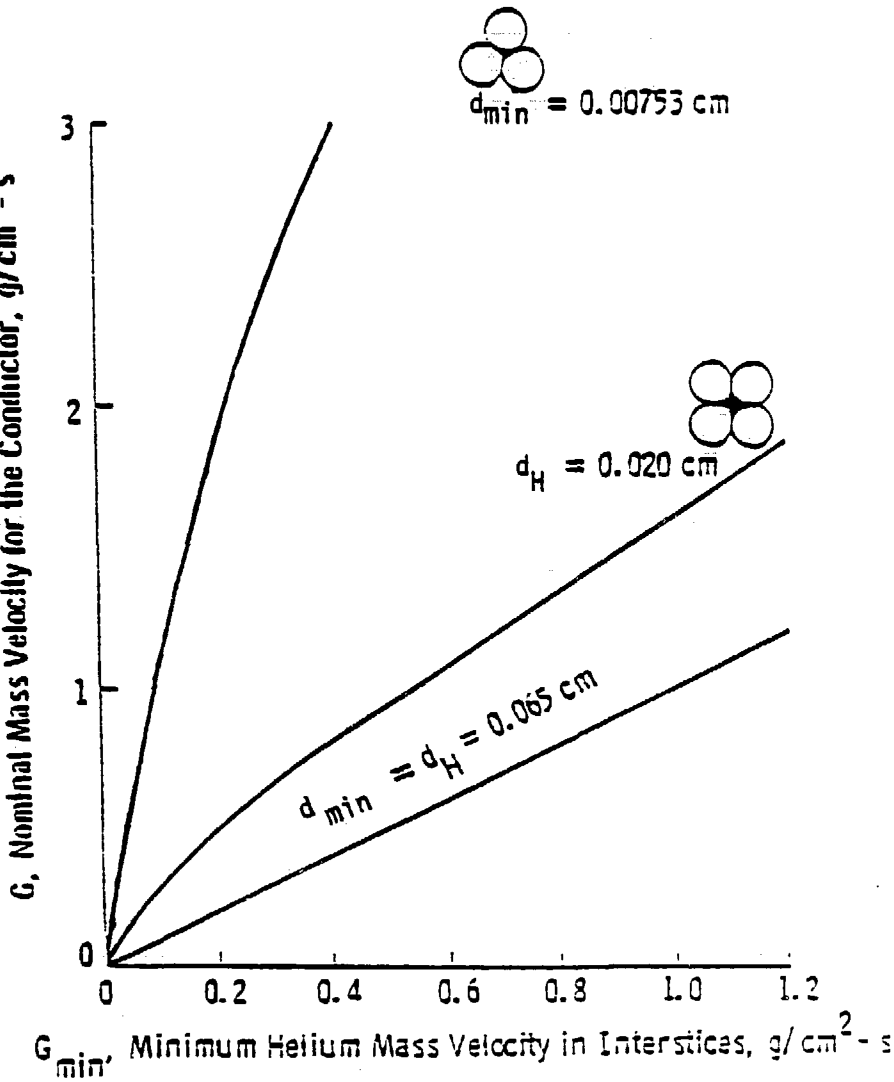

Figure 3. [illegible]retical Relations Between Nominal Helium Mass [illegible]city and Minimum Subchannel Mass Velocity.

In the absence of actual experimental measurements on subchannel flows and a verification of the "cascaded recovery" theory the conductor design approach proposed here could only be viewed as a conservative design technique. A verification of the cascaded recovery theory will require experimental heat transfer and stability measurements. Work in this area is in progress.

REFERENCES

1. Chi, J. W. H., J. H. Murphy, and C. K. Jones, "Selection of a Cryostabilized Nb_3 Sn Conductor Cooling System for the Large Coil Program," Proceedings of the 7th Symposium on Engrg. Prob. of Fusion Research, Volume II, pp. 940-947, October 1977.

2. Sanger, P., et al., "Design Considerations for the Nb_3 Sn Forced Flow Conductor for LCP, Idem, pp. 948-951.

3. Hoening, M. O. et al., "Supercritical Helium Cooled Cabled Superconducting Hollow Conductors for Large High Field Magnets," 6th Int'l. Cryo. Engrg. Conf., Grenoble, France, 1976.

4. Ergun, S., Chem. Eng. Prog., Volume 48, pp. 89-94, 1952.