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Final Report on Fluid Dynamics of Supercritical Helium within Cable-in-Conduit
Conductors

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Abstract

The enclosed report summarizes work carried out under DOE/MFE support during the past four years. Emphasis is placed on progress during the last year. Results of experiments on pressure drop and heat transfer within several Cable-in-Conduit conductors are described. These results are compared to models developed for flow in similar geometries. The work provides a basis for design of magnets using CIC conductors in fusion magnetic systems.

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Summary of Results from Previous Grant

Over the past four years, our research program has focused on measurements of steady state pressure drop in model CIC conductors. Our first results on pressure drop and friction factor on two conductor samples were reported at the 1988 Applied Superconductivity Conference¹. Conductor 1, a prototype supplied by LLNL, had a large number of small copper strands and a relatively small void fraction (36%). Conductor 2 had fewer strands of somewhat larger diameter and larger void fraction (40%). Although these conductors were not the central focus of our study, which involved a range of wire size, void fraction and cabling configurations, they provided a test for the experimental facility. In addition, these preliminary experiments did provide two significant new findings.

The first new observation was the existence of a laminar to turbulent transition in these conductors much as occurs in smooth tube pressure drop. Our paper at ASC was the first to suggest that these conductors experience a laminar-turbulent transition. Since then we have focused a considerable effort toward understanding this effect. The other new observation in these preliminary results was that the so-called hydraulic diameter ($d_H = 4A/p$) does not appear to adequately scale the friction factor in these conductors. This observation is not too surprising considering the complex hydraulic path that fluid within these conductors must follow. However, previous results (e.g., Lue, Miller and Lottin) have been able to correlate the friction factor to within at least a factor of three based on d_H . Our results on these two conductors showed a larger

variation, which encouraged measurements on a variety of samples of different hydraulic configurations.

To attempt a correlation of pressure drop in CIC conductors, we obtained from LLNL nine samples of varying geometry. Pressure drop measurements on five of these samples were reported at the 1990 Applied Superconductivity Conference². The samples studied had variable void fraction (36 to 54%), strand diameter (0.4 to 1 mm) and cabling pattern. Pressure drop measurements were carried out between 1.8 and 5 K at supercritical pressures. Again, the results obtained lead to some surprises. The most notable of these was a calculated friction factor in the turbulent regime which was below that predicted by the Blasius correlation for the measured hydraulic diameter. The spread of the measured friction factors was not as large as reported previously, but we attribute that to the more similar design to the conductors. For example, all conductors contained the same number of strands. We also observed a significant temperature dependence to the derived friction factor. This result may be attributable to the variation of fluid properties provided ordinary Reynolds number scaling is insufficient to correlate the friction factor.

In an effort to understand the results obtained through our experimental program and provide data for design purposes, we developed a new model of the flow pressure drop in the CIC conductor. The main assumption of this model is to treat the contained cable as a type of porous media consisting of a distribution of pore sizes within the conduit. This pore size distribution is interpreted as a bundle of channels,

each having a prescribed hydraulic diameter. This is a one dimensional model since we assume that the channels have a constant cross section over their hydraulic path length. For a given mass flow rate, some of the channels may be in laminar flow while others turbulent. Those channels experiencing laminar flow should follow the classical friction factor formula,

$$f = \frac{A}{Re_d} \quad (2)$$

with the exception that the coefficient A is better described by a star pattern than that of a smooth tube. We have measured the pore size distribution by microscopic image analysis and used that value as an input to calculations.

Results from these calculations have been very encouraging. For example, the model is able to reconstruct the laminar-turbulent transition as well as predict friction factors which deviate from the Blasius form, Fig. 1. The model and its results were published at the 1991 Cryogenic Engineering Conference³ and represented the final

Fig. 1: Comparison between experiment and calculation for friction factor.

aspects of the PhD thesis⁴ of Mark Daugherty, who left our group to join Superconductivity, Inc. in June 1991. Flow measurements on the model CIC conductors are now complete and we are finishing the analysis of the results.⁵ A review article was also written for the SSS-90 conference that summarized some of these findings.⁶

Since June 1991, our grant with DOE/MFE has supported a new graduate student, R. Maekawa, who is preparing for the next phase of experiments. We are in the process of obtaining a sample of ITER relevant conductor from the NET team in order to do more extensive flow studies of this concept. In the mean time, we have been working on development of an eddy current heater for the large CIC conductor appropriate for ITER. This project has involved fabrication in house of a short (5 cm) length of conductor. The sample is instrumented with thermometers and potted in epoxy. We then heat the sample inductively and measure the energy transfer by monitoring the fluid temperature within the conduit. Once we are satisfied with the performance of the inductive heater, it will be installed in the LHFF along with the conductor sample obtained from NET.

The other work with which we have been involved over the past year has been a study of heat transport in He II (superfluid helium) contained in CIC conductors. The work was intended to add information to the basic study of CICC concept while we waited for the full scale conductor to arrive. The principle is to use the heat transport modelling in bulk He II as a way of hydraulic characterization for CICC. In particular, the method provides a separate and fairly simple technique for determining the effective flow cross section of the conductor. This result is being used to reanalyze the flow data from the nine model conductors. Abstracts on the subject have been

submitted to ICEC 14 in Kiev, Ukraine and the 1992 Applied Superconductivity Conference.^{7,8} The technique may prove to be a cheap and easy way to establish hydraulic characteristics of a CICC before it is installed in a full scale magnet.

We believe that the body of results obtained from our previous four years of support has provided some important input to the design and development of future CICC magnet systems. It is our desire to continue this effort in fluid dynamics related to the cooling of these systems, with special emphasis on problems relevant to ITER.

List of publications bases on work supported during the previous grant period

- 1) M. A. Daugherty, Y. Huang and S. W. Van Sciver, "Pressure Drop Measurements on Supercritical Helium Cooled Cable in Conduit Conductors", IEEE Trans. on Magnetics 25, 1512 (1989).
- 2) M. A. Daugherty and S. W. Van Sciver, "Pressure Drop Measurements on Cable in Conduit Conductors of Various Geometries", IEEE Trans. on Magnetics 27, 2108 (1991).
- 3) M. A. Daugherty and S. W. Van Sciver, "Distribution of Diameters Analysis of Pressure Drop in Internally Cooled Cabled Superconductors", Adv. Cryo. Engn. 37, 163 (1992).
- 4) M. A. Daugherty, "Helium Hydrodynamics of Internally Cooled Cabled Superconductors", PhD Thesis, University of Wisconsin-Madison (1991).
- 5) S. W. Van Sciver, "Stability of Superconductors Cooled Internally by He II Heat Transfer", Cryogenics 31, 516 (1991).
- 6) M. A. Daugherty and S. W. Van Sciver, "Influence of Helium Properties on the

Pressure Drop in Cable in Conduit Superconductors" Abstract submitted to 1992
Applied Superconductivity Conference, Chicago, IL

- 7) R. Maekawa, S. W. Van Sciver and H. J. Schneider-Muntau, "Heat Transport in
Cable in Conduit Conductors (CICC) Cooled by He II" Abstract submitted to 1992
Intern. Cryo. Engn. Conference, Kiev, Ukraine.
- 8) R. Maekawa, M. A. Daugherty and S. W. Van Sciver, "He II Counterflow
measurements as a method of Characterization for Cable in Conduit Conductors"
Abstract submitted to 1992 Applied Superconductivity Conference, Chicago, IL.