CONF-860914--2

UCRL-95391
PREPRINT

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RECEIVED by OSTI
OCT 22 1986

Presented at the 1986 Applied Superconductivity
Conference, Baltimore, Md.
September 28—October 3, 1986

September 1986

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LIQUID HELIUM COOLING OF THE MFTF SUPERCONDUCTING MAGNETS

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UCRL--95391

DE87 000530

Abstract

During acceptance testing of the Mirror Fusion Test Facility (MFTF), we measured these tests: liquid helium heat loads and flow rates in selected magnets. We used the data from these tests to estimate helium vapor quality in the magnets so that we could determine if adequate conductor cooling conditions had occurred. We compared the measured quality and flow with estimates from a theoretical model developed for the MFTF magnets. The comparison is reasonably good, considering influences that can greatly affect these values. This paper describes the methods employed in making the measurements and developing the theoretical estimates. It also describes the helium system that maintained the magnets at required operating conditions.

Introduction

Construction and acceptance testing of the Mirror Fusion Test Facility at the Lawrence Livermore National Laboratory was completed in March 1986.¹ Major systems that make up the facility include 42 superconducting magnets, the 11-kW liquid helium (LHe) system, the 500-kW liquid nitrogen system, and a 4000-m³ (60-m-long) vacuum vessel that contains the magnets.² The superconducting magnet system is currently the world's largest, having a combined weight of approximately 1200 tonnes, the largest magnet weighing 160 tonnes.

Sufficient liquid helium flow through the superconductor coils to ensure a conductor temperature of less than 4.5 K is essential to successful operation of the magnets. Cooling is accomplished by LHe flow over the conductor external surfaces and magnet case internal surfaces. Heat loads to the magnets result in unavoidable helium vapor generation that degrades the cooling effectiveness of the LHe. If the vapor fraction of the helium should become too great, cryostability of the conductors would be inadequate for them to recover from incipient normal conduction zones. To ensure that this does not occur, we designed the LHe flow system to maintain the helium vapor quality in the magnets below 15 vol%.

We developed a computer thermal-flow model of the LHe cooling circuits to aid our design of the flow circuits. The model estimates LHe flow rates and vapor qualities. In conjunction with the model, we installed flow meters in selected magnet LHe circuits so that measured flows and qualities could be compared with theoretical estimates. In this paper, we describe the methods we used to make the

theoretical estimates and obtain experimental measurements. We then compare the estimates and the measurements.

The Helium Flow System

LHe flow through the magnets is accomplished by closed-circuit natural convection. Dewars installed on top of the vacuum vessel supply LHe to the bottom of each magnet through connected piping. After the LHe flows upward through the magnets and exits at their highest point, it is returned to the Dewars through connecting piping. Heat loads on the magnets cause evaporation of some LHe; this results in a density reduction that thereby induces natural convection. Figure 1 illustrates these circuits for the magnets in the west half of the MFTF vacuum vessel.

1 Helium Dewars, 600 L	6 Transition magnet T1
2 Yin-yang magnets, M1, M2	7 Solenoid magnets S1-S6
3 Axicell magnet A1	8 Trim coils TR1-TR4
4 Axicell magnets A2o, A2i	9 Trim coils TR5-TR8
5 Transition magnet T2	10 Vacuum vessel

Fig. 1. Schematic of the west magnet LHe system in the MFTF.

The LHe level in the Dewars is maintained nearly steady by a feed system from a 60-kL storage Dewar. Vapor in the magnet return flow is separated from the liquid in the Dewars, then returned to the helium liquefying system.

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Thermal protection of the magnets and helium piping is provided by a vacuum environment and liquid nitrogen-

cooled shields. Heat loads to the LHe consist mostly of thermal radiation from these shields and heat conduction through their support brackets attached to the magnets and piping. Other heat loads come from heat conduction through the magnet support struts and electrical heating in conductor joints. Some heat is transferred to the LHe through the vapor-cooled current leads and their enclosures, but most of the vapor generated by this heat load is vented through the current leads.

Calculation of LHe Flow

Method

Our method of calculating LHe flows and qualities employed conventional engineering flow analysis methods. We discretized a flow loop of piping, magnets, and Dewar, shown in Fig. 2, with finite-length flow elements. Beginning at the Dewar outlet, we calculated the fluid exit pressure of each element by accounting for pressure changes caused by gravity and friction. A mass flow rate must be assumed to perform the pressure calculations; if the correct flow is selected, the Dewar supply and return pressures are equal. Consequently, we used an iterative procedure to arrive at the correct flow and resulting vapor quality.

Fig. 2. Schematic of the helium system for a solenoid magnet pair.

The calculations require an assignment of heat loads to the elements. Heat transferred to the LHe results in a reduction of density—the principal force that causes the natural convection flow. In contrast, forces that resist flow are caused by friction. Therefore, friction coefficients must also be assigned to each flow element. We considered including forces caused by changes in bulk flow momentum, but these forces were small enough to be neglected.

We used published friction factors³ for the various components of the piping system, e.g., bends, elbows, tees, pipe sections, etc., to estimate friction pressure losses. We obtained magnet friction factors from measurements in two magnets.^{4,5} We developed a Reynolds number correlation of the Blasius friction factor from measured pressure loss and gas flow through the magnet coils. The resulting correlation is expressed in the form:

$$f = C1/Re^{C2},$$

where $C1 = 69.2$ and $C2 = 0.46$ for a yin-yang magnet (M1 or M2), and $C1 = 1.95$ and $C2 = 0.23$ for a solenoid magnet (S1 - S6)

The Reynolds number is based on a bulk velocity in the coil pack and a hydraulic diameter. The estimated diameter values are 0.29 cm for the yin-yang and 0.16 cm for the solenoid magnets. The length value used to estimate pressure loss in the coils is the coil path length—890 cm for the yin-yang and 785 cm for the solenoid magnets. Two-phase flow effects on frictional pressure losses are accounted for with the Lockhart-Martenelli correlation.⁶ For the range of vapor fractions that occurred, this correlation is approximated by using a friction factor multiplier defined as $FFM = (1 + Xv)^2$, where Xv is the volume fraction of vapor.

The model flow calculations include temperature-dependent fluid properties. It is essential to include these properties in this type of calculation because helium properties are very sensitive to temperature.⁷

The flow circuit illustrated in Fig. 2 includes parallel piping in the return lines. The lower one is the main line that returns flow to the Dewar. The upper line is defined as the current-lead vapor bypass line, which provides a vent the current-lead pipe. Heat conduction through the current leads and their containment piping generates more vapor than is vented through the leads. This excess creates enough pressure to depress the liquid-vapor interface until the vapor escapes through the bypass line. The LHe is maintained at this level during normal operation. The flow model accounts for the vapor bypass line by including two effects in the calculations. The first is allowing a fraction of the vapor exiting the magnet to rise into the current lead pipe and flow through the bypass line. The other is including the excess vapor from the current leads in the bypass line. These two vapor flows are added to the LHe flow in the main return line at the appropriate location.

All magnets, except the yin-yangs, are paired in parallel flow circuits connected to one Dewar. The flow modeling accounts for this arrangement by computing the flow in both branches. The flow through nearly all magnet pairs is assumed to be equal because the parallel circuits are identical and the heat loads are assumed to be equal. The transition magnet circuits are an exception because the circuit branches and heat loads are not identical.

The computational process for the parallel circuits is basically the same as for a single-loop circuit. That is, flow

rates through the branches are iteratively selected until fluid pressures are equal at the point where the two lines merge.

Results

We computed helium flow and quality for two selected magnet circuits; the results are presented in Figs. 3 and 4. The two curves for each magnet circuit represent a possible range of values as influenced by the uncertainty range of model parameters and assumptions. For example, piping friction factors, loss factors, and distribution of heat loads significantly affect computed flow rates. The curves and their value ranges differ because the two circuits have very different characteristics.

Fig. 3. Liquid helium flow vs system heat load for yin-yang magnet M1W and solenoid magnets S1W + S2W. Curves are limits of estimates. Bars are ranges of measurements.

Fig. 4. Vapor quality of helium return flow to the Dewar for yin-yang magnet M1W and solenoid magnets S1W + S2W. Curves are limits of estimates. Bars are ranges of measurements.

We selected the two magnet circuits represented in Figs. 3 and 4 as examples for the flow analysis because these circuits are the ones that contained helium flow meters.

Measurement of Helium Flow

Method

We installed a venturi-type flow meter in the Dewar supply line of the helium piping circuits for yin-yang magnet M1W and solenoids S1W + S2W. (See Fig. 2.) The meters had a high-pressure recovery (>95%), which created only a small addition of flow resistance to the circuits. We used high-sensitivity pressure transducers (10 Pa) to measure the differential pressure developed by the venturis. Stainless steel tubing (6 mm) connected the venturis to the transducers, which were installed outside the vacuum vessel. We selected this type of flow instrumentation because it was compatible with the high-vacuum, low-temperature, and high-magnetic field environment.

We are aware of the possibility of developing thermally induced pressure oscillations in the pressure measurement tubing.⁶ To overcome this, we anchored the tubing with clamps to the helium piping for approximately 1 m. We anchored the remaining length to the liquid nitrogen shields up to the vacuum vessel penetrations. This helped minimize thermal gradients in the tubing and heat transfer to the flow meters. The long length of tubing (>6 m) also provided some dampening to pressure oscillations and helped inhibit thermal pumping conditions.

We also measured the heat loads to the magnet circuits by interrupting the supply of LHe to the Dewars and measuring the LHe volume decrease rate in them. We determined the circuit heat load, Q , including the Dewar, as the product Vdh , where V is the volume boiloff rate, d is the liquid density, and h is the phase change enthalpy.

Helium vapor quality (wt%) at the Dewar return is determined by the quantity $Q/(Mh)$, where M is the measured mass flow rate minus the helium vent rate through the current leads. (Flow through the current leads was less than 1 g/s.)

Results

Measured LHe flow rates in the selected magnet circuits are shown in Fig. 3. Only one heat load for each circuit could be obtained because heating was not a varied parameter during the magnet tests. However, heat loads were greater than design estimates. A main contributor was a vacuum pressure of 0.1 mTorr that allowed heat convection to occur.

The vertical bars in Fig. 3 represent the range of measured flow rate. These results indicate that the flow was unsteady, as would be expected. Several factors can contribute to the unsteady flow; a principal factor is the nature of two-phase flow in systems such as these. Periodic

coalescence of the vapor into large bubbles promotes surging. Also, the Dewar LHe level control system causes pressure variations that can result in flow changes.

The vapor qualities of the Dewar return flows are shown in Fig. 4. The range of qualities is derived from the range of flows in Fig. 3. (The ratio of vol% to wt% is approximately 5 for the return flow conditions.) To determine the vapor quality in the magnets, the return flow qualities must be corrected for pressure and heat load changes between the Dewars and magnets. On making these adjustments, we find that bulk qualities in the magnets did not exceed our 15 vol% limit.

Conclusions

We conclude that the methods we employed to estimate and measure LHe flows show reasonable agreement, especially for large-scale systems such as the MFTF magnets. Even though the range of measured flows is not entirely within the range of estimates, the results are sufficiently close to strongly indicate acceptable bulk vapor qualities in the magnets. This agreement was further evidenced by the fact that during testing the magnet conductors always recovered from incipient normal zones. This implies that cooling of the conductors was sufficiently good to recool the conductors to superconducting temperatures.

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