the range of the test data,[2] and extrapolation of the equation should be handled with caution especially when the ratios of Y/δ and L/Y are concerned. Equation (1) was applied to preliminary, unpublished test data having numerically similar parameters as presented herein with the exception of Mach number which was 5.2; the agreement was within $+10\%$ in all cases. Extrapolation to higher Mach numbers is not recommended because of the real-gas effects in the hypersonic regime.

Conclusion

In conclusion, the equations presented herein can be used for aerodynamic heating calculations with reasonable accuracy only if the limitations of the equations are not greatly exceeded. In all cases, the ratio of heat-transfer coefficients immediately behind the protuberance were below unity, and further downstream the ratio of coefficients never exceeded twice the value of the flat-plate coefficient.

The highest ratios occur in the regime immediately upstream of the protuberances where some of the ratios exceed four times that of flat plate. Consequently, maximum heating will occur in front of a two-dimensional stringer where the magnitude of heating approaches that of stagnation-point heating.

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Effect of Rocket Engine Vibration on an Air-Core Superconducting Magnet

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THE behavior of an air-core superconducting magnet in the presence of rocket engine vibration is discussed in this note. Observations reported herein were obtained as secondary information while performing applied research on the effect of an axial magnetic field on rocket nozzle heat transfer.[1, 2]

Experimental Apparatus

Project THERMA‡ experiments utilized an 85-lb thrust, water-cooled liquid-fuel rocket engine burning gaseous oxygen and methyl alcohol at a chamber pressure of 20 atm. The reactants were seeded with cesium carbonate to enhance the electron density and electrical conductivity of the combustion products. The instrumented, contoured rocket nozzle had a throat diameter of 0.5 in. and a radius of curvature of 4 in. The injector was of the impinging stream type and gave smooth and efficient combustion over a wide range of chamber pressures and oxidizer-fuel ratios. The rocket engine was mounted coaxially with the air-core superconducting magnet and fired vertically downward into a water-cooled exhaust duct (Fig. 1).

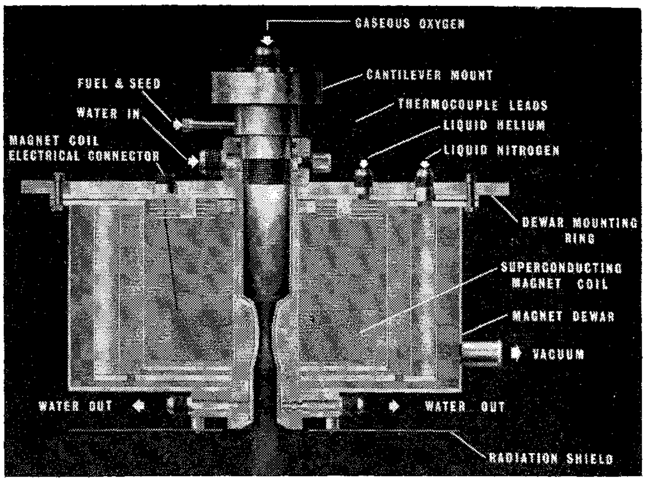

Fig. 1 Simplified cutaway of THERMA II experimental device.

The superconducting solenoid was found on an aluminum mandrel using 55,000 ft of Westinghouse 10-mil niobium-25% zirconium wire. The 40,357-turn solenoid (3.1-in. i.d., 7.25-in. o.d., and 2.12 in. in length) was wound from four lengths of wire with a total of five joints. The wire was restrained by two thin aluminum disks, punched to provide additional direct contact with the liquid helium. Wire ends were brought outside the solenoid and connected through copper blocks around its periphery. The resistance of the dry solenoid was 110,000 ohms; when cooled with liquid nitrogen its resistance was 81,000 ohms, and with liquid helium, zero ohms. The solenoid (Fig. 2) was designed§ so that the flux lines would follow the contoured nozzle wall. It was mounted inside a stainless-steel dewar, which had a 2.5 in.-diam air-core extending for the entire 8-in. length of the dewar. The dewar contained liquid helium at 4.2°K and was insulated from the external environment by vacuum (5×10^{-7} torr) and liquid nitrogen shields.

The solenoid was connected to its transistorized power supply through an energy transfer circuit that disconnected the power supply from the solenoid when a transition to the normal resistive state began to propagate in the solenoid windings. The circuit was opened by an electromechanical switch that actuated in approximately 1 msec upon receiving an indication that a voltage increase was occurring on the solenoid windings. The energy dissipated during a transition was absorbed in the solenoid windings and in a resistive load located in the energy transfer circuit. Oscilloscope data indicated that about 20% of the stored energy was dissipated in the resistive load, the remainder in the solenoid itself.

The pancake-type solenoid could not be charged at rapid rates; to do so was to insure a normal transition. When the total current in the solenoid was low, the charging rate could be relatively high, but, as the current in the solenoid increased, the charging rate had to be decreased to avoid a normal transition. The safe charging rate for the solenoid was determined during 17 hr of superconducting operation in which the solenoid sustained 40 normal transitions. The most energetic transition was from a current of 6.6 amp, corresponding to a measured flux density on the solenoid axis of 26 kgauss and a calculated flux density on the inner windings of about 30 kgauss. Oscilloscope data of transition-induced voltage from each winding indicated that the transitions did

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‡ Acronym for transfer of heat reduced magnetically.

§ The superconducting magnet system was designed and fabricated especially for the project by Advanced Kinetics, Inc., under the direction of Ralph Waniek.

Table 1 THERMA sound data

Band width, cps	Sound field, db^a
20–20,000	122
9600–20,000	105
6800–9600	112.5
4800–6800	114
3400–4800	114
2400–3400	114.5
1700–2400	114
1200–1700	113
850–1200	108
600–850	104.5
300–600	104.5
212–425	104.5
106–212	107
53–106	99
20–53	90

[a] *db* reference to 0.0002 dynes/cm²rms.

not always begin in the inner winding but could begin anywhere in the solenoid. The other windings very rapidly picked up the transition. Attempts to operate the solenoid at currents greater than 6.6 amp were unsuccessful. The program schedule did not permit further evaluation of the peculiar charging behavior.

The vibration environment produced by the rocket engine presented unknown factors in the operation and performance of the superconducting solenoid. To evaluate these factors, measurements of the acoustic spectrum and the magnet dewar vibration were made during the test firings. The acoustic environment was evaluated using an H. H. Scott-type 410-B sound meter connected to an H. H. Scott octave band analyzer. The sound meter was mounted about 4 ft from the rocket engine with the microphone pointing at the exhaust. A three-axis Endevco accelerometer was mounted on the dewar mounting ring, which was attached to the cantilever beam holding the downward firing rocket engine. The electrical signal from the accelerometer was amplified and photographically recorded on an oscilloscope. Two data points were obtained: one with a slow sweep speed during ignition of the rocket engine and the other with a fast sweep speed during the firing.

Experiments

Typical experimental procedure for the heat-transfer investigation was to bring the superconducting magnet to the desired field value and then fire the rocket engine. When all flow and pressure conditions had been adjusted and stabilized, a normal transition was manually induced in the solenoid through the energy transfer circuit. The magnetic field would rapidly decrease to zero. During the firing, environmental data were being taken. After several seconds at the zero field condition the firing was terminated. Typical firing duration was 2–3 min.

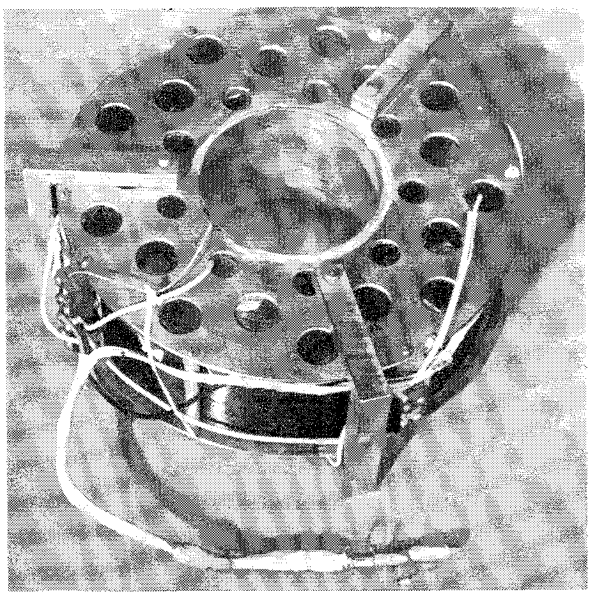

Fig. 2 Superconducting solenoid.

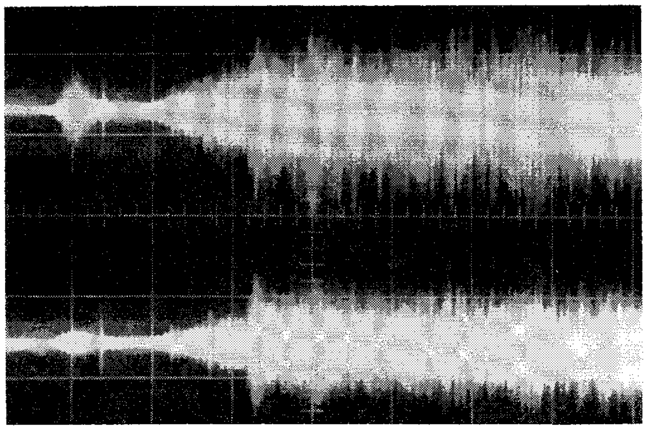

Fig. 3 Magnet dewar vibration. Engine firing begins at left of photograph. Sweep: 0.2 sec/cm Z axis (longitudinal) shown on upper trace, gain: 11.55 g/cm, peak loading: 29.6 g. Y axis (transverse) shown on lower trace, gain: 9 g/cm, peak loading: 16 g.

The vibration and acoustic environment of the rocket engine often caused the superconducting solenoid to undergo a normal transition upon ignition of the propellants. In runs at 15,700 and 17,500 gauss, the magnet sustained a normal transition approximately 0.5 sec after opening of the main propellant valves. The oscillograph record of rocket engine parameters indicated that each transition occurred at the onset of combustion when all propellant flows had become stable; this was confirmed by photographic evidence that showed that a jet of helium, caused by energy dissipation from the solenoid, began issuing from the dewar vent at the same time that the rocket exhaust became fully developed.

Figure 3 shows the amplified output of the Y and Z axes of the accelerometer as displayed on a Tektronix 535-A oscilloscope. The normal transitions apparently occurred at the onset of peak g-loading since the respective times coincide almost exactly. Typical sound levels measured in the vicinity of the rocket engine are given in Table 1.

Summary

Dynamic vibration, caused by combustion and jet effects, can apparently affect the operational stability of a superconducting magnet. The charging behavior of the solenoid may be related to the operational instability noted during rocket engine firings; hence, the observations made in this note may not be applicable to all superconducting solenoids.

References

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