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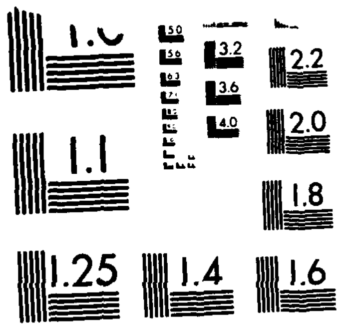
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David W. Taylor Naval Ship Research and Development Center
Bethesda, MD 20084-5000

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Propulsion and Auxiliary Systems Department
Research and Development Report

THE USE OF ALLOY 117 AS A LIQUID METAL CURRENT COLLECTOR

by
David Maribo and
Neal Sondergaard

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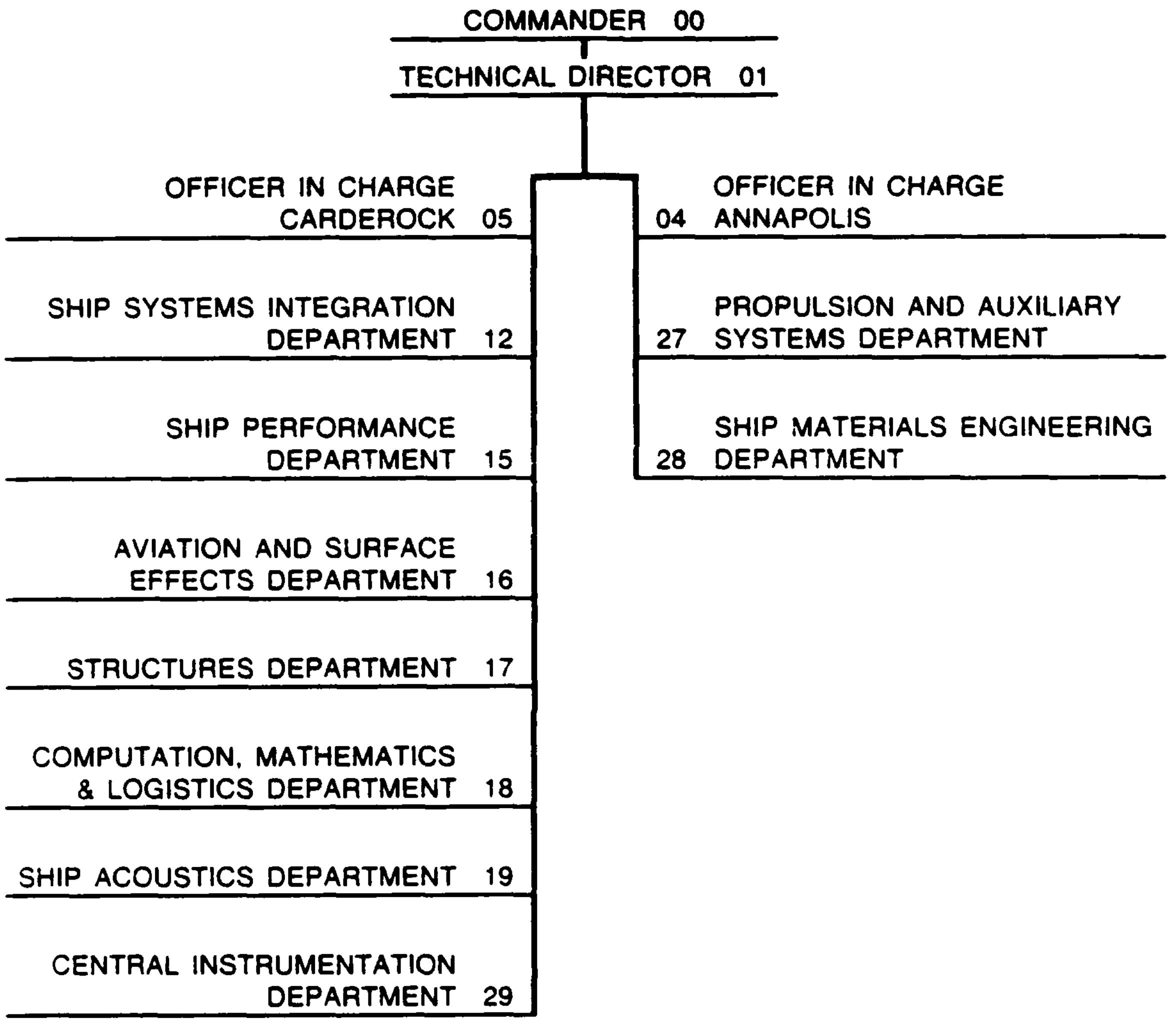

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ABSTRACT

Low melting point, bismuth-based alloys are potential replacements for NaK_{78} as liquid metal slip ring material because of their lower reactivity and potentially greater hydrodynamic stability. This paper describes experiments with one such alloy in a model of a 300 kW superconducting homopolar motor using close clearance braid type collectors. Slip ring tip velocities varied from 5 to 20 m/s and currents ranging from 500 to 2500 A. Viscous power losses tend to follow a simple turbulent model. In all, the data supports the use of low melting point alloys as an alternative to NaK^{78}.

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INTRODUCTION

Homopolar motors and generators are being considered for future Naval ship propulsion systems. These machines are characterized by relatively low voltages and extremely high currents and, therefore, require low loss current collectors if high efficiency and power density are to be achieved. The current densities required are well above the capacity of conventional solid brushes. Laboratory scale (300 kW) homopolar machines have been successfully demonstrated[1-3] using the eutectic alloy NaK_{78} (22% sodium and 78% potassium) in a liquid metal current collector. NaK is compatible with machine components and exhibits excellent electrical and physical properties. The disadvantage of NaK is that it is highly reactive with oxygen and water; therefore, exposure to normal atmosphere must be prevented, resulting in added machine shaft seal complexity.

Previous investigations have been conducted to find a suitable liquid metal alloy to replace NaK.[4-8] Low melting point alloys (LMPA) have the potential to be such a replacement. Alloys with melting points below 65°C containing various proportions of bismuth, lead, tin, indium, and cadmium were selected as candidates for initial screenings. Many of the physicochemical properties of these alloys were studied at DTNSRDC by Arora[4] and Smith.[6] Table 1 compares the physical characteristics of the previously tested alloys; NaK and alloy 136 (Sondergard et al.[9]) and the subject of the present investigation, alloy 117. (Note: The name of the alloy is the melting point in degrees F.)

Table 1. Characteristics of alloy 117, alloy 136, and NaK_{78}.

Liquid Metal	Density (g/cm^2)	Resistivity (μΩ-cm)	Viscosity cP	Composition (%)						
				Bi	pB	Sn	In	Cd	Na	K
Alloy 117	9.75	88.4 (at 77°C)	3.31	45	23	8	19	5		
Alloy 136	9.23	89.2 (at 77°C)	3.53	49	18	12	21			
NaK_{78}	0.85	33.8 (at 20°C)	0.5						22	78

The advantage of using the low melting point alloys in a motor is the relative ease of handling compared to NaK. In addition, although these alloys still require a cover gas to prevent oxidation, exposure to air for a short time can be tolerated. In fact, complete deterioration does not occur for 50 to 100 hours.

The purpose of the investigation reported here was to evaluate the performance of alloy 117 in a test rig with current collectors similar to those of an existing 300 kW motor, in anticipation of using the alloy in that motor. The initial experimental objectives were to measure the electrical and mechanical losses for the alloy 117 in a braid collector.

DESCRIPTION OF EXPERIMENTS

The apparatus consists of two adjacent collectors (referred to as the free side and motor side collectors) on a 0.312 m (12.29 in.) diameter rotor. The width of the collector tips is 2.54 mm (0.100 in.). Figure 1 is a photo of the assembled rig.

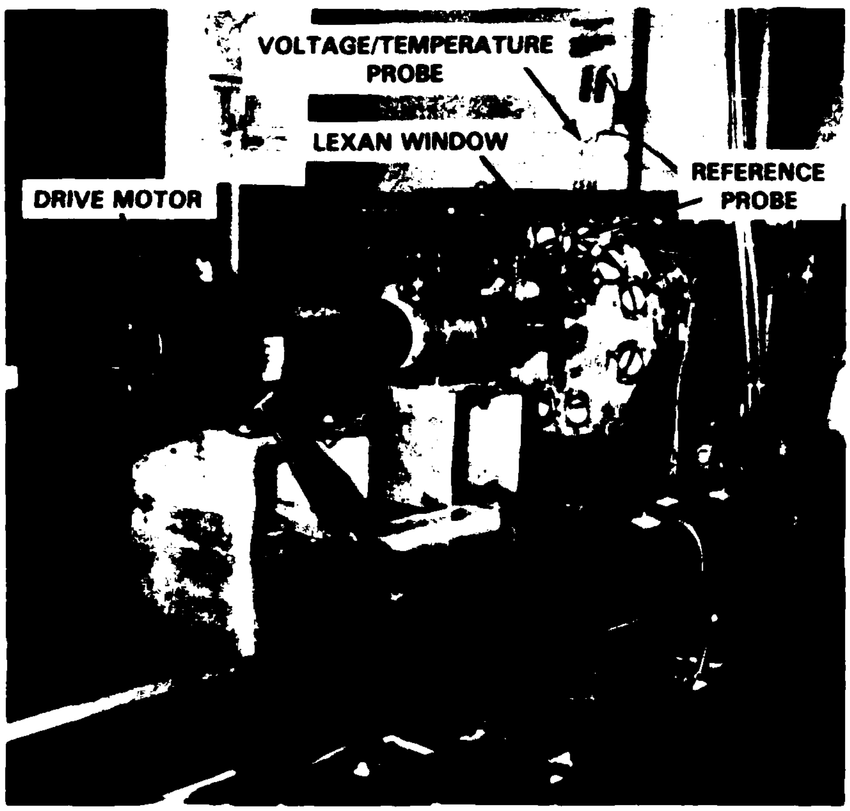

Fig. 1. Photo of test rig.

A copper grounding braid was used to provide minimum clearance between the rotor tip and the stator. On assembly there is an interference fit, which wears away to a clearance of 50 to 100 μm after several hours running. This scheme has proved successful in previous tests with this rig and the 300 kW motor. A cross sectional view of the braid is shown in Fig. 2. A photograph of the braid is shown in Fig. 3.

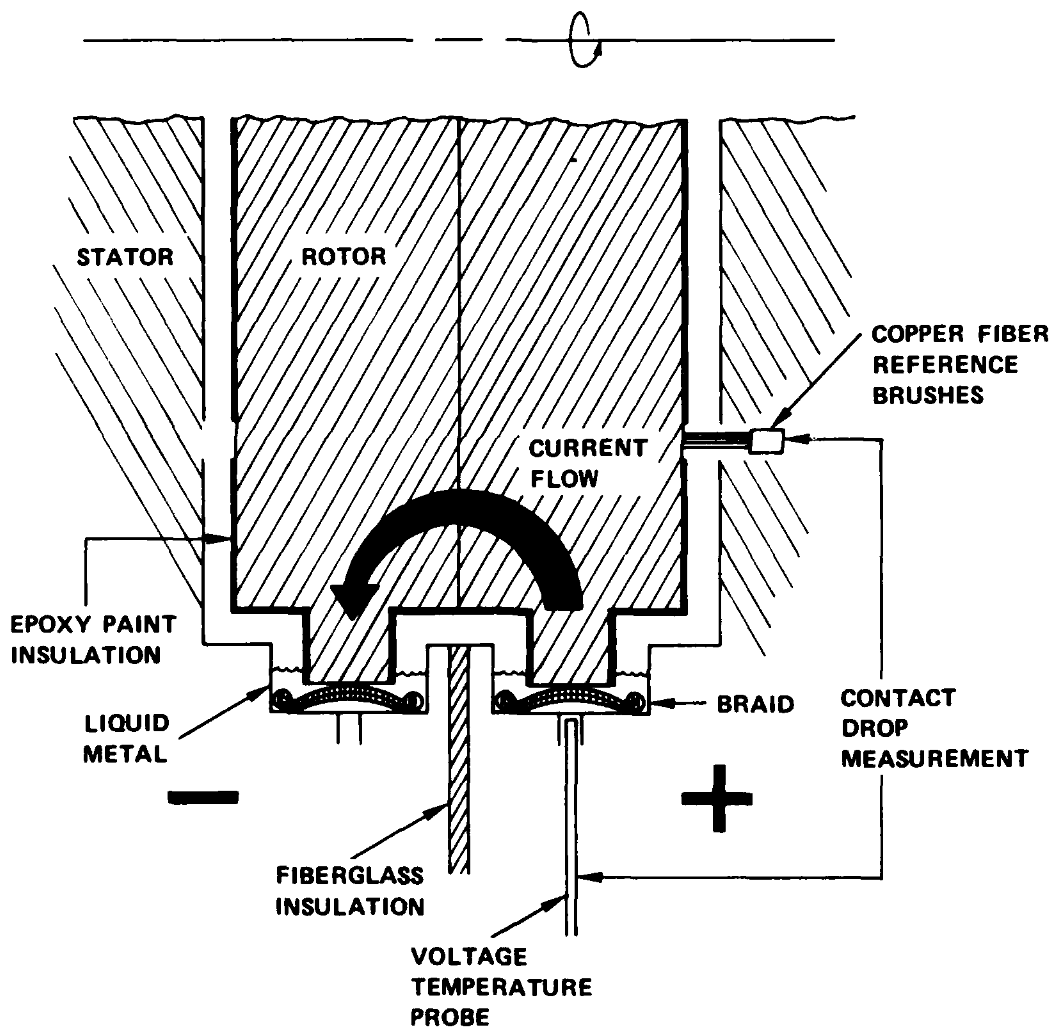

Fig. 2. Cross section of DTNSRDC liquid metal braid narrow gap collector.

Fig. 3. Close up of braid in holder before assembly into rig.

The voltage drop from stator to rotor could be monitored by using two copper fiber brushes, one riding on each side of the rotor. The reference brushes consist of a 2.5-mm dia. bundle of 127 μm dia. (0.005 in.) strands. As can be seen in Fig. 2, the resulting contact drop is the voltage across the liquid metal gap. The entire rotor was insulated with an epoxy paint coating except for the outside diameter (the rotor tip that conducts the current) and the tracks where the copper fiber reference brushes ride. The rotor tip was nickel plated, then tinned with alloy 117 to promote wetting.[10] A torque transducer provided information on mechanical drag.

The alloy was introduced into the rig with heated syringes through a 10-μm filter. The volume was varied from 6 to 12 cm^2 per collector. The rig was maintained at 70°C, as in previous tests. A positive pressure of dry nitrogen cover gas was maintained to prevent oxidation of the alloy. The velocities used, 5 to 20 m/s, are typical of a 300-kW motor. The maximum current of 2500 A was the limit of the power supply.

Figures 4 and 5 show the electrical characteristics of the collector; Figs. 6 and 7 show the torque losses resulting from viscous drag.

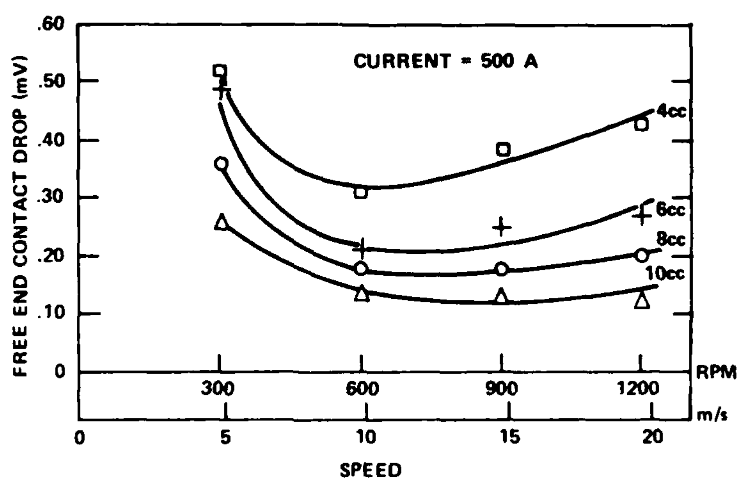

Fig. 4. Effect of speed and fill volume on contact drop.

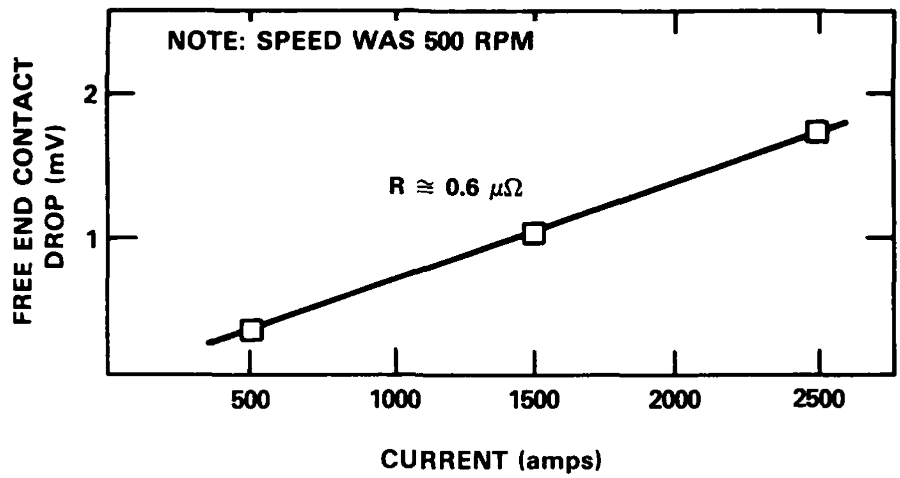

Fig. 5. Effect of current on contact drop.

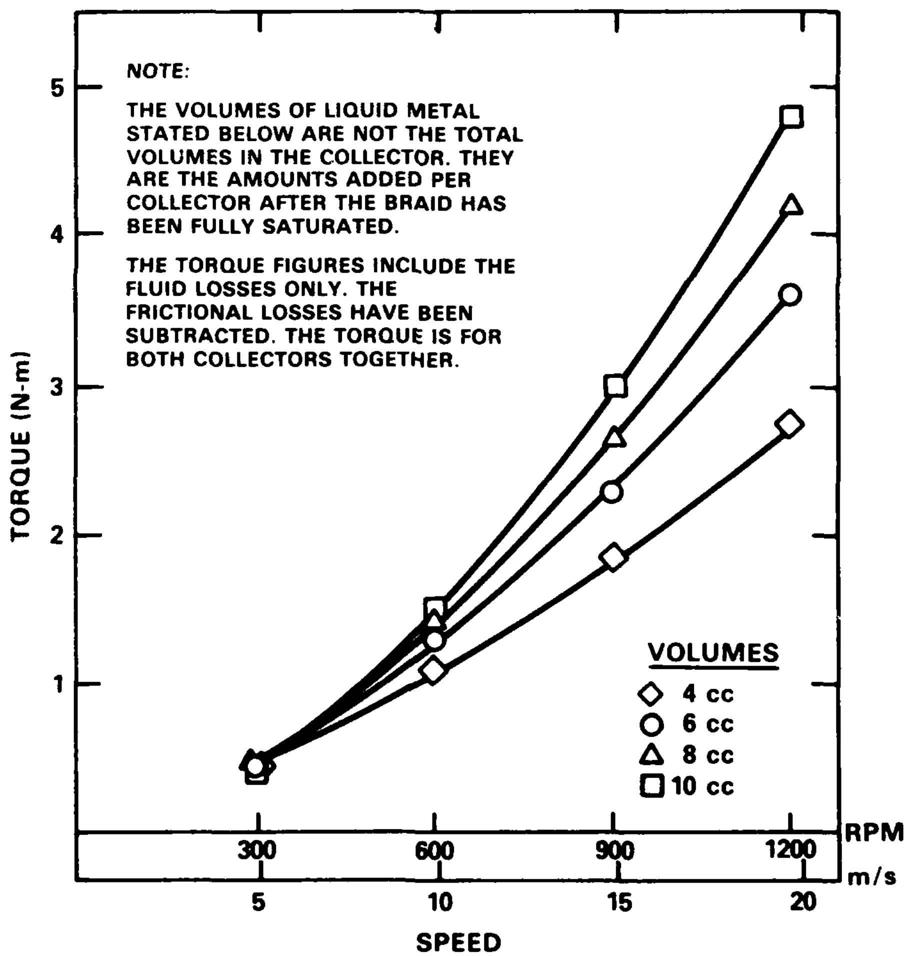

Fig. 6. Effect of speed and liquid metal volume on fluid losses.

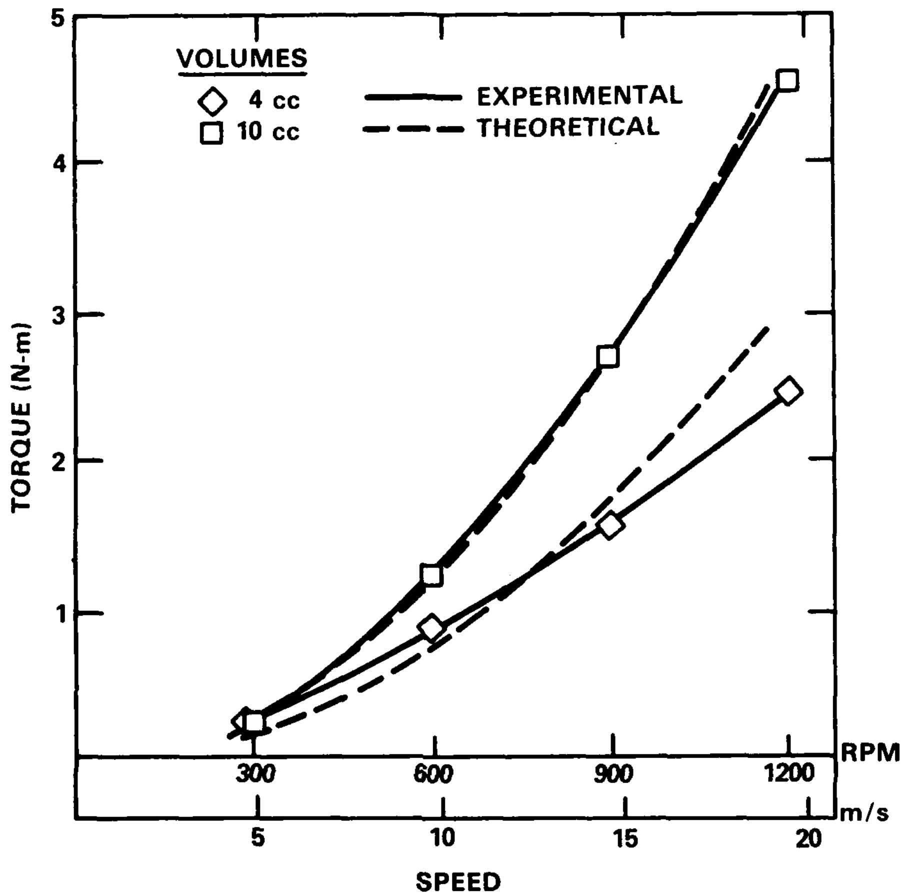

Fig. 7. Comparison of experimental and theoretical results.

DISCUSSION OF RESULTS

In a liquid metal current collector the electrical contact area can be increased by adding liquid metal and thus reducing the electrical losses. This technique, however, increases mechanical losses due to fluid resistance. Therefore, collector performance at several fill levels was investigated.

Figure 4 shows the result of electrical drop versus speed at several fill volumens. As fill volume is increased, the overall voltage drop decreases over the speed range studied. The curves all show a minimum around 10 m/s rotor tip speed. The increase in contact drop below 10 m/s is due to incomplete filling of the collector volume around the periphery at low velocities. The distribution of the liquid was easily observed through the lexan windows. As the speed in increased above 10 m/s, contact drop also increases. This high speed effect is more pronounced at lower fills. The origins of this increase and the low speed increase are different, because at higher speed the contact drop is quite steady compared to that at 5 m/s. Possibly the higher speed increase in contact drop is due to some separation of the fluid from the conducting surface of the rotor. This effect is discussed further below, with regards to mechanical losses.

Figure 5 is a plot of the contact drop of the collector with increasing current at 500 rpm. The collector resistance of about 0.6 μΩ is two to three times the resistance of the same collector with NaK in it. This is simply the ratio of the resistivities of the liquid metals. This increase in collector resistance is not a significant factor in machine applications because the loss is still very small compared to losses in conventional current collectors. Figure 6 shows the torque on the collectors due to viscous drag at several levels of LMPA in the collector.

Figure 7 compares two of the torque-speed curves to turbulent analytical model predictions.[11-13] The model gives the following expression for torque:

$$T = (\pi/4)\ f d v^2 r^2\ (w+k)$$

where

T = torque, N-m

f = Fanning friction factor (Darcy friction factor/4

d = fluid mass density, kg/m^3

v = collector rotor surface velocity, m/s

r = collector rotor radius, m

w = collector electrical contact width, m

k = height of fluid contact on sidewall, m

As the volume of liquid in the collector increases, the experimental results come very close to the analytical results. At the lower level, the curvature is less than predicted by the model. We suspect that these deviations from predicted behavior as the speed increases result from the changed profile of the fluid on the sidewall between the rotor and the stator. This effect would be more pronounced at lower fill volumes because here the fluid may separate partially from the disk, decreasing viscous loss and an increasing contact resistance as discussed above.

Although not addressed in the present study, a comment on magnetic fields is warranted. The use of an LMPA in a homopolar motor will subject the moving liquid metal to magnetic fields which have two principle effects: the creation of eddy currents, which will increase the electrical loss of the collector; and the modification of the fluid velocity profile, which can change the mechanical drag. The LMPA, with its lower electrical conductivity than NaK, will sustain lower eddy current losses, which are proportional to conductivity.[11] Furthermore, the greater mass of the LMPA will make it less responsive to magnetic field-induced fluid movement and the resulting fluid drag losses. Since motors for naval ships are run at low speeds, where the fluid losses are not great, the improvement in eddy current drag will permit the total losses to be not much greater than those of NaK.

CONCLUSIONS AND RECOMMENDATIONS

A low melting point, bismuth based, quintinery alloy was used in a 300 kW motor model test rig and found to have electrical and mechanical properties that make it a viable substitute for NaK_{78} in a low speed motor. Although electrical losses were found to be two to three times those of NaK, they were still acceptable. Fluid losses appeared to follow a turbulent model with some deviation, believed to result from changes in flow profile not accounted for in the model.

Future efforts will be directed at the following: First, as discussed above, magnetic field is an important parameter not addressed in the present study. The magnetic field effects are complicated and include pumping, eddy currents, and turbulence suppression. Due to its increased density, alloy 117 is expected to have lower magnetohydrodynamic losses under a magnetic field. These effects should be determined experimentally and correlated with theoretical models.

The use of alternative liquid metals, such as alloy 107 (which contains a higher fraction of cadmium than alloy 117) should be pursued further, and materials studies to develop even lower melting point alloys should be continued. Long term wear tests, under realistic machinery operating conditions, must be done with emphasis on alloy and component degradation.

Finally, the acid test of any collector is its operation in a real machine, usually the only environment where simultaneous conditions of tip velocity, current density, and magnetic field at significant levels can be achieved. The 300 kW homopolar motor will be used in obtaining data on the true effectiveness of low melting point alloys in a liquid metal current collector.

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