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REFRIGERATION AND HEAT TRANSFER IN SUPERCONDUCTING POWER LINES

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1. Scope of the Study

The first phase of this study investigated the effects which the transmission line operating conditions (pressure, temperature, pressure drop, etc.) have on refrigerator performance and cost. This work, which is reported in reference 1, concentrated on the low temperature losses of supercritical helium refrigerators for transmission line temperatures from 8 K to 14 K.

The current work under the present contract was to be a more general study of the problems associated with cooling a hydrogen temperature (14 K and above) superconducting transmission line. Specifically, the tasks were:

a. Investigate cooling of transmission lines using subcooled liquid hydrogen at temperatures up to 16 K. Cooling of the hydrogen by a helium refrigerator will be the primary scheme investigated. This activity is primarily concerned with refrigeration cycle analysis.

b. Investigate the safety, economics, and general systems problems related to hydrogen cooled superconducting transmission lines.

c. Investigate supercritical helium cycles for temperatures up to 16 K. This includes a more detailed investigation of the irreversibilities in the higher temperature portion of the refrigerator than was undertaken in the previous work for Stanford.

d. General conditions on system costs with the sponsor.

2. Accomplishments

Because of a withdrawal of funds by the sponsor, only item b is reported here. Although a considerable part of the effort was spent on item c, this work was discontinued before numerical results were obtained.

*Final report to sponsor.

3. Discussion

3.1 Advantages of higher temperatures.

Development of higher temperature superconducting transmission lines could result in cost reductions for two components of the system: (1) refrigerator costs, and (2) cryogenic envelope costs. Because we wish to minimize the yearly cost (operating, capital, and interest) of the cryogenic envelope plus the refrigerator, higher temperatures may offer greater flexibility in this optimization.

Our previous study [1] as well as the work of Strobridge [2] indicates that the Carnot efficiency of cryogenic refrigerators is relatively independent of operating temperature. Thus the power costs are simply proportional to the Carnot work

$$\frac{\text{Work of Compression}}{\text{Refrigeration}} \sim \frac{300-T}{T} \,,$$

and increasing the line operating temperature from 8 K to 16 K will decrease the compressor power by a factor of 2 (for the same thermal load) if the cryogenic envelope has no intermediate temperature shield. For a shielded line the savings would be about half this.

The capital cost of cryogenic refrigerators varies with the 0.6 power of the installed horsepower, so that

$$\text{Capital Cost} \sim \left(\frac{300-T}{T}\right)^{0.6} \,.$$

By raising the line temperature from 8 K to 16 K, a 35 percent reduction in installed refrigerator cost would result for an unshielded line, and as with the compressor power, the savings for a shielded line would be about one-half this amount.

As the temperature approaches 20 K, gas-refrigerating machines based on the Stirling cycle become feasible. At 80 K these machines are significantly cheaper than conventional machines, and it may be possible to extend these economics to the hydrogen temperature range.

Because the cost of the cryogenic enclosure is the dominant cost of the entire project (nearly half the total cost in the recent Brookhaven study [3]), changes in enclosure design have the greatest potential for large cost savings. The reduced cost of refrigeration at higher temperatures might make a higher-heat-leak, lower-cost enclosure economically attractive by shifting a larger portion of the cost to the refrigerator. The distribution of costs between labor and materials for the Cryenco (Brookhaven) enclosure is not clear, but at nearly \$200/ft [4], it would appear that labor is a good fraction of the total enclosure cost.

Examples of how potential enclosure cost savings might result for a hydrogen temperature line are:

1) The thickness of the inner enclosure wall could be reduced because subcooled or slush hydrogen would require pressures of only a few atmospheres compared to 15 or 20 atmospheres for supercritical helium. Savings of 5 to \$10/ft would result for a 300 series-stainless steel inner line.

2) Use of powder insulations or elimination of intermediate temperature shields might be feasible. The savings resulting from these construction changes are unknown, but merit investigation.

An additional advantage of higher temperature lines is a reduced tendency towards oscillations and flow instabilities for both helium and hydrogen [5].

3.2 Hydrogen cooled lines.

For temperatures above 14 K (the melting point of hydrogen), hydrogen as well as supercritical helium becomes available as a coolant. Both subcooled liquid and slush hydrogen are considered, but until a suitable method for producing slush hydrogen at positive gauge pressure is devised, slush must be considered unsuited for transmission line cooling.

In either case the hydrogen would be cooled with a helium refrigerator via a heat exchanger, and circulated by a centrifugal pump. Positive gauge pressure would be maintained on the liquid hydrogen at all times by hydrogen gas pressurization of a thermally-stratified column of liquid in a stand pipe. The liquid at the bottom of the column is subcooled at the line temperature (e.g. 15 K) and the liquid at the top is at the saturation temperature corresponding to the pressure (e.g. 22 K).

3.2.1 Coolant and flow characteristics.

Approximate expressions for the thermal property dependence of the pressure drop and pumping power may be obtained by neglecting the Joule-Thomson effect and the compressibility. If we write the mass rate of flow in the coolant channel as

$$\dot{m} = \frac{(Q/L)L}{C_p \Delta T}$$

then the pressure drop becomes

$$\Delta P = \frac{32\ f\ (Q/L)^2\ L^3}{\pi^2 \rho C_p^{\ 2}\ \Delta T^2\ D^5} ,$$

and the pump power is

$$\dot{W} = \frac{\Delta P \dot{m}}{\rho \eta_p} = \frac{32\ f\ (Q/L)^3\ L^4}{\pi^2 \rho^2 C_p^{\ 3}\ \Delta T^3\ D^5 \eta_p} .$$

For turbulent flow the friction factor, f, is given by

$$f \sim \frac{1}{Re^{0.2}} \sim (\mu C_p \Delta T)^{0.2} ,$$

so that the expressions for pressure drop and pump power are

$$\Delta P \sim \frac{(Q/L)^{1.8}\ L^{2.8}}{\Delta T^{1.8}\ D^{4.8}} \cdot \frac{\mu^{0.2}}{\rho C_p^{\ 1.8}}$$

and

$$\dot{W} \sim \frac{(Q/L)^{2.8}\, L^{3.8}}{\eta_p\, \Delta T^{2.8}\, D^{4.8}} \cdot \frac{\mu^{0.2}}{\rho^2 C_p^{\,2.8}} \quad .$$

Table 3.1 summarizes the coolant properties of liquid helium, supercritical helium, subcooled liquid hydrogen, and slush hydrogen. This simplified analysis indicates that the coolant properties of subcooled liquid hydrogen are comparable to those of 7 K supercritical helium, and superior (lower pressure drop and pumping power) to those of 15 K, 10 atm supercritical helium. The relatively high heat of fusion of solid hydrogen gives slush hydrogen a marked superiority over both supercritical helium and subcooled hydrogen.

Consideration of the compressibility and especially the Joule-Thomson (J-T) effect, somewhat modifies the comparison shown in table 3.1. Table 3.2 gives the results of detailed numerical calculations based on the real fluid properties and on a particular cooling passage geometry. For short lines (low flow resistance) the pressure drops for subcooled hydrogen and supercritical helium are comparable. For longer lines with nominal pressure drops in excess of 2 atm, however, the negative J-T coefficient of subcooled liquid hydrogen seriously reduces its cooling capacity.

At first sight, it would appear that the negative J-T coefficient of subcooled hydrogen (μ_J = -0.16 K/atm) would not have a serious effect at nominal pressure drops as low as 2 atm. A negative J-T coefficient results in an unstable condition, however, when the ΔT and heat load are held constant. It requires a higher mass flow rate which in turn causes a higher pressure drop and lower cooling capacity.

3.2.2 Subcooled liquid hydrogen.

Except for the safety hazard associated with hydrogen, the use of subcooled liquid hydrogen should present few difficulties since liquid hydrogen technology has been extensively developed in the space program. The low compressibility of liquid hydrogen compared to that of helium should make a hydrogen-cooled line less susceptible to flow instabilities [5]. A high latent heat of vaporization (449 j/g) provides excellent fault protection.

As discussed in the previous section the negative Joule-Thomson coefficient (-0.16 K/atm) limits the use of subcooled liquid hydrogen to nominal pressure drops (neglecting the J-T effect) below about 2 atm. It should be noted that a negative J-T coefficient does not increase the refrigeration load directly, however, since no more heat is added to the line.

3.2.3 Slush hydrogen.

Slush hydrogen is a slurry of liquid and solid hydrogen. As produced by the freeze-thaw method [6], the solid hydrogen particles are irregular flakes with an average size of 3-mm and a log-normal size distribution. In the freeze-thaw production method the surface of a triple-point bath of liquid hydrogen (P = .07 atm) is periodically vacuum-pumped so that successive crusts of solid form on the surface, then sink into the liquid and break into small particles.

At its present state of development this production technique is ill-suited to transmission line cooling for two reasons. First, the freeze-thaw process is essentially a batch process requiring operator control. With further development it is likely that a continuous-batch process could be developed in which liquid is pumped to, and slush pumped from, a production chamber. Careful attention to crust (solid-hydrogen) build-up would be required. Secondly, and more importantly, the process requires a negative gauge pressure in the production chamber, and as will be discussed in the safety section, positive gauge pressure is nearly mandatory in order to prevent leakage of air into the hydrogen. Shrouding the slush generator with a hydrogen-filled chamber at positive gauge pressure might be a solution to this air contamination problem. Although these difficulties do not preclude the use of slush hydrogen for transmission line cooling, they will require careful attention in the design of a practical slush cooling system.

If suitable production techniques were developed, then slush hydrogen would be an excellent coolant. The maximum practical solid fraction is about 40 percent.

At velocities above 0.5 m/s the solid particles remain fully suspended and pass easily through orifices and valves [7]. Although slush generally has a higher friction factor than liquid [7], the increased density and heat capacity (latent heat) make the slush flow losses considerably lower than the liquid losses as shown in table 3.1. Slush can also be pumped in a centrifugal pump without degradation of the pump performance [8].

3.2.4 Hydrogen safety.

Advocacy of liquid hydrogen as a transmission line coolant causes severe anxiety (sometimes referred to as the Hindenburg syndrome) in some individuals, but we note that it has been extensively used in the space program with an excellent safety record. Flammable liquids and gases such as natural gas, liquified natural gas, and gasoline are handled extensively--and when the proper safety precautions are taken--without mishap. We do not wish to minimize the potential hazard of hydrogen if it is mishandled, but to merely put it in perspective.

The two cardinal principles of hydrogen safety are:

1) No ignition sources,
2) No air (oxygen) contamination.

At the terminals and refrigeration stations, explosion-proof electrical fixtures can be used to eliminate ignition sources; but in the line itself, the possibility of arcs and shorts means that an ignition source is always potentially present. For this reason it is absolutely mandatory that there be no sources of contamination of the hydrogen. This means, in turn, that the hydrogen must be kept at a positive gauge pressure (or shrouded with positive gauge pressure hydrogen) at all times since leaks will inevitably occur in the piping system.

Even low levels of contamination must be prevented since a gradual build-up of solid air in the dielectric could result in arcing and a potential explosion hazard. Thus any made-up hydrogen will require a high quality purification system, and sampling of the purity of the circulating liquid will be necessary. The problem of purity is not confined to hydrogen, however, since arcing across the dielectric due to impurity build-up is also considered a serious potential problem with helium (although, of course, no explosive hazard exists).

3.2.5 Fluid and fluid storage costs.

For a hydrogen-cooled line, the cost of the coolant fluid represents another source of savings since the cost of the liquid hydrogen required to fill a line is about a factor of 10 lower than the cost of liquid or supercritical helium. For a 12-inch diameter enclosure, this saving would be about $10/ft. In the event that warm-up of the line is required for repairs, either storage of the coolant would be required, or it would have to be vented and lost. Because of its low cost, hydrogen could simply be vented with little cost penalty, whereas the cost of either venting or storing helium is substantial.

4. Conclusions

1. Higher temperature superconducting transmission lines offer definite savings in refrigeration costs and possible savings in enclosure costs.

2. At transmission line pressure drops below about 2 atm, subcooled liquid hydrogen has coolant properties comparable to those of supercritical helium. At higher pressure drops, a negative Joule-Thomson coefficient severely reduces the cooling capacity of subcooled liquid hydrogen.

3. Slush hydrogen offers significant advantages as a coolant, but a suitable practical production process which is contamination free needs to be developed.

4. Maintenance of a positive gauge pressure on a hydrogen coolant is an absolute safety requirement.

Table 3.1 Coolant Properties of Helium and Hydrogen

Fluid	ρ	C_p	ρC_p	Compressibility $-\frac{1}{v}\left(\frac{\partial v}{\partial p}\right)_T$	J-T Coefficient $\left(\frac{\partial T}{\partial p}\right)_h$	Pressure Drop $\frac{\mu^{0.2}}{\rho C_p^{1.8}}$	Pumping Power $\frac{\mu^{0.2}}{\rho^2 C_p^{2.8}}$
	(g/cm^3)	(J/gm-K)	$(j/cm^3\text{-}K)$	(1/atm)	(K/atm)	(cgs)	(cgs)
Liquid Helium							
(4.5 K, 5 atm)	0.137	3.8	0.53	0.023	-0.10	.085	0.162
Supercritical Helium							
(7 K, 10 atm)	0.115	6.4	0.74	0.043	+0.02	.039	.054
(7 K, 15 atm)	0.132	4.8	0.64	0.019	-0.06	.060	.094
(15 K, 10 atm)	0.035	6.2	0.22	0.103	+0.13	.137	.630
Subcooled Liquid Hydrogen							
(15 K, 2 atm)	0.076	7.0	0.53	.0012	-0.16	.074	.139
Slush Hydrogen							
(40% solid, 13.9 K and 2 atm)	0.081	23.3*	1.89	.0011	----	.028†	.030†

* Latent heat of fusion = 58.2 j/g, or 0.4 x h_{s-1} = 23.3 j/g

† Assumes ΔT = 2K for the other coolants (i.e., $C_{p_{slush}}$ = 11.65)

Table 3.2 Typical Transmission Line Pressure Losses*

Length (km)	Inlet Temperature (K)	Return Temperature (K)	Pressure Drop (atm)
	Supercritical Helium, 10 atm inlet		
5	14	15	0.25
5	14	16	0.05
10	14	15	1.60
10	14	16	0.55
10	12	15	0.23
10	12	16	0.15
10	10	15	0.08
10	10	16	0.06
20	12	15	1.61
20	12	16	1.05
20	10	15	0.56
20	10	16	0.45
	Supercritical Helium, 15 atm inlet		
5	14	15	0.17
5	14	16	0.05
10	14	15	1.10
10	14	16	0.36
	Subcooled Liquid Hydrogen, 5 atm inlet		
5	14	15	0.19
5	14	16	0.05
10	14	15	2.02
10	14	16	0.34
20	14	15	no solution
20	14	16	3.13

*The system characteristics chosen were:

enclosure diameter = 14 cm

return line I.D. = 6.25 cm

number of return lines = 2

losses = 200 W/km

conductor I.D. = 3.2 cm

conductor O.D. = 6.22 cm

number of conductors = 3

5. Nomenclature

C_p	specific heat at constant pressure
D	channel diameter
f	friction factor
L	line length
$\dot{m}$	mass flow rate
P	pressure
Q	total heat input
Re	Reynolds number
T	absolute temperature, K
$\dot{W}$	circulating pump power

Greek

η_p	circulating pump efficiency
μ	viscosity
ρ	density

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