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ABSTRACT

A closed circuit tubular cooling system for superconducting magnets offers advantages of limiting boiloff and containing high pressures during quenches. Proper location of automatic valves to lower pressures and protect the refrigerator in the event of quenches is described. Theoretical arguments and experimental evidence are given against a previously suggested method to determine He two phase flow regimes. If loss of flow occurs due to some types of refrigeration failure and transfer lines have enough heat leak to warm up, quenches are induced when the flow is restored. Examples are taken from experience with the TPC magnet.

INTRODUCTION

Under many circumstances forced flow two phase helium is an attractive coolant for superconducting magnets. Forced flow can utilize tubular cooling systems which can withstand higher pressures than the larger tanks of a conventional pool bath system. A tubular cooling system also reduces the helium inventory involved in quenches, and can be used to guide cooling specifically to areas where it is most needed during the cooldown. However, designing such a system involves problem areas not encountered in a pool bath system. The magnet designed for use in the TPC detector at PEP utilizes two phase cooling. Examples are given based on experience with that magnet. The emphasis will be primarily on general problems with two phase design rather than the design of a specific magnet.

THE PRESSURE DURING QUENCHES

The largest pressures a forced flow system is likely to experience will probably occur at the time when the magnet quenches. At that time LHe in the vicinity of the magnet will begin to boil rapidly until a one phase status is reached; then, the pressure will continue to rise as the He and magnet temperature rises. The calculation of the real pressure distribution in the system is very difficult because He is flowing out of the tubular part of the system. However, it is relatively simple to calculate an upper limit for the pressure by assuming that no He is leaving the tube. To compute this, one has to know the initial density and the final temperature which the magnet system will reach. From He data at that temperature, one can determine the pressure that corresponds to the initial density. That pressure is maximum if the tube is initially full of pure liquid. It would be desirable to design the cooling system to withstand this pressure. In the case of the TPC magnet, T_{max} is around 60 K and P_{max} would be 240 atmospheres. The finned cooling tube wrapped around the solenoid was designed to withstand this pressure, as were the transfer lines running to and from the magnet.

Unfortunately, in the TPC magnet, part of the lines feeding He cooling to the current leads was built using flex tubing which, as it was subsequently discovered, could not withstand P_{max} with absolute certainty and these pieces of flex tubing were relatively inaccessible. Since the system does not run with only liquid everywhere in the cooling tube, and much of the He is vented out during quenches, the actual pressure exerted on the flex tubing was much less than the upper limit computed above. We increased the venting by adding an additional relief valve. Then a more realistic pressure was calculated based on compressible flow dynamics with the relief valves included. The final pressure was proportional to the assumed initial He density. Our prediction of the initial density used thermodynamic analysis of the coil and refrigerator system assuming that liquid traveled at the same velocity as gas through the system before a quench. This assumption was based on applying to He a diagram based on water and air which had been developed by Ovid Baker in 1954.[1] It indicated that, under our conditions, the flow regime should be bubble and froth, a regime where the liquid and gas flow at the same velocity. Our operating point should be far from the boundary with any other type flow on that diagram (see Table 1 for TPC magnet operating conditions). With this initial density, the pressures during quenches were predicted to be acceptable, but during tests using induced quenches at low magnet stored energies the measured pressures were found to be higher than the predictions. Then the initial density was measured and found to be higher than our prediction, and in just the right ratio to correspond to predictions of the pressure calculation. This could be explained by assuming that liquid was moving slower than gas in the tube and hence that the flow regime we were experiencing was different from that predicted by applying Baker's diagram to our two phase He. This assumption was strengthened by observations of pressure and temperature variations which could also be explained by assuming slug flow, a flow regime where liquid and gas do not necessarily flow at the same rate. We then realized that using Baker's parameters to extrapolate the water and air data to He violates the rules of dimensional analysis. Therefore, a warning is in order not to use the plot by Baker for two phase He.

Table 1. Operating Parameters of the TPC Magnet

	All Flow through He Bath Heat Exchanger	Partial Bypass around He Bath Heat Exchanger
inlet pressure Pascal (abs)	1.67×10^5	1.53×10^5
outlet pressure Pascal (abs)	1.33×10^5	1.34×10^5
magnet temp. (K)	4.67	4.62
dewar pressure Pascal (abs)	1.30×10^5	1.31×10^5
pre-JT pressure Pascal (abs)	8.51×10^5	8.12×10^5
pre-JT temp. (K)	5.7	5.7
Baker parameter B_x	3.7×10^3	3.0×10^3
Baker parameter B_y	6.9×10^3	7.5×10^3

THE BAKER DIAGRAM

One of the more difficult problems in designing a fluid transport system with two phases flowing in the same pipe is determining the flow regime of the two phases. That is, how do the two phases coexist: as froth, slugs, plugs, stratified flow, etc.? Pressure drops and density throughout a system are dependent on this flow regime. In 1954, Ovid Baker, as part of a study on pressure drops in oil and gas lines, developed a graphical method of summarizing experimental results on flow regimes of two phases flowing together in the same pipeline. He collected data points from four experimenters[2-5] working on two phase flow of air and water, organized them on a two dimensional plot based on two parameters recommended by a major handbook in his field of study,[6] and drew lines representing boundaries between the flow regimes. This is the "Baker Diagram". The two parameters were based on several physical properties thought to be relevant. This system has been in use for many years in chemical engineering. It has been suggested that one might use this diagram with its flow regime boundaries to predict flow regimes for two phase helium[7,8]; however, we find it fails to correctly predict flow regimes that we have seen in the TPC magnet. A closer examination of the development of Baker's work shows that such a failure in predicting flow regimes for He should come as no surprise.

The two parameters of the Baker diagram are $B_x = L/G(\lambda\Psi)$ for the abscissa, and $B_y = G/\lambda$ for the ordinate. L is the liquid's mass velocity, and G is the gas's mass velocity, $\lambda = [(\rho_G/0.075)(\rho_L/62.3)]^{1/2}$ and $\Psi = (73/\nu)[\mu_L(62.3/\rho_L)^2]^{1/3}$, where ρ_L and ρ_G are the liquid and gas densities, ν is the surface tension of the liquid, and μ_L is the liquid's viscosity. This parameterization was supposed to allow use of the Baker diagram for predicting flow regimes of liquids and gasses other than water and air and in fact was applied to oil and natural gas.

Dimensional analysis shows that there is need for other relevant dimensional parameters of the system in order, for instance, to allow points like the intersection of two lines separating various flow regimes to be fixed on the diagram. This must be since the axes have dimensions (and these dimensions are not trivially canceled by the gravitational constant or some other obvious parameter universal to the problem). We can point to parameters missing in Baker's parameters, and these are precisely some of the potentially relevant characteristics of the gas. The Baker diagram has been developed using water and air properties, and successfully applied to oil and natural gas. This success may be explained if the additional parameters are functions of the gas characteristics and these parameters are similar for natural gas and air. When it comes to applying the same diagram with the same fixed points, which depend on unknown relevant parameter(s) of the system, to two phase He, one should first consider the extrapolation in material properties involved. We show in Table 2 the physical properties of He, air, and water. A quick examination shows that the values of the important ratios and material properties used to evaluate the Baker parameters differ by more than two orders of magnitude in more than one case. In addition, the viscosity of gas He is about 40% of liquid He, while the viscosity of air is 70 times less than water. In view of the magnitude of this extrapolation, it is not surprising that we find the Baker diagram does not apply to two phase He around 4.2 K.

LIMITING MAXIMUM PRESSURES

As mentioned earlier in this report, the density of He in the cooling tubes was found to be higher than anticipated. Since there was concern that the flex tubing connecting the current leads might be of inadequate burst strength, it was finally decided to reduce liquid density in the cooling tube to reduce the pressure there during quenches. We were able to change He density in the TPC by two different methods. By either method we were able to cross the boundary between a pulsing slug/plug flow at B_x=3.7x10^3, B_y=6.9x10^3, and a smoother flow regime (probably bubble/froth) at B_x=3.0x10^3, B_y=7.5x10^3 (see Table 1). This boundary point falls far from the boundary shown on the Baker diagram and further confirms that the diagram does not apply to the case of two phase He.

Table 2. Properties of Air, Water, and Helium

	Air Room temp.	Water Room temp.	He Gas 4.2 K	He Liquid 4.2 K
density (g/cc)	0.0012	1.0	0.017	0.125
surface tension (dyne/cm)	-	73	-	0.10
viscosity micro-Poise	183	10000	12.5	31.7

The He density in the cooling tubes was much higher than at the refrigerator outlet due to a heat exchanger immersed in liquid helium through which coolant flowed before entering the magnet's cooling tube (see Fig 1.). The first method of reducing the density was to install a heater after the heat exchanger. While this method worked and allowed testing of the magnet to full stored energy, it was viewed as a temporary solution. It was not fail safe and reduced reserve refrigeration. The second method involved adding a valve which allowed a portion of the refrigerator's output to bypass the He bath heat exchanger. Operating with this valve partially opened gave a density which lead to safe pressures during quenches at full stored energy.

ACTIVE VALVES FOR THE PROTECTION OF THE SYSTEM

The final relief valve system used to minimize pressures during quenches utilized two automatic safety relief valves, one at either end of the cooling tube. These valves are of the same design used on the Fermilab beam magnets[9] and have proven to be very satisfactory. They open to full flow quickly, can operate in a partially opened mode, and reseat reliably.

The refrigerator for the TPC magnet is a CTI model 2800 with two turboexpanders. These turboexpanders rotate at high speeds, and their support bearings are easily damaged, particularly in the event of sudden temperature and pressure changes which accompany quenches. In order to protect the turboexpanders and thin walled heat exchangers of the refrigerator, a valve (V_{ret}) on the transfer line returning to the refrigerator can be closed when required. We have chosen to close this valve on any of several situations: 1) a quench is detected, 2) the pressure in the dewar rises above 15 psig, 3) the pressure difference between supply and return transfer lines rises above 15 psi, 4) a refrigerator shutdown. A check valve prevents flow in the reverse direction back into the supply transfer line. Automatic controllers have been added to regulate temperatures at the refrigerator and permit it to continue running, even when flow to and from the magnet is interrupted.

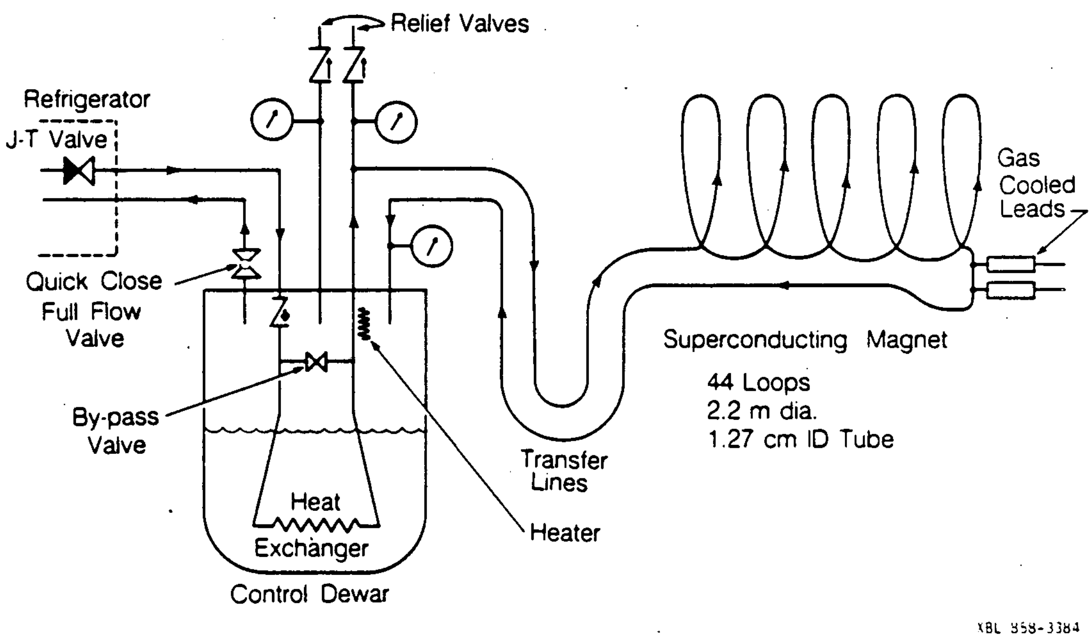

Fig. 1. Helium flow circuit--TPC magnet.

If cooling is interrupted, the magnet warms slowly. In the case of the TPC magnet, T_c is reached about ten minutes after the loss of cooling, and the magnet quenches. Heat leaks in the supply transfer line cause the helium in the line to rise in temperature faster than the magnet. Thus, if one attempts to restart the flow of coolant, it is likely that warm He in the transfer line will raise the magnet temperature and cause a quench. If the refrigeration is lost, we turn off the magnet current supply in order to drop the magnet's stored energy. This leads to lower temperatures when the magnet quenches, and reduces recovery time.

CONCLUSION

While two phase forced flow cooling may be considered as an attractive technique, it involves design problems which differ in many cases from those encountered with pool bath designs. In particular, the prediction of flow regimes, pressure drops, and He density are complicated by the lack of an appropriate design guide. It would be of great benefit for the cryogenics community if such a design tool specifically for He near 4.2 K was developed.

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