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Pressure drop of two-phase helium flowing in a large solenoidal magnet cooling path and a long transfer line

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The pressure drop of two-phase helium flowing in a 64 m cooling path of a magnet and a 58 m connecting transfer line was investigated. A large thin superconducting solenoidal magnet which was developed for the SDC detector (Solenoidal Detector Collaboration for the former SSC project) was used for this experiment. The magnet is 3.8 m in diameter, 2 m in length with a total cold mass of 4.5 tons. It was cooled by two-phase helium flow passing through a serpentine cooling path. The pressure drops of single-phase gas helium flow during cool down and two-phase helium flow in steady cooling were measured and compared with predictions. The measured pressure drop of single-phase helium was well agreed with the prediction, however, measured pressure drop of two-phase helium was much larger than the predictions based on separated and homogeneous flow models. In the high mass flow region of two-phase flow, slight pressure oscillations were observed in the inlet, outlet and differential pressures of the magnet. The magnet temperature was stable and not affected by those oscillations.

Keywords: two-phase helium; pressure drop; magnet cooling

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Introduction

The SDC detector required a large thin superconducting solenoidal magnet to provide an axial magnetic field of 2 T over the particle tracking volume¹. The magnet was to be 3.8 m in diameter and 8.8 m in length. In order to investigate the feasibility of this magnet, a full diameter, quarter length prototype magnet was designed and developed successfully.

The prototype magnet was cooled by using a helium refrigerator with a cooling capacity of 700 W at 4.4 K. It took five days to cool the magnet by single-phase cold gas of about 20 g/s supplied by the helium refrigerator².

At first, the pressure drop of single-phase gas helium flowing in a 64 m serpentine cooling path and a 58 m connecting transfer line were measured at 289 K, 254 K, 230 K, 83 K and 5.2 K during magnet cool down. Measured results agreed well with the predictions based on the frictional pressure drop under turbulent conditions. The pressure drop of two-phase helium was predicted by multiplying the single-phase pressure drop equations. However, the measured pressure drop of two-phase helium flowing was much larger than the predictions for both the magnet cooling path and transfer line. Also, under high mass flow conditions, slight pressure oscillations were observed, but they did not induced serious effects on magnet operations.

Cryogenic system and heat loads

The magnet was cooled by using a cryogenic facility in the East experimental hall at KEK. It was connected to a dedicated helium refrigerator and a 3000 L liquid helium dewar through a 58 m long insulated transfer line. Due to spatial constraints in the experimental hall, the transfer line was installed with 14 bends and an up-and-down flow configuration.

Figure 1 shows a schematic diagram of the magnet cooling system at KEK. The helium refrigerator has a cooling capacity of 700W at 4.4 K, or a liquefaction capacity of 200 L/h. Two screw compressors with flow capacities of 1100 and 1900 Nm³/h, respectively, are operated to feed helium gas at a pressure of 1.5 MPa to the Brayton-cycle refrigerator.

The cryogenic system is controlled by a computer-aided system. Primary operations such as compressor start-up, system gas purification, cold box cool down, gas temperature control, emergency sequence operation, etc., can be carried out automatically.

Figure 1. Magnet cooling system at KEK.

Figure 2. SDC solenoidal magnet

Figure 3. Schematic model of the cooling pipe

Figure 2 shows an isometric view of the prototype solenoidal magnet. The magnet is 3.8 m in diameter, 2 m in length with a total cold mass of 4.5 tons. A helium cooling pipe of 25 mm in diameter and 64 m in length was welded onto the outer surface of the support cylinder with a single serpentine configuration. Figure 3 shows a schematic model of the magnet cooling path.

The heat loads of the magnet and a chimney pot were measured to be 11 W and 16 W, respectively³. Also, the heat load of the transfer line was calculated to be 84 W as discussed, later. These values were used to calculate helium qualities at the upstream and downstream ends of the magnet for two-phase pressure drop predictions.

Magnet cool down and single-phase flow pressure drop measurement

To avoid any excessive thermal stress, the magnet was cooled with a cooling speed of about 3 K/h down to 80 K. Precooling gas temperature was controlled by properly mixing of warm and cold gas at the cold box exit. After the magnet temperature reached at 80 K, two expansion turbines of the refrigerator were operated. It took five days to cool the magnet from 300 K to 4 K. Figure 4 shows the temperature profiles of the magnet coil, support cylinder and the radiation shield during cool down.

Single-phase helium mass flow and the pressure drop in the transfer lines and the magnet were measured during cool down. Figures 5 and 6 show the measured results of $m\Delta P$ for the transfer line and magnet at 289 K, 230-254 K, 83-85 K and 5.2 K. The solid lines in the figures are the predictions from the frictional pressure drop in turbulent flow and is given by

$$\Delta P = \left(f \frac{L}{D} + nK \right) \left(\frac{8m^2}{\pi^2 D^5 \rho_g} \right) \quad (1)$$

$$f = \frac{0.3164}{Re^{0.25}} \quad (2)$$

$$K = 0.096 + 13f \quad (\text{in the case of } R/D=5)^4 \quad (3)$$

Figure 4. Cool down characteristics

Figure 5. Single-phase $\dot{m}$ - ΔP relationship (in the transfer line)

Figure 6. Single-phase $\dot{m}$ - ΔP relationship (in the magnet)

Table 1. Parameters of the magnet cooling pipe.

L	D	R	n	l_f	l_d
(m)	(mm)	(mm)		(m)	(m)
58	25	125	54	1.59	0.252

where f is the Darcy's friction factor, L is the total length of straight parts (l_f and l_d in Figure 3), D is the diameter of cooling pipe and n is the total number of bends. Also, K is the loss coefficient in the bends, Re is the Reynolds number ($4\dot{m}/\pi D \eta_G$). ρ_G and η_G are the density and viscosity of gas helium, respectively. R is the center line bend radius of the cooling pipe. The parameters used for the predictions are listed in Table 1. The predictions seem agree well with the measured results at 289K and 83-85K, because temperatures were kept constant at these temperatures. The deviations of the measured results from the predictions at 230-254K may be attributed to large temperature variations in the transfer line and magnet during cool down.

Two-phase pressure drop

Under the steady two-phase helium flow, the minimum mass flow was measured. It is defined as a mass flow required to keep the magnet temperature and the helium level of the chimney pot constant and to keep the transfer line cooling. It was measured to be 6.11 g/s. In this case, evaporated gas of 3.5 Nm³/h in each current lead was used to cancel the heat input through the current leads.

Based on the measured minimum mass flow, the heat load of a 58 m long helium transfer line was calculated to be 84 W at 4.6 K. Helium qualities at the inlet(x_i) and outlet(x_o) of the magnet were also calculated to be 0.78 and 0.87, respectively.

The two-phase pressure drop in the magnet cooling path and the transfer line are predicted by two models, homogeneous and separated flow models⁵⁻⁶, depending on the flow pattern of two-phase helium in the cooling pipe. Only a frictional pressure drop was considered because an accelerational pressure drop was calculated to be negligible in this case ($\Delta P_{acc}/\Delta P_{fric} < 0.5\%$ at $\dot{m}=7$ g/s for the homogeneous flow, for example). The two-phase pressure drop is given by

$$\frac{\Delta P_{TP}}{\Delta P_{LO}} = \frac{1}{x_o - x_i} \int_{x_i}^{x_o} \Phi_{LO}^2 dx \quad (4)$$

$$\Phi_{LO}^2 = \left(1 + x \left(\frac{\rho_L}{\rho_G} - 1 \right) \right) \left(1 + x \left(\frac{\eta_L}{\eta_G} - 1 \right) \right)^{0.25} \quad (\text{Homogeneous flow}) \quad (5)$$

$$\Phi_{LO}^2 = (1-x)^{1.75} \Phi_L^2 \quad (\text{Separated flow}) \quad (6)$$

$$\Phi_L^2 = 1 + \frac{20}{X} + \frac{1}{X^2} \quad (7)$$

$$X^2 = \left(\frac{\eta_L}{\eta_G} \right)^{0.25} \left(\frac{\rho_G}{\rho_L} \right) \left[\frac{(1-x)}{x} \right]^{1.75} \quad (8)$$

where ΔP_{TP} is the two-phase pressure drop, ΔP_{LO} is the pressure drop when a total mass flow of liquid helium flows, Φ_{LO} and Φ_L are the multipliers for two-phase flow, X is the Lockhart-Martinelli parameter, respectively⁵⁻⁶.

Helium qualities x at the magnet inlet and outlet were calculated using following equations.

$$\dot{m} L_v (x_i - x_t) = Q_T \quad (9)$$

$$\dot{m} L_v (x_o - x_i) = Q_M \quad (10)$$

where L_v is the latent heat of helium (=19 J/g at 0.13 MPa), x_t is the helium quality at the inlet of the transfer line (regarded as constant of 0.04, after isenthalpic expansion at the valve near the transfer line inlet), Q_T is the heat load of transfer line (=84 W) and Q_M is the heat load of the magnet (=11 W, without the chimney pot heat load). The calculated helium qualities at the inlet and outlet of the magnet are listed in Table 2.

Table. 2. Helium quality at the inlet and outlet of the magnet for typical mass flow rates.

$\dot{m}$ (g/s)	6	8	10	12
x_i	0.777	0.593	0.482	0.408
x_o	0.873	0.665	0.540	0.456

Figure 7. Two-phase m - ΔP relationship (in the transfer line)

Figure 8. Two-phase m - ΔP relationship (in the magnet)

A high precision differential-pressure transducer with a precision of ± 0.05 kPa was used to measure the pressure drop across the magnet. The helium mass flow and the inlet and outlet pressures were also measured by an orifice flow meter and absolute pressure gauges, respectively.

Figure 7 and 8 show the relationship between the mass flow and the pressure drop of two-phase flow in the transfer line and the magnet cooling path, respectively. There were no pressure oscillations at the mass flow less than 8 g/s. Both the inlet and outlet pressure of the magnet were quite stable. The pressure oscillations were observed in every case in the high mass flow region (> 8 g/s).

There are several specific characteristics on the two-phase pressure drop both in the transfer line and the magnet cooling path:

(Transfer line)

- The pressure drop has very little mass flow dependence, and is almost constant in the quiet region (< 8 g/s).
- Even in the oscillating region, the average value of the pressure drop seems to be independent of the mass flow.
- The measured pressure drop was about 4-7 times larger than the prediction of the homogeneous model

(Magnet cooling path)

- A negative pressure drop was observed at a mass flow around 7.5 g/s, just before beginning of oscillation.
- The amplitude of oscillations are much larger than that of the transfer line.
- The measured pressure drop was about 8-10 times larger than the prediction of the homogeneous model.

Several papers have reported that the homogeneous model can predict pressure drops even for helium two-phase flow⁷⁻⁸. In this study, however, there is a large discrepancy between the measured and predicted pressure drop in both transfer line and magnet cooling path.

Figure 9. Temperature profiles of the magnet during pressure oscillations

When the mass flow was increased to ~ 10 g/s in order to provide enough cooling power during magnet excitation, pressure oscillations with a period of 5-6 seconds occurred. The pressure amplitude of the oscillations across the magnet was around 1.7 kPa peak-to-peak, at typical mean pressure of 2.06 kPa. The magnet inlet and outlet pressure also oscillated with 0.98 kPa and 0.25 kPa peak-to-peak amplitudes, at typical mean pressures of 0.129 MPa and 0.127 MPa, respectively. Similar pressure oscillations were observed in the transfer lines, but with less oscillation amplitude.

Both the coil and support cylinder temperatures of the magnet were unaffected by these oscillations. Figure 9 shows the magnet inlet pressure and the temperature profiles of the coil and support cylinder. There are small temperature fluctuations. However, it is hard to say that these fluctuations can be attributed to the pressure oscillations. These oscillations were observed for hours in some cases, but the magnet was operated without any problems. Detailed results of the magnet performance were reported elsewhere⁹.

Discussions

In case of single-phase helium gas flow, the predictions of the frictional pressure drop agreed well with the experimental results both for the transfer line and magnet cooling path. This means that the equations for two-phase pressure drop predictions based on the equations of single-phase flow are reasonable. However, the measured pressure drop was much larger than the predictions for two-phase helium flow.

The accelerational pressure drop usually increases the total pressure drop. However, a rough calculation indicates that the accelerational pressure drop is negligibly small in this case.

There is a long transfer line with high heat load before helium flow enters into the magnet. Helium quality may change from ~ 0 to 0.7 in this transfer line with many up-and-down bends. These configuration possibly causes some sort of two-phase flow instability resulting in a large pressure drop. It has been believed for a long time that the homogeneous model can be used for the prediction of two-phase pressure drop for helium flow; however, it must be noted that under a certain flow scheme, e.g., connecting with the long, up-and-down transfer tube with large heat loads, a large pressure drop could possibly be induced.

At a mass flow of around 7.5 g/s, a negative relationship between mass flow and pressure drop was observed in the magnet cooling path. In general, the Ledinegg type flow instability is possibly induced by these negative pressure-mass flow relationship. However, it is hard to fix a clear origin of oscillation from this study.

Conclusion

The pressure drop in the transfer line and magnet cooling path have been experimentally investigated for single-phase and two-phase helium flow. The model and equation for single-phase flow seem to be reasonable for frictional pressure drop evaluation. By multiplying the single-phase pressure drop equation, the two-phase pressure drop equations were obtained. Based on these equations, the two-phase pressure drop in the transfer line and the magnet cooling path were predicted and compared with the measured results. Possibly due to the long transfer line with many up-and-down bends and large heat loads, the measured pressure drop was much larger than the prediction. In the high mass flow region, slight pressure oscillations were observed during two-phase helium cooling. The magnet operations were not affected by these pressure oscillations.

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