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An Investigation into Flow Regimes for Two-Phase Helium Flow*

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ABSTRACT

The Tevatron accelerator at Fermilab incorporates long two-phase helium passages. During magnet design, the generalized flow map of Baker was used to predict homogeneous flow. Longer than expected magnet time constants led to this investigation. The importance of predicting the flow regime has been amplified with the advent of non-horizontal accelerator designs.

A test setup was constructed at Fermilab to investigate two-phase helium flow regimes for conditions practical in accelerator designs. The setup consisted of a standard Tevatron satellite refrigerator, subcooling dewar, heater, 35 m long transfer line, and a specialized end box. A knife blade on the midplane of the end of the transfer line diverted the flow from the upper and lower halves of the pipe to separate vessels in the end box. The amount of liquid above and below the plane was measured at various total mass flow rates and liquid percentages.

The results show that stratified flow occurs at much higher liquid percentages than predicted by the Baker diagram (several orders of magnitude). We were not able to produce high enough steady state flows to find a boundary to a homogenous flow regime. Stratified flow occurred over all practical conditions for long accelerator magnet systems.

INTRODUCTION

The Tevatron accelerator at Fermilab was designed with continuous two-phase helium heat exchange with the collared coil assembly. This ensures a uniform temperature distribution throughout the magnet strings as long as the two-phase pressure drop is minimized. To achieve good

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radial heat transfer and to minimize system time constants, it was desirable to design for a homogeneous two-phase flow. Future superconducting accelerators (HERA, LEP, SSC, UNK) are being proposed with longer magnet strings (up to 4000 m long) on inclines (up to 1 1/2% grade). Under these conditions it becomes more important to verify the two-phase flow regime.

Flow regime maps are used to design for a specific flow pattern. Two-phase flow can exist in a variety of homogeneous and nonhomogeneous regimes as shown in Fig. 1. Savery[1] reviewed flow maps developed for horizontal as well as vertical channels. One of the more popular horizontal channel charts is that of Baker[2] (Fig. 2). Using this chart, the Tevatron was designed to operate in the froth flow regime.

During the commissioning of the Tevatron, longer than expected time constants were measured for the magnet two-phase circuit. This suggested a nonhomogeneous two-phase flow. As a result, this investigation was made to experimentally locate the boundaries between homogeneous (froth) and nonhomogeneous (stratified, wavy, slug/plug, annular) flows for two-phase helium. Results show that stratified flow occurs at much higher liquid percentages than predicted by the Baker diagram. We were unable to locate the homogeneous flow boundary boundaries over the operating range of the test setup.

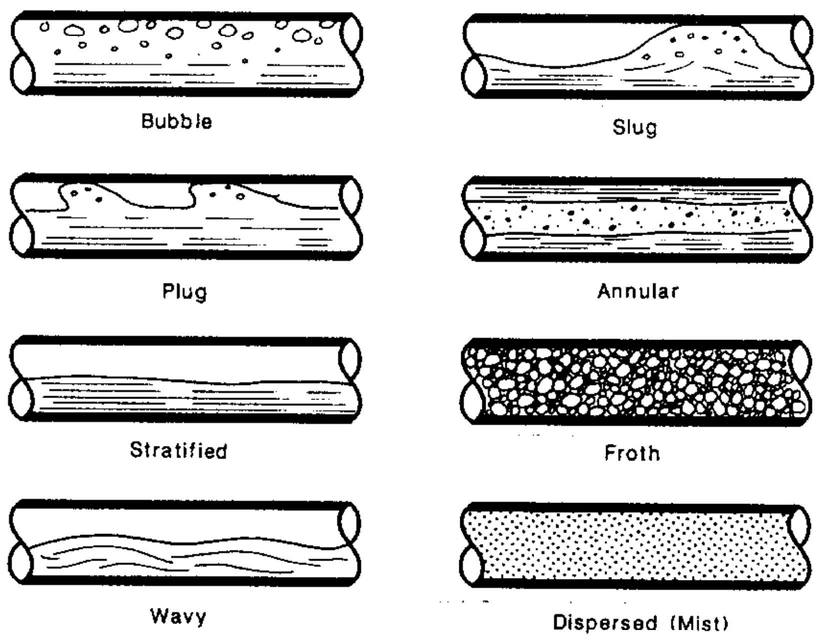

Fig. 1. Two phase flow regimes.

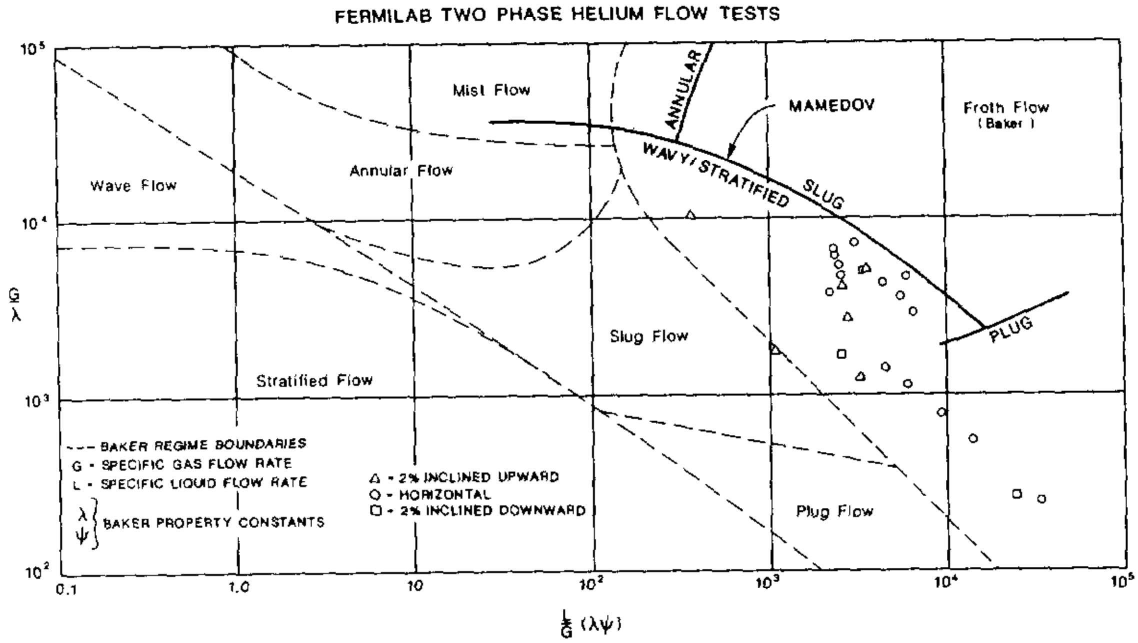

Fig. 2. Baker diagram for horizontal channels.

SYSTEM DESCRIPTION

The experimental setup is shown schematically in Fig. 3. It consists of the following components:

- 625 watt refrigerator (standard Tevatron satellite refrigerator operating in stand-alone mode)
- 450 liter subcooling dewar
- Transition box
- Adiabatic test line
- Collection box

Output from the refrigerator (typically 1.6 atm) is first subcooled by 1.2 atm boiling liquid in the subcooling dewar. This assured a constant temperature output. Between each test run, the dewar is refilled using the refrigerator. After the dewar is full, the reciprocating expansion engines are turned off to reduce the noise on the pressure and flow measurements.

Subcooled liquid helium then enters the transition box where the following took place:

- Amount of subcooling is measured with a vapor pressure thermometer and pressure measurement.
- Flow rate is measured with a venturi flowmeter
- An electric heater is used to burn off the subcooling and to adjust liquid percentage

The resulting two-phase helium first passes through an 8m long, 23mm ID pipe before entering the 24 m long, 45 mm ID test line. Both lines are made adiabatic by shielding them with the 4.5 K return flow.

At the end of the test line, a knife blade separates the top and bottom halves of the flow and drains each into phase separators. The collected liquid can be measured as a rate of change in liquid levels or

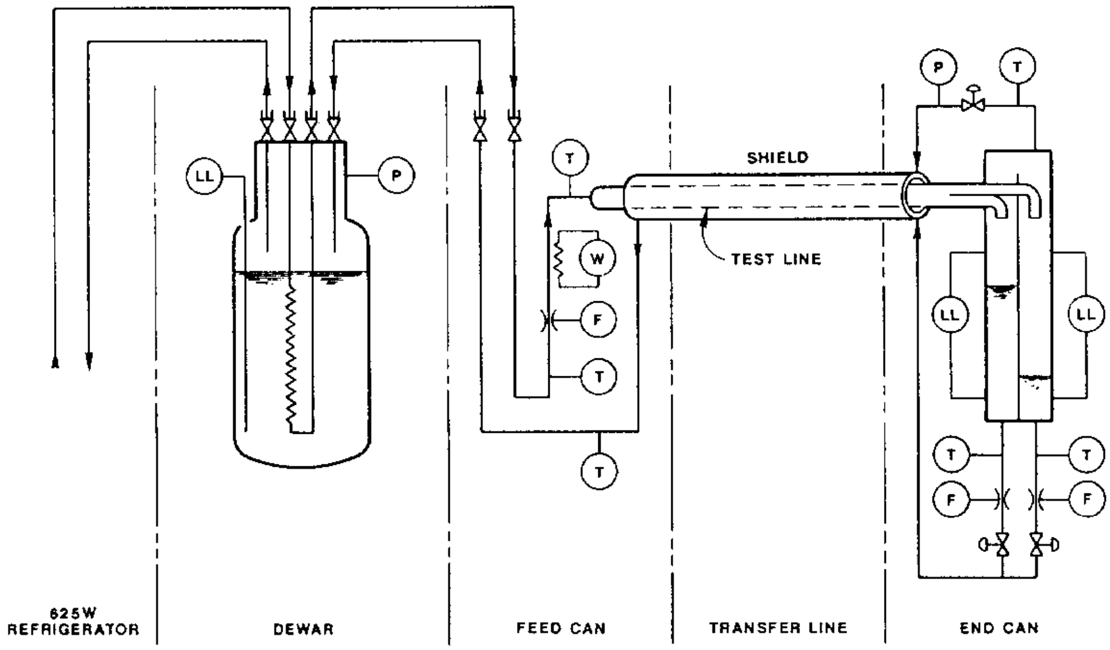

Fig. 3. Two phase test schematic.

by drain venturi flowmeters. The gas flows are combined and pass through a pressure regulating valve, returning to the refrigerator through the test line shield.

This setup was designed to distinguish between stratified flow and other two-phase flow regimes. The specific type of flow regime could not be determined in most cases. For stratified flow with a liquid percentage <80% (the point at which perfectly stratified vapor and liquid phases traveling at the same velocity each occupy half the cross section at 1.6 atm), one would expect to see liquid only in the phase separator of the lower half of the pipe. If however, there where nearly equal amounts of liquid reaching each phase separators, then the regime would not be clear. In this case, the flow could be homogeneous (froth) or nonhomogeneous (annular).

For circumstances where the liquid flow is predominantly in the lower half of the pipe, again assuming a liquid percentage <80%, then any of the following conditions could be true.

- wavy flow
- slug flow
- gravitational effected annular flow
- stratified flow

To further investigate the characteristics of two-phase helium flow, the test setup was built to allow inclines of ±2%. This angle includes all proposals for large accelerators.

RESULTS

A total of 26 test runs were made; six inclined 2% upward, 18 horizontal, and two inclined 2% downward. For operational convenience, all runs were made at 1.6 atm with the exception of five of the six runs inclined 2% upward which were 1.8 atm. All of the test points indicated a stratified or wavy two-phase flow. Results of the flow geometries are discussed below.

2% Inclined Upward

For the test, the line was first filled with saturated vapor. The line was then filled with a two-phase mixture and the time delay for liquid to reach the phase separators was measured. Test results are shown in Table I.

For a homogeneous froth flow, one would expect a fast time response. On the other hand, the slowest possible time response would be to consider just the liquid flow filling the inclined volume. The calculated delays for these extremes are given in Table 1 columns 4 and 5 respectively. Measured time delays are given in column 6. Column 7 is the ratio of measured (column 6) to liquid only (column 5) time delays. This represents the fraction of the inclined volume which is actually filled with liquid. To cross check the data, we followed the test with a second wave with a few percent gas to "top off" the line (column 8). The top off time should be the difference between columns 5 and 6. Data point #6 was the only point whose top off time was inconsistant with this rule.

Time delays in Table 1 clearly shows a stratified flow for the first few runs. The decreasing ratio in column 7 corresponds to an increase in gas phase flow (i.e., the gas phase requires more of the volume in order to escape). This gas volume is shown in Figure 4a. As an attempt to verify the mechanics of Fig. 4, the gas cross sectional area necessary to result in a pressure drop equal to the liquid head was calculated. Since the liquid head per unit length is constant, one would expect the gas pressure drop to also be constant. As a result, the gas cross sectional area would be nearly constant along the length. The results are shown in Fig. 5. The gas flow point near 40 g/s (#6) deviates from the curve, suggesting that the gas flow may be breaking up the liquid column.

The two 44 g/s data points both appear to be near phase boundaries. The high liquid data point (#5) showed liquid hitting the upper pot 0.4 min after hitting the lower pot (slug or plug flow?). This was the only one of the six points that liquid reached the upper pot. The high gas point (#6) showed an effect that may have been a decreasing frequency wave action hitting the knife.

Table 1. Two-Phase Test Results for 2% Incline Upward.

Run	1 Press	2 Flow	3 Quality	4 Froth	5 Liquid	6 Measured	7 Ratio	8 Top Off Time
				Time Delay				
#	(atm	(g/sec)	% Gas	(Min)	(Min)	(Min)	(Col. 6/5	(Min)
1	1.6	10.5	60	2.8	18.5	16.0	.865	2.2
2	1.8	10.6	45	3.6	12.6	10.5	.832	~2.5
3	1.8	20.8	49	1.8	6.9	5.0	.721	1.5
4	1.8	30.2	51	1.2	5.0	3.0	.600	~1.3
5	1.8	44.	43	0.9	3.0	1.8	.600	1.2
6	1.8	44.	88	0.6	13.9	1.8	.129	1.9

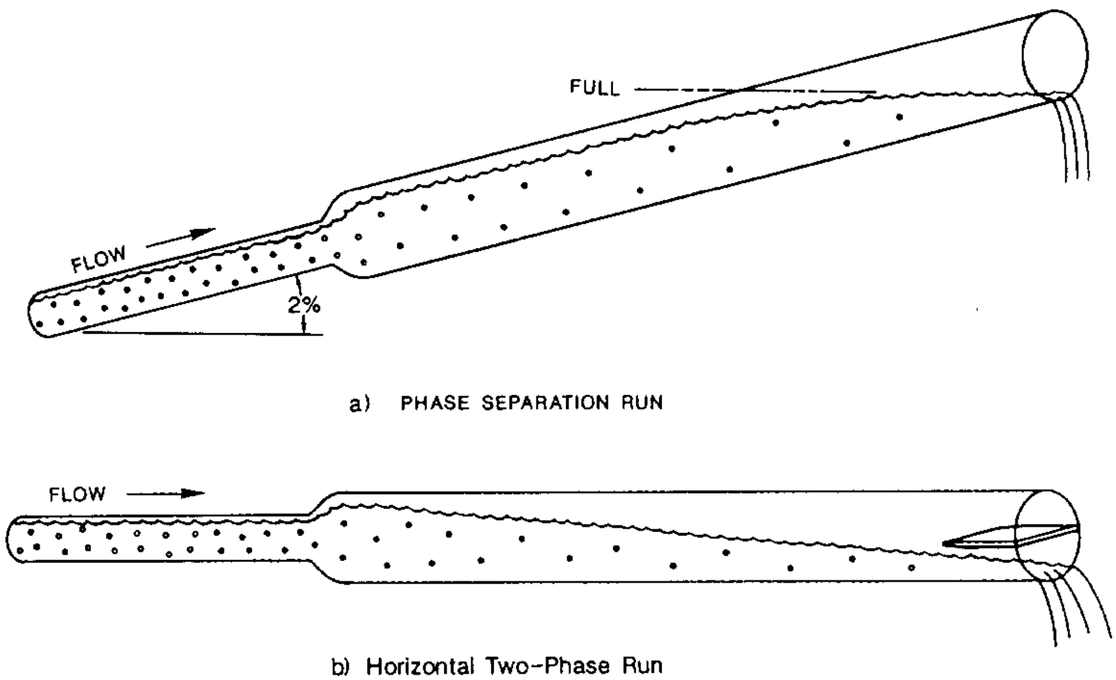

Fig. 4. Liquid separation in test line.

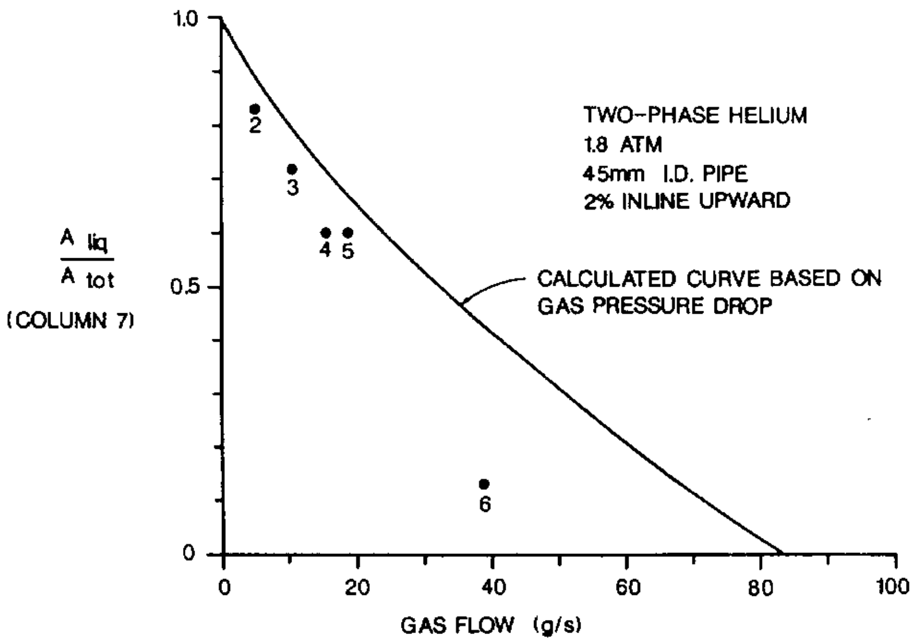

Fig. 5. Liquid flow area results for inclined upward flow.

Horizontal

For the eighteen horizontal test runs, subcooled liquid (at 1.6 atm) was first circulated through the test line. The heater was then gradually increased to eliminate the subcooling. From the saturated liquid point, the heater was increased to achieve the desired percent liquid. After the line reached an equilibrium, liquid flow rates for the top and bottom halves of the pipe were measured. These flows were found by measuring the rate of rise in the phase separator liquid levels for low flows, or by venturi flowmeters for high flows. Test results are shown in Table 2.

Included in Table 2 are calculated values of half pipe liquid flow for froth and separated flow regimes. In both cases, values were calculated assuming the liquid and vapor velocities were equal. Column 4 shows that for many runs, no liquid would be expected in the top half of the pipe if a smooth stratified flow exists. Measurements in column 6 shows that wave flow must exist, allowing some liquid above the midplane. Comparing column 6 to 3 shows that a homogeneous froth flow does not exist, as would be predicted by the Baker diagram (Fig. 2). The boundary of the stratified flow regime appears to be shifted at least three orders of magnitude to the right.

Table 2. Horizontal Two-Phase Results

	1	2	3	4	5	6	7	8
			Half Pipe Liquid Flows					
			Calculated			Measured		
			Froth	Separated Flow				
Run #	Mass Flow (g/s)	Liquid Mass (%)	Top (g/s)	Top (g/s)	Bottom (g/s)	Top (g/s)	Bottom (g/s)	Gas Vol Ratio (Actual/calc)
7	57.5	94.6%	27.2	21.3	33.1	>10	<44	<0.46
7	57.5	90.1%	25.9	15.1	36.7	>10	<42	<0.77
7	57.5	86.3%	24.8	9.8	39.8	>10	<40	<1.01
7	57.5	80.8%	23.2	2.2	44.3	>10	<36	<1.31
8	31.	57.3%	8.9	0.0	17.8	1.5	16.	0.61
9	42.5	60.7%	12.9	0.0	25.8	2.	24.	0.65
10	48.5	60.4%	14.6	0.0	29.3	≲0.5	28.5	≳0.69
11	53.	59.0%	15.6	0.0	31.3	≲0.5	31.	≳0.68
12	56.5	59.0%	16.7	0.0	33.3	≲0.5	33.	≳0.68
13	56.5	62.2%	19.3	0.0	38.6	≲0.5	36.	≳0.77
14	56.5	72.8%	20.6	0.0	41.1	3.5	37.5	0.77
15	56.5	77.0%	21.8	0.0	43.5	7.5	36.	0.75
16	56.5	81.9%	23.1	3.7	42.6	>10.	<33.5	<0.77
17	56.5	77.0%	21.8	0.0	43.5	8.5	35.5	0.71
18	19.	95.4%	9.1	7.4	10.7	4.	14.	2.27
19	18.5	89.4%	9.3	4.5	12.0	3.	13.5	1.25
20	18.5	18.5%	7.9	2.6	13.2	2.5	13.5	1.01
21	18.5	18.5%	7.3	0.0	14.5	2.	12.5	0.82
22	18.5	18.5%	6.8	0.0	13.3	1.	12.5	0.79
23	78.	78.6%	30.7	0.0	61.3	7.5	52.	0.84
24	73.	65.9%	24.1	0.0	48.1	0.	48.	>0.75
25*	15.2	93.8	7.1	5.3	8.9	1.	12.	2.27
26*	15.2	60.6%	4.6	0.0	9.2	0.	7.5	>0.70

* Inclined 2% downward
** Unable to measure liquid reaching phase separators in points #7 due to a choked venturi

For fixed conditions, the velocity of the liquid is proportional to the pipe cross sectional area occupied by vapor. Theoretical vapor areas are easily calculated for conditions of stratified flow with equal liquid and vapor velocities. Measured vapor areas can be estimated by examining the fraction of the liquid flow which is below the midplane and assuming a smooth stratified flow. The ratio of "measured" vapor area to calculated is shown in column 8 of Table 2. Values less than one indicate either a wavy flow or vapor velocities greater than liquid. The four data points in the lower right of Fig. 2 were the only points where this ratio was greater than one. This implies that the liquid velocity is greater than the vapor, possibly due to gravitational effects as shown in Fig. 4b.

Also shown on Fig. 2 is the two-phase helium data (1.2 atm) of Mamedov et al[4] converted to Baker diagram coordinates. They found the boundary between stratified/wavy flow and intermittent (slug) flow. Their data confirms that we were operating in a stratified or wavy flow regime.

CONCLUSIONS

From the results of this experiment we draw the following conclusion about two-phase helium flow:

- It is not practical to design long continuous two-phase heat exchange accelerator systems in a flow regime other than stratified or wavy.
- Two-phase flow is not suitable for an inclined SSC (due to time constants and control).
- Nonhomogeneous regimes exist for total flow<5g/s-cm^2 (D=45 mm)

<u>Inclined 2% Upward</u>

- For G<2 g/s cm^2:	Perfectly separated flow, Gas area predicted by pressure drop.
- For G>2 g/s cm^2:	Gas flow area is larger than predicted

<u>Inclined 2% Downward</u>

- Liquid velocity ~0.5 m/s

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