DØ SOLENOID UPGRADE PROJECT

**LHe Flow Regime/Pressure Drop
for
DØ Solenoid at Steady State Conditions**

D-ZERO ENGINEERING NOTE # 3823.111-EN-338

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**Liquid helium flow regime/pressure drop investigation
for steady state conditions for the DØ solenoid upgrade**

Abstract:

This paper describes in a note taking format what was learned from several sources on two phase liquid helium flow regimes and pressure drops as applied to the D-Zero solenoid upgrade project. Calculations to estimate the steady state conditions for the D-Zero solenoid at 5, 10 and 15 g/s are also presented. For the lower flow rates a stratified type regime can be expected with a pressure drop less than 0.5 psi. For the higher flow rate a more homogeneous flow regime can be expected with a pressure drop between 0.4 to 1.5 psi.

Investigation:

All papers found on the subject of two phase liquid helium flow indicated that the long standing models used to predict pressure drops (Lockhart-Martinelli, homogeneous) and flow regimes (Baker diagram) don't accurately predict experimental results for two phase liquid helium. Three papers were selected which contained information useful to our situation. They are outlined below.

1. The paper titled Pressure Drop in forced Two-Phase cooling of the Venus thin Superconducting solenoid by T. Haruyama, T. Mito and Y. Doi describes pressure drops and flow regimes for a magnet of almost identical tube sizes, flow rates and pressures.

Pipe size was 0.69" I.D. x 1100 ft {DØ I.D. will be 0.59" in solenoid, 0.68" in chimney}
Thermal load = 40 W + 17 L/h {current prediction for DØ is 30 W + 14 L/h}

For the higher flow rate (15 g/s) the flow pattern is considered nearly bubble flow. As the mass flow rate decreases it will change to a completely stratified flow.

The chosen operating flow rate for Venus was 5 g/s, which provided for the lowest magnet temperature, 4.6K.

Table 1: Experimental results selected from paper on Venus solenoid

Flow rate (g/s)	Pressure drop (Psi)	Press. drop per 100 ft. (Psi)	Quality at outlet	Regime
5	0.8	0.07	0.38	Stratified
10	1.3	0.12	0.21	Stratified
15	1.9	0.17	0.13	Bubble

2. The paper titled Characteristics of Horizontal Two-Phase Helium flow at Low Mass velocities by Yu. P. Filippov, I.S. Mamedov, and S. Yu. Selyunin came to the following conclusions.

Ranges of mass flow/unit area were 20 to 300 kg/m²-s (See table 2 for DØ range)
Pressure ranges 1.18 atm/2.7 psig to 1.97 atm/14.3 psig

Bubble flow occurrence is only possible when quality is small $x < 0.05$

For $m=20$ kg/m²-s and $x=0.11$ stratified helium flow was photographed

For $m=36$ kg/m²-s and $x=0.37$ stratified helium flow was photographed

3. The paper titled An Investigation into Flow Regimes for Two-Phase Helium flow by J. C. Theilacker and C. H. Rode shows data describing the flow regimes for different flow rates. The flow rates/unit area for this paper were in most cases less than 36 kg/m²-s and qualities were much larger than what we are expecting. Almost all the regimes in this paper were stratified/wavy flow. The inside diameter of the tube was 45 mm = 1.77" I.D. which doesn't match our situation.

Nonhomogeneous regimes exist for total flow < 50 kg/m²-s.

This paper contained a Baker diagram with with a curve supplied by using a paper by I. S. Mamedov superimposed onto it. This modified Baker diagram was developed for predicting two phase liquid helium flow regimes. Data for our estimated conditions was plotted onto that chart (See figure 1) for different mass flow rates. Table 2 shows the results of that information as well as other estimated information.

Discussion:

In an attempt to understand the flow regimes better, I wanted to calculate what the gas and liquid speeds would be for the estimated stratified regimes. I only concerned myself with the points mid way through the solenoid and at the outlet of the solenoid. The flow at the inlet of the control dewar is more vertical than horizontal and stratified flow would certainly not exist there.

For the stratified flow regimes it seems logical to use the Lockhart-Martinelli correlations as described in Cryogenic Systems by Barron to arrive at estimated volume fractions and then speed. I was rather shocked by the numbers which indicate the liquid speed is greater than the gas speed. This conflicts with a statement in the Venus paper and by the general description of the two phase flow phenomena. After spending some time looking at the matter, I believe that analytically the numbers work out this way because the density of the liquid phase is only about 4.6 times more than the density of the gas phase. Rather than trust what the numbers indicate, I would rather make the conclusion that because of the unique qualities of LHe, the Lockhart Martinelli correlation doesn't accurately predict separated/stratified two phase liquid helium flow.

The Venus paper figures 4 and 5 support this conclusion about the L-M correlation. (See the appendix for the Venus figures) Figure 4 shows that calculated pressure drop using L-M model is 1.1 to 2.5 times higher as the flow rate was increased from 5 g/s to 15 g/s. Figure 5 shows the dimensionless ratio of two phase pressure drop to single phase liquid pressure drop plotted for flow rates of 5 to 15 g/s. The L-M model predicted ratios are 1.7 to 4.2 times higher than actual data collected.

FERMILAB TWO PHASE HELIUM FLOW TESTS

LEGEND	
Mass flow rate	Location
X	5 g/s Pt. 6.5 - Middle of solenoid
Δ	10 g/s Pt. 6 - Exit of solenoid
●	16 g/s Pt. 7 - Inlet of control dewar

Figure 1: Baker diagram with Mamedov curves for two phase helium in horizontal channels

Table 2: Estimated qualities and regimes for the D-Zero solenoid for 5, 10 and 15 g/s flow rates at steady state conditions¹

	Flow rate 5 (g/s)	Flow rate 10 (g/s)	Flow rate 15 (g/s)
Flow rate/area based on .68" I.D. (kg/m ² -s)	21.3	42.7	64.0
Flow rate/area based on 15 mm I.D. (kg/m ² -s)	28.3	56.6	84.9
Estimated quality at middle of solenoid {+/- 0.02}	0.09	0.05	0.03
Estimated quality at outlet of solenoid {+/- 0.02}	0.17	0.10	0.07
Estimated quality at inlet to control dewar {+/- 0.02}	0.20	0.12	0.09
Estimated regime at middle of solenoid if horizontal pipe	Wavy/Stratified	Plug/Wavy	Bubble/Plug
Estimated regime at outlet of solenoid if horizontal pipe	Stratified	Stratified	Plug/Wavy
Estimated regime at inlet to control if horizontal pipe	Stratified	Stratified	Wavy/Stratified

¹ Conservative due to neglecting subcooling of 1Ø supply in transfer line before control dewar by 2Ø return to refrigerator.

Table 3: Estimated gas and liquid volume fractions, speeds, and pressure drop assuming stratified flow and using Lockhart Martinelli correlation

Flow rate (g/s)	Quality (m(gas)/m(total))	Volume fraction of gas	Volume fraction of liquid	Gas speed (m/s)	Liquid speed (m/s)	L - M Pressure drop per 100 ft. (psi)
5	0.09	0.59	0.41	0.17	0.55	0.09
5	0.17	0.69	0.31	0.28	0.67	0.14
10	0.05	0.49	0.51	0.23	0.91	0.22
10	0.10	0.61	0.39	0.37	1.1	0.35
15	0.07	0.55	0.45	0.43	1.5	0.58

The homogeneous model with heat input used in the Venus paper did better at matching the observed pressure drops for mass flow rates greater than 10 g/s.

Trying to accurately predict the pressure drop for the two phase steady state conditions for the D-Zero solenoid is impossible. Rough guesses can be made using information supplied in the Venus paper, the Lockhart-Martinelli model, homogeneous model and bounding cases of pure liquid and gas flow. Table 4 was constructed on this basis to show the range of estimated pressure drops for the D-Zero solenoid at 5, 10, and 15 g/s mass flow rates.

Table 4: Estimated pressure drops for the D-Zero solenoid at steady state conditions

Flow Rate (g/s)	Quality used for L-M & homogeneous	ΔP (x = 0) Liquid only (psi)	ΔP (x = 1) Gas only (psi)	ΔP Lockhart Martinelli (psi)	ΔP Homogeneous (psi)	ΔP Venus Paper (psi)
5	0.17	0.05	0.21	0.20	0.06	0.20
10	0.10	0.18	0.75	1.00	0.20	0.34
15	0.07	0.39	1.63	1.65	0.40	0.48

The pressure drop is from the outlet of the control dewar, thru the solenoid, and back into the control dewar at steady state conditions. Simplifying assumptions were used in predicting the pressure drops which could change the values somewhat. For the accuracy expected however, I feel all the simplifying assumptions are valid. See figure 2 for a graph of the estimated pressure drop for the D-Zero solenoid versus flow rate.

Figure 2: Pressure drop for DØ solenoid versus flow rate at Steady State

Conclusion:

It is hard to accurately predict the flow regime or pressure drop for two phase liquid helium flow. My best attempt at it involves used simplifying assumptions which I feel are conservative or at least reasonable. For flow rates of 5 to 10 g/s I predict a stratified type flow regime downstream of the midpoint of the solenoid with a pressure drop less than 0.5 psi from the outlet of the control dewar, thru the solenoid and back to the control dewar. For flow rates near 15 g/s I predict a flow regime of a bubble/plug mixed nature with pressure drop best predicted by a homogeneous type model. The pressure drop would be expected to be somewhere between 0.4 and 1.5 psi.

APPENDIX

1. References
2. Acknowledgements
3. Some assumptions used in calculations
4. Figures from Venus paper
5. Output data for Lockhart Martinelli runs for table 3, (TK solver application format)

REFERENCES

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SOME ASSUMPTIONS

1. The equivalent piping length used was 285 feet.
2. Assumed to be drawn tubing with roughness epsilon = 0.000 005.
3. Used inside dia. = 15 mm = .59 inches for entire length.
4. Qualities in Table 2 do not take into account subcooling in transfer line.
5. Liquid and gas densities taken at 0.145 MPa pressure = 6.3 psig.
6. Densities, viscosities the same for 5, 10, 15 g/s even though pressure does change.
7. Calculated pressure drops used fluid state at outlet of solenoid for entire length of pipe.

own in Figure. A helium saturated pressure must be rise as 0.13 from 10^{-3} kg/sec (20 $\times 10^5$ Pa) that helium is also rate of 5×10^{-6} margin of the

superconducting pipe of 17.6 mm rate from 5 to 16 with calculated mass flow region, the flow pattern occur in small on the calculated variation and a optimum operating (c) at the magnet

continuous helpful comments. KEK.

Helium cooling of (10), pp.420-430

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Table 1. VENUS magnet specifications.

Inner diameter	3.54 m	② PRESSURE GAUGE
Length	5.24 m	③ FLOW METER
Radiation thickness	0.52 I_0	
Inductance	1.48 H	
Rated current	3978 A	
Central field	0.75 T	
Stored energy	11.7 MJ	
Cooling path	17.6 mm eq.ID $\times$ 340 m + 14 mm ID $\times$ 260 m	
LHe capacity	210 L	
Cold mass	4.3 tonnes (Al)	
Thermal load	40 W + 17 L/h	
Cool down time	14 days

Fig. 2 Conceptual sketch of two-phase cooling.

Fig. 1 Flow diagram between magnet and control dewar.

Fig. 3 Simplified cooling pipe.

Fig. 4 Two-phase pressure drop. Experimental results and Calculated as
(1) Liquid single
(2) Homogeneous model
(3) L-M-N model (separated).

Fig. 5 Dimensionless pressure drop.

Fig. 6 Flow pattern estimation on the Baker diagram of helium [5,6].

Fig. 7 Relation between magnet temperature and inlet pressure.

St	Input	Name	Output	Unit	Comment
					Lockhart Martinelli correlation for two phase pressure drop through an adiabatic horizontal pipe
		valid	'accurate		model validity
		flow	'turbulen		flow type
		f	.01777538		friction factor ; Must enter a guess
.000005		epsilon		ft	pipe roughness
.59		D		in	Pipe inside diameter
100		L		ft	Length of pipe
		A	.00017638	m^2	cross sectional area
5		mdot		g/s	Total mass flow rate
115.627		rhoL		kg/m^3	Liquid density
25.12752		rhog		kg/m^3	density of the gas
3.085		muL		μPa-s	Liquid viscosity
1.409		muG		μPa-s	Gas viscosity
.0000791		sigmaL		N/m	Surface tension of liquid
.09		x			quality = mdotG/mdot
		ReL	125300		Reynold's # for liquid
		mdotL	.00455	kg/s	Mass flow rate for liquid
		ReG	27130		Reynold's # for gas
		mdotG	.00045	kg/s	Mass flow rate for gas
		dPdLL	3.413061	Pa/m	ΔP/ΔL for the liquid
		dPdLTP	20.762631	Pa/m	ΔP/ΔL for the two phase
		deltaP	.09178784	psig	Total pressure drop for the pipe
		phiL	2.4664321		Lockhart-Martinelli parameter
		X	3.9838421		Lockhart-Martinelli parameter
.184		CL			L-M constant; Look up in Table 7.19
.25		m			L-M constant; Look up in Table 7.19
.316		CG			L-M constant; Look up in Table 7.19
.2		n			L-M constant; Look up in Table 7.19
20		C			L-M constant; Look up in Table 7.19
		lambda	1.5575735		Baker diagram dimensionless parameter
1.2		rhoair		kg/m^3	density of air
998		rhoH2O		kg/m^3	density of water
		sigh	565.29996		Baker diagram dimensionless parameter
.073		sigmaH2		N/m	Surface tension of water
1000		muH2O		μPa-s	viscosity of water
		BakerXa	8900		X - axis value for Baker plot
		BakerYa	1210	lbm/hr-ft	Y - axis value for Baker plot
		c	1		
		M	1		
		RsubL	.40544396		Volume fraction of liquid phase
		RsubG	.59455604		Volume fraction of gas phase
		GasVel	.17076889	m/s	Gas velocity
		LiqVel	.55024989	m/s	Liquid velocity

Input	Name	Output	Unit	Comment
				Lockhart Martinelli correlation for two phase pressure drop through an adiabatic horizontal pipe
	valid	'accurate		model validity
	flow	'turbulen		flow type
	f	.01807232		friction factor ; Must enter a guess
.000005	epsilon		ft	pipe roughness
.59	D		in	Pipe inside diameter
100	L		ft	Length of pipe
	A	.00017638	m^2	cross sectional area
5	mdot		g/s	Total mass flow rate
115.627	rhoL		kg/m^3	Liquid density
25.12752	rhog		kg/m^3	density of the gas
3.085	muL		μPa-s	Liquid viscosity
1.409	muG		μPa-s	Gas viscosity
.0000791	sigmaL		N/m	Surface tension of liquid
.17	x			quality = mdotG/mdot
	ReL	114300		Reynold's # for liquid
	mdotL	.00415	kg/s	Mass flow rate for liquid
	ReG	51250		Reynold's # for gas
	mdotG	.00085	kg/s	Mass flow rate for gas
	dPdLL	2.8867717	Pa/m	ΔP/ΔL for the liquid
	dPdLTP	31.02604	Pa/m	ΔP/ΔL for the two phase
	deltaP	.13716051	psig	Total pressure drop for the pipe
	phiL	3.2783624		Lockhart-Martinelli parameter
	X	2.1006121		Lockhart-Martinelli parameter
.184	CL			L-M constant; Look up in Table 7.19
.2	m			L-M constant; Look up in Table 7.19
.184	CG			L-M constant; Look up in Table 7.19
.2	n			L-M constant; Look up in Table 7.19
20	C			L-M constant; Look up in Table 7.19
	lambda	1.5575735		Baker diagram dimensionless parameter
1.2	rhoair		kg/m^3	density of air
998	rhoH2O		kg/m^3	density of water
	sigh	565.29996		Baker diagram dimensionless parameter
.073	sigmaH2		N/m	Surface tension of water
1000	muH2O		μPa-s	viscosity of water
	BakerXa	4300		X - axis value for Baker plot
	BakerYa	2280	lbm/hr-ft	Y - axis value for Baker plot
	c	1		
	M	1		
	RsubL	.30503034		Volume fraction of liquid phase
	RsubG	.69496966		Volume fraction of gas phase
	GasVel	.27595745	m/s	Gas velocity
	LiqVel	.66709004	m/s	Liquid velocity

St. Input	Name	Output	Unit	Comment
				Lockhart Martinelli correlation for two phase pressure drop through an adiabatic horizontal pipe
	valid	'accurate		model validity
	flow	'turbulen		flow type
	f	.01575608		friction factor ; Must enter a guess
.000005	epsilon		ft	pipe roughness
.59	D		in	Pipe inside diameter
100	L		ft	Length of pipe
	A	.00017638	m^2	cross sectional area
10	mdot		g/s	Total mass flow rate
115.627	rhoL		kg/m^3	Liquid density
25.12752	rhog		kg/m^3	density of the gas
3.085	muL		μPa-s	Liquid viscosity
1.409	muG		μPa-s	Gas viscosity
.0000791	sigmaL		N/m	Surface tension of liquid
.05	x			quality = mdotG/mdot
	ReL	261600		Reynold's # for liquid
	mdotL	.0095	kg/s	Mass flow rate for liquid
	ReG	30150		Reynold's # for gas
	mdotG	.0005	kg/s	Mass flow rate for gas
	dPdLL	13.188571	Pa/m	ΔP/ΔL for the liquid
	dPdLTP	50.884372	Pa/m	ΔP/ΔL for the two phase
	deltaP	.22495061	psig	Total pressure drop for the pipe
	phiL	1.9642345		Lockhart-Martinelli parameter
	X	7.0470167		Lockhart-Martinelli parameter
.25	m			L-M constant; Look up in Table 7.19
.2	n			L-M constant; Look up in Table 7.19
.316	CG			L-M constant; Look up in Table 7.19
.184	CL			L-M constant; Look up in Table 7.19
20	C			L-M constant; Look up in Table 7.19
	lambda	1.5575735		Baker diagram dimensionless parameter
1.2	rhoair		kg/m^3	density of air
998	rhoH2O		kg/m^3	density of water
	sigh	565.29996		Baker diagram dimensionless parameter
.073	sigmaH2		N/m	Surface tension of water
1000	muH2O		μPa-s	viscosity of water
	BakerXa	16700		X - axis value for Baker plot
	BakerYa	1340	lbm/hr-ft	Y - axis value for Baker plot
	c	1		
	M	1		
	RsubL	.50910418		Volume fraction of liquid phase
	RsubG	.49089582		Volume fraction of gas phase
	GasVel	.22981042	m/s	Gas velocity
	LiqVel	.91494786	m/s	Liquid velocity

St Input	Name	Output	Unit	Comment
				Lockhart Martinelli correlation for two phase pressure drop through an adiabatic horizontal pipe
	valid	'accurate		model validity
	flow	'turbulen		flow type
	f	.01588409		friction factor ; Must enter a guess
.000005	epsilon		ft	pipe roughness
.59	D		in	Pipe inside diameter
100	L		ft	Length of pipe
	A	.00017638	m^2	cross sectional area
10	mdot		g/s	Total mass flow rate
115.627	rhoL		kg/m^3	Liquid density
25.12752	rhog		kg/m^3	density of the gas
3.085	muL		μPa-s	Liquid viscosity
1.409	muG		μPa-s	Gas viscosity
.0000791	sigmaL		N/m	Surface tension of liquid
.1	x			quality = mdotG/mdot
	ReL	247900		Reynold's # for liquid
	mdotL	.009	kg/s	Mass flow rate for liquid
	ReG	60300		Reynold's # for gas
	mdotG	.001	kg/s	Mass flow rate for gas
	dPdLL	11.933	Pa/m	ΔP/ΔL for the liquid
	dPdLTP	78.353593	Pa/m	ΔP/ΔL for the two phase
	deltaP	.34638707	psig	Total pressure drop for the pipe
	phiL	2.5624455		Lockhart-Martinelli parameter
	X	3.6424857		Lockhart-Martinelli parameter
.2	m			L-M constant; Look up in Table 7.19
.2	n			L-M constant; Look up in Table 7.19
.184	CG			L-M constant; Look up in Table 7.19
.184	CL			L-M constant; Look up in Table 7.19
20	C			L-M constant; Look up in Table 7.19
	lambda	1.5575735		Baker diagram dimensionless parameter
1.2	rhoair		kg/m^3	density of air
998	rhoH2O		kg/m^3	density of water
	sigH	565.29996		Baker diagram dimensionless parameter
.073	sigmaH2		N/m	Surface tension of water
1000	muH2O		μPa-s	viscosity of water
	BakerXa	7920		X - axis value for Baker plot
	BakerYa	2680	lbm/hr-ft	Y - axis value for Baker plot
	c	1		
	M	1		
	RsubL	.3902522		Volume fraction of liquid phase
	RsubG	.6097478		Volume fraction of gas phase
	GasVel	.37003158	m/s	Gas velocity
	LiqVel	1.1307759	m/s	Liquid velocity

<u>St</u>	<u>Input</u>	<u>Name</u>	<u>Output</u>	<u>Unit</u>	<u>Comment</u>
					Lockhart Martinelli correlation for two phase pressure drop through an adiabatic horizontal pipe
		valid	'accurate		model validity
		flow	'turbulen		flow type
		f	.01493191		friction factor ; Must enter a guess
.000005		epsilon		ft	pipe roughness
.59		D		in	Pipe inside diameter
100		L		ft	Length of pipe
		A	.00017638	m^2	cross sectional area
15		mdot		g/s	Total mass flow rate
115.627		rhoL		kg/m^3	Liquid density
25.12752		rhog		kg/m^3	density of the gas
3.085		muL		μPa-s	Liquid viscosity
1.409		muG		μPa-s	Gas viscosity
.0000791		sigmaL		N/m	Surface tension of liquid
.07		x			quality = mdotG/mdot
		ReL	384200		Reynold's # for liquid
		mdotL	.01395	kg/s	Mass flow rate for liquid
		ReG	63310		Reynold's # for gas
		mdotG	.00105	kg/s	Mass flow rate for gas
		dPdLL	26.950455	Pa/m	ΔP/ΔL for the liquid
		dPdLTP	132.18268	Pa/m	ΔP/ΔL for the two phase
		deltaP	.58435572	psig	Total pressure drop for the pipe
		phiL	2.2146455		Lockhart-Martinelli parameter
		X	5.171613		Lockhart-Martinelli parameter
.2		m			L-M constant; Look up in Table 7.19
.2		n			L-M constant; Look up in Table 7.19
.184		CG			L-M constant; Look up in Table 7.19
.184		CL			L-M constant; Look up in Table 7.19
20		C			L-M constant; Look up in Table 7.19
		lambda	1.5575735		Baker diagram dimensionless parameter
1.2		rhoair		kg/m^3	density of air
998		rhoH2O		kg/m^3	density of water
		sigh	565.29996		Baker diagram dimensionless parameter
.073		sigmaH2		N/m	Surface tension of water
1000		muH2O		μPa-s	viscosity of water
		BakerXa	11700		X - axis value for Baker plot
		BakerYa	2820	lbm/hr-ft	Y - axis value for Baker plot
		c	1		
		M	1		
		RsubL	.45153953		Volume fraction of liquid phase
		RsubG	.54846047		Volume fraction of gas phase
		GasVel	.43194953	m/s	Gas velocity
		LiqVel	1.5148088	m/s	Liquid velocity

S Rule

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* c=step(ReL,2300)           "c=0 for laminar flow, 1 for turbulent flow
* epsilon*given('epsilon,0,1)=0 "sets epsilon=0 if not given
* M=min(1, step(ReL,100000)+abs(sgn(epsilon))) "M=1 when Colebrook sol'n
* (1-M)* f=((1-c)*64/ReL + c*.316*ReL^-.25) *(1-M) "uses Blasius's eq'n
* M* 1/sqrt(f)=-2*log(epsilon/(3.7*D)+2.51/(ReL*sqrt(f))) *M "Colebrook eq'n
" ** FOR REFERENCE **
"if ReL<10^5, laminar flow, and smooth pipe : f=64/ReL
"if ReL<10^5, turbulent flow, and smooth pipe : f=.316*ReL^-.25
" [Blasius's equation]
"if ReL>10^5 or rough pipe:1/sqrt(f)=-2*log(epsilon/(3.7*D)+2.51/(Re*sqrt(f)))
" [Colebrook equation]

* flow=flow_type(c)
* valid=accurate(ReL)
* ReL = D * mdotL / ( A * muL ) "Reynold's # for liquid
* ReG = D * mdotG / ( A * muG ) "Reynold's # for gas
* A = pi ( ) * D^2 / 4
* dpdLL = f * ( mdotL / A ) ^ 2 / ( 2 * rhoL * D ) "press. drop per unit leng
* mdot = mdotL + mdotG "mass conservation
* x = mdotG/mdot "def. of quality
* dpdLTP = phiL ^ 2 * dpdLL "Eq. 7.56 Barron
* X^2 = ((CL * ReG^m * rhog)/(CG * ReL^n * rhoL)) * ((1-x)/x)^2 "Eq. 7.57 Barro
* phiL = ((X^2 + C * X + 1) ^0.5 ) / X "Eq. 7.59 Barron
* lambda = ((rhog/rhoair)*(rhoL/rhoH2O)) ^ 0.5 "Baker plot
* sigh = (sigmaH2O/sigmaL)*((muL/muH2O)*(rhoH2O/rhoL)^2)^(1/3) "Baker Plot
* BakerXaxis = (lambda * (mdotL/A) * sigh) / (mdotG/A) "Baker plot
* BakerYaxis = ( mdotG / A ) / lambda "Baker plot
* deltaP = dpdLTP * L "total pressure drop across pipe
* RsubL = X/(X^2 + C*X + 1)^0.5 "Eq. 7.65 , vol. fraction of liquid phase
* RsubG = 1 - RsubL
* GasVel = mdotG / (rhog * A * RsubG)
* LiqVel = mdotL / (rhoL * A * RsubL)

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