STRATIFIED FLOW TEST

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by

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1. Introduction

During transient flow-boiling in a duct, many flow regimes are possible. In some flow regimes, such as the stratified or annular regimes, water and steam are not in thermal equilibrium and flow with unequal velocities. These flow regimes have a marked effect on heat transfer and transport. They may occur during a reactor cooling system blowdown or after water injection into a hot channel, as in an emergency cooling system. Flow boiling models in general require auxiliary relationships to describe mass, momentum and energy transfer between phases and duct walls. These relationships contain transfer coefficients that depend on the flow regime. It is therefore necessary to predict the flow regime from the operating conditions. Generalized flow regime maps exist but have not yet been verified for steam-water flow.

An experiment has been designed to obtain infomration on flow regime transitions, phase velocities, pressure gradient, interfacial and wall shear stresses for the flow of a steam-water mixture in a horizontal section of a Candu feeder pipe. The purpose of this report is to give an account of the design of the test and the progress made on the experiment to date.

2. Stratified Flow Test

A flow regime map for horizontal steam-water flow was plotted based on the Taitel-Dukler model[5]. A test matrix was layed out to cover the transition from stratified to indermittent flow, from stratified to dispersed-annular flow and intermittent to dispersed-annular flow. A horizontal section of a Candu feeder pipe was instrumented and installed into a high pressure loop at Westinghouse Canada Ltd. (WCL).

2.1 Objectives

1) To verify the Taitel-Dukler model for flow transitions from the stratified flow regime and
2) To obtain data on phase velocities, pressure gradient, interfacial and wall shear stress for stratified steam-water flow in a horizontal pipe.

2.2 Test Section and Loop Description

The test section to be used was taken from a Candu type feeder pipe that had previously been used in a pressure drop test performed at WCL.

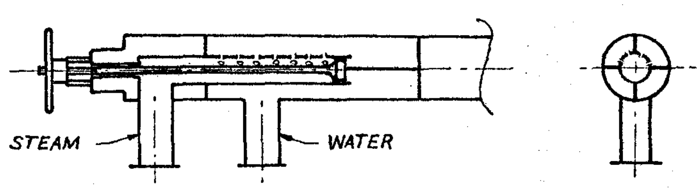
2.2.1 Loop Description

Saturated steam and water from the WCL boiler air connected to the horizontal test section inlet. A modified gate valve is used to function as a weir at the test section outlet. Steam and water are separated upon leaving the test section and condensate is pumped back to the boiler. The piping has been layed out and remains to be installed.

2.2.2 Test Section and Inlet

The test section is a 22 ft. long 3 in. schedule 80 pipe equipped with various burr-free pressure taps. These pressure taps were drilled and tested in a previous pressure drop test (WNRE-265).*

An inlet section was designed to introduce the two phases with the least amount of mixing taking place. The steam enters through a perforated pipe at the top of the inlet section. A manually controlled piston inside the pipe is used for adjusting the steam flow area to obtain a pressure drop of approximately 50 psi. The slightly higher pressure in the steam inlet is necessary to prevent condensation in the steam line. The saturated water is introduced from the bottom of the inlet section. The inlet section has been constructed and connected to the test section.



INLET SECTION

Fig. 1

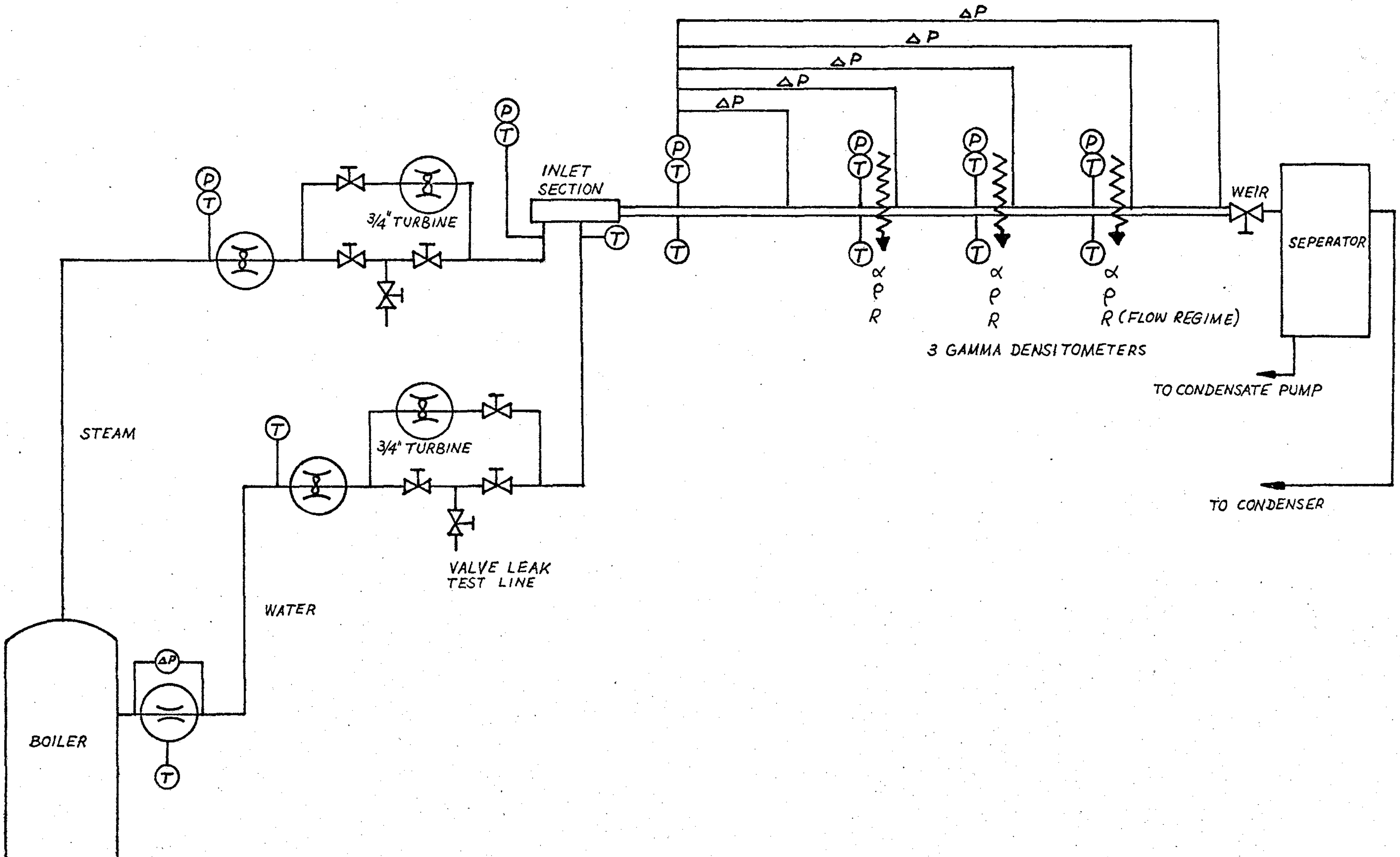
*After installation the test section was leveled with a surveyors level to within 1/8 in. over the total length of the pipe. The pipe was found to have a 1/4 in. camber and had to be loaded in place to achieve straightness.

2.3 Instrumentation

Steam and water flow-rate is measured upstream of the inlet section by a venturi and a 2 in. or 3/4 in. turbine flow meter in each line. Three gamma-densitometers are positioned on the test section, the first one a distance of 40 pipe diameters downstream of the inlet. Pressures and temperatures are measured at the inlet and at several places along the test section (Fig. 2).

2.4 Test Calculations to be performed 'on-line'

Steam and water flow rates in the test section are obtained from a mass and energy balance on the inlet section. Wall to liquid and wall to gas shear stresses are calculated using average pressure gradients at a void fraction of 0 and 1 respectively. Using this information in addition to the void fraction obtained from the densitometers, the interfacial shear stress is determined. Other output information is the steam-water velocity ratio, void fraction, volumetric quality, mass quality, steam and water volumetric flow rates, and the flow regime obtained from the densitometer measurements.



STRATIFIED FLOW TEST ARRANGEMENT

FIG. 2

3. Summary of Progress Made

3.1 Theoretical Preliminaries

a) The Taitel-Dukler general flow regime map for horizontal flow was transformed to steam and water volumetric flow rate coordinates at pressures of 800 psi and 500 psi.

b) Test matrices were set up within the flow ranges available from the WCL oil fired boiler.

c) Pressure drops for the various test points were estimated using the homogeneous flow model.

d) An'on-line' calculation procedure was established.

3.2 Physical Installations

a) The steam-water inlet section was designed.

b) The test section instrumentation needed was determined.

c) Piping layout was designed

d) The test section was installed and leveled.

APPENDIX A

Transformation of the Taitel-Dukler general flow regime map for horizontal flow to steam and water volumetric flow rate coordinates at pressures of 800 psi and 500 psi.

1. Stratified-Intermittent to Stratified-Annular Dispersed Transition.

Criterion:

$$\frac{\rho_G}{(\rho_L - \rho_G)} \frac{U_G^{s^2}}{Dg \cos\alpha} \frac{1}{C_2^2} \frac{\frac{\tilde{A}}{\tilde{A}_G} \sqrt{1 - (2\tilde{h}_L - 1)^2}}{\tilde{A}_G} \geq 1$$

where

$$U_G^{s^2} = \left(\frac{Q_G}{A}\right)^2$$

$$\tilde{A} = \frac{A}{D^2} = \frac{\pi}{4}$$

then

$$\frac{\rho_G}{(\rho_L - \rho_G)} \frac{Q_G^2}{A^2 Dg\cos\alpha} \frac{1}{C_2^2} \frac{(\pi/4) \sqrt{1 - (2\tilde{h}_L - 1)^2}}{\tilde{A}_G^2} \geq 1$$

or

$$\frac{\rho_G}{(\rho_L - \rho_G)} \frac{Q_G^2}{(\pi/4)\ D^5 g \cos\alpha} \frac{1}{C_2^2} \frac{\sqrt{1 - (2\tilde{h}_L - 1)^2}}{\tilde{A}_G^2} \geq 1$$

transition takes place when

$$Q_G^2 = (\pi/4) D^5 g \cos\alpha \frac{(\rho_L - \rho_G)}{\rho_G} \frac{C_2^2 \tilde{A}_G^2}{\sqrt{1 - (2\tilde{h}_L - 1)^2}}$$

where

$$C_2 = 1 - \tilde{h}_L$$

and

$$\sqrt{1 - (2\tilde{h}_L - 1)^2} = \tilde{S}_i$$

let

$$k_1^2 = \frac{\pi}{4} D^5 g \cos\alpha \frac{(\rho_L - \rho_G)}{\rho_G}$$

then at transition

$$Q_G = K_1 \frac{(1 - \tilde{h}_L) \tilde{A}_G}{\sqrt{\tilde{S}_i}}$$

Now obtain water flow rate at transition

$$x^2 = \frac{\frac{4C_L}{D} (\frac{U_L^s D}{\nu_L})^{-n} \frac{\rho_L (u_L{}^s)^2}{2}}{\frac{4C_G}{D} (\frac{U_G^s D}{\nu_G})^{-m} \frac{\rho_G (u_G^s)^2}{2}}$$

assume turbulent flow both phases

then $n = m = 0.2$

$$C_G = C_L = .046$$

and

$$x^2 = (\frac{U_L^s \nu_G}{U_G^s \nu_L})^{-.2} \frac{\rho_L}{\rho_G} (\frac{U_L^s}{U_G^s})^2$$

$$= \left(\frac{\nu_G}{\nu_L}\right)^{-.2} \frac{\rho_L}{\rho_G} \left(\frac{Q_L}{Q_G}\right)^{1.8}$$

solving for Q_L

$$Q_L = \left(\frac{\nu_G}{\nu_L}\right)^{1/9} \left(\frac{\rho_G}{\rho_L}\right)^{5/9} X^{10/9} Q_G$$

let

$$K_2 = \left(\frac{\nu_G}{\nu_L}\right)^{1/9} \left(\frac{\rho_G}{\rho_L}\right)^{5/9}$$

then

$$Q_L = K_2 X^{10/9} Q_G$$

Obtain steam quality from equation 7 Ref. 5

$$X^2 = \frac{\left[(\tilde{U}_G \tilde{D}_G)^{-m} \tilde{U}_G^2 \left(\frac{\tilde{S}_G}{\tilde{A}_G} + \frac{\tilde{S}_i}{\tilde{A}_L} + \frac{\tilde{S}_i}{\tilde{A}_G}\right)\right]}{\left[(\tilde{U}_L \tilde{D}_L)^{-n} \tilde{U}_L^2 \frac{\tilde{S}_L}{\tilde{A}_L}\right]}$$

where n = m = .2 for turbulent flow

$$\tilde{D}_G = \frac{D_G}{D} = \frac{4 A_G}{(S_G + S_i)D} = \frac{4 \tilde{A}_G D}{S_G + S_i} = \frac{4 \tilde{A}_G}{(\tilde{S}_G + S_i)}$$

now

$$X^2 = (\tilde{S}_L)^{-1} \left(\frac{\tilde{S}_G + \tilde{S}_i}{\tilde{S}_L}\right)^{.2} (\tilde{A}_L)^3 (\tilde{A}_G)^{-2} \left[\frac{\tilde{S}_G}{\tilde{A}_G} + \tilde{S}_i \left(\frac{1}{\tilde{A}_L} + \frac{1}{\tilde{A}_G}\right)\right]$$

where

$$\tilde{S}_L = \pi - \cos^{-1} (2\tilde{h}_L - 1) = \pi - \tilde{S}_G$$

$$\tilde{S}_G = \cos^{-1}(2\tilde{h}_L - 1)$$

$$\tilde{S}_i = \sqrt{1 - (2\tilde{h}_L - 1)^2}$$

$$\tilde{A}_L = .25\,[\pi - \cos^{-1}(2\tilde{h}_L - 1) + (2\tilde{h}_L - 1)\sqrt{1 - (2\tilde{h}_L - 1)^2}]$$

$$= .25\,[\tilde{S}_L + (2\tilde{h}_L - 1)\tilde{S}_i]$$

$$\tilde{A}_G = .25\,[\cos^{-1}(2\tilde{h}_L - 1) - (2\tilde{h}_L - 1)\sqrt{1 - (2\tilde{h}_L - 1)^2}]$$

$$= .25\,[\tilde{S}_G - (2\tilde{h}_L - 1)\tilde{S}_i]$$

$$\chi^2 = \frac{\left(\frac{\tilde{S}_G + \tilde{S}_i}{\tilde{S}_L}\right)^{.2} (\tilde{A}_L)^3 \left[\frac{\tilde{S}_G}{\tilde{A}_G} + \tilde{S}_i \left(\frac{1}{\tilde{A}_L} + \frac{1}{\tilde{A}_G}\right)\right]}{(\tilde{A}_G)^2\,\tilde{S}_L}$$

check assumption of turbulence in both phases:

$$Re_G = \frac{U_G\,D_G}{\nu_G} = \frac{Q_G\,D_G}{A_G\,\nu_G} = Q_G\,\frac{4}{\nu_G D(\tilde{S}_G + \tilde{S}_i)}$$

where

$$A_G = \tilde{A}_G D^2$$

$$D_G = \tilde{D}_G D = \frac{4\,\tilde{A}_G\,D}{(\tilde{S}_G + \tilde{S}_i)} \quad \text{was used}$$

let

$$k_3 = \frac{4}{D\nu_G}$$

then

$$Re_G = k_3\left[\frac{Q_G}{\tilde{S}_G + \tilde{S}_i}\right]$$

similarly

$$Re_L = \frac{U_L \; D_L}{\nu_L} = \frac{4}{D \; \nu_L} \frac{Q_L}{\tilde{S}_L}$$

let $K_4 = \frac{4}{D \; \nu_L}$

then

$$Re_L = k_4 \left[\frac{Q_L}{\tilde{S}_L}\right]$$

2. Transition between Intermittent (slug) and Dispersed Bubble Flow (mixed)

Criterion:

$$T^2 \geq \left[\frac{8\tilde{A}_G}{\tilde{S}_i \; \tilde{U}_L^2 \; (\tilde{U}_L \; \tilde{D}_L)^{-n}}\right]$$

or

$$\frac{\frac{4C_L}{D} \left(\frac{U_L^s D}{\nu_L}\right)^{-n} \frac{\rho_L \; U_L^{s2}}{2}}{(\rho_L - \rho_G) \; g \; \cos\alpha} \geq \frac{8 \; \tilde{A}_G}{\tilde{S}_i \; \tilde{U}_L^2 (\tilde{U}_L \tilde{D}_L)^{-n}}$$

$$(U_L^s)^{1.8} \geq \frac{4 \; \tilde{A}_G}{\tilde{S}_i \; \tilde{U}_L^{\;1.8} \; \tilde{D}_L^{\;-.2}} \; \frac{D^{1.2} \; (\rho_L - \rho_G) g \; \cos\alpha}{C_L \; \nu_L^{.2} \; \rho_L}$$

$$Q_L^{1.8} = \frac{A^{1.8} \; 4\tilde{A}_G \; \tilde{A}_L^{\;1.8} \; (4 \; \tilde{A}_L)^{.2} \; D^{1.2} \; (\rho_L - \rho_G) g \; \cos\alpha}{\tilde{S}_i \; (\frac{\pi}{4})^{1.8} \; (\tilde{S}_L)^{.2} \; C_L \; \nu_L^{\;.2} \; \rho_L}$$

$$= \frac{4^{1.2} \; D^{4.8} \; (\rho_L - \rho_G) \; g \; \cos\alpha}{C_L \; \nu_L^{.2} \; \rho_L} \; \frac{\tilde{A}_G \; \tilde{A}_L^2}{\tilde{S}_i \; \tilde{S}_L^{.2}}$$

let

$$k_5 = \left[\frac{4^{1.2} D^{4.8} (\rho_L - \rho_G) g \cos\alpha}{C_L \nu_L^{.2} \rho_L}\right]^{\frac{1}{1.8}}$$

then

$$Q_{L2} = k_5 \left[\frac{\tilde{A}_G \tilde{A}_L^2}{\tilde{S}_i \tilde{S}_L^{.2}}\right]^{\frac{1}{1.8}}$$

3. Transition between Intermitttent and Annular Dispersed Flow

Criteria:

$\alpha = .5$

or $\tilde{h} = .5$

$$Q_{L3} = k_2 X^{10/9}_{(\tilde{h} = .5)} Q_G$$

A calculation routine was set up, where by Q_G, X, Q_L, Q_{L2}, Re_G, and Re_L are calculated using the normalized water height in the pipe $\tilde{h}_L$ as the input parameter.

Properties

800 psi (55 Bar)

$T_{SAT} = 270°C$

$\rho_L = 767.9$ kg/m^3

$\rho_G = 28.1$ kg/m^3

$\nu_L = .132 \times 10^{-6}$ m^2/s

$\nu_G = .652 \times 10^{-6}$ m^2/s

500 psi (34.5 Bar)

$T_{SAT} = 242°C$

$\rho_L = 811.03 \text{ kg/m}^3$

$\rho_G = 17.26 \text{ kg/m}^3$

$\nu_L = .138 \times 10^{-6} \text{ m}^2/\text{s}$

$\nu_G = .652 \times 10^{-6} \text{ m}^2/\text{s}$

Coefficients

	K_1	K_2	K_3	K_4	K_5
800 psi	.0214	.190	8.3×10^7	4.1×10^8	.27437
500 psi	.02823	.140	8.27×10^7	3.9×10^8	.2754

Results

800 psi

$\tilde{h}_L$	Q_G (ℓ/s)	X	Q_L (ℓ/s)	$Re_G \times 10^8$	$Re_L \times 10^8$	Q_{L2} (ℓ/s)
.02	31.0	.0062	.021	8.0	.3	1.12
.03	27.7	.0113	.036	7.0	.4	1.93
.05	23.73	.024	.072	6.3	.66	3.78
.1	18.5	.070	.184	4.9	1.17	9.31
.2	12.9	.221	.458	3.6	2.03	22.04
.25	10.9	.332	.608	3.0	2.3	28.56
.3	9.19	.473	.760	2.63	2.6	34.9
.4	6.38	.884	1.058	1.9	3.2	46.3
.5	4.20	1.58	1.330	1.3	3.5	55.0
.6	2.54	2.87	1.56	.89	3.6	60.0
.7	1.33	5.62	1.72	.53	3.56	60.1

$\tilde{h}_L$	Q_G (ℓ/s)	X	Q_L (ℓ/s)	$Re_G \times 10^8$	$Re_L \times 10^8$	Q_{L2} (ℓ/s)
.8	.535	13.22	1.79	.25	3.3	54.3
.85	.281	23.5	1.78	.16	3.1	48.5
.9	.113	51.8	1.724	.075	2.8	40.1

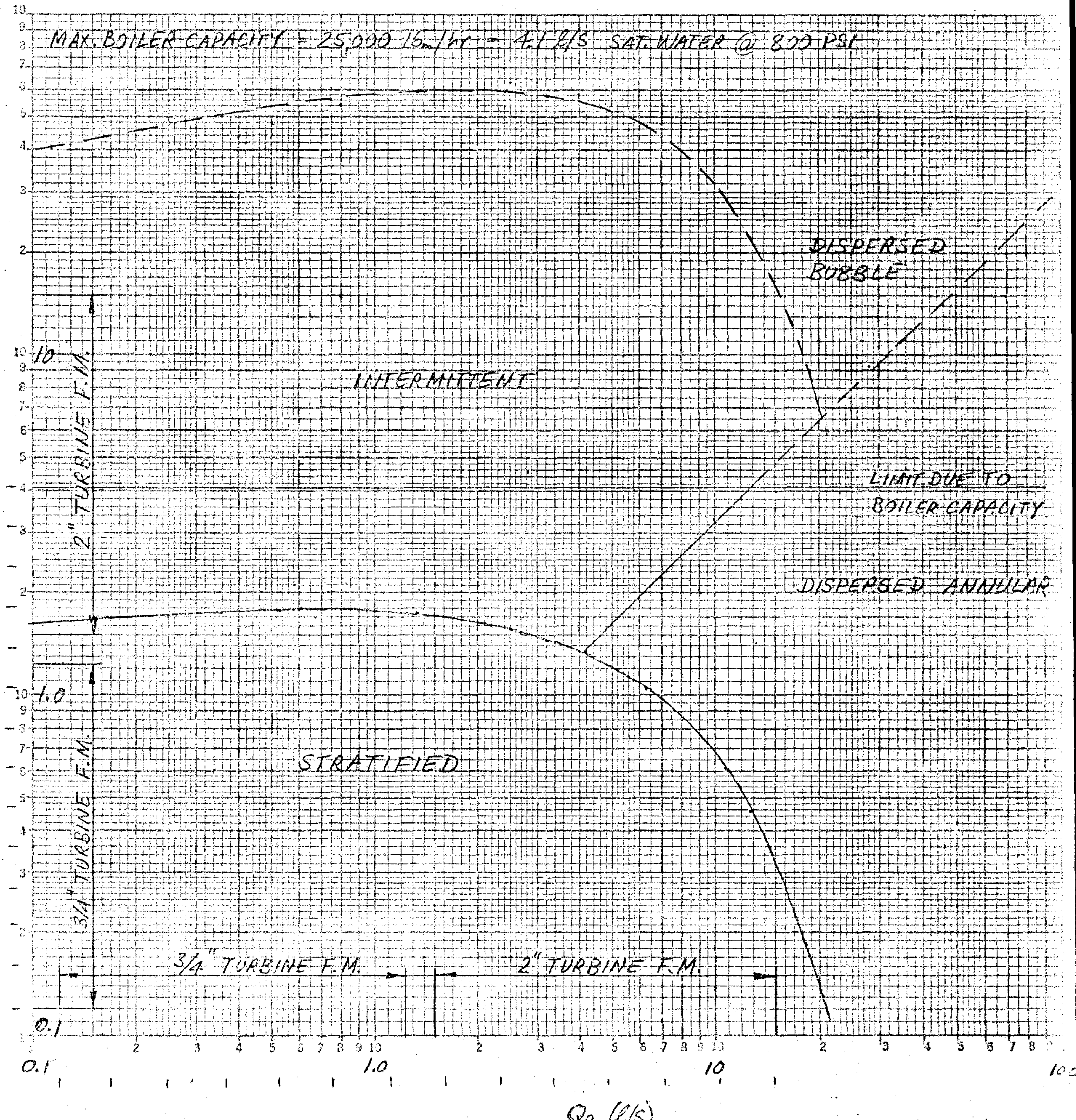
500 psi

$\tilde{h}_L$	Q_G (ℓ/s)	X	Q_L (ℓ/s)	Q_{L2} (ℓ/s)
.02	40.9	.0062	.020	1.13
.03	36.5	.0113	.035	1.93
.04	33.54	.0173	.052	2.83
.05	31.3	.024	.070	3.79
.075	27.3	.045	.122	6.44
.1	24.4	.070	.179	9.34
.125	22.1	.10	.24	12.41
.15	20.2	.14	.306	15.6
.175	18.5	.175	.375	18.84
.2	17.0	.22	.445	22.12
.3	12.12	.473	.738	35.0
.4	8.42	.884	1.03	46.4
.5	5.54	1.58	1.29	55.16
.6	3.35	2.87	1.51	60.14
.7	1.75	5.62	1.67	60.3
.8	.71	13.22	1.74	54.47
.85	.37	23.5	1.73	48.7
.9	.15	51.8	1.67	40.3

FLOW REGIME PREDICTIONS BASED ON TAITELS MODEL

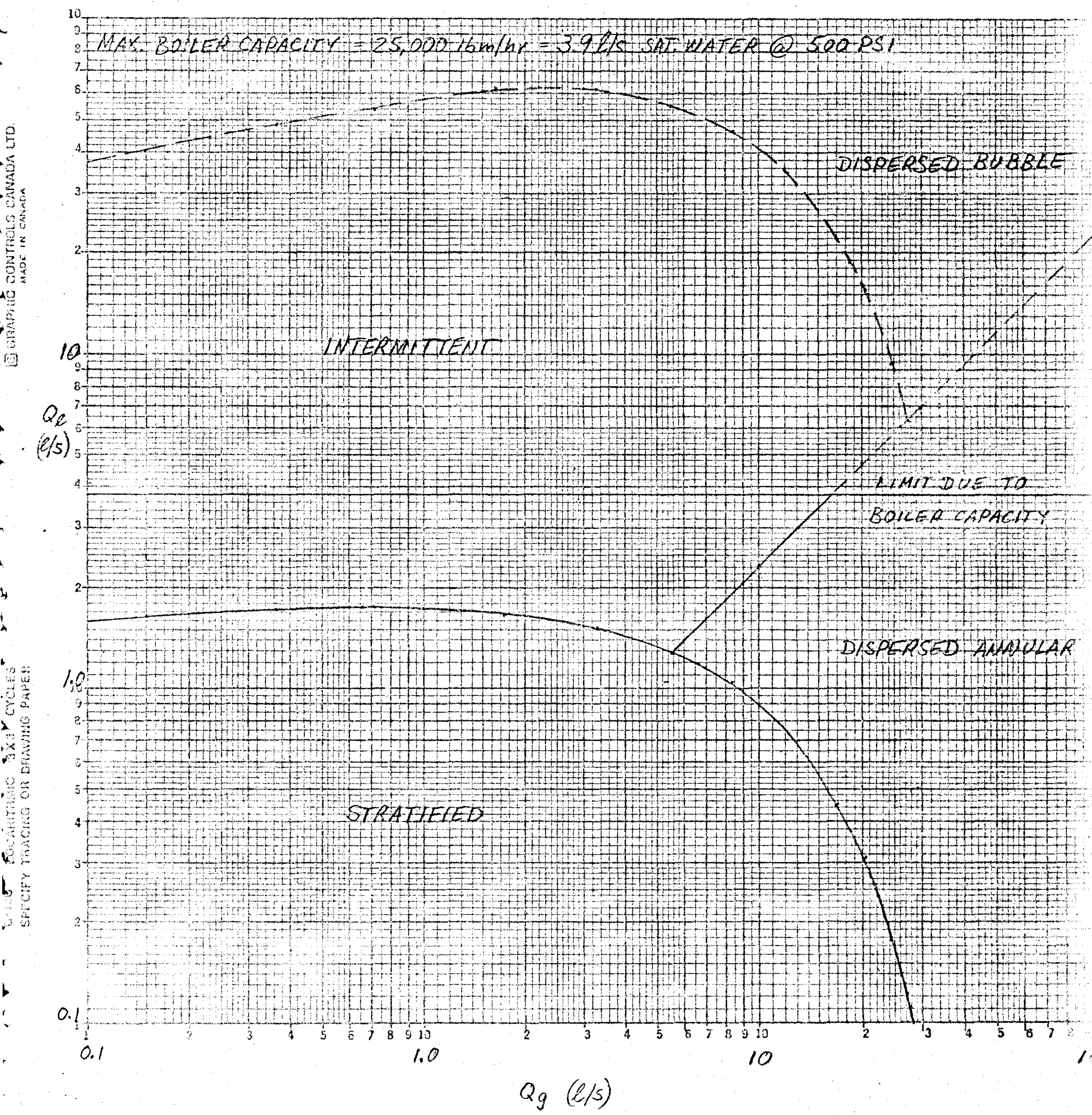
STEAM-WATER @ 5.5 MPa (in thermal equilibrium)

3" SCH. 80 PIPE (.0742 m I.D.)



FLOW REGIME PREDICTIONS BASED ON TAITELS MODEL

STEAM-WATER @ 3.45 MPa (in thermal equilibrium)
3" SCH. 80 PIPE (.0742 m I.D.)



NOTATION

A = flow cross-sectional area

D = pipe diameter and hydraulic diameter

g = acceleration of gravity

h = liquid level

m = exponent

n = exponent

P = pressure

Re = Reynolds number

S = Perimeter over which the stress acts

T = dispersed bubble flow dimensionless parameter

v = velocity in the x-direction

v = velocity normal to the x-direction

X = Martinelli parameter

α = angle between the pipe axis and the horizontal, positive for down ward flow

ρ = density

τ = shear stress

ν = kinematic viscosity

Subscripts and Superscripts

G = gas

i = liquid gas interface

L = liquid

s = superficial, for single fluid flow

W = pipe surface

$\sim$ = dimensionless variable

APPENDIX B

TEST MATRIX FOR STRATIFIED FLOW TEST

TABLE ENTRIES :
(55 BAR)

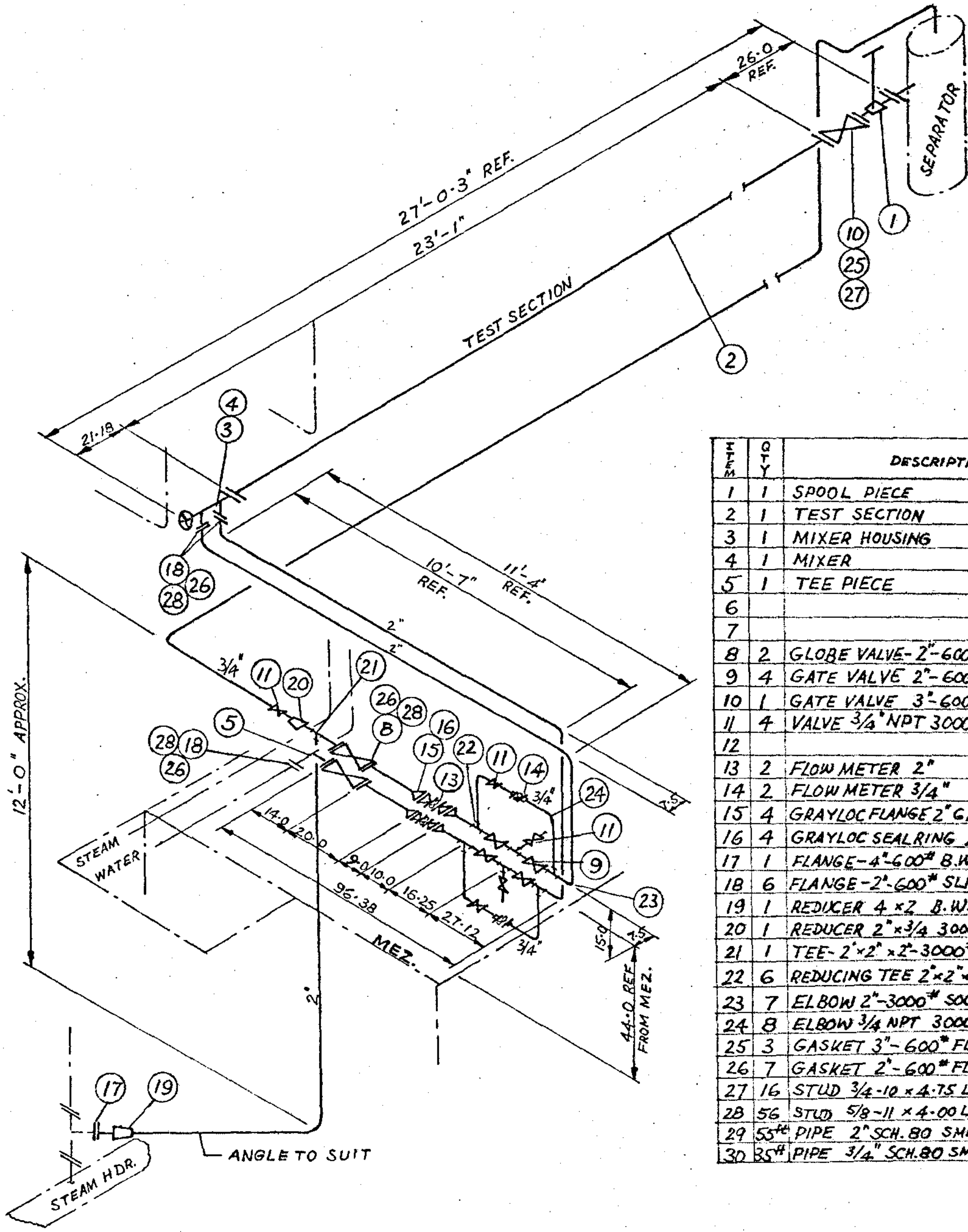
X	QUALITY
G	MASS VELOCITY [$kg/m^2/s$]
$\left(\frac{dP}{dz}\right)$	PRESSURE GRADIENT [$N/m^2/m$] (HOMOGENEOUS MODEL)

Q_G (ℓ/s)

Q_L (ℓ/s)	0	.12	.19	.29	.45	.69	1.08	1.67	2.59	4.0	6.23	9.67	15.0
0	1.0 0.0 0.0	1.0 .79 .0017	1.0 1.25 .0043	1.0 1.91 .01	1.0 2.97 .024	1.0 4.6 .057	1.0 7.1 .14	1.0 11.0 .33	1.0 17.1 .80	1.0 26.4 1.92	1.0 41.1 4.66	1.0 64 11.2	1.0 99 27
.12	0.0 21.6 .072	.035 22.4 .14	.055 22.9 .19	.08 23.5 .25	.12 24.6 .35	.17 26.2 .51	.25 28.7 .80	.34 32.6 1.29	.44 38.7 2.2	.55 48.0 4.04	.66 62.7 7.9	.75 85.4 16.1	.82 120 34.5
.17	0.0 30.6 .145	.025 31.4 .25	.04 31.9 .31	.06 32.6 .39	.09 33.6 .53	.13 35.2 .75	.19 37.8 1.28	.26 41.7 1.76	.36 47.7 2.89	.46 57.0 5.0	.57 71.7 9.3	.65 98 18.3	.76 130 37.7
.23	0.0 41.5 .266	.019 42.2 .40	.03 42.7 .49	.04 43.4 .60	.067 44.4 .79	.099 46.0 1.1	.15 48.6 1.56	.21 52.5 2.35	.29 58.5 3.73	.39 67.8 6.21	.50 82.5 11.1	.61 105 20.9	.70 140 41.7
.31	0.0 55.9 .48	.014 56.7 .67	.02 57.1 .78	.03 57.8 .93	.05 58.8 1.19	.075 60.4 1.57	.11 63.0 2.2	.16 66.9 3.2	.23 73.0 4.93	.32 82.3 7.9	.42 97 13.5	.53 120 24.5	.64 155 47.1
.43	0.0 77.5 .93	.010 78.3 1.19	.016 78.8 1.34	.02 79.4 1.55	.037 80.5 1.9	.055 82.0 2.42	.08 84.6 3.3	.12 88.5 4.64	.18 94.6 6.86	.25 104 10.6	.35 119 17.4	.45 141 30.1	.56 176 55.4
.60	0.0 108.1 1.8	.007 108.9 2.17	.011 109.4 2.38	.017 110. 2.68	.027 111. 3.2	.04 113. 3.89	.06 115 5.08	.09 119 6.9	.14 125 9.88	.20 135 14.7	.28 149 23.2	.37 172 38.5	.48 207 67.6
.82	0.0 148. 3.38	.005 148.6 3.87	.008 149 4.2	.01 150 4.57	.02 150.7 5.23	.03 152 6.22	.046 155 7.83	.07 159 10.3	.10 165 14.25	.15 174 20.6	.22 189 31.3	.30 212 50	.40 247 84.0
1.14	0.0 205.5 6.53	.0038 206.2 7.22	.006 206.7 7.6	.009 207 8.19	.014 208 9.1	.022 210 10.5	.034 213 12.7	.051 216 16.1	.08 223 21.5	.11 232 30	.17 247 44	.24 269 67.7	.33 304 110
1.57	0.0 283 12.4	.0027 283.7 13.3	.004 284.2 13.9	.007 285 14.7	.010 286 15.9	.016 288 17.8	.025 290 20.9	.04 294 25.6	.06 300 32.9	.085 309 44.3	.13 324 62.9	.18 347 93.4	.26 382 145
2.16	0.0 389. 23.5	.002 390.1 24.8	.003 390.5 25.5	.005 391 26.6	.008 392 28.3	.012 394 30.9	.018 396 35.1	.03 400 41.5	.04 406 51.6	.063 416 67.1	.10 430 92.1	.14 453 132	.20 488 199
2.97	0.0 535 44.4	.0014 536.1 46.1	.002 536.5 47.2	.0035 537 48.7	.0055 538 51	.008 540 54.6	.013 542 60.4	.02 546 69.2	.03 552 82.9	.047 562 104	.07 576 138	.11 599 191	.16 634 278
4.1	0.0 739 84.5	.001 739.7 87.	.0016 740.2 88.4	.0025 741. 90.5	.004 742. 93.8	.006 743 98.7	.010 746 107	.015 750 119	.02 756 138	.03 765 167	.05 780 213	.08 803 286	.12 838 401

APPENDIX C

PIPING LAYOUT



ITEM	QTY	DESCRIPTION
1	1	SPOOL PIECE
2	1	TEST SECTION
3	1	MIXER HOUSING
4	1	MIXER
5	1	TEE PIECE
6		
7		
8	2	GLOBE VALVE- 2"-600# FLANGED
9	4	GATE VALVE 2"-600# SOC. WELD
10	1	GATE VALVE 3"-600# FLANGED
11	4	VALVE 3/4" NPT 3000#
12		
13	2	FLOW METER 2"
14	2	FLOW METER 3/4"
15	4	GRAYLOC FLANGE 2" GR 20" 52105 w/CLAMP #69002
16	4	GRAYLOC SEALRING 2" #51273
17	1	FLANGE-4"-600# B.W.
18	6	FLANGE-2"-600# SLIP-ON
19	1	REDUCER 4×2 B.W. SCH. 80
20	1	REDUCER 2"×3/4 3000# SOC. WELD
21	1	TEE- 2"×2"×2"-3000# SOC. WELD
22	6	REDUCING TEE 2"×2"×3/4" 3000# SOC. WELD
23	7	ELBOW 2"-3000# SOC. WELD
24	8	ELBOW 3/4 NPT 3000#
25	3	GASKET 3"-600# FLEXITALLIC
26	7	GASKET 2"-600# FLEXITALLIC
27	16	STUD 3/4-10 × 4·75 LG ASTM A193 w/NUTS A194
28	56	STUD 5/8-11 × 4·00 LG MAT'L AS ITEM 28
29	55 ft	PIPE 2" SCH. 80 SMLS ASTM A106
30	35 ft	PIPE 3/4" SCH. 80 SMLS ASTM A106

APPENDIX D

'On-Line' Test Calculations

Input to program:

W_{G1} = steam mass flow rate at inlet section

W_{L1} = water mass flow rate at inlet section

α = void fraction from densitometers

ΔP_n = pressure drops over several sections of the test section, taken with reference to upstream pressure at the inlet

T_{G1} = steam temperature at the inlet section

P_{G1} = steam pressure at the inlet section

T_{W1} = water temperature at the inlet section

T_{G2} = steam temperature at the densitometer

P_{G2} = steam pressure at the densitometer

T_{W2} = water temperature at the densitometer

A = test section flow area

Output:

<u>At densitometer</u>

W_G = steam mass flow rate

W_L = water mass flow rate

Q_G = steam volumetric flow rate

Q_L = water volumetric flow rate

β = homogeneous void fraction (= volumetric quality)

X = mass quality

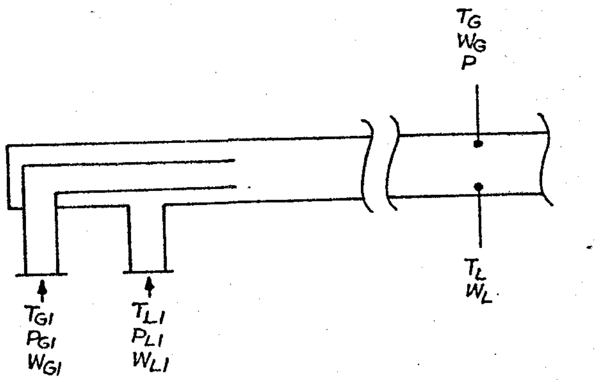
U_G/U_L = velocity slip ratio

τ_{WL} = liquid-wall shear stress

τ_{WG} = gas-wall shear stress

τ_i = interfacial shear stress

Calculations



Mass balance

$$W_{G1} + W_{L1} = W_G + W_L$$

Energy balance

$$W_{G1}\, h_{G1} + W_{L1}\, h_{L1} = W_G\, h_G + W_L\, h_L$$

(enthalpies determined through a properties subroutine)

written in matrix form:

$$\begin{bmatrix} 1 & 1 \\ h_G & h_L \end{bmatrix} \begin{bmatrix} W_G \\ W_L \end{bmatrix} = \begin{bmatrix} W_{G1} + W_{L1} \\ W_{G1}\, h_{G1} + W_{L1}\, h_{L1} \end{bmatrix}$$

$$W_G = \frac{\begin{vmatrix} (W_{G1} + W_{L1}) & 1 \\ (W_{G1}\ h_{G1} + W_{L1}\ h_{L1}) & h_L \end{vmatrix}}{\begin{vmatrix} 1 & 1 \\ h_{G2} & h_{L2} \end{vmatrix}} = \frac{(W_{G1} + W_{L1})h_L - (W_{G1}\ h_{G1} + W_{L1}\ h_{L1})}{h_L - h_G}$$

$$W_G = \frac{W_{G1}\ (h_L - h_{G1}) + W_{L1}\ (h_L - h_{L1})}{h_L - h_G}$$

$$W_L = \frac{\begin{vmatrix} 1 & (W_{G1} + W_{L1}) \\ h_G & (W_{G1}\ h_{G1} + W_{L1}\ h_{L1}) \end{vmatrix}}{h_L - h_G}$$

$$W_L = \frac{W_{G1}\ (h_{G1} - h_G) + W_{L1}\ (h_{L1} - h_G)}{h_L - h_G}$$

$$Q_G = \frac{W_G}{\rho_G}$$

$$Q_L = \frac{W_L}{\rho_L}$$

$$\alpha_{homo} = \beta = \frac{Q_G}{Q_G + Q_L}$$

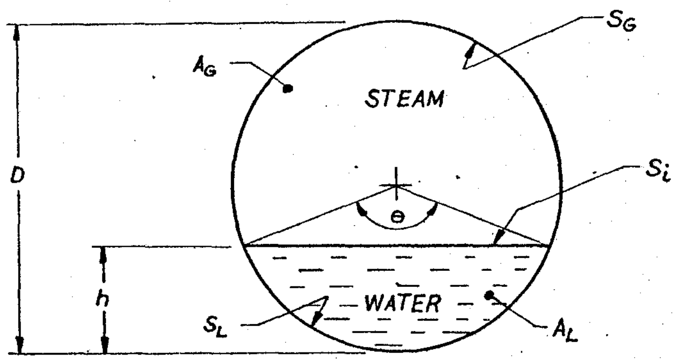
$$X = \frac{W_G}{W_G + W_L}$$

$$A_G = \alpha A$$

$$A_L = (1 - \alpha)A$$

$$U_G/U_L = \frac{Q_G}{Q_L}\left(\frac{1}{\alpha} - 1\right)$$

Momentum balance for a horizontal pipe (neglecting hydraulic gradient):



$$-A_L \left(\frac{dP}{dZ}\right) - \tau_{WL} S_L + \tau_i S_i = 0$$

$$-A_G \left(\frac{dP}{dZ}\right) - \tau_{WG} S_G - \tau_i S_i = 0$$

$$S_G + S_L = \pi D$$

in matrix form

$$\begin{bmatrix} -\tau_{WL} & 0 & S_i \\ 0 & -\tau_{WG} & -S_i \\ 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} S_L \\ S_G \\ \tau_i \end{bmatrix} = \begin{bmatrix} A_L \left(\frac{dD}{dZ}\right) \\ A_G \left(\frac{dD}{dZ}\right) \\ \pi D \end{bmatrix}$$

$$\tau_{WL} = -\frac{D}{4} \left(\frac{dP}{dZ}\right)_{\alpha = 0}$$

$$\tau_{WG} = -\frac{D}{4} \left(\frac{dP}{dZ}\right)_{\alpha = 0}$$

$$\tau_i = \frac{\begin{vmatrix} -\tau_{WL} & 0 & A_L\left(\frac{dP}{dZ}\right) \\ 0 & -\tau_{WG} & A_G\left(\frac{dP}{dZ}\right) \\ 1 & 1 & \pi D \end{vmatrix}}{\begin{vmatrix} -\tau_{WL} & 0 & S_i \\ 0 & -\tau_{WG} & -S_i \\ 1 & 1 & 0 \end{vmatrix}}$$

$$\tau_i = \frac{\tau_{WL}\left[\pi D \tau_{WG} + A_G\left(\frac{dP}{dZ}\right)\right] + A_L\left(\frac{dP}{dZ}\right)\tau_{WG}}{S_i\left(\tau_{WG} - \tau_{WL}\right)}$$

where

$$S_i = 2[h(D - h)]^{1/2}$$

$$h = \left[1 - \cos\left(\frac{\theta}{2}\right)\right]\frac{D}{2}$$

$$\theta \xrightarrow[\text{numerically}]{\text{solve}} \left[1 - \frac{1}{2\pi}(\theta - \sin\theta) = \alpha\right] \text{ for } \theta$$

(Regula Falsi Method as programmed in 'Applied Numerical Methods', B. Carnahan,converges very fast).

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