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 information 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 laid out to cover the transition from stratified to intermittent 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 laid 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.

*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:

\[
\frac{\rho_G}{(\rho_L - \rho_G)} \frac{U_G^2}{D g \cos \alpha} \frac{1}{C_2^2} \frac{\tilde{A}}{\tilde{A}_G} \sqrt{1 - (2\tilde{h}_L - 1)^2} \geq 1
\]

where

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

then

\[
\frac{\rho_G}{(\rho_L - \rho_G)} \frac{Q_G^2}{A^2 D g \cos \alpha} \frac{1}{C_2^2} \frac{\sqrt{1 - (2\tilde{h}_L - 1)^2}}{\tilde{A}_G^2} \geq 1
\]

or

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

transition takes place when

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

\[ x^2 = \frac{4C_L}{D} \frac{U_L^S}{\nu_L} (\frac{D}{u_L^s})^{-n} \frac{\rho_L (u_L^s)^2}{2} \]

\[ + \frac{4C_G}{D} \frac{U_G^S}{\nu_G} (\frac{D}{u_G^s})^{-m} \frac{\rho_G (u_G^s)^2}{2} \]

assume turbulent flow both phases

then \( n = m = 0.2 \)

\[ C_G = C_L = .046 \]

and

\[ x^2 = \frac{U_L^S}{U_G^S} (\frac{\nu_G}{\nu_L})^{-0.2} \frac{\rho_L}{\rho_G} (\frac{U_L^s}{U_G^s})^2 \]
solving for \( Q_L \)

\[
Q_L = \left( \frac{\nu_G}{\nu_L} \right)^{1/9} \left( \frac{\rho_G}{\rho_L} \right)^{5/9} \times 10^{0.9} Q_G
\]

let

\[
k_2 = \left( \frac{\nu_G}{\nu_L} \right)^{1/9} \left( \frac{\rho_G}{\rho_L} \right)^{5/9}
\]

then

\[
Q_L = k_2 \times 10^{0.9} Q_G
\]

Obtain steam quality from equation 7 Ref. 5

\[
x^2 = \frac{\left[ \left( \frac{\bar{U}_G}{D_G} \right)^m \bar{U}_G^2 \left( \frac{\bar{S}_G}{A_G} + \frac{\bar{S}_i}{A_L} + \frac{\bar{S}_s}{A_G} \right) \right]}{\left[ \left( \frac{\bar{U}_L}{D_L} \right)^n \bar{U}_L^2 \frac{\bar{S}_i}{A_L} \right]}
\]

where \( n = m = .2 \) for turbulent flow

\[
\bar{D}_G = \frac{D_G}{D} = \frac{4 A_G}{(S_G + S_i) D} = \frac{4 D_D}{S_G + S_i} = \frac{4 D_D}{\bar{S}_G + \bar{S}_i}
\]

now

\[
x^2 = (S_L)^{-1} \left( \frac{\bar{S}_G}{S_L} \right) \left( \frac{\bar{S}_i}{S_L} \right) \left( A_L \right) \left( A_G \right)^{-2} \left[ \frac{\bar{S}_G}{A_G} + \bar{S}_i \left( \frac{1}{A_L} + \frac{1}{A_G} \right) \right]
\]

where

\[
\bar{S}_L = \pi - \cos^{-1} \left( 2 \beta_L - 1 \right) = \pi - \bar{S}_G
\]
\[ \tilde{S}_G = \cos^{-1} (2\tilde{h}_L - 1) \]
\[ \tilde{S}_i = \sqrt{1 - (2h_L - 1)^2} \]
\[ \tilde{A}_L = 0.25 \left[ \pi - \cos^{-1} (2\tilde{h}_L - 1) + (2\tilde{h}_L - 1) \sqrt{1 - (2\tilde{h}_L - 1)^2} \right] \]
\[ = 0.25 [\tilde{S}_L + (2\tilde{h}_L - 1)\tilde{S}_i] \]
\[ \tilde{A}_G = 0.25 \left[ \cos^{-1} (2\tilde{h}_L - 1) - (2\tilde{h}_L - 1) \sqrt{1 - (2\tilde{h}_L - 1)^2} \right] \]
\[ = 0.25 [\tilde{S}_G - (2\tilde{h}_L - 1)\tilde{S}_i] \]
\[ x^2 = \frac{(\tilde{S}_G + \tilde{S}_i)^2 (\tilde{A}_L)^3 [\tilde{S}_G + \tilde{S}_i (\frac{1}{\tilde{A}_G} + \frac{1}{\tilde{A}_G})]}{(\tilde{A}_G)^2 \tilde{S}_L} \]

check assumption of turbulence in both phases:

\[ \text{Re}_G = \frac{U_G D_G}{\nu_G} = \frac{Q_G D_G}{\tilde{A}_G \nu_G} = \frac{Q_G}{\nu_G} \frac{4}{\nu_G D_G (\tilde{S}_G + \tilde{S}_i)} \]

where

\[ A_G = \tilde{A}_G D^2 \]
\[ D_G = D_G D = \frac{4 \tilde{A}_G D}{(\tilde{S}_G + \tilde{S}_i)} \]

was used

let

\[ k_3 = \frac{4}{\nu_G} \]

then

\[ \text{Re}_G = k_3 \left[ \frac{Q_G}{\tilde{S}_G + \tilde{S}_i} \right] \]
similarly

\[ \text{Re}_L = \frac{U_L D_L}{v_L} = \frac{4}{D} \frac{Q_L}{S_L} \]

let \( K_4 = \frac{4}{D} \frac{v_L}{v_L} \)

then

\[ \text{Re}_L = k_4 \left[ \frac{Q_L}{S_L} \right] \]

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

Criterion:

\[ T^2 > \left[ \frac{8A_G}{S_i \tilde{U}_L^* \tilde{U}_D \tilde{U}_L^D} \right] \]

or

\[ \frac{4C_L \left( \frac{U_L^S}{v_L} \right)^n - \rho_L \frac{U_L^S}{2}}{\rho_L - \rho_G} \frac{g \cos \alpha}{\rho_L} > \frac{8A_G}{S_i \tilde{U}_L^* \tilde{U}_D \tilde{U}_L^D} \]

\[ (U_L^S)^{1.8} \geq \frac{4A_G}{S_i \tilde{U}_L^* \tilde{U}_D \tilde{U}_L^D} \frac{D^{1.2} (\rho_L - \rho_G) g \cos \alpha}{C_L v_L^* \rho_L} \]

\[ Q_L^{1.8} = \frac{A^{1.8} 4A_G \tilde{A}_L^{1.8} (4 \tilde{A}_L)^{1.2} D^{1.2} (\rho_L - \rho_G) g \cos \alpha}{S_i \left( \frac{\pi}{4} \right)^{1.8} (\tilde{S}_L)^{1.2} C_L v_L^* \rho_L} \]

\[ = \frac{4^{1.2} D^{4.8} (\rho_L - \rho_G) g \cos \alpha}{C_L v_L^* \rho_L} \frac{A_G \tilde{A}_L^{2}}{S_i \tilde{S}_L^2} \]
let
\[ k_5 = \left[ \frac{4^{1.2} D^{4.8} (\rho_L - \rho_G) g \cos \alpha \frac{1}{\nu_L^2}}{C_L \nu_L^2 \rho_L} \right] \]

then
\[ Q_{L2} = k_5 \left[ \frac{\tilde{A}_G \tilde{A}_L^2}{S_1 \tilde{s}_L^2} \right]^{\frac{1}{1.8}} \]

3. Transition between Intermittent and Annular Dispersed Flow

Criteria:

\[ \alpha = .5 \]

or \( \tilde{h} = .5 \)

\[ Q_{L3} = k_2 \chi^{10/9} Q_G \quad (\tilde{h} = .5) \]

A calculation routine was set up, where by \( Q_G \), \( \chi \), \( Q_L \), \( Q_{L2} \), \( \text{Re}_G \), and \( \text{Re}_L \) are calculated using the normalized water height in the pipe \( \tilde{h}_L \) as the input parameter.

Properties

800 psi (55 Bar)

\[ T_{\text{SAT}} = 270^\circ \text{C} \]
\[ \rho_L = 767.9 \text{ kg/m}^3 \]
\[ \rho_G = 28.1 \text{ kg/m}^3 \]
\[ \nu_L = .132 \times 10^{-6} \text{ m}^2/\text{s} \]
\[ \nu_G = .652 \times 10^{-6} \text{ m}^2/\text{s} \]
500 psi (34.5 Bar)

\[ T_{\text{SAT}} = 242°C \]

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

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

\[ \nu_L = 0.138 \times 10^{-6} \text{ m}^2/\text{s} \]

\[ \nu_G = 0.652 \times 10^{-6} \text{ m}^2/\text{s} \]

**Coefficients**

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**Results**

**800 psi**

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500 psi

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FLOW REGIME PREDICTIONS BASED ON TAITELS MODEL

STEAM-WATER @ 5.5 MPa (in thermal equilibrium)
3" SCH. 80 PIPE (0.0742 m I.D.)

MAX. BOILER CAPACITY = 25,000 g/hr = 41 g/s SAT. WATER @ 820 PSI

DISPERSED BUBBLE

LIMIT DUE TO BOILER CAPACITY

DISPERSED ANNULAR

INTERMITTENT

STRATIFIED

QG (g/s)
FLOW REGIME PREDICTIONS BASED ON TAITELS MODEL

STEAM-WATER @ 3.45 MPa (in equilibrium)
3" SCH. 80 PIPE (0.0742 m I.D.)

MAX. BOILER CAPACITY = 25,000.16 m³/hr = 3.98% SAT. WATER @ 500 PSI

DISPERSED BUBBLE

INTERMITTENT

LIMIT DUE TO BOILED CAPACITY

DISPERSED ANGULAR

STRATIFIED

Qg (l/s)

Qg (l/s)
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
\( \alpha \) = angle between the pipe axis and the horizontal, positive for downward flow
\( \rho \) = density
\( \tau \) = shear stress
\( \nu \) = kinematic viscosity

Subscripts and Superscripts

\( G \) = gas
\( i \) = liquid gas interface
\( L \) = liquid
\( s \) = superficial, for single fluid flow
\( W \) = pipe surface
\sim = \text{dimensionless variable}
## APPENDIX B

**TEST MATRIX FOR STRATIFIED FLOW TEST**

**TABLE ENTRIES:**

<table>
<thead>
<tr>
<th>X QUALITY</th>
<th>G MASS VELOCITY [kg/m²/s]</th>
<th>Q̇G (ℓ/s)</th>
<th>ΩL (ℓ/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(55 BAR)</td>
<td>PR ESSURE GRADIENT [N/m²]</td>
<td>(HOMOGENEOUS MODEL)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th>.19</th>
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<th>.45</th>
<th>.69</th>
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<th>4.0</th>
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</tbody>
</table>

### Notes:
- The table entries represent various parameters for stratified flow tests under different conditions.
- The values are provided in units of quality (X), mass velocity (G), and flow rate (Q̇G) as specified.
- The matrix format is used to organize the data for ease of reference and analysis.
- The table entries cover a range of conditions, with specific entries highlighted for clarity.
APPENDIX D

'On-Line' Test Calculations

Input to program:

\[ W_{G1} = \text{steam mass flow rate at inlet section} \]
\[ W_{L1} = \text{water mass flow rate at inlet section} \]
\[ \alpha = \text{void fraction from densitometers} \]
\[ \Delta P_n = \text{pressure drops over several sections of the test section, taken with reference} \]
\[ \text{to upstream pressure at the inlet} \]
\[ T_{G1} = \text{steam temperature at the inlet section} \]
\[ P_{G1} = \text{steam pressure at the inlet section} \]
\[ T_{W1} = \text{water temperature at the inlet section} \]
\[ T_{G2} = \text{steam temperature at the densitometer} \]
\[ P_{G2} = \text{steam pressure at the densitometer} \]
\[ T_{W2} = \text{water temperature at the densitometer} \]
\[ A = \text{test section flow area} \]

Output:

At densitometer

\[ W_G = \text{steam mass flow rate} \]
\[ W_L = \text{water mass flow rate} \]
\[ Q_G = \text{steam volumetric flow rate} \]
\[ Q_L = \text{water volumetric flow rate} \]
\[ \beta = \text{homogeneous void fraction (= volumetric quality)} \]
\[ X = \text{mass quality} \]
\[
U_G / U_L = \text{velocity slip ratio}
\]
\[
\tau_{WL} = \text{liquid-wall shear stress}
\]
\[
\tau_{WG} = \text{gas-wall shear stress}
\]
\[
\tau_i = \text{interfacial shear stress}
\]

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:
\[
\begin{bmatrix}
1 & 1 \\
\h_G & \h_L
\end{bmatrix}
\begin{bmatrix}
W_G \\
W_L
\end{bmatrix}
= 
\begin{bmatrix}
W_{G1} + W_{L1} \\
W_{G1} h_{G1} + W_{L1} h_{L1}
\end{bmatrix}
\]
\[
W_G = \frac{(W_{G1} + W_{L1})}{h_L} = \frac{(W_{G1} + W_{L1})}{h_L} - (W_{G1} h_{G1} + W_{L1} h_{L1})}
\]

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

\[
W_L = \frac{1 (W_{G1} + W_{L1})}{h_G} = \frac{(W_{G1} h_{G1} + W_{L1} h_{L1})}{h_L - h_G}
\]

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

\[
Q_G = \frac{W_G}{\rho_G}
\]

\[
Q_L = \frac{W_L}{\rho_L}
\]

\[
\alpha_{\text{homo}} = \beta = \frac{Q_G}{Q_G + Q_L}
\]

\[
X = \frac{W_G}{W_G + W_L}
\]

\[
A_G = \alpha A
\]

\[
A_L = (1 - \alpha)A
\]

\[
U_G/U_L = \frac{Q_G}{Q_L} \left( \frac{1}{\alpha} - 1 \right)
\]
Momentum balance for a horizontal pipe (neglecting hydraulic gradient):

\[-A_L \frac{dP}{dz} - \tau_{WL} S_L + \tau_i S_i = 0\]

\[-A_G \frac{dP}{dz} - \tau_{WG} S_G - \tau_i S_i = 0\]

\[S_G + S_L = \pi D\]

in matrix form

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

\[\tau_{WL} = -\frac{D}{4} \left( \frac{dP}{dz} \right) _\alpha = 0\]

\[\tau_{WG} = -\frac{D}{4} \left( \frac{dP}{dz} \right) _\alpha = 0\]
\[
\tau_i = \begin{vmatrix}
-t_{WL} & 0 & A_L \left(\frac{dP}{dZ}\right) \\
0 & -t_{WG} & A_G \left(\frac{dP}{dZ}\right) \\
1 & 1 & 1
\end{vmatrix}
\]

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

where

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

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

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

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


