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RL-REA-WSU-2

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HYDRAULIC MODEL STUDIES OF K-DOWNCOMER

for

General Electric Company

Edited by

Claud C. Lomax

The R. L. Albrook Hydraulic Laboratory

This document consists of
32 pages.

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CG-NMP-1, 5-4-94

By DK Hanson, 5-23-94

Verified By Quinn Males, 5-27-94

November, 1965

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College of Engineering Research Division Research Report No. 65/9-163

Project No. 873

Sponsors Contract No. Design, Development, and Research Contract DDR-206

Washington State University
Pullman, Washington

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by Richard W. Crain, jr. and John H. Lienhard

Part I

A Review of 'RL-REA-2679 RD " KE Downcomer Development Test- IP-778
Interim Report' by S. S. Jones.

Prepared by Claud Lomax and F. Roy Tinney

General Comments:

This is probably as good a treatment of this problem as possible with the number of assumptions that must be made and the type of instrumentation that is available. Indeed the computed total flows are on the average (Table I p. 11) only 5% greater than the fourteen measured flows and for the 10 high flows the two agree within 0.2%, which is quite remarkable. However, the principal interest is in predicting the condition under which downcomer flooding occurs and the computations for runs D-4, and E-7 give discharges 10% and 12% low respectively at flows of 200,000 and 214,000 gpm which are of prime interest. It appears, therefore that this analytical approach is not sufficiently accurate to predict flooding conditions for a particular flow rate and temperature even though the method does elucidate many of the key phenomena.

The major weaknesses in the computational method lie in the assumptions that must be made on entrance coefficients, the assumption on the location and influence of the cavitation, and in the unreliability of the orifice plates as a metering device when the position of the vena contracta is so uncertain.

If a good method for computing individual channel flows were available then the prediction of the behavior at higher power levels would proceed with much greater confidence. Since this is such an important problem it seems prudent to consider a more positive means of measuring channel flows. One such scheme would be to use a combination of the current meters (the type not sensitive to flow direction) and four pitot cylinders in front of the elbow. This scheme is shown in the attached sketch. It should first be tried in the 1:6 model to verify its reliability (in the model detailed pitot tube traverses could be made to verify the method in addition to measurement of total flow). With the velocities and flow directions defined in a plane just six inches in front of the channel entrance, reliable computations of individual channel flows could be made independent of temperature effects or the internal behavior

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ELEVATION PLAN DETAIL OF CURRENT
METER CONNECTION PITOT CYLINDER
DETAILNOTE:

THIS SHEET DESCRIBES INSTRUMENTATION
FOR MEASURING FLOW RATES & DIRECTIONS
INTO INDIVIDUAL CHANNELS.

WASHINGTON STATE UNIVERSITY INSTITUTE OF TECHNOLOGY DIVISION OF INDUSTRIAL RESEARCH THE R. L. ALBROOK HYDRAULIC LABORATORY		
<u>DOWNCOMER</u>		
DR. BY <u>RJ</u>	TR. BY <u>SCALE NONE</u>	DATE <u>11-30-63</u>
CHKD. BY <u>---</u>	SCALE <u>---</u>	DWG. <u>---</u>

of the elbow and orifice plate.

Since temperature, pressure, and air content (two phase flow) will influence the current meter rating, calibration curves for various conditions should be made using the test setup prepared for the cavitation bubble scaling studies.

Detailed Questions:

- 1) what is H_x^1 in Eq. (I-2).
- 2) where does 10.4 come from in Eq. I-1 and I-2. It should be stated that the arises because reference tap o-c is 10.4 ft. above floor.
- 3) P. 8 2nd sentence (No. 3). Design change #1052 lowered the water level in the box on Figure 1 if one considers the average value of the three points:
pre-change average level = 8.62 feet
post-change average level = 8.35 feet
- 4) P. 8 7th sentence (No. 4) and Figures 1 and 2. The circle points (open or closed) could be expected to fall below the o-a and o-b' data because the water level has dropped in passing from o-a into the channels. This is borne out in most cases by the data but not all. In interpreting Figure 2 it might be more realistic to ignore the circle points. Then no temperature effect occurs under pre-change conditions until the temperature rises above 90°C . This agrees better with model behavior.

The effect of temperature seems to be greater under post-change conditions but the level is decidedly lower at both 80°C and 90°C . The modification cannot be expected to have any effect at 95°C because the flow is being choked at the elbow and the elbow configuration and behavior are really identical under pre- and post-change conditions. The data on Figure 2 is good evidence of this behavior and is a good check also on the reproducibility of

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the water level data (six readings all agree within less than 0.5 feet!).

- 5) The conclusion in the middle of p. 8 regarding the baffle plate is not borne out by the data. Change #1052 lowered the water level under both cold and hot conditions.
- 6) P. 10 Eq.(2) should have $\sqrt{2g}$ in it.
- 7) Table I - On run E-7 the table indicates only 9 channels with flow yet APP. V - 10 Table 1b shows a 2.4 ft. head across the orifice plate. Would the flow in Channel 10 account for some of the missing calculated channel flow (26,000 gpm).
- 8) Figure 6. This figure should also show backpressure level to show true picture.
- 9) P. 13 The method for determining the downcomer water level ignores the fact that the pressure in that portion of the column above the water level may be less than atmospheric. Indeed this region will most likely be less than atmospheric because of the eductor effect of the plunging jet. However, it cannot be less than the vapor pressure so that at temperatures just below 100°C the pressure in this region will be only slightly below atmospheric.
- 10) Equations are missing on pp 39 and 41.
- 11) Appendix I Page 21 The area between the 2.5 ft. and 3.0 ft. elevations below tap o-b' appeared to be a separation pocket. This area should be excluded for calculating $\frac{v^2}{2g}$ at tap o-b'.
- 12) Page 12 Table II and page 26 Table II-1 The method of determining the distance to the vena contracta is questioned. It seems correct to use the artificial β but the distance should be based on d_s divided by the square root of the number of holes not d_s .

e.g. Channel 1 with 9 holes
 $\beta = 0.765$ gives 0.39 D to vena contracta
 $d_s = 11.1"$
 dist. to vena contracta = $0.39 \frac{11.1}{\sqrt{9}} = 1.44"$

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13) Appendix III par. 3 page 28 The only reasons for cavitation on the lower channel entrances first are:

- 1) angularity of the approach velocity or
- 2) higher approach velocity in the lower section.

Both are contrary to assumptions justifying the theory presented herein.

14) Appendix III par. 3 pages 28 and 29 Equation III-2. The velocity of approach does not appear to be included in H_c^* ? This correction will be greater for cooler flows. If the curvature and not the entrance causes the flow limiting cavitation, then equation III-2 must include an elevation correction---that is the vertical distance from the entrance to the point of cavitation.

15) Appendix III page 29 Last sentence. Agreement of total is good but individual channels could have much larger error and still compensate each other in the total.

16) Appendix III Figures III-2 and III-3. It appears from the scatter of the data and the curves which have been drawn that one could fit a single straight line to the data for each temperature. Furthermore, these lines could all be parallel. As these curves were drawn, one must ask---Are the data for 95°C and 20°C in Figure III-2 discontinuous? If not, how can the curves as drawn be justified---a straight line thru a single point?

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Part II

Model Data from the K-Downcomer Tests.

Prepared by Claud Lomax

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SUMMARY OF TEST CONDITIONS

Test Number	Prototype Q 1,000 gpm	Temperature		T-Tsat*		Air Injected	Conditions		
		Prototype °C	Model °C	Prototype °C	Model °C		Original Orifice	Ch.5,6,& 7 Opened	Second Vane
I-63	125	Cold	Cold	--	--	no	yes	--	--
I-95	190	Cold	Cold	--	--	no	yes	--	--
I-106	212	Cold	Cold	--	--	no	yes	--	--
I-110	220	Cold	Cold	--	--	no	yes	--	--
I-120	240	Cold	Cold	--	--	no	yes	--	--
II-63	125	Cold	Cold	--	--	no	--	yes	--
II-95	190	Cold	Cold	--	--	no	--	yes	--
II-106	212	Cold	Cold	--	--	no	--	yes	--
II-110	220	Cold	Cold	--	--	no	--	yes	--
II-120	240	Cold	Cold	--	--	no	--	yes	--
D-4	200	20	94.9	-78.9	-2.8	no	--	yes	yes
E-1	210	80	95.1	-18.9	-2.6	yes	--	yes	yes
E-2	212	90	96.4	-8.9	-1.7	yes	--	yes	yes
E-2-X	212	90	88.8	-8.9	-8.9	yes	--	yes	yes
E-7	214	95	97.0	-3.9	-0.7	yes	--	yes	yes
E-7-Y	214	95	97.0	-3.9	-0.7	yes	--	yes	no
E-7-X	214	95	94.0	-3.9	-3.9	yes	--	yes	yes
F-7	230	95	96.9	-3.9	-0.7	yes	--	yes	yes
H-7	240	95	96.9	-3.9	-0.7	yes	--	yes	yes
H-7-Y	240	95	96.9	-3.9	-0.7	yes	--	yes	no
I-7	250	95	96.9	-3.9	-0.7	yes	--	yes	yes
I-7-X	250	95	96.9	-3.9	-0.7	no	--	yes	yes
E-8	214	102	98.1	+3.1	+0.6	yes	--	yes	yes
G-7	220	102	98.1	+3.1	+0.6	yes	--	yes	yes
G-7-Y	220	102	98.1	+3.1	+0.6	yes	--	yes	no
G-7-X	220	102	98.1	+3.1	+0.6	no	--	yes	yes
G-8	220	Transient		Transient		yes	--	yes	yes

*Actual model values may vary slightly from these.

Tsats Prototype assumed to be 98.9°C.

Date	15 Sept 65	14 Sept 65	14 Sept 65	14 Sept 65	14 Sept 65
Test Series	I-63	I-95	I-106	I-110	I-120
Temperature Side					
Bottom					
Barometer in. Hg					
Cells 0-a					+0.2'
0-b					+0.48'
0-c (P-2)					+1.34'
1-a					+0.41'
3-a					-0.68'
3-b					-0.78'
3-c					+0.05'
EBP	11.5"	25.0"	32.0"	35.4"	42.5"
Piezometers 1-d	86.1"	95.8"	94.8"	101.3"	103.4"
2-d					
3-d	52.5"	69.2"	74.0"	75.8"	78.3"
4-d					
5-d	12.5"	62.5"	69.0"	69.5"	78.8"
6-d					
7-d	8.2"	48.5"	71.5"	74.2"	73.5"
8-d					
9-d	8.0"	23.5"	37.2"	44.0"	69.0"
10-d	8.2"	22.4"	30.0"	34.2"	58.0"
1-e	-47.0"	-27.5"	-17.0"	-12.5"	0
2-e					
3-e	-48.7"	-28.5"	-19.0"	-14.5"	-3.0"
4-e					
5-e	8.2"	-26.5"	-16.0"	-11.5"	-1.0"
6-e					
7-e	8.5"	13.0"	1.5"	8.0"	24.0"
8-e					
9-e	8.5"	23.2"	29.2"	33.0"	20.8"
10-e	8.5"	23.0"	30.0"	33.5"	37.0"
4" F-P Meter @ A+10	33.5%	47.5%	52.5%	54.0%	58.5%
6" F-P Meter @ A+10	18.0%	24.5%	27.0%	28.0%	30.0%
Air Manometer 4	0	0	0	0	0
Air Manometer 6	0	0	0	0	0

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Date	22 Sept 65	22 Sept 65	22 Sept 65	22 Sept 65	22 Sept 65
Test Series	II-63	II-95	II-106	II-110	II-120
Temperature Side	27.5°	27.0°	26.2°	25.4°	24.8°
Bottom	26.6°	27.0°	26.5°	25.5°	24.9°
Barometer in. Hg					
Cells 0-a	-1.00'	-0.8'	-0.6'	-0.56'	-0.28'
0-b	-0.04'	-0.02'	+0.04'	+0.12'	+0.40'
0-c (P-2)	+0.86'	+1.0'	+1.14'	+1.18'	+1.30'
1-a	-2.73'	-1.76'	-1.60'	-1.52'	-1.02'
3-a	-1.80'	-1.16'	-0.88'	-0.80'	-0.48'
3-b	-2.43'	-1.52'	-1.10'	-1.04'	-0.30'
3-c	-1.62'	-0.72'	-0.38'	-0.28'	+0.13'
EBP	11.4"	25.0"	32.0"	35.0"	42.3"
Piezometers 1-d	49.0"	61.0"	65.5"	66.0"	74.0"
2-d					
3-d	51.5"	64.2"	70.0"	71.5"	78.0"
4-d					
5-d	7.5"	46.5"	53.0"	54.0"	64.0"
6-d					
7-d	8.0"	36.8"	54.0"	62.0"	73.0"
8-d					
9-d	8.5"	22.5"	31.0"	36.0"	70.8"
10-d	9.0"	22.8"	29.8"	32.2"	45.5"
1-e	-15.2"	3.5"	9.0"	12.3"	22.0"
2-e					
3-e	-38.5"	-21.0"	-15.5"	-12.0"	0
4-e					
5-e	8.0"	-5.5"	3.0"	7.5"	18.8"
6-e					
7-e	8.0"	24.2"	3.5"	9.0"	19.8"
8-e					
9-e	8.4"	22.0"	30.0"	32.0"	23.5"
10-e	8.7"	23.0"	29.8"	32.5"	42.8"
4" F-P Meter @ A+10	33.5%	47.5%	52.5%	54.0%	58.5%
6" F-P Meter @ A+10	18.0%	24.5%	27.0%	28.0%	30.0%
Air Manometer 4	0	0	0	0	0
Air Manometer 6	0	0	0	0	0

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Date	12 Oct 65	12 Oct 65	12 Oct 65	12 Oct 65	12 Oct 65
Test Series	D-4	E-1	E-2	E-2-X	E-7
Temperature Side	94.8°	95.2°	96.5°	89.5°	97.0°
Bottom	94.9°	95.3°	96.5°	89.5°	97.0°
Barometer in. Hg	27.68	27.68	27.68	27.68	27.68
Cells 0-a	+0.2'	+0.2'	+1.6'	+0.2'	+1.8'
0-b	+0.4'	+0.6'	+2.2'	+2.2'	+2.1'
0-c (P-2)	+1.1'	+0.8'	+3.8'	+1.4'	+2.4'
1-a	-0.6'	-0.2'	+1.2'	-0.3'	+1.6'
3-a	-1.3'	-0.1'	+1.5'	-0.6'	+1.2'
3-b	-1.4'	-0.4'	+0.7'	-1.2'	+1.0'
3-c	-0.3'	-0.1'	+0.8'	-1.8'	+1.1'
EBP	28.0"	31.5"	32.5"	32.0"	32.5"
Piezometers 1-d	72.5"	76.8"	92.0"	75.0"	93.6"
2-d					
3-d	72.3"	73.5"	81.0"	69.5"	85.5"
4-d					
5-d	53.0"	57.5"	61.5"	53.0"	64.0"
6-d					
7-d	53.5"	60.5"	63.0"	61.5"	62.5"
8-d					
9-d	31.8"	63.0"	70.0"	58.0"	76.0"
10-d	27.0"	54.0"	75.0"	35.5"	82.5"
1-e	11.8"	6.0"	23.5"	18.0"	22.0"
2-e					
3-e	-42.0"	18.0"	18.5"	-25.0"	18.5"
4-e					
5-e	7.0"	7.8"	18.0"	8.0"	16.5"
6-e					
7-e	-7.0"	5.5"	26.5"	11.5"	24.0"
8-e					
9-e	29.0"	3.5"	11.5"	25.5"	10.5"
10-e	27.8"	24.5"	-12.0"	32.5"	-11.0"
4" F-P Meter @ A+10	50%	52%	53%	53%	53%
6" F-P Meter @ A+10	26%	27%	27%	27%	27%
Air Manometer 4	0	0.16'	0.20'	0.16'	0.22'
Air Manometer 6	0	1.9"	2.4"	1.9"	2.45"

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Date	27 Oct 65	12 Oct 65	13 Oct 65	13 Oct 65	27 Oct 65
Test Series	E-7-Y	E-7-X	F-7	H-7	H-7-Y
Temperature Side	97.1°	94.7°	97.0°	97.0°	96.8°
Bottom	97.0°	94.1°	97.0°	97.0°	96.6°
Barometer in. Hg	27.70	27.68	27.48	27.48	27.70
Cells 0-a	+1.0'	+0.1'	+2.1'	+2.9'	+1.9'
0-b	+1.6'	+0.6'	+2.7'	+3.1'	+2.4'
0-c (2-2)	+3.2'	-1.2'	+4.7'	+5.3'	+3.8'
1-a	+0.7'	-0.2'	+2.7'	+3.2'	+1.5'
3-a	+0.8'	0	+1.3'	+1.7'	+2.0'
3-b	+1.0'	-0.4'	+1.9'	+2.1'	+2.0'
3-c	+1.2'	-0.2'	+1.6'	+1.9'	+2.4'
EBP	32.5"	33.0"	38.0"	42.5"	44.0"
Piezometers 1-d	73.5"	76.0"	102.0"	102.8"	85.0"
2-d	86.0"				97.0"
3-d	86.5"	72.5"	91.0"	94.0"	98.5"
4-d	88.5"				100.0"
5-d	66.0"	55.0"	69.5"	71.5"	68.0"
6-d	61.0"				76.0"
7-d	59.5"	59.0"	75.0"	76.5"	77.5"
8-d	71.0"				86.0"
9-d	69.0"	69.0"	82.0"	86.5"	84.5"
10-d	70.5"	55.0"	84.0"	85.5"	86.0"
1-e	7.8"	8.5"	26.0"	32.0"	15.0"
2-e	14.5"				21.0"
3-e	18.0"	12.5"	24.5"	27.0"	28.0"
4-e	13.0"				20.0"
5-e	12.5"	0	18.0"	23.0"	13.0"
6-e	18.5"				17.0"
7-e	19.5"	-7.0"	27.0"	28.5"	18.5"
8-e	7.5"				-1.0"
9-e	4.0"	3.5"	2.5"	2.0"	1.5"
10-e	1.5"	23.0"	-7.0"	-7.0"	-1.0"
4" F-P Meter @ A+10	53%	53%	56.5%	58.5%	58.5%
6" F-P Meter @ A+10	27%	27%	29.0%	30.0%	31.0%
Air Manometer 4	0.22'	0.15'	0.25'	0.28'	0.28'
Air Manometer 6	2.45'	1.8"	3.0"	3.4"	3.4"

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Date	13 Oct 65	13 Oct 65	13 Oct 65	13 Oct 65	27 Oct 65
Test Series	I-7	I-7-X	E-8	G-7	C-7-Y
Temperature Side	96.7°	97.4°	97.7°	98.1°	98.1°
Bottom	98.0°	97.0°	98.1°	98.1°	98.1°
Barometer in. Hg	27.48	27.48	27.48	27.48	27.70
Cells 0-a	+3.0'	+0.7'	+2.6'	+2.9'	+2.0'
0-b	+3.4'	+0.9'	+3.0'	+3.4'	+2.6'
0-c (P-2)	+5.3'	+2.6'	+4.5'	+4.6'	+4.1'
1-a	+3.8'	+1.7'	+2.1'	+3.2'	+1.8'
3-a	+2.2'	-0.6'	+2.9'	+2.2'	+2.1'
3-b	+2.8'	-0.9'	+2.3'	+2.6'	+2.2'
3-c	+2.5'	-0.4'	+2.3'	+2.5'	+2.4'
EBP	47.0"	48.0"	32.5"	35.0"	35.2"
Piezometers 1-d	108.5"	90.0"	103.0"	104.0"	87.0"
2-d					99.5"
3-d	101.0"	86.5"	97.0"	97.0"	99.0"
4-d					103.0"
5-d	77.0"	68.5"	74.0"	76.0"	72.0"
6-d					72.5"
7-d	83.0"	79.0"	65.0"	72.0"	68.0"
8-d					86.0"
9-d	92.5"	30.0"	86.0"	92.5"	76.0"
10-d	92.0"	79.5"	102.0"	102.0"	88.0"
1-e	35.0"	41.0"	32.5"	33.0"	21.5"
2-e					27.0"
3-e	29.5"	-10.5"	29.2"	27.0"	29.5"
4-e					28.0"
5-e	23.0"	31.0"	30.5"	27.5"	27.2"
6-e					30.5"
7-e	26.0"	35.5"	33.0"	32.5"	31.0"
8-e					28.0"
9-e	2.0"	36.0"	32.0"	29.0"	24.0"
10-e	-7.5"	39.5"	30.5"	28.5"	9.6"
4" F-P Meter @ A+10	60.5%	60.5%	53%	54%	54%
6" F-P Meter @ A+10	31.0%	31.0%	27%	28%	28%
Air Manometer 4	0.30'	0	0.25'	0.26'	0.26'
Air Manometer 6	3.6"	0	3.0"	3.1"	3.1"

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Date	13 Oct 65			
Test Series	G-7-X			
Temperature Side	93.0°			
Bottom	93.2°			
Barometer in. Hg	27.48			
Cells C-a	+0.7'			
0-b	+1.0'			
0-c (P-2)	+1.9'			
1-a	+0.1'			
3-a	0			
3-b	-0.2'			
3-c	0			
EBP	35.0"			
Piezometers 1-d	85.0"			
2-d				
3-d	77.0"			
4-d				
5-d	51.5"			
6-d				
7-d	51.0"			
8-d				
9-d	53.5"			
10-d	56.0"			
1-e	2.5"			
2-e				
3-e	2.5"			
4-e				
5-e	1.0"			
6-e				
7-e	2.0"			
8-e				
9-e	12.5"			
10-e	12.0"			
4" F-P Meter @ A+10	54%			
6" F-P Meter @ A+10	28%			
Air Manometer 4	0			
Air Manometer 6	0			

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CAVITATION AND BUBBLE FORMATION IN
NEARLY SATURATED WATER FLOW

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A Study made for the R. L. Albrock Hydraulics Laboratory

October 18 to October 29, 1965

CAVITATION AND BUBBLE FORMATION IN NEARLY SATURATED WATER FLOW

OBJECT

The purpose of this study was to determine, if possible, the relationship between the scale of an object and the size of the bubble which forms behind it in the flow of water which is very close to its saturation temperature.

APPARATUS

The experimental work was conducted in Albrook Laboratory where there is a hot water loop available for supplying water to a 4-inch diameter test section at velocities up to about 25 ft/sec and a large range of temperatures. A branch in this hot water loop was run to a 20-inch diameter standpipe. The test section shown in Figure 1 was attached to the standpipe. It consisted of a 4-inch I.D. plexiglass tube. The entrance to the test section is located inside the standpipe and consists of a rounded plexiglass ring attached to a 4-inch I.D. steel pipe. The model is held in place by a stinger on its downstream side and is located approximately 8 inches downstream from the entrance inside the standpipe. The spider used to support the stinger is located 6 inches downstream of the model.

A mercury thermometer is located in the standpipe to measure water temperature. A mercury manometer connected to the standpipe at the same elevation as the centerline of the test section is used to measure total pressure. A 0-15 psi bourdon tube gage is located in the 4-inch I.D. exit pipe, downstream of the test section. Flow is measured by use of a magnetic flow meter in the main loop.

Pressure in the test section is varied by use of a valve in the exit section of the test branch. The test section and standpipe are shown in Figure 2.

RESULTS

Four runs were made with the apparatus described in the previous section. These runs were for a 1/4-inch diameter disc, a 1-inch diameter disc and two runs for a 1/2-inch diameter disc. In all cases the discs were oriented with their surface perpendicular to the axis of the test section. Pertinent data from these runs are included in Table I. In this table, T is the water temperature as read from the thermometer in the standpipe; p_{amb} is the pressure in the test section as read from the bourdon gage, corrected to the axis of the test section and corrected for the barometric pressure; V is the velocity of the flow as read from the magnetic flow meter in the main loop; and ΔT is defined as

$$\Delta T = T - T_{sat}$$

where T_{sat} is the saturation temperature corresponding to the pressure in the test section, p_{amb} . The terms in the remarks column are defined as follows:

Incipient cavitation is the condition when sporadic cavitation bubbles can be seen in the wake downstream of the disc.

Cavitation is the condition when cavitation bubbles form in the wake downstream of the disc on a continuous basis.

Intermediate cavitation is the condition when a large mass of bubbles forms continuously downstream of the disc, but there is

a space between the disc and the mass of bubbles.

Super cavitation is the condition when a large mass of bubbles form continuously downstream of the disc and the mass of bubbles is partially attached to the disc and has the general shape of a single attached bubble.

Detached bubble is the condition when one large bubble is formed downstream of the disc, but there is a space between the disc and the bubble. Also included in this is a bubble only partly attached to the disc.

Attached bubble is the condition when one large bubble forms behind the disc and is attached completely to it.

Examples of all but incipient cavitation are shown in Figures 5 through 10.

The dimensions listed with attached bubble in the remarks column are $l_{\max}$ and b . The length $l_{\max}$ is the average of the maximum lengths of the bubble, determined over several minutes of observation at the given conditions. The actual length varied from instant to instant. The breadth b is the diameter of the bubble--again an average determined over several minutes of observation.

The following paragraphs contain general observations and comments about each specific run.

10-22-65. 1/4-inch disc. Because of its small diameter this disc was suspended at the axis of the test section by wires of 0.007-inch diameter. During the run, at constant temperature, the pressure was varied and the dimensions of the attached bubbles were measured by eyeball and ruler. One detached bubble point was determined.

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It was of interest to note that a series of bubbles formed on each wire and, although the wire had a very small diameter, the bubbles were nearly as long as the one behind the 1/4-inch disc. Their diameter, of course, was much smaller.

10-27-65, 1/2-inch disc. During this run pressure and temperature were both varied and data recorded in the attached bubble region. One detached bubble point was determined. Figures 5 and 6 are typical photographs of the bubble attached to the 1/2-inch disc during this run.

10-28-65, 1-inch disc. Prior to this run, the entrance ring apparently fell off into the standpipe and as a result a sharp edged entrance was left instead of the smooth entrance. This sharp edge caused cavitation to take place at the entrance under certain pressure conditions. As a result it was not possible to get attached bubbles because so much cavitation was taking place at the entrance. However, data were recorded for various pressures and temperatures at various degrees of cavitation.

10-29-65, 1/2-inch disc. For the same reason as the previous run, the attached bubble condition could not be achieved. The conditions for various degrees of cavitation were recorded. Figures 7 through 10 are typical photographs of these conditions. The presence of the extra bubbles in these photographs is due to the cavitation at the entrance.

The usual method of presenting cavitation data is by use of the cavitation number, σ ,

$$\sigma = \frac{P_{amb} - P_v}{(1/2)(\rho V^2)}$$

where: p_{amb} is the fluid pressure in the region where cavitation is occurring

p_v is the vapor pressure corresponding to the fluid temperature

ρ is the fluid density

V is the fluid velocity in the cavitation region.

The cavitation number can be thought of as a dimensionless measure of the liquid subcooling. Negative cavitation numbers accordingly designate superheated liquids.

The observed bubble sizes from the first two runs were plotted against cavitation numbers in the form of a dimensionless length, l_{max} , divided by disc diameter. This is shown as Figure 3.

The data on degree of cavitation from the last two runs are shown in Figure 4 where cavitation number is plotted against disc diameter.

DISCUSSION

Because of the urgency of this study and its limitations in both time and money, the number of data collected was limited. They were sufficient, however, to provide the basis for certain qualitative conclusions. We shall discuss these with the use of Figures 3 and 4.

Figure 3--a plot of dimensionless bubble length vs. cavitation number--shows a definite scale effect. The data for the 1/2-inch disc are located roughly along a line, but separated from a line representing the 1/4-inch disc. This means that the bubbles are proportionately longer for the smaller disc. This conclusion

was also verified by the very long slender bubbles which formed on the support wires for the 1/4-inch disc. It is also to be noted in Figure 3 that a small change in superheat has a large effect on bubble size and since the two lines are nearly parallel, this superheat effect is independent of scale.

Figure 4 shows the range of cavitation number between incipience of cavitation and attachment of the bubble. In general the larger cavitation numbers represent incipience, with increasing cavitation as the cavitation number decreases. Here again a scale effect is noted. The range for the 1-inch disc is at larger cavitation numbers than the range of values for the 1/2-inch disc.

CONCLUSIONS

1. There is a scale effect on bubble size as seen in Figure 3.
2. There is a very strong dependence of bubble size on superheat as indicated by the extremely high slope of the lines in Figure 3.
3. The dependence of bubble size on superheat is independent of scale as seen by the lines of Figure 3 being nearly parallel.
4. There is a scale effect on incipience and amount of cavitation as seen in Figure 4.
5. The results indicate that further investigation of a long term duration is necessary to learn more about the problem and to provide quantitative results. This further investigation would provide general information for answering further questions of this nature. A one-year program of this kind, involving one graduate student would cost between \$12,000 and \$15,000.

Fig. 1. Physical arrangement of base section and standard

Fig. 2. Base section arrangement

FIG. 3 EFFECT OF SUPERHEAT ON BUBBLE SIZE

Fig. 5. Photograph of bubble attached to 1/2-inch disc
Data no. 5 of Oct. 27, 1965

Fig. 6. Photograph of bubble attached to 1/2-inch disc
Data no. 6 of Oct. 27, 1965

Fig. 7. Photograph of cavitation behind 1/2-inch disc
Data no. 2 of Oct. 29, 1965

Fig. 8. Photograph of intermediate cavitation behind 1/2-inch disc. Data no. 3 of Oct. 29, 1965

Fig. 9. Photograph of cavitation behind 1/2-inch disc.
Data no. 11 of Oct. 29, 1965

Fig. 10. Photograph of super cavitation behind 1/2-inch
disc. Data no. 12 of Oct. 29, 1965

TABLE I
TABULATED RESULTS

A. Date: Oct. 22, 1965 Disc: 1/4 in. (data for attached bubble except as noted)

No.	T(°F)	p _{amb} (psia)	V(ft/sec)	T(°F)	Remarks
1	216.6	16.32	6	-0.4	l _{max} =2.75" b=0.7"
2	216.6	16.42	6	-0.6	l _{max} =2" b=0.5"
3	216.6	16.42	6	-0.6	l _{max} =2" b=0.5"
4	216.6	16.32	6	-0.4	l _{max} =3.5" b=0.8"
5	216.6	16.22	6	+0.1	l _{max} =3.5" b=1.0"
6	216.6	16.12	6	+0.3	l _{max} =4.5" b=1.0"
7	216.6	16.22	6	+0.1	l _{max} =2" b=0.5"
8	216.6	16.47	6	-0.8	detached bubble

B. Date: Oct. 27, 1965 Disc: 1/2 in. (data for attached bubble except as noted)

1	215.6	16.17	5.7	+0.1	l _{max} =2" b=1"
2	215.6	16.42	5.7	-0.7	detached bubble
3	217	16.17	5.7	+1.5	photograph
4	217	16.17	5.7	+1.5	photograph
5	217	16.17	5.7	+1.5	photograph Fig. 5
6	217	16.17	5.7	+1.5	photograph Fig. 6
7	217	16.17	5.7	+1.5	l _{max} =1.75" b=1"
8	217	16.17	5.7	+1.5	l _{max} =2.5" b=1"
9	217	16.10	5.7	+1.5	l _{max} =3.75" b=1.25"
10	219.2	17.10	5.7	-0.7	l _{max} =4" b=1.25"
11	220.2	17.05	5.7	+1.9	l _{max} =4.5" b=1.5"
12	220.2	17.29	5.7	+1.2	l _{max} =2.5" b=1.25"
13	221	17.79	5.7	+0.5	l _{max} =2.5" b=1.25"

B Cont.

No.	T(°F)	p _{amb} (psia)	V(ft./sec)	T(°F)	Remarks
14	222.2	17.85	5.7	+1.5	l _{max} =4" b=1.5"
15	222.2	17.87	5.7	+1.4	l _{max} =5" b=1.5"
16	222.2	17.77	5.7	+1.7	l _{max} 5.5" b=1.5"

C. Date: Oct. 28, 1965

Disc: 1 in.

1	218.6	17.15	5.2	+0.2	detached bubble
2	221.9	18.23	5.2	+0.9	detached bubble
3	221.3	18.01	5.2	-0.3	detached bubble
4	220.5	17.75	5.2	-1.1	cavitation
5	217.3	16.70	5.2	-4.8	super cavitation
6	216.6	16.52	5.2	-0.1	attached bubble
7	219	17.26	5.2	-2.0	cavitation
8	217.3	16.70	5.6	-1.6	cavitation
9	216.9	16.60	5.6	-1.3	detached bubble
10	216.5	16.50	5.6	-0.3	detached bubble
11	213.7	15.60	6.2	-1.7	intermediate cavitation
12	213.2	15.45	6.2	-1.2	detached bubble
13	212.4	15.20	6.2	-0.4	detached bubble
14	211	14.80	6.6	-1.7	detached bubble
15	212.6	15.30	6.6	-2.9	cavitation
16	208.4	14.45	6.6	-1.4	detached bubble
17	206.6	14.70	6.8	-4.0	cavitation
18	206.6	14.10	6.8	-1.9	detached bubble
19	206.2	13.82	6.8	-1.3	would not cavitate

D. Date: Oct. 29, 1965 Disc: 1/2 in.

No.	T(°F)	p _{amb} (psia)	V(ft/sec)	T(°F)	Remarks
1	212	15.41	6.0	-1.0	incipient cavitation (Fig. 7)
2	212.7	15.34	6.0	0	cavitation (Fig. 8)
3	212.7	15.41	6.0	-0.3	intermediate cavitation
4	215.6	15.36	6.0	+2.8	incipient cavitation
5	215.6	16.16	6.0	+0.1	cavitation
6	218.8	16.66	6.0	+1.7	incipient cavitation
7	218.8	16.61	6.0	+1.8	cavitation
8	218.3	17.04	5.6	0	incipient cavitation
9	218.3	16.71	5.6	+1.0	intermediate cavitation
10	222.2	18.36	5.6	0	incipient cavitation
11	221	18.06	5.6	-0.3	cavitation (Fig. 10)
12	221	17.76	5.6	+0.5	super cavitation

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