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WATER FLOW AND CAVITATION IN CONVERGING-DIVERGING BOILER-INLET NOZZLE

by James R. Stone and Nick J. Sekas

Lewis Research Center
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ABSTRACT

Experimental flow-pressure relations were determined for water flowing through a 0.025-inch (0.64-mm) throat-diameter converging-diverging conical nozzle. The nozzle was tested with and without a plug-and-wire-helix insert downstream of the throat. Such nozzles are being studied for possible use as inlets for single-tube once-through Rankine-cycle boilers. The test nozzle is made of transparent plastic. Cavitating and noncavitating data are reported for throat velocities from 49 to 94 ft/sec (15 to 29 m/sec) and temperatures from 57° to 171° F (287 to 351 K). In well-developed cavitation, the flow is insensitive to nozzle exit pressure, thus minimizing the possibility of feed-system - boiler coupling instability. The plug-and-wire-helix insert reduces the tendency for slugging.

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SUMMARY

Experimental flow-pressure relations were determined for water flowing through a 0.025-inch (0.064-cm) throat-diameter converging-diverging conical nozzle. The nozzle was tested with and without a plug-and-wire-helix insert downstream of the throat. Such nozzles are being studied for possible use as inlets for single-tube once-through boilers for Rankine-cycle space power systems. The test nozzle is machined from transparent acrylic plastic and is sized for use with a 60.5-inch (154-cm) long, 0.44-inch (1.12-cm) inside-diameter boiler tube.

Cavitating and noncavitating data are presented over a range of throat velocity from 49 to 94 feet per second (15 to 29 m/sec) and fluid temperatures from 57° to 171° F (287 to 351 K). The corresponding range of mass flow rate is from 27 to 72 pounds per hour (0.0034 to 0.0090 kg/sec). With well-developed cavitation, the throat velocity is insensitive to variations in nozzle exit pressure. Using such a nozzle at a boiler inlet would greatly reduce the possibility of flow instabilities due to coupling of the subcooled boiling region with the feed system. Also, subcooled boiling may be eliminated by flashing the feed liquid to a saturated two-phase mixture in the nozzle. When flashing to about 0.01 vapor quality in the nozzle, with the plug-and-wire-helix insert installed, no liquid slugs are observed for about 20 tube diameters downstream (vertically) of the end of the insert.

INTRODUCTION

One of the problem areas of alkali-metal Rankine cycle space power systems is the design of high-performance, dependable, compact boilers. The boilers must operate stably with a minimum of entrained liquid in the exit vapor stream. One approach to the stability problem has been to add a large pressure drop at the boiler inlet. This pressure drop has generally been obtained from orifices and area-reducing plugs. In addition to increasing the pressure drop, the plugs may reduce the tendency for slug flow. Flow swirlers, such as wire helices, are often used to promote separation of liquid from vapor.

There are numerous reports on subcooled-boiling instabilities, for example, that of Jeglic and Grace (ref. 1). Lowdermilk, et al., (ref. 2) observed that increasing the pressure drop at the inlet to an electrically-heated boiler yielded higher burnout heat fluxes. A study of boiler dynamics by Grace and Krejsa (ref. 3) showed that the boiler and its feed system may interact so as to cause flow and pressure oscillations.

In reference 4, the type of inlet restriction as well as the magnitude of the pressure drop had an effect on boiler performance. The boiler was found to operate more stably when entrance-region plugs were used. Orifices generally minimized slug-flow instabilities; however, the boiling-fluid exit temperature rose well above saturation temperature, while the exit quality was less than one. A converging-diverging nozzle inlet performed well over a limited flow range, but was not properly sized for the full flow range of interest. Although the role of the inlet in stabilizing the system was and fully understood, it appeared that cavitation was involved. The boiler of reference 4 operated more stably when the nozzle was cavitating. Although venturi cavitation has been the subject of several investigations (e.g., refs. 5 and 6), boiler-inlet nozzles of interest for water simulation of Rankine-cycle power systems are much smaller than the referenced venturis.

The objective of this investigation was, therefore, to study the performance of a converging-diverging boiler-inlet nozzle with a 0.025-inch (0.64-mm) diameter throat (sized for a boiler similar to that of ref. 4). The inception of visible cavitation and the flow-pressure relations for cavitating and noncavitating flow were determined. Some observations are made concerning the flow pattern downstream of the nozzle.

The test nozzle was machined from transparent acrylic plastic. The nozzle was tested both with and without a plug-and-wire-helix insert downstream of the throat. Experimental results are presented over a range of throat velocity from 49 to 94 feet per second (15 to 29 m/sec) and fluid temperatures from 57° to 171° F (287 to 351 K). The corresponding mass flow rate range was from 27 to 72 pounds per hour (0.0034 to 0.0090 kg/sec). Test operation included flashing to about 0.02 vapor quality at the nozzle exit.

SYMBOLS

C fully developed cavitating-flow coefficient, v/v_I, dimensionless

C_1	conversion factor, 144 in.^{2}/ft^2; 1.00 m^2/m^2
C_2	conversion factor, 12 in./ft; 1.00 m/m
D	throat diameter, in.; m
g_c	conversion factor, 32.2 $(lb_{mass})(ft)/(lb_{force})(sec^2)$; 1.00 $(m)(kg)/(N)(sec^2)$
K_f	frictional pressure-loss coefficient (eq. (1)), dimensionless
P_e	test nozzle exit pressure, psia; N/m^2
P_i	test nozzle inlet pressure, psia; N/m^2
P_s	test nozzle inlet saturation pressure, psia; N/m^2
Re	throat liquid Reynolds number (eq. (2)), dimensionless
T_i	test nozzle inlet temperature, $^{\circ}$F; K
v	throat velocity, ft/sec; m/sec
v_I	throat velocity for ideal cavitation process (eq. (3)), ft/sec; m/sec
x	vapor quality at nozzle exit, dimensionless
μ	liquid viscosity, $lb_{mass}/(ft)(sec)$; kg/(m)(sec)
ρ	liquid density, lb_{mass}/ft^3; kg/m^3

APPARATUS

A schematic diagram of the test flow system, including its instrumentation, is shown in figure 1. The flow is supplied to this system from a 50-gallon (~0.18-m^3) capacity deaerating and storage tank. During the operation of the system, this tank is pressurized with nitrogen. The flow passes through a filter to a heat exchanger, wherein the test fluid is either heated or cooled to provide the desired inlet temperature to the test nozzle. The flow then passes through the turbine flowmeter, the inlet flow-control valve, and the inlet plenum into the vertically-mounted test nozzle. The test nozzle discharges into a 0.44-inch (1.12-cm) inside-diameter, 1.00-inch (2.54-cm) outside-diameter transparent acrylic plastic tube. The tube is the same length (60.5 in. (154 cm)) as the test boiler of reference 4. The upper end of this tube is connected to the exit plenum chamber. The test fluid is discharged through the exit flow-control valve into a large vacuum exhaust system.

A drawing of the test nozzle is shown in figure 2. This nozzle consists of conical contraction and diffuser sections connected by a 0.025-inch (0.64-mm) diameter, 0.020-inch (0.51-mm) long throat section. The nozzle is tested both with and without a plug-and-wire-helix insert downstream of the throat. A sketch of the test nozzle and straight

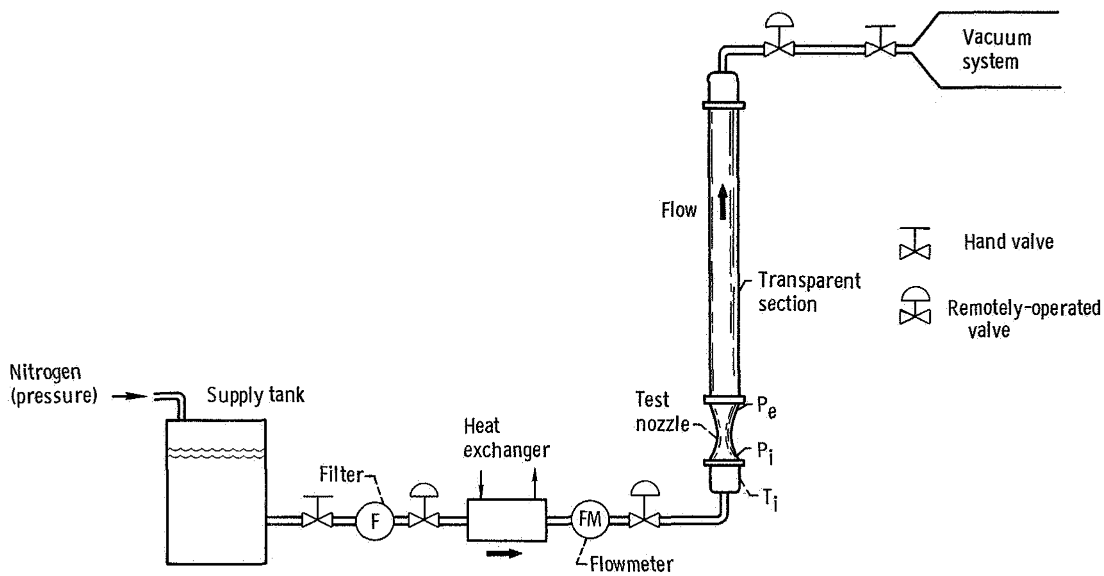


Figure 1. - Schematic diagram of test-flow system with instrumentation.

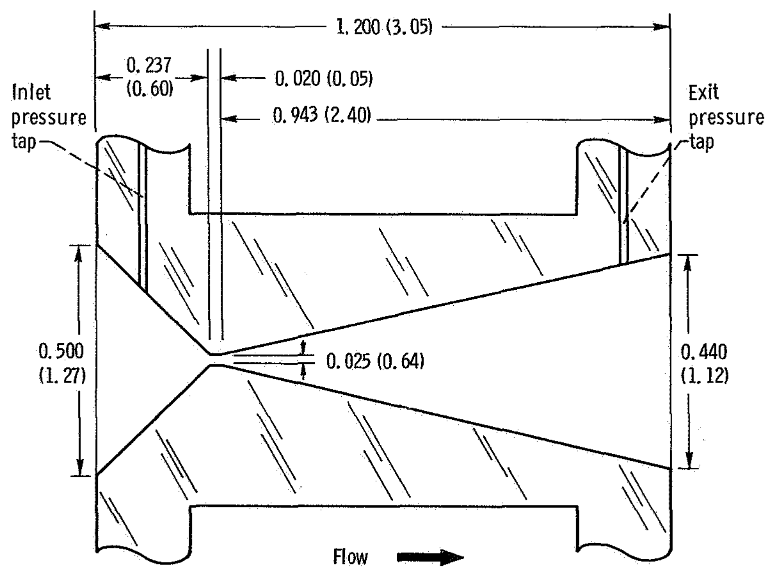


Figure 2. - Test nozzle (All dimensions are in inches (cm)).

section with this insert installed is shown in figure 3. A 0.063-inch (0.159-cm) copper wire is brazed to the brass plug, yielding a helix with a 0.83-inch (2.11-cm) pitch.

The inlet and exit pressures to the test nozzle are measured by Bourdon gages. The inlet temperature is measured by means of two copper-constantan thermocouples in the inlet plenum. The throat velocity is calculated from the measured flow rate through the turbine flowmeter by using the continuity equation.

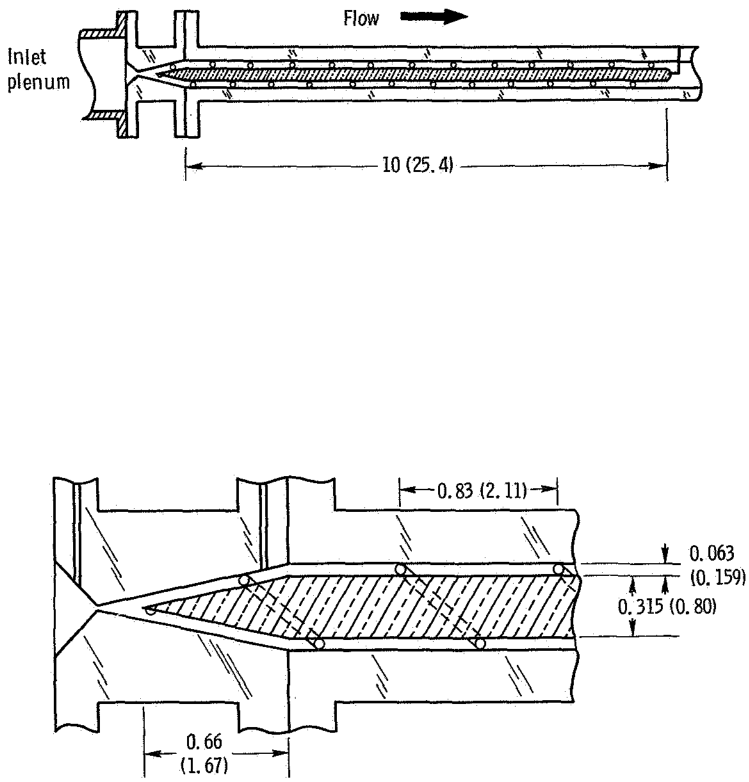


Figure 3. - Test nozzle and straight section with plug-and-wire-helix insert (All dimensions are in inches (cm)).

PROCEDURE

Three modes of operation were used: (1) constant inlet temperature and pressure and variable exit pressure, (2) constant inlet temperature and exit pressure with variable inlet pressure, and (3) constant inlet and exit pressures with variable inlet temperature.

For each of these modes of operation, the dissolved-gas content of the water was maintained at about 7 parts per million by weight. A limited amount of data was also obtained with air-saturated water.

RESULTS AND DISCUSSION

The experimental data are tabulated in tables I and II for the test nozzle with and without the plug-and-wire-helix insert, respectively. Throat velocity, inlet temperature, inlet pressure, and exit pressure (not including any part of the straight section) are tabulated. The flow regime is indicated for each run; the term flashing indicates that the exit pressure is less than the saturation pressure for the inlet temperature. The quality for flashing runs is calculated assuming an adiabatic process. The data for the constant inlet temperature and pressure mode are ordered in the tables first according to temperature and then according to inlet pressure.

Noncavitating Data

The noncavitating data for both configurations are normalized in terms of a frictional pressure-loss coefficient, defined as follows:

$$K_f = \frac{P_i - P_e}{\left(\dfrac{\rho v^2}{C_1 2g_c}\right)} \tag{1}$$

This pressure-loss coefficient is correlated as a function of throat liquid Reynolds number Re where

$$Re = \frac{1}{C_2} \frac{Dv\rho}{\mu} \tag{2}$$

Figure 4 shows K_f against Re for both configurations. The performance of the test nozzle shows the same general trends both with and without the insert: K_f decreases with increasing Re until a critical Re is reached, above this critical Reynolds number, K_f remains essentially constant. At low Re, the performances of the two configurations are about the same. However, at a higher Reynolds number, K_f is considerably less for the test nozzle with the insert. The effective diffuser angle is less with this insert than without it; thus, the diffusion and pressure recovery are more efficient.

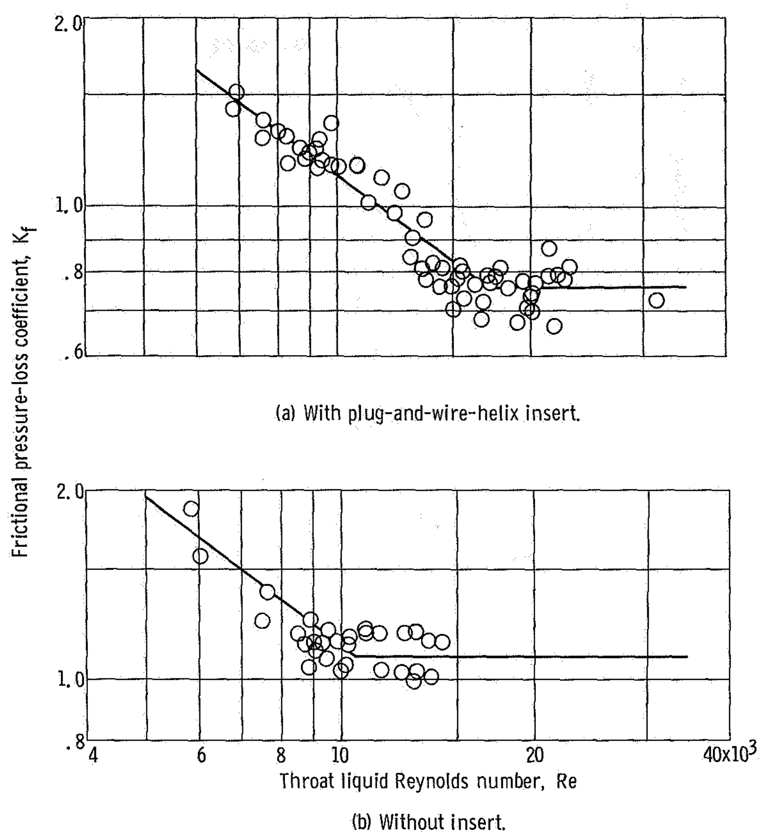


Figure 4. - Noncavitating frictional pressure-loss coefficient as function of throat liquid Reynolds number.

Cavitating Data

Typical test results. - Typical test results are shown in figure 5, where throat velocity is plotted against nozzle pressure drop for a nominal inlet temperature of 170° F (350 K) and inlet pressure about 50 psia (~345 kN/m^2). The all-liquid curve is calculated using K_f values from figure 4(a). As exit pressure is reduced (thus increasing the pressure drop) the velocity increases until visible cavitation occurs just beyond the start of the diffuser. As the exit pressure is further decreased, there is no perceptible change in the position where cavitation starts, but the length of the cavitated region increases. In the fully cavitated regime, the velocity remains essentially constant as the pressure drop is further increased. This insensitivity of velocity and inlet pressure to exit pressure variations can be quite important in boiler-inlet applications. Such a flow-pressure relation can greatly reduce the possibility of instabilities due to coupling of the boiler

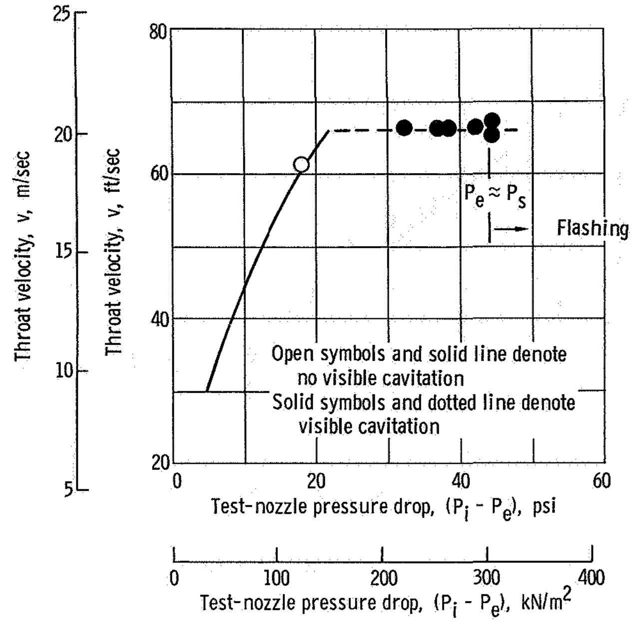
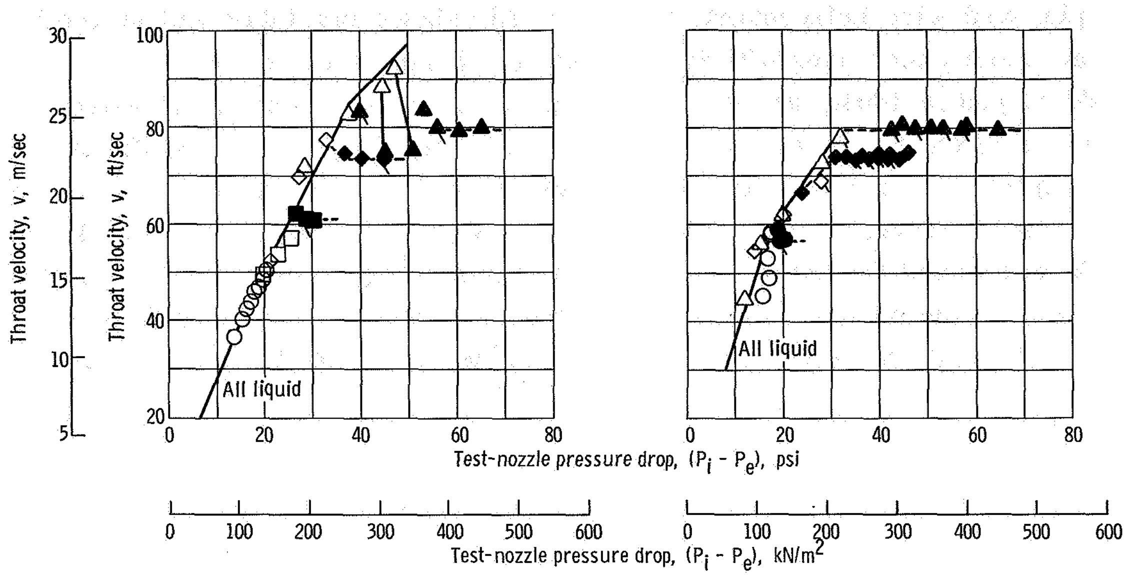


Figure 5. - Typical data: throat velocity as function of nozzle pressure drop; nominal inlet temperature, 170° F (350 K); nominal inlet pressure, 50 psia (350 kN/m^2); with plug- and-wire-helix insert.

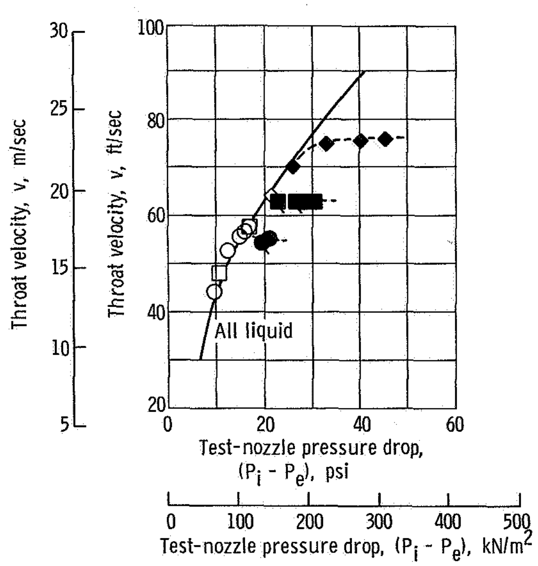
and feed system. When the exit pressure is reduced below the saturation pressure, flashing (net vaporization) occurs, but there is still no effect on velocity or inlet pressure.

Specific trends. - Plots of throat velocity against nozzle pressure drop for various inlet temperatures and pressures are given in figure 6 for the nozzle with the plug-and-wire-helix insert. Figure 6 shows data for nominal inlet temperatures of 68°, 98°, and 120° F (293, 310, and 322 K). The all-liquid curves are calculated using K_f values from figure 4(a). As in figure 5, for constant inlet temperature and pressure, increasing the pressure drop increases the throat velocity until cavitation occurs, and when fully developed cavitation is established, further increases in pressure drop do not effect the velocity. Near the onset of cavitation, however, hysteresis effects and intermittent cavitation with unsteady flow are observed in some cases. For example, see the nominal 70-psia (480-kN/m^2) data of figure 6(a). The double data points (two symbols connected by a line) indicate intermittent all-liquid and cavitating conditions. Velocities higher than critical are observed before the choking phenomenon occurs. It can be seen from figure 6 that any effects of temperature on the critical throat velocity are quite small between 68° and 120° F (293 and 322 K).



(a) Nominal inlet temperature of 68° F (293 K).

(b) Nominal inlet temperature 98° F (310 K).



(c) Nominal inlet temperature 120° F (322 K).

Nominal inlet pressure, P_i,

	psia	(kN/m^2)
○	25	(170)
□	35	(240)
◇	50	(340)
△	70	(480)

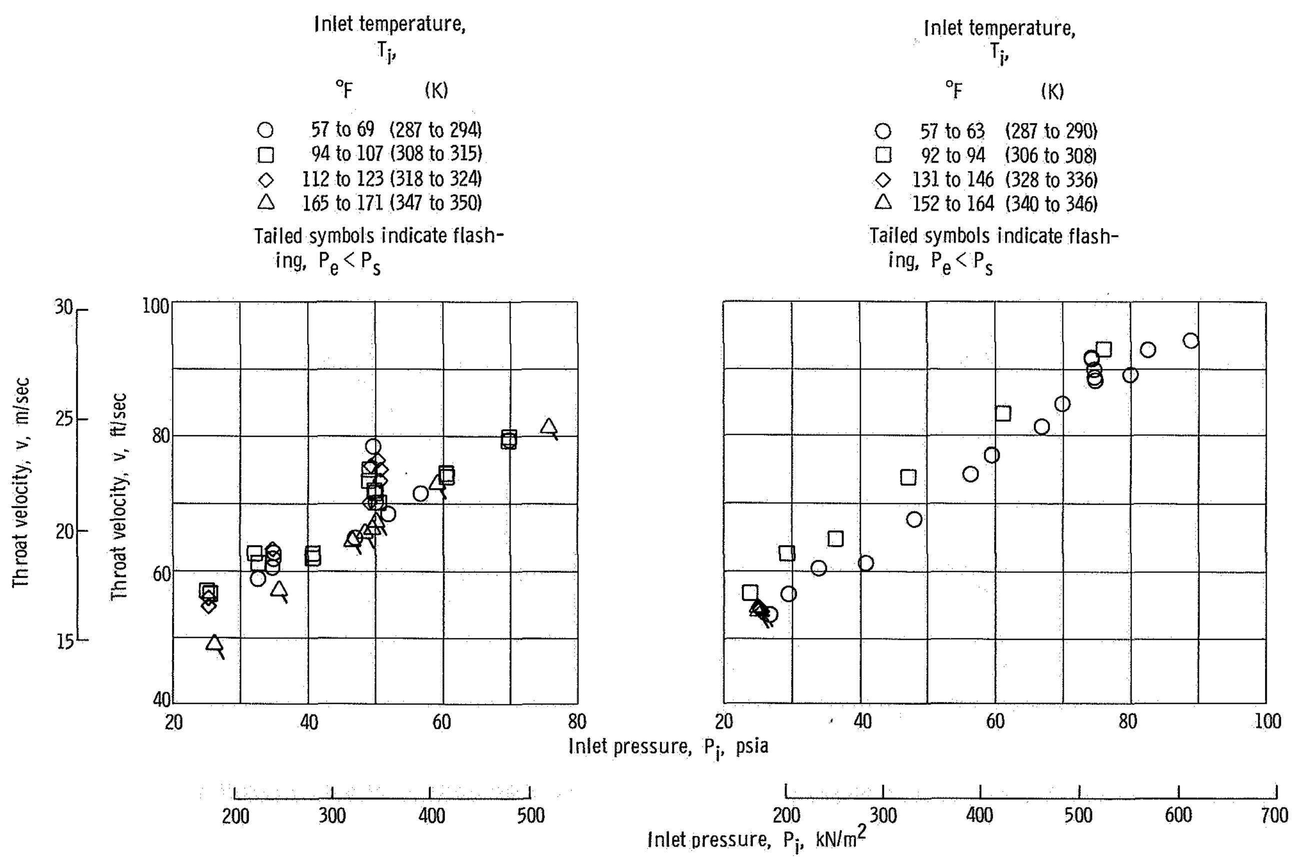
Open symbols and solid line denote no visible cavitation
Solid symbols and dotted line denote visible cavitation
Connected open and solid symbols indicate intermittent visible cavitation)
Plain symbols denote decreasing exit pressure mode
Tailed symbols denote increasing exit pressure mode

Figure 6. - Throat velocity as function of pressure drop across test nozzle with plug-and-wire-helix insert.

Fully Developed Cavitating Flow

Figure 7 gives plots of throat velocity in fully developed cavitation as a function of inlet pressure for various inlet temperatures. Figure 7(a) shows data for the nozzle with the plug-and-wire-helix insert, and figure 7(b) shows data taken without the insert. The throat velocity increases with inlet pressure. Temperature effects on throat velocity in fully developed cavitation are slight. The presence of the insert has no effect on throat velocity except at high pressures and is only slight there. No significant effects would be expected, because the choking-like phenomenon occurs upstream of the inserts.

For cavitating flow, an ideal velocity can be calculated by assuming that (1) the pressure at the exit end of the throat is equal to the saturation pressure at inlet temperature, (2) the flow from the inlet to the end of the throat is frictionless, and (3) the inlet velocity is negligible because of the large area change. This ideal velocity may then be calculated as follows:



(a) With plug-and-wire-helix insert.

(b) Without insert.

Figure 7. - Throat velocity as function of inlet pressure for fully developed cavitation at various inlet temperatures.

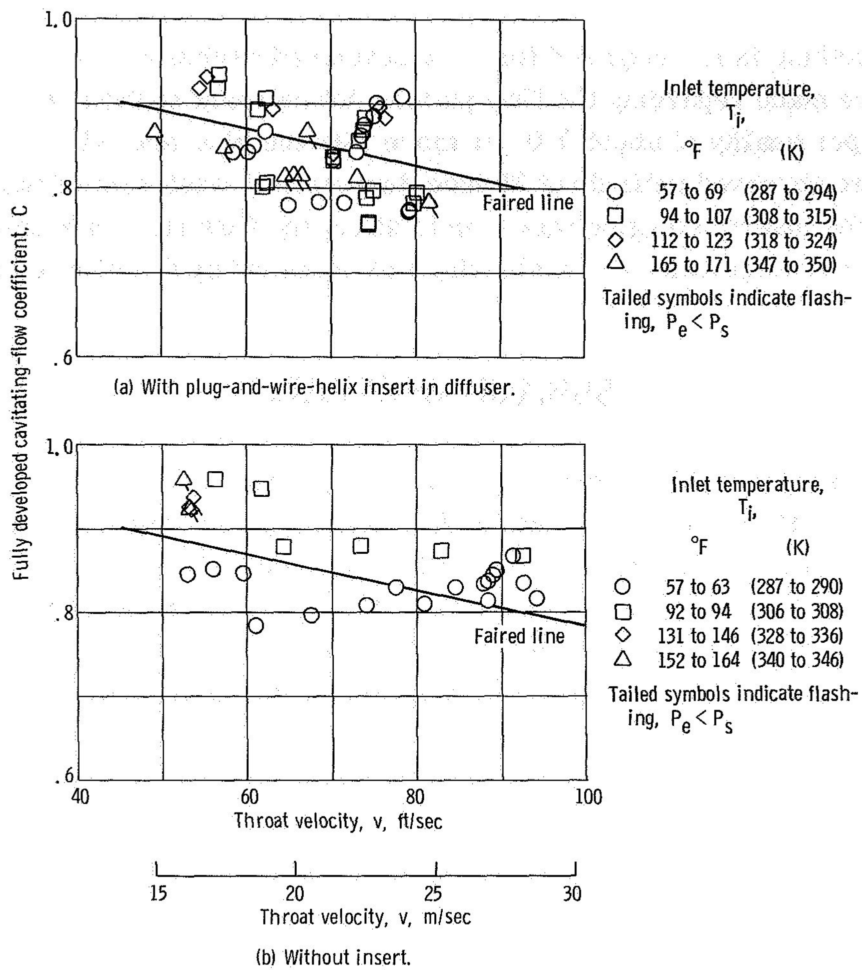


Figure 8. - Fully developed cavitating-flow coefficient as function of throat velocity.

$$v_I = \sqrt{\frac{2g_c C_1}{\rho}(P_i - P_s)} \tag{3}$$

In a real process, the flow is not frictionless, which tends to decrease the velocity. But metastable liquid tension (throat pressure less than P_s) would tend to make v greater than v_I. A fully developed cavitating-flow coefficient can be defined as $C = V/v_1$. If C is greater than 1.0, tension effects are dominant; if C is less than 1.0, friction effects are dominant.

The fully developed cavitating-flow coefficient C is plotted against the throat velocity in figure 8(a) for the nozzle with the plug-and-wire-helix insert and in figure 8(b) for the nozzle without the insert. The decrease of C with increasing v is reasonable because frictional pressure losses increase with velocity.

Flashing

Although flashing is not required for fully developed cavitating flow, some pertinent observations are made regarding the flow pattern downstream of the nozzle. When flashing to a vapor quality of about 0.01 or more with the plug-and-wire-helix insert, no liquid slugs were observed until about 20 tube diameters downstream of the end of the plug. Without the insert, slugging was seen to affect the flow pattern even in the nozzle diffuser. In both configurations, the slugging was lessened by flashing to higher qualities.

SUMMARY OF RESULTS

The major results of this investigation are as follows:

1. Normalized flow-pressure relations for cavitating and noncavitating flow for this nozzle with and without the plug-and-wire-helix insert were determined. The cavitating data are normalized in terms of a fully developed cavitating-flow coefficient; the non-cavitating data are normalized in terms of a frictional pressure drop coefficient.

2. As expected, with well-developed cavitation in this small nozzle, the throat velocity and inlet pressure were insensitive to exit pressure variations.

3. When flashing to about 0.01 vapor quality at the nozzle exit, no liquid slugs were observed with the plug-and-wire-helix insert for about 20 tube diameters downstream (vertically) of the end of the plug.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 1, 1968,
120-27-02-03-22.

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TABLE I. - EXPERIMENTAL DATA FOR TEST NOZZLE WITH PLUG-AND-WIRE-HELIX INSERT

Run	Throat velocity, v		Inlet temperature, T_i		Inlet pressure, P_i		Exit pressure, P_e		Flow regime
	ft/sec	m/sec	^oF	K	psia	kN/m^2	psia	kN/m^2	
1	36.9	11.2	67.8	293.1	25.2	174	11.3	78	No visible cavitation
2	40.7	12 4	67.7	293.0	25.1	173	9.5	65	
3	42.8	13.0	67.8	293.1	25.0	172	8.7	60	
4	44.4	13.5			25.0	172	7.8	54	
5	46.4	14.1			25.1	173	7.0	48	
6	47.5	14.5			25.0	172	6.3	43	
7	48.4	14.7	68.0	293.2	25.0	172	5.5	38	
8	48.7	14.8	68.0	293.2	25.0	172	5.1	35	
9	50.4	15.3	67.8	293.1	25.2	172	4.8	33	
10	50.7	15.4	67.8	293.1	25.2	172	5.7	32	
11	49.9	15.2	68.0	293.2	35.4	244	15.7	108	No visible cavitation
12	53.9	16.4	68.2	293.3	35.0	241	12.0	83	No visible cavitation
13	56.9	17.3			35.2	243	9.5	65	No visible cavitation
14	62.3	19.0			34.8	240	8.2	56	Visible cavitation
15	60.7	18.5			34.9	241	4.8	33	Visible cavitation
16	61.0	18.6			34.8	240	6.2	43	Visible cavitation
17	52.3	15.9	68.2	293.3	49.8	343	28.3	195	No visible cavitation
18	69.3	21.1	68.2	293.3	50.2	346	22.8	157	No visible cavitation
19	77.4	23.6	68.3	293.3	49.7	342	16.5	114	No visible cavitation
20	74.5	22.7	68.5	293.4	50.0	344	13.3	92	Visible cavitation
21	73.6	22.4	68.2	293.3	50.2	346	10.1	70	
22	73.6	22.4	68.2	293.3	50.2	346	4.8	33	
23	73.6	22.4	68.2	293.3	50.3	347	5.7	39	
24	73.2	22.3	57.5	287.3	50.2	346	3.8	26	Visible cavitation
25	78.3	23.9	57.3	287.2	49.5	341	7.1	49	Visible cavitation
26	66.6	20.3	57.5	287.3	50.2	346	19.6	135	No visible cavitation
27	73.2	22.3	57.5	287.3	49.8	343	13.8	95	No visible cavitation
28	74.5	22.7	58.2	287.7	49.5	341	11.0	76	Visible cavitation
29	71.6	21.8	68.0	293.2	70.5	486	42.2	292	No visible cavitation
30	82.8	25.2	68.2	293.3	70.1	483	32.1	221	No visible cavitation
31	88 - 75	27 - 23	68.7	293.5	69.7	481	25.3	174	Intermittent visible
32	92 - 75	28 - 23	68.7	293.5	69.2 - 69.8	477 - 481	22.0 - 19.0	152 - 131	cavitation
33	84.1	25.6	68.0	293.2	69.8	481	16.7	115	Visible cavitation
34	79.4	24.2	69.0	293.7	70.0	483	9.3	63	
35	79.4	24.2	68.2	293.3	70.0	483	4.8	33	
36	79.4	24.2	68.2	293.3	69.6	480	13.7	94	
37	83.6	25.5	68.2	293.3	69.6	480	29.8	205	Intermittent visible cavitation

TABLE I. - Continued. EXPERIMENTAL DATA FOR TEST NOZZLE WITH PLUG-AND-WIRE-HELIX INSERT

Run	Throat velocity, v		Inlet temperature, T_i		Inlet pressure, P_i		Exit pressure, P_e		Flow regime
	ft/sec	m/sec	^oF	K	psia	kN/m^2	psia	kN/m^2	
38	45.7	13.9	90.5	305.6	25.2	174	9.4	65	No visible cavitation
39	48.7	14.9	91.5	306.2	25.0	172	8.0	55	No visible cavitation
40	53	16	92.0	306.5	24.8	171	7.8	54	No visible cavitation, flow unsteady
41	57.4	17.5	92.7	306.9	24.8	171	7.4	51	No visible cavitation
42	58.1	17.7	93.5	307.3	24.9	172	6.2	43	No visible cavitation
43	59.1	18.0	93.8	307.5	24.9	172	5.9	41	Visible cavitation
44	56.6	17.3	94.2	307.7	25.0	172	5.0	34	Visible cavitation
45	56.4	17.2	94.0	307.6	25.3	174	5.5	38	Visible cavitation
46	56.9	17.4	94.3	307.8	25.2	174	6.3	43	No visible cavitation
47	58.6	17.9	94.3	307.8	25.2	174	6.3	43	No visible cavitation
48	54.3	16.6	93.5	307.3	32.5	224	16.2	112	No visible cavitation
49	57.3	17.5	94.2	307.7	32.0	221	15.1	104	
50	59.7	18.2	94.8	308.0	32.0	221	13.6	94	
51	63.1	19.2	95.2	308.2	32.0	221	11.4	79	
52	64.5	19.7	95.7	308.5	31.9	220	9.8	68	
53	64	20	96.0	308.7	31.8	219	8.4	58	Visible cavitation
54	61.5	18.8			32.6	225	5.1	35	
55	61.4	18.7			32.2	222	5.9	40	
56	62.3	19.0			32.0	221	6.4	44	
57	57.5	17.5	95.5	308.4	40.2	277	23.0	159	No visible cavitation
58	62.5	19.0	95.7	308.5	40.0	276	19.4	134	
59	67.2	20.5	96.0	308.7	39.2	270	15.3	105	
60	70.4	21.5	96.0	308.7	39.0	269	12.2	84	
61	72.5	22.1	96.5	309.0	39.0	269	11.0	76	Visible cavitation
62	61.9	18.9	96.2	308.8	40.5	279	7.5	52	
63	62.3	19.0	96.0	308.7	40.5	279	5.3	37	
64	61.9	18.9			40.6	280	8.7	60	
65	61.5	18.7			40.6	280	11.2	77	
66	61.5	18.7			40.6	280	14.9	103	
67	74.9	22.8	98.3	310.0	49.2	339	3.4	23	Visible cavitation
68	74.5	22.7	98.3	310.0			7.1	49	
69	74.5	22.7	98.5	310.1			9.8	68	
70	73.9	22.5	98.3	310.0			12.8	88	
71	73.6	22.4	98.5	310.1	49.0	338	16.2	112	

TABLE I. - Continued. EXPERIMENTAL DATA FOR TEST NOZZLE WITH PLUG-AND-WIRE-HELIX INSERT

Run	Throat velocity, v		Inlet temperature, T_i		Inlet pressure, P_i		Exit pressure, P_e		Flow regime
	ft/sec	m/sec	^oF	K	psia	kN/m^2	psia	kN/m^2	
72	54.5	16.6	97.8	309.7	50.6	348	36.6	252	No visible cavitation
73	61.6	18.8	98.5	310.1	49.8	343	30.0	207	No visible cavitation
74	66.4	20.2	100.0	310.9	49.7		25.5	176	Visible cavitation
75	73.8	22.5	101.0	311.5	49.8		18.4	127	
76	73.6	22.4	101.8	311.9	49.8		14.2	98	
77			102.0	312.0	49.8		12.4	85	
78			102.3	312.2	49.7		9.9	68	
79			102.5	312.3	49.7		7.9	54	
80	73.3	22.3	102.7	312.4	49.5	341	5.8	40	
81	47.8	14.6	100.8	311.4	60.6	418	48.6	335	No visible cavitation
82	58.9	18.0	101.2	311.6	59.6	411	41.8	288	
83	69.1	21.1	102.8	312.5	59.7	412	33.7	232	
84	77.3	23.6	103.7	313.0	58.7	404	26.1	180	
85	74 - 78	23 - 24	104.3	313.3	59.7 - 60.5	412 - 417	23.0 - 23.6	159 - 163	Intermittent visible cavitation
86	74.4	22.7			60.3	415	17.6	121	Visible cavitation
87	74.4	22.7			60.2	415	15.2	105	
88	74.8	22.8			60.1	414	12.0	83	
89	74.8	22.8					9.7	67	
90	74.8	22.8					4.8	33	
91	74.4	22.7					11.7	81	
92	74.1	22.6			60.0	413	19.8	137	
93	74.1	22.6			60.0	413	22.0	152	
94	73.8	22.5			59.8	412	28.2	194	No visible cavitation
95	44.5	13.6	103.0	312.6	69.5	479	57.5	396	No visible cavitation
96	56.0	17.0	102.5	312.3	69.2	477	53.9	372	
97	61.5	18.8	102.5	312.3	68.5	472	49.1	339	
98	72.7	22.2	103.5	312.9	69.2	477	41.0	283	
99	79 - 81	24 - 25	104.2	313.3	69.2	477	24.6	170	Visible cavitation, flow unsteady
100	79.4	24.2	104.5	313.4	69.5	479	18.6	128	Visible cavitation
101	80.0	24.4	104.7	313.5	69.7	480	11.6	80	
102	79.7	24.3	104.5	313.4	69.5	479	4.8	33	
103	79.7	24.3	104.5	313.4	69.2	477	11.8	81	
104	79.4	24.2	104.5	313.4	69.2		16.2	112	
105	79.4	24.2	104.3	313.3	69.3		21.8	150	
106	79.4	24.2	104.3	313.3	69.3		26.5	183	
107	77.6	23.7	104.2	313.3	69.8	481	37.8	261	No visible cavitation

TABLE I. - Continued. EXPERIMENTAL DATA FOR TEST NOZZLE WITH PLUG-AND-WIRE-HELIX INSERT

Run	Throat velocity, v		Inlet temperature, T_i		Inlet pressure, P_i		Exit pressure, P_e		Flow regime
	ft/sec	m/sec	^oF	K	psia	kN/m^2	psia	kN/m^2	
108	44.0	13.4	120.0	322.0	24.8	171	15.3	105	No visible cavitation
109	52.8	16.1	120.5	322.3	25.0	172	12.5	86	↓
110	55.7	17.0	120.5	322.3	24.8	171	10.0	69	↓
111	56.6	17.3	120.5	322.3	24.8	171	8.7	60	↓
112	58.1	17.7	120.7	322.4	25.0	172	7.8	54	↓
113	55.4	16.9	121.0	322.6	25.2	174	4.2	29	Visible cavitation
114	54.5	16.6	120.0	322.0	25.2	174	5.5	38	Visible cavitation
115	48.6	14.8	119.5	321.8	35.0	241	24.3	167	No visible cavitation
116	57.7	17.6	120.7	322.4	34.0	243	16.7	115	No visible cavitation
117	63.1	19.2	120.0	322.0	34.8	240	12.1	83	Visible cavitation
118	62 - 63	18.9 - 19.2	120.5	322.3	↓	↓	7.4	51	Visible cavitation, flow unsteady
119	63.1	19.2	120.3	322.2	↓	↓	4.2	29	Visible cavitation
120	63.1	19.2	120.3	322.2	↓	↓	8.2	57	Visible cavitation
121	63.1	19.2	120.3	322.3	↓	↓	12.1	83	Visible cavitation
122	64.3	19.6	119.5	321.8	50.3	347	28.6	197	No visible cavitation
123	70.4	21.5	121.0	322.6	49.0	338	22.5	155	Visible cavitation
124	75.0	22.9	120.3	322.2	48.9	337	15.7	108	↓
125	75.4	23.0	122.7	323.5	49.3	340	9.3	64	↓
126	75.7	23.1	119.5	321.8	49.4	340	4.4	30	↓
127	65.4	19.9	169.0	349.3	48.1	332	3.9	27	Flashing, x = 0.016
128	67.2	20.5	170.8	350.3	50.0	345	4.5	31	Flashing, x = 0.013
129	66.3	20.2	170.7	350.2	49.6	342	7.6	52	Visible cavitation
130	↓	↓	170.3	350.0	↓	↓	11.2	77	↓
131	↓	↓	170.5	350.1	↓	↓	12.8	88	↓
132	↓	↓	170.5	350.1	↓	↓	17.1	118	↓
133	61.3	18.7	171.5	350.6	50.7	350	32.8	226	No visible cavitation
134	41.3	12.6	57.5	287.3	21.3	147	4.6	32	No visible cavitation
135	45.7	13.9	57.3	287.2	23.1	159	4.7	↓	↓
136	50.4	15.4	57.3	287.2	25.2	174	↓	↓	↓
137	53.7	16.4	57.5	287.3	28.2	194	↓	↓	↓
138	55.7	17.0	57.3	287.2	30.4	210	↓	↓	↓
139	58 - 59	17.5 - 18	57.3	287.2	32.8	226	↓	↓	Visible cavitation, flow unsteady
140	56.3	17.2	57.5	287.3	32.8	226	5.2	36	No visible cavitation
141	58.9	18.0	↓	↓	35.4	244	4.7	32	No visible cavitation
142	59 - 63	18 - 19	↓	↓	37.2 - 37.4	256 - 258	4.7	32	Intermittent visible cavitation
143	65.1	19.9	↓	↓	47.2	325	4.8	33	Visible cavitation

TABLE I. - Concluded. EXPERIMENTAL DATA FOR TEST NOZZLE WITH PLUG-AND-WIRE-HELIX INSERT

Run	Throat velocity, v		Inlet temperature, T_i		Inlet pressure, P_i		Exit pressure, P_e		Flow regime
	ft/sec	m/sec	^oF	K	psia	kN/m^2	psia	kN/m^2	
144	68.6	20.9	57.7	287.4	51.8	357	5.1	35	Visible cavitation
145	69 - 75	21 - 23	↓	↓	51.7	357	8.8	61	Visible cavitation, flow unsteady
146	68 - 77	21 - 24	↓	↓	51.5	355	11.5	79	Intermittent visible cavitation
147	71.6	21.8	↓	↓	56.4	388	4.9	34	Visible cavitation
148	81.3	24.8	165.5	347.3	75.6	521	3.8	26	Flashing, x = 0.015
149	73.0	22.3	167.5	348.4	59.0	406	4.2	29	Flahsing, x = 0.012
150	64.5	19.7	165.7	347.4	46.4	320	3.8	26	Flashing, x = 0.015
151	57.3	17.5	166.0	347.6	35.5	245	3.2	22	Flashing, x = 0.021
152	49.0	14.9	165.0	347.0	26.3	181	3.2	22	Flashing, x = 0.020
153	79.1	24.1	98.5	310.1	49.0	338	21.0	145	No visible cavitation
154	76.4	23.3	111.8	317.5	50.4	347	2.3	16	Visible cavitation
155	75.0	22.9	112.3	317.8	50.5	348	13.2	91	↓
156	73.9	22.5	112.5	317.9	50.3	347	18.4	127	↓
157	74.4	22.7	90.2	305.5	49.5	341	5.0	34	↓
158	74.4	22.7	98.2	310.0	49.7	343	5.0	34	↓
159	70.4	21.5	96.0	308.7	49.7	↓	4.4	30	↓
160	70.7	21.6	101.7	311.9	49.8	↓	↓	↓	↓
161	70.1	21.4	107.2	314.9	49.7	↓	↓	↓	↓
162	70.4	21.5	112.7	318.0	49.7	↓	↓	↓	↓
163	70.1	21.4	114.5	319.0	49.4	340	↓	↓	↓
164	70.4	21.5	121.7	323.0	49.6	342	↓	↓	

TABLE II. - EXPERIMENTAL DATA FOR TEST NOZZLE WITHOUT INSERT

Run	Throat velocity, v		Inlet temperature, T_i		Inlet pressure, P_i		Exit pressure, P_e		Flow regime
	ft/sec	m/sec	^oF	K	psia	kN/m^2	psia	kN/m^2	
165	55.4	16.9	56.2	286.6	75.0	517	53.3	367	No visible cavitation
166	58.2	17.8	56.2	286.6	74.4	513	50.7	350	
167	62.0	18.9	56.2	286.6	74.6	515	47.8	330	
168	68.7	20.9	57.2	287.1	74.2	512	41.3	285	
169	74.0	22.6	57.0	287.0	75.0	517	37.5	258	
170	77.9	23.7	57.2	287.1	74.8	516	33.2	229	
171	82.6	25.2	57.5	287.3	74.7	515	28.2	194	
172	86.2	26.3	57.5	287.3	74.5	514	24.8	171	
173	89 - 94	27 - 29	57.8	287.5	74.1	511	20.0 - 20.7	138 - 143	Intermittent visible cavitation
174	95.0	29.0	58.2	287.7	74.1	511	17.6	121	Visible cavitation
175	91.3	27.8	58.0	287.6	74.1	511	11.0	76	
176	89.3	27.2	58.3	287.8	74.4	513	6.2	43	
177	89.3	27.2	58.3	287.8	74.4	513	4.2	29	
178	88.9	27.1	58.2	287.7	74.6	515	6.6	45	
179	91.3	27.8			74.5	514	12.7	88	
180	88.0	26.8			74.5	514	20.5	141	
181	88.3	26.9			74.6	515	30.0	207	
182	77.4	23.6			75.3	518	35.5	244	No visible cavitation
183	35.4	10.8	58.2	287.7	19.8	136	4.2	29	No visible cavitation
184	45.7	13.9	59.2	288.3	23.4	161			No visible cavitation
185	51.3	15.6	59.8	288.6	26.0	179			No visible cavitation
186	53.0	16.1	60.0	288.7	26.4	184			Visible cavitation
187	56.1	17.1	59.5	288.4	29.5	203			
188	59.7	18.2	59.5	288.4	34.0	234			
189	61.0	18.6	59.5	288.4	40.8	281			
190	67.4	20.5	60.0	288.6	48.2	332			
191	73.9	22.5	60.8	289.1	56.4	389			
192	80.9	24.6	62.0	289.8	66.8	460			
193	88.5	27.0	62.2	289.9	79.7	549			
194	93.9	28.6	62.5	290.1	89.0	613			
195	35.7	10.9	57.0	287.0	30.8	212	17.0	120	No visible cavitation
196	44.9	13.7	56.5	286.8	34.2	236			
197	51.8	15.8	56.7	286.9	39.6	273			
198	53.9	16.4	56.7	286.9	39.6	273			
199	55.7	17.0	56.8	286.9	41.0	283			
200	58.6	17.9	57.2	287.1	43.9	302			
201	61.5	18.7	57.8	287.5	46.8	322			
202	65.6	20.0	58.3	287.8	49.5	341			
203	69.4	21.2	58.8	288.1	52.8	364			
204	73 - 75	22 - 23	59.8	288.6	56.0	386	17.4	117	Incipient visible cavitation
205	77.7	23.7	59.8	288.6	59.4	409	17.0	120	Visible cavitation
206	84.5	25.8	60.0	288.7	70.0	482	17.0	120	Visible cavitation
207	92.4	28.2	60.2	288.8	82.7	570	17.0	120	Visible cavitation

TABLE II. - Concluded. EXPERIMENTAL DATA FOR TEST NOZZLE WITHOUT INSERT

Run	Throat velocity, v		Inlet temperature, T_i		Inlet pressure, P_i		Exit pressure, P_e		Flow regime (a)
	ft/sec	m/sec	^oF	K	psia	kN/m^2	psia	kN/m^2	
208	36.7	11.2	91.7	306.3	15.6	107	4.8	33	No visible cavitation
209	56.3	17.2	91.8	306.4	23.7	156			Visible cavitation
210	61.9	18.9	92.2	306.6	29.2	201			
211	64.3	19.6	92.8	306.9	36.5	252			
212	73.3	22.4	93.2	307.1	47.2	325	4.7	32	
213	83.0	25.3	93.7	307.4	61.2	422	5.0	34	
214	92.3	28.1	94.2	307.7	76.2	525	5.0	34	
215	53.1	16.2	56.5	286.8	25.2	174	5.0	34	Visible cavitation
216	53.3	16.3	74.0	296.5	25.0	172	5.1	35	Visible cavitation
217	51.9	15.8	58.0	287.6	25.8	178	4.2	29	No visible cavitation
218	53.1	16.2	61.8	289.7	25.3	174			No visible cavitation
219	54.3	16.6	68.3	293.3	25.0	172			No visible cavitation
220	54 - 56	16 - 17	112.0	317.6	24.8	171			Visible cavitation, flow unsteady
221	53.7	16.4	131.0	328.1	25.0	172			Visible cavitation
222	53.3	16.3	145.0	335.9	25.2	174	2.9 - 3.8	20 - 26	Visible cavitation with intermittant flashing
223	53.1	16.2	146.0	336.5	25.2	174	3.0	21	Flashing, x = 0.004
224	53.3	16.3	152.3	340.0	25.2	174	2.9	20	Flashing, x = 0.011
225	52.8	16.1	163.5	345.9	25.0	172	2.9	21	Flashing, x = 0.021
226	51.3	15.6	71.0	294.8	60.3	415	40.2	277	No visible cavitation
227	68.9	21.0	71.0	294.8	60.7	419	24.3	167	No visible cavitation
228	72 - 80	22 - 24	70.8	294.7	60.1	414	21.5 - 24	152 - 170	Intermittent visible cavitation
229	74.5	22.7	70.8	294.7	60.0	413	22.1	157	Visible cavitation
230	74.5	22.7	70.8	294.7	59.9	412	16.2	115	
231	75.1	22.9	71.2	294.9	59.8	412	11.6	80	
232	75.7	23.1	71.3	295.0	59.8	412	7.6	52	
233	75.7	23.1	71.3	295.0	59.7	411	5.8	40	
234	75.7	23.1	71.5	295.1	59.7		5.4	37	
235	74.5	22.7			59.6		23.6	163	
236	75 - 68	23 - 21			59.6		28.3 - 25.4	195 - 175	Intermittent visible cavitation
237	58.6	17.9			60.0	413	34.8	240	No visible cavitation
238	53.3	16.2	69.8	294.2	74.2	512	51.7	356	No visible cavitation
239	58.3	17.8	69.5	294.0	75.5	520	48.2	332	
240	64.2	19.6			75.5	520	42.7	294	
241	67.0	20.4			75.2	518	39.3	271	
242	73.2	22.3			74.7	515	34.0	234	
243	83.3	25.4	69.3	293.9	74.8	515	34.2	236	Noise, but no visible cavitation
244	67.4	20.5			76.2	525	40.7	280	No visible cavitation
245	71.9	21.9			75.9	523	37.2	256	No visible cavitation
246	83.6	25.5			74.8	515	23.7	163	Visible cavitation
247	83.6	25.5					19.8	136	
248	84.1	25.7					15.8	109	
249	84.6	25.8					8.1	56	
250	40.7	12.4	56.2	286.6	17.5	121	3.5	24	Visible cavitation
251	56.0	17.1	56.2	286.6	26.6	183	3.3	23	
252	67.7	20.6	57.2	287.1	38.8	277	3.3	23	
253	75.6	23.0	58.2	287.7	59.5	410	3.2	22	

[a]Aerated water for runs 226 to 253.

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