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A Study of Hydraulic Air Compression for Ocean Thermal Energy Conversion Open-Cycle Applications

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OPERATED BY
UNION CARBIDE CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A05 Microfiche A01

ORNL/TM-8384
Dist. Category UC-64

Contract No. W-7405-eng-26

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Prepared for the
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Date Published - January 1983

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
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ACKNOWLEDGMENTS

This investigation was performed at the Oak Ridge National Laboratory (ORNL), operated by Union Carbide Corporation for the Department of Energy (DOE). The study was a part of the general Ocean Energy Conversion program being carried out by ORNL for the DOE Ocean Energy Systems Division and was under the direction of E. H. Kinelski, Program Manager, DOE Headquarters.

The authors wish to express their appreciation for the assistance of many ORNL staff members, particularly R. W. Murphy, G. L. Yoder, H. W. Hoffman, and J. W. Michel for their helpful suggestions throughout the program and R. L. Linkous (project technician) for operating the test equipment and collecting data. The computer software provided by Professor W. Rice is gratefully acknowledged.

NOMENCLATURE

A_d	pipe cross-sectional area
C_0	flow distribution parameter
C_1	drift velocity coefficient
D	pipe diameter
f	frictional factor
g	gravitational acceleration
h	head
$\langle J \rangle$	$(Q_a + Q_w)/A_d$ = average volumetric flux of mixture
$\langle J_a \rangle$	air volumetric flux
$\langle J_w \rangle$	water volumetric flux
K	loss coefficient
$\dot{m}$	mass flow rate
P	pressure
Q	volumetric flow rate
S	wetted perimeter
T	temperature
V	velocity
V_r	drift velocity of gas phase relative to liquid phase
Z	vertical coordinate
β	$Q_a/(Q_a + Q_w)$ = flow volumetric concentration
ρ	density

Subscripts

0',0,1,...4	boundary designations
a	gas/air phase
b	bubble
d	down-pipe
elb	elbow
L	liquid/water phase
u	up-pipe
w	water

A STUDY OF HYDRAULIC AIR COMPRESSION FOR OCEAN THERMAL ENERGY CONVERSION OPEN-CYCLE APPLICATIONS

A. Golshani F. C. Chen

ABSTRACT

A hydraulic air compressor, which requires no mechanical moving parts and operates in a nearly isothermal mode, can be an alternative for the noncondensible gas disposal of an Ocean Thermal Energy Conversion (OTEC) open-cycle power system. The compressor requires only a downward flow of water to accomplish air compression. An air compressor test loop was assembled and operated to obtain test data that would lead to the design of an OTEC hydraulic air compressor. A one-dimensional, hydraulic gas compressor, computer model was employed to simulate the laboratory experiments, and it was tuned to fit the test results. A sensitivity study that shows the effects of various parameters on the applied head of the hydraulic air compression is presented.

1. INTRODUCTION

A hydraulic air compressor is driven by a vertical downward flow of water with an applied hydraulic head. Downward water flow entrains air bubbles. Because of their buoyancy force in water, the bubbles tend to rise against the flow of water, but they are carried downward when the viscous drag force acting on them overcomes their buoyancy. Thus, air compression is achieved as the bubbles are carried downward by water flow, because the air pressure of the bubbles equals the hydrostatic pressure of the water at depth.

The hydraulic air compression process is rather simple. The device requires no moving parts; only a downward flow of water is necessary. Therefore, a hydraulic air compressor is proposed as a candidate for noncondensible gas disposal at an Ocean Thermal Energy Conversion (OTEC) open-cycle power system.

Seawater is the working fluid in an open-cycle OTEC power system. Power generation requires that ~0.5% of the warm seawater flow is flashed into steam, and the rest of the seawater is returned to the ocean.

Seawater contains dissolved air that will be evolved during the flashing process but cannot be condensed at the OTEC power cycle conditions. To ensure efficient power generation, the noncondensible gas in an OTEC open-cycle power system must be removed. A common method for noncondensible gas disposal is the use of mechanical compressors that pump the gas from the power system and vent it to the atmosphere. Mechanical compression is usually an adiabatic process; a considerable amount of energy is required to operate the compressors in OTEC power systems. Staged compression with intercooling has been proposed to save compression power. However, that increases the mechanical complexity of the disposal subsystem for noncondensibles. In a hydraulic air compressor for OTEC applications, the discharge of the downward flow of the unflashed seawater will be the moving source for the disposal of the noncondensible gas, which may result in less mechanical complexity and better efficiency.

To explore the feasibility of using hydraulic air compression in an OTEC open-cycle power system, experimental and analytical studies of the compressor were conducted. Test results were obtained in a bench-scale laboratory setup to examine the compressor concept. A computer code was modified to simulate the experiments. Finally, an analysis is presented that uses these results to evaluate the performance of an OTEC noncondensible gas removal system using hydraulic air compressors.

2. BACKGROUND

The concept of a hydraulic air compressor is an old one. In 1877, J. P. Frizell[1] applied for the first U.S. patent on the compression of air by direct action of water. A sketch of his device is shown in Fig. 1. A hydraulic air compressor may be described as an inverted siphon, consisting of (1) an intake head where air is entrained in water, (2) a gravity-fall pipe in which air bubbles are mixed with the water and compressed as the water pressure increases during the fall down the pipe, and (3) a separating chamber in which air bubbles rise to the water surface and collect in the upper portion of the chamber at a pressure equal to the water head maintained by the height of water in the discharge leg of the system (Fig. 1). The water passes out of the separating chamber and rises up

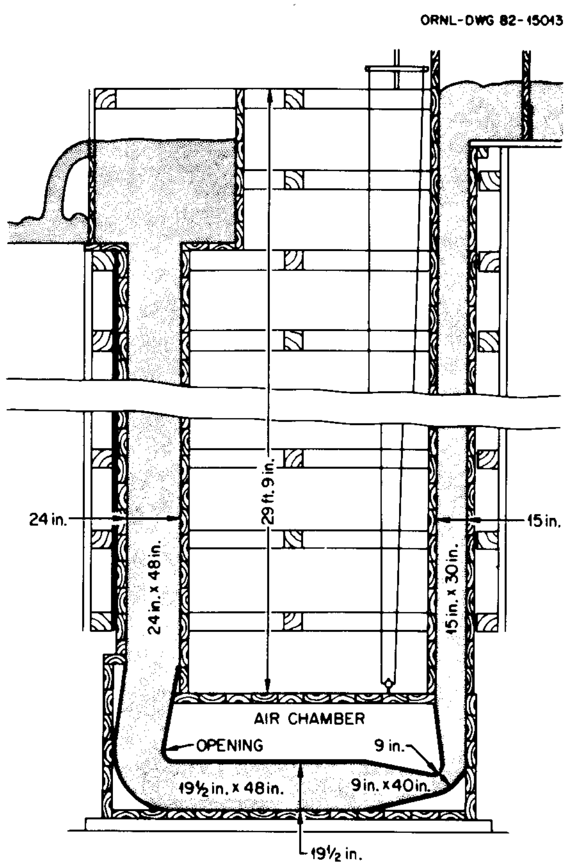

Fig. 1. Sketch of Frizell's shaft, St. Anthony Falls, Minneapolis, Minn. Source: J. P. Frizell, *Experiments on the Compression of Air by Direct Action of Water*, 1880.

the discharge leg to the surface, which is at some height below the level of the intake. This height difference represents the power required to achieve air compression.

Many hydraulic air compressors had been constructed from 1900 through 1930 in the United States, Canada, and European countries, mainly to produce compressed air for general mine use. Some of them are still operating. The compressed air pressures of these hydraulic air compressors vary from 15 to 150 psig, and efficiencies vary from 40% to substantially better than 70%. With the advent of mechanically driven reciprocating and centrifugal compressors, the use of hydraulic air compressor technology slowed down.

The old type of hydraulic air compressor, which compresses air isothermally and produces free-of-oil contamination and low-moisture-content compressed air, could have several present-day applications as pointed out by Schultz:[2] (1) use of low hydraulic heads, which otherwise have little commercial value, in reclamation work to supply compressed air; (2) use of medium heads, at dam and lock installations, to produce compressed air for pneumatic heads of airlifts, gates, valves, and rubber gate seals; and (3) development of a large air supply at pressures up to 150 psig, which, after performing work through air-turbine expanders, is available at temperatures approximately -50°F for supplying dry air for process work, wind-tunnel tests, or large air-conditioning installations (such as ventilation of underwater traffic tunnels). The old type of compressor may also prove to be economic for supplying supercharged air to gas-turbine plants (Fig. 2). Lately, such a concept was put forth by Norton,[3] who has reported that compressor efficiencies of 80 to 95% are readily attained with reasonable flow heads.

In a theoretical analysis of the performance of hydraulic gas compressors, Rice[4] confirmed the performances of some of the early hydraulic compressor installations and pointed out the potential for using hydraulic air compressors.

Because there is a rather large water flow of low hydraulic head source in an open-cycle OTEC power system together with a noncondensible gas flow to be disposed of, a study of the possibility of applying the hydraulic air compressor was initiated.

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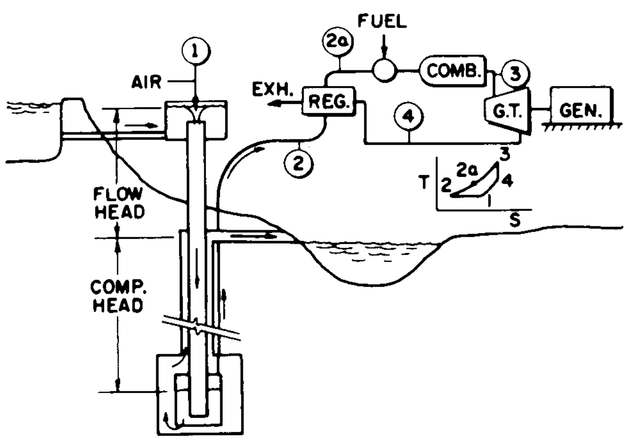

Fig. 2. Typical hydraulic air compressor/gas turbine combination. Source: J. R. Norton, "Innovating Old Concept for Hydroelectric Power Generation," *Prof. Eng.*, 31–32 (June 1979).

3. TEST LOOP DESIGN FOR OTEC HYDRAULIC AIR COMPRESSION

The major components of the test loop are described in the following sections.

3.1 Test Setup

The test loop design, the equipment for the OTEC Gas Desorption Test Facility, and the barometric intake system were explained in Vols. 1 (Ref. 5) and 2 (Ref. 6) of the OTEC gas desorption study. However, some modifications and expansion have taken place since then, with the addition of a hydraulic air compressor test section to the gas desorption test loop. A schematic of the hydraulic air compressor, including water circulation and air injection position, is shown in Fig. 3. The major components of the hydraulic air compression test facility, which includes a water circulation and control system, a hydraulic air compression test section, and instrumentation, are described in the following sections.

3.2 Water Circulation and Control

Flow directions for the hydraulic air compression system and the flow path are indicated by arrows in the simplified schematic diagram (Fig. 3). The experimental system consists of three components: a water holding tank equipped with manual level control to maintain different water heights, a discharge pipe (downcomer) equipped with an air injection system, and a water recirculation system.

For hydraulic air compression water circulation, tank 1 (Fig. 3) was filled with building water to the desired height. Through the use of a vacuum system, water was pulled up into the barometric leg and entered into the test column. The water was also deaerated because of the vacuum effect. The deaerated water was then recirculated into holding tank 2. Pump B forced the water to flow through the downcomer unit where air injection took place. The air-injected water then entered water storage tank 1, and circulation continued. The flow rates through storage tanks 2 and 1 were controlled by adjusting the valve across pump A and pump B,

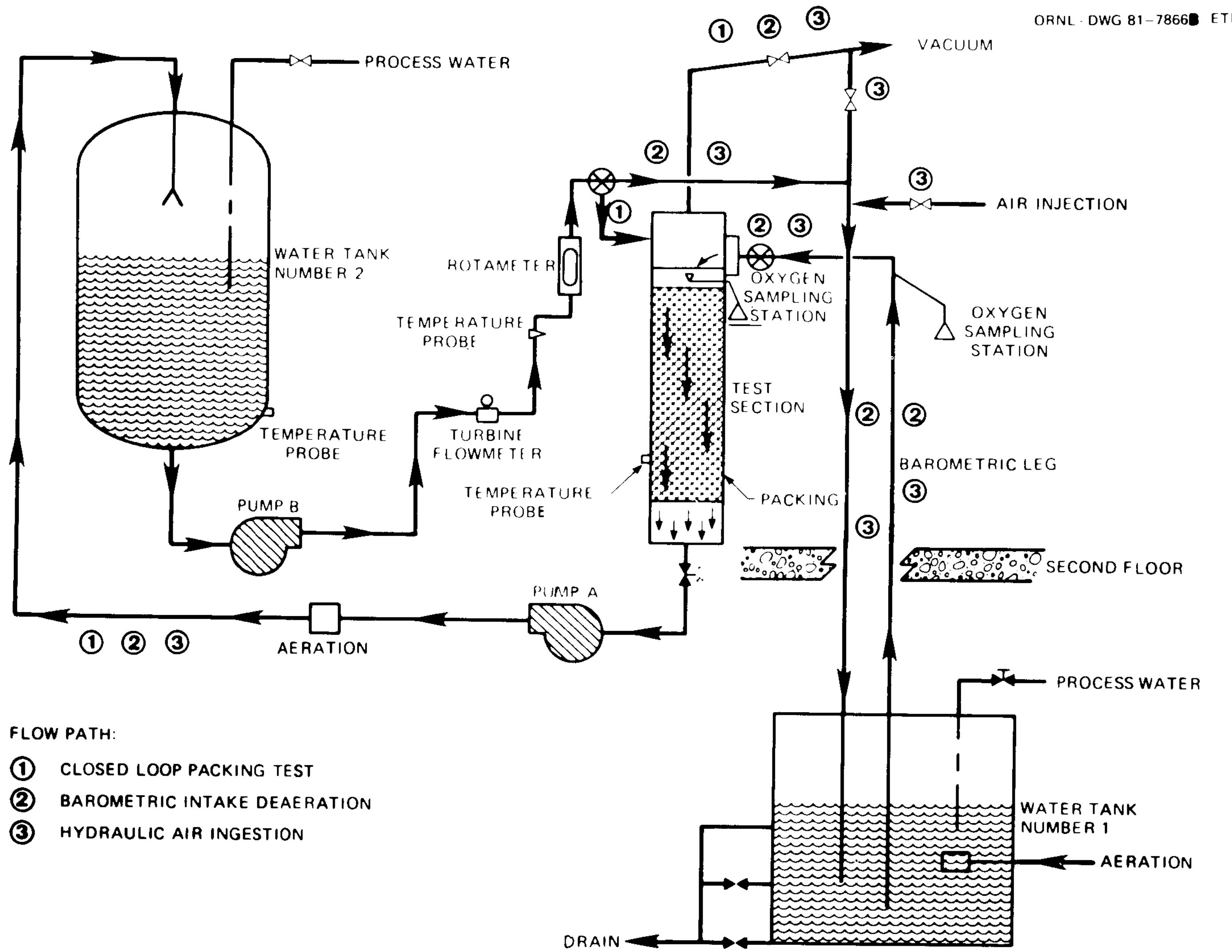

Fig. 3. Schematic of gas desorption and hydraulic air compression systems.

respectively. These bypasses and manual control valves are not shown in Fig. 3.

A manually operated valve located at the top of holding tank 1 was used to maintain constant liquid level in the tank. Excess water entering the tank was drained through valves located in the side of the tank. Water flow was measured by a turbine flowmeter as it entered the downcomer pipe.

3.3 Hydraulic Air Compression Test Section

A schematic of a hydraulic air compression test section is shown in Fig. 4. The test loop provides the vacuum pumping and liquid circulation capability to the test section. The water pipe in the test section is a 5.1-cm-diam (2-in.) clear pipe. In a hydraulic air compression test, the

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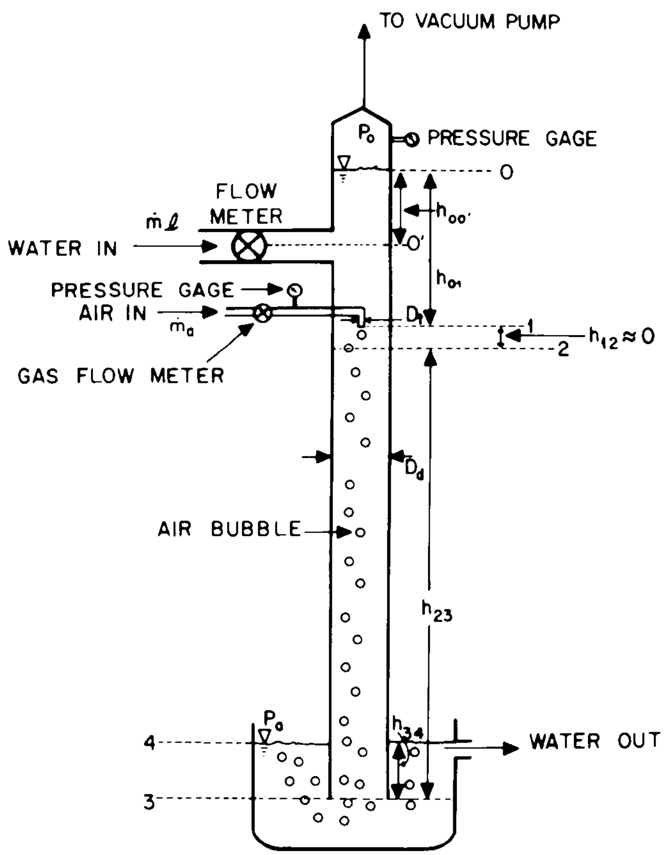

Fig. 4. Schematic of hydraulic air compression test section.

building compressed air is measured with a calibrated ball-tube-type rotameter and bled (injected) into the downward water flow through air injection nozzles. Two sizes of single air injection nozzles and one multi-injection nozzle (two 1.14-mm nozzles) were tested. The diameters of two single nozzles were 1.14 and 0.46 mm (0.045 and 0.018 in.). Each nozzle was used in two injection ports located 45.7 and 106.7 cm (45.7 and 42 in.), respectively, below the free water surface in the water discharge pipe (downcomer). When there was no air injection, the free water surface was maintained by applying vacuum pressure at the top of the discharge pipe. The vacuum pressure was controlled by a pressure regulator, and the air and water mass flows were regulated by proper control valve settings and measured by flowmeters.

3.4 Instrumentation

Instruments used for monitoring the hydraulic air compression test loop include thermistors, well-type mercury manometers, and flowmeters.

Water temperatures are measured at four locations by means of thermolinear probes (Yellow Spring Instrument Model YSI 710X). The first point is located just before the entrance of the packed column. The second point is located below the packing in the water accumulator. The third and fourth points are positioned to measure the air and water storage tank temperatures.

The thermolinear probe network is a composite device consisting of resistors and precise thermistors that produce an output voltage linear with temperature or a resistance linear with temperature.

The temperature probe, digital ohmmeter (Data Precision Multimeter Model 3500), and associated components were selected as a system to ensure compatibility. The temperature range and accuracy of the system is -1.11 to 37.78 $\pm$ 0.09°C (30 to 100°F). The maximum recommended time constant is 1.5 s for a probe diameter of 0.397 cm (5/32 in.) with a single-hex National Pipe Thread mounting. The probe signals are processed by a digital multimeter to yield the temperature, and a strip chart recorder is used to record and monitor the temperatures.

Well-type mercury manometers (Meriam, Model 30EB25) measure the pressure in the hydraulic air compression system at three locations: (1) in the vapor line (vacuum pipe), (2) above the distributor plate (packed column), and (3) above the hydraulic air compression test section.

The water flow rate into the hydraulic air compression test section is measured by two instruments: a turbine flow transducer (Flow Technology Model FT-16) and a rotameter (Fischer and Porter Serial No. X11-4425/2). (These two instruments are in series.) The turbine flow transducer (Flow Technology Model FT-16) was installed to facilitate operation. The range of the meter is 18.93–189.3 L/min (5.0–50 gpm), and its accuracy is $\pm$0.05% at all points. The flow signal is processed by flow rate monitors (Flow Technology Model PRI-102D) to yield the mass flow rates.

The air flow rate into the test section was determined with a calibrated ball-tube-type rotameter (Brook Instrument Model No. 1110-05F1B1B). Liquid and air volumetric calculations are shown in Appendix A.

In addition to the instruments listed, a manual needle valve (Ridge Valve Model B18VF8-Vec) is employed to control the vacuum pressure.

3.5 Hydraulic Air Compression System Startup

A standard startup procedure was implemented for each day of experimental tests. The drain on storage tank 1 was closed, and the building water fill line was opened. After a closely estimated water level was achieved, the vacuum valve (not shown in Fig. 3) was opened and set at its desired pressure for that day's run. As the barometric leg began to discharge water into the test column, pump A was turned on to force the water into tank 2. When the water level in tank 2 was half-filled, pump B was turned on to force the water through the flowmeters, downcomer, and back to tank 1. Tests were carried out under steady-state flow conditions.

4. EXPERIMENTAL INVESTIGATION

In an experimental run, water at subatmospheric pressure enters the inlet of the compressor test section via the gas desorption loop (Fig. 4). The water in the pipe flows downward past the air injection nozzle where air is injected into the flowing water stream. An air-water two-phase flow mixture is created. The mixture flows down the water pipe in which the air is being compressed and is eventually discharged into water tank 1 (Fig. 3) at the lower end of the water pipe. Through the use of a vacuum system, water is pulled up into the barometric leg.

When air is injected into the water stream, change in void fraction within the pipe causes the free water surface (point 0′, Fig. 4) to move upward (to point 0). The vertical change in free water surfaces with and without air injection is the applied water head needed for the water stream to achieve air compression. The applied head can be directly converted to compressor power consumption.

Vertical distances of downcomer were (1) $h_{0'1}$ = 0.46 or 1.07 m, depending on the location of the air injection port, (2) $h_{12} = 0$, (3) h_{23} = 10.06 or 9.45 m, depending on the location of the air injection port, and (4) h_{34}, which varied between 0.14 and 0.88 m for each particular experiment. The net applied head $h_{00'}$ was measured for each particular experiment.

In the test, the pressure, temperature, flow rates, and applied water head data were recorded. The test conditions included the variation in water flow rate, the air injection rate, injection nozzle sizes (single and multinozzle), and locations of injection nozzles in the water pipe.

4.1 Steady-State Operation

Constant water levels were maintained in both water tanks. Temperature and vacuum pressures were monitored to determine when steady-state conditions existed.

Steady state was assumed when there was no significant change in temperature (±0.1°C) and vacuum pressure, and when flow rate change was less than ±2% throughout the system over a 10-min span. Once steady state was achieved, the following data were recorded: (1) water and air flow rates through the downcomer; (2) temperatures of the air and the water in the downcomer; (3) level of water in tank 1; (4) applied water head; and (5) pressure of the atmosphere, air injection, and downcomer systems.

After all data were recorded, the air flow rate through the downcomer was changed; adjustment was made until a new steady-state condition was achieved. Experimental data were again recorded, and the procedure was repeated.

4.2 Results of Hydraulic Air Compression Tests

Experimental results for hydraulic air compression with water were studied in a 5.1-cm-diam clear pipe. Liquid velocity was varied from 40 to 155 cm/s, air flow from 0.7 to 37 cm/s, and the system vacuum pressure from 1.3 to 10.1 kPa absolute. Two sizes of single air nozzles (1.14- and 0.46-mm ID) and two 1.14-mm-ID multinozzles were tested. The positions of injection ports were 45.7 and 106.7 cm below the point 0′, respectively (Fig. 4).

Six series of tests were completed. In the first series of runs, a single air injection nozzle was used. The nozzle opening was 0.46 mm in diameter and was located 45.7 cm below the water surface (point 0′, Fig. 4). The second series of runs was identical to the first series, but the air injection nozzle was located 106.7 cm below the water surface. The only difference between series 3 and series 1 was the air injection nozzle size; the nozzle for series 3 was 1.14 mm in diameter. In the fourth series of runs, a single air injection nozzle, 1.14-mm diam, was used. The nozzle was located 106.7 cm below the water surface. Series 5 was a multinozzle (two-nozzle) test, with the air injection nozzles located 45.7 cm below the water surface and nozzle diameters of 1.14 mm. Test series 6 was similar to series 5 with the only difference being the location of aeration. In series 6, the air injection port was 106.7 cm below the water surface. Data obtained in this investigation are presented in Tables 1–6. Data on the hydraulic head requirement for all series of tests are shown in Figs. 5–10. As shown in all these figures, for a fixed air flow rate, the applied head decreased as the water flow increased. The applied head

Table 1. Test series 1 (single nozzle, 0.46-mm diam)

Run	⟨J_w⟩ (cm/s)	⟨J_a⟩ (cm/s)	⟨J⟩ (cm/s)	h_{23} (m)	h_{34} (m)	P, atm (psia)	P, test (psig)	T, test (°F)	β	ΔH (m)	Flow regime[a]
100	40.54	1.27	41.8	10.1	0.86	14.24	-13.9	65.3	0.03	0.2	B
101	40.54	2.53	43.1	10.1	0.86	14.24	-13.9	65.3	0.06	1.22	S
102	40.54	8.68	49.2	10.1	0.86	14.24	-13.9	65.3	0.18	1.6	S
103	56.8	1.43	58.2	10.1	0.79	14.25	-13.94	61.0	0.02	0.01	B
104	56.8	3.96	60.7	10.1	0.79	14.25	-13.94	61.0	0.06	0.37	B
105	56.8	10.10	66.86	10.1	0.79	14.25	-13.94	61.0	0.15	0.84	B
106	56.8	11.70	68.7	10.1	0.79	14.25	-13.94	61.0	0.17	1.4	B
107	72.97	1.38	74.4	10.1	0.71	14.26	-13.92	60.5	0.02	0.02	B
108	72.97	4.15	77.1	10.1	0.71	14.26	-13.92	60.5	0.05	0.23	B
109	72.97	10.42	83.4	10.1	0.71	14.26	-13.92	60.5	0.13	0.65	B
110	72.97	12.67	85.65	10.1	0.71	14.26	-13.92	60.5	0.15	1.1	B
111	89.2	1.5	90.7	10.1	0.51	14.3	-13.92	61.1	0.02	0.013	B
112	89.2	4.65	93.8	10.1	0.51	14.3	-13.92	61.1	0.05	0.16	B
113	89.2	10.9	100.1	10.1	0.51	14.3	-13.92	61.1	0.11	0.47	B
114	89.2	13.4	102.6	10.1	0.51	14.3	-13.92	61.1	0.13	0.82	B
115	105.4	0.97	106.4	10.1	0.48	14.3	-13.91	59.4	0.01	0.01	B
116	105.4	4.61	110.0	10.1	0.48	14.3	-13.91	59.4	0.04	0.13	B
117	105.4	10.88	116.3	10.1	0.48	14.3	-13.91	59.4	0.09	0.36	B
118	105.4	13.80	119.2	10.1	0.48	14.3	-13.91	59.4	0.12	0.59	B
119	121.6	1.54	123.2	10.1	0.38	14.3	-13.98	58.9	0.01	0.01	B
120	121.6	5.03	126.6	10.1	0.38	14.3	-13.98	58.9	0.04	0.13	B
121	121.6	11.4	133.0	10.1	0.38	14.3	-13.98	58.9	0.09	0.30	B
122	121.6	14.5	136.1	10.1	0.38	14.3	-13.98	58.9	0.11	0.52	B
123	137.8	1.57	139.4	10.1	0.33	14.3	-14.02	59.6	0.011	0.01	B

Table 1 (continued)

Run	⟨J_w⟩ (cm/s)	⟨J_a⟩ (cm/s)	⟨J⟩ (cm/s)	h_{23} (m)	h_{34} (m)	P, atm (psia)	P, test (psig)	T, test (°F)	β	ΔH (m)	Flow regime[a]
124	137.8	4.98	142.8	10.1	0.53	14.3	-14.02	59.6	0.03	0.14	B
125	137.8	11.64	149.5	10.1	0.33	14.3	-14.02	59.6	0.08	0.27	B
126	137.8	14.58	152.4	10.1	0.33	14.3	-14.02	59.6	0.10	0.51	B
127	154.1	1.4	155.6	10.1	0.28	14.3	-13.9	62.3	0.01	0.01	B
128	154.1	5.0	159.1	10.1	0.28	14.3	-13.9	62.3	0.03	0.07	B
129	154.1	11.5	165.6	10.1	0.28	14.3	-13.9	62.3	0.07	0.21	B
130	154.1	14.7	168.7	10.1	0.28	14.3	-13.9	62.3	0.09	0.40	B

[a]B = bubbly flow, and S = slug flow.

Table 2. Test series 2 (single nozzle, 0.46-mm diam)

Run	$\langle J_w \rangle$ (cm/s)	$\langle J_a \rangle$ (cm/s)	$\langle J \rangle$ (cm/s)	h_{23} (m)	h_{34} (m)	P, atm (psia)	P, test (psig)	T, test (°F)	β	ΔH (m)	Flow regime[a]
150	40.5	1.3	33.72	9.45	0.88	14.2	-13.87	65.0	0.04	0.25	S+B
151	40.5	1.4	41.94	9.45	0.88	14.2	-13.87	65.0	0.03	0.24	S
152	40.5	3.3	43.82	9.45	0.88	14.2	-13.87	65.0	0.075	0.71	S
153	40.5	9.5	50.01	9.45	0.88	14.2	-13.87	65.0	0.19	1.14	S
154	64.9	1.11	65.98	9.45	0.77	14.2	-13.83	63.7	0.02	0.015	B
155	64.9	4.56	69.43	9.45	0.77	14.2	-13.83	63.7	0.07	0.184	B
156	64.9	10.75	75.62	9.45	0.77	14.2	-13.83	63.7	0.14	0.50	B
157	64.9	13.42	78.30	9.45	0.77	14.2	-13.83	63.7	0.17	0.79	B
158	89.2	1.07	90.26	9.45	0.66	14.2	-13.89	62.7	0.012	0.009	B
159	89.2	3.24	92.43	9.45	0.66	14.2	-13.89	62.7	0.035	0.12	B
160	89.2	7.71	96.9	9.45	0.66	14.2	-13.89	62.7	0.079	0.27	B
161	89.2	10.2	99.4	9.45	0.66	14.2	-13.89	62.7	0.103	0.60	B
162	113.52	1.8	115.3	9.45	0.51	14.3	-14.01	65.1	0.015	0.006	B
163	113.52	5.3	118.8	9.45	0.51	14.3	-14.01	65.1	0.045	0.09	B
164	113.52	11.9	125.4	9.45	0.51	14.3	-14.01	65.1	0.095	0.22	B
165	113.52	15.2	128.7	9.45	0.51	14.3	-14.01	65.1	0.12	0.38	B
166	137.8	1.7	139.6	9.45	0.41	14.3	-14.03	63.6	0.012	0.006	B
167	137.8	5.2	143.0	9.45	0.41	14.3	-14.03	63.6	0.036	0.06	B
168	137.8	12.2	150.0	9.45	0.41	14.3	-14.03	63.6	0.08	0.18	B
169	137.8	15.5	153.3	9.45	0.41	14.3	-14.03	63.6	0.10	0.34	B
170	154.06	1.74	155.8	9.45	0.33	14.3	-14.05	61.9	0.011	0.006	B
171	154.06	5.44	159.5	9.45	0.33	14.3	-14.05	61.9	0.034	0.047	B
172	154.06	12.46	166.5	9.45	0.33	14.3	-14.05	61.9	0.075	0.15	B
173	154.06	15.96	170.0	9.45	0.33	14.3	-14.05	61.9	0.094	0.29	B

[a]B = bubbly flow, and S = slug flow.

Table 3. Test series 3 (single nozzle, 1.14-mm diam)

Run	$\langle J_w \rangle$ (cm/s)	$\langle J_a \rangle$ (cm/s)	$\langle J \rangle$ (cm/s)	h_{23} (m)	h_{34} (m)	P, atm (psia)	P, test (psig)	T, test (°F)	β	ΔH, test (m)	ΔH,[a] computer (m)	Flow regime[b]
200	56.8	2.21	58.97	10.1	0.74	14.3	-14.08	61.9	0.04	0.08	0.28	B
201	56.8	4.43	61.18	10.1	0.74	14.3	-14.08	61.9	0.07	0.36	0.62	B
202	56.8	6.23	63.0	10.1	0.74	14.3	-14.08	61.9	0.10	0.78	0.93	B
203	56.8	8.23	65.4	10.1	0.74	14.3	-14.08	61.9	0.13	1.02	1.3	B
204	73.0	2.06	75.03	10.1	0.66	14.3	-14.05	60.7	0.03	0.06	0.124	B
205	73.0	4.61	77.58	10.1	0.66	14.3	-14.05	60.7	0.06	0.27	0.325	B
206	73.0	7.07	80.04	10.1	0.66	14.3	-14.05	60.7	0.09	0.51	0.55	B
207	73.0	9.81	82.8	10.1	0.66	14.3	-14.05	60.7	0.12	0.72	0.83	B
208	73.0	12.81	85.8	10.1	0.66	14.3	-14.05	60.7	0.15	0.99	1.2	B
209	89.2	2.1	91.3	10.1	0.56	14.3	-14.05	59.2	0.02	0.03	0.09	B
210	89.2	4.7	93.9	10.1	0.56	14.3	-14.05	59.2	0.05	0.16	0.22	B
211	89.2	7.6	96.8	10.1	0.56	14.3	-14.05	59.2	0.08	0.34	0.38	B
212	89.2	10.9	100.1	10.1	0.56	14.3	-14.05	59.2	0.11	0.48	0.61	B
213	89.2	13.4	102.6	10.1	0.56	14.3	-14.05	59.2	0.13	0.83	0.80	B
214	113.5	2.01	115.6	10.1	0.36	14.4	-14.15	61.2	0.02	0.02	0.06	B
215	113.5	4.8	118.4	10.1	0.36	14.4	-14.15	61.2	0.04	0.11	0.15	B
216	113.5	8.1	121.6	10.1	0.36	14.4	-14.15	61.2	0.07	0.24	0.28	B
217	113.5	11.4	124.9	10.1	0.36	14.4	-14.15	61.2	0.09	0.32	0.42	B
218	113.5	15.4	129.0	10.1	0.36	14.4	-14.15	61.2	0.12	0.53	0.62	B
219	137.8	2.2	140.0	10.1	0.24	14.4	-14.24	57.8	0.02	0.01	0.01	B
220	137.8	5.7	143.5	10.1	0.24	14.4	-14.24	57.8	0.04	0.1	0.13	B

Table 3 (continued)

Run	$\langle J_w \rangle$ (cm/s)	$\langle J_a \rangle$ (cm/s)	$\langle J \rangle$ (cm/s)	h_{23} (m)	h_{34} (m)	P, atm (psia)	P, test (psig)	T, test (°F)	β	ΔH, test (m)	ΔH,[a] computer (m)	Flow regime[b]
221	137.8	9.7	147.5	10.1	0.24	14.4	−14.24	57.8	0.07	0.2	0.25	B
222	137.8	13.75	150.7	10.1	0.24	14.4	−14.24	57.8	0.09	0.3	0.39	B
223	137.8	17.05	171.1	10.1	0.24	14.4	−14.24	57.8	0.1	0.5	0.44	B
224	154.1	2.15	156.2	10.1	0.23	14.4	−14.2	59.1	0.014	0.01	0.04	B
225	154.1	5.12	159.2	10.1	0.23	14.4	−14.2	59.1	0.03	0.08	0.11	B
226	154.1	8.7	162.7	10.1	0.23	14.4	−14.2	59.1	0.05	0.19	0.20	B
227	154.1	13.1	167.2	10.1	0.23	14.4	−14.2	59.1	0.08	0.30	0.33	B
228	154.1	17.4	171.2	10.1	0.23	14.4	−14.2	59.1	0.1	0.48	0.46	B
229	40.5	2.1	42.6	10.1	0.66	14.4	−14.2	58.2	0.05	0.15	0.98	S
230	40.5	5.1	45.6	10.1	0.66	14.4	−14.2	58.2	0.11	0.24	2.07	S
231	40.5	5.6	46.1	10.1	0.66	14.4	−14.2	58.2	0.12	1.0	2.2	S
229.1	48.6	1.06	49.7	10.1	0.71	14.4	−14.1	60.2	0.02	0.01	0.22	B
230.2	48.6	2.04	50.7	10.1	0.71	14.4	−14.1	60.2	0.04	0.11	0.11	B
231.3	48.6	3.14	51.8	10.1	0.71	14.4	−14.1	60.2	0.06	0.31	0.72	B
232.4	48.6	3.9	52.5	10.1	0.71	14.4	−14.1	60.2	0.07	0.51	0.92	B
233	48.6	4.8	53.5	10.1	0.71	14.4	−14.15	60.2	0.09	0.7	1.16	B
234	48.6	5.8	54.4	10.1	0.71	14.4	−14.15	60.2	0.11	0.9	0.88	S
235	48.6	6.6	55.2	10.1	0.71	14.4	−14.15	60.2	0.12	1.09	1.09	S
236	48.6	6.0	54.6	10.1	0.71	14.4	−14.15	60.2	0.11	1.6	1.44	
237	48.6	1.05	41.6	10.1	0.74	14.4	−14.15	59.1	0.025	0.01	0.58	B
238	48.6	2.01	42.5	10.1	0.74	14.4	−14.15	59.1	0.05	0.22	1.05	B
239	48.6	2.5	43.1	10.1	0.74	14.4	−14.15	59.1	0.06	0.48	1.3	B
240	48.6	3.5	44.1	10.1	0.74	14.4	−14.15	59.1	0.08	0.81	1.7	S

[a] In computation, V_r (drift velocity) was a constant (45.7 cm/s) for all tests.

[b] B = bubbly flow, and S = slug flow.

Table 4. Test series 4 (single nozzle, 1.14-mm diam)

Run	$\langle J_w \rangle$ (cm/s)	$\langle J_a \rangle$ (cm/s)	$\langle J \rangle$ (cm/s)	h_{33} (m)	h_{34} (m)	P, atm (psia)	P, test (psig)	T, test (°F)	β	ΔH (m)	Flow regime[a]
302	56.8	1.54	58.3	9.45	0.61	14.5	-14.2	58.2	0.03	0.07	B
303	56.8	3.53	60.3	9.45	0.61	14.5	-14.2	58.2	0.06	0.39	B
304	56.8	6.06	62.8	9.45	0.61	14.5	-14.2	58.2	0.1	0.80	B
305	56.8	18.62	75.4	9.45	0.61	14.5	-14.2	58.2	0.25	1.44	B+S
306	72.9	0.79	73.8	9.45	0.74	14.2	-13.9	62.0	0.01	0.003	B
307	72.9	1.7	74.7	9.45	0.74	14.2	-13.9	62.0	0.02	0.025	B
308	72.9	2.7	75.6	9.45	0.74	14.2	-13.9	62.0	0.03	0.10	B
309	72.9	3.9	76.9	9.45	0.74	14.2	-13.9	62.0	0.05	0.3	B
310	72.9	6.3	79.3	9.45	0.74	14.2	-13.9	6.20	0.08	0.4	B
311	72.9	8.1	81.1	9.45	0.74	14.2	-13.9	6.20	0.1	0.56	B
312	72.9	10.2	83.2	9.45	0.74	14.2	-13.9	61.2	0.12	0.67	B
313	72.9	23.1	96.1	9.45	0.74	14.2	-13.9	61.2	0.24	0.85	B
314	72.9	22.4	95.4	9.45	0.74	14.2	-13.9	61.2	0.23	1.03	S
315	72.9	24.3	97.3	9.45	0.74	14.2	-13.9	61.2	0.25	1.31	S
316	97.3	0.76	98.1	9.45	0.62	14.2	-13.95	60.0	0.01	0.013	B
317	97.3	1.65	99.0	9.45	0.62	14.2	-13.95	60.0	0.02	0.05	B
318	97.3	2.7	100.0	9.45	0.62	14.2	-13.95	60.0	0.03	0.1	B
319	97.3	3.99	101.3	9.45	0.62	14.2	-13.95	60.0	0.04	0.16	B
320	97.3	5.5	102.8	9.45	0.62	14.2	-13.95	60.0	0.05	0.25	B
321	97.3	7.5	104.8	9.45	0.62	14.2	-13.95	60.0	0.07	0.36	B
322	97.3	9.6	106.9	9.45	0.62	14.2	-13.95	59.4	0.09	0.47	B
323	97.3	20.6	117.9	9.45	0.62	14.2	-13.95	59.4	0.17	0.74	B
324	97.3	23.2	120.5	9.45	0.62	14.2	-13.95	59.4	0.19	0.74	B
325	97.3	25.15	122.5	9.45	0.62	14.2	-13.95	59.4	0.21	1.02	B

Table 4 (continued)

Run	⟨J_w⟩ (cm/s)	⟨J_a⟩ (cm/s)	⟨J⟩ (cm/s)	h_{23} (m)	h_{34} (m)	P, atm (psia)	P, test (psig)	T, test (°F)	β	ΔH (m)	Flow regime[a]
326	121.6	0.76	122.4	9.45	0.36	14.4	-14.15	61.3	0.01	0.01	B
327	121.6	1.64	123.3	9.45	0.36	14.4	-14.15	61.3	0.013	0.04	B
328	121.6	2.7	124.3	9.45	0.36	14.4	-14.15	61.3	0.02	0.09	B
329	121.6	3.9	125.5	9.45	0.36	14.4	-14.15	61.3	0.03	0.14	B
330	121.6	1.15	122.8	9.45	0.36	14.4	-14.15	61.3	0.01	0.16	B
331	121.6	2.64	124.3	9.45	0.36	14.4	-14.15	61.3	0.02	0.28	B
332	121.6	4.26	125.9	9.45	0.36	14.4	-14.15	60.9	0.034	0.42	B
333	121.6	10.5	132.1	9.45	0.36	14.4	-14.15	60.9	0.079	0.52	B+S
334	121.6	23.2	144.9	9.45	0.36	14.4	-14.15	60.9	0.16	0.67	S
335	121.6	24.9	146.6	9.45	0.36	14.4	-14.15	60.9	0.17	1.1	S
336	137.8	0.75	138.6	9.45	0.28	14.4	-14.2	59.4	0.005	0.01	B
337	137.8	1.61	139.4	9.45	0.28	14.4	-14.2	59.4	0.01	0.04	B
338	137.8	2.66	140.5	9.45	0.28	14.4	-14.2	59.4	0.02	0.08	B
339	137.8	3.92	141.8	9.45	0.28	14.4	-14.2	59.4	0.03	0.14	B
340	137.8	5.87	143.7	9.45	0.28	14.4	-14.2	59.4	0.04	0.15	B
341	137.8	7.7	145.5	9.45	0.28	14.4	-14.2	59.4	0.05	0.27	B
342	137.8	9.9	147.7	9.45	0.28	14.4	-14.2	59.0	0.07	0.36	S
343	137.8	21.1	159.0	9.45	0.28	14.4	-14.2	59.0	0.13	0.44	S
344	137.8	23.5	161.4	9.45	0.28	14.4	-14.2	59.0	0.15	0.61	S
345	137.8	25.1	162.9	9.45	0.28	14.4	-14.2	59.0	0.15	1.1	S
346	154.1	0.92	155.0	9.45	0.14	14.0	-12.5	66.9	0.006	0.006	B
347	154.1	2.03	156.1	9.45	0.14	14.0	-12.5	66.9	0.013	0.038	B
348	154.1	3.4	157.4	9.45	0.14	14.0	-12.5	66.9	0.02	0.072	B
349	154.1	4.9	159.0	9.45	0.14	14.0	-12.5	66.9	0.03	0.13	B

Table 4 (continued)

Run	$\langle J_w \rangle$ (cm/s)	$\langle J_a \rangle$ (cm/s)	$\langle J \rangle$ (cm/s)	h_{23} (m)	h_{34} (m)	P, atm (psia)	P, test (psig)	T, test (°F)	β	ΔH (m)	Flow regime[a]
350	154.1	7.75	161.8	9.45	0.14	14.0	-12.5	66.9	0.05	0.15	B
351	154.1	10.1	164.1	9.45	0.14	14.0	-12.5	66.9	0.06	0.2	S
352	154.1	12.98	167.0	9.45	0.14	14.0	-12.5	66.9	0.08	0.34	S
353	154.1	26.5	180.6	9.45	0.14	14.0	-12.5	66.9	0.15	0.42	S
354	154.1	29.8	183.8	9.45	0.14	14.0	-12.5	66.9	0.16	0.54	S
355	154.1	32.1	186.2	9.45	0.14	14.0	-12.5	66.9	0.17	0.7	S
356	40.5	0.7	41.3	9.45	0.69	14.4	-14.15	63.7	0.02	0.08	B
357	40.5	1.45	42.0	9.45	0.69	14.4	-14.15	63.7	0.03	0.29	B
358	40.5	2.26	42.8	9.45	0.69	14.4	-14.15	63.7	0.05	0.49	B
359	40.5	3.2	43.7	9.45	0.69	14.4	-14.15	63.7	0.07	0.7	S
360	40.5	2.9	43.5	9.45	0.69	14.4	-14.15	63.7	0.07	1.6	S
361	73.0	1.9	74.9	9.45	0.84	14.15	-13.76	68.0	0.025	0.08	B
362	73.0	5.6	78.5	9.45	0.84	14.15	-13.76	68.0	0.07	0.67	B
363	73.0	15.7	88.7	9.45	0.84	14.15	-13.76	68.0	0.18	1.51	S
364	73.0	1.9	74.9	9.45	0.74	14.15	-13.76	65.8	0.025	0.08	B
365	73.0	5.6	78.5	9.45	0.74	14.15	-13.76	65.8	0.07	0.67	B
366	73.0	15.7	88.7	9.45	0.74	14.15	-13.76	65.8	0.18	1.5	S
367	105.4	1.82	107.2	9.45	0.66	14.2	-13.77	65.8	0.02	0.05	B
368	105.4	6.01	111.4	9.45	0.66	14.2	-13.77	65.8	0.05	0.5	B
369	105.4	15.6	121.0	9.45	0.66	14.2	-13.77	65.8	0.13	1.6	S
370	121.6	1.93	123.6	9.45	0.43	14.4	-14.01	66.6	0.02	0.06	B
371	121.6	6.2	127.8	9.45	0.43	14.4	-14.01	66.6	0.05	0.5	B
372	121.6	15.8	137.4	9.45	0.43	14.4	-14.01	66.6	0.11	1.6	S
373	137.8	1.8	139.6	9.45	0.36	14.4	-13.9	63.8	0.01	0.04	B
374	137.8	6.4	144.2	9.45	0.36	14.4	-13.9	63.8	0.04	0.39	S
375	137.8	16.02	153.9	9.45	0.36	14.4	-13.9	63.8	0.10	1.8	S
376	137.8	16.04	153.9	9.45	0.36	14.4	-13.9	63.8	0.10	1.6	S

[a]B = bubbly flow, and S = slug flow.

Table 5. Test series 5 (multinozzle, two 1.14-mm diam)

Run	$\langle J_w \rangle$ (cm/s)	$\langle J_a \rangle$ (cm/s)	$\langle J \rangle$ (cm/s)	h_{23} (m)	h_{34} (m)	P, atm (psia)	P, test (psig)	T, test (°F)	β	ΔH, test (m)	ΔH,[a] computer (m)	Flow regime[b]
400	73.0	2.2	75.1	10.1	0.71	14.3	−13.9	65.0	0.03	0.04	0.13	B
401	73.0	4.6	77.6	10.1	0.71	14.3	−13.9	65.0	0.06	0.34	0.30	B
402	73.0	8.8	81.8	10.1	0.71	14.3	−13.9	65.0	0.11	0.84	0.71	B
403	73.0	10.0	82.9	10.1	0.71	14.3	−13.9	65.0	0.12	1.53	0.91	S
404	89.2	2.2	91.4	10.1	0.60	14.27	−13.9	63.7	0.02	0.025	0.087	B
405	89.2	4.8	94.0	10.1	0.60	14.27	−13.9	63.7	0.05	0.22	0.23	B
406	89.2	10.4	99.6	10.1	0.60	14.27	−13.9	63.7	0.10	0.76	0.58	B
407	89.2	11.4	100.6	10.1	0.60	14.27	−13.9	63.7	0.11	1.21	1.29	S
409	105.4	2.2	107.6	10.1	0.48	14.3	−14.02	64.1	0.02	0.01	0.07	B
410	105.4	5.1	110.5	10.1	0.48	14.3	−14.02	64.1	0.05	0.16	0.20	B
411	105.4	8.2	113.6	10.1	0.48	14.3	−14.02	64.1	0.07	0.68	0.83	B
412	105.4	11.6	117.0	10.1	0.48	14.3	−14.02	64.1	0.1	1.2	1.23	B+S
413	105.4	32.7	138.1	10.1	0.48	14.3	−14.02	64.1	0.24	1.7	2.01	S
414	121.6	1.99	123.6	10.1	0.39	14.3	−14.01	62.6	0.02	0.01	0.06	B
415	121.6	4.96	126.6	10.1	0.39	14.3	−14.01	62.6	0.04	0.12	0.15	B
416	121.6	9.83	131.4	10.1	0.39	14.3	−14.01	62.6	0.07	0.65	0.75	B
417	121.6	12.3	133.9	10.1	0.39	14.3	−14.01	62.6	0.09	1.05	1.13	B
418	121.6	33.0	154.6	10.1	0.39	14.3	−14.01	62.6	0.21	1.49	1.67	S
419	121.6	35.2	156.8	10.1	0.39	14.3	−14.01	62.6	0.22	1.66	1.79	S
420	137.8	2.01	139.8	10.1	0.33	14.3	−14.02	62.1	0.014	0.013	0.05	B

Table 5 (continued)

Run	$\langle J_w \rangle$ (cm/s)	$\langle J_a \rangle$ (cm/s)	$\langle J \rangle$ (cm/s)	h_{33} (m)	h_{34} (m)	P, atm (psia)	P, test (psig)	T, test (°F)	β	ΔH, test (m)	ΔH, computer[a] (m)	Flow regime[b]
421	137.8	2.4	140.2	10.1	0.33	14.3	−14.02	62.1	0.017	0.095	0.07	B
422	137.8	8.4	146.2	10.1	0.33	14.3	−14.02	62.1	0.057	0.6	0.67	B+S
423	137.8	12.04	150.0	10.1	0.33	14.3	−14.02	62.1	0.08	0.98	1.07	B+S
424	137.8	9.34	147.2	10.1	0.33	14.3	−14.02	62.1	0.06	1.63	1.58	B+S
425	137.8	1.96	156.02	10.1	0.32	14.2	−13.9	62.3	0.013	0.006	0.044	B
426	137.8	5.73	159.8	10.1	0.32	14.2	−13.9	62.3	0.036	0.038	0.140	B
427	137.8	8.85	162.9	10.1	0.32	14.2	−13.9	62.3	0.054	0.55	0.69	S
428	137.8	12.64	166.7	10.1	0.32	14.2	−13.9	62.3	0.076	0.89	1.14	S
429	137.8	35.01	189.1	10.1	0.32	14.2	−13.9	62.3	0.18	1.19	1.31	S
430	137.8	36.14	190.2	10.1	0.32	14.2	−13.9	62.3	0.19	1.5	1.63	S
431	154.1	1.93	58.7	10.1	0.84	14.2	−13.9	60.4	0.03	0.08	0.18	B
432	154.1	4.42	61.2	10.1	0.84	14.2	−13.9	60.4	0.07	0.32	0.51	B
433	154.1	6.85	63.6	10.1	0.84	14.2	−13.9	60.4	0.01	1.05	0.97	S

[a]In computation, V_r (drift velocity) was a variable for each test.

[b]B = bubbly flow, and S = slug flow.

Table 6. Test series 6 (multinozzle, two 1.14-mm diam)

Run	$\langle J_w \rangle$ (cm/s)	$\langle J_a \rangle$ (cm/s)	$\langle J \rangle$ (cm/s)	h_{23} (m)	h_{34} (m)	P, atm (psia)	P, test (psig)	T, test (°F)	β	ΔH (m)	Flow regime[a]
450	56.8	1.76	58.5	9.45	0.85	14.3	-13.97	64.2	0.03	0.10	B
451	56.8	5.02	61.8	9.45	0.85	14.3	-13.97	64.2	0.08	0.86	B+S
452	56.8	15.9	72.7	9.45	0.85	14.3	-13.97	64.2	0.22	2.0	S
453	73.0	1.76	74.7	9.45	0.67	14.3	-13.95	62.4	0.02	0.051	B
454	73.0	5.7	78.7	9.45	0.67	14.3	-13.95	62.4	0.07	0.61	B
455	73.0	15.8	88.8	9.45	0.67	14.3	-13.95	62.4	0.18	1.76	B
456	89.2	1.8	91.0	9.45	0.6	14.3	-13.96	61.5	0.02	0.04	B
457	89.2	5.85	95.0	9.45	0.6	14.3	-13.96	61.5	0.06	0.56	B
458	89.2	15.8	105.0	9.45	0.6	14.3	-13.96	61.5	0.15	1.7	B
459	105.4	1.82	107.2	9.45	0.4	14.4	-14.15	63.0	0.02	0.04	B
460	105.4	6.02	111.4	9.45	0.4	14.4	-14.15	63.0	0.05	0.5	B
461	105.4	15.9	121.3	9.45	0.4	14.4	-14.15	63.0	0.13	1.6	B
465	137.8	1.82	139.7	9.45	0.27	14.4	-14.15	59.6	0.013	0.04	B
466	137.8	6.34	144.2	9.45	0.27	14.4	-14.15	59.6	0.04	0.43	B
467	137.8	15.9	153.7	9.45	0.27	14.4	-14.15	59.6	0.10	1.55	B
468	154.1	1.74	155.8	9.45	0.18	14.4	-14.15	61.4	0.01	0.006	B
469	154.1	6.4	160.5	9.45	0.18	14.4	-14.15	61.4	0.04	0.43	B
470	154.1	15.7	170.0	9.45	0.18	14.4	-14.15	61.4	0.09	1.50	B

[a]B = bubbly flow, and S = slug flow.

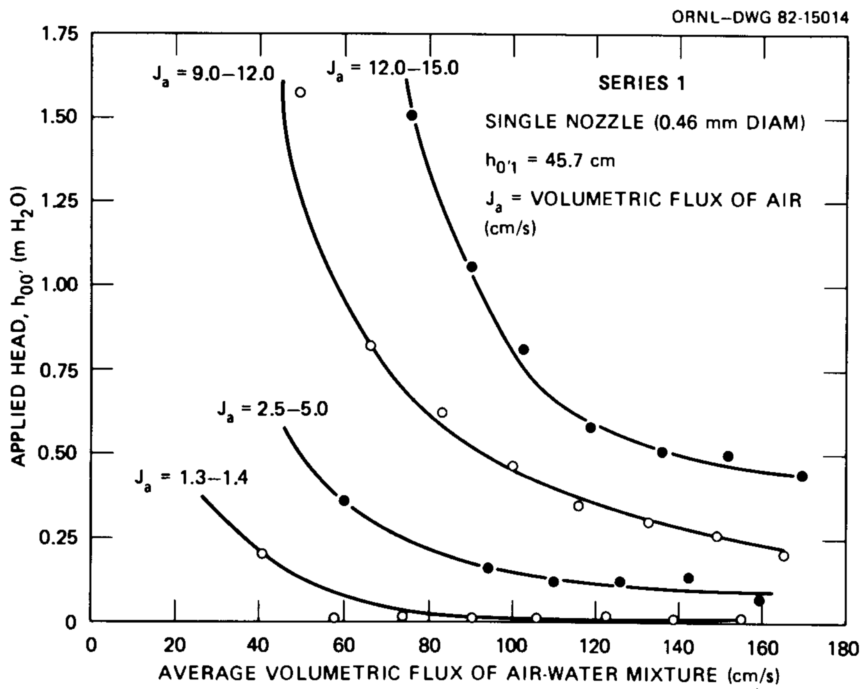

Fig. 5. Performance of hydraulic air compression for test series 1.

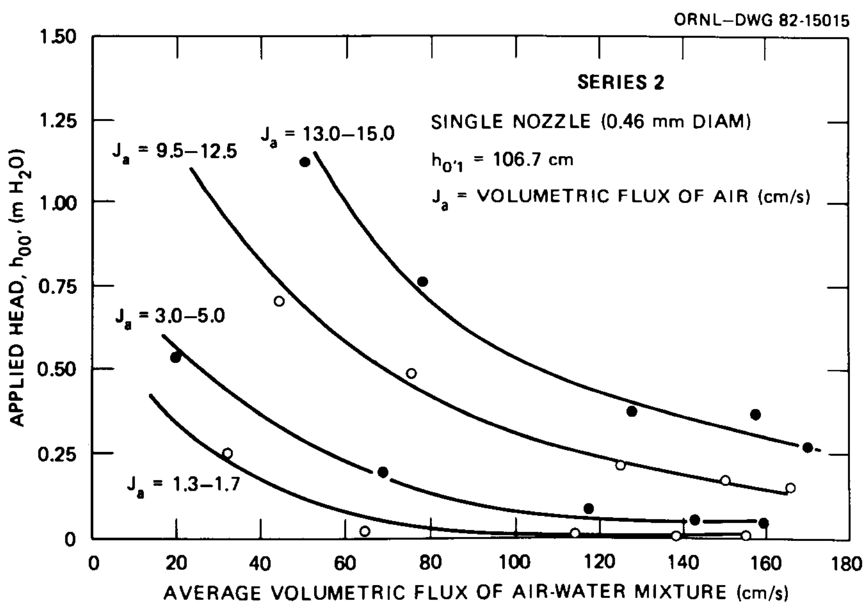

Fig. 6. Performance of hydraulic air compression for test series 2.

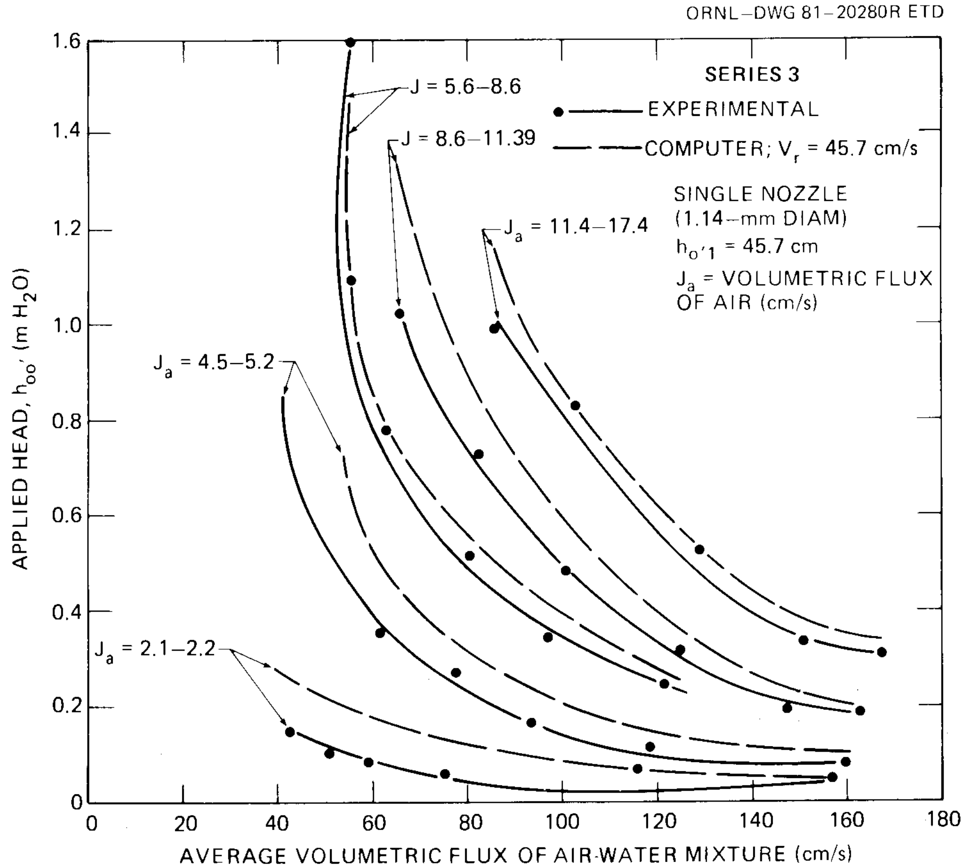

Fig. 7. Performance of hydraulic air compression for test series 3 and comparison of test results with computer simulation.

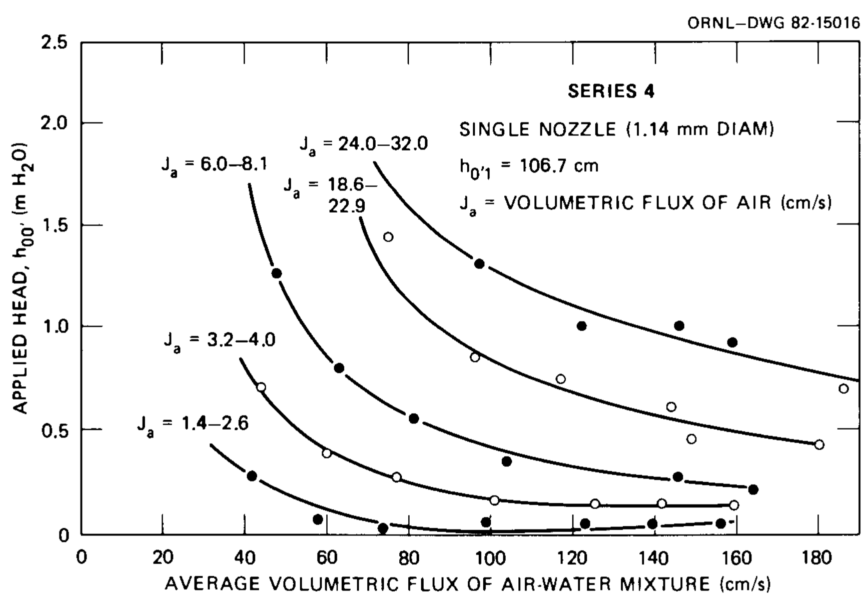

Fig. 8. Performance of hydraulic air compression for test series 4.

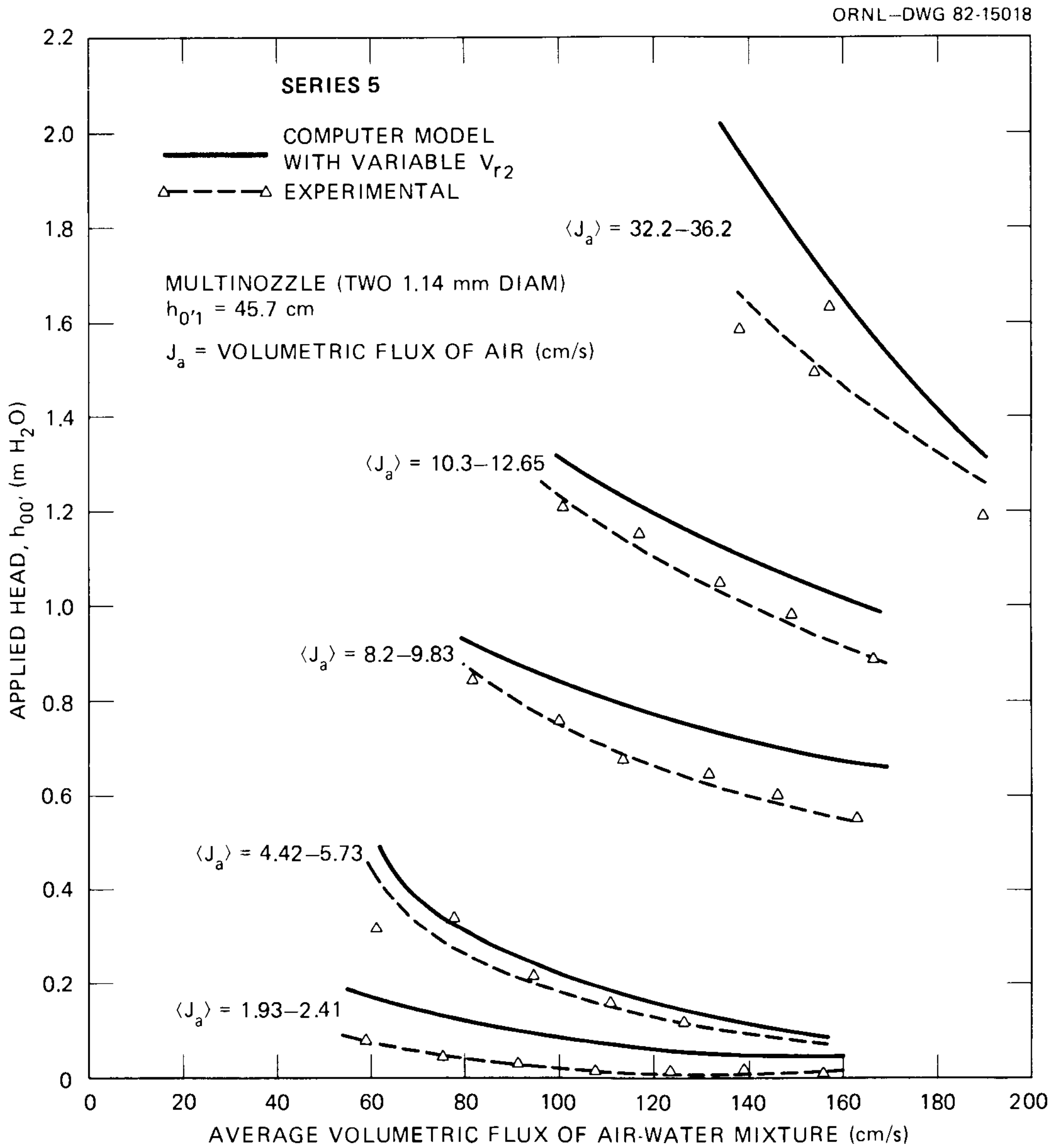

Fig. 9. Performance of hydraulic air compression for test series 5 and comparison of test results with computer simulation.

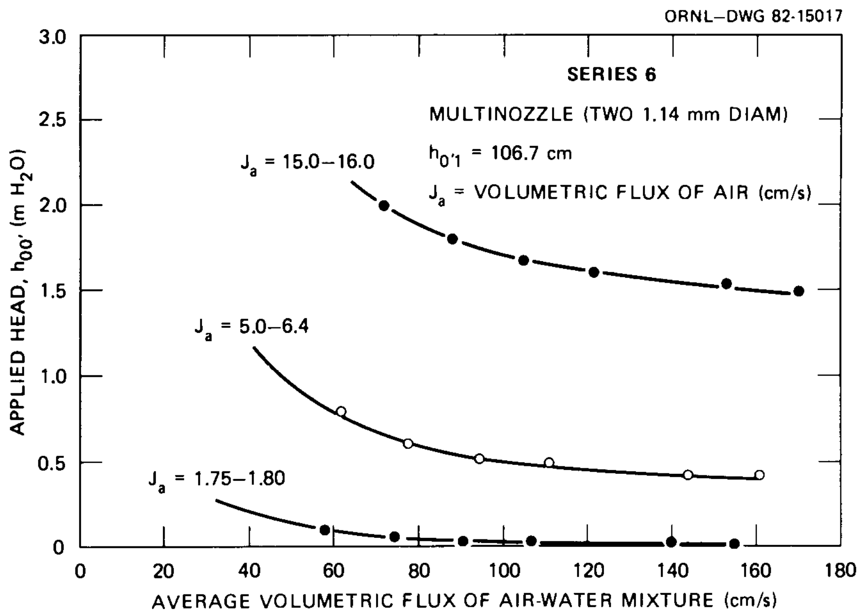

Fig. 10. Performance of hydraulic air compression for test series 6.

also increased as the air injection rate increased. Computer data on the hydraulic head requirements (which are explained in detail in Sect. 5 of this report) to simulate the experiments are also shown in Tables 3 and 5. A reasonable agreement between the test results and the simulation is shown in Figs. 7 and 9.

In these two cases, a constant drift velocity (water velocity less air velocity) of 0.45 m/s was used in the computer model to simulate the test data of the series 3. However, a variable drift velocity was used to obtain the computer simulation results that match the experimental values of the test series 5.

5. COMPUTER SIMULATION OF HYDRAULIC AIR COMPRESSION

An analytical model was developed for the hydraulic air compression process, and it was implemented for calculation on a digital computer. The analytical derivation of the model is based on a similar application developed by Rice,[4] but it differs from his model in the numerical implementation scheme of the analytical results. The analysis of the hydraulic air compression process is one-dimensional. Average velocities across the pipe cross section are used. The flow is assumed steady and the liquid incompressible. A two-phase flow model is employed where air and water are present. The air is treated as an ideal gas. A schematic of a hydraulic air compression test section is shown in Fig. 4. Four control volumes are drawn and shown (Fig. 4) to simulate the hydraulic air compression: (1) the flow above air entrainment zone, (0) to (1); (2) air entrainment zone, (1) to (2); (3) two-phase air compression zone, (2) to (3); and (4) an air-water separation zone, (3) to (4).

Flow above air entrainment zone, (0) to (1). Water is fed from point (0′) in Fig. 4 into a down pipe. The incompressible form of energy equations applied between (0-0′) and (0′-1) with $V_0 = 0$ and the free surface at the elevation datum (0′) are

$$\frac{P_0}{\rho_\ell} + gh_{00'} = \frac{P_{0'}}{\rho_\ell} , \tag{1}$$

and

$$\frac{V_{\ell_{0'}}^2}{2} + \frac{P_{0'}}{\rho_\ell} = \frac{P_1}{\rho_\ell} + (K_{0'1} + K_{elb}) \left(\frac{V_{\ell_1}^2}{2}\right) - gh_{0'1} + \frac{V_{\ell_1}^2}{2} , \tag{2}$$

where $K_{0'1}$ is the friction loss coefficient, K_{elb} is the elbow coefficient ($K_{elb} = 0.9$), and $V_{0'} = V_1$. Considering that $h_{01} = h_{0'1} + h_{00'}$ and substituting Eq. (1) in Eq. (2),

$$P_1 = P_0 + \rho_\ell \left[gh_{01} - (K_{0'1} + 0.9) \frac{V_\ell^2}{2}\right] . \tag{3}$$

Air entrainment zone, (1) to (2). In this zone, boundaries (1) and (2) are assumed close together; fluid friction and the weight of the fluid within the control volume are neglected. Air enters across area A_a, and liquid enters across the cross-sectional area $(A_d - A_a)$. At (2) the air bubbles will have a relative velocity V_r with respect to water flow because of buoyancy. With given state variables at point (1) and air mass flow rate $\dot{m}_a$, the state variables at point (2), namely, $V_{\ell 2}$, P_2, and T_2, can be solved algebraically from the conservation of mass, momentum, and energy equations shown by Rice.[4]

Two-phase air compression zone, (2) to (3). After the air leaves the entrainment region, an air-water mixture is created that flows downward in the pipe where air bubbles are being compressed. The two-phase flow model in this zone assumes that each phase is one-dimensional in the pipe cross section. In the air compression zone, the volumetric change of air is significant, and it cannot be assumed constant throughout the control volume. To obtain the state variables at point (3), the conservation principles are applied to a differential control volume. A set of three differential equations with unknowns P, V_ℓ, and T as a function of z is obtained. A coordinate system is needed in this zone where z represents a positive downward distance from point (2). After some algebraic manipulation, the conservation of energy, mass, and momentum equations take the following forms:

$$[(\dot{m}_\ell + \dot{m}_a) V_\ell - \dot{m}_a V_r] \, dV_\ell + \frac{\dot{m}_\ell}{\rho_\ell} dP + (\dot{m}_\ell C_{v\ell} + \dot{m}_a C_{pa}) dT = g(\dot{m}_\ell + \dot{m}_a) dz \ , \quad (4)$$

$$\left[\frac{\dot{m}_\ell}{\rho_\ell V_\ell^2 \quad A_d - \dfrac{\dot{m}_a}{\rho_\ell V_\ell}} + \frac{1}{(V_\ell - V_r)} \right] dV_\ell + \frac{dP}{P} - \frac{dT}{T} = 0 \ , \quad (5)$$

and

$$dP + \frac{\dot{m}_\ell + \dot{m}_a}{A_d} dV_\ell = \left[\frac{\dot{m}_a g}{A_d(V_\ell - V_r)} + \frac{m_\ell g}{A_d V_\ell} - \frac{f\rho_\ell V_\ell^2 s}{8A_d} \right] dz \ . \qquad (6)$$

Starting from the values of $V_{\ell 2}$, P_2, and T_2 for $z = 0$ at point (2), Eqs. (4)–(6) can be solved by a forward-marching scheme using a small value of Δz to result in values of $V_{\ell 3}$, P_3, and T_3 at the bottom of the down pipe, point (3).

Air-water separation zone, (3) to (4). When the air-water mixture exits from the down pipe and enters the separation tank, the kinetic energy contained in the mixture will be dissipated if the tank is sufficiently large in volume. The air bubbles rise and enter the surrounding atmosphere above the water surface at atmospheric pressure, while the water is discharged to ambient. Therefore, the pressure balance in this zone is

$$P_4 = P_a = P_3 - \rho_\ell g h_{34} \ . \qquad (7)$$

5.1 Computation of Hydraulic Head Requirement

In the computer simulation of the analytical results, computation requires data on (1) pipe sizes, (2) geometrically fixed heads (excluding $h_{oo'}$), (3) fluid properties, (4) frictional parameters, and (5) air and water mass flow rates at point (2) (Fig. 4). An arbitrary value for the applied (hydraulic) head required to compress the air through the pipe is assumed, and the program calculates other values of the compressor (e.g., pressure and flow rates) using this value. The value for pressure at boundary point (4) (Fig. 4) should be equal to the atmospheric pressure. If the value calculated by the program is different from the atmospheric, a new value for applied head is tried and the calculations are repeated. The iteration scheme is continued until the calculated final pressure is the atmospheric pressure within an error bound.

The input data that vary from run to run define the area of the gas pipe, the values for liquid flow rate, air flow rate in terms of volumetric concentration (β), and the value of h_{34}.

To compare the computer-generated values of the applied hydraulic head with experimental values, test series 3 and 5 were chosen, and their applied hydraulic heads were compared with those generated by the computer model. The same experimental parameters were applied to numerical computation. Computer programs necessary to compute the applied hydraulic head are presented in Appendix B.

5.2 Theory for Bubble Velocity

In fully developed slug flow, the bubble velocity relative to the flowing mixture depends on the bubble shape and the distribution of void fraction and flow velocity across the pipe. A frequently used expression for upward gas-liquid mixture is

$$V_b = C_0 \frac{Q_a + Q_w}{A_d} + C_1 \sqrt{\frac{g \Delta\rho D}{\rho_w}} , \qquad (8)$$

where V_b is the absolute bubble velocity, C_0 is a distribution parameter that reflects both the flow and concentration distribution across the pipe, C_1 is a factor that depends on the fluid properties, and Q_w and Q_a are the volumetric flow rates of the liquid and gas phases, respectively. Furthermore, A_d is the cross-sectional pipe area, g is the acceleration caused by gravity, D is the pipe diameter, and ρ_w is the mass density of the liquid phase. The density difference $\Delta\rho = \rho_w - \rho_a$ can be approximated by ρ_w for gas-liquid mixtures, allowing Eq. (8) to be rewritten as

$$V_b = C_0 \langle J \rangle + C_1 \sqrt{gD} , \qquad (9)$$

in which $\langle J \rangle$ is the average volumetric flux for the entire mixture.

For a downward flow of the liquid, the bubble may either rise or descend, depending on the relative magnitudes of gas and liquid velocities. Equations (8) and (9) are valid, but the coefficients C_0 and C_1 would only be expected to be identical to the values for upward flow if the slugs remain centered on the pipe axis. If the bubbles migrate off center, C_0 would be expected to decrease because the bubble is traveling relative to a fluid velocity less than the maximum on the pipe axis. An eccentric bubble location would cause C_1 to increase because the drift velocity increases as the bubble comes closer to a boundary. Martin[7] concludes that downward flow can be represented by Eq. (9) but that the values of the coefficients C_0 and C_1 differ from those for upward flow. Thus, in his study of downward flow for D = 14 cm, C_0 = 0.86, and C_1 = 0.58; for D = 10.16 cm, C_0 = 0.90, and C_1 = 0.66; and for D = 2.6 cm, C_0 = 0.93. Apparently, the magnitude of the pipe diameter becomes unimportant once a certain value of D is exceeded.

Based on Martin's investigation, we have correlated the coefficients C_0 and C_1 for the pipe diameter of our test section; that is, for D = 5.08 cm, C_0 = 0.924, and C_1 = 0.642. Substituting these values in Eq. (9) yields

$$V_b = 0.924 \langle J \rangle + 0.642 \sqrt{gD} .$$

5.3 Analysis of Hydraulic Air Compression

A computer model developed by Rice[4] was modified to simulate the noncondensibles disposal through hydraulic air compression. An example is presented here to display the characteristics of the air compression process. It is assumed that noncondensible air at 6.90 kPa (1 psia) will be compressed to atmospheric pressure by the downward water flow in a 5.08-cm-diam pipe. Other data follow: air temperature = 21.1°C, water temperature = 15.6°C, h_{12} = 0, h_{23} = 914 cm, h_{34} = 45.7 cm, V_r = 24.7 cm/s, P_a = 101.4 kPa, k_{01} = 0.20, and V = 183 cm/s (6 fps). The air mass flow $\dot{m}_a$ and, consequently, the volumetric flow J are varied in the calculation. The resulting applied head as a function of J and air injection flux J_a is shown in Fig. 11. The dashed curves in the figure are the constant initial volumetric concentration (β) lines. When Fig. 11 is compared with Fig. 12, the characteristics of the computer simulation results remarkably resemble the test data, even though the geometric and physical parameters

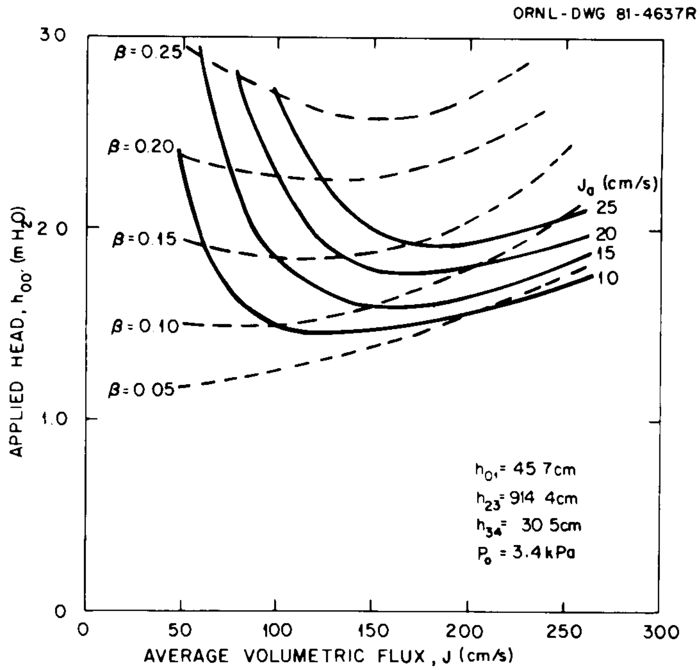

Fig. 11. Results of computer simulation case.

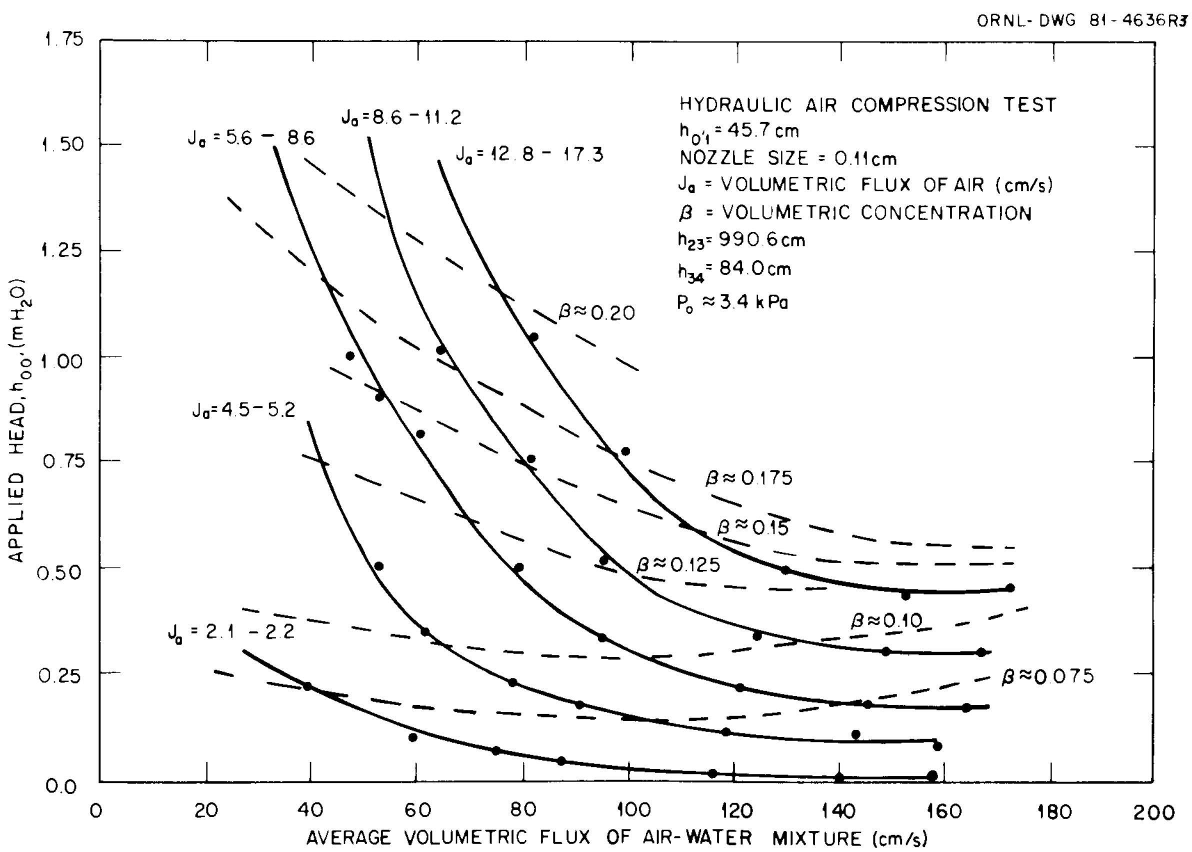

Fig. 12. Performance of hydraulic air compression test.

of these two cases are not entirely the same. The computer simulation model is derived from phenomenological equations involving empirical constants, notably the drift velocity. Information concerning the bubble drift velocity for air in water is scarce. Fine tuning of empirical constants in the model is needed to produce the best agreement between the calculated and experimental data.

A sensitivity analysis was carried out to test the effects of the bubble drift velocity and volumetric concentration variations upon the applied head. The results of the analysis are shown in Fig. 13; the baseline conditions are those specified in Fig. 12, and the volumetric concentration is assumed to be $\beta = 0.20$. As one can see in Fig. 13, lowering the drift velocity reduces the applied head. For a given volumetric concentration, the drift velocity can be reduced by dispersing smaller air bubbles in the water stream.

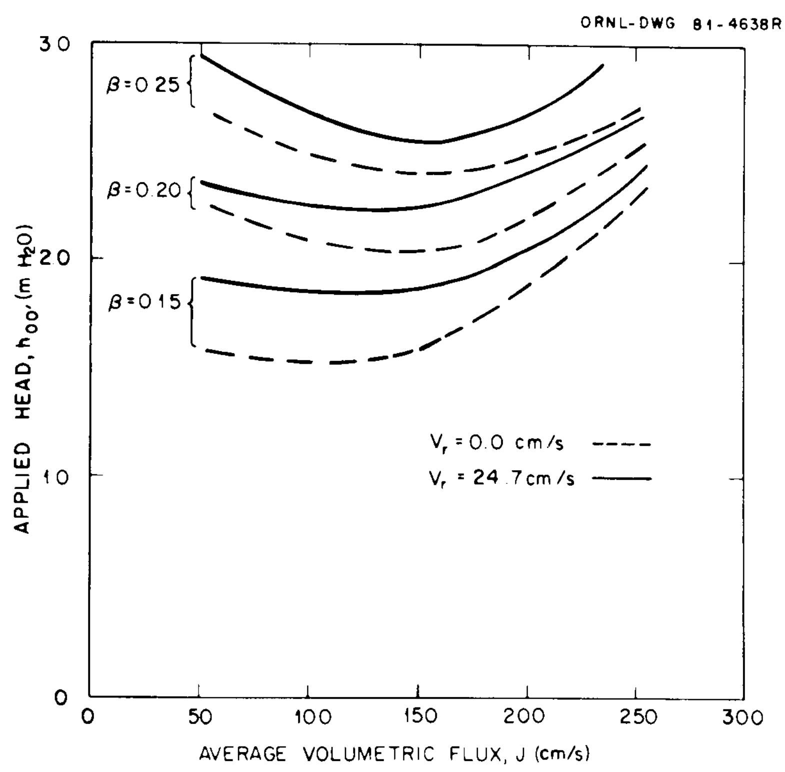

Fig. 13. Variations of applied head with drift velocity and void fraction.

5.4 Hydraulic Air Compression for OTEC Applications

Because the warm seawater discharge stream in an OTEC open-cycle plant design can be used as the moving source for air compression, the possible applications of the hydraulic gas compressor were assessed. In an open-cycle plant design, such as the Westinghouse study,[8] the pressure at the free water surface in the warm seawater discharge pipe will be around 2.97 kPa (0.43 psia). Air pressure at the air compressor injection point has to be equal to or greater than the local water pressure so that the gas could be discharged into a water stream. If a barometric intake deaerator is employed in an open-cycle plant design, the hydraulic air compressor can be used to dispose of the noncondensible gas removed at the deaerator. No additional gas compression is required because the gas pressure at the deaerator is around 11.8 kPa (1.71 psia).

To dispose of the combined noncondensible gas from a deaerator and a condenser through a hydraulic air compressor, the pressure of the condenser vent gas stream needs to be brought up by mechanical compressors before the gas can be injected into the warm seawater stream. Two competing power consumption mechanisms are involved. To reduce the mechanical compressor power consumption, the mechanical compressor should be used only to raise the gas stream pressure to the minimum acceptable injection level in an effluent water stream. However, the minimum gas pressure would lead to a high volumetric concentration of the air-water mixture at the injection point, which would cause a high water operating head for the hydraulic air compressor. From the hydraulic air compression viewpoint, a small operating water head requires a small initial volumetric concentration of the mixture, which implies a high gas injection pressure and more mechanical compression work. The net power consumption of a combined mechanical and hydraulic air compressor will vary with the noncondensible gas injection pressure and may be calculated from the hydraulic air compressor computer code together with a staged mechanical compressor computation scheme. The result of a sample calculation is shown in Table 7, in which no minimum power consumption is reached among the three different gas injection pressure cases. However, the change in net power consumption at high gas injection pressure is small.

Table 7. Performance of a combined mechanical and hydraulic compressor at different air injection pressures[a]

	Air injection pressure (kPa)		
	11.8	21.7	36.4
Initial volumetric concentration of the air–water mixture	0.19	0.087	0.044
Mechanical compressor power (water head equivalent, m)[b]	2.54	2.74	2.90
Hydraulic air compressor (applied head, m)	1.16	0.50	0.28
Net compression power consumption (water head, m)	3.70	3.24	3.18

[a]Basis: 100-MWe OTEC plant; warm seawater flow = 357 m^3/s, discharge velocity = 1.83 m/s; dissolved air content = 17.2 ppm; multistage mechanical compressors with intercooling, stage compression ratio = 1.83, and efficiency = 0.80.

[b]1-m water head equivalent = 3.6 MW.

6. CONCLUSIONS

The following conclusions were drawn from the feasibility study of hydraulic air compression for OTEC open-cycle applications:

1. A hydraulic air compressor is a simple machine, and cost savings will be realized if a mechanical compressor is replaced by a hydraulic air compressor.
2. A hydraulic air compressor is environmentally more acceptable for OTEC applications because it may improve the effluent water quality by redissolving the noncondensible air into water during the compression process.
3. The conversion of part of the kinetic energy contained in the warm seawater effluent flow (which is otherwise wasted in previous design) into air compression and the capability of direct-contact condensing of steam in the noncondensible gas stream make the hydraulic air compressor a promising device for OTEC open-cycle applications.
4. Additional experiments need to be conducted to confirm the design performance of OTEC hydraulic air compressors.
5. The OTEC applications of hydraulic air compressors need to be analyzed through the power system cost-optimization methodology, where both cost and power consumption are taken into account.

REFERENCES

1. J. P. Frizell, "A New Method of Compressing Air," *J. Frankin Inst.* 104(3), 193–98 (September 1887).

2. L. E. Schultz, "Hydraulic Air Compressors," *U.S.D.O.I. Information Circular 7683* (May 1954).

3. J. R. Norton, "Innovating Old Concept for Hydroelectric Power Generation," *Prof. Eng.*, 31–32 (June 1979).

4. W. Rice, "Performance of Hydraulic Gas Compressors," *ASME, J. of Fluids Eng.* 98, 645–53 (December 1976).

5. A. Golshani and F. C. Chen, *OTEC Gas Desorption Studies*, ORNL/TM-7438/V1 (October 1980).

6. A. Golshani and F. C. Chen, *OTEC Gas Desorption Studies, Vol. 2, Deaeration in a Packed Column and a Barometric Intake System*, ORNL/TM-7438/V2 (September 1981).

7. C. S. Martin, "Vertically Downward Two-phase Slug Flow," *ASME, J. of Fluid Eng.* 98, 715–22 (December 1976).

8. Westinghouse Electric Corp., *100-MWe OTEC Alternate Power Systems, Final Report*, DOE Contract EG-77-C-05-1473 (March 1979).

Appendix A

FLOW RATE CALCULATIONS

A.1 Calculation of Volumetric Air Flow

The calibrated ball-tube-type rotameter measures the amount of air flow in standard condition STP (P = 14.7 psia, T = 70°F). The following method is established to evaluate the volumetric air flow at testing conditions, as the test conditions are generally different from STP conditions:

$$Q_{STP} = Q_{T,P} \sqrt{\frac{\rho_{T,P}}{\rho_{STP}}} = Q_{T,P} \sqrt{\frac{P_{T,P}}{P_{STP}}} , \qquad (A.1)$$

or

$$Q_{T,P} = Q_{STP} \sqrt{\frac{P_{STP}}{P_{T,P}}} , \qquad (A.2)$$

where

$$Q_{STP} = (\%\ \text{scale})(0.633) \qquad (A.3)$$

for the ball-tube rotameter used in the experiment.

Substituting Eq. (A.3) in (A.2) and replacing P_{STP} with 14.7 psia,

$$Q_{T,P} = (\%\ \text{scale})\ (0.633) \sqrt{\frac{14.7}{P_{T,P}}} , \qquad (A.4)$$

where $Q_{T,P}$ and $P_{T,P}$ are the volumetric air flow (cm³/s) and the measured air pressure (psia) before entering the test section, respectively. The test pressure is always in vacuum condition, and it is different from $P_{T,P}$. Therefore, the actual air flow into the test section, which is entrained by water down flow, is Q_a:

$$Q_{T,P}\ P_{T,P} = Q_a\ P_2 ,$$

or

$$Q_a = Q_{T,P}\left(\frac{P_{T,P}}{P_2}\right) . \qquad (A.5)$$

Referring to Fig. A.1 and Fig. 4,

$$P_2 = P_1' + P_0 , \qquad (A.6)$$

where

$$P_0 = P_{bar} - P_4 , \qquad (A.7)$$

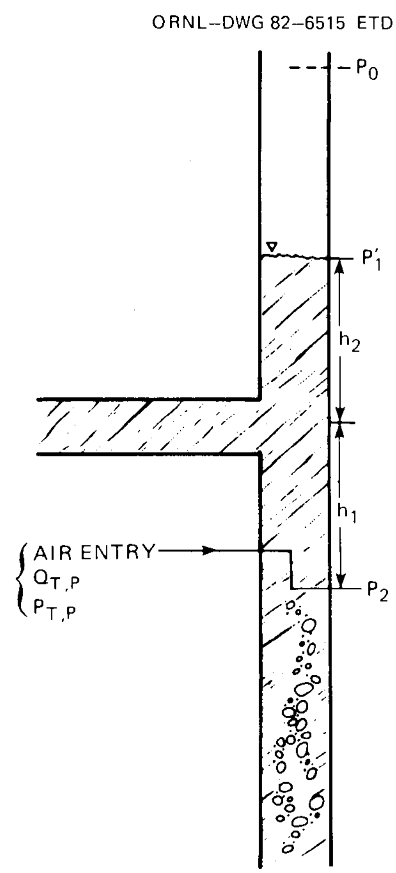

Fig. A.1. Detail of Fig. 4 at air entrance configuration.

and

$$P_1' = 0.0361\ (h_1 + h_2)\ . \qquad \text{(A.8)}$$

Equations (A.7) and (A.8) and their associated conversion factors can be substituted in Eq. (A.6):

$$P_2 = 0.0361\ (h_1 + h_2) + 0.491\ (P_{bar} - P_4)\ . \qquad \text{(A.9)}$$

The values of Eqs. (A.4) and (A.9) are substituted in Eq. (A.5):

$$Q_a = \frac{(\%\ \text{scale})(2.427)\sqrt{P_{T,P}}}{[0.491\ (P_{bar} - P_4) + 0.0361\ (h_1 + h_2)]}\ , \qquad \text{(A.10)}$$

where

% scale = rotameter reading when air injection is in place (the scale has been calibrated between 0 to 100),

$P_{T,P}$ = measured air pressure (psia),

P_{bar} = barometric pressure (in. Hg),

P_4 = vacuum pressure of the test setup (in. Hg),

h_1 = the distance of the air injection port from 0′ (Fig. 4) (in.),

h_2 = level of water in the pipe after air injection (in.),

Q_a = volumetric air flow into the hydraulic air compression test section (cm^3/s).

A.2 Calculation of Volumetric Water Flow

The water flow rate into the hydraulic air compression test section is measured by a turbine flow transducer (Flow Technology Model FT-16). The rotation of the turbine rotor generates electrical pulses in the pick-up, which is attached to the flowmeter. The frequency or pulse repetition rate represents the flow rate. When the flowmeter is in place, the water flow rate is expressed by

$$Q_w = (\text{turbine reading})(1.75545) \ , \qquad (A.11)$$

where the turbine reading is the pulse read by the flow rate monitoring device, and Q_w is the water flow rate in cubic centimeters per second.

Appendix B

COMPUTER PROGRAMS

The following computer programs were developed to calculate the applied head requirement for the hydraulic air compression process. Computer programs developed by Rice[1] were modified for this investigation. A schematic diagram and symbol definition of Rice's studies is shown in Fig. B.1. The system vacuum pressure is the pressure at point '0', P_0, and the barometric intake is eliminated for this modification. When $P_4 = P_0 = P_6 = P_7 = P_{atm}$ and $h_{45} = h_{56} = h_{67} = 0$ in the computer programs, the up pipe is eliminated.

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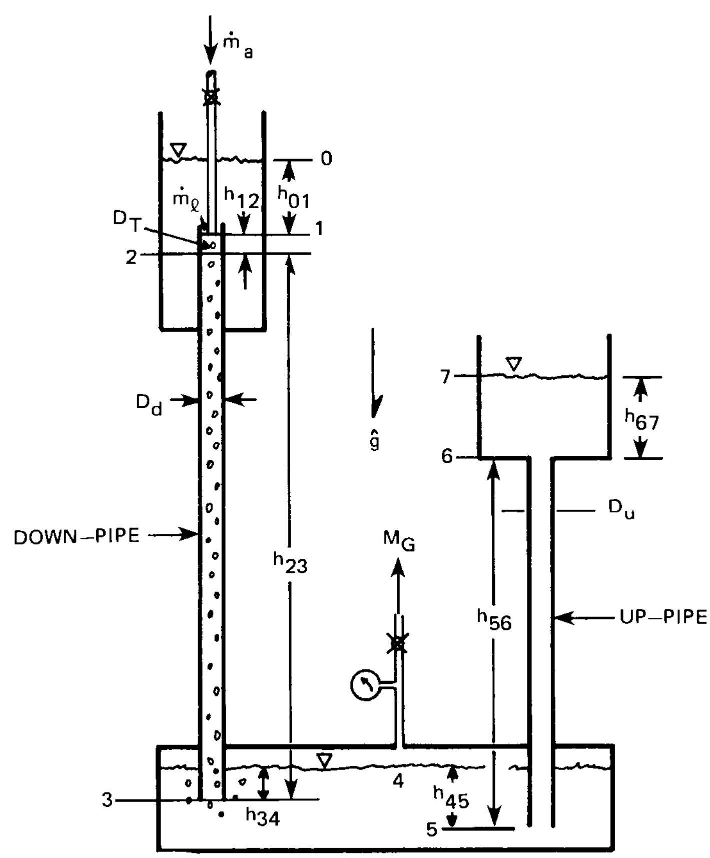

Fig. B.1. Schematic diagram and symbol definition of hydraulic gas compressor.

Reference

1. W. Rice, "Performance of Hydraulic Gas Compressors," *ASME, J. of Fluids Eng.* 98, 645–53 (December 1976).

B.1 Program Listing

```
 1   //FATROAIR JOB (17997),'Y-12 9204-1 GOL',                                        JOB 5293
     // PASSWORD=
     ***CLASS CPU91=150S,REGION=270K,IO=001
 2   // EXEC FORTQCLG,PARM.FORT='NOMAP',TIME.GO=(5,10),
     // REGION.GO=90K,
     // PARM.GO='EU=-1,DUMP=I'
 3   XXFORTQCLG PROC CLSIZE=270K,LKSIZE=150K,PLOT=DISS,CONC=5,                        00000010
     XX               GOSIZE=100K,GOTIME=,OUT=A                                       00000020
 4   XXFORT     EXEC PGM=IFEAAB,REGION=&CLSIZE                                        00000030
 5   XXSYSLIN     DD DSN=&&LOADSET,UNIT=SYSDA,SPACE=(800,(400,20),RLSE),              00000040
     XX               DISP=(MOD,PASS),DCB=(RECFM=FB,LRECL=80,BLKSIZE=800)             00000050
 6   XXSYSPRINT   DD SYSOUT=&OUT,DCB=BLKSIZE=1100                                     00000060
 7   XXSYSPUNCH   DD SYSOUT=B                                                         00000070
 8   XXSYSTERM    DD SYSOUT=&OUT,DCB=(RECFM=FB,LRECL=121,BLKSIZE=1089)                00000080
 9   XXSYSUT1     DD UNIT=SYSDA,DCB=(RECFM=FB,LRECL=105,BLKSIZE=3465),                00000090
     XX               SPACE=(3465,(10,10))                                            00000100
10   XXSYSUT2     DD UNIT=SYSDA,SPACE=(1024,(30,10))                                  00000110
11   //FORT.SYSIN DD *
12   XXLKED     EXEC PGM=IEWL,PARM='LIST,MAP',REGION=&LKSIZE,                         00000120
     XX               COND=(&CONC,LT,FORT)                                            00000130
13   XXSYSLIB     DD DSN=SYS1.ENHLIB,DISP=SHR                                         00000140
14   XX           DD DSN=SYS1.LOGLIB,DISP=SHR                                         00000150
15   XX           DD DSN=SYS1.&PLOT.LIB,DISP=SHR                                      00000160
16   XXSYSLIN     DD DSN=&&LOADSET,DISP=(OLD,DELETE)                                  00000170
17   XX           DD DDNAME=SYSIN                                                     00000180
18   XXSYSLMOD    DD DSN=&&FJOBLIB(NAMEX),UNIT=SYSDA,DISP=(NEW,PASS),                 00000190
     XX               SPACE=(3072,(50,10,1),RLSE)                                     00000200
19   XXSYSPRINT   DD SYSOUT=&OUT,DCB=BLKSIZE=605                                      00000210
20   XXSYSUT1     DD UNIT=(SYSDA,SEP=(SYSLIN,SYSLMOD)),SPACE=(3072,(50,10))           00000220
21   XXGO       EXEC PGM=*.LKED.SYSLMOD,COND=((&CONC,LT,FORT),(5,LT,LKED)),           00000230
     XX               REGION=&GOSIZE,TIME=&GOTIME                                     00000240
22   XXDELETE     DD DSN=&&FJOBLIB(NAMEX),DISP=(OLD,DELETE)                           00000250
23   XXFT06F001   DD SYSOUT=&OUT,DCB=(RECFM=VBA,LRECL=137,BLKSIZE=1100)               00000260
24   //GO.FT05F001 DD *
     //
```

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 STMT NO. MESSAGE
-
     4       IEF653I SUBSTITUTION JCL - PGM=IFEAAB,REGION=270K
     6       IEF653I SUBSTITUTION JCL - SYSOUT=A,DCB=BLKSIZE=1100
     8       IEF653I SUBSTITUTION JCL - SYSOUT=A,DCB=(RECFM=FB,LRECL=121,BLKSIZE=1089)
    12       IEF653I SUBSTITUTION JCL - PGM=IEWL,PARM='LIST,MAP',REGION=150K,
    12       IEF653I SUBSTITUTION JCL - COND=(5,LT,FORT)
    15       IEF653I SUBSTITUTION JCL - DSN=SYS1.DISSLIB,DISP=SHR
    19       IEF653I SUBSTITUTION JCL - SYSOUT=A,DCB=BLKSIZE=605
    21       IEF653I SUBSTITUTION JCL - PGM=*.LKED.SYSLMOD,COND=((5,LT,FORT),(5,LT,LKED)),
    21       IEF653I SUBSTITUTION JCL - REGION=100K,TIME=
    23       IEF653I SUBSTITUTION JCL - SYSOUT=A,DCB=(RECFM=VBA,LRECL=137,BLKSIZE=1100)
    21       IEF686I DDNAME REFERRED TO ON DDNAME KEYWORD IN PRIOR STEP WAS NOT RESOLVED
IEF236I ALLOC. FOR FATROAIR FORT
IEF237I 180  ALLOCATED TO SYSLIN
IEF237I JES2 ALLOCATED TO SYSPRINT
IEF237I JES2 ALLOCATED TO SYSPUNCH
IEF237I JES2 ALLOCATED TO SYSTERM
IEF237I 181  ALLOCATED TO SYSUT1
IEF237I 48A  ALLOCATED TO SYSUT2
IEF237I JES2 ALLOCATED TO SYSIN
IEF142I FATROAIR FORT - STEP WAS EXECUTED - COND CODE 0004
IEF285I   SYS82047.T125505.RA000.FATROAIR.LOADSET       PASSED
IEF285I   VOL SER NOS= X3B1C0.
IEF285I   JES2.JOB05293.S00103                          SYSOUT
IEF285I   JES2.JOB05293.S00104                          SYSOUT
IEF285I   JES2.JOB05293.S00105                          SYSOUT
IEF285I   SYS82047.T125505.RA000.FATROAIR.R0000001      DELETED
IEF285I   VOL SER NOS= X3B1C1.
IEF285I   SYS82047.T125505.RA000.FATROAIR.R0000002      DELETED
IEF285I   VOL SER NOS= MVSDA1.
IEF285I   JES2.JOB05293.SI0101                          SYSIN
IEF373I STEP /FORT    / START 82047.1255
IEF374I STEP /FORT    / STOP  82047.1257 CPU    0MIN 02.60SEC SRB    0MIN 00.37SEC VIRT   336K SYS   236K
*----------------------------------------------------------------------------------------*
*KXY0001  DDNAME   CUU DSNAME                                     EXCP'S(IO) BLOCKSIZE*
*KXY0002  SYSLIN   180 SYS82047.T125505.RA000.FATROAIR.LOADSET          52       800  *
*KXY0002  SYSUT1   181 SYS82047.T125505.RA000.FATROAIR.R0000001                 3465  *
*KXY0002  SYSUT2   48A SYS82047.T125505.RA000.FATROAIR.R0000002                       *
*KXY0003  VIRTUAL STORAGE USED   336K     TOTAL EXCP COUNT FOR STEP     52            *
*KXY0004  16 FEB 82.047  12.57.05.99        CPU TIME FOR STEP 0000 MIN 02.97 SEC      *
*----------------------------------------------------------------------------------------*
IEF236I ALLOC. FOR FATROAIR LKED
IEF237I 41D  ALLOCATED TO SYSLIB
IEF237I 41D  ALLOCATED TO
IEF237I 474  ALLOCATED TO
IEF237I 180  ALLOCATED TO SYSLIN
IEF237I DMY  ALLOCATED TO
IEF237I 181  ALLOCATED TO SYSLMOD
IEF237I JES2 ALLOCATED TO SYSPRINT
IEF237I 48A  ALLOCATED TO SYSUT1
IEF142I FATROAIR LKED - STEP WAS EXECUTED - COND CODE 0000
IEF285I   SYS1.ENHLIB                                   KEPT
IEF285I   VOL SER NOS= MVT918.
IEF285I   SYS1.LOGLIB                                   KEPT
IEF285I   VOL SER NOS= MVT918.
IEF285I   SYS1.DISSLIB                                  KEPT
IEF285I   VOL SER NOS= DISK8B.
IEF285I   SYS82047.T125505.RA000.FATROAIR.LOADSET       DELETED
IEF285I   VOL SER NOS= X3B1C0.
IEF285I   SYS82047.T125505.RA000.FATROAIR.FJOBLIB       PASSED
IEF285I   VOL SER NOS= X3B1C1.
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IEF285I   JES2.JOB05293.SO0106                                  SYSOUT
IEF285I   SYS82047.T125505.RA000.FATROAIR.R0000003             DELETED
IEF285I   VOL SER NOS= MVSDA1.
IEF373I STEP /LKED     / START 82047.1257
IEF374I STEP /LKED     / STOP  82047.1257 CPU     0MIN 00.53SEC SRB    0MIN 00.14SEC VIRT   156K SYS    224K
*-------------------------------------------------------------------------------------------------*
*KXY0001  DDNAME    CUU DSNAME                                              EXCP'S(IO)  BLOCKSIZE*
*KXY0002  SYSLIB    41D SYS1.ENHLIB                                             162        13030  *
*KXY0002            41D SYS1.LOGLIB                                                               *
*KXY0002            474 SYS1.DISSLIB                                              2               *
*KXY0002  SYSLIN    180 SYS82047.T125505.RA000.FATROAIR.LOADSET                  52          800  *
*KXY0002  SYSLMOD   181 SYS82047.T125505.RA000.FATROAIR.FJOBLIB                  38        19069  *
*KXY0002  SYSUT1    48A SYS82047.T125505.RA000.FATROAIR.R0000003                 68        19064  *
*KXY0003  VIRTUAL STORAGE USED    156K      TOTAL EXCP COUNT FOR STEP           322               *
*KXY0004  16 FEB 82.047   12.57.29.40          CPU TIME FOR STEP 0000 MIN 00.67 SEC               *
*-------------------------------------------------------------------------------------------------*
IEF236I ALLOC. FOR FATROAIR GO
IEF237I 181   ALLOCATED TO PGM=*.DD
IEF237I 181   ALLOCATED TO DELETE
IEF237I JES2 ALLOCATED TO FT06F001
IEF237I JES2 ALLOCATED TO FT05F001
IEF142I FATROAIR GO - STEP WAS EXECUTED - COND CODE 0016
IEF285I   SYS82047.T125505.RA000.FATROAIR.FJOBLIB           KEPT
IEF285I   VOL SER NOS= X3B1C1.
IEF285I   SYS82047.T125505.RA000.FATROAIR.FJOBLIB           DELETED
IEF285I   VOL SER NOS= X3B1C1.
IEF285I   JES2.JOB05293.SO0107                              SYSOUT
IEF285I   JES2.JOB05293.SI0102                              SYSIN
IEF373I STEP /GO       / START 82047.1257
IEF374I STEP /GO       / STOP  82047.1258 CPU     0MIN 12.12SEC SRB    0MIN 00.01SEC VIRT    64K SYS    228K
*-------------------------------------------------------------------------------------------------*
*KXY0001  DDNAME    CUU DSNAME                                              EXCP'S(IO)  BLOCKSIZE*
*KXY0002  PGM=*.DD  181 SYS82047.T125505.RA000.FATROAIR.FJOBLIB                            19069  *
*KXY0002  DELETE    181 SYS82047.T125505.RA000.FATROAIR.FJOBLIB                                   *
*KXY0003  VIRTUAL STORAGE USED     64K     TOTAL EXCP COUNT FOR STEP                              *
*KXY0004  16 FEB 82.047   12.58.32.10          CPU TIME FOR STEP 0000 MIN 12.13 SEC               *
*-------------------------------------------------------------------------------------------------*
IEF375I  JOB /FATROAIR/ START 82047.1255
IEF376I  JOB /FATROAIR/ STOP  82047.1258 CPU     0MIN 15.25SEC SRB    0MIN 00.52SEC
*-------------------------------------------------------------------------------------------------*
*KXY0003                                    TOTAL EXCP COUNT FOR JOB        374                   *
*KXY0004  16 FEB 82.047   12.58.32.15          CPU TIME FOR JOB  0000 MIN 15.77 SEC               *
*-------------------------------------------------------------------------------------------------*
*KXY0005                                    **APPROXIMATE JOB COST* $        2.90                 *
*-------------------------------------------------------------------------------------------------*
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REQUESTED OPTIONS: NOMAP
OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL

                  C       PROGRAM HYDGAS (MODIFIED BY CHEN,PROGRAM HYDG2)
                  C       THIS PROGRAM CONSIDER DVR IN THE DOWNPIPE REGION
                  C       WARREN RICE,OCTOBER 1976, LI-TING CHEN, 1980
                  C
ISN 0002                  DIMENSION HH01(201),PDIF(201),P7F(201),HDIF(201)
ISN 0003                  COMMON ALPHA,QL,VLM,FLUX1,FLUXG,KDT
ISN 0004                  ICW=6
ISN 0005                  ICR=5
                  C
                  C       RHOL---DENSITY OF LIQUID---LBM/FTCU
                  C       FMU---VISCOSITY OF LIQUID---LBM/FT-SEC
                  C       CVL---SP. HT. AT CONST. VOL. OF LIQUID---BTU/LBM-DEGF
                  C       R---ENGINEERING GAS CONST. OF GAS---FT-LBF/LBM-DEGF
                  C       CPG---SP. HT. AT CONST. PRESS. OF GAS---BTU/LBM-DEGF
                  C       TAF---AMBIENT ATMOS. TEMP.---DEGF
                  C       TL0F---TEMP. OF LIQUID ENTERING AT (0)---DEGF
                  C       TF1F---TEMP. OF GAS ENTERING AT (1)---DEGF
                  C       PAA---AMBIENT ATMOS. PRESS.---PSIA
                  C       PL0G---PRESS. OF LIQUID ENTERING AT (0)---PSIG
                  C       PGIG---PRESS. OF GAS ENTERING AT (1)---PSIG
                  C       DUP---DIAMETER OF UP-PIPE---FT
                  C       GAMA---SP. HT. RATIO OF GAS (CPG/CVG)---DIMENSIONLESS
                  C       DDP---DIAMETER OF DOWN-PIPE---FT
                  C       EODU---ROUGHNESS RATIO OF UP-PIPE---DIMENSIONLESS
                  C       EODD---ROUGHNESS RATIO OF DOWN-PIPE---DIMENSIONLESS
                  C       CR67---RECOVERY COEFFICIENT (6-7)---DIMENSIONLESS
                  C       CR34---RECOVERY COEFFICIENT (3-4)---DIMENSIONLESS
                  C       CK45---INLET LOSS COEFF (4-5)---DIMENSIONLESS
                  C       CK01---INLET LOSS COEFF (0-1)---DIMENSIONLESS
                  C       H01,H12,H23,H34,H45,H56,H67---HEADS---FT
                  C
                  C       RAT CARDS MUST BE IN ORDER OF INCREASING VALUES OF RAT.
                  C
                  C       RAT MUST NOT BE ZERO.
                  C
                  C       TERMINATION CAUSED BY NEGATIVE VALUE OF RAT, (END OF FILE).
                  C
ISN 0006                  READ (ICR,1) KDT
ISN 0007                1 FORMAT (I3)
                  C       SEE STATEMENT NUMBER 132. USE KDT=0 UNLESS INTERMEDIATE PRINT
                  C        DETAILS ARE DESIRED.
                  C
ISN 0008                  WRITE (ICW,5)
ISN 0009                5 FORMAT (1H1)
ISN 0010                  READ (ICR,7) AGP
ISN 0011                7 FORMAT (F10.0)
                  C       AGP IS THE AREA OF THE GAS INLET PIPE (FTSQ). IF AGP=0. ON
                  C        THIS CARD, THEN PROGRAM IGNORES THE VALUE AND OPTIMIZES
                  C        AGP, BUT IF A VALUE OTHER THAN ZERO IS ON THIS CARD ,
                  C        THE VALUE IS USED AND THE OPTIMIZING LOOP IS BYPASSED.
ISN 0012                  INDEX=0
ISN 0013                  KAT=1
ISN 0014                9 READ (ICR,10) RHOL,FMU,CVL
ISN 0015               10 FORMAT (3F10.0)
ISN 0016                  READ (ICR,10) R,CPG,GAMA
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  ISN 0017              READ (ICR,10) TAF,TLOF,TG1F
  ISN 0018              READ (ICR,18) DDP,DUP,EODD,EODU
  ISN 0019              READ (ICR,16) CK01,CK45,CK34,CK67
  ISN 0020              READ (ICR,19) XO2,XN2
                  C     IF H01=0. ON DATA CARD, THEN PROGRAM IGNORES THE VALUE AND
                  C      CALCULATES H01 TO CAUSE PG1G=0. BUT IF A VALUE OF H01
                  C      OTHER THAN ZERO IS ON THE CARD THE VALUE ON THE CARD IS USED.
                  C      WHEN H01=0. IS ON THE CARD, HNET MUST BE ON THE CARD BUT
                  C      H23 NEED NOT BE. WHEN H01 IS NOT ZERO ON THE CARD, H23
                  C      MUST BE ON THE CARD BUT HNET NEED NOT BE.
  ISN 0021           15 FORMAT (8F10.0)
  ISN 0022           16 FORMAT (4F10.0)
  ISN 0023           18 FORMAT (4F10.0)
  ISN 0024           19 FORMAT (3F10.0)
  ISN 0025              H01=1.5
  ISN 0026              JH01=1
  ISN 0027              IF (H01-.001) 20,20,21
  ISN 0028           20 JH01=0
                  C     GG---GRAVITATIONAL ACCEL.---FT/SECSQ
  ISN 0029           21 GG=32.2
  ISN 0030              PI=3.141592653
  ISN 0031              ADP=.25*PI*DDP*DDP
                  C     ADP,AUP,AGP---FTSQ
  ISN 0032              AUP=.25*PI*DUP*DUP
  ISN 0033              READ(ICR,50) RAT,RCA,SN,SO
  ISN 0034              READ (ICR,19) PAA,PLOG,H001
  ISN 0035              READ (ICR,15) H01,H12,H23,H34,H45,H56,H67,HNET
  ISN 0036           50 FORMAT(4F10.0)
  ISN 0037           40 READ (ICR,211) MSG1,MSG2,MSG3,MSG4
  ISN 0038          211 FORMAT (4A4)
  ISN 0039              READ (ICR,55) VLM,ALP
  ISN 0040           55 FORMAT(2F10.7)
  ISN 0041              TLO =TLOF+460.
  ISN 0042              TG1=TG1F+460.
  ISN 0043              TA=TAF+460.
  ISN 0044              PLO = PAA+PLOG
                  C***********************PRINT1-- INPUT DATA.   $$$$$*********************
  ISN 0045              QL=VLM*ADP
  ISN 0046              QL1=QL
  ISN 0047              QG1=ALPHA*QL1/(1.-ALPHA)
  ISN 0048              FLUX1=(QG1+QL1)/ADP
  ISN 0049              VB=0.924*FLUX1+1.49
  ISN 0050              VR2=VB-VLM
  ISN 0051              WRITE(6,58) MSG1,MSG2,MSG3,MSG4
  ISN 0052           58 FORMAT(/,5X,6H INPUT,10X,4A4//)
  ISN 0053              WRITE(6,70) KDT
  ISN 0054           70 FORMAT (10X,6HKDT   =I3)
  ISN 0055              WRITE (6,71) AGP
  ISN 0056           71 FORMAT (10X,6HAGP   =F10.7)
  ISN 0057              WRITE (6,72) RHOL,FMU,CVL
  ISN 0058           72 FORMAT (10X,6HRHOL  =F10.5,3X,6HFMU   =F10.5,3X,6HCVL   =F10.5 )
  ISN 0059              WRITE (6,73) R,CPG,GAMA
  ISN 0060           73 FORMAT (14X,3HR =F10.5,3X,6HCPG   =F10.5,3X,6HGAMA =F10.5)
  ISN 0061              WRITE (6,74) TAF,TLOF,TG1F
  ISN 0062           74 FORMAT (10X,6HTAF   =F10.5,3X,6HTLOF =F10.5,3X,6HTG1F =F10.5)
  ISN 0063              WRITE (6,75) PAA,PLOG,H001
  ISN 0064           75 FORMAT (10X,6HPAA   =F10.5,3X,6HPLOG =F10.5,3X,6HH001 =F10.5)
  ISN 0065              WRITE (6,76) DDP,DUP,EODD,EODU
  ISN 0066           76 FORMAT (10X,6HDDP   =F10.6,3X,6HDUP   =F10.6,3X,6HEODD =F10.6,3X,
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                          1 6HEODU =F10.6)
ISN 0067                    WRITE (6,77) CK01,CK45,VR2,CR34,CR67
ISN 0068                 77 FORMAT (10X,6HCK01 =F10.6,3X,6HCK45 =F10.6,3X,6HVR2  =F10.5,3X,
                          1 6HCR34 =F10.6,3X,6HCR67 =F10.6)
ISN 0069                    WRITE (6,78) H01,H12,H23,H34
ISN 0070                 78 FORMAT (10X,6HH01  =F10.5,3X,6HH12  =F10.5,3X,6HH23  =F10.5,3X,
                          1 6HH34  =F10.5)
ISN 0071                    WRITE (6,79) H45,H56,H67,HNET
ISN 0072                 79 FORMAT (10X,6HH45  =F10.5,3X,6HH56  =F10.5,3X,6HH67  =F10.5,3X,
                          1 6HHNET =F10.5)
ISN 0073                    WRITE (6,80)  XO2,XN2
ISN 0074                 80 FORMAT(10X,6HX/2   =F10.5,3X,6HXN2  =F10.6)
ISN 0075                    WRITE (6,81) RAT,RCA,SN,SO
ISN 0076                 81 FORMAT (10X,6HRAT  =F10.7,3X,6HRCA  =F10.5,3X,6HSN   =F10.5,3X,
                          1 6HSO   =F10.5)
ISN 0077                    WRITE(6,82) VLM,ALP
ISN 0078                 82 FORMAT (10X,6HVLM  =F10.4,3X,6HALP  =F10.8)
                  C      **************END DATA PRINT.*********************************
ISN 0079                    ALPHA=ALP
ISN 0080                    RATS=RAT
ISN 0081                    KRT=0
ISN 0082                    RINC=.1
ISN 0083                     HH01(1)=H01
ISN 0084                    HDIF(1)=0.
ISN 0085               1600 FORMAT(/,5X,6H H01= ,F10.4,6H HNET=,F10.4)
ISN 0086                    IF(RAT) 6000,60,60
                  C         *****
ISN 0087                 60 QL=VLM*ADP
ISN 0088                    FML=QL*RHOL
ISN 0089                    VL1=VLM
ISN 0090                    K=0
                  C         ********
ISN 0091                    DO 300 K=1,200
ISN 0092                    H01=HH01(K)+HDIF(K)
ISN 0093                    HNET=H01+H12+H23-H34+H45-H56-H67
ISN 0094                    IF(KDT) 3000,3000,3005
ISN 0095               3005 CONTINUE
ISN 0096                    WRITE(6,1600)H01,HNET
ISN 0097                    FK=K
ISN 0098                    WRITE(6,56)FK,ALPHA
ISN 0099                 56 FORMAT (5X,F6.0,3X,6HALPHA=F10.8)
ISN 0100               3000 CONTINUE
ISN 0101                120 CALL MOD01(PLO,RHOL,GG,H01,CK01,VL1,PL1,R,TG1,ADP,FML,RAT,FMG,
                          1 AGP,VG1,KAT,JH01,H001,DDP,FMU,EODD,FML)
ISN 0102                    FMG1=FMG
ISN 0103                    PG1=PL1
ISN 0104                    PG1G=PG1-PAA
ISN 0105                    RAT=FMG/FML
ISN 0106                    CALL MOD12(FML,FMG,RHOL,VR2,CVL,CPG,R,ADP,AGP,PG1,PL1,TG1,TLO,H12,
                          1 ICW,VL2,VG2,P2,T2,II,VG1,RAT,VL1)
ISN 0107                    IF(II) 130,130,5000
ISN 0108                130 CALL MOD23(FML,FMG,RHOL,VR2,CVL,CPG,ADP,P2,T2,VL2,H23,DDP,FMU,
                          1 VL3,VG3,P3,T3,EODD,XO2,XN2,XXO2,XXN2,RAT,SO,SN,FF)
ISN 0109                    XXO23=XXO2
ISN 0110                    XXN23=XXN2
ISN 0111                    FMGS=FMG1-FMG
ISN 0112                    CALL MOD34(P3,RHOL,H34,P4,CR34,VL3)
ISN 0113                    FMGU=FMG*RCA
ISN 0114                    P5=P4
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  ISN 0115             P6=P5
  ISN 0116             P7=P6
  ISN 0117             V5=0.
  ISN 0118             V6=0
  ISN 0119             IF (KDT) 135,135,132
  ISN 0120         132 CALL PRNT4(PL1,PG1G,VL1,VG1,TLO,TG1F,P2,VL2,VG2,T2,P3,VL3,VG3,T3,
                      1 P4,P5,V5,P6,V6,P7,FMG,FML,DDP,DUP,FMU,ICW,PAA,H01,H23)
  ISN 0121         135 P7F(K)=P7
  ISN 0122             PDIF(K)=(PAA-P7F(K))/PAA
  ISN 0123             WRITE(6,2) PDIF(K)
  ISN 0124       2     FORMAT('0','PDIF(K)=',F20.10)
  ISN 0125             WRITE(6,406) FF
  ISN 0126         406 FORMAT('0','FRICTION FACTOR=',F20.10)
  ISN 0127             PDIFF=ABS(PDIF(K))
  ISN 0128             HDIF(K)=PDIF(K)*PAA*2.31
  ISN 0129             HH01(K+1)=H01
  ISN 0130             IF(PDIFF-0.001)500,500,137
  ISN 0131         137 HDIF(K+1)=PDIF(K)*PAA*2.31
  ISN 0132             IF(PDIF(K))160,500,300
  ISN 0133         160 IF(K-5)300,170,170
  ISN 0134         170 KK=K
  ISN 0135               INDEX=0
  ISN 0136        1190 INDEX=INDEX+1
  ISN 0137        1192 H01=(HH01(KK-1)+HH01(KK))/2
  ISN 0138             HNET=H01+H12+H23-H34+H45-H56-H67
  ISN 0139             WRITE(6,1195)H01,HNET,K
  ISN 0140        1195 FORMAT (/,10X,6H H01= ,F10.4,6H HNET=,F10.4,4H K= ,I3)
  ISN 0141             CALL MOD01(PLO,RHOL,GG,H01,CK01,VL1,PL1,R,TG1,ADP,FML,RAT,FMG,
                      1 AGP,VG1,KAT,JH01,H001,DDP,FMU,EODD,FML)
  ISN 0142             CALL MOD12(FML,FMG,RHOL,VR2,CVL,CPG,R,ADP,AGP,PG1,PL1,TG1,TLO,H12,
                      1 ICW,VL2,VG2,P2,T2,II,VG1,RAT,VL1)
  ISN 0143             CALL MOD23(FML,FMG,RHOL,VR2,CVL,CPG,ADP,P2,T2,VL2,H23,DDP,FMU,
                      1 VL3,VG3,P3,T3,EODD,XO2,XN2,XXO2,XXN2,RAT,SO,SN)
  ISN 0144             CALL MOD34(P3,RHOL,H34,P4,CR34,VL3)
  ISN 0145             P7=P4
  ISN 0146             PDIF2=(PAA-P7)/PAA
  ISN 0147             CALL PRNT4(PL1,PG1G,VL1,VG1,TLO,TG1F,P2,VL2,VG2,T2,P3,VL3,VG3,T3,
                      1 P4,P5,V5,P6,V6,P7,FMG,FML,DDP,DUP,FMU,ICW,PAA,H01,H23)
  ISN 0148       4     WRITE(6,3)PDIF2
  ISN 0149       3     FORMAT('0','PDIF2=',F20.10)
  ISN 0150             PDIFA=ABS(PDIF2)
  ISN 0151             IF(PDIFA-0.001)500,500,1200
  ISN 0152        1200 IF(INDEX-20)1210,1500,1500
  ISN 0153        1210 IF(PDIF2)1250,500,1300
  ISN 0154        1250 HH01(KK-1)=H01
  ISN 0155             P7F(KK)=P7
  ISN 0156             GO TO 1190
  ISN 0157        1300 HH01(KK)=H01
  ISN 0158             P7F(KK-1)=P7
  ISN 0159             GO TO 1190
  ISN 0160         300 CONTINUE
  ISN 0161             CALL PRNT1(RHOL,FMU,CVL,R,CPG,GAMA,TAF,TLOF,TG1F,PAA,PLOG,PG1G,
                      1 DUP,AGP,GNUM,CK01,CK45,VR2,H01,H12,H23,H34,H45,H56,H67,HNET,DDP,
                      2ICW,CR34,CF67,EODD,EODU,RCA,XO2,XXO23,SO,SN,H001)
  ISN 0162             CALL PRNT2(RAT,ICW)
  ISN 0163             WRITE (ICW,310) K,PDIF(50),PDIF(99),PDIF(200)
  ISN 0164         310 FORMAT (//,16H NO SOLUTION. K=I3,3X,9HPDIF(50)=E15.8,3X,
                      1 9HPDIF(99)=E15.8,3X,10HPDIF(200)=E15.8,1H1)
  ISN 0165             GO TO 40
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```
 ISN 0166          CALL PRNT1(RHOL,FMU,CVL,R,CPG,GAMA,TAF,TLOF,TG1F,PAA,PLOG,PG1G,
                  1 DUP,AGP,GNUM,CK01,CK45,VR2,H01,H12,H23,H34,H45,H56,H67,HNET,DDP,
                  2ICW,CR34,CR67,EODD,EODU,RCA,XO2,XXO23,SO,SN,H001)
 ISN 0167          CALL PRNT2(RAT,ICW)
 ISN 0168          KRT=KRT+1
 ISN 0169          IF (KRT-2) 405,5000,5000
 ISN 0170      405 WRITE (ICW,410)
 ISN 0171      410 FORMAT (//,10X,30H ALL VALUES OF P7 ARE NEGATIVE)
            C      **********DO NOT CONVERGE AT P7  **********
 ISN 0172     1500 WRITE(ICW,1510)
 ISN 0173     1510 FORMAT(//,10X,30H DONT CONVERGE IN 9 I ERATIONS/)
 ISN 0174          WRITE(ICW, 1520)HH01(KK-1),P7P(KK-1),HH01(KK),P7P(KK)
 ISN 0175     1520 FORMAT(/,5X,7H HH01+=,F10.5,4HP7+=,F10.5,7H HH01-=,F10.5,4HP7-=,
                  CF10.5/)
 ISN 0176          CALL PRNT1(RHOL,FMU,CVL,R,CPG,GAMA,TAF,TLOF,TG1F,PAA,PLOG,PG1G,
                  1 DUP,AGP,GNUM,CK01,CK45,VR2,H01,H12,H23,H34,H45,H56,H67,HNET,DDP,
                  2ICW,CR34,CR67,EODD,EODU,RCA,XO2,XXO23,SO,SN,H001)
 ISN 0177          GO TO 5000
 ISN 0178      500 CALL PRNT1(RHOL,FMU,CVL,R,CPG,GAMA,TAF,TLOF,TG1F,PAA,PLOG,PG1G,
                  1 DUP,AGP,GNUM,CK01,CK45,VR2,H01,H12,H23,H34,H45,H56,H67,HNET,DDP,
                  2ICW,CR34,CR67,EODD,EODU,RCA,XO2,XXO23,SO,SN,H001)
 ISN 0179          CALL PRNT2(RAT,ICW)
 ISN 0180          IF (VG2) 510,530,530
 ISN 0181      510 WRITE (ICW,520) VG2
 ISN 0182      520 FORMAT (//,10X,18H NO SOLUTION. VG2=F8.4,4H FPS)
 ISN 0183          GO TO 5000
 ISN 0184      530 IF (VG3) 540,560,560
 ISN 0185      540 WRITE (ICW,550) VG3
 ISN 0186      550 FORMAT (//,10X,18H NO SOLUTION. VG3=F8.4,4H FPS)
 ISN 0187          GO TO 5000
 ISN 0188      560 CALL PERF(RHOL,FML,FMG,R,P4,HNET,GAMA,PAA,QL,QG,EFF,POWL,POWG,
                  1T3,TA,CPG,PG1,RCA,QGA,FMGA,FMG1)
 ISN 0189          CALL PRNT3(FML,FMG1,QL,QG,QGA,FMGA,P4,EFF,POWL,POWG,ICW,T3,PAA)
 ISN 0190          CALL PRNT4(PL1,PG1G,VL1,VG1,TLO,TG1P,P2,VL2,VG2,T2,P3,VL3,VG3,T3,
                  1 P4,P5,V5,P6,V6,P7,FMG,FML,DDP,DUP,FMU,ICW,PAA,H01,H23)
 ISN 0191          WRITE(6,700) FLUX1,FLUXG,ALPHA
 ISN 0192      700 FORMAT(//,10X,7H FLUX1=,F12.6,7H FLUXG=,F12.6,7H ALPHA=,F12.8)
 ISN 0193          WRITE (ICW,565)
 ISN 0194      565 FORMAT (1H1)
 ISN 0195     5000 WRITE (ICW,5010)
 ISN 0196     5010 FORMAT (1H1)
 ISN 0197          GO TO 40
 ISN 0198     6000 STOP
            C      **********  END OF MAIN PROGRAM  **********
 ISN 0199          END
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NUMBER   LEVEL                    FORTRAN H EXTENDED ERROR MESSAGES

IFE224I   4(W)      ISN     0166     THE STATEMENT AFTER AN ARITHMETIC IF, GO TO, STOP OR RETURN HAS NO LABEL
IFE610I   4(W)      LABEL100003      THE STATEMENT NUMBER OR GENERATED LABEL IS UNREACHABLE.
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL
*STATISTICS*     SOURCE STATEMENTS =       198, PROGRAM SIZE =       8720, SUBPROGRAM NAME =  MAIN
*STATISTICS*     2 DIAGNOSTICS GENERATED, HIGHEST SEVERITY CODE IS  4
****** END OF COMPILATION ******                              120K BYTES OF CORE NOT USED
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REQUESTED OPTIONS: NOMAP
OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL

   ISN 0002           SUBROUTINE PRNT1(RHOL,FMU,CVL,R,CPG,GAMA,TAF,TLOF,TG1F,PAA,PLOG,
                     1 PG1G,DUP,AGP,GNUM,CK01,CK45,VR2,H01,H12,H23,H34,H45,H56,H67,HNET,
                     2 DDP,ICW,CR34,CR67,EODD,EODU,RCA,XO2,XXO2,SO,SN,H001)
   ISN 0003           WRITE (ICW,5)
   ISN 0004         5 FORMAT (1H1)
   ISN 0005           WRITE(ICW,10)
   ISN 0006        10 FORMAT (10X,16HPROGRAM HYDROAIR)
   ISN 0007           WRITE(ICW,20)
   ISN 0008        20 FORMAT (10X,21HWARREN RICE, MAY 1973,
                     15X,26HLI-TING CHEN DECEMBER 1980,/
                     25X,38HMODIFIED BY CHEN/NICHOLAS  MARCH, 1981,//,'MODIFIED BY WEIS
                     $END-AUGUST 1981',/)
   ISN 0009           WRITE(ICW,30) TAF
   ISN 0010        30 FORMAT (10X,13HATMOS. TEMP.=F6.2,4HDEGF)
   ISN 0011           WRITE(ICW,40) PAA
   ISN 0012        40 FORMAT (10X,14HATMOS. PRESS.=F6.2,4HPSIA)
   ISN 0013           WRITE(ICW,50) RHOL
   ISN 0014        50 FORMAT (10X,18HDENSITY OF LIQUID=F6.2,9H LBM/FTCU)
   ISN 0015           WRITE(ICW,60) FMU
   ISN 0016        60 FORMAT(10X,20HVISCOSITY OF LIQUID=F10.7,11H LBM/FT-SEC)
   ISN 0017           WRITE(ICW,70) CVL
   ISN 0018        70 FORMAT (10X,34HSP. HT. AT CONST. VOL. FOR LIQUID=F6.3,
                     1 13H BTU/LBM-DEGF)
   ISN 0019           WRITE(ICW,80) R
   ISN 0020        80 FORMAT (10X,11HGAS CONST.=F5.1,16H FT-LBF/LBM-DEGF)
   ISN 0021           WRITE(ICW,90) CPG
   ISN 0022        90 FORMAT (10X,33HSP. HT. AT CONST. PRESS. FOR GAS=F6.3,
                     1 13H BTU/LBM-DEGF)
   ISN 0023           WRITE(ICW,100) GAMA
   ISN 0024       100 FORMAT (10X,22HSP. HT. RATIO FOR GAS=F5.2)
   ISN 0025           WRITE(ICW,110) PLOG
   ISN 0026       110 FORMAT (10X,24HPRESS. OF LIQUID AT (0)=F6.2,5H PSIG)
   ISN 0027           WRITE(ICW,120) TLOF
   ISN 0028       120 FORMAT (10X,23HTEMP. OF LIQUID AT (0)=F5.1,5H DEGF)
   ISN 0029           WRITE(ICW,130) PG1G
   ISN 0030       130 FORMAT (10X,21HPRESS. OF GAS AT (1)=F6.2,5H PSIG)
   ISN 0031           WRITE(ICW,140) TG1F
   ISN 0032       140 FORMAT (10X,20HTEMP. OF GAS AT (1)=F5.1,5H DEGF,/)
   ISN 0033           WRITE(ICW,150) DDP,DUP
   ISN 0034       150 FORMAT (10X,18HDIA. OF DOWN-PIPE=F7.3,3H FT,3X,16HDIA. OF UP-PIPE=
                     1 F7.3,3H FT)
   ISN 0035           WRITE (ICW,155) EODD,EODU
   ISN 0036       155 FORMAT (10X,27HROUGHNESS RATIO, DOWN-PIPE=F8.6,3X,
                     1 25HROUGHNESS RATIO, UP-PIPE=F8.6)
   ISN 0037           WRITE(ICW,160) AGP
   ISN 0038       160 FORMAT (10X,17HAREA OF GAS PIPE=F12.7,5H FTSQ,/)
   ISN 0039           WRITE(ICW,170) H01,H12,H23
   ISN 0040       170 FORMAT (10X,13HDISTANCES, FT,10X,4HH01=F9.6,3X,4HH12=F5.2,3X,
                     1 4HH23=F6.2)
   ISN 0041           H000=H01-H001
   ISN 0042           WRITE(ICW,180) H34,H45,H56,H67,H001,H000
   ISN 0043       180 FORMAT (10X,4HH34=F5.2,3X,4HH45=F5.2,3X,4HH56=F6.2,3X,4HH67=F5.2,
                     1 5HH001=F5.2,3X,5HH000=F5.2/)
   ISN 0044           WRITE(ICW,190) CK01,CK45,VR2
   ISN 0045       190 FORMAT (10X,5HCK01=F5.3,5X,5HCK45=F5.3,8X,4HVR2=F6.2,7H FT/SEC)
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+VERSION 1.3.0 (01 MAY 80)      PRNT1     SYSTEM/370 FORTRAN H EXTENDED (ENHANCED)     DATE 82.047/12.56.42         PAGE   2
   ISN 0046            WRITE (ICW,200) CR34,CR67
   ISN 0047        200 FORMAT (10X,5HCR34=F5.3,5X,5HCR67=F5.3,/)
   ISN 0048            WRITE(ICW,210) HNET
   ISN 0049        210 FORMAT (10X,19HNET HYDRAULIC HEAD=F6.2,3H FT,/)
   ISN 0050            WRITE(ICW,220) RCA,XO2,XXO2
   ISN 0051        220 FORMAT(10X,17HCARRY-OVER RATIO=,F10.5,5X,8HXO2(IN)=,
                      1F10.5,5X,9HXO2(OUT)=,F10.5)
   ISN 0052            WRITE(ICW,230) SO,SN
   ISN 0053        230 FORMAT(10X,19HSOLUBILITY IS SO2=,F10.7,5X,4HSN2=,F10.7)
   ISN 0054            RETURN
   ISN 0055            END
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL
*STATISTICS*     SOURCE STATEMENTS =      54, PROGRAM SIZE =      2594, SUBPROGRAM NAME = PRNT1
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                          152K BYTES OF CORE NOT USED
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+VERSION 1.3.0 (01 MAY 80)          SYSTEM/370 FORTRAN H EXTENDED (ENHANCED)     DATE 82.047/12.55.20        PAGE   1
REQUESTED OPTIONS: NOMAP
OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL

    ISN 0002              SUBROUTINE MOD01(PL0A,RHOL,GG,H01,CK01,VL1,PL1,R,TG1,ADP,FML,RAT,
                        1 FMG,AGP,VG1,KAT,JH01,H001,DDP,FMU,EODD,FML)
    ISN 0003              COMMON ALPHA,QL,VLM,FLUX1,FLUXG,KDT
                  C       MODELS FLOW OF LIQUID FROM FREE SURFACE IN INITIAL RESERVOIR (0)
                  C        TO CROSS-SECTION IN PIPE JUST BEFORE GAS INJECTION (1).
    ISN 0004              VL1=VLM*ADP/(ADP-AGP)
    ISN 0005              QL1=QL
    ISN 0006              CALL REN(FML,DDP,FMU,REY)
    ISN 0007              CALL MOOD (REY,EODD,FF)
    ISN 0008              BBBB=FF*H001/DDP
    ISN 0009              IF (JH01) 5,5,7
    ISN 0010            5 PL1=PL0A
    ISN 0011              H01=(.9+BBBB)*.5*VL1*VL1/GG
    ISN 0012              GO TO 9
    ISN 0013            7 PL1=PL0A+RHOL*(GG*H01-(.9+BBBB)*.5*VL1*VL1)/(32.2*144.)
                  C       PL1---LBF/INSQ
    ISN 0014            9 PG1=PL1
    ISN 0015              RHOG1=PG1*144./(R*TG1)
                  C       FMG---MASS FLOW RATE OF GAS    ---LBM/SEC
                  C       FML---MASS FLOW RATE OF LIQUID---LBM/SEC
                  C       AGP---AREA OF GAS PIPE---FTSQ
    ISN 0016           20 CONTINUE
    ISN 0017              QG1=ALPHA*QL/(1.0-ALPHA)
    ISN 0018              FMG=QG1*RHOG1
    ISN 0019              VG1=QG1/AGP
    ISN 0020              RAT=FMG/FML
    ISN 0021              FLUX1=(QG1+QL1)/ADP
    ISN 0022              FLUXG=QG1/ADP
    ISN 0023              IF(KDT)3000,3000,3005
                  C    ******************** PRINT 01-- INTERMEDIATE VALUES *********************
                  C
    ISN 0024         3005 CONTINUE
    ISN 0025              WRITE(6,1100) PL1,VL1,VG1,FML,FMG,AGP,RAT
    ISN 0026         1100 FORMAT (10X,7HMOD01PT,7F10.5)
                  C    ************************* ENDMOD 01 *************************
    ISN 0027         3000 CONTINUE
    ISN 0028              RETURN
    ISN 0029              END
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL
*STATISTICS*     SOURCE STATEMENTS =       28, PROGRAM SIZE =      1044, SUBPROGRAM NAME = MOD01
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                     164K BYTES OF CORE NOT USED
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+VERSION 1.3.0 (01 MAY 80)              SYSTEM/370 FORTRAN H EXTENDED (ENHANCED)     DATE 82.047/12.55.25        PAGE    1
REQUESTED OPTIONS: NOMAP
OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL

      ISN 0002                SUBROUTINE MOD12(FMLZ,FMGZ,RHOLZ,VR2Z,CVLZ,CPGZ,RZ,ADPZ,AGPZ,PG1Z,
                             1 PL1Z,TG1Z,TL0Z,H12Z,ICW,VL2,VG2,P2,T2,II,VG1Z,RATZ,VL1Z)
      ISN 0003                COMMON ALPHA,CL,VLM,FLUX1,FLUXG,KDT
                        C     MODELS FLOW IN GAS INJECTION ZONE, FROM (1) JUST AHEAD OF GAS
                        C      INJECTION TO (2) AFTER GAS INJECTION. CONTINUITY, LINEAR
                        C      MOMENTUM, AND COMPRESSIBLE ENERGY EQUATIONS ARE SATISFIED.
                        C      TEMP. OF GAS AND LIQUID ARE DIFFERENT AT (1) BUT SAME AT (2).
                        C      PRESSURE OF GAS AND LIQUID ARE SAME AT (1).
      ISN 0004                DOUBLE PRECISION HOR,HYP,PHI,PI,TL1,RHOG1,A,B,C,D,E,F,G,H,HYPSQ,
                             1VL2Z,VG2Z,P2Z,T2Z,PG1,R,TG1,CVL,PL1,RHOL,RAT,CPG,VG1,AGP,
                             2ADP,FML,VR2,TL0
      ISN 0005                FML=FMLZ
      ISN 0006                FMG=FMGZ
      ISN 0007                RHOL=RHOLZ
      ISN 0008                VR2=VR2Z
      ISN 0009                CVL=CVLZ
      ISN 0010                CPG=CPGZ
      ISN 0011                R=RZ
      ISN 0012                ADP=ADPZ
      ISN 0013                AGP=AGPZ
      ISN 0014                PG1=PG1Z
      ISN 0015                PL1=PL1Z
      ISN 0016                TG1=TG1Z
      ISN 0017                TL0=TL0Z
      ISN 0018                H12=H12Z
      ISN 0019                VG1=VG1Z
      ISN 0020                RAT=RATZ
      ISN 0021                VL1=VL1Z
      ISN 0022                PI=3.141592653
      ISN 0023                II=0
      ISN 0024                TL1=TL0
      ISN 0025                RHOG1=PG1*144.D0/(R*TG1)
                        C     A---FTSQ/SECSQ
      ISN 0026             50 A=CVL*TL1*778.D0*32.2D0+PL1*144.D0*32.2D0/RHOL+.5D0*VL1*VL1+RAT*
                             1 (CPG*TG1*778.D0*32.2D0+.5D0*VG1*VG1)
                        C     B---FT/SEC
      ISN 0027                B=(PG1*144.D0*AGP+PL1*144.D0*(ADP-AGP))*32.2D0/FML+RAT*(VG1+VR2)
                             1 +VL1
      ISN 0028             70 C=(CVL+RAT*CPG)*778.D0/(R*RAT)
                        C     C---DIMENSIONLESS
                        C     D---FT/SEC
      ISN 0029                D=((C-1.D0)*(1.D0+RAT)*FML/(ADP*RHOL)+B*C+C*(1.D0+RAT)*VR2-RAT*
                             1 VR2)/((.5D0-C)*(1.D0+RAT))
                        C     E---FTSQ/SECSQ
      ISN 0030                E=((1.D0-C)*(B*FML/(ADP*RHOL))-A-C*(1.D0+RAT)*(FML/(ADP*RHOL))*
                             1 VR2-B*C*VR2+.5D0*RAT*VR2*VR2)/((.5D0-C)*(1.D0+RAT))
                        C     F---FTCU/SECCU
      ISN 0031                F=(B*C*FML*VR2/(ADP*RHOL))/((.5D0-C)*(1.D0+RAT))
      ISN 0032             80 G=(3.D0*E-D*D)/3.D0
      ISN 0033                H=(2.D0*D*D*D-9.D0*D*E+27.D0*F)/27.D0
      ISN 0034                DIS=H*H*.25+G*G*G/27.
      ISN 0035                IF(KDT)3000,3000,3005
                        C  ***********************PRINT 12-- MOD 12 *************************
      ISN 0036           3005 CONTINUE
      ISN 0037                WRITE (6,1200) A,B,C,D,E,F,G,H,DIS
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   ISN 0038        1200 FORMAT (5X,5HMOD12,9E12.4)
                 C  $$$$$$$$$$$$$$$$******* END MOD 12 ***************************
   ISN 0039        3000 CONTINUE
   ISN 0040             IF (DIS) 100,500,500
   ISN 0041         100 HYPSQ=-G*G*G/27.D0
   ISN 0042             HYP=DSQRT(HYPSQ)
   ISN 0043             HOR=-H*.5D0
   ISN 0044             PHI=DARCOS(HOR/HYP)
   ISN 0045         120 VL2Z=2.*DSQRT(-G/3.D0)*DCOS(PHI/3.D0+PI*4.D0/3.D0)-D/3.D0
   ISN 0046             VL2=VL2Z
   ISN 0047             VG2Z=VL2Z-VR2
   ISN 0048             VG2=VG2Z
   ISN 0049             P2Z=((B*FML/ADP)-(1.D0+RAT)*(FML*VL2Z/ADP))/(144.D0*32.2D0)
   ISN 0050             P2=P2Z
   ISN 0051             IF (RAT-0.00001D0) 150,150,130
   ISN 0052         130 T2Z=P2Z*144.D0*(ADP*(VL2Z-VR2)-FML*(VL2Z-VR2)/(RHOL*VL2Z))/(FMG*R)
   ISN 0053             T2=T2Z
   ISN 0054             IF (T2-TL0) 150,200,200
   ISN 0055         150 T2=TL0
   ISN 0056         200 RETURN
   ISN 0057         500 WRITE (ICW,510) RAT, DIS
   ISN 0058         510 FORMAT (19H ERR IN MOD12. RAT=F10.6,5X,4HDIS=E15.8)
   ISN 0059             II=1
   ISN 0060             RETURN
   ISN 0061             END
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL
*STATISTICS*     SOURCE STATEMENTS =       60, PROGRAM SIZE =      2232, SUBPROGRAM NAME = MOD12
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                   152K BYTES OF CORE NOT USED
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+VERSION 1.3.0 (01 MAY 80)              SYSTEM/370 FORTRAN H EXTENDED (ENHANCED)     DATE 82.047/12.56.05        PAGE    1
REQUESTED OPTIONS: NOMAP
OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL

   ISN 0002              SUBROUTINE MOD23(FML,FMG,RHOL,VR2,CVL,CPG,ADP,PS,T2,VL2,H23,DDP,
                        1 FMU,VL3,VG3,P3,T3,EODD,XO2,XN2,XXO2,XXN2,RAT,SO,SN,FF)
   ISN 0003              COMMON ALPHA,QL,VLM,FLUX1,FLUXG,KDT
                   C     MODELS TWO-PHASE FLOW FROM CROSS-SECTION FOLLOWING GAS INJECTION
                   C      (2) TO CROSS SECTION AT LOWER END OF DOWN-PIPE (3). EACH PHASE
                   C      IS CONSIDERED 1-D, WITH THE GAS PHASE HAVING A DRIFT VELOCITY
                   C      WHICH CHANGES WITH PRESSURE. CONTINUITY, LINEAR MOMENTUM, AND
                   C      COMPRESSIBLE ENERGY EQUATIONS ARE SATISFIED
   ISN 0004              ICW=6
   ISN 0005              G=32.2
   ISN 0006              DZ=H23*.001
   ISN 0007              HD=.00001
   ISN 0008              PI=3.141592653
   ISN 0009              PPS=PS*144.
   ISN 0010              P3=PPS
   ISN 0011              T3=T2
   ISN 0012              V3=VL2
   ISN 0013              XXO2=XO2
   ISN 0014              XXN2=XN2
   ISN 0015              VR=VR2*(PPS/P3)**0.16666
   ISN 0016              RAT1=RAT
   ISN 0017          100 CALL DSOL(RAT1,FML,FMG,XO2,XN2,P3,XXO2,XXN2,FMG3,SO,SN)
   ISN 0018              FMG=FMG3
   ISN 0019              FM2=FML+FMG
   ISN 0020              CALL REN(FM2,DDP,FMU,REY)
   ISN 0021              CALL MOOD (REY,EODD,FF)
   ISN 0022              TONE=FML*CVL+FMG*CPG
   ISN 0023              F1=(FML*CVL+FMG*CPG)*778.0
   ISN 0024              G=32.2
   ISN 0025              F2=FML/RHOL
   ISN 0026              TTWO=FML/(RHOL*V3*V3*(ADP-FML/(RHOL*V3)))+1./(V3-VR)
   ISN 0027              F3=-(FML+FMG)*G/32.2
   ISN 0028              F4=((FML+FMG)*V3-FMG*VR)/32.2
   ISN 0029              F5=-FMG*(V3-VR)/32.2
   ISN 0030              F6=TTWO
   ISN 0031              F7=1.0/P3
   ISN 0032              F8=-1.0/T3
   ISN 0033              F9=-1.0/(V3-VR)
   ISN 0034              F10=((FMG/(ADP*(V3-VR))+FML/(ADP*V3))*G
                        1 -FF*RHOL*V3*V3*PI*DDP/(8.0*ADP))/32.2
   ISN 0035              F11=-((FML+FMG)/ADP)/32.2
   ISN 0036              F12=(FMG/ADP)/32.2
   ISN 0037              F13=-VR/(6.0*P3)
   ISN 0038              F14=F10/(1.-F12*F13)
   ISN 0039              F15=F11/(1.0-F12*F13)
   ISN 0040              F16=F6/F8-F4/F1
   ISN 0041              F17=F7/F8+F9*F13/F8-F2/F1-F5*F3/F1
   ISN 0042              F18=-F3/F1
   ISN 0043              F19=-F18/(F16+F17*F15)-F17*F14/(F16+F17*F15)
   ISN 0044              F20=-F18/F17-F16*F19/F17
   ISN 0045              DV=F19*DZ
   ISN 0046              DP=F20*DZ
   ISN 0047              DT=-F6/F8*F19*DZ-F7*F20*DZ/F8-F9*F13*F20*DZ/F8
   ISN 0048              DVR=F13*F20*DZ
   ISN 0049              V3=V3+DV
```

```
+VERSION 1.3.0 (01 MAY 80)      MOD23     SYSTEM/370 FORTRAN H EXTENDED (ENHANCED)     DATE 82.047/12.56.05        PAGE   2
    ISN 0050            VR=VR+DVR
    ISN 0051            P3=P3+DP
    ISN 0052            T3=T3+DT
    ISN 0053            HD=HD+DZ
    ISN 0054            IF (HD-H23) 100,120,120
    ISN 0055        120 P3=P3/144.
    ISN 0056            VL3=V3
    ISN 0057            VG3=V3-VR
    ISN 0058            IF(KDT)3000,3000,3005
                 C   ********************* PRINT 23--MOD 23  $$$$$$$$$$$$$$$$$$$$$$$
    ISN 0059       3005 CONTINUE
    ISN 0060            WRITE (6,1300) F1,F2,F3,F4,F5,F6,F7,F8,F9
    ISN 0061            WRITE(6,1400) F10,F11,F12,F13,F14,F15,F16,F17,F18,F19,F20,T3
    ISN 0062            WRITE (6,1500) DV,DP,DVR,V3,VR,P3,HD
    ISN 0063       1300 FORMAT (5X,6H1MOD23/10X,9F10.4/)
    ISN 0064       1400 FORMAT(5X,6H2MOD23/2(5X,6E12.4/))
    ISN 0065       1500 FORMAT (5X,6H3MOD23/10X,7F10.4)
                 C   $$$$$$$$$$$$$$$$$$$$$$  END 23  $$$$$$$$$$$$$$$$$
    ISN 0066       3000 CONTINUE
    ISN 0067            RETURN
    ISN 0068            END
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL
*STATISTICS*     SOURCE STATEMENTS =      67, PROGRAM SIZE =      2204, SUBPROGRAM NAME = MOD23
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                   152K BYTES OF CORE NOT USED
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```
+VERSION 1.3.0 (01 MAY 80)               SYSTEM/370 FORTRAN H EXTENDED (ENHANCED)     DATE 82.047/12.56.12        PAGE    1
REQUESTED OPTIONS: NOMAP
OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL

    ISN 0002              SUBROUTINE DSOL(RAT1,FML,FMG2,XO2,XN2,P3,XXO2,XXN2,FMG3,SO,SN)
    ISN 0003              SN2=SN/14.72
    ISN 0004              SO2=SO/14.72
    ISN 0005              TN1=RAT1*(XO2+XN2)/(XO2*32.+XN2*28.)
    ISN 0006              P2=P3/144.
    ISN 0007              PO2=P2*XXO2
    ISN 0008              PN2=P2*XXN2
    ISN 0009              ENO2=SO2*PO2
    ISN 0010              ENN2=SN2*PN2
    ISN 0011              RAT=RAT1-1.7777*ENO2-1.5555*ENN2
    ISN 0012              TN2=RAT1*(XO2+XN2)/(XO2*32.+XN2*28.)-(ENO2+ENN2)/18.
    ISN 0013              C1=XO2/(XO2*32.+XN2*28.)
    ISN 0014              C2=(XO2+XN2)/(XO2*32.+XN2*28.)
    ISN 0015              C3=ENO2/18.
    ISN 0016              C4=(ENO2+ENN2)/18.
    ISN 0017              IF (RAT-0.00001D0) 2500,2500,2400
    ISN 0018         2400 XXO2=(RAT1*C1-C3)/(RAT1*C2-C4)
    ISN 0019              GO TO 2200
    ISN 0020         2500 XXO2=C1/C2
    ISN 0021         2200 XXN2=1.-XXO2
    ISN 0022              FMG3=RAT*FML
    ISN 0023              RETURN
    ISN 0024              END
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL
*STATISTICS*     SOURCE STATEMENTS =       23, PROGRAM SIZE =       710, SUBPROGRAM NAME =   DSOL
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                          164K BYTES OF CORE NOT USED
```

```
+VERSION 1.3.0 (01 MAY 80)                SYSTEM/370 FORTRAN H EXTENDED (ENHANCED)    DATE 82.047/12.56.18        PAGE   1
REQUESTED OPTIONS: NOMAP
OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL

   ISN 0002                 SUBROUTINE MOD34(P3,RHOL,H34,P4,CR34,VL3)
                  C         MODELS FLOW FROM PIPE CROSS-SECTION AT BOTTOM OF DOWNPIPE (3)
                  C          TO SURFACE OF LIQUID IN SEPARATION TANK (4).
   ISN 0003                 P4=P3-RHOL*H34/144.+CR34*VL3*VL3*.5*RHOL/(32.2*144.)
   ISN 0004                 RETURN
   ISN 0005                 END
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL
*STATISTICS*     SOURCE STATEMENTS =        4, PROGRAM SIZE =       332, SUBPROGRAM NAME = MOD34
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                          164K BYTES OF CORE NOT USED
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+VERSION 1.3.0 (01 MAY 80)              SYSTEM/370 FORTRAN H EXTENDED (ENHANCED)     DATE 82.047/12.56.22         PAGE    1
REQUESTED OPTIONS: NOMAP
OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL

   ISN 0002              SUBROUTINE PERF(RHOL,FML,FMG,R,P4,HNET,GAMA,PAA,QL,QG,EFF,POWL,
                        1POWG,T3,TA,CPG,PG1,RCA,QGA,FMGA,FMG1)
                 C       QL---GAL/MIN
   ISN 0003              QL=FML*7.48*60./RHOL
                 C       QG---CFM AT STD. COND. (14.72 PSIA, 70 DEGF)
   ISN 0004              QG=FMG1*R*530.*60./(14.72*144.)
   ISN 0005              FMGA=FMG*(1.-RCA)
   ISN 0006              QGA=FMGA*R*530.*60./(14.72*144.)
                 C       POWL---HP
   ISN 0007              POWL=QL*HNET*RHOL/(33000.*7.48)
                 C       POWG---HP
   ISN 0008              FMG=FMG*(1.-RCA)
   ISN 0009              WISO=-FMG*CPG*T3*(((PAA/P4)**((GAMA-1.)/GAMA))-1.)*778./550.
   ISN 0010              WISI=FMG*CPG*TA*(((PG1/PAA)**((GAMA-1.)/GAMA))-1.)*778./550.
   ISN 0011              POWG=WISO-WISI
   ISN 0012              TEXH=T3-WISO*550./(FMG*CPG*778.)-460.
   ISN 0013              EFF=POWG/POWL
   ISN 0014              REF=WISO/4.71
                 C       REF---TONS
   ISN 0015              EFFEC=(POWG+WISO)/POWL
   ISN 0016              RETURN
   ISN 0017              END
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL
*STATISTICS*     SOURCE STATEMENTS =       16, PROGRAM SIZE =       964, SUBPROGRAM NAME =  PERF
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                          164K BYTES OF CORE NOT USED
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```
*VERSION 1.3.0 (01 MAY 80)          SYSTEM/370 FORTRAN H EXTENDED (ENHANCED)     DATE 82.047/12.56.27        PAGE    1
REQUESTED OPTIONS: NOMAP
OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL

   ISN 0002                SUBROUTINE REN(G,D,FMU,REY)
                 C         CALCULATES REYNOLDS NUMBER IN PIPE FLOW.
                 C         G---MASS FLOW RATE---LBM/SEC
                 C         D---PIPE DIAMETER---FT
                 C         FMU---VISCOSITY---LBM/FT-SEC
   ISN 0003                PI=3.141592653
   ISN 0004                REY=4.*G/(PI*D*FMU)
   ISN 0005                RETURN
   ISN 0006                END
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL
*STATISTICS*     SOURCE STATEMENTS =       5, PROGRAM SIZE =       270, SUBPROGRAM NAME =    REN
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                        164K BYTES OF CORE NOT USED
```

```
+VERSION 1.3.0 (01 MAY 80)            SYSTEM/370 FORTRAN H EXTENDED (ENHANCED)     DATE 82.047/12.56.36         PAGE    1
REQUESTED OPTIONS: NOMAP
OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL

   ISN 0002                SUBROUTINE MOOD(RE,EOD,FF)
                   C       CALCULATES FRICTION FACTOR FOR GIVEN REYNOLDS NUMBER AND
                   C        ROUGHNESS RATIO FOR LAMINAR OR TURBULENT FLOW.
   ISN 0003                IF (RE-2300.) 10,10,20
   ISN 0004             10 FF=64./RE
   ISN 0005                RETURN
   ISN 0006             20 A=EOD/3.7
   ISN 0007                B=2.51/RE
   ISN 0008                DFF=.01
   ISN 0009                FF=0.
   ISN 0010             30 FF=FF+DFF
   ISN 0011                RFF=SQRT(FF)
   ISN 0012                C=1./RFF+.86*ALOG(A+B/RFF)
   ISN 0013                IF (C) 40,100,30
   ISN 0014             40 AC=ABS(C)
   ISN 0015                IF (AC-.00001) 100,100,50
   ISN 0016             50 FF=FF-DFF
   ISN 0017                DFF=DFF*.1
   ISN 0018                GO TO 30
   ISN 0019            100 RETURN
   ISN 0020                END
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL
*STATISTICS*     SOURCE STATEMENTS =       19, PROGRAM SIZE =       508, SUBPROGRAM NAME =  MOOD
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                       164K BYTES OF CORE NOT USED
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```
+VERSION 1.3.0 (01 MAY 80)              SYSTEM/370 FORTRAN H EXTENDED (ENHANCED)    DATE 82.047/12.56.50       PAGE    1
REQUESTED OPTIONS: NOMAP
OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL

   ISN 0002               SUBROUTINE PRNT2(RAT,ICW)
   ISN 0003               WRITE (ICW,10) RAT
   ISN 0004            10 FORMAT (10X,28HMASS FLOW RATIO, GAS/LIQUID=F10.8)
   ISN 0005               RETURN
   ISN 0006               END
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL
*STATISTICS*     SOURCE STATEMENTS =        5, PROGRAM SIZE =       266, SUBPROGRAM NAME = PRNT2
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                     164K BYTES OF CORE NOT USED
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```
+VERSION 1.3.0 (01 MAY 80)          SYSTEM/370 FORTRAN H EXTENDED (ENHANCED)     DATE 82.047/12.56.53        PAGE   1
REQUESTED OPTIONS: NOMAP
OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL

    ISN 0002             SUBROUTINE PRNT3(FML,FMG1,QL,QG,QGA,FMGA,P4,EFF,POWL,POWG,ICW,T3,
                        1PAA)
    ISN 0003             WRITE (ICW,10) FML
    ISN 0004          10 FORMAT (10X,25HMASS FLOW RATE OF LIQUID=F14.6,8H LBM/SEC)
    ISN 0005             WRITE(ICW,20) QL
    ISN 0006          20 FORMAT (10X,27HVOLUME FLOW RATE OF LIQUID=F14.5,8H GAL/MIN,/)
    ISN 0007             WRITE(ICW,30) FMG1
    ISN 0008          30 FORMAT(10X,28HTOTAL MASS FLOW RATE OF GAS=F12.8,8H LBM/SEC)
    ISN 0009             WRITE(ICW,35) FMGA
    ISN 0010          35 FORMAT(10X,32HAVAILABLE MASS FLOW RATE OF GAS=F12.8,8H LBM/SEC)
    ISN 0011             WRITE(ICW,40) QG
    ISN 0012          40 FORMAT(10X,30HTOTAL VOLUME FLOW RATE OF GAS=F12.6,
                        1 26H CFM AT 14.72 PSIA,70 DEGF,/)
    ISN 0013             WRITE(ICW,45) QGA
    ISN 0014          45 FORMAT(10X,34HAVAILABLE VOLUME FLOW RATE OF GAS=F12.6,
                        126H CFM AT 14.72 PSIA,70 DEGF,/)
    ISN 0015             PG4=P4-PAA
    ISN 0016             WRITE(ICW,50) PG4
    ISN 0017          50 FORMAT (10X,35HPRESSURE OF GAS IN SEPARATION TANK=F6.2,5H PSIG)
    ISN 0018             T3F=T3-460.
    ISN 0019             WRITE(ICW,60) T3F
    ISN 0020          60 FORMAT (10X,38HTEMPERATURE OF GAS IN SEPARATION TANK=F6.2,5H DEGF,
                        1 /)
    ISN 0021             WRITE(ICW,70) POWL
    ISN 0022          70 FORMAT (10X,22HIDEAL HYDRAULIC POWER=F10.5,3H HP)
    ISN 0023             WRITE (ICW,75) POWG
    ISN 0024          75 FORMAT (10X,26HISENTROPIC EXP. GAS POWER=F10.5,3H HP)
    ISN 0025             WRITE(ICW,90) EFF
    ISN 0026          90 FORMAT (10X,49HEFFICIENCY, BASED ON ISENTROPIC EXPANSION OF GAS=
                        1 F5.3)
    ISN 0027             RETURN
    ISN 0028             END
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL
*STATISTICS*     SOURCE STATEMENTS =       27, PROGRAM SIZE =      1266, SUBPROGRAM NAME = PRNT3
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END CF COMPILATION ******                                      164K BYTES OF CORE NOT USED
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*VERSION 1.3.0 (01 MAY 80)           SYSTEM/370 FORTRAN H EXTENDED (ENHANCED)     DATE 82.047/12.56.57        PAGE   1
REQUESTED OPTIONS: NOMAP
OPTIONS IN EFFECT: NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
                   SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL

   ISN 0002             SUBROUTINE PRNT4(PL1,PG1G,VL1,VG1,TL0,TG1F,P2,VL2,VG2,T2,P3,VL3,
                       1 VG3,T3,P4,P5,V5,P6,V6,P7,FMG,FML,DDP,DUP,FMU,ICW,PAA,H01,H23)
   ISN 0003             PL1G=PL1-PAA
   ISN 0004             TL1F=TL0-460.
   ISN 0005             CALL REN(FML,DDP,FMU,REY1)
   ISN 0006             T2F=T2-460.
   ISN 0007             FM2=FML+FMG
   ISN 0008             CALL REN(FM2,DDP,FMU,REY2)
   ISN 0009             T3F=T3-460.
   ISN 0010             PG3=P3-PAA
   ISN 0011             PG2=P2-PAA
   ISN 0012             PG4=P4-PAA
   ISN 0013             PG5=P5-PAA
   ISN 0014             CALL REN(FML,DUP,FMU,REY5)
   ISN 0015             PG6=P6-PAA
   ISN 0016             PG7=P7-PAA
   ISN 0017             WRITE(ICW,10)
   ISN 0018          10 FORMAT (10X,44HVEL,FT/SEC, PRESSURE,PSIG, TEMPERATURE,DEGF,/)
   ISN 0019             WRITE(ICW,20) VL1,PL1G,TL1F,REY1
   ISN 0020          20 FORMAT(10X,4HVL1=F6.2,3X,4HPL1=F6.2,3X,4HTL1=F7.2,
                       13X,4HRE1=F9.0)
   ISN 0021             WRITE(ICW,30) VG1,PG1G,TG1F
   ISN 0022          30 FORMAT (10X,4HVG1=F6.2,3X,4HPG1=F6.2,3X,4HTG1=F7.2)
   ISN 0023             WRITE(ICW,40) VL2,PG2,T2F,REY2
   ISN 0024          40 FORMAT (10X,4HVL2=F6.2,3X,4HP2 =F6.2,3X,4HT2 =F7.2,3X,4HRE2=F9.0)
   ISN 0025             WRITE(ICW,50) VG2
   ISN 0026          50 FORMAT (10X,4HVG2=F6.2)
   ISN 0027             WRITE(ICW,60) VL3,PG3,T3F,REY2
   ISN 0028          60 FORMAT (10X,4HVL3=F6.2,3X,4HP3 =F6.2,3X,4HT3 =F7.2,3X,4HRE3=F9.0)
   ISN 0029             WRITE(ICW,70) VG3
   ISN 0030          70 FORMAT (10X,4HVG3=F6.2)
   ISN 0031             WRITE(ICW,80) PG4,T3F
   ISN 0032          80 FORMAT (23X,4HP4 =F6.2,3X,4HT4 =F7.2)
   ISN 0033             WRITE(ICW,90) V5,PG5,T3F,REY5
   ISN 0034          90 FORMAT (10X,4HV5 =F6.2,3X,4HP5 =F6.2,3X,4HT5 =F7.2,3X,4HRE5=F9.0)
   ISN 0035             WRITE(ICW,100) V6,PG6,T3F,REY5
   ISN 0036         100 FORMAT (10X,4HV6 =F6.2,3X,4HP6 =F6.2,3X,4HT6 =F7.2,3X,4HRE6=F9.0)
   ISN 0037             WRITE(ICW,110) PG7
   ISN 0038         110 FORMAT (23X,4HP7 =F6.2)
   ISN 0039             RETURN
   ISN 0040             END
*OPTIONS IN EFFECT*NAME(MAIN) OPTIMIZE(3) LINECOUNT(60) SIZE(MAX) AUTODBL(NONE)
*OPTIONS IN EFFECT*SOURCE EBCDIC NOLIST NODECK OBJECT NOMAP NOFORMAT GOSTMT NOXREF NOALC NOANSF TERM IBM FLAG(I) XL
*STATISTICS*    SOURCE STATEMENTS =       39, PROGRAM SIZE =      1720, SUBPROGRAM NAME = PRNT4
*STATISTICS*  NO  DIAGNOSTICS GENERATED
****** END OF COMPILATION ******                                      164K BYTES OF CORE NOT USED

*STATISTICS*    2 DIAGNOSTICS THIS STEP, HIGHEST SEVERITY CODE IS  4
```

```
FORTRAN H EXTENDED (ENHANCED)

 *** FORTRAN H EXTENDED ERROR MESSAGES ***

 LINE                                           CALL PRNT1(RHOL,FMU,CVL,R,CPG,GAMA,TAF,TLOF,TG1F,PAA,PLOG,PG1G,
 LINE                                          1 DUP,AGP,GNUM,CK01,CK45,VR2,H01,H12,H23,H34,H45,H56,H67,HNET,DDP,
 LINE                                          2ICW,CR34,CR67,EODD,EODU,RCA,XO2,XXO23,SO,SN,H001)
 IFE224I SEVERITY  4(W)   ISN 0166   THE STATEMENT AFTER AN ARITHMETIC IF, GO TO, STOP OR RETURN HAS NO LABEL

 LABEL100003
 IFE6101 SEVERITY  4(W)              THE STATEMENT NUMBER OR GENERATED LABEL IS UNREACHABLE.

SOURCE STATEMENTS =      198, PROGRAM SIZE =      8720, SUBPROGRAM NAME =  MAIN

SOURCE STATEMENTS =       28, PROGRAM SIZE =      1044, SUBPROGRAM NAME = MOD01

SOURCE STATEMENTS =       60, PROGRAM SIZE =      2232, SUBPROGRAM NAME = MOD12

SOURCE STATEMENTS =       67, PROGRAM SIZE =      2204, SUBPROGRAM NAME = MOD23

SOURCE STATEMENTS =       23, PROGRAM SIZE =       710, SUBPROGRAM NAME =  DSOL

SOURCE STATEMENTS =        4, PROGRAM SIZE =       332, SUBPROGRAM NAME = MOD34

SOURCE STATEMENTS =       16, PROGRAM SIZE =       964, SUBPROGRAM NAME =  PERF

SOURCE STATEMENTS =        5, PROGRAM SIZE =       270, SUBPROGRAM NAME =   REN

SOURCE STATEMENTS =       19, PROGRAM SIZE =       508, SUBPROGRAM NAME =  MOOD

SOURCE STATEMENTS =       54, PROGRAM SIZE =      2594, SUBPROGRAM NAME = PRNT1

SOURCE STATEMENTS =        5, PROGRAM SIZE =       266, SUBPROGRAM NAME = PRNT2

SOURCE STATEMENTS =       27, PROGRAM SIZE =      1266, SUBPROGRAM NAME = PRNT3

SOURCE STATEMENTS =       39, PROGRAM SIZE =      1720, SUBPROGRAM NAME = PRNT4
```

F64-LEVEL LINKAGE EDITOR OPTIONS SPECIFIED LIST,MAP
DEFAULT OPTION(S) USED - SIZE=(196608,65536)
SYSPRINT DEFAULT BLOCKING USED 1 - 1

MODULE MAP

CONTROL SECTION NAME	ORIGIN	LENGTH	ENTRY NAME	LOCATION	NAME	LOCATION	NAME	LOCATION	NAME	LOCATION
MAIN	00	2210								
MOD01	2210	414								
MOD12	2628	8B8								
MOD23	2EE0	89C								
DSCL	3780	2C6								
MOD34	3A48	14C								
PERF	3B98	3C4								
BEN	3F60	10E								
MOOD	4070	1FC								
PRNT1	4270	A22								
PRNT2	4C98	10A								
PRNT3	4DA8	4F2								
PRNT4	52A0	6B8								
IHOSLGN *	5958	244	ALOG	5958	IH$ALOG	5958	LOG	5958		
IHOLASCN*	5BA0	267	DARCOS	5BA0	IH$DARCS	5BA0	DARSIN	5BB8	IH$DARSN	5BB8
IHOLCOS *	5E08	280	DCOS	5E08	IH$DCOS	5E08				
IHOLSQRT*	6088	170	DSQRT	6088	IH$DSQRT	6088				
IHOFRXPR*	61F8	4A4	FRXPR#	61F8						
IHOECOMH*	66A0	E30	IBCOM#	66D4	FDIOCS#	6790	INTSWTCH	7418		
FIOAP# *	74D0	61C								
IHOCOMH2*	7AF0	9A5	SEQDASD	7EC2						
IHOSSQRT*	8498	174	SQRT	8498	IH$SQRT	8498				
IHOFCVTH*	8610	CFA	ADCON#	8610	FCVAOUTP	867C	FCVLOUTP	8694	FCVZOUTP	86AC
			FCVIOUTP	86C4	FCVEOUTP	86FC	FCVCOUTP	86FC	ADCONI#	8E0C
			ADCONO#	8E28	INT6SWCH	9309				
IHOEFNTH*	9310	800	ARITH#	9310	ADJSWTCH	98A4				
IHOEFIOS*	9B10	118C	FIOCS#	9B10	FIOCSBEP	9B16				
IHOFIOS2*	ACA0	642								
IHOSEXP *	B2E8	258	IH$$EXP	B2E8	EXP	B2E8				
IHOERRM *	B540	624	ERRMON	B540	IHOERRE	B558				
IHOUOPT *	BB68	388								

NAME	ORIGIN	LENGTH
IHOFCONI*	BEF0	418
IHOFCONO*	C308	8B8
IHOETRCH*	CBC0	2AE
IHOUATBL*	CE70	638
IHOFTEN *	D4A8	220
$BLANKCOM	D6C8	18

NAME	LOCATION	NAME	LOCATION	NAME	LOCATION	NAME	LOCATION
FQCONI#	BEF0						
FQCONO#	C308						
IHOTRCH	CBC0	ERRTRA	CBC8				
FTEN#	D4A8						

ENTRY ADDRESS 00

TOTAL LENGTH D6E0
****NAMEX DOES NOT EXIST BUT HAS BEEN ADDED TO DATA SET
AUTHORIZATION CODE IS 0.

B.2 Printout of a Sample Run

```
INPUT                 CASE 1

    KDT   =  0
    AGP   = 0.0000221
    RHOL  =  62.30000    FMU   =    0.00088    CVL   =   1.00000
        R =   53.30000    CPG   =    0.24000    GAMA =    1.40000
    TAF   =  74.60001    TLOF  =  65.00000    TG1F  =  65.00000
    PAA   =  14.27000    PLOG  = -13.95000    H001  =   1.50000
    DDP   =  0.166700    DUP   =   0.166700   EODD  =  0.000400    EODU  =  0.000400
    CK01  =  0.200000    CK45  =   0.250000   VR2   =   1.30805    CR34  =  0.350000    CR67 =  0.500000
    H01   =   1.50000    H12   =    0.0       H23   =  33.00000    H34   =   2.33300
    H45   =   0.0        H56   =    0.0       H67   =    0.0       HNET  =  32.16701
    X/2   =   0.21000    XN2   =   0.790000
    RAT   = 0.0002500    RCA   =    0.0       SN    =    0.0       SO    =    0.0
    VLM   =    2.3940    ALP   =0.00000010

PDIF(K)=          0.0169840902

FRICTION FACTOR=          0.0252822563

PDIF(K)=          0.0000108266

FRICTION FACTOR=          0.0252822563
```

```
        PROGRAM HYDROAIR
        WARREN RICE, MAY 1973      LI-TING CHEN DECEMBER 1980
    MODIFIED BY CHEN/NICHOLAS  MARCH, 1981

ODIFIED BY WEIS END-AUGUST 1981

        ATMOS. TEMP.= 74.60DEGF
        ATMOS. PRESS.= 14.27PSIA
        DENSITY OF LIQUID= 62.30 LBM/FTCU
        VISCOSITY OF LIQUID= 0.0008800 LBM/FT-SEC
        SP. HT. AT CONST. VOL. FOR LIQUID= 1.000 BTU/LBM-DEGF
        GAS CONST.= 53.3 FT-LBF/LBM-DEGF
        SP. HT. AT CONST. PRESS. FOR GAS= 0.240 BTU/LBM-DEGF
        SP. HT. RATIO FOR GAS= 1.40
        PRESS. OF LIQUID AT (0)=-13.95 PSIG
        TEMP. OF LIQUID AT (0)= 65.0 DEGF
        PRESS. OF GAS AT (1)=-13.10 PSIG
        TEMP. OF GAS AT (1)= 65.0 DEGF

        DIA. OF DOWN-PIPE=  0.167 FT   DIA. OF UP-PIPE=  0.167 FT
        ROUGHNESS RATIO, DOWN-PIPE=0.000400   ROUGHNESS RATIO, UP-PIPE=0.000400
        AREA OF GAS PIPE=   0.0000221 FTSQ

        DISTANCES, FT             H01= 2.959858   H12= 0.0    H23= 33.00
        H34= 2.33   H45= 0.0    H56=  0.0    H67= 0.0 H001= 1.50   H000= 0.56

        CK01=0.200      CK45=0.250          VR2=  1.31 FT/SEC
        CR34=0.350      CR67=0.500

        NET HYDRAULIC HEAD= 32.73 FT

        CARRY-OVER RATIO=   0.0          XO2(IN)=    0.21000     XO2(OUT)=   0.21000
        SOLUBILITY IS SO2=, 0.0              SN2= 0.0
        MASS FLOW RATIO, GAS/LIQUID=0.00000000
        MASS FLOW RATE OF LIQUID=       3.255165 LBM/SEC
        VOLUME FLOW RATE OF LIQUID=      23.44972 GAL/MIN

        TOTAL MASS FLOW RATE OF GAS=  0.00000000 LBM/SEC
        AVAILABLE MASS FLOW RATE OF GAS=  0.00000000 LBM/SEC
        TOTAL VOLUME FLOW RATE OF GAS=    0.000000 CFM AT 14.72 PSIA,70 DEGF

        AVAILABLE VOLUME FLOW RATE OF GAS=    0.000000 CFM AT 14.72 PSIA,70 DEGF

        PRESSURE OF GAS IN SEPARATION TANK= -0.00 PSIG
        TEMPERATURE OF GAS IN SEPARATION TANK= 65.00 DEGF

        IDEAL HYDRAULIC POWER=   0.19369 HP
        ISENTROPIC EXP. GAS POWER=   0.00000 HP
        EFFICIENCY, BASED ON ISENTROPIC EXPANSION OF GAS=0.000
        VEL,FT/SEC, PRESSURE,PSIG, TEMPERATURE,DEGF,

        VL1=  2.40   PL1=-13.10   TL1=  65.00   RE1=   28253.
        VG1=  0.00   PG1=-13.10   TG1=  65.00
        VL2=  2.39   P2 =-13.10   T2 =  65.00   RE2=   28253.
        VG2=  1.09
        VL3=  2.39   P3 =  1.00   T3 =  65.00   RE3=   28253.
        VG3=  1.54
                     P4 = -0.00   T4 =  65.00
        V5 =  0.0    P5 = -0.00   T5 =  65.00   RE5=   28253.
        V6 =  0.0    P6 = -0.00   T6 =  65.00   RE6=   28253.
                     P7 = -0.00

         FLUX1=    2.394000 FLUXG=    0.000000 ALPHA=  0.00000010
```

```
INPUT                    CASE 2

    KDT   =  0
    AGP   = 0.0000221
    RHOL  =  62.30000   FMU   =    0.00088   CVL   =   1.00000
        R =   53.30000   CPG   =    0.24000   GAMA =    1.40000
    TAF   =  74.60001   TLOF =  65.00000   TG1F =  65.00000
    PAA   =  14.27000   PLOG = -13.95000   HD01 =   1.50000
    DDP   =  0.166700   DUP   =  0.166700   EODD =  0.000400   EODU =  0.000400
    CK01 =  0.200000   CK45 =  0.250000   VR2   =   1.30805   CR34 =  0.350000   CR67 =  0.500000
    H01   =   2.05986   H12   =    0.0        H23   =  33.00000   H34   =   2.33300
    H45   =   0.0        H56   =    0.0        H67   =   0.0        HNET =  32.72684
    X/2   =   0.21000   XN2   =  0.790000
    RAT   = 0.0000000   RCA   =    0.0        SN    =   0.0        SO    =   0.0
    VLM   =    2.3940   ALP   =0.00001000

PDIF(K)=          0.0000115617

FRICTION FACTOR=          0.0252822563
```

```
           PROGRAM HYDROAIR
           WARREN RICE, MAY 1973      LI-TING CHEN DECEMBER 1980
       MODIFIED BY CHEN/NICHOLAS  MARCH, 1981

 ODIFIED BY WEIS END-AUGUST 1981

           ATMOS. TEMP.= 74.60DEGF
           ATMOS. PRESS.= 14.27PSIA
           DENSITY OF LIQUID= 62.30 LBM/FTCU
           VISCOSITY OF LIQUID= 0.000880 LBM/FT-SEC
           SP. HT. AT CONST. VOL. FOR LIQUID= 1.000 BTU/LBM-DEGF
           GAS CONST.= 53.3 FT-LBF/LBM-DEGF
           SP. HT. AT CONST. PRESS. FOR GAS= 0.240 BTU/LBM-DEGF
           SP. HT. RATIO FOR GAS= 1.40
           PRESS. OF LIQUID AT (0)=-13.05 PSIG
           TEMP. OF LIQUID AT (0)= 65.0 DEGF
           PRESS. OF GAS AT (1)=-13.10 PSIG
           TEMP. OF GAS AT (1)= 65.0 DEGF

           DIA. OF DOWN-PIPE=  0.167 FT   DIA. OF UP-PIPE=  0.167 FT
           ROUGHNESS RATIO, DOWN-PIPE=0.000400   ROUGHNESS RATIO, UP-PIPE=0.000400
           AREA OF GAS PIPE=   0.0000221 FTSQ

           DISTANCES, FT          H01= 2.059858   H12= 0.0     H23= 33.00
           H34= 2.33    H45= 0.0     H56=  0.0     H67= 0.0 H001= 1.50   H000= 0.56

           CK01=0.200      CK45=0.250          VR2=  1.31 FT/SEC
           CR34=0.350      CR67=0.500

           NET HYDRAULIC HEAD= 32.73 FT

           CARRY-OVER RATIO=    0.0          XO2(IN)=    0.21000      XO2(OUT)=    0.21000
           SOLUBILITY IS SO2=, 0.0              SN2= 0.0
           MASS FLOW RATIO, GAS/LIQUID=0.00000000
           MASS FLOW RATE OF LIQUID=        3.255165 LBM/SEC
           VOLUME FLOW RATE OF LIQUID=       23.44972 GAL/MIN

           TOTAL MASS FLOW RATE OF GAS=  0.00000000 LBM/SEC
           AVAILABLE MASS FLOW RATE OF GAS=  0.00000000 LBM/SEC
           TOTAL VOLUME FLOW RATE OF GAS=    0.000003 CFM AT 14.72 PSIA,70 DEGF

           AVAILABLE VOLUME FLOW RATE OF GAS=     0.000003 CFM AT 14.72 PSIA,70 DEGF

           PRESSURE OF GAS IN SEPARATION TANK= -0.00 PSIG
           TEMPERATURE OF GAS IN SEPARATION TANK= 65.00 DEGF

           IDEAL HYDRAULIC POWER=   0.19369 HP
           ISENTROPIC EXP. GAS POWER=   0.00000 HP
           EFFICIENCY, BASED ON ISENTROPIC EXPANSION OF GAS=0.000
           VEL,FT/SEC, PRESSURE,PSIG, TEMPERATURE,DEGF,

           VL1=  2.40    PL1=-13.10    TL1=  65.00    RE1=    28253.
           VG1=  0.02    PG1=-13.10    TG1=  65.00
           VL2=  2.39    P2 =-13.10    T2 =  65.00    RE2=    28253.
           VG2=  1.09
           VL3=  2.39    P3 =  1.00    T3 =  65.00    RE3=    28253.
           VG3=  1.54
                         P4 = -0.00    T4 =  65.00
           V5 =  0.0     P5 = -0.00    T5 =  65.00    RE5=    28253.
           V6 =  0.0     P6 = -0.00    T6 =  65.00    RE6=    28253.
                         P7 = -0.00

            FLUX1=    2.394023 FLUXG=      [illegible]24 ALPHA=  [illegible]
```

```
INPUT                CASE 3

        KDT   =  0
        AGP   = 0.0000221
        RHOL  =  62.30000   FMU   =   0.00388   CVL   =   1.00000
           R  =   53.30000   CPG   =    0.24000   GAMA =    1.40000
        TAF   =  74.60001   TLOF  =  65.00000   TG1F  =  65.00000
        PAA   =  14.27000   PLOG  = -13.95000   H001  =   1.50000
        DDP   =  0.166700   DUP   =  0.166700   EODD  =  0.000400   EODU  =  0.000400
        CK01  =  0.200000   CK45  =  0.250000   VR2   =   1.30808   CR34  =  0.350000   CR67  =  0.500000
        H01   =   2.05986   H12   =   0.0       H23   =  33.00000   H34   =   2.33300
        H45   =   0.0       H56   =   0.0       H67   =   0.0       HNET  =  32.72684
        X/2   =   0.21000   XN2   =  0.790000
        RAT   = 0.0000000   RCA   =   0.0       SN    =   0.0       SO    =   0.0
        VLM   =    2.3940   ALP   =0.00100000

PDIF(K)=         0.0003799326

FRICTION FACTOR=         0.0252822563
```

```
           PROGRAM HYDROAIR
           WARREN RICE, MAY 1973      LI-TING CHEN DECEMBER 1980
      MODIFIED BY CHEN/NICHOLAS  MARCH, 1981

ODIFIED BY WEIS END-AUGUST 1981

           ATMOS. TEMP.= 74.60DEGF
           ATMOS. PRESS.= 14.27PSIA
           DENSITY OF LIQUID= 62.30 LBM/FTCU
           VISCOSITY OF LIQUID= 0.00088[illegible] LBM/FT-SEC
           SP. HT. AT CONST. VOL. FOR LIQUID= 1.000 BTU/LBM-DEGF
           GAS CONST.= 53.3 FT-LBF/LBM-DEGF
           SP. HT. AT CONST. PRESS. FOR GAS= 0.240 BTU/LBM-DEGF
           SP. HT. RATIO FOR GAS= 1.40
           PRESS. OF LIQUID AT (0)=-13.95 PSIG
           TEMP. OF LIQUID AT (0)= 65.0 DEGF
           PRESS. OF GAS AT (1)=-13.10 PSIG
           TEMP. OF GAS AT (1)= 65.0 DEGF

           DIA. OF DOWN-PIPE=  0.167 FT   DIA. OF UP-PIPE=  0.167 FT
           ROUGHNESS RATIO, DOWN-PIPE=0.000400   ROUGHNESS RATIO, UP-PIPE=0.000400
           AREA OF GAS PIPE=   0.0000221 FTSQ

           DISTANCES, FT             H01= 2.055858   H12= 0.0    H23= 33.33
           H34= 2.33   H45= 0.0    H56=  0.0    H67= 0.0 H001= 1.50   H000= 0.56

           CK01=0.200      CK45=0.250         VR2=  1.31 FT/SEC
           CR34=0.350      CR67=0.500

           NET HYDRAULIC HEAD= 32.73 FT

           CARRY-OVER RATIO=   0.0          XO2(IN)=   0.21000      XO2(OUT)=   0.21000
           SOLUBILITY IS SO2=, 0.0              SN2= 0.0
           MASS FLOW RATIO, GAS/LIQUID=0.00000010
           MASS FLOW RATE OF LIQUID=       3.255165 LBM/SEC
           VOLUME FLOW RATE OF LIQUID=       23.44972 GAL/MIN

           TOTAL MASS FLOW RATE OF GAS=  0.00000031 LBM/SEC
           AVAILABLE MASS FLOW RATE OF GAS=  0.00000031 LBM/SEC
           TOTAL VOLUME FLOW RATE OF GAS=    0.000251 CFM AT 14.72 PSIA,70 DEGF

           AVAILABLE VOLUME FLOW RATE OF GAS=    0.000251 CFM AT 14.72 PSIA,70 DEGF

           PRESSURE OF GAS IN SEPARATION TANK= -0.01 PSIG
           TEMPERATURE OF GAS IN SEPARATION TANK= 65.00 DEGF

           IDEAL HYDRAULIC POWER=    0.19369 HP
           ISENTROPIC EXP. GAS POWER=    0.00093 HP
           EFFICIENCY, BASED ON ISENTROPIC EXPANSION OF GAS=0.000
           VEL,FT/SEC, PRESSURE,PSIG, TEMPERATURE,DEGF,

           VL1=   2.40    PL1=-13.10    TL1=   65.00    RE1=    28253.
           VG1=   2.37    PG1=-13.10    TG1=   65.00
           VL2=   2.40    P2 =-13.10    T2 =   65.00    RE2=    28253.
           VG2=   1.09
           VL3=   2.39    P3 =   0.99   T3 =   65.00    RE3=    28253.
           VG3=   1.54
                          P4 = -0.01    T4 =   65.00
           V5 =   0.0     P5 = -0.01    T5 =   65.00    RE5=    28253.
           V6 =   0.0     P6 = -0.01    T6 =   65.00    RE6=    28253.
                          P7 = -0.01

            FLUX1=     2.396396 FLUXG=     0.002396 ALPHA=  0.001[illegible]
```

```
     INPUT                 CASE 4

          KDT   =   0
          AGP   =  0.0000221
          RHOL  =   62.30000     FMU   =    0.00088    CVL   =    1.00000
              R =    53.30000     CPG   =     0.24000    GAMA  =    1.40000
          TAF   =   74.60001     TLOF  =   65.00000    TG1F  =   65.00000
          PAA   =   14.27000     PLOG  =  -13.95000    H001  =    1.50000
          DDP   =   0.166700     DUP   =   0.166700    EODD  =   0.000400    EODU  =  0.000400
          CK01  =   0.200000     CK45  =   0.250000    VR2   =    1.31027    CR34  =  0.350000    CR67  =  0.500000
          H01   =    2.05986     H12   =    0.0        H23   =   33.00000    H34   =   2.33309
          H45   =    0.0         H56   =    0.0        H67   =    0.0        HNET  =  32.72684
          X/2   =    0.21000     XN2   =   0.790000
          RAT   =  0.0000001     RCA   =    0.0        SN    =    0.0        SO    =   0.0
          VLM   =     2.3940     ALP   =0.02886000
PDIF(K)=          0.0115202777

FRICTION FACTOR=          0.0252822563

PDIF(K)=          0.0010952884

FRICTION FACTOR=          0.0252822563

PDIF(K)=          0.0001002461

FRICTION FACTOR=          0.0252822563
```

```
          PROGRAM HYDROAIR
          WARREN RICE, MAY 1973       LI-TING CHEN DECEMBER 1980
      MODIFIED BY CHEN/NICHOLAS  MARCH, 1981

 ODIFIED BY WEIS END-AUGUST 1981

          ATMOS. TEMP.= 74.60DEGF
          ATMOS. PRESS.= 14.27PSIA
          DENSITY OF LIQUID= 62.30 LBM/FTCU
          VISCOSITY OF LIQUID= 0.0008800 LBM/FT-SEC
          SP. HT. AT CONST. VOL. FOR LIQUID= 1.000 BTU/LBM-DEGF
          GAS CONST.= 53.3 FT-LBF/LBM-DEGF
          SP. HT. AT CONST. PRESS. FOR GAS= 0.240 BTU/LBM-DEGF
          SP. HT. RATIO FOR GAS= 1.40
          PRESS. OF LIQUID AT (0)=-13.95 PSIG
          TEMP. OF LIQUID AT (0)= 65.0 DEGF
          PRESS. OF GAS AT (1)=-12.92 PSIG
          TEMP. OF GAS AT (1)= 65.0 DEGF

          DIA. OF DOWN-PIPE=  0.167 FT    DIA. OF UP-PIPE=  0.167 FT
          ROUGHNESS RATIO, DOWN-PIPE=0.000400    ROUGHNESS RATIO, UP-PIPE=0.000400
          AREA OF GAS PIPE=    0.0000221 FTSQ

          DISTANCES, FT           H01= 2.475713   H12= 0.0     H23= 33.00
          H34= 2.33    H45= 0.0     H56=  0.0     H67= 0.0 H001= 1.50    H100= 0.98

          CK01=0.200     CK45=0.250          VR2=  1.31 FT/SEC
          CR34=0.350     CR67=0.500

          NET HYDRAULIC HEAD= 33.14 FT

          CARRY-OVER RATIO=    0.0          XO2(IN)=    0.21000      XO2(OUT)=    0.21000
          SOLUBILITY IS SO2=, 0.0              SN2= 0.0
          MASS FLOW RATIO, GAS/LIQUID=0.00000331
          MASS FLOW RATE OF LIQUID=         3.255165 LBM/SEC
          VOLUME FLOW RATE OF LIQUID=        23.44972 GAL/MIN

          TOTAL MASS FLOW RATE OF GAS=  0.00001077 LBM/SEC
          AVAILABLE MASS FLOW RATE OF GAS=  0.00001077 LBM/SEC
          TOTAL VOLUME FLOW RATE OF GAS=     0.008610 CFM AT 14.72 PSIA,70 DEGF

          AVAILABLE VOLUME FLOW RATE OF GAS=     0.008610 CFM AT 14.72 PSIA,70 DEGF

          PRESSURE OF GAS IN SEPARATION TANK= -0.00 PSIG
          TEMPERATURE OF GAS IN SEPARATION TANK= 65.00 DEGF

          IDEAL HYDRAULIC POWER=    0.19615 HP
          ISENTROPIC EXP. GAS POWER=    0.00096 HP
          EFFICIENCY, BASED ON ISENTROPIC EXPANSION OF GAS=0.005
          VEL,FT/SEC, PRESSURE,PSIG, TEMPERATURE,DEGF,

          VL1=  2.40    PL1=-12.92    TL1=  65.00    RE1=    28253.
          VG1= 70.26    PG1=-12.92    TG1=  65.00
          VL2=  2.54    P2 =-12.93    T2 =  65.00    RE2=    28253.
          VG2=  1.23
          VL3=  2.40    P3 =   0.99   T3 =  65.00    RE3=    28253.
          VG3=  1.53
                        P4 = -0.00    T4 =  65.00
          V5 =  0.0     P5 = -0.00    T5 =  65.00    RE5=    28253.
          V6 =  0.0     P6 = -0.00    T6 =  65.00    RE6=    28253.
                        P7 = -0.00

           FLUX1=     2.465143 FLUXG=     0.071144 ALPHA=  0.0288600
```

```
INPUT                    CASE 5

      KDT   =  0
      AGP   = 0.0000221
      RHOL  =  62.30000    FMU   =    0.00088    CVL   =   1.00000
          R =   53.30000    CPG   =    0.24000    GAMA =    1.40000
      TAF   =  74.60001    TLOF  =  65.00000    TG1F  =  65.00000
      PAA   =  14.27000    PLOG  = -13.95000    H001  =   1.50000
      DDP   =  0.166700    DUP   =  0.166700    EODD  =  0.000420    EODU  =  0.000400
      CK01  =  0.200000    CK45  =  0.250000    VR2   =   1.37379    CR34  =  0.350000    CR67 =  0.500000
      H01   =   2.47571    H12   =   0.0        H23   =  33.00000    H34   =   2.33300
      H45   =   0.0        H56   =   0.0        H67   =   0.0        HNET  =  33.14270
      X/2   =   0.21000    XN2   =  0.790000
      RAT   = 0.0000033    RCA   =   0.0        SN    =   0.0        SO    =   0.0
      VLM   =    2.3940    ALP   =0.05918000

PDIF(K)=         0.0147127137

FRICTION FACTOR=          0.0252822526

PDIF(K)=         0.0027458735

FRICTION FACTOR=          0.0252822526

PDIF(K)=         0.0004885325

FRICTION FACTOR=          0.0252822526
```

```
          PROGRAM HYDROAIR
          WARREN RICE, MAY 1973      LI-TING CHEN DECEMBER 1980
     MODIFIED BY CHEN/NICHOLAS  MARCH, 1981

ODIFIED BY WEIS END-AUGUST 1981

          ATMOS. TEMP.= 74.60DEGF
          ATMOS. PRESS.= 14.27PSIA
          DENSITY OF LIQUID= 62.30 LBM/FTCU
          VISCOSITY OF LIQUID= 0.0008800 LBM/FT-SEC
          SP. HT. AT CONST. VOL. FOR LIQUID= 1.000 BTU/LBM-DEGF
          GAS CONST.= 53.3 FT-LBF/LBM-DEGF
          SP. HT. AT CONST. PRESS. FOR GAS= 0.240 BTU/LBM-DEGF
          SP. HT. RATIO FOR GAS= 1.40
          PRESS. OF LIQUID AT (0)=-13.95 PSIG
          TEMP. OF LIQUID AT (0)= 65.0 DEGF
          PRESS. OF GAS AT (1)=-12.67 PSIG
          TEMP. OF GAS AT (1)= 65.0 DEGF

          DIA. OF DOWN-PIPE=  0.167 FT    DIA. OF UP-PIPE=  0.167 FT
          ROUGHNESS RATIO, DOWN-PIPE=0.000400    ROUGHNESS RATIO, UP-PIPE=0.000400
          AREA OF GAS PIPE=   0.0000221 FTSQ

          DISTANCES, FT           H01= 3.051211    H12= 0.0     H23= 33.00
          H34= 2.33    H45= 0.0    H56=  0.0    H67= 0.0 H001= 1.50    H900= 1.55

          CK01=0.200       CK45=0.250          VR2=  1.37 FT/SEC
          CR34=0.350       CR67=0.500

          NET HYDRAULIC HEAD= 33.72 FT

          CARRY-OVER RATIO=    0.0            XO2(IN)=    0.21000      XO2(OUT)=   0.21000
          SOLUBILITY IS SO2=, 0.0              SN2= 0.0
          MASS FLOW RATIO, GAS/LIQUID=0.00000830
          MASS FLOW RATE OF LIQUID=        3.255165 LBM/SEC
          VOLUME FLOW RATE OF LIQUID=       23.44972 GAL/MIN

          TOTAL MASS FLOW RATE OF GAS=  0.00002700 LBM/SEC
          AVAILABLE MASS FLOW RATE OF GAS=  0.00002700 LBM/SEC
          TOTAL VOLUME FLOW RATE OF GAS=     0.021592 CFM AT 14.72 PSIA,70 DEGF

          AVAILABLE VOLUME FLOW RATE OF GAS=     0.021592 CFM AT 14.72 PSIA,70 DEGF

          PRESSURE OF GAS IN SEPARATION TANK= -0.01 PSIG
          TEMPERATURE OF GAS IN SEPARATION TANK= 65.00 DEGF

          IDEAL HYDRAULIC POWER=    0.19956 HP
          ISENTROPIC EXP. GAS POWER=    0.00228 HP
          EFFICIENCY, BASED ON ISENTROPIC EXPANSION OF GAS=0.011
          VEL,FT/SEC, PRESSURE,PSIG, TEMPERATURE,DEGF,

          VL1=  2.40    PL1=-12.67    TL1=  65.00    RE1=   28253.
          VG1=148.72    PG1=-12.67    TG1=  65.00
          VL2=  2.70    P2 =-12.68    T2 =  65.00    RE2=   28253.
          VG2=  1.33
          VL3=  2.42    P3 =  0.99    T3 =  65.00    RE3=   28253.
          VG3=  1.48
                        P4 = -0.01    T4 =  65.00
          V5 =  0.0     P5 = -0.01    T5 =  65.00    RE5=   28253.
          V6 =  0.0     P6 = -0.01    T6 =  65.00    RE6=   28253.
                        P7 = -0.01

           FLUX1=    2.544588 FLUXG=    0.150589 ALPHA=  0.05918000
```

```
INPUT                CASE 6

      KDT   =  0
      AGP   = 0.0000221
      RHOL  =  62.30000   FMU   =   0.00088   CVL   =   1.00000
          R =  53.30000    CPG  =   0.24000    GAMA =   1.40000
      TAF   =  74.60001   TLOF  =  65.00000   TG1F  =  65.00000
      PAA   =  14.27000   PLOG  = -13.95000   H001  =   1.50000
      DDP   =  0.166700   DUP   =  0.166700   EODD  =  0.000400   EODU  =  0.000400
      CK01  =  0.200000   CK45  =  0.250000   VP2   =   1.44720   CR34  =  0.350000   CR67  =  0.500000
      H01   =   3.05121   H12   =   0.0       H23   =  33.00000   H34   =   2.33300
      H45   =   0.0       H56   =   0.0       H67   =   0.0       HNET  =  33.71820
      X/2   =   0.21000   XN2   =  0.790000
      RAT   = 0.0000083   RCA   =   0.0       SN    =   0.0       SO    =   0.0
      VLM   =    2.3940   ALP   =0.10800999
PDIF(K)=          0.0288283639

FRICTION FACTOR=           0.0252822526

PDIF(K)=          0.0088842735

FRICTION FACTOR=           0.0252821594

PDIF(K)=          0.0024917831

FRICTION FACTOR=           0.0252821594

PDIF(K)=          0.0006828762

FRICTION FACTOR=           0.0252821557
```

```
        PROGRAM HYDROAIR
        WARREN RICE, MAY 1973      LI-TING CHEN DECEMBER 1980
     MODIFIED BY CHEN/NICHOLAS  MARCH, 1981

ODIFIED BY WEIS END-AUGUST 1981

        ATMOS. TEMP.= 74.60DEGF
        ATMOS. PRESS.= 14.27PSIA
        DENSITY OF LIQUID= 62.30 LBM/FTCU
        VISCOSITY OF LIQUID= 0.0008800 LBM/FT-SEC
        SP. HT. AT CONST. VOL. FOR LIQUID= 1.000 BTU/LBM-DEGF
        GAS CONST.= 53.3 FT-LBF/LBM-DEGF
        SP. HT. AT CONST. PRESS. FOR GAS= 0.240 BTU/LBM-DEGF
        SP. HT. RATIO FOR GAS= 1.40
        PRESS. OF LIQUID AT (0)=-13.95 PSIG
        TEMP. OF LIQUID AT (0)= 65.0 DEGF
        PRESS. OF GAS AT (1)=-12.10 PSIG
        TEMP. OF GAS AT (1)= 65.0 DEGF

        DIA. OF DOWN-PIPE=  0.167 FT    DIA. OF UP-PIPE=  0.167 FT
        ROUGHNESS RATIO, DOWN-PIPE=0.000400   ROUGHNESS RATIO, UP-PIPE=0.000400
        AREA OF GAS PIPE=   0.0000221 FTSQ

        DISTANCES, FT           H01= 4.376496   H12= 0.0    H23= 33.00
        H34= 2.33   H45= 0.0    H56=  0.0    H67= 0.0 H001= 1.50   H000= 2.88

        CK01=0.200     CK45=0.250         VR2=  1.45 FT/SEC
        CR34=0.350     CR67=0.500

        NET HYDRAULIC HEAD= 35.04 FT

        CARRY-OVER RATIO=   0.0          XO2(IN)=   0.21000     XO2(OUT)=   0.21000
        SOLUBILITY IS SO2=, 0.0              SN2= 0.0
        MASS FLOW RATIO, GAS/LIQUID=0.00002170
        MASS FLOW RATE OF LIQUID=       3.255165 LBM/SEC
        VOLUME FLOW RATE OF LIQUID=      23.44972 GAL/MIN

        TOTAL MASS FLOW RATE OF GAS=  0.00007065 LBM/SEC
        AVAILABLE MASS FLOW RATE OF GAS=  0.00007065 LBM/SEC
        TOTAL VOLUME FLOW RATE OF GAS=    0.056493 CFM AT 14.72 PSIA,70 DEGF

        AVAILABLE VOLUME FLOW RATE OF GAS=     0.056493 CFM AT 14.72 PSIA,70 DEGF

        PRESSURE OF GAS IN SEPARATION TANK= -0.01 PSIG
        TEMPERATURE OF GAS IN SEPARATION TANK= 65.02 DEGF

        IDEAL HYDRAULIC POWER=   0.20740 HP
        ISENTROPIC EXP. GAS POWER=    0.00533 HP
        EFFICIENCY, BASED ON ISENTROPIC EXPANSION OF GAS=0.026
        VEL,FT/SEC, PRESSURE,PSIG, TEMPERATURE,DEGF,

        VL1=  2.40    PL1=-12.10    TL1=  65.00    RE1=    28253.
        VG1=286.28    PG1=-12.10    TG1=  65.00
        VL2=  2.97    P2 =-12.12    T2 =  65.02    RE2=    28254.
        VG2=  1.52
        VL3=  2.46    P3 =   0.99    T3 =  65.02    RE3=    28254.
        VG3=  1.42
                      P4 = -0.01    T4 =  65.02
        V5 =  0.0     P5 = -0.01    T5 =  65.02    RE5=    28253.
        V6 =  0.0     P6 = -0.01    T6 =  65.02    RE6=    28253.
                      P7 = -0.01

         FLUX1=    2.683886 FLUXG=    0.289886 ALPHA=  0.10800999
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```
INPUT                    CASE 7

       KDT   =  0
       AGP   = 0.0000221
       RHOL  =  62.30000    FMU   =    0.00088    CVL   =    1.00000
           R =   53.30000    CPG  =     0.24000    GAMA =     1.40000
       TAF   =  74.60001    TLOF = 65.00000      TG1F =  65.00000
       PAA   =  14.27000    PLOG = -13.95000     H001 =    1.50000
       DDP   =  0.166700    DUP  =  0.166700     EODD =  0.000400    EODU =  0.000400
       CK01  =  0.200000    CK45 =  0.250000     VR2  =    1.57591   CR34 =  0.350000    CR67 =  0.500000
       H01   =   4.37650    H12  =   0.0         H23  =  33.00000    H34  =   2.33300
       H45   =   0.0        H56  =   0.0         H67  =    0.0       HNET =  35.04349
       X/2   =   0.21000    XN2  =  0.790000
       RAT   = 0.0000217    RCA  =   0.0         SN   =    0.0       SO   =   0.0
       VLM   =    2.3940    ALP  =0.12026000
PDIF(K)=           0.0146647952

FRICTION FACTOR=          0.0252821557

PDIF(K)=           0.0045637339

FRICTION FACTOR=          0.0252821557

PDIF(K)=           0.0013601386

FRICTION FACTOR=          0.0252821557

PDIF(K)=           0.0004011178

FRICTION FACTOR=          0.0252821557
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          PROGRAM HYDROAIR
          WARREN RICE, MAY 1973      LI-TING CHEN DECEMBER 1980
     MODIFIED BY CHEN/NICHOLAS  MARCH, 1981

ODIFIED BY WEIS END-AUGUST 1981

          ATMOS. TEMP.= 74.60DEGF
          ATMOS. PRESS.= 14.27PSIA
          DENSITY OF LIQUID= 62.30 LBM/FTCU
          VISCOSITY OF LIQUID= 0.0008800 LBM/FT-SEC
          SP. HT. AT CONST. VOL. FOR LIQUID= 1.000 BTU/LBM-DEGF
          GAS CONST.= 53.3 FT-LBF/LBM-DEGF
          SP. HT. AT CONST. PRESS. FOR GAS= 0.240 BTU/LBM-DEGF
          SP. HT. RATIO FOR GAS= 1.40
          PRESS. OF LIQUID AT (0)=-13.95 PSIG
          TEMP. OF LIQUID AT (0)= 65.0 DEGF
          PRESS. OF GAS AT (1)=-11.81 PSIG
          TEMP. OF GAS AT (1)= 65.0 DEGF

          DIA. OF DOWN-PIPE=  0.167 FT   DIA. OF UP-PIPE=  0.167 FT
          ROUGHNESS RATIO, DOWN-PIPE=0.000400   ROUGHNESS RATIO, UP-PIPE=0.000400
          AREA OF GAS PIPE=   0.0000221 FTSQ

          DISTANCES, FT           H01= 5.055174   H12= 0.0    H23= 33.00
          H34= 2.33   H45= 0.0    H56=  0.0    H67= 0.0 H001= 1.50   H000= 3.56

          CK01=0.200     CK45=0.250        VR2=  1.58 FT/SEC
          CR34=0.350     CR67=0.500

          NET HYDRAULIC HEAD= 35.72 FT

          CARRY-OVER RATIO=   0.0         XO2(IN)=   0.21000     XO2(OUT)=   0.21000
          SOLUBILITY IS SO2=, 0.0             SN2= 0.0
          MASS FLOW RATIO, GAS/LIQUID=0.00002782
          MASS FLOW RATE OF LIQUID=       3.255165 LBM/SEC
          VOLUME FLOW RATE OF LIQUID=      23.44972 GAL/MIN

          TOTAL MASS FLOW RATE OF GAS=  0.00009055 LBM/SEC
          AVAILABLE MASS FLOW RATE OF GAS=  0.00009055 LBM/SEC
          TOTAL VOLUME FLOW RATE OF GAS=    0.072406 CFM AT 14.72 PSIA,70 DEGF

          AVAILABLE VOLUME FLOW RATE OF GAS=    0.072406 CFM AT 14.72 PSIA,70 DEGF

          PRESSURE OF GAS IN SEPARATION TANK= -0.01 PSIG
          TEMPERATURE OF GAS IN SEPARATION TANK= 65.02 DEGF

          IDEAL HYDRAULIC POWER=   0.21142 HP
          ISENTROPIC EXP. GAS POWER=   0.00648 HP
          EFFICIENCY, BASED ON ISENTROPIC EXPANSION OF GAS=0.031
          VEL,FT/SEC, PRESSURE,PSIG, TEMPERATURE,DEGF,

          VL1=  2.40    PL1=-11.81    TL1=  65.00    RE1=    28253.
          VG1=323.19    PG1=-11.81    TG1=  65.00
          VL2=  3.07    P2 =-11.83    T2 =  65.02    RE2=    28254.
          VG2=  1.50
          VL3=  2.49    P3 =  0.99    T3 =  65.02    RE3=    28254.
          VG3=  1.33
                        P4 = -0.01    T4 =  65.02
          V5 =  0.0     P5 = -0.01    T5 =  65.02    RE5=    28253.
          V6 =  0.0     P6 = -0.01    T6 =  65.02    RE6=    28253.
                        P7 = -0.01

           FLUX1=    2.721258 FLUXG=    0.327258 ALPHA=  0.12926000
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