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ABSTRACT

The frequency response technique was used to measure some of the dynamic properties of a heat exchanger boiler. The boiling fluid, Freon-113, exhausted through an orifice to a constant pressure. The boiling fluid inlet flow rate was varied sinusoidally about a mean value. The magnitude and phase of the perturbations of the boiler inlet flow, inlet pressure, and orifice pressure drop were measured. The data were used to compute the boiler inlet impedance (the complex ratio of the perturbations of inlet pressure and inlet flow) and the transfer impedance (the complex ratio of the perturbations of orifice pressure drop and boiler inlet flow).

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SUMMARY

The frequency response technique was used to measure some of the dynamic properties of a heat exchanger forced-flow boiler with inserts and an exit restriction. The boiler consisted of a single inner tube (0.430 in. or 1.09 cm i.d.) and a coaxial outer tube which formed an annulus with the inner tube. The boiling fluid was Freon 113. The boiling fluid flowed vertically upward through the inner tube. The heating fluid, pressurized hot water, flowed parallel to the boiling fluid through the annulus. A steel coil, brazed to the inside wall of the boiler, and a plug at the boiler inlet induced a spiral motion of the boiling fluid. An orifice was placed at the boiler exit as a restriction. A series of frequency response tests were performed with the boiler for each of two exit restrictions. The open area of one of the orifice exit restrictions was 1.78 times as large as the other.

The boiling-fluid inlet flow rate was varied sinusoidally about a mean value. The magnitude and phase of the resultant perturbations in boiler-inlet pressure, orifice pressure drop, and boiler-inlet flow rate were computed by a frequency-response analyzer. The data from the analyzer were used to compute the following dynamic properties of the boiler-orifice combination: (1) the inlet impedance of the boiler-orifice combination (complex ratio of the perturbations in boiler-inlet pressure and inlet flow rate) and (2) the transfer impedance of the boiler-orifice combination (complex ratio of the perturbations in orifice pressure drop and boiler-inlet flow rate).

INTRODUCTION

The occurrence of unstable flow in the boiling loop of a Rankine cycle space-power system can be detrimental to the system performance. Hence, a research program is being conducted at the NASA Lewis Research Center to establish the dynamic properties of this type of space-power system. Part of this research has been devoted to a study of those instabilities that arise as a result of a coupling effect between the boiler and its feed system.

To analyze this type of coupling, Grace and Krejsa (ref. 1) applied the impedance concept to the boiler study. Using this impedance concept they proposed a model for an electrically heated boiler with a constant-pressure exit condition. The boiler impedance was defined as the complex ratio of the perturbations of inlet pressure to inlet flow perturbations.

The model was verified with data obtained from boiler-feed-system coupled instabilities. Grace and Krejsa recognized that for this type of instability the negative of the boiler impedance was approximately equal to the feed-system impedance. Hence, the model was verified by comparing the calculated feed-system impedance with the calculated boiler impedance. The boiler-model parameters were determined from the steady-state data, and the frequency was taken from oscillographic recordings.

The data obtained using this technique were less than satisfactory. However, the trends indicated the model could account for the dominant dynamic properties of this type of boiler.

To obtain better experimental data, frequency response testing was added to the boiler study. This technique enables a model-data comparison over a wide range of frequencies. This is an improvement over the work of reference 1 in which comparisons were made only at the frequency of the natural oscillations.

Experimental frequency response datafor a single hollow-tube heat exchanger boiler were obtained, and the results were reported in reference 2. A simple analytical model for this type of boiler was proposed by Krejsa (ref. 3). He compared his model with the data of reference 2 and obtained good agreement.

The boiler study was continued by testing more complex boiler geometries. The results obtained for a single-tube boiler with inserts was reported in reference 4. The inserts induced a spiral motion of the boiling fluid that held the liquid against the boiler wall.

Both the boiler with inserts (ref. 4) and the hollow tube boiler (ref. 2) had operating conditions where the inlet impedance had a negative real part. This negative real part was shown to cause a boiler-feed-system coupled instability in reference 4.

The previous impedance data (refs. 1, 2, and 4) were obtained for boilers with a constant exit pressure. This experimental condition facilitated the development of the simple analytical models of references 1 and 3. However, the actual space-power boiler will have a downstream load. This will cause the exit pressure to be a function of the flow rate out of the boiler. Therefore, a more complete analytical model must include the effects of the varying exit pressure. In order to develop this more general model, impedance data are needed for a boiler with a downstream load.

The objective of the work of this report was to obtain data for a single-tube boiler with a simple downstream load. An orifice, placed at the boiler exit, was used as the load.

Two sets of impedance data were obtained for each operating condition. In addition to the inlet impedance, the transfer impedance was also obtained. The transfer impedance was defined as the complex ratio of the perturbations in the orifice pressure drop and the inlet flow rate.

The boiler geometry was identical to that used in reference 4, which consisted of two concentric tubes with an annulus between them. The boiling fluid, Freon 113 (trichlorotrifluoroethane), flowed vertically upward through the inner tube. The heating fluid, pressurized hot water, flowed parallel to the boiling fluid through the boiler annulus (parallel flow was chosen over counterflow because superheated vapor was obtained with parallel flow).

Two different orifice sizes were employed. Fluid state at the exit of the boiler ranged from a quality of 4 percent to a superheat of 50° F (27.8 K) with a 1/4-inch (6.35 mm) diameter orifice. The range was from 9 percent quality to a superheat of 20° F (11.3 K) with a 3/16-inch (4.76-mm) diameter orifice. Boiling fluid flow rate ranged from 110 to 740 pounds mass per hour (0.0139 to 0.0933 kg/sec) for the larger orifice, and the range was 140 to 425 pounds mass per hour (0.0176 to 0.0536 kg/sec) for the smaller orifice.

SYMBOLS

f	frequency, Hz
P_{in}	boiler inlet pressure, psig (N/m^2 gage)
P_{out}	boiler-exit pressure (upstream of orifice), psig; N/m^2 gage
W	Freon flow rate indicated by flowmeter, lbm/hr; kg/sec
W_{in}	Freon flow rate into boiler, lbm/hr; kg/sec
W_o	mean flow rate of frequency response test, lbm/hr; kg/sec
Δ	symbol preceding a variable indicating the perturbation value of the variable
χ	vapor quality
$\varphi_{\Delta P_{in}}$	phase angle of boiler inlet pressure perturbation, deg
$\varphi_{\Delta P_{out}}$	phase angle of boiler exit pressure perturbation, deg
$\varphi_{\Delta W_{in}}$	phase angle of Freon flow perturbation into boiler, deg

BOILING DYNAMICS FACILITY

General

The facility used to obtain the data of this report (fig. 1) was the same two-loop, two-fluid system described in reference 2. The boiling fluid, Freon 113, was circulated by means of a gear pump. The fluctuations in flow rate generated by the gear pump were attenuated by an air charged accumulator located downstream of the pump. Forced oscillations of the inlet flow and pressure were generated by sinusoidally perturbing the open area of a throttle valve located downstream of the accumulator.

The boiling fluid flowed vertically upward through the boiler test section and exhausted into a plenum chamber. The end of the boiler tube extended into the plenum chamber for a short distance to prevent a liquid buildup at the orifice exit. A 0.870-inch (2.21-cm) inside diameter tube connected the plenum tank to a large volume condenser. This flow passage, from the plenum tank to the condenser, was large enough so that no measurable pressure drop existed between these points for the range of flows encountered in the tests. The condenser was vented to the atmosphere for all the tests. Therefore, the boiler always exhausted through the orifice to a constant pressure. The heating fluid, pressurized hot water, flowed parallel to the boiling fluid through the boiler annulus.

Boiler Test Section

The boiler test section was a heat exchanger consisting of a single inner tube surrounded by a coaxial outer tube. A sketch of the boiler is shown in figure 2.

The inner tube was a 0.430-inch (1.09-cm) inside diameter stainless-steel tube with a heated length of 32 inches (0.813 m). Inserts, in the form of a helical coil brazed to the inside wall of the inner tube and an 8-inch (20.3-cm) plug inserted into the flow passage at the inlet of the boiler, induced a spiral motion of the boiling fluid. Five inches (12.7 cm) of the rod extended into the heated region of the boiler.

For each series of boiler runs, an orifice was placed at the end of the inner tube which extended into the plenum tank. One orifice consisted of a 1/4-inch (6.35-mm) diameter hole drilled through a 1/8-inch (3.17-mm) thick brass plate. The other orifice consisted of a 3/16-inch (4.26-mm) diameter hole through the same type of brass plate.

Instrumentation

Instrumentation was provided to measure both the steady-state and dynamic vari-

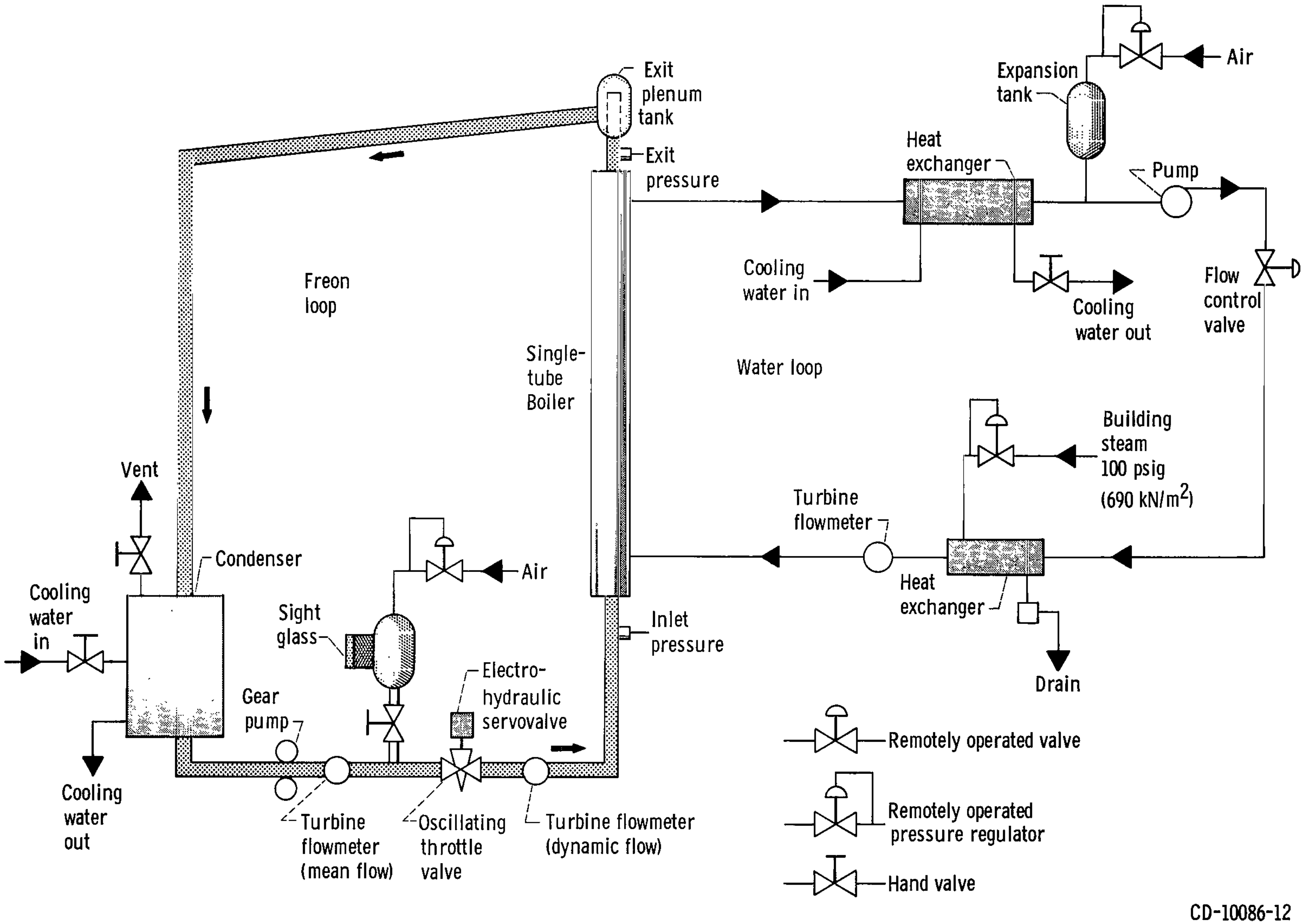


Figure 1. - Boiling dynamics facility.

ables of the boiler. The steady-state values of Freon flow rate, water flow rate, pressure and temperature at the inlet of the boiler, vapor pressure and temperature upstream of the orifice, temperature at the boiler exit, and the water temperature profile in the boiler were recorded. The dynamic variables of interest were the perturbations of the boiling fluid inlet flow rate and the perturbations in pressure at the boiler inlet and exit (orifice pressure drop).

Freon and water steady-state flow rates were measured with turbine flowmeters. The Freon flowmeter was located between the gear pump and the accumulator in the boiling fluid loop. The water flowmeter was located between the heat exchanger used to heat the water and the boiler water inlet. Steady-state pressures were measured at the boiler inlet and upstream of the orifice with Bourdon tube pressure gages (These gages were valved off during the frequency-response tests). Bare junction thermocouples, made from 0.005-inch (12.7-mm) diameter copper and constantan wires, were used to measure steady-state temperature. The Freon temperature was measured at the boiler inlet, upstream of the orifice, and in the plenum tank. Water temperature in the boiler was measured at the positions shown in figure 2.

Dynamic pressure at the boiler inlet was measured with a flush-mounted piezoelectric pressure transducer. Dynamic pressure at the boiler exit was measured with a strain gage pressure transducer. Dynamic flow rate was measured with a turbine flowmeter located between the servovalve and the boiler inlet.

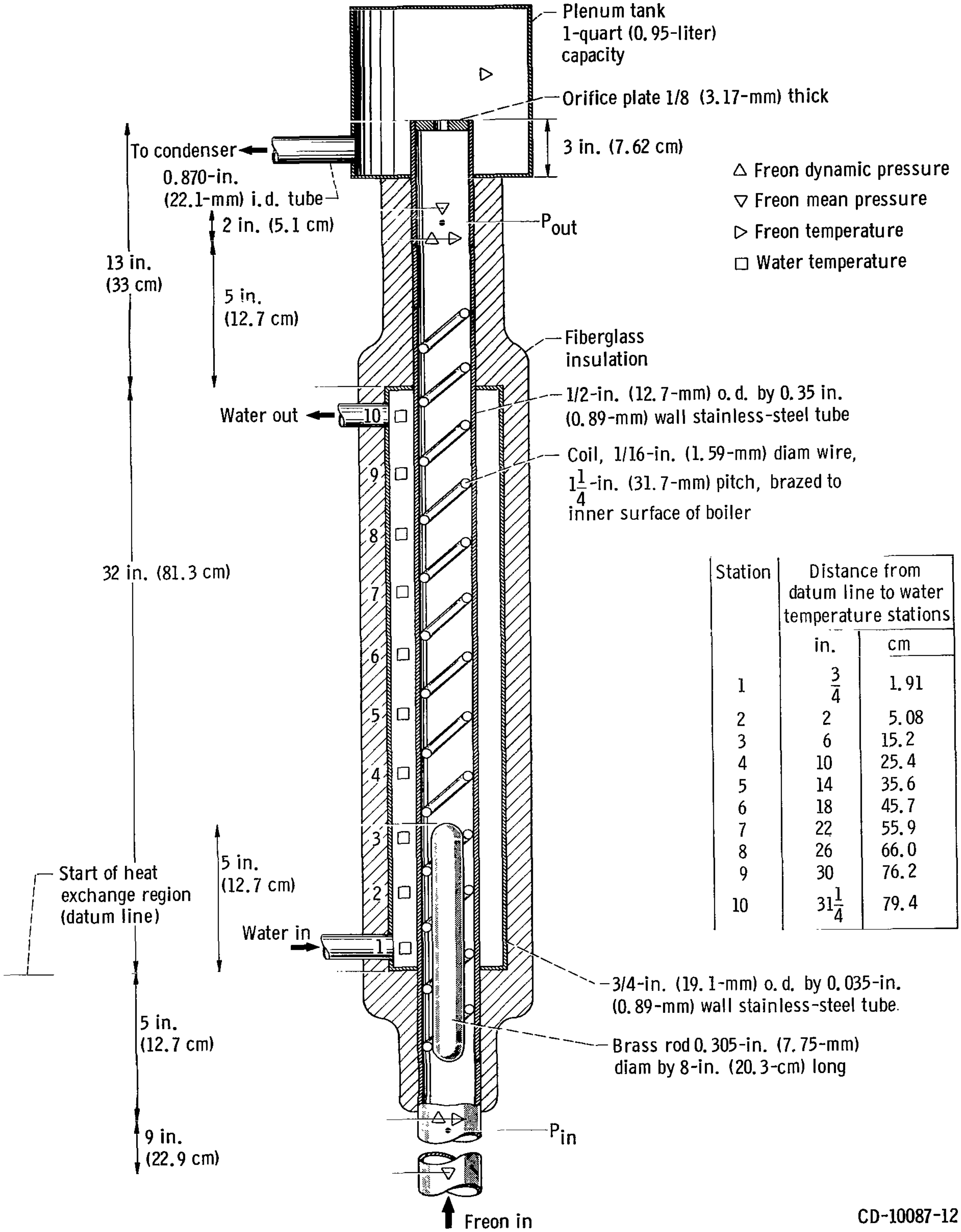
The dynamic variables, boiler inlet pressure, pressure at the boiler exit, and boiler inlet flow are analyzed by a frequency response analyzer. In order that the analyzer function, each dynamic variable had to have sinusoidal content at exactly the frequency of the analyzer reference. Hence, the analyzer reference oscillator was used drive the electrohydraulicly actuated throttle valve.

PROCEDURE

Calibration

The pressure transducers were statically calibrated by applying known pressures and recording the voltage output. It was assumed that the pressure transducers followed their steady-state calibration curves over the range of the frequency-response tests. Static calibration curves for the turbine flowmeters were supplied by their manufactures. The biggest source of error in the dynamic measurements was the flowmeter frequency response.

As is generally true, the frequency-response limit of the turbine flowmeter was a function of the mean flow rate, deteriorating rapidly with decreasing flow rate (refs. 5 and 6). Therefore, a dynamic calibration of the turbine flowmeter was made. The



Station	Distance from datum line to water temperature stations	
	in.	cm
1	3/4	1.91
2	2	5.08
3	6	15.2
4	10	25.4
5	14	35.6
6	18	45.7
7	22	55.9
8	26	66.0
9	30	76.2
10	31 1/4	79.4

Figure 2. - Single-tube boiler test section.

calibration procedure and the method used to process the flow signal are given in reference 6.

Steady-State Tests

The steady-state characteristics of the boiler were measured prior to the dynamic testing. The steady-state tests were performed extensively with the 1/4-inch (6.35-mm) orifice as an exit restriction. Because of the occurrence of boiler instabilities, only a narrow range of tests could be performed with the 3/16-inch (4.26-mm) exit orifice. For each orifice, the steady-state procedure consisted of measuring the steady-state pressures and temperatures for each of a series of Freon flow rates for a fixed water-inlet temperature. The water flow rate and temperature were kept constant while the Freon flow rate was decreased in steps from the facility maximum. For each of the steps, all flow rates, pressure, and temperatures were recorded. The steady-state measurements were made for a series of water-inlet temperatures for the larger orifice.

Fluid state at the exit of the boiler (upstream of the orifice) was evaluated using two techniques. For exit qualities between 0 and 95 percent, a heat balance between the water and the Freon was used. The heat balance method was based on the assumption that equilibrium conditions, corresponding to the boiler exit pressure, existed at the boiler exit. For qualities above 95 percent and superheat conditions, the exit orifice and plenum tank were used as a throttling calorimeter. This method also assumed that thermal equilibrium existed upstream of the orifice.

Frequency-Response Tests

After the steady-state tests were completed, the data were examined, and particular operating conditions were selected for the frequency-response tests. Emphasis was placed on the superheat region since this region is to be used in the actual space-power system. However, two low-quality runs were made because this region has application in other power generation systems. For each operating condition, the servovalve was activated and operated over a frequency range of 0.04 to about 4.0 hertz.

At each perturbation frequency, the frequency-response analyzer computed the magnitude and phase of each dynamic variable. The analyzer data were used to compute the boiler-inlet impedance and transfer impedance. The impedance data were plotted as a function of frequency while the tests were being run. When rapid changes with frequency were encountered, closer spacing of test frequencies were chosen until the trends were established. The mean conditions of Freon flow rate, water flow rate, and water inlet temperature were continuously monitored to ensure that appreciable deviations did not occur. All mean flow rates and temperatures were recorded periodically.

The frequency-response data were corrected by making the proper amplitude and phase adjustment to compensate for the response of the turbine flowmeter. The proper adjustments were determined from the following equation obtained from reference 6.

$$\Delta W_{in} = \left[1 + j\left(\frac{19.9\ f}{W_o}\right)\right]\Delta W$$

where

ΔW flow rate perturbation indicated by flowmeter

W_o the mean flow rate of frequency response test

f frequency, Hz

Stability Test

A boiler stability test was performed to obtain a quantitative comparison of the boiler inlet impedance and the feed-system impedance for a boiler-feed-system coupled instability. The test was performed by adjusting the feedline impedance presented to the boiler until a natural oscillation occurred. The feedline impedance was adjusted by two methods. One method involved opening and closing the accumulator to the boiling loop. The other involved an adjustment of the throttle-valve open area.

For the accumulator test, the throttle valve was fixed at its 75-percent open position. The accumulator pressure was made equal to the feedline pressure before the accumulator valve was opened. This prevented flow transients due to a pressure difference between the accumulator and feedline.

For the throttle valve test, the accumulator was open to the boiling loop. (The throttle valve had very little effect unless the accumulator was open to the boiling loop. This was expected since gear pumps tend to be constant flow devices.) The throttle valve was closed to the 70 percent open position momentarily and then re-opened to the 75 percent open position.

After the stability test had been performed, an all-liquid run was made to measure the resistance component of the feedline impedance. This resistance component, the slope of the feedline pressure drop (from the accumulator to the boiler inlet) against flow curve, was measured for the two throttle-valve positions. For each valve position the slope of the curve was measured by making a change in flow rate of 10 percent above and 10 percent below the mean flow rate.

The feedline resistance components were compared with the boiler-inlet impedance resistance component corresponding to the frequency of the instability. The comparison provided a measure of how accurately the frequency-response technique predicted the onset of a boiler-feed-system coupled instability.

RESULTS

Tabulation of Data

The results of the frequency-response tests are presented in tables I and II. Table I gives the mean conditions for each of the dynamic runs. The location of the water temperature stations in the table are shown in figure 2.

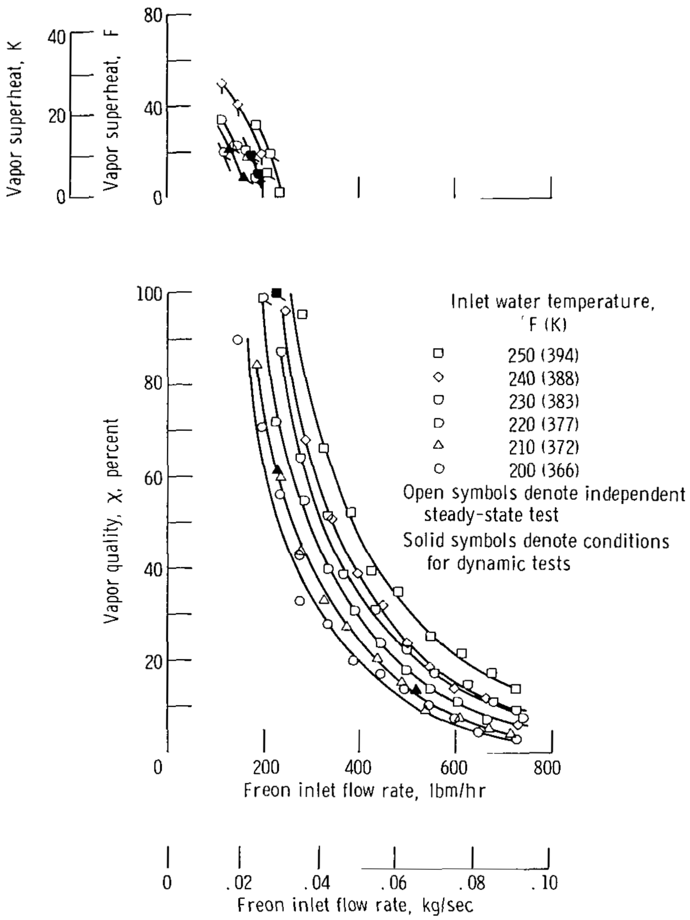
The difference between the measured temperature upstream of the orifice and the saturation temperature does not agree with the calculated superheat. This disagreement probably arose because of nonequilibrium conditions upstream of the orifice.

The boiler perturbation data are given in table II. The magnitude and the phase, relative to the frequency response analyzer reference oscillator, are tabulated for the inlet Freon flow rate and the inlet and exit pressures. The boiler inlet impedance and transfer impedance are tabulated as magnitude and phase.

Steady-State Results

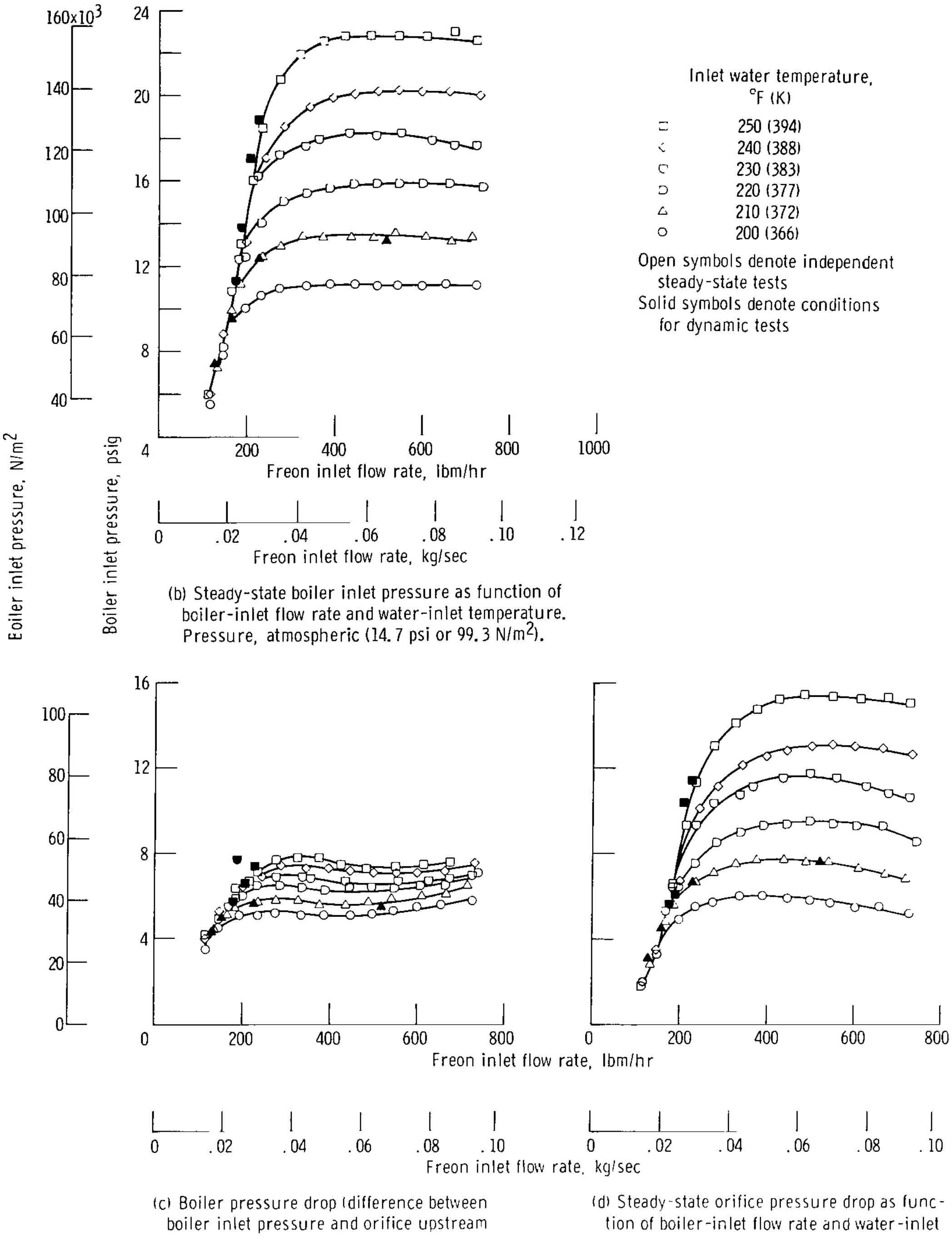
The results of the steady-state pressure drop tests performed independently of the dynamic tests are shown in figures 3 to 5. The fluid condition upstream of the 1/4-inch (6.35-mm) orifice as a function of flow rate and water-inlet temperature is shown in figure 3(a). Superheated vapor was easily obtained as evidenced by the data shown in the superheat range.

The steady-state boiler inlet pressure as a function of Freon flow rate and water-inlet temperature for the larger orifice is shown in figure 3(b). The curves exhibit steep positive slopes for low flow rates. The curves show small negative slopes for high flow rates. The boiler pressure drop as a function of flow rate and water-inlet temperature is shown in figure 3(c). These curves exhibit a negative slope at intermediate flow rates and a positive slope at the low and high flow rates. The steady-state orifice pressure drop as a function of flow rate and water-inlet temperature is shown in figure 3(d). As is the case with the boiler-inlet pressure, the orifice curve has a negative slope at high flow rates. The negative slope reflects the decrease in vapor flow rate as the total flow is increased (exit quality decreased; fig. 3(a)).



(a) Vapor condition upstream of orifice as function of Freon flow rate and water-inlet temperature.

Figure 3. - Steady-state data obtained with 1/4-inch (6.35-mm) orifice exit restriction.



(b) Steady-state boiler inlet pressure as function of boiler-inlet flow rate and water-inlet temperature. Pressure, atmospheric (14.7 psi or 99.3 N/m²).

(c) Boiler pressure drop (difference between boiler inlet pressure and orifice upstream pressure) as function of boiler-inlet flow rate and water-inlet temperature.

(d) Steady-state orifice pressure drop as function of boiler-inlet flow rate and water-inlet temperature.

Figure 3. - Concluded.

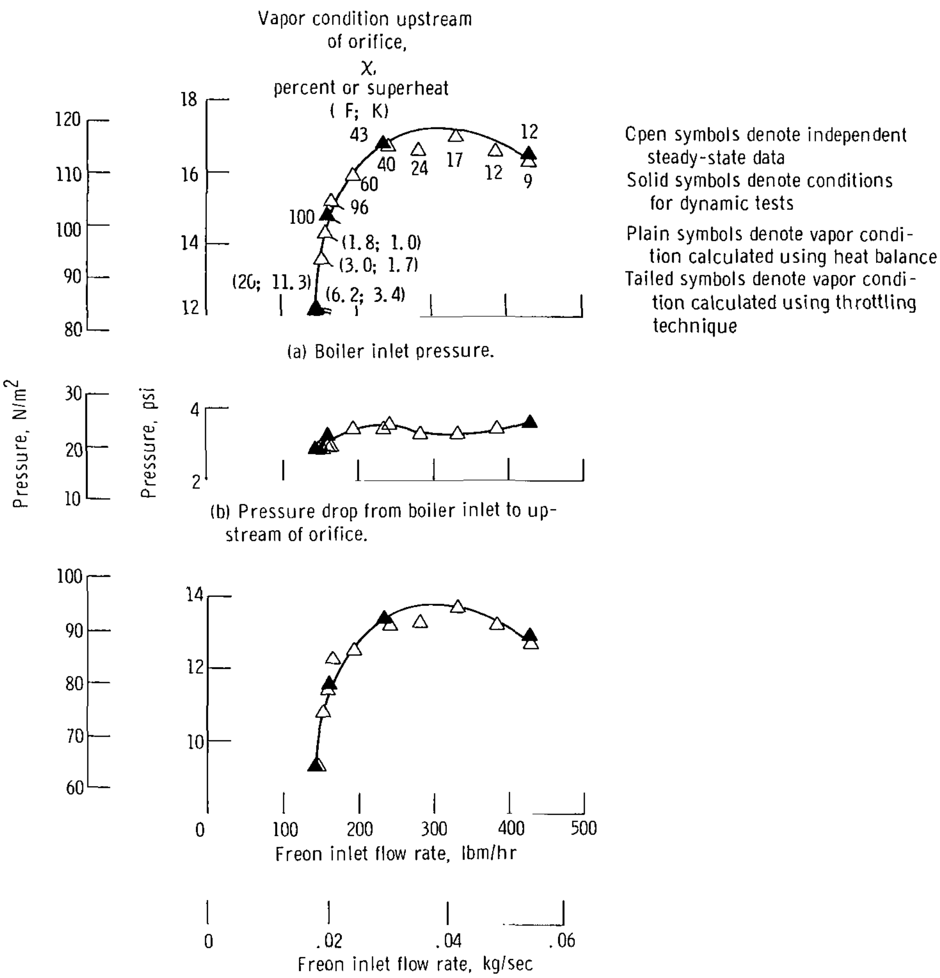


Figure 4. - Steady-state pressure drops for boiler with 3/16-inch (4.76-mm) orifice as a function of inlet flow rate. Water temperature, 214 F (374 K).

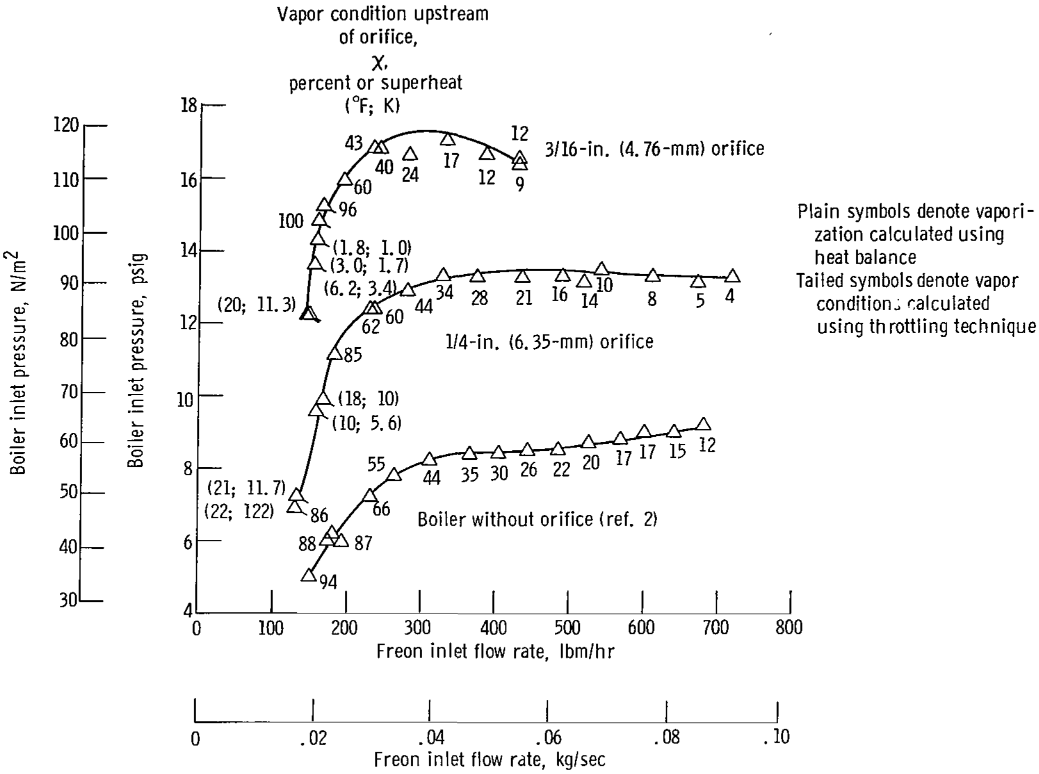


Figure 5. - Steady-state boiler-inlet pressure as function of inlet flow rate with exit restriction as a parameter. Water temperature, approximately 210° F (372 K) for each case.

The steady-state pressure drops obtained for the boiler with the smaller orifice restriction are shown in figure 4. These data are similar to the data obtained with the larger orifice. The data exhibit steeper positive and negative slopes than those obtained with the larger orifice.

The boiler inlet pressure as a function of inlet flow rate and exit restriction for a fixed water-inlet temperature is shown in figure 5. The lower curve is the pressure drop of the boiler without an exit restriction (ref. 2). The pressure drop curve for the boiler without an orifice does not have a negative slope characteristic for the same range of flow rates. The positive slopes of the curves at low flow rates generally increase as the orifice diameter decreases.

Frequency-Response Results

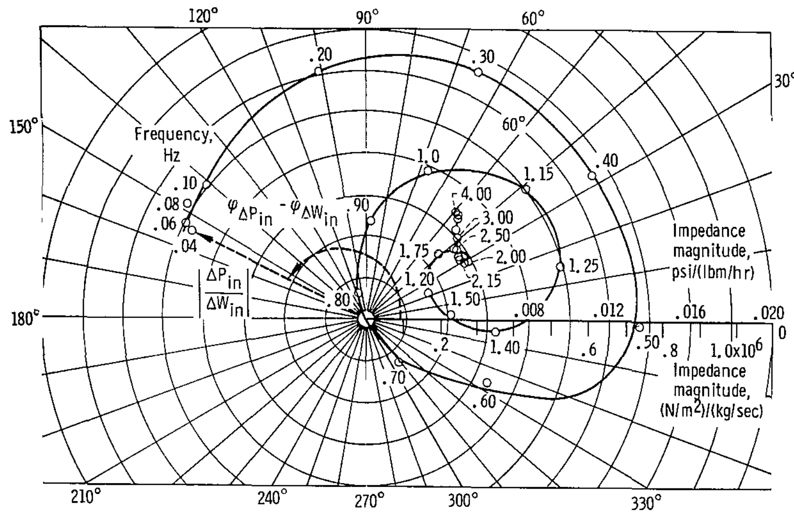
Three types of runs were selected from table II as being typical of the frequency-response data and are shown in figures 6 to 9. The frequency response of the boiler for a low-quality (12 percent) exit condition (run 9 of table II) is shown in polar coordinate form in parts (a) and (b) of figure 6.

Low-quality run. - The inlet impedance as a function of frequency is shown in figure 6(a). (The magnitude of the impedance is plotted as distance from the origin and the impedance phase is measured in a counter-clockwise direction from the 0 axis). Since the steady-state boiler inlet pressure against flow curve had a negative slope for this run, the zero frequency asymptote of the impedance phase was 180°. Following the convention of the impedance concept, the horizontal axis (0 and 180° axis) corresponds to a resistance component. Consequently, because of the negative slope condition, the boiler-inlet impedance at zero frequency corresponds to a negative hydraulic resistance. As the perturbation frequency increases the impedance phasor rotates in a clockwise direction from the 180° axis. Over the frequency range of 0 to about 0.24 hertz, the phasor can be resolved into two components, one of which lies on the negative resistance axis. The presence of a negative resistance component is very significant because it can cause a boiler-feed-system coupled instability. Therefore, for this operating condition, the boiler is potentially unstable over the frequency range of 0 to about 0.24 hertz. Between 0.24 and about 0.75 hertz, the resistance component of the impedance is always positive. Therefore, over this second frequency range, this boiler cannot be the source of a boiler-feed-system coupled instability. This stable condition is also present for the frequency range of about 0.89 to 4.0 hertz.

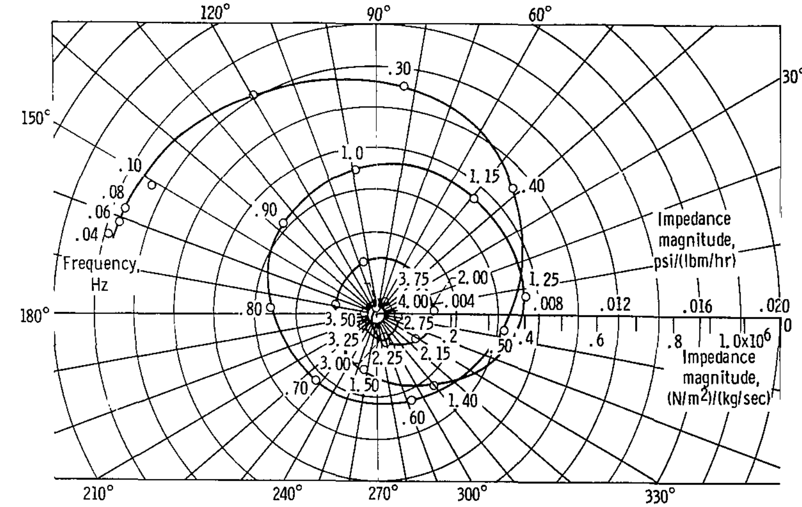
Over the frequency range from 0 to 2.5 hertz, the inlet impedance data form a spiral shaped locus made up of loops that attenuate as frequency increases. This spiral shape was characteristic of all the frequency response data of this report, and it was also characteristic of the data reported in references 1 and 3. The model presented in reference 2 suggests that the increasing phase lag results from the time lag between liquid flow into the boiler and vapor flow out. Other effects cause the magnitude of the loops to attenuate as frequency increases. Figure 6(a) shows that the loops have attenuated completely above 2.5 hertz and that the impedance data form a vertical line.

The transfer impedance for the same low quality run is shown as a function of frequency in figure 6(b). Like the inlet impedance, the transfer impedance data also form a spiral shaped locus about the origin.

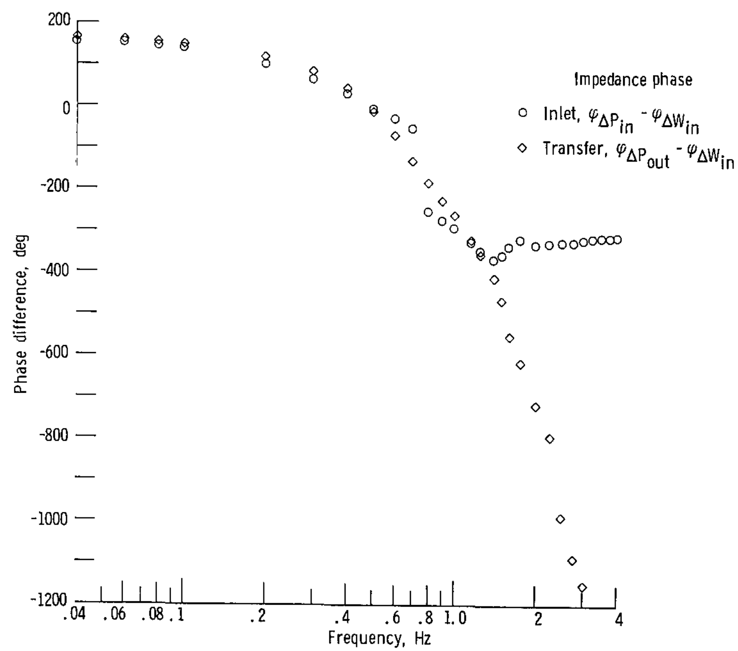
A comparison of the inlet impedance and transfer impedance of figure 6 shows that the two impedances are similar at least up to 0.5 hertz. Above 0.5 hertz, the similarity becomes less obvious, and above 2.5 hertz the two appear to be unrelated. This effect above 2.5 hertz is illustrated clearly in the comparison of the two phase angles as a function of frequency shown in figure 6(c). The inlet impedance phase and the transfer impedance phase vary in an almost identical fashion with frequency up to 0.5 hertz. Above 0.5 hertz, the inlet impedance phase departs from the transfer impedance phase, and, above 2.4 hertz, the relation between the two functions is not clear (The 180° discontinuity at about 0.75 Hz in the inlet impedance phase indicates the passage of the locus through the origin and has no other significance). The large phase lag in the



(a) Inlet impedance as function of frequency.



(b) Transfer impedance as function of frequency.

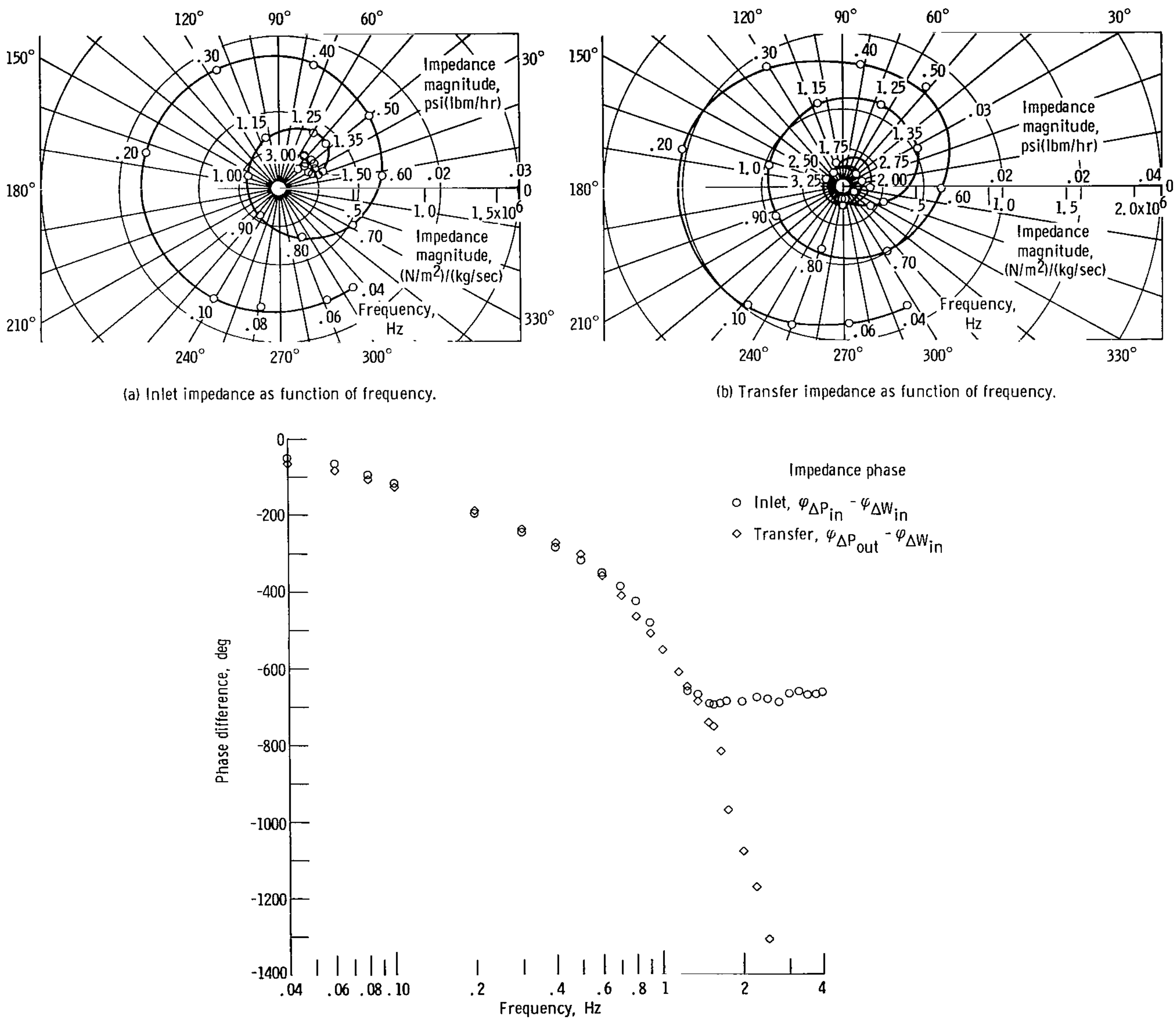


(c) Impedance phase as function of frequency.

Figure 6. - Frequency response data for boiler with 3/16-inch (4.76-mm) orifice exit restriction. Vapor quality, 12 percent; run 9.

transfer impedance is characteristic of functions with time lag.

Intermediate quality run. - The frequency-response data for an intermediate-quality (43 percent) exit condition (run 10 of table II) is shown in figure 7. For the conditions of this test, the slope of the inlet pressure against flow curve was positive. Consequently, the low-frequency asymptote of the inlet impedance phase (fig. 7(a)) was the 0 axis or a positive hydraulic resistance. As the perturbation frequency increases, the data form a characteristic spiral about the origin. The locus of the boiler inlet impedance shows that the inlet impedance has a negative resistance component over the

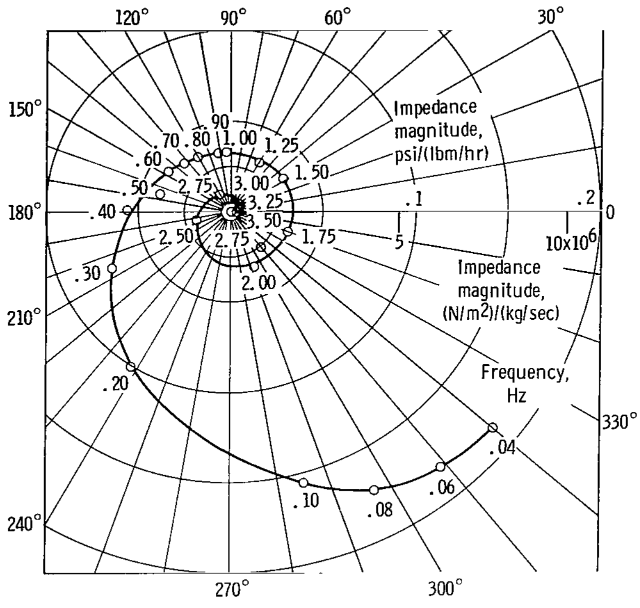


(a) Inlet impedance as function of frequency.

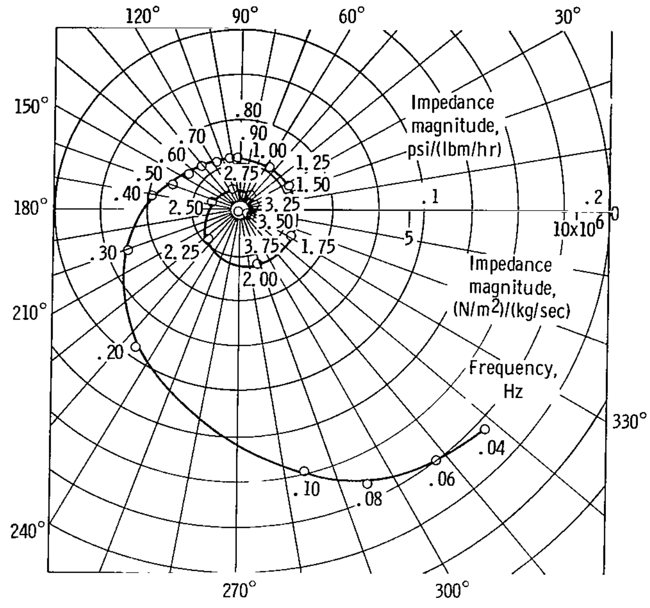
(b) Transfer impedance as function of frequency.

(c) Impedance phase as function of frequency.

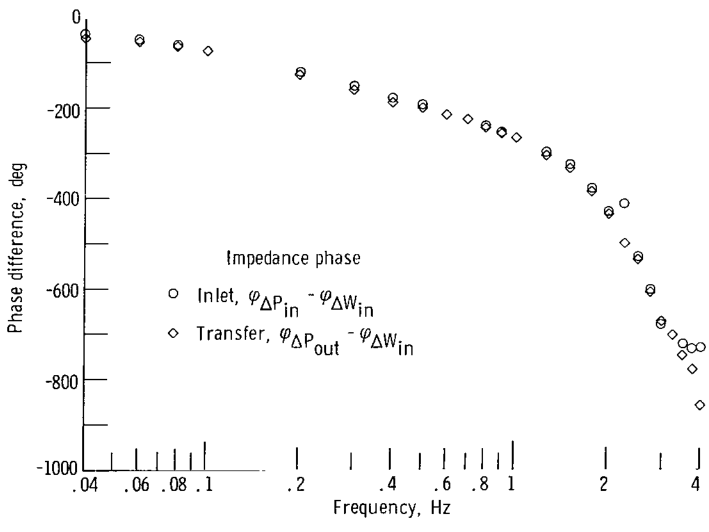
Figure 7. - Frequency response data for boiler with 3/16 inch (4.76-mm) orifice exit restriction. Vapor quality, 43 percent; run 10.



(a) Inlet impedance as function of frequency.



(b) Transfer impedance as function of frequency.



(c) Impedance phase as function of frequency.

Figure 8. - Frequency response data for boiler with 3/16-inch (4.76-mm) orifice exit restriction. Vapor quality, 20° F (11.3 K) superheat; run 12.

frequency range of 0.08 to about 0.35 hertz. At about 0.19 hertz the locus crosses the 180° axis where the inlet impedance consists only of a negative resistance component. The impedance locus makes another loop into the negative resistance region over the approximate frequency range 0.85 to 1.17 hertz. Since the magnitude of the inlet impedance decreases with frequency, the magnitude of the negative resistance components of the second frequency range are smaller than the components of the first excursion into the negative resistance region. Above 1.5 hertz, the spiral motion of the locus has attenuated to such an extent that the inlet impedance always has a positive resistance component. The transfer impedance for the same run is shown in figure 7(b). Like the inlet impedance, the transfer impedance forms a spiral about the origin. Also, like the transfer impedance of the low quality run, the transfer impedance is similar to the inlet impedance at low frequencies. At higher frequencies, the similarity is less obvious. A comparison of the impedance phases as a function of frequency is shown in figure 7(c). The inlet impedance phase follows the transfer impedance phase almost identically up to about 1.4 hertz. Above 1.4 hertz, the inlet impedance phase is relatively constant, but the transfer impedance phase decreases rapidly with frequency. Thus, for the low quality cases and for low frequencies, the inlet impedance and transfer impedance are similar. However, above some intermediate frequency the similarity seems to disappear.

Superheat run. - The frequency-response data for a superheat exit condition (20° F or 11.3 K), is shown in figure 8 (run 12 of table II). As was the case with the intermediate quality exit condition, the inlet impedance phasor (fig. 8(a)) rotates in a clockwise direction from the 0 axis as frequency increases. As the phasor rotates, it makes two excursions into the negative resistance region.

The transfer impedance for the same run (fig. 8(b)) forms a locus that is almost identical to the inlet impedance locus. The duplicate behavior of the impedance functions is further illustrated in a comparison of the impedance phase angles as is shown in figure 8(c). The phase functions are approximately the same up to 3.5 hertz.

With superheated vapor at the boiler exit, the transfer impedance had a special significance. The orifice pressure-drop perturbations were proportional to the vapor flow perturbations. Therefore, the transfer impedance indicated how the exit vapor flow was related to the inlet liquid flow. This was not true for the low-quality cases because the pressure drop was a function of exit quality and exit quality was a function of time.

For superheated exit conditions, the impedance magnitudes varied with frequency in a fashion similar to that illustrated in figure 9. As frequency increased, the impedance magnitudes generally decreased for low frequencies. For intermediate frequencies there was a peaking action in both impedance functions. The effect of the peaking action, on the inlet impedance, varied. In some cases, the inlet impedance was constant for a range of frequencies between 1.0 and 4.0 hertz. In other cases, the inlet impedance had

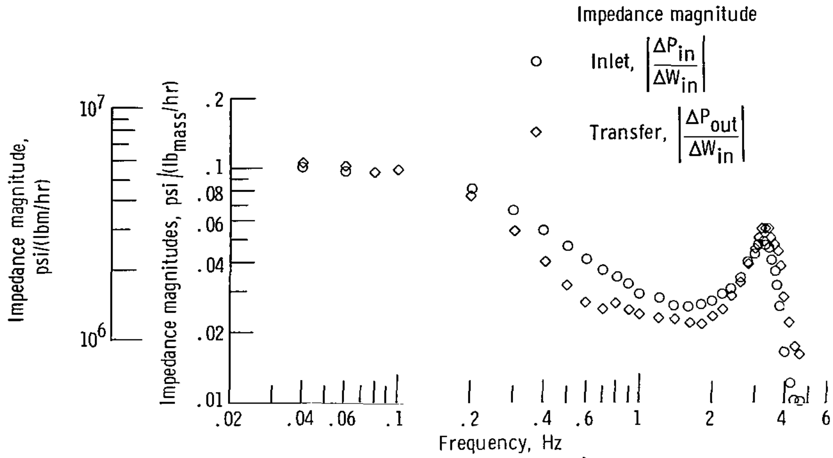


Figure 9. - Impedance magnitudes as function of frequency for 19.6° F (10.9 K) superheat (run 6).

a very noticeable peak as shown in figure 9. For all the superheat runs, the transfer impedance had a noticeable peak between 1.0 and 4.0 hertz.

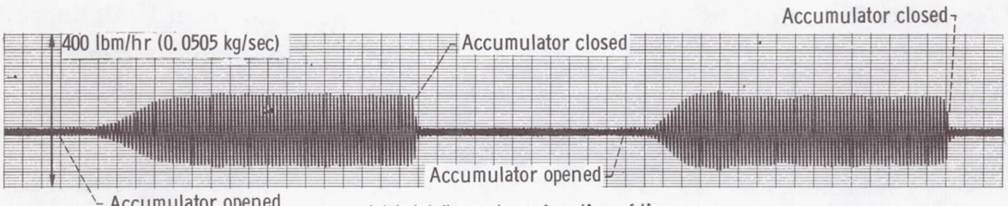
For all operating conditions tested, the frequency response data indicated that there was always a range of frequencies for which the boiler-inlet impedance had a negative resistance component. For low exit quality, the negative resistance component was present from 0 to, typically, 0.2 hertz. For intermediate qualities and superheat conditions, the negative resistance component was present for an intermediate range of frequencies, typically 0.2 to 1.0 hertz. Also, for the higher exit qualities and superheat conditions, the negative resistance component was present for more than one range of frequencies.

The inlet impedance and transfer impedance had very similar characteristics. The similarity between the two impedance functions seemed to be a function of exit quality. For low exit quality, the two functions were similar only for the low frequencies. For superheat exit conditions, the two impedance functions were almost identical.

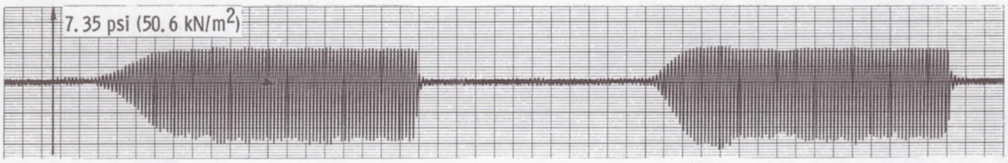
Stability Test Results

A boiler stability test was performed to obtain a quantitative comparison of the boiler-inlet impedance and the feed-system impedance for a boiler-feed-system coupled instability.

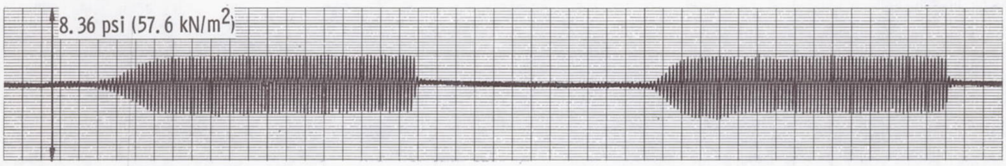
A similar test was performed in reference 4, which showed that loop stability could be controlled by varying the restriction at the boiler inlet. The test of this report shows



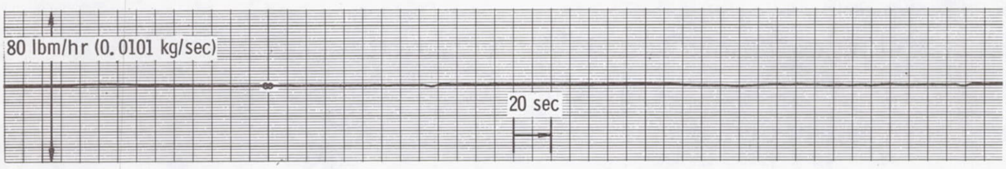
(a) Inlet flow rate as function of time.



(b) Inlet pressure as function of time.



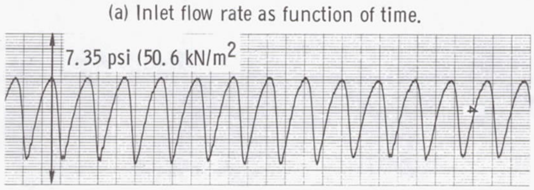
(c) Exit pressure as function of time.



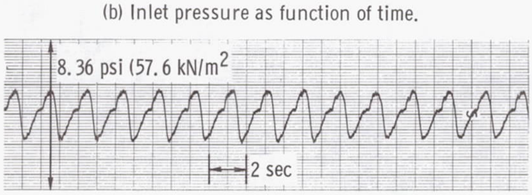
(d) Average flow as function of time.

Figure 10. - Effect of accumulator on loop stability: pressure and flow signals as function of time.

(a) Inlet flow rate as function of time.



(b) Inlet pressure as function of time.



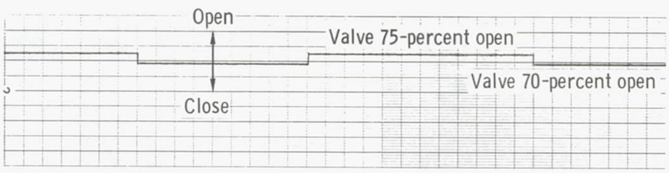
(c) Exit pressure as function of time.

Figure 11. - Form of oscillations after oscillations are well developed.

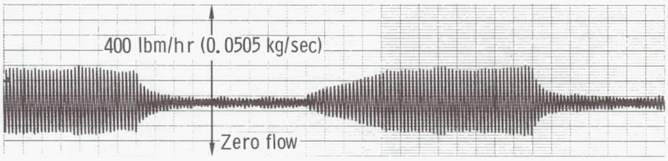
that the stabilizing effect of the inlet restriction can be cancelled if there is compliance downstream of the restriction. The results of the test are shown in figures 10 to 12. The boiler inlet impedance for the conditions of the test is included in figure 13. Also shown in figure 13 is the calculated feed system impedance. The calculation was for a 75-percent open position of the throttle valve.

Effect of accumulator. - The effect of the accumulator is shown in figures 10 and 11. The throttle valve was 75 percent open.

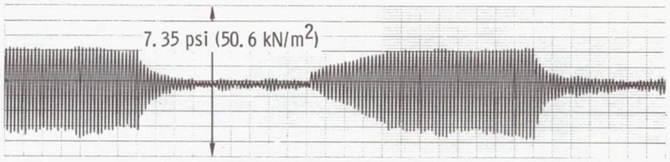
With the accumulator closed, the flow rate was held constant (Gear pumps tend to be constant flow devices). Since the flow could not change, the loop was stable as is shown at the start of the traces in figure 10. The small perturbations at the start of the trace were probably the result of flow pulses from the gear pump. The peak to peak amplitude



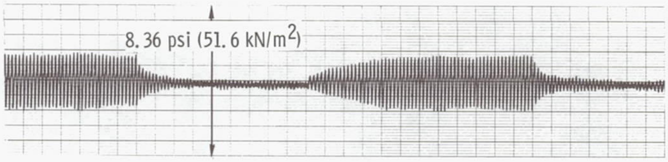
(a) Valve position as function of time.



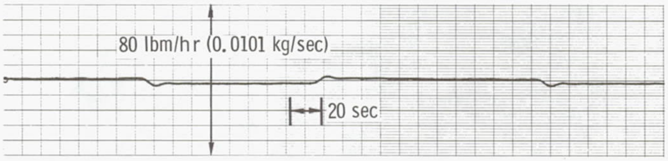
(b) Inlet flow rate as function of time.



(c) Inlet pressure as function of time.



(d) Exit pressure as function of time.



(e) Average flow rate as function of time.

Figure 12. - Effect of throttle-valve position on stability of system with accumulator opened to the freon loop.

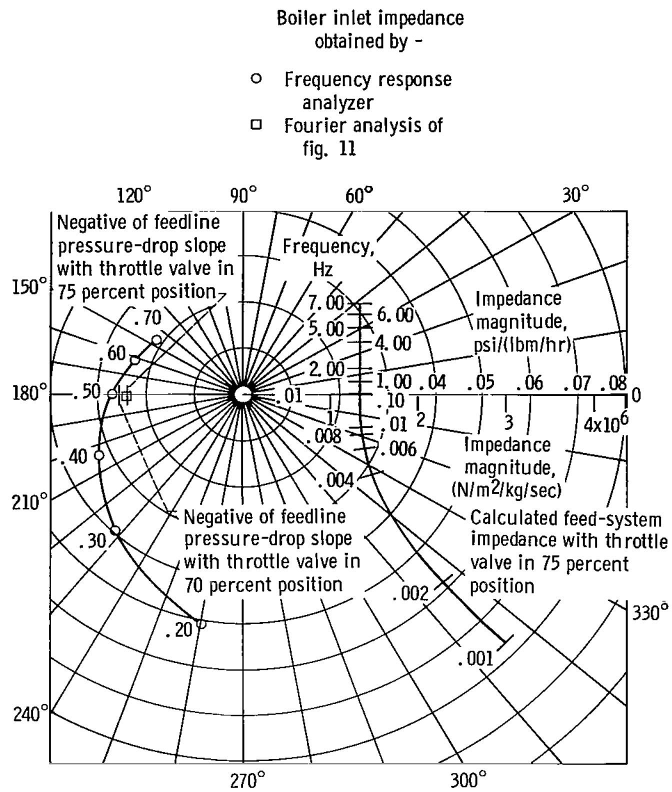


Figure 13. - Comparison of boiler-inlet impedance and feed-system impedance for unstable condition.

of the flow perturbations is only 12 percent of the mean flow.

When the accumulator was opened, the gear pump no longer controlled the flow into the boiler. Also the restriction (throttle valve) downstream of the accumulator was not sufficient for stable operation. Therefore, a natural oscillation resulted as shown in figure 10. The peak to peak amplitude of the flow oscillation was about 120 percent of the mean flow.

When the accumulator was closed, the gear pump controlled the flow rate and the oscillation decayed almost immediately. (The time for growth to full amplitude was 20 to 30 sec; the time for complete decay was about 5 sec.)

During this part of the test, the mean flow rate was approximately constant as is shown in figure 10(d). (The peak to peak variation was about 2 percent.) The authors have noticed that this is a good indication that the oscillations are only mildly nonlinear. Extreme nonlinear oscillations caused a large shift in mean flow rate.

The form of the oscillation after it was well developed is shown in figure 11. By comparing the trace of inlet flow rate with the trace of inlet pressure, an approximate 180° phase difference can be seen between the two traces. Hence, the oscillation frequency was such that the imaginary part of the boiler-inlet impedance was zero and the real part (resistance) was negative. Therefore the feed-system impedance also had a zero imaginary part, but the real part was positive. This agrees with the calculated feed system impedance (which will be discussed shortly) which indicates that the accumulator impedance was approximately zero at the frequency of the oscillations.

The effect of the accumulator was to provide an alternate path for flow perturbations. The impedance of this path was much smaller than the path through the gear pump. Therefore the gear pump was dynamically decoupled from the boiler. Thus, the only restriction affecting the boiler was the throttle valve. This restriction was not sufficient for stable operation and natural oscillations occurred.

Effect of throttle valve restriction. - The effect of the throttle valve restriction is shown in figure 12. For this test the accumulator was opened to the loop.

With the throttle valve in the 75 percent open position, the loop was unstable. This was shown in figures 10 and 11 and, also, in figure 12. However, when the valve was closed to the 70 percent open position, the amplitude of the oscillations decayed. The amplitude of the small flow oscillations in figure 12(b) is about 16 percent of the mean flow, peak to peak. These small oscillations were not due to pressure pulses from the gear pump because the accumulator was open to the loop.

More likely, the loop was very near neutral stability. Near neutral stability the loop should act like a resonant system with very little damping. If this was true, random pressure and flow pulses inherent in the boiling process may have been sufficient to sustain a small oscillation.

The change in valve position was only 5 percent of full open position. Therefore, small changes in inlet restriction can have a large effect on loop stability if the nominal position is near neutral stability.

The total change in mean flow rate during this test was less than 3 percent.

Comparison of boiler-inlet impedance and feed-system impedance. - The boiler impedance is compared with the feed system impedance in figure 13. The conditions for the test were as follows:

Freon flow rate, lbm/hr; kg/sec	145; 0.0182
Freon temperature, ^{O}R; K	70; 294
Water temperature, ^{O}F; K.	210; 372

These conditions correspond to the lower portion of the positive slope region of the steady-state pressure drop curve in figure 3(b). Superheated vapor was present at the boiler exit.

In figure 13 data are presented that represent the inlet impedance obtained with the frequency response analyzer prior to the stability test. The arrows indicate the negative of the feedline resistance components for each valve position. The magnitude of the feedline resistance component for the 70 percent open position is slightly less than the boiler impedance magnitude at 0.5 hertz.

The magnitude of the feedline resistance component decreases as the throttle valve is opened. The curve plotted to the right of the origin represents the calculated feed-system impedance for a throttle valve position of 75 percent open. The calculation was based on the assumption of an isothermal gas for the air in the accumulator. The accumulator volume was about 390 cubic inches ($6.39\ mm^3$). The resistance component of the feedline (slope of feedline pressure drop curve) was measured as outlined in the Procedure section. The pump resistance was determined from the pump pressure rise against flow curve. The inertance of the feedline was the inertance of the liquid in a 54-inch (0.137-m) long line with a 3/8-inch (0.952-cm) outside diameter and a 0.035-inch (0.0875-cm) wall thickness. (A thorough discussion of a similar feed-system impedance calculation can be found in ref. 1.)

The calculated impedance indicates that the resistance component of the feed-system impedance is constant above 0.01 hertz. In addition, over the frequency range of 0.01 to 1.00 hertz, the impedance is predominately resistive. Hence, equality of the feed-system impedance and the boiler impedance (neutral stability) of figure 13 can occur only for a boiler impedance very near the 180° axis. This 180° boiler impedance phase was verified by the recording of the natural oscillations of figure 11. Hence, the stability of this particular system with the accumulator open was approximately determined by the resistance component of the feedline and the 180° impedance of the boiler.

At this point it should be emphasized that the impedance concept is based on the assumption of linearity. With boilers, this usually requires small perturbations. However, it is of interest to note that the perturbations can be quite large without affecting the boiler impedance appreciably (In the large amplitude case, the harmonics of the perturbation are disregarded, and only the fundamental frequency components are analyzed). This can be seen by comparing the position of the square symbol of figure 13 with the position of the 0.5-hertz round symbol. The square symbol corresponds to the impedance obtained by making a Fourier analysis of the flow and inlet-pressure traces of figure 11. Only the fundamental frequency components for these traces were calculated. All other harmonics were disregarded. (In addition, amplitude and phase corrections were made for the flow signal. The corrections included the effect of the flowmeter (ref. 6) and a 6.0-hertz single-order low-pass filter, which was used only for the stability test.) Considering the circumstance of large-amplitude oscillations, the agreement between the two data points is excellent.

The excellent agreement obtained for the impedances indicated that the frequency response data can be used to accurately predict the onset of a boiler-feed-system coupled instability.

SUMMARY OF RESULTS

The steady-state inlet pressure against flow curve for the boiler with inserts and an exit restriction had a negative slope for low-vapor qualities. The negative slope was not present in the curve for the same boiler without the exit restriction. The negative slopes obtainable with the smaller orifice were larger than those obtainable with the larger orifice for the range of flow rates tested.

For all conditions tested, there was always a frequency range for which the boiler with an exit restriction had an inlet impedance with a negative resistance component. The negative resistance component was present even though the slope of the inlet pressure against flow curve was positive for most of the test conditions.

With superheat vapor conditions at the boiler exit, the inlet impedance function was almost identical to the transfer impedance function. The similarity between the two functions decreased as vapor state at the boiler exit approached the low-quality range.

A quantitative comparison of the boiler inlet impedance and the feed-system impedance was obtained for a boiler feed-system-coupled instability. The excellent agreement obtained for the impedances indicated that the frequency response data can be used to accurately predict the onset of a boiler-feed-system coupled instability.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 9, 1968,
120-27-04-27-22.

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5. Grey, Jerry: Transient Response of the Turbine Flowmeter. Jet Propulsion, vol. 26, no. 2, Feb. 1956, pp. 98-100.

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TABLE I. - MEAN CONDITIONS FOR DYNAMIC TESTS

(a) U.S. Customary Units

Orifice diameter, in.	Run	Freon: Freon flow rate, lbm/hr	Freon inlet absolute pressure, psia	Orifice upstream absolute pressure, psia	Orifice upstream saturation temperature, °F	Temperature at boiler inlet, °F	Orifice upstream temperature, °F	Temperature in plenum tank, °F	Vapor condition upstream of orifice, percent, or °F superheat	Water: Water flow rate, lbm/hr	Temperature, °F, at station -, 1	2	3	4	5	6	7	8	9	10
1/4	1	520	27.5	22.0	140	72	138	114	[a]14	674	210	208	206	204	202	200	197	195	194	192
	2	229	26.8	21.1	138	69	137	114	[a]62		210	209	207	205	203	201	199	197	195	192
	3	158	24.0	19.0	132	69	145	140	(9.3° F)		210	208	206	204	202	200	197	195	193	192
	4	129	22.0	17.6	127	75	159	148	(21.3° F)		210	208	206	204	201	199	197	196	195	194
	5	189	28.1	20.4	136	71	151	145	(10.7° F)	666	230	227	225	222	219	216	213	211	209	207
	6	177	25.7	20.0	135	70	163	153	(19.6° F)	666	230	228	226	222	219	216	213	211	210	210
	7	228	33.2	25.8	150	71	151	145	100	660	250	247	244	242	238	235	231	229	226	222
	8	209	31.3	24.7	147	72	166	156	(11.3° F)	660	250	246	244	241	237	233	229	227	225	222
3/16	9	426	30.8	27.2	153	52	151	114	[a]12	672	213	211	209	207	204	202	200	199	197	196
	10	234	31.2	27.8	154	53	151	114	[a]43		214	212	210	208	206	204	201	200	199	197
	11	159	29.1	25.0	148	55	155	144	100		213	211	209	207	205	203	200	200	199	197
	12	143	26.8	24.0	145	55	164	152	(20.4° F)		214	212	210	208	205	203	201	199	199	199

(b) SI Units

Orifice diameter, m	Run	Freon: Freon flow rate, kg/sec	Freon inlet absolute pressure, N/m^2	Orifice upstream absolute pressure, N/m^2	Orifice upstream saturation temperature, K	Temperature at boiler inlet, K	Orifice upstream temperature, K	Temperature in plenum tank, K	Vapor condition upstream of orifice, percent, or K superheat	Water: Water flow rate, kg/sec	Temperature, K, at station -, 1	2	3	4	5	6	7	8	9	10
6.35×10^{-3}	1	0.0655	1.9×10^5	1.52×10^5	333	296	332	319	[a]14	0.085	372	371	370	369	368	366	365	364	363	362
	2	.0289	1.85	1.46	332	294	332	319	[a]62			372	371	370	368	367	366	365	364	362
	3	.020	1.66	1.31	329	294	336	333	(5.2 K)			371	370	369	368	366	365	364	363	362
	4	.0163	1.52	1.21	326	297	344	338	(11.8 K)			371	370	369	367	366	365	365	364	363
	5	.0238	1.94	1.41	331	295	340	336	(6.0 K)	.084	384	382	381	379	377	376	374	373	372	371
	6	.0223	1.77	1.38	330	294	346	341	(10.9 K)	.084	384	382	381	379	377	376	374	373	372	372
	7	.0287	2.29	1.78	339	295	340	336	100	.0831	394	393	391	390	388	386	384	382	381	379
	8	.0264	2.16	1.70	337	296	348	342	(6.3 K)	.0831	394	392	391	389	387	385	382	382	380	379
4.76×10^{-3}	9	0.0537	2.12	1.88	340	284	340	319	[a]12	0.0846	374	373	372	371	368	368	366	366	365	365
	10	.0295	2.15	1.92	341	285	340	319	[a]43			374	372	371	370	369	367	366	366	365
	11	.02	2.01	1.73	338	286	342	335	100			373	372	371	369	368	366	366	366	365
	12	.018	1.85	1.66	336	286	347	340	(11.3 K)			374	372	371	369	368	367	366	366	366

[a]Qualities calculated using heat balance; others calculated using orifice and plenum as throttling calorimeter.

TABLE II. - BOILER PERTURBATION DATA

(a) Orifice exit restriction, 1/4 inch (6.35 mm); run 1; Freon flow rate, 520 pounds per hour (0.065 kg/sec); boiler exit condition, χ = 14 percent; inlet water temperature, 210° F (372 K)

Frequency, f, Hz	Perturbation data									Boiler inlet impedance			Transfer impedance		
	Freon flow at boiler inlet			Pressure at boiler inlet			Pressure at boiler exit			Magnitude, $\left\lvert\frac{\Delta P_{in}}{\Delta W_{in}}\right\rvert$		Phase, $\varphi_{\Delta P_{in}} - \varphi_{\Delta W_{in}}$, deg	Magnitude, $\left\lvert\frac{\Delta P_{out}}{\Delta W_{in}}\right\rvert$		Phase, $\varphi_{\Delta P_{out}} - \varphi_{\Delta W_{in}}$, deg
	Magnitude,[a] $\lvert\Delta W_{in}\rvert$		Phase relative to oscillator, $\varphi_{\Delta W_{in}}$, deg	Magnitude,[a] $\lvert\Delta P_{in}\rvert$		Phase relative to oscillator, $\varphi_{\Delta P_{in}}$, deg	Magnitude,[a] $\lvert\Delta P_{out}\rvert$		Phase relative to oscillator, $\varphi_{\Delta P_{out}}$, deg						
	lb/hr	kg/sec		psi	N/m^2		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.04	46.6	0.00587	-8	0.0800	552	145	0.195	1342	170	0.00172	0.940×10^5	153	0.00418	2.29×10^5	178
.06	46.6	.00589	-9	.0768	530	135			169	.00165	.903	144	.00418	2.29	178
.08	46.6	.00589	-11	.0784	540	123			168	.00168	.919	134	.00418	2.29	179
.10	45.5	.00573	-13	.0864	596	115			164	.00190	1.04	128	.00428	2.34	177
.20	45.0	.00567	-16	.173	1190	86	.246	1694	145	.00384	2.10	102	.00546	2.99	161
.25	42.1	.00530	-15	.188	1290	76	.226	1559	135	.00446	2.44	91	.00537	2.94	150
.30	44.1	.00555	-16	.256	1760	64	.255	1756	120	.00581	3.18	80	.00578	3.16	136
.40	43.6	.00549	-18	.312	2150	45	.247	1704	92	.00716	3.92	63	.00567	3.10	110
.50	43.6	.00549	-19	.365	2510	29	.223	1539	66	.00837	4.58	48	.00511	2.80	85
.60	43.1	.00543	-19	.376	2590	14	.179	1240	40	.00872	4.77	33	.00415	2.27	59
.70	42.6	.00537	-19	.376	2590	3	.154	1064	10	.00883	4.83	22	.00362	1.98	29
.80	42.1	.00530	-20	.344	2370	-8	.115	796	-26	.00817	4.47	12	.00273	1.49	-6
.90	42.6	.00537	-20	.300	2070	-15	.097	671	-74	.00704	3.85	5	.00228	1.25	-54
1.0	43.6	.00549	-19	.240	1650	-19	.105	723	-129	.00550	3.01	0	.00241	1.32	-110
1.25	43.6	.00549	-22	.160	1100	2	.154	1064	-207	.00367	2.01	22	.00353	1.93	-185
1.4	43.6	.00549	-24	.230	1590	24	.225	1549	-257	.00527	2.88	48	.00516	2.82	-233
1.6	43.1	.00543	-25	.314	2160	19	.261	1797	-307	.00728	3.98	44	.00605	3.31	-272
1.8	42.6	.00537	-27	.370	2550	6	.258	1777	-355	.00868	4.75	33	.00605	3.31	-328
2.0			-27	.366	2520	-8	.216	1487	-413	.00859	4.69	19	.00507	2.77	-386
2.2			-28	.304	2090	-14	.156	1074	-468	.00714	3.90	14	.00366	2.00	-440
2.4			-28	.250	1720	-11	.089	620	-528	.00587	3.21	17	.00209	1.14	-500
2.6	42.8	.00539	-31	.243	1680	-2	.055	382	-602	.00568	3.11	29	.00128	.700	-571
2.8	42.4	.00534	-32	.262	1810	5	.055	377	-671	.00618	3.38	37	.00130	.711	-639
3.0	42.9	.00540	-34	.296	204	6	.054	372	-762	.00690	3.77	40	.00126	.689	-728
3.2	41.9	.00528	-35	.312	2150	3	.032	222	-840	.00745	4.07	38	.000764	.418	-805
3.4	42.0	.00529	-36	.312	2150	0	.041	282	-956	.00743	4.06	36	.000976	.534	-920
3.6	42.0	.00529	-36	.296	2040	0	.068	470	-1011	.00705	3.86	36	.00162	.886	-975
3.8	42.1	.00530	-39	.296	2040	2	.106	733	-1055	.00703	3.84	41	.00252	1.37	-1016
4.0	43.1	.00543	-39	.320	2210	5	.119	826	-1105	.00742	4.06	44	.00276	1.51	-1066

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(b) Orifice exit restriction, 1/4 inch (6.35 mm); run 2; Freon flow rate, 229 pounds per hour (0.029 kg/sec); boiler exit condition, χ = 62 percent; inlet water temperature, 210° F (372 K)

Frequency, f, Hz	Perturbation data: Freon flow at boiler inlet: Magnitude,[a] $\lvert\Delta W_{in}\rvert$, lb/hr	kg/sec	Phase relative to oscillator, $\varphi_{\Delta W_{in}}$, deg	Pressure at boiler inlet: Magnitude,[a] $\lvert\Delta P_{in}\rvert$, psi	N/m^2	Phase relative to oscillator, $\varphi_{\Delta P_{in}}$, deg	Pressure at boiler exit: Magnitude,[a] $\lvert\Delta P_{out}\rvert$, psi	N/m^2	Phase relative to oscillator, $\varphi_{\Delta P_{out}}$, deg	Boiler inlet impedance: Magnitude, $\frac{\lvert\Delta P_{in}\rvert}{\lvert\Delta W_{in}\rvert}$, psi/(lb/hr)	$(N/m^2)/(kg/sec)$	Phase, $\varphi_{\Delta P_{in}} - \varphi_{\Delta W_{in}}$, deg	Transfer impedance: Magnitude, $\frac{\lvert\Delta P_{out}\rvert}{\lvert\Delta W_{in}\rvert}$, psi/(lb/hr)	$(N/m^2)/(kg/sec)$	Phase, $\varphi_{\Delta P_{out}} - \varphi_{\Delta W_{in}}$, deg
0.04	13.6	0.00171	2	0.396	2730	-26	0.382	2634	-33	0.0292	1.60×10^6	-28	0.0281	1.54×10^6	-35
.06	13.1	.00165	3	.368	2540	-38	.367	2530	-47	.0281	1.54	-41	.0280	1.53	-50
.08	14.1	.00178	4	.360	2480	-52	.374	2582	-59	.0255	1.39	-56	.0265	1.45	-63
.10	15.5	.00195	5	.360	2480	-65	.374	2582	-72	.0232	1.27	-70	.0241	1.32	-77
.20	20.9	.00263	2	.408	2810	-122	.429	2964	-136	.0195	1.07	-124	.0205	1.12	-138
.30	23.8	.00300	-12	.392	2700	-178	.468	3233	-189	.0165	.902	-166	.0197	1.08	-177
.40	23.3	.00293	-25	.336	2320	-226	.389	2685	-230	.0144	.788	-201	.0167	.913	-205
.50	21.4	.00269	-27	.288	1990	-258	.322	2206	-260	.0135	.738	-231	.0150	.820	-233
.60	18.9	.00238	-32	.272	2720	-285	.277	1910	-289	.0144	.788	-253	.0147	.804	-257
.70	17.0	.00214	-33	.248	1710	-307	.179	1240	-313	.0146	.798	-274	.0105	.574	-280
.80	16.7	.00210	-30	.240	1650	-322	.217	1497	-384	.0144	.788	-292	.0130	.711	-354
.90	15.8	.00199	-29	.227	1570	-339	.223	1539	-360	.0144	.788	-310	.0141	.771	-331
1.0	16.6	.00209	-28	.228	1570	-355	.217	1497	-383	.0137	.749	-327	.0131	.716	-355
1.2	16.1	.00203	-24	.192	1320	-385	.198	1363	-435	.0119	.650	-361	.0123	.673	-411
1.4	16.8	.00212	-23	.134	930	-420	.189	1302	-496	.00797	.436	-397	.0113	.618	-473
1.6	18.9	.00238	-25	.080	551	-454	.187	1291	-555	.00423	.231	-429	.00989	.541	-530
1.8	18.7	.00236	-31	.011	74	-570	.165	1136	-622	.000588	.0321	-539	.00882	.482	-591
2.0	19.1	.00241	-34	.049	342	-670	.149	1033	-684	.00256	.140	-636	.00780	.427	-650
2.2	17.9	.00225	-38	.075	518	-700	.124	857	-749	.00419	.229	-662	.00693	.379	-711
2.4	17.4	.00219	-39	.086	596	-717	.089	620	-814	.00494	.270	-678	.00511	.279	-775
2.6	17.5	.00220	-41	.080	552	-727	.081	558	-883	.00457	.250	-686	.00463	.253	-842
2.8	17.2	.00217	-43	.075	518	-732	.075	516	-957	.0044	.241	-689	.00436	.238	-914
3.0	17.6	.00222	-45	.070	485	-735	.087	599	-1030	.00397	.217	-690	.00494	.270	-986
3.2	17.4	.00219	-46	.064	441	-735	.094	650	-1081	.00368	.201	-689	.00540	.295	-1035
3.4	17.5	.00220	-48	.061	419	-732	.093	640	-1131	.00348	.190	-684	.00531	.290	-1083
3.6	17.3	.00218	-50	.064	441	-729	.097	671	-1192	.00370	.202	-679	.00561	.307	-1142
3.8	17.4	.00219	-52	.069	480	-727	.082	568	-1232	.00396	.217	-675	.00471	.258	-1180
4.0	18.3	.00231	-54	.075	518	-728	.064	441	-1291	.00410	.224	-674	.00350	.191	-1237

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(c) Orifice exit restriction, 1/4 inch (6.35 mm); run 3; Freon flow rate, 158 pounds per hour (0.020 kg/sec); boiler condition, superheat (9.3° F or 5.2 K); inlet water temperature, 210° F (372 K)

Frequency, f, Hz	Perturbation data									Boiler inlet impedance			Transfer impedance		
	Freon flow at boiler inlet			Pressure at boiler inlet			Pressure at boiler exit			Magnitude, $\left\|\frac{\Delta P_{in}}{\Delta W_{in}}\right\|$		Phase $\varphi_{\Delta P_{in}} - \varphi_{\Delta W_{in}}$, deg	Magnitude, $\left\|\frac{\Delta P_{out}}{\Delta W_{in}}\right\|$		Phase, $\varphi_{\Delta P_{out}} - \varphi_{\Delta W_{in}}$, deg
	Magnitude,[a] $\|\Delta W_{in}\|$		Phase relative to oscillator, $\varphi_{\Delta W_{in}}$, deg	Magnitude,[a] $\|\Delta P_{in}\|$		Phase relative to oscillator, $\varphi_{\Delta P_{in}}$, deg	Magnitude,[a] $\|\Delta P_{out}\|$		Phase relative to oscillator, $\varphi_{\Delta P_{out}}$, deg						
	lb/hr	kg/sec		psi	N/m²		psi	N/m²		psi/(lb/hr)	(N/m²)/(kg/sec)		psi/(lb/hr)	(N/m²)/(kg/sec)	
0.04	6.31	0.000795	4	0.624	4300	-17	0.517	3563	-19	0.0989	5.41×10^6	-21	0.0819	4.49×10^6	-23
.08	6.70	.000844	13	.632	4360	-26	.532	3666	-28	.0943	5.16	-39	.0794	4.34	-41
.10	7.16	.000902	18	.648	4470	-31	.554	3821	-34	.0905	4.95	-49	.0774	4.24	-52
.20	10.7	.00135	40	.768	5290	-49	.644	4440	-57	.0718	3.93	-89	.0602	3.30	-97
.30	11.7	.00147	46	.640	4410	-76	.502	3459	-86	.0547	2.99	-122	.0429	2.36	-132
.40	21.6	.00272	37	1.01	6950	-108	.697	4802	-120	.0467	2.55	-145	.0323	1.77	-157
.50	35.9	.00452	8	1.38	9540	-163	.689	4751	-165	.0384	2.10	-171	.0192	1.05	-173
.60	32.0	.00403	-35	1.10	7610	-216	.659	4544	-228	.0344	1.88	-181	.0206	1.42	-183
.70	35.4	.00446	-44	1.03	7110	-243	.712	4906	-243	.0291	1.59	-199	.0201	1.10	-199
.80	30.2	.00380	-49	.828	5710	-257	.569	3924	-259	.0274	1.50	-208	.0188	1.04	-210
.90	26.4	.00333	-51	.704	4850	-269	.524	3615	-271	.0267	1.46	-218	.0198	1.10	-220
1.0	23.3	.00293	-51	.600	4140	-281	.449	3098	-282	.0257	1.41	-230	.0193	1.07	-231
1.2	19.6	.00246	-52	.480	3310	-300	.367	2530	-305	.0245	1.34	-248	.0187	1.04	-253
1.4	18.7	.00236	-49	.456	3140	-315	.344	2375	-323	.0244	1.33	-266	.0184	1.03	-274
1.6	16.8	.00212	-49	.432	2980	-332	.337	2324	-341	.0257	1.40	-283	.0201	1.12	-292
1.8	15.0	.00189	-44	.408	2810	-351	.334	2303	-363	.0272	1.49	-307	.0223	1.26	-319
2.0	13.5	.00170	-39	.416	2870	-368	.352	2427	-382	.0308	1.68	-329	.0261	1.47	-343
2.2	12.6	.00159	-33	.432	2980	-371	.374	2582	-396	.0343	1.87	-336	.0297	1.69	-363
2.4	13.2	.00166	-23	.444	3060	-406	.442	3047	-425	.0336	1.84	-383	.0335	1.92	-402
2.6	16.9	.00213	-13	.472	3250	-440	.532	3666	-457	.0279	1.53	-427	.0315	1.82	-444
2.7	11.3	.00142	-21	.292	2010	-453	.329	2272	-472	.0258	1.41	-432	.0291	1.69	-451
2.8	21.7	.00273	-15	.531	3660	-446	.599	4131	-455	.0245	1.34	-431	.0276	1.61	-440
2.9	15.6	.00196	-37	.244	1680	-528	.344	2375	-541	.0156	.854	-491	.0221	1.30	-504
2.91	25.6	.00322	-25	.563	3880	-449	.652	4492	-472	.0220	1.20	-424	.0255	1.48	-447
3.0	16.6	.00209	-56	.224	1540	-550	.337	2324	-563	.0135	.738	-494	.0203	1.19	-507
3.1	16.2	.00204	-53	.184	1270	-557	.315	2169	-576	.0113	.618	-504	.0194	1.14	-523
3.2	26.3	.00331	-48	.344	2370	-563	.577	3976	-562	.0131	.716	-515	.0219	1.30	-514
3.4	24.2	.00304	-53	.184	1270	-635	.397	2737	-603	.00760	.416	-582	.0164	.984	-550
3.6	23.2	.00292	-57	.224	1540	-626	.315	2169	-627	.00965	.523	-569	.0136	.816	-570
3.8	21.1	.00265	-59	.149	1030	-673	.225	1549	-664	.00706	.386	-614	.0107	.650	-605
4.0	19.8	.00249	-67	.164	1130	-699	.184	1271	-693	.00828	.453	-632	.00929	.569	-626

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(d) Orifice exit restriction, 1/4 inch (6.35 mm); run 4; Freon flow rate, 129 pounds per hour (0.016 kg/sec); boiler exit condition, superheat (21.3° F or 11.8 K); inlet water temperature, 210° F (372 K)

Frequency, f, Hz	Perturbation data: Freon flow at boiler inlet, Magnitude,[a] $\lvert\Delta W_{in}\rvert$, lb/hr	kg/sec	Phase relative to oscillator, $\varphi_{\Delta W_{in}}$, deg	Pressure at boiler inlet, Magnitude,[a] $\lvert\Delta P_{in}\rvert$, psi	N/m²	Phase relative to oscillator, $\varphi_{\Delta P_{in}}$, deg	Pressure at boiler exit, Magnitude,[a] $\lvert\Delta P_{out}\rvert$, psi	N/m²	Phase relative to oscillator, $\varphi_{\Delta P_{out}}$, deg	Boiler inlet impedance: Magnitude, $\left\lvert\frac{\Delta P_{in}}{\Delta W_{in}}\right\rvert$, psi/(lb/hr)	(N/m²)/(kg/sec)	Phase, $\varphi_{\Delta P_{in}} - \varphi_{\Delta W_{in}}$, deg	Transfer impedance: Magnitude, $\left\lvert\frac{\Delta P_{out}}{\Delta W_{in}}\right\rvert$, psi/(lb/hr)	(N/m²)/(kg/sec)	Phase, $\varphi_{\Delta P_{out}} - \varphi_{\Delta W_{in}}$, deg
0.04	6.33	0.000797	0	0.320	2210	-6	0.285	1962	-13	0.0506	2.77×10^6	-6	0.0450	2.46×10^6	-13
.06	6.51	.000820	1	.349	2410	-17	.291	2003	-17	.0536	2.93	-18	.0447	2.44	-18
.08	6.61	.000832	5	.352	2430	-16	.294	2024	-20	.0533	2.91	-21	.0445	2.43	-25
.10	6.68	.000842	9	.352	2430	-21	.299	2065	-22	.0527	2.88	-30	.0448	2.45	-31
.20	7.91	.000997	23	.392	2700	-37	.322	2221	-42	.0495	2.71	-60	.0407	2.23	-65
.30	10.2	.00128	33	.440	3030	-55	.337	2324	-51	.0431	2.36	-88	.0330	1.81	-84
.40	14.1	.00177	37	.528	3640	-74	.374	2582	-68	.0374	2.05	-111	.0265	1.45	-105
.50	19.7	.00248	32	.628	4330	-96	.419	2891	-99	.0319	1.74	-128	.0213	1.16	-131
.60	25.2	.00317	22	.688	4740	-114	.469	3232	-122	.0273	1.49	-136	.0186	1.02	-144
.70	30.4	.00383	-6	.720	4960	-151	.487	3357	-150	.0237	1.30	-157	.0160	.885	-156
.80	30.9	.00389	-9	.672	4630	-178	.464	3202	-176	.0217	1.19	-169	.0150	.820	-165
.90	29.5	.00372	-22	.752	5180	-196	.412	2840	-194	.0255	1.39	-174	.0140	.766	-172
1.0	27.5	.00346	-30	.512	3530	-216	.367	2530	-212	.0186	1.02	-186	.0133	.727	-182
1.25	22.3	.00281	-43	.352	2430	-250	.262	1808	-249	.0158	.864	-207	.0117	.640	-206
1.50	19.1	.00241	-48	.288	1990	-267	.225	1549	-268	.0151	.825	-219	.0118	.645	-220
1.75	16.7	.00210	-53	.240	1650	-279	.195	1342	-292	.0144	.787	-226	.0117	.640	-239
2.00	15.2	.00191	-52	.216	1490	-306	.174	1198	-312	.0142	.777	-258	.0114	.623	-260
2.25	13.7	.00173	-57	.196	1350	-324	.165	1136	-333	.0143	.782	-267	.0120	.656	-276
2.50	12.6	.00159	-54	.182	1250	-339	.166	1147	-350	.0144	.788	-285	.0132	.722	-296
2.75	11.5	.00145	-54	.168	1160	-358	.165	1136	-372	.0146	.799	-304	.0143	.782	-318
3.00	11.4	.00144	-49	.162	1120	-376	.175	1209	-395	.0142	.777	-327	.0154	.842	-346
3.25	11.2	.00141	-47	.142	982	-398	.175	1209	-420	.0127	.695	-351	.0156	.853	-373
3.50	12.3	.00155	-43	.120	827	-418	.179	1240	-443	.00976	.534	-375	.0146	.799	-400
3.75	14.0	.00176	-45	.076	524	-467	.162	1116	-464	.00543	.297	-422	.0116	.634	-419
4.00	14.8	.00186	-49	.046	320	-468	.148	1022	-504	.00311	.170	-419	.0100	.547	-455

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(e) Orifice exit restriction, 1/4 inch (6.35 mm); run 5; Freon flow rate, 189 pounds per hour (0.024 kg/sec); boiler exit condition, superheat (10.7° F or 6 K); inlet water temperature, 230° F (383 K)

Frequency, f, Hz	Perturbation data: Freon flow at boiler inlet, Magnitude,[a] $\lvert \Delta W_{in} \rvert$, lb/hr	Freon flow at boiler inlet, Magnitude,[a] $\lvert \Delta W_{in} \rvert$, kg/sec	Freon flow at boiler inlet, Phase relative to oscillator, $\varphi_{\Delta W_{in}}$, deg	Pressure at boiler inlet, Magnitude,[a] $\lvert \Delta P_{in} \rvert$, psi	Pressure at boiler inlet, Magnitude,[a] $\lvert \Delta P_{in} \rvert$, N/m²	Pressure at boiler inlet, Phase relative to oscillator, $\varphi_{\Delta P_{in}}$, deg	Pressure at boiler exit, Magnitude,[a] $\lvert \Delta P_{out} \rvert$, psi	Pressure at boiler exit, Magnitude,[a] $\lvert \Delta P_{out} \rvert$, N/m²	Pressure at boiler exit, Phase relative to oscillator, $\varphi_{\Delta P_{out}}$, deg	Boiler inlet impedance: Magnitude, $\left\lvert \frac{\Delta P_{in}}{\Delta W_{in}} \right\rvert$, psi/(lb/hr)	Boiler inlet impedance: Magnitude, $\left\lvert \frac{\Delta P_{in}}{\Delta W_{in}} \right\rvert$, (N/m²)/(kg/sec)	Boiler inlet impedance: Phase, $\varphi_{\Delta P_{in}} - \varphi_{\Delta W_{in}}$, deg	Transfer impedance: Magnitude, $\left\lvert \frac{\Delta P_{out}}{\Delta W_{in}} \right\rvert$, psi/(lb/hr)	Transfer impedance: Magnitude, $\left\lvert \frac{\Delta P_{out}}{\Delta W_{in}} \right\rvert$, (N/m²)/(kg/sec)	Transfer impedance: Phase, $\varphi_{\Delta P_{out}} - \varphi_{\Delta W_{in}}$, deg
0.04	8.64	0.00109	7	0.808	5570	-17	0.779	5370	-18	0.0935	5.11×10^{6}	-24	0.0902	4.93×10^{6}	-25
.06	8.89	.00112	10	.792	5460	-24	.786	5422	-26	.0891	4.87	-34	.0884	4.83	-36
.08	9.17	.00116	14	.808	5570	-33	.779	5370	-33	.0881	4.82	-47	.0849	4.64	-47
.10	9.88	.00124	19	.824	5680	-40	.806	5556	-40	.0834	4.56	-59	.0816	4.46	-59
.20	14.1	.00178	24	.880	6070	-74	.846	5835	-74	.0624	3.41	-98	.0600	3.28	-98
.30	19.4	.00244	15	.944	6510	-114	.839	5783	-122	.0487	2.66	-129	.0432	2.36	-137
.40	21.9	.00276	-2	.856	5900	-154	.726	5008	-160	.0391	2.14	-152	.0332	1.82	-158
.50	21.9	.00276	-4	.745	5130	-183	.614	4234	-179	.0340	1.86	-179	.0280	1.53	-175
.60	20.4	.00257	-10	.592	4080	-204	.509	3511	-203	.0290	1.59	-194	.0249	1.36	-193
.70	19.1	.00240	-20	.520	3580	-226	.434	2995	-225	.0272	1.49	-206	.0227	1.24	-205
.80	17.9	.00225	-23	.464	3200	-238	.397	2737	-236	.0259	1.42	-215	.0222	1.21	-213
.90	17.0	.00214	-26	.440	3030	-252	.359	2478	-250	.0259	1.42	-226	.0211	1.15	-224
1.0	17.0	.00214	-27	.392	2700	-264	.359	2478	-265	.0231	1.26	-237	.0211	1.15	-238
1.25	15.4	.00194	-24	.344	2370	-287	.315	2169	-292	.0223	1.22	-263	.0204	1.12	-268
1.50	15.3	.00193	-23	.336	2320	-305	----	----	----	.0220	1.20	-282	-----	----	----
1.75	12.9	.00162	-32	.328	2260	-341	.318	2190	-353	.0254	1.39	-309	.0246	1.34	-321
2.00	12.2	.00154	-29	.356	2450	-366	.344	2375	-380	.0292	1.60	-337	.0283	1.55	-351
2.25	11.6	.00146	-24	.360	2480	-404	.382	2634	-423	.0310	1.70	-380	.0329	1.80	-399
2.50	14.4	.00181	-20	.304	2100	-465	.415	2861	-479	.0211	1.15	-445	.0288	1.57	-459
2.75	16.2	.00204	-18	.224	1540	-507	.325	2241	-530	.0138	.755	-489	.0201	1.10	-512
3.00	17.0	.00214	-26	.160	1100	-561	.344	2375	-576	.00941	.515	-535	.0202	1.10	-550
3.25	15.8	.00199	-31	.128	882	-617	.217	1497	-620	.00810	.443	-586	.0137	.750	-589
3.50	15.1	.00190	-33	.116	799	-671	.153	1053	-680	.00768	.420	-638	.0101	.552	-647
3.75	14.5	.00183	-35	.116	799	-693	.135	929	-711	.00800	.438	-658	.0093	.509	-676
4.00	14.7	.00185	-33	.092	634	-736	.131	904	-748	.00626	.342	-703	.0089	.487	-715

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(f) Orifice exit restriction, 1/4 inch (6.35 mm); run 6; Freon flow rate, 177 pounds per hour (0.022 kg/sec); boiler exit condition, superheat (19.6° F or 10.9 K); inlet water temperature, 230° F (383 K)

Frequency, f, Hz	Perturbation data									Boiler inlet impedance			Transfer impedance		
	Freon flow at boiler inlet			Pressure at boiler inlet			Pressure at boiler exit			Magnitude, $\left\|\frac{\Delta P_{in}}{\Delta W_{in}}\right\|$		Phase, $\varphi_{\Delta P_{in}} - \varphi_{\Delta W_{in}}$, deg	Magnitude, $\left\|\frac{\Delta P_{out}}{\Delta W_{in}}\right\|$		Phase, $\varphi_{\Delta P_{out}} - \varphi_{\Delta W_{in}}$, deg
	Magnitude,[a] $\|\Delta W_{in}\|$		Phase relative to oscillator, $\varphi_{\Delta W_{in}}$, deg	Magnitude,[a] $\|\Delta P_{in}\|$		Phase relative to oscillator, $\varphi_{\Delta P_{in}}$, deg	Magnitude,[a] $\|\Delta P_{out}\|$		Phase relative to oscillator, $\varphi_{\Delta P_{out}}$, deg						
	lb/hr	kg/sec		psi	N/m^2		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.04	16.0	0.00202	-3	1.64	11 300	-21	1.68	11 570	-20	0.102	5.58×10^6	-18	0.105	5.74×10^6	-17
.06	16.5	.00208	-2	1.64	11 300	-26	1.68	11 570	-28	.0994	5.44	-24	.102	5.58	-26
.08	16.7	.00210	-2	1.62	11 100	-33	1.65	11 360	-36	.0970	5.31	-31	.0988	5.40	-34
.10	16.5	.00208	-2	1.64	11 300	-39	1.66	11 465	-43	.0994	5.44	-37	.101	5.52	-41
.20	20.4	.00257	7	1.69	11 700	-68	1.59	10 950	-78	.0828	4.53	-75	.0780	4.27	-85
.30	25.5	.00321	5	1.72	11 900	-101	1.42	9 790	-112	.0674	3.69	-106	.0557	3.05	-117
.40	29.1	.00367	-2	1.60	11 000	-130	1.19	8 260	-141	.0550	3.01	-128	.0409	2.24	-139
.50	30.5	.00384	-7	1.42	9 790	-159	.98	6 816	-165	.0465	2.54	-152	.0321	1.76	-148
.60	30.5	.00384	-13	1.26	8 690	-175	.85	5 887	-180	.0413	2.26	-162	.0279	1.53	-167
.70	29.6	.00373	-18	1.10	7 580	-195	.76	5 267	-196	.0372	2.03	-177	.0257	1.41	-178
.80	29.1	.00367	-22	1.00	6 890	-211	.79	5 474	-205	.0344	1.88	-189	.0271	1.48	-183
.90	28.7	.00361	-23	.92	6 340	-220	.73	5 060	-216	.0321	1.76	-197	.0254	1.39	-193
1.0	28.2	.00355	-24	.84	5 790	-227	.69	4 751	-224	.0298	1.63	-203	.0245	1.34	-200
1.2	27.0	.00340	-28	.76	5 210	-248	.63	4 338	-244	.0281	1.54	-220	.0233	1.27	-216
1.4	26.1	.00329	-36	.69	4 750	-267	.61	4 234	-262	.0264	1.44	-231	.0234	1.28	-226
1.6	25.6	.00322	-33	.67	4 610	-278	.58	3 976	-279	.0262	1.43	-245	.0226	1.24	-246
1.8	24.8	.00312	-34	.66	4 550	-292	.55	3 770	-293	.0266	1.45	-258	.0222	1.21	-259
2.0	24.0	.00302	-36	.67	4 610	-307	.58	3 976	-310	.0279	1.53	-271	.0242	1.32	-274
2.2	23.5	.00296	-38	.69	4 750	-319	.61	4 234	-324	.0293	1.60	-281	.0259	1.42	-286
2.4	22.6	.00285	-38	.71	4 890	-328	.66	4 550	-333	.0314	1.72	-290	.0292	1.60	-295
2.6	21.8	.00275	-39	.76	5 270	-343	.73	5 060	-350	.0349	1.91	-304	.0335	1.83	-311
2.8	20.4	.00257	-40	.82	5 650	-359	.83	5 732	-366	.0402	2.20	-319	.0407	2.23	-326
3.0	20.5	.00258	-38	.89	6 120	-376	.96	6 609	-386	.0434	2.37	-338	.0468	2.56	-348
3.1	19.7	.00248	-34	.95	6 560	-395	1.03	7 135	-407	.0482	2.64	-361	.0523	2.86	-373
3.2	19.7	.00248	-35	.98	6 730	-409	1.12	7 749	-424	.0497	2.72	-374	.0568	3.11	-389
3.3	20.3	.00256	-39	.96	6 620	-419	1.15	7 956	-427	.0473	2.59	-380	.0566	3.10	-388
3.4	20.6	.00259	-39	.96	6 620	-430	1.17	8 052	-448	.0466	2.55	-391	.0568	3.11	-409
3.5	22.0	.00277	-28	.89	6 180	-453	1.14	7 852	-466	.0404	2.21	-425	.0518	2.83	-438
3.6	23.6	.00297	-29	.88	6 070	-467	1.14	7 852	-482	.0373	2.04	-438	.0483	2.64	-453
3.7	24.3	.00306	-30	.78	5 370	-479	1.11	7 646	-491	.0321	1.76	-449	.0457	2.50	-461
3.8	26.1	.00329	-32	.68	4 690	-505	1.03	7 128	-514	.0260	1.42	-473	.0395	2.16	-482
4.0	27.2	.00343	-39	.46	3 170	-552	.79	5 474	-552	.0169	.924	-514	.0290	1.59	-513
4.2	26.5	.00334	-43	.33	2 280	-588	.61	4 234	-583	0124	.678	-545	.0230	1.26	-540
4.4	25.6	.00323	-46	.27	1 860	-623	.46	3 202	-609	.0105	.574	-577	.0180	.985	-563
4.6	25.3	.00319	-48	.26	1 770	-644	.42	2 891	-644	.0103	.563	-596	.0166	.908	-596

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(g) Orifice exit restriction, 1/4 inch (6.35 mm); run 7; Freon flow rate, 228 pounds per hour (0.029 kg/sec); boiler exit condition, χ = 100 percent; inlet water temperature, 250° F (394 K)

Frequency, f, Hz	Perturbation data: Freon flow at boiler inlet: Magnitude,[a] $\lvert\Delta W_{in}\rvert$, lb/hr	Magnitude,[a] $\lvert\Delta W_{in}\rvert$, kg/sec	Phase relative to oscillator, $\varphi_{\Delta W_{in}}$, deg	Pressure at boiler inlet: Magnitude,[a] $\lvert\Delta P_{in}\rvert$, psi	Magnitude,[a] $\lvert\Delta P_{in}\rvert$, N/m²	Phase relative to oscillator, $\varphi_{\Delta P_{in}}$, deg	Pressure at boiler exit: Magnitude,[a] $\lvert\Delta P_{out}\rvert$, psi	Magnitude,[a] $\lvert\Delta P_{out}\rvert$, N/m²	Phase relative to oscillator, $\varphi_{\Delta P_{out}}$, deg	Boiler inlet impedance: Magnitude, $\left\lvert\frac{\Delta P_{in}}{\Delta W_{in}}\right\rvert$, psi/(lb/hr)	Magnitude, (N/m²)/(kg/sec)	Phase, $\varphi_{\Delta P_{in}} - \varphi_{\Delta W_{in}}$, deg	Transfer impedance: Magnitude, $\left\lvert\frac{\Delta P_{out}}{\Delta W_{in}}\right\rvert$, psi/(lb/hr)	Magnitude, (N/m²)/(kg/sec)	Phase, $\varphi_{\Delta P_{out}} - \varphi_{\Delta W_{in}}$, deg
0.04	22.0	0.00277	13	2.08	14 300	-12	2.13	14 660	-12	0.0945	5.17×10⁶	-25	0.0968	5.29×10⁶	-25
.06	23.1	.00291	19	2.11	14 600	-19	1.92	13 220	-20	.0913	4.99	-38	.0831	4.55	-39
.08	24.9	.00314	23	2.16	14 900	-5	2.26	15 590	-27	.0867	4.74	-28	.0908	4.97	-50
.10	26.4	.00333	29	2.18	15 000	-31	2.26	15 590	-35	.0826	4.52	-60	.0856	4.68	-64
.20	40.9	.00515	38	2.46	17 000	-63	2.49	17 150	-76	.0601	3.29	-101	.0609	3.33	-114
.30	59.9	.00755	29	2.70	18 640	-101	2.41	16 630	-115	.0451	2.47	-130	.0402	2.20	-144
.40	70.9	.00893	14	2.64	18 200	-145	2.17	14 970	-159	.0372	2.03	-159	.0306	1.67	-173
.50	72.7	.00916	-1	2.48	17 100	-178	2.01	13 840	-186	.0341	1.86	-177	.0276	1.51	-185
.60	67.7	.00853	-11	2.14	14 780	-205	1.66	11 470	-213	.0316	1.73	-194	.0245	1.34	-202
.70	62.8	.00791	-16	1.86	12 800	-224	1.49	10 330	-226	.0296	1.62	-208	.0237	1.30	-210
.80	55.7	.00702	-20	1.57	10 810	-241	1.33	9 190	-241	.0282	1.54	-221	.0239	1.31	-221
.90	40.9	.00515	-22	1.34	9 270	-256	1.18	8 156	-257	.0328	1.79	-234	.0288	1.57	-235
.90	53.6	.00675	-21	1.42	9 820	-251	1.33	9 190	-249	.0265	1.45	-230	.0248	1.36	-228
1.00	49.8	.00627	-23	1.31	9 040	-267	1.18	8 107	-268	.0263	1.44	-244	.0237	1.30	-245
1.24	43.3	.00546	-22	1.17	8 050	-292	1.06	7 335	-294	.0270	1.48	-270	.0245	1.34	-272
1.50	39.2	.00494	-23	1.09	7 500	-311	1.04	7 177	-316	.0278	1.52	-288	.0265	1.45	-293
1.75	35.4	.00446	-24	1.09	7 500	-330	1.09	7 500	-337	.0308	1.68	-306	.0308	1.68	-314
2.00	32.9	.00414	-17	1.14	7 830	-355	1.17	8 052	-367	.0346	1.89	-338	.0356	1.95	-350
2.25	33.1	.00417	-10	1.09	7 560	-388	1.06	7 335	-412	.0329	1.80	-378	.0320	1.75	-402
2.50	40.9	.00515	-2	1.02	7 060	-425	1.13	7 797	-450	.0249	1.36	-423	.0276	1.51	-448
2.75	48.4	.00610	-11	.66	4 520	-492	.70	4 854	-520	.0136	.74	-481	.0145	.79	-509
3.00	50.7	.00639	-19	.40	2 760	-571	.59	4 131	-571	.0079	.43	-552	.0116	.63	-552
3.25	46.2	.00502	-26	.38	2 650	-629	.56	3 873	-620	.0082	.45	-603	.0121	.66	-594
3.50	43.5	.00548	-26	.40	2 760	-671	.49	3 357	-671	.0092	.50	-645	.0113	.62	-645
3.75	41.3	.00520	-27	.39	2 700	-704	.45	3 098	-709	.0094	.51	-677	.0109	.60	-682
4.00	43.5	.00548	-24	.30	2 070	-745	.38	2 608	-773	.0069	.38	-721	.0087	.47	-749

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(h) Orifice exit restriction, 1/4 inch (6.35 mm); run 8; Freon flow rate, 209 pounds per hour (0.026 kg/sec); boiler exit condition, superheat (11.3° F or 6.3 K); inlet water temperature, 250° F (394 K)

Frequency, f, Hz	Perturbation data									Boiler inlet impedance			Transfer impedance		
	Freon flow at boiler inlet			Pressure at boiler inlet			Pressure at boiler exit			Magnitude, $\left\lvert\frac{\Delta P_{in}}{\Delta W_{in}}\right\rvert$		Phase, $\varphi_{\Delta P_{in}} - \varphi_{\Delta W_{in}}$, deg	Magnitude, $\left\lvert\frac{\Delta P_{out}}{\Delta W_{in}}\right\rvert$		Phase, $\varphi_{\Delta P_{out}} - \varphi_{\Delta W_{in}}$, deg
	Magnitude,[a] $\lvert\Delta W_{in}\rvert$		Phase relative to oscillator, $\varphi_{\Delta W_{in}}$, deg	Magnitude,[a] $\lvert\Delta P_{in}\rvert$		Phase relative to oscillator, $\varphi_{\Delta P_{in}}$, deg	Magnitude,[a] $\lvert\Delta P_{out}\rvert$		Phase relative to oscillator, $\varphi_{\Delta P_{out}}$, deg						
	lb/hr	kg/sec		psi	N/m^2		psi	N/m^2		psi/(lb/hr)	$(N/m^2)/(kg/sec)$		psi/(lb/hr)	$(N/m^2)/(kg/sec)$	
0.04	12.7	0.00160	12	1.36	9 380	-9	1.53	10 530	-10	0.107	5.85×10^6	-21	0.120	6.56×10^6	-22
.06	13.2	.00166	17	1.44	9 930	-14	1.53	10 530	-15	.109	5.96	-31	.116	6.34	-32
.08	13.2	.00166	22	1.42	9 820	-18	1.53	10 530	-21	.108	5.91	-40	.116	6.34	-43
.10	14.5	.00182	28	1.44	9 930	-23	1.57	10 840	-27	.0993	5.43	-51	.108	5.91	-55
.20	21.2	.00267	44	1.69	11 700	-46	1.74	11 980	-55	.0797	4.36	-90	.0821	4.49	-99
.30	33.9	.00427	43	2.06	14 200	-77	1.92	13 220	-88	.0608	3.32	-120	.0566	3.10	-131
.40	47.7	.00601	32	2.40	16 500	-110	2.04	14 040	-121	.0503	2.75	-142	.0428	2.34	-153
.50	57.2	.00721	13	2.32	16 000	-149	1.87	12 910	-158	.0405	2.21	-162	.0327	1.79	-171
.60	55.8	.00703	-4	2.02	13 900	-183	1.56	10 740	-188	.0362	1.98	-179	.0279	1.53	-184
.70	49.8	.00627	-14	1.65	11 400	-206	1.33	9 190	-205	.0331	1.81	-192	.0267	1.46	-191
.80	44.5	.00561	-19	1.38	9 490	-222	1.14	7 852	-220	.0310	1.69	-203	.0756	1.40	-201
.90	40.9	.00515	-23	1.17	8 050	-235	1.05	7 232	-234	.0286	1.56	-212	.0257	1.41	-211
1.00	37.6	.00474	-25	1.06	7 280	-250	.91	6 300	-248	.0282	1.54	-250	.0242	1.32	-223
1.25	32.0	.00403	-30	.84	5 790	-274	.77	5 319	-273	.0262	1.43	-244	.0241	1.32	-243
1.50	29.2	.00367	-29	.75	5 180	-291	.70	4 802	-294	.0257	1.41	-262	.0240	1.31	-265
1.75	26.8	.00337	-31	.72	4 960	-308	.67	4 596	-314	.0269	1.47	-277	.0250	1.37	-283
2.00	24.4	.00307	-28	.73	5 020	-325	.69	4 751	-335	.0299	1.64	-297	.0283	1.55	-307
2.25	21.7	.00273	-27	.75	5 180	-347	.72	4 964	-360	.0346	1.89	-320	.0332	1.82	-333
2.50	20.4	.00257	-18	.82	5 630	-370	.81	5 577	-385	.0402	2.20	-352	.0397	2.17	-367
2.75	20.8	.00262	-10	.82	5 630	-400	.46	3 150	-415	.0394	2.16	-390	.0221	1.21	-405
3.00	27.9	.00352	-2	.82	5 630	-444	.52	3 615	-366	.0294	1.61	-442	.0186	1.02	-364
3.25	34.0	.00428	-10	.67	4 630	-491	.99	6 816	-510	.0197	1.08	-481	.0291	1.59	-500
3.50	36.2	.00456	-21	.48	3 310	-544	.75	5 164	-557	.0132	.72	-523	.0207	1.13	-536
3.75	33.2	.00418	-31	.40	2 760	-590	.63	4 338	-587	.0120	.66	-559	.0190	1.04	-556
4.00	31.9	.00402	-35	.31	2 150	-640	.35	2 427	-629	.0097	.53	-605	.0110	.60	-594

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(i) Orifice exit restriction, 3/16 inch (4.76 mm); run 9; Freon flow rate, 426 pounds per hour (0.0535 kg/sec); boiler exit condition, χ = 12 percent; inlet water temperature, 213° F (374 K)

Frequency, f, Hz	Perturbation data: Freon flow at boiler inlet: Magnitude,[a] $\lvert\Delta W_{in}\rvert$, lb/hr	Magnitude,[a] $\lvert\Delta W_{in}\rvert$, kg/sec	Phase relative to oscillator, $\varphi_{\Delta W_{in}}$, deg	Pressure at boiler inlet: Magnitude,[a] $\lvert\Delta P_{in}\rvert$, psi	Magnitude,[a] $\lvert\Delta P_{in}\rvert$, N/m²	Phase relative to oscillator, $\varphi_{\Delta P_{in}}$, deg	Pressure at boiler exit: Magnitude,[a] $\lvert\Delta P_{out}\rvert$, psi	Magnitude,[a] $\lvert\Delta P_{out}\rvert$, N/m²	Phase relative to oscillator, $\varphi_{\Delta P_{out}}$, deg	Boiler inlet impedance: Magnitude, $\lvert\Delta P_{in}/\Delta W_{in}\rvert$, psi/(lb/hr)	Magnitude, $\lvert\Delta P_{in}/\Delta W_{in}\rvert$, (N/m²)/(kg/sec)	Phase, $\varphi_{\Delta P_{in}} - \varphi_{\Delta W_{in}}$, deg	Transfer impedance: Magnitude, $\lvert\Delta P_{out}/\Delta W_{in}\rvert$, psi/(lb/hr)	Magnitude, $\lvert\Delta P_{out}/\Delta W_{in}\rvert$, (N/m²)/(kg/sec)	Phase, $\varphi_{\Delta P_{out}} - \varphi_{\Delta W_{in}}$, deg
0.04	60.3	0.00760	-6	0.584	4030	148	0.829	5720	158	0.00968	0.53×10⁶	154	0.0138	0.755×10⁶	164
.06	60.3	.00760	-9	.608	4190	144	.816	5630	152	.0101	.553	153	.0135	.739	161
.08	60.3	.00760	-10	.624	4310	138	.816	5630	148	.0104	.569	148	.0135	.739	158
.10	62.7	.00790	-11	.640	4420	130	.790	5450	140	.0102	.558	141	.0126	.690	151
.20	61.3	.00771	-12	.744	5130	89	.734	5100	108	.0121	.662	101	.0121	.662	120
.30	58.8	.00740	-12	.776	5350	53	.650	4480	71	.0132	.722	65	.0111	.608	83
.40	56.4	.00710	-12	.736	5080	20	.510	3510	30	.0131	.717	32	.00904	.495	42
.50	57.9	.00728	-11	.776	5350	-10	.369	2540	-18	.0134	.733	-1	.00637	.349	-7
.60	60.3	.00759	-12	.400	2760	-39	.268	1850	-80	.00663	.363	-27	.00444	.243	-68
.70	62.7	.00789	-12	.160	1100	-64	.274	1890	-146	.00255	.140	-52	.00437	.240	-134
.80	61.8	.00777	-14	.08	552	92	.325	2240	163	.00129	.0706	-254	.00526	.288	-183
.90	61.3	.00771	-15	.288	1990	72	.389	2680	122	.00470	.257	-273	.00635	.348	-223
1.00	60.3	.00759	-15	.472	3260	52	.433	2990	84	.00783	.429	-293	.00718	.393	-261
1.15	57.9	.00728	-18	.584	4030	19	.427	2940	31	.0101	.553	-323	.00737	.403	-311
1.25	58.8	.0074	-17	.584	4030	-2	.408	2820	-10	.00993	.544	-345	.00694	.380	-353
1.40	58.8	.0074	-15	.376	2590	-20	.255	1760	-66	.00639	.350	-365	.00434	.238	-411
1.50	60.8	.00765	-16	.248	1710	-19	.179	1230	-119	.00408	.223	-357	.00294	.161	-463
1.60	59.9	.00754	-15	.200	1380	8	.127	876	176	.00334	.183	-337	.00212	.116	-551
1.75	59.9	.00754	-19	.288	1990	22	.153	1060	86	.00481	.263	-319	.00255	.140	-615
2.00	60.1	.00758	-19	.348	2400	10	.177	1220	-15	.00579	.317	-331	.00294	.161	-716
2.15	58.8	.00740	-21	.320	2210	10	.122	842	-63	.00544	.299	-329	.00208	.113	-762
2.25	59.2	.00746	-22	.320	2210	11	.0892	615	-94	.00541	.296	-327	.00151	.0826	-792
2.50	60.4	.00761	-21	.336	2320	15	.0191	132	72	.00556	.304	-324	.000316	.0173	-987
2.75	59.4	.00749	-24	.328	2260	14	.0688	475	-32	.00552	.302	-322	.00116	.0635	-1088
3.00	59.4	.00749	-24	.352	2430	17	.0790	545	-95	.00592	.324	-319	.00133	.0728	-1151
3.25	58.6	.00739	-26	.360	2480	18	.0535	369	-169	.00614	.336	-316	.000913	.0500	-1223
3.50	62.8	.00791	-27	.408	2810	20	.0382	264	146	.00650	.356	-313	.000608	.0333	-1267
3.75	58.8	.00741	-29	.40	2760	19	.0408	281	+36	.00680	.372	-312	.000694	.0380	-1375
4.00	61.1	.0077	-29	.416	2870	20	.0395	272	-40	.00681	.373	-311	.000646	.0354	-1411

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(j) Orifice exit restriction, 3/16 inch (4.76 mm); run 10; Freon flow rate, 234 pounds per hour (0.0294 kg/sec); boiler exit condition, χ = 43 percent; inlet water temperature, 213° F (374 K)

Frequency, f, Hz	Perturbation data: Freon flow at boiler inlet: Magnitude,[a] $\lvert\Delta W_{in}\rvert$, lb/hr	Magnitude,[a] $\lvert\Delta W_{in}\rvert$, kg/sec	Phase relative to oscillator, $\varphi_{\Delta W_{in}}$, deg	Pressure at boiler inlet: Magnitude,[a] $\lvert\Delta P_{in}\rvert$, psi	Magnitude,[a] $\lvert\Delta P_{in}\rvert$, N/m²	Phase relative to oscillator, $\varphi_{\Delta P_{in}}$, deg	Pressure at boiler exit: Magnitude,[a] $\lvert\Delta P_{out}\rvert$, psi	Magnitude,[a] $\lvert\Delta P_{out}\rvert$, N/m²	Phase relative to oscillator, $\varphi_{\Delta P_{out}}$, deg	Boiler inlet impedance: Magnitude, $\left\lvert\frac{\Delta P_{in}}{\Delta W_{in}}\right\rvert$, psi/(lb/hr)	Magnitude, (N/m²)/(kg/sec)	Phase, $\varphi_{\Delta P_{in}} - \varphi_{\Delta W_{in}}$, deg	Transfer impedance: Magnitude, $\left\lvert\frac{\Delta P_{out}}{\Delta W_{in}}\right\rvert$, psi/(lb/hr)	Magnitude, (N/m²)/(kg/sec)	Phase, $\varphi_{\Delta P_{out}} - \varphi_{\Delta W_{in}}$, deg
0.04	22.1	0.00278	-5	0.352	2430	-60	0.382	2640	-68	0.0159	0.870×10⁶	-55	0.0173	0.947×10⁶	-63
.06	23.5	.00296	-5	.368	2540	-73	.421	2910	-93	.0157	.859	-68	.0179	.980	-88
.08	24.0	.00302	-5	.376	2590	-104	.459	3170	-115	.0157	.859	-99	.0191	1.05	-110
.10	25.5	.00321	-8	.424	2930	-128	.497	3430	-136	.0166	.909	-120	.0195	1.07	-128
.20	27.0	.00340	-16	.464	3200	-212	.558	3850	-210	.0172	.941	-196	.0207	1.13	-194
.30	24.5	.00308	-21	.424	2930	-264	.446	3080	-260	.0173	.947	-243	.0182	.996	-239
.40	23.1	.00291	-23	.384	2650	-308	.370	2550	-301	.0166	.909	-285	.0160	.876	-278
.50	22.1	.00278	-20	.328	2260	-340	.370	2550	-339	.0148	.810	-320	.0167	.914	-309
.60	22.1	.00278	-19	.288	1990	-372	.268	1850	-380	.0130	.712	-353	.0121	.662	-361
.70	22.6	.00284	-15	.232	1600	-403	.227	1570	-432	.0103	.564	-388	.0100	.547	-417
.80	24.0	.00302	-16	.168	1160	-442	.208	1440	-485	.007	.383	-426	.00867	.475	-469
.90	24.6	.00310	-17	.104	718	-501	.227	1570	-533	.00423	.231	-484	.00923	.505	-516
1.00	25.1	.00316	-20	.104	718	-573	.242	1670	-577	.00414	.226	-553	.00964	.528	-557
1.15	22.7	.00286	-26	.154	1060	-642	.255	1760	-640	.00678	.371	-616	.0112	.613	-614
1.25	23.2	.00292	-27	.194	1340	-688	.268	1850	-681	.00836	.457	-661	.0116	.635	-654
1.35	21.7	.00273	-26	.176	1210	-701	.227	1570	-718	.00811	.444	-675	.0105	.574	-692
1.50	23.0	.00290	-25	.134	925	-724	.127	876	-768	.00582	.318	-699	.00552	.302	-743
1.55	22.3	.00281	-26	.116	800	-727	.0918	633	-784	.00520	.284	-701	.00412	.225	-758
1.65	21.8	.00274	-27	.096	662	-724	.0338	233	-838	.00440	.241	-697	.00155	.0848	-811
1.75	22.8	.00287	-28	.092	635	-718	.00712	157	-1003	.00403	.220	-690	.00312	.171	-975
2.00	22.9	.00288	-28	.092	635	-720	.0765	528	-1109	.00401	.219	-692	.00334	.183	-1081
2.25	22.0	.00277	-24	.092	635	-704	.0510	352	-1201	.00418	.229	-680	.00232	.127	-1177
2.50	21.6	.00272	-26	.118	814	-710	.0446	308	-1342	.00546	.299	-684	.00206	.113	-1316
2.75	21.2	.00267	-28	.0984	679	-725	.0523	361	-1450	.00464	.254	-697	.00247	.135	-1422
3.00	22.3	.00281	-34	.0784	541	-705	.0535	369	-1564	.00351	.192	-671	.00240	.131	-1530
3.25	21.9	.00275	-38	.114	787	-704	.0484	334	-1685	.00521	.285	-666	.00221	.121	-1647
3.50	22.0	.00277	-37	.116	800	-716	.0459	317	-1789	.00527	.288	-679	.00209	.114	-1752
3.75	21.6	.00272	-41	.096	662	-718	.0344	237	-1870	.00444	.243	-677	.00159	.0869	-1829
4.00	21.8	.00275	-43	.110	759	-710	.0331	228	-1926	.00504	.276	-667	.00152	.0831	-1883

[a]Zero to peak.

TABLE II. - Continued. BOILER PERTURBATION DATA

(k) Orifice exit restriction, 3/16 inch (4.76 mm); run 11; Freon flow rate, 159 pounds per hour (0.02 kg/sec); boiler exit condition, χ = 100 percent; inlet water temperature, 214° F (374 K)

Frequency, f, Hz	Perturbation data									Boiler inlet impedance			Transfer impedance		
	Freon flow at boiler inlet			Pressure at boiler inlet			Pressure at boiler exit			Magnitude, $\left\|\frac{\Delta P_{in}}{\Delta W_{in}}\right\|$		Phase, $\varphi_{\Delta P_{in}} - \varphi_{\Delta W_{in}}$, deg	Magnitude, $\left\|\frac{\Delta P_{out}}{\Delta W_{in}}\right\|$		Phase, $\varphi_{\Delta P_{out}} - \varphi_{\Delta W_{in}}$, deg
	Magnitude,[a] $\|\Delta W_{in}\|$		Phase relative to oscillator, $\varphi_{\Delta W_{in}}$, deg	Magnitude,[a] $\|\Delta P_{in}\|$		Phase relative to oscillator, $\varphi_{\Delta P_{in}}$, deg	Magnitude,[a] $\|\Delta P_{out}\|$		Phase relative to oscillator, $\varphi_{\Delta P_{out}}$, deg						
	lb/hr	kg/sec		psi	N/m^2		psi	N/m^2		psi/(lb/hr)	(N/m^2)/(kg/sec)		psi/(lb/hr)	(N/m^2)/(kg/sec)	
0.04	9.34	0.00118	15	1.56	10 800	-34	1.5	10 400	-37	0.167	9.14×10^6	-49	0.161	8.81×10^6	-52
.06	10.3	.0013	24	1.6	11 000	-42	1.53	10 600	-47	.155	8.48	-66	.149	8.16	-71
.08	11.8	.00148	29	1.68	11 600	-52	1.71	11 800	-57	.142	7.77	-81	.145	7.94	-86
.10	14.7	.00185	30	1.84	12 700	-61	1.78	12 300	-68	.125	6.84	-91	.121	6.62	-98
.20	27.5	.00346	13	1.92	13 300	-128	1.91	13 200	-137	.0698	3.82	-141	.0695	3.80	-150
.30	29.9	.00376	-14	1.60	11 000	-192	1.40	9 660	-207	.0535	2.93	-178	.0468	2.56	-193
.40	26.0	.00327	-30	1.20	8 280	-235	1.02	7 040	-247	.0462	2.53	-205	.0392	2.15	-217
.50	22.1	.00278	-33	.928	6 400	-254	.765	5 280	-271	.0420	2.30	-221	.0346	1.89	-238
.60	20.1	.00253	-33	.720	4 970	-286	.605	4 170	-289	.0358	1.96	-253	.0301	1.65	-256
.70	18.2	.00229	-34	.624	4 310	-304	.529	3 650	-305	.0343	1.88	-270	.0291	1.59	-271
.80	17.0	.00214	-33	.560	3 860	-318	.472	3 260	-317	.0329	1.80	-285	.0277	1.52	-284
.90	16.5	.00208	-32	.528	3 640	-326	.427	2 950	-328	.0320	1.75	-294	.0259	1.42	-296
1.0	16.2	.00204	-30	.464	3 200	-342	.389	2 680	-343	.0286	1.56	-312	.0240	1.31	-313
1.25	15.9	.00200	-27	.348	2 400	-386	.312	2 150	-394	.0219	1.19	-359	.0196	1.07	-367
1.50	17.7	.00223	-24	.192	1 330	-439	.198	1 370	-451	.0108	.591	-415	.0112	.613	-427
1.75	18.4	.00232	-21	.0176	121	-594	.035	242	-566	.000956	.0523	-573	.00190	.104	-545
2.00	18.0	.00227	-33	.146	1 010	-720	.153	1 060	-746	.0081	.443	-687	.00850	.465	-713
2.25	17.4	.00219	-33	.184	1 270	-759	.204	1 410	-713	.0106	.579	-726	.0117	.639	-680
2.50	18.8	.00237	-33	.184	1 270	-838	.223	1 540	-871	.00979	.535	-805	.0119	.651	-838
2.75	19.1	.00241	-39	.114	787	-932	.200	1 380	-932	.00597	.326	-893	.0105	.574	-893
3.00	18.9	.00238	-44	.122	842	-1004	.178	1 230	-994	.00645	.353	-960	.00942	.515	-950
3.25	18.2	.00229	-47	.132	911	-1052	.140	966	-1030	.00725	.396	-1005	.00769	.421	-983
3.50	17.3	.00218	-45	.110	759	-1082	.108	745	-1086	.00636	.348	-1037	.00624	.341	-1041
3.75	17.6	.00221	-48	.076	524	-1106	.0637	440	-1145	.00432	.236	-1058	.00362	.198	-1097
4.00	18.1	.00228	-50	.040	276	-1103	.0382	264	-1212	.00221	.121	-1153	.00211	.115	-1162

[a]Zero to peak.

TABLE II. - Concluded. BOILER PERTURBATION DATA

(l) Orifice exit restriction, 3/16 inch (4.76 mm); run 12, Freon flow rate, 143 pounds per hour (0.018 kg/sec); boiler exit condition, superheat (20.4° F or 11.3 K); inlet water temperature, 214° F (374 K)

Frequency, f, Hz	Perturbation data									Boiler inlet impedance			Transfer impedance		
	Freon flow at boiler inlet			Pressure at boiler inlet			Pressure at boiler exit			Magnitude, $\left\lvert \frac{\Delta P_{in}}{\Delta W_{in}} \right\rvert$		Phase, $\varphi_{\Delta P_{in}} - \varphi_{\Delta W_{in}}$, deg	Magnitude, $\left\lvert \frac{\Delta P_{out}}{\Delta W_{in}} \right\rvert$		Phase, $\varphi_{\Delta P_{out}} - \varphi_{\Delta W_{in}}$, deg
	Magnitude,[a] $\lvert\Delta W_{in}\rvert$		Phase relative to oscillator, $\varphi_{\Delta W_{in}}$, deg	Magnitude,[a] $\lvert\Delta P_{in}\rvert$		Phase relative to oscillator, $\varphi_{\Delta P_{in}}$, deg	Magnitude,[a] $\lvert\Delta P_{out}\rvert$		Phase relative to oscillator, $\varphi_{\Delta P_{out}}$, deg						
	lb/hr	kg/sec		psi	N/m^2		psi	N/m^2		psi/(lb/hr)	$(N/m^2)/(kg/sec)$		psi/(lb/hr)	$(N/m^2)/(kg/sec)$	
0.04	4.61	0.000581	3	0.856	5910	-37	0.828	5710	-39	0.186	10.2×10^6	-40	0.18	9.85×10^6	-42
.06	4.8	.000604	5	.880	6070	-46	.841	5800	-47	.183	10.0	-51	.175	9.58	-52
.08	5.1	.000642	8	.880	6070	-55	.854	5890	-57	.173	9.47	-63	.167	9.14	-65
.10	5.88	.00074	8	.912	6290	-67	.879	6060	-68	.155	8.48	-75	.149	8.16	-76
.20	8.86	.0011	2	.896	6180	-120	.841	5800	-124	.101	5.53	-122	.0949	5.19	-126
.30	10.8	.00136	-11	.768	5300	-165	.700	4830	-170	.0711	3.89	-154	.0648	3.55	-159
.40	10.4	.00131	-21	.576	3970	-202	.497	3430	-210	.0554	3.03	-181	.0478	2.62	-189
.50	9.60	.00121	-32	.376	2590	-226	.382	2640	-232	.0391	2.14	-194	.0398	2.18	-200
.60	8.98	.00113	-38	.360	2480	-251	.306	2110	-253	.0401	2.19	-213	.0342	1.88	-215
.70	8.65	.00109	-40	.320	2210	-266	.280	1930	-268	.0370	2.02	-226	.0323	1.77	-228
.80	8.10	.00102	-42	.284	1960	-282	.242	1670	-286	.0351	1.92	-240	.0299	1.63	-244
.90	7.80	.000983	-43	.260	1790	-300	.226	1560	-301	.0333	1.82	-257	.0290	1.59	-258
1.00	7.65	.000964	-44	.252	1740	-310	.216	1490	-310	.0329	1.80	-266	.0282	1.54	-266
1.25	6.96	.000877	-45	.216	1490	-345	.191	1320	-349	.0310	1.69	-300	.0274	1.50	-304
1.50	6.67	.000840	-44	.224	1550	-371	.198	1370	-378	.0336	1.84	-327	.0297	1.62	-334
1.75	6.45	.000813	-41	.212	1460	-421	.208	1440	-429	.0329	1.80	-380	.0322	1.76	-388
2.00	6.98	.000879	-40	.228	1570	-467	.229	1580	-472	.0327	1.79	-427	.0328	1.79	-432
2.25	7.87	.000992	-40	.208	1430	-450	.189	1300	-538	.0264	1.44	-410	.0240	1.31	-498
2.50	8.34	.00105	-51	.158	1090	-578	.134	925	-605	.0189	1.03	-527	.0160	.875	-554
2.75	7.80	.000983	-58	.0904	624	-657	.0956	660	-664	.0116	.634	-599	.0122	.667	-606
3.00	7.78	.000980	-60	.064	442	-739	.0714	493	-729	.00822	.449	-676	.00918	.502	-669
3.25	7.60	.000958	-62	.056	386	-762	.0637	440	-763	.00736	.402	-700	.00838	.458	-701
3.50	7.72	.000973	-62	.0488	337	-781	.0484	334	-805	.00632	.346	-719	.00627	.343	-743
3.75	7.85	.000989	-65	.0288	199	-794	.0395	273	-840	.00367	.201	-729	.00503	.275	-775
4.00	7.93	.000999	-67	.004	27.6	-794	.0185	128	-925	.000504	.276	-727	.00233	.127	-858

[a]Zero to peak.

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