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EXPERIMENTAL EVALUATION OF FOUR TRANSFER FUNCTIONS FOR A SINGLE TUBE BOILER WHICH ARE DYNAMICALLY INDEPENDENT OF EXIT RESTRICTIONS

by Grady H. Stevens, Jack H. Goodykoontz, and Eugene A. Krejsa

Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract

Four transfer functions of electrical network theory were applied to boiler dynamics. These functions were calculated from impedance measurements taken for a single tube boiler with inserts. The data were taken for a single steady-state condition for which the boiler generated superheated vapor. Hot water was used to boil the working fluid, Freon-113. Dynamic data were obtained showing these functions to be independent of restrictions placed at the boiler exit. The inlet impedance and the flow to flow transfer ratio were shown to be dominated by time delay effects. The exit pressure to exit flow ratio was shown to have characteristics of mass storage.

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SUMMARY

Four transfer functions of electrical network theory were applied to boiler dynamics. These functions were calculated from impedance measurements taken for a single tube boiler with inserts. The data were taken for a single steady-state condition for which the vertical boiler generated superheated vapor. Hot water was used to boil the working fluid, Freon-113.

Dynamic data were obtained showing these functions to be independent of restrictions placed at the boiler exit. Two of these functions, the boiler inlet impedance with constant exit pressure and the boiler flow to flow transfer function with constant exit pressure, were dominated by time delay effects. The remaining two, the reverse pressure transfer ratio with constant inlet flow and the exit flow to exit pressure ratio with constant inlet flow, apparently did not involve time delay effects. Over the frequency range tested the inlet impedance, reverse pressure transfer ratio, and flow to flow ratio had magnitudes that changed very little with frequency. The exit pressure to exit flow ratio, however, had a magnitude variation which suggested a mass storage effect.

INTRODUCTION

Measurement of transfer functions is a useful tool for evaluating analytical models for the dynamics of single tube boilers. Work performed at the Lewis Research Center and by others attests to the utility of this technique (refs. 1 to 5).

Earlier work at Lewis was concentrated on establishing stability criteria. More recently, the work was aimed at establishing the effect of feedline impedance on boiler loop stability (refs. 1 to 3). The data of these references are limited to describing the boiler dynamics for particular steady-state conditions and loads. A simple analytical model, based on the data of reference 1, was developed and reported in reference 6.

This report describes a more general approach to obtaining boiler dynamic data. Essentially, it involves making three sequential sets of impedance measurements for a single hollow tube boiler with three different loads (relation between flow and pressure downstream of boiler) and calculating special forms of transfer functions. Simple loads (orifices) are used to facilitate the calculation. With this particular method of calculation the effect of load can be removed from the data. The only qualification is that the steady-state conditions within the boiler be the same for all three loads. The experimental procedure for satisfying this requirement is described fully in this report. The transfer functions that result from this calculation are analogous to the h-parameter functions of electrical network theory (ref. 7).

The principal objective of the work described herein is to show that such functions can be obtained for a boiler and that these functions are independent of the load used to make the measurements.

These functions have several advantages. Because they are independent of load, they can be measured with two simple loads and used to predict the performance of the boiler in a loop containing a more complicated load. They are defined for boundary conditions which are convenient analytically. This allows direct comparison with analytic treatments which assume true constant pressure and/or flow conditions which may be difficult to realize experimentally.

THEORY

The development of the definitions for the h-parameter functions is similar to the development for electrical networks by Ryder in reference 7. If the boiler inlet pressure and the boiler exit flow are assumed to be functionally related to only inlet flow and exit pressure, the boiler variables can be expressed analytically as

$$P_i = f_1(W_i, P_o)$$

$$W_o = f_2(W_i, P_o)$$

(Symbols are defined in the appendix.)

The incremental operation about a mean condition is given by

$$\left.\begin{aligned} P_i' &= \left(\left.\frac{\partial P_i}{\partial W_i}\right|_{P_o'=o}\right) W_i' + \left(\left.\frac{\partial P_i}{\partial P_o}\right|_{W_i'=o}\right) P_o' \\ W_o' &= \left(\left.\frac{\partial W_o}{\partial W_i}\right|_{P_o'=o}\right) W_i' - \left(\left.\frac{\partial W_o}{\partial P_o}\right|_{W_i'=o}\right) P_o' \end{aligned}\right\} \tag{1}$$

The sign for $\partial W_o/\partial P_o$ in the second equation was chosen as negative to indicate flow being stored in the boiler.

This particular choice of variables and assumptions has led to a pair of equations with coefficients similar to the h-parameters of reference 7. These are

Boiler inlet impedance with a constant pressure exit condition

$$h_i = \left.\frac{\partial P_i}{\partial W_i}\right|_{P_o'=o}$$

Reverse pressure transfer ratio with constant inlet flow

$$h_r = \left.\frac{\partial P_i}{\partial P_o}\right|_{W_i'=o}$$

Flow to flow transfer ratio with constant exit pressure

$$h_f = \left.\frac{\partial W_o}{\partial W_i}\right|_{P_o'=o}$$

Ratio of exit flow to exit pressure (shunt exit admittance) with constant inlet flow

$$h_o = \left.\frac{\partial W_o}{\partial P_o}\right|_{W_i'=o}$$

Equations (1) imply that each of these transfer functions could be obtained directly by imposing the appropriate boundary conditions and taking the ratio of the appropriate variables. This technique would require two independent experiments with difficult control requirements. A simpler scheme is to calculate the h-parameters from relatively easily obtained impedance data.

Equations (1) can be rewritten in terms of impedance measurements, as follows:

$$\left.\begin{aligned} \frac{P_i'}{W_i'} &= h_i + h_r \frac{P_o'}{W_i'} \\ \frac{W_o'}{W_i'} &= h_f - h_o \frac{P_o'}{W_i'} \end{aligned}\right\} \qquad (2)$$

where W_o' is related to P_o' through the load equation (exit restriction):

$$P_o' = ZW_o'$$

When the load equation is combined with equations (2), the h-parameters can be expressed as functions of impedances:

$$\left.\begin{aligned} h_i + h_r z_o &= z_i \\ h_f - h_o z_o &= z_o/Z \end{aligned}\right\} \qquad (3)$$

where

$$z_i = \frac{P_i'}{W_i'}$$

$$z_o = \frac{P_o'}{W_i'}$$

These ratios have analogies in electrical network theory which lead one to call z_i the boiler inlet impedance and z_o the boiler transfer impedance.

Obviously, two more equations are needed to specify the h-parameters, and these extra equations are obtained by changing the load Z while maintaining the same steady-state conditions within the boiler. With the subscripts 1 and 2 representing measurements made with loads 1 and 2, respectively, the complete set of equations is

$$\left.\begin{aligned}
h_i + h_r z_{o,1} &= z_{i,1} \\
h_i + h_r z_{o,2} &= z_{i,2} \\
h_f - h_o z_{o,1} &= z_{o,1}/Z_1 \\
h_f - h_o z_{o,2} &= z_{o,2}/Z_2
\end{aligned}\right\} \qquad (4)$$

Solving equations (4) for each h-parameter results in

$$\left.\begin{aligned}
h_i &= \frac{z_{i,1} \cdot z_{o,2} - z_{o,1} \cdot z_{i,2}}{z_{o,2} - z_{o,1}} \\
h_r &= \frac{z_{i,2} - z_{i,1}}{z_{o,2} - z_{o,1}} \\
h_f &= \frac{z_{o,1} \cdot z_{o,2}}{z_{o,2} - z_{o,1}} \left(\frac{1}{Z_1} - \frac{1}{Z_2}\right) \\
h_o &= \frac{1}{z_{o,2} - z_{o,1}} \left(\frac{z_{o,1}}{Z_1} - \frac{z_{o,2}}{Z_2}\right)
\end{aligned}\right\} \qquad (5)$$

Therefore, all four h-parameters can be calculated from two sets of impedance data. However, an examination of equations (5) will show that under certain circumstances these h-parameter calculations can be very inaccurate. This condition arises when two impedance measurements are nearly the same value. To avoid this situation the loads should be chosen so as to ensure as large a difference as possible between the two measurements.

APPARATUS

The rig used to obtain the impedance data for the h-parameter calculations was similar to that used in references 1 to 3. A simple schematic is shown in figure 1. Freon-113 was boiled by a heat exchange with hot water flowing in an annulus in the vertical boiler and condensed by a heat exchange with city water. A relief valve downstream of the plenum maintained the plenum at a set mean pressure during operation. An oscillating electrohydraulic servovalve upstream of the boiler generated the flow and pressure perturbations for the impedance measurement. The gear pump flow fluctuations were attenuated with a mechanical low pass filter consisting of two accumulators and an intermediate restriction.

The boiler was the same as that used in reference 3 and is shown in figure 2. This was a single tube with inserts to induce swirl flow and an exit restriction to simulate an exit load. For this report the exit load was varied by changing the exit restriction. Three orifices, having diameters of 3/16, 1/4, and 5/16 inch (4.8, 6.4, and 7.9 mm), were used as exit restrictions.

Thermocouples were spaced along the boiler inside the annulus to measure the water temperature profile. Thermocouples were also placed at the boiler inlet and exit to monitor the mean temperature of the Freon-113.

In addition to the pressure gages placed at the boiler inlet and exit for mean pressures, strain-gage-type pressure transducers were also placed to measure pressure perturbations at the boiler inlet and exit.

Both the mean and dynamic flow were measured with a turbine flowmeter. The mean flow was obtained by measuring the frequency of the flowmeter signal. The dynamic flow was obtained by processing the flow signal with a frequency to voltage converter and a tracking band-pass filter as in reference 8.

The pressure and flow perturbations were analyzed with a frequency response analyzer. The impedance data were calculated from the measured pressure and flow perturbations. The impedances were corrected for the lagging response of the flowmeter as outlined in reference 8.

PROCEDURE

The first step in the experiment was to establish a mean condition with a linear relation between pressure and flow for all three orifices. This linearity had to span over a reasonable range of pressure and flow. In addition, it was desired to have superheated vapor at the boiler exit. This condition was established by taking pressure drop data for the boiler with the 3/16-inch (4.8-mm) exit restriction over a 1.5 to 1 range of flow. A curve of pressure drop as a function of mass flow rate was plotted and examined for a region which was reasonably linear (over a ±10 percent range of flow) and for which the boiler generated superheated vapor. The center of this region established the mean conditions for the tests with the two remaining orifices.

Of course, after the change was made from the 3/16-inch (4.8-mm) to the 1/4-inch (6.4-mm) orifice, the orifice pressure drop was less and the pressure downstream of the orifice had to be increased to restore the mean condition at the boiler exit. This pressure increase was obtained with an adjustable relief valve downstream of the plenum. Repeatability of the steady-state condition was tested by monitoring the water temperature profile as well as mean pressures. After the mean condition had been restored, steady-state data were taken for the 1/4-inch (6.4-mm) orifice. This procedure was repeated for the 5/16-inch (7.9-mm) orifice. These additional pressure drop data were plotted along with the 3/16-inch (4.8-mm) pressure drop as a function of mass flow. As will be shown later, all three intersecting curves were reasonably linear, so the frequency response testing was begun.

The mean conditions were established first with the 3/16-inch (4.8-mm) orifice, and impedance data were obtained with frequency response tests. This same procedure was used for the 1/4-inch (6.4-mm) and 5/16-inch (7.9-mm) orifices. The resulting impedance data were corrected for the frequency response of the flowmeter as outlined in reference 8. The corrected impedance data were then used to calculate the h-parameters as outlined in the section THEORY.

RESULTS

Steady-state data for the boiler are shown in the form of inlet and exit pressure as a function of mass flow rate in figure 3. The data emphasize the region near the operating condition of 115 pounds mass per hour (0.0145 kg/sec). The slope was greater with the 3/16-inch (4.8-mm) orifice and decreased as the orifice opening increased. All three curves intersect at approximately the same mean flow and pressure. The small differences can be attributed to the lack of resolution with the type of relief valve used to set these pressures.

The slope for each curve was taken as the slope of the line faired through the data. This slope for each orifice was used for the load Z in the calculation of the h-parameters.

The boiler inlet impedance as a function of frequency is shown in figure 4. Three sets of data are shown. Each set of data corresponds to a different orifice diameter. Each data point of each set represents the average of three impedance measurements. For each data set, the low-frequency asymptote of magnitude as a function of frequency equals the slope of the curve of steady-state inlet pressure as a function of flow corresponding to that orifice.

The boiler transfer impedance as a function of frequency is shown in figure 5. The variation with frequency of the transfer impedance magnitude is similar to that of the inlet impedance. The same is true for the phase angle variation for both functions.

These data are typical of boiler data and are similar to data reported previously (refs. 1 to 3). The large lagging phase angle at 1 hertz (-350°) is especially typical and is characteristic of systems dominated by time delay effects.

The results of the h-parameter calculations are shown in figures 6 to 9. The magnitude and phase of h_i are shown in figure 6. As with figures 4 and 5 the data were plotted only up to 1 hertz because of excessive scatter in the h-parameter calculation results above this frequency. This scatter occurred for all the h-parameters and was assumed due to numerical magnification of experimental inaccuracies. The potential for this error magnification was discussed in the development of equation (5). To minimize this type of error, the ratio of exit loads was chosen as large as possible. However, as can be seen from figures 4 and 5, the three sets of impedance data converged as frequency approached 1 hertz. Above 1 hertz the sets of data were almost equal and as a result the h-parameter calculations were very inaccurate in this range.

From its definition h_i has units of impedance. Also, from its definition, this would be the inlet impedance of the boiler if no load were placed at the boiler exit (constant pressure exit). The magnitude of h_i shows a slight decrease with frequency as the data approach 1 hertz. The phase of h_i shows an increasing lagging angle with increasing frequency. The large lagging angle (up to -300°) suggests a dominant time delay effect. For frequencies up to 1 hertz the data are consistent for the three orifices. These orifices spanned a 12 to 1 range in exit load. Consistency of the h_i data over such a wide range of loads indicates that h_i is independent of load.

The ratio h_r is shown as a function of frequency in figure 7. From its definition, h_r is a dimensionless ratio. The trend in the magnitude of h_r is similar to that of h_i, but the phase angle is radically different. The lagging angle for h_r is very small, suggesting that there is no time delay effect in the reverse pressure transfer ratio.

As with h_i the three sets of data for h_r are consistent, indicating h_r to also be independent of the load at the boiler exit.

The flow to flow transfer function h_f is shown in figure 8. The function h_f is a dimensionless ratio, and its magnitude has a low-frequency asymptote of 1.0. The phase of h_f as a function of frequency is similar to that of h_i because it increases in a lagging direction as frequency increases. The time lag effect is apparent from the large lagging angle. Again, the data are consistent for all three orifices. Thus, h_f is also independent of load.

The ratio of exit flow to exit pressure (boiler shunt admittance) h_o is shown as a function of frequency in figure 9. The linear variation of the magnitude with frequency from 0.04 to 1 hertz suggests h_o could be approximated by a storage element such as compliance, but more likely it reveals the type of mass storage discussed by Krejsa in reference 6. Whatever the mechanism, the data indicate a greater proportion of mass flow will be shunted into h_o as frequency increases. A simple shunt storage admittance would have a 90° phase independent of frequency. The phase of h_o as a function of frequency indicates this is approximately true up to 0.7 hertz. The consistency of the data for both magnitude and phase suggests that h_0 is also independent of load.

CONCLUSIONS

Because data were taken only for a superheated exit condition, the following conclusions are necessarily restricted to a superheated exit. The consistency of the data indicates that the boiler h-parameters are independent of load. Time delay effects apparently dominated the inlet impedance and the flow to flow transfer function. In contrast, the reverse pressure transfer ratio and exit flow to exit pressure ratio seemed not to include time delay effects. The inlet impedance, reverse pressure transfer ratio, and flow to flow ratio had magnitudes that changed only slightly with frequency at least to 1 hertz. The exit flow to exit pressure ratio had a magnitude variation with frequency which suggested a mass storage effect.

Lewis Research Center,
National Aeronautics and Space Administration
Cleveland, Ohio, December 29, 1970,
120-27.

APPENDIX - SYMBOLS

f_1, f_2 arbitrary functionals

h_f ratio of exit flow to inlet flow with constant exit pressure

h_i ratio of inlet pressure to inlet flow with constant exit pressure

h_o ratio of exit flow to exit pressure with constant inlet flow (shunt exit admittance)

h_r ratio of inlet pressure to exit pressure with constant inlet flow

P_i instantaneous inlet pressure

P_o instantaneous exit pressure

W_i instantaneous inlet flow

W_o instantaneous exit flow

Z slope of orifice pressure drop curve at a mean condition

z_i inlet impedance, ratio of inlet pressure to inlet flow with exit restriction (exit pressure varying)

z_o transfer impedance, ratio of exit pressure to inlet flow with exit restriction

Superscript:

$'$ perturbation

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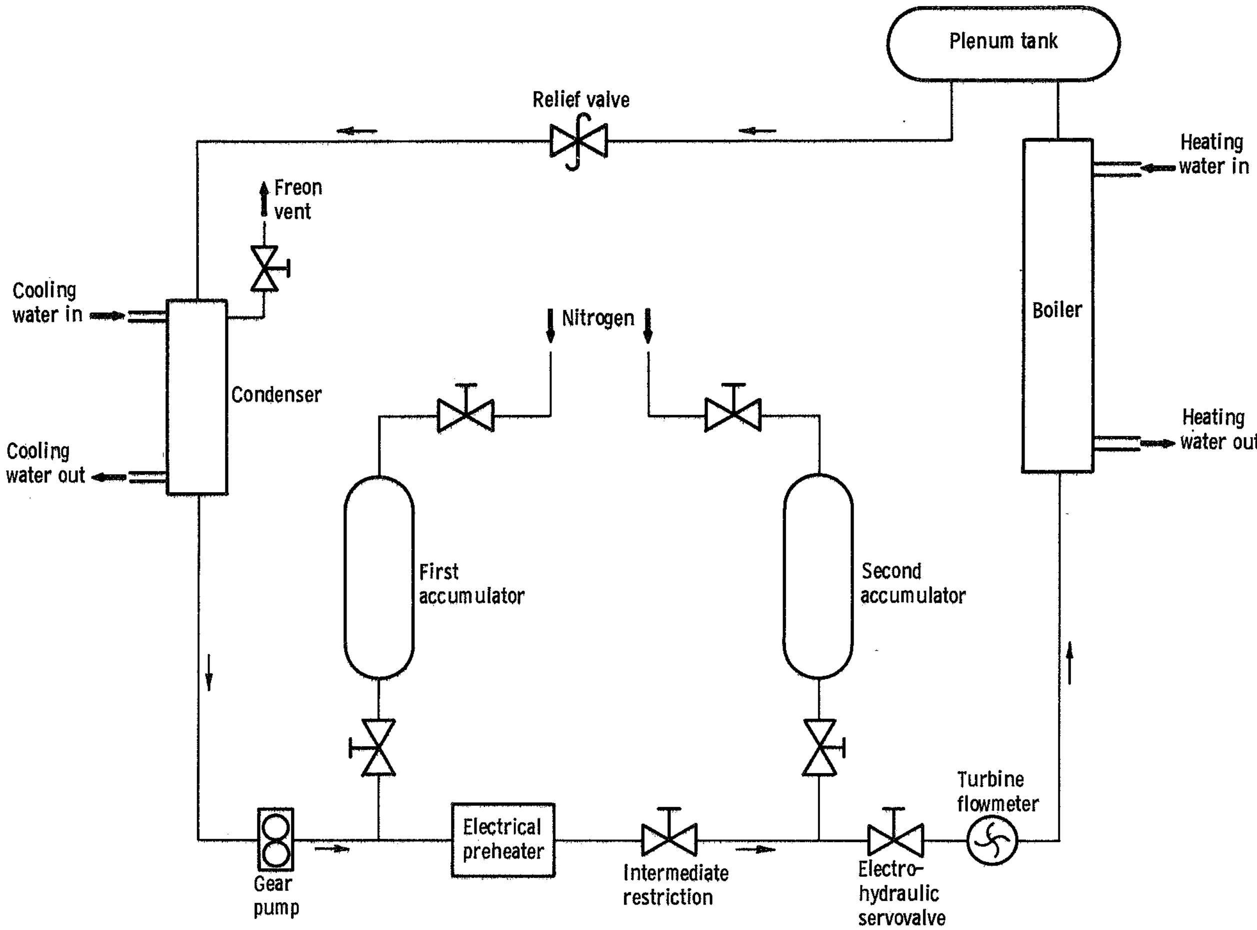
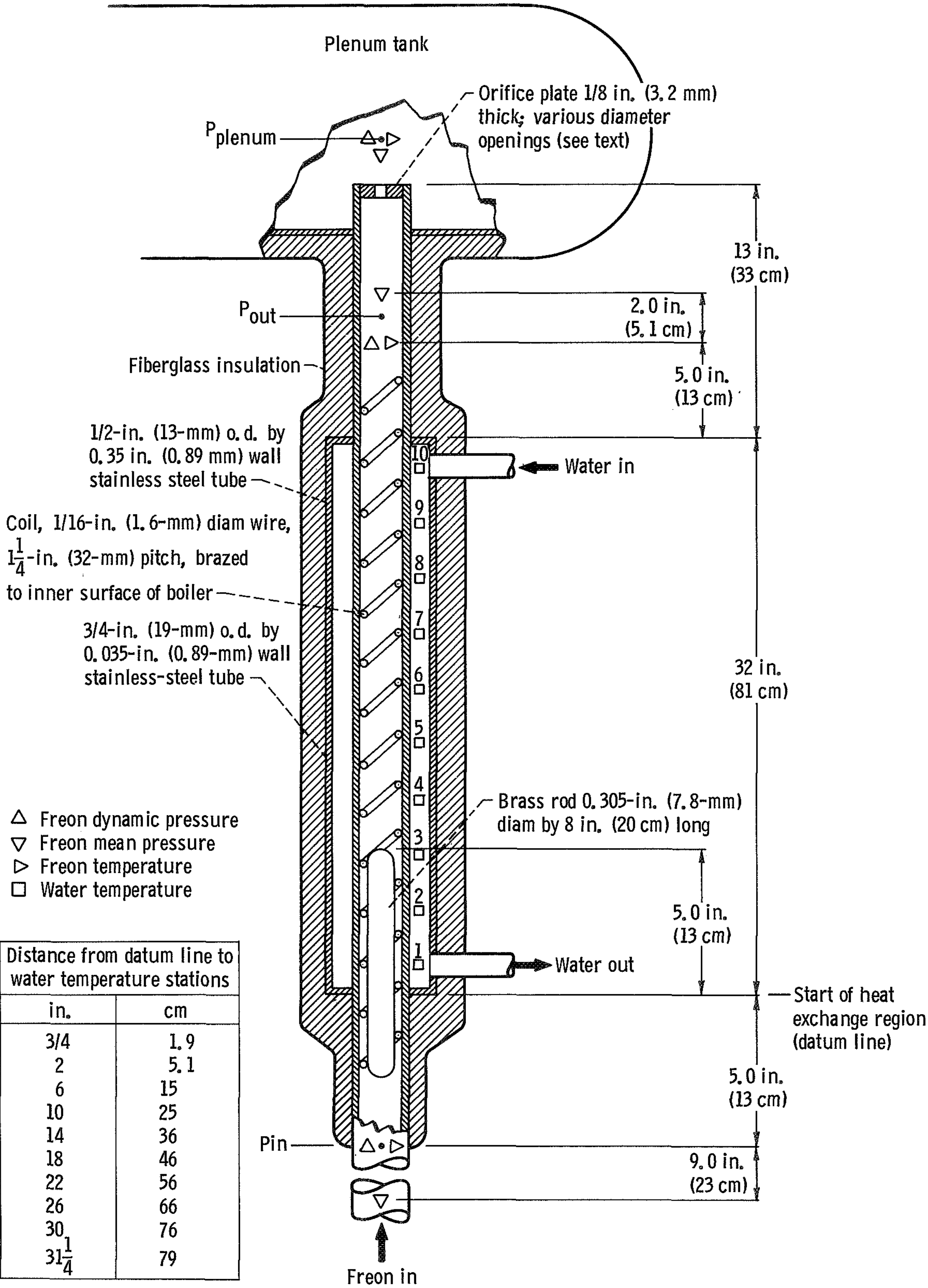


Figure 1. - Schematic of rig used to obtain h-parameter data.



Station	Distance from datum line to water temperature stations	
	in.	cm
1	3/4	1.9
2	2	5.1
3	6	15
4	10	25
5	14	36
6	18	46
7	22	56
8	26	66
9	30	76
10	$31\frac{1}{4}$	79

Figure 2. - Single tube boiler test section.

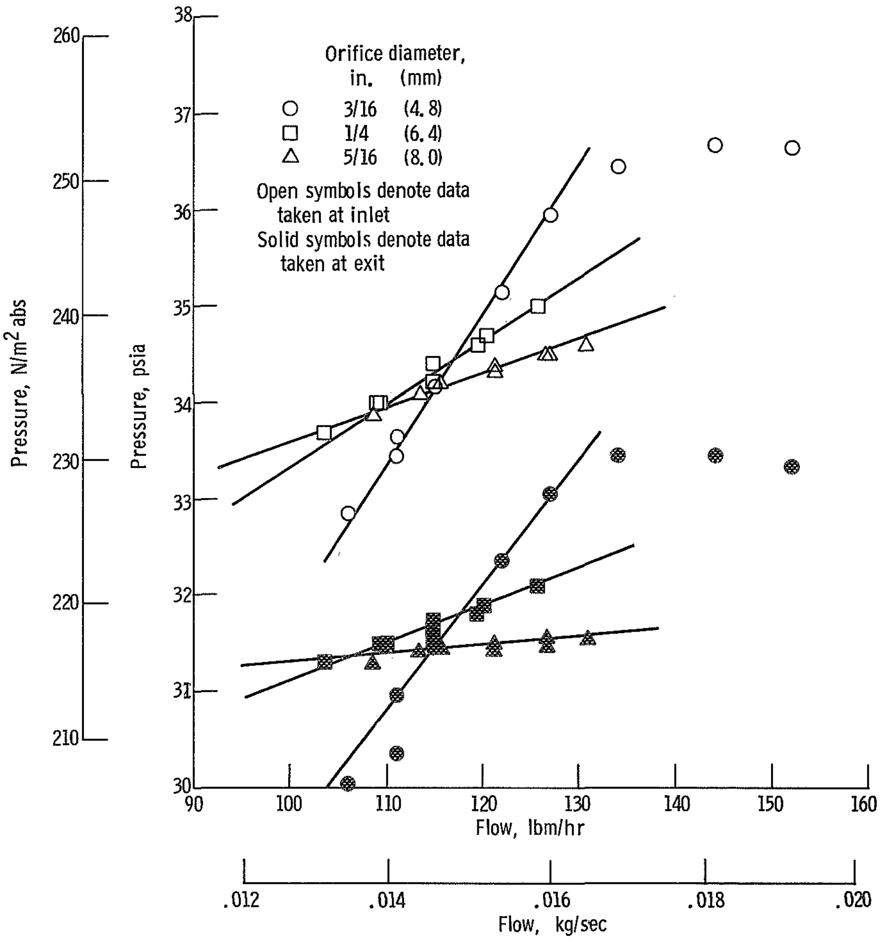


Figure 3. - Boiler pressures as function of Freon-113 flow rate with orifice diameter as parameter.

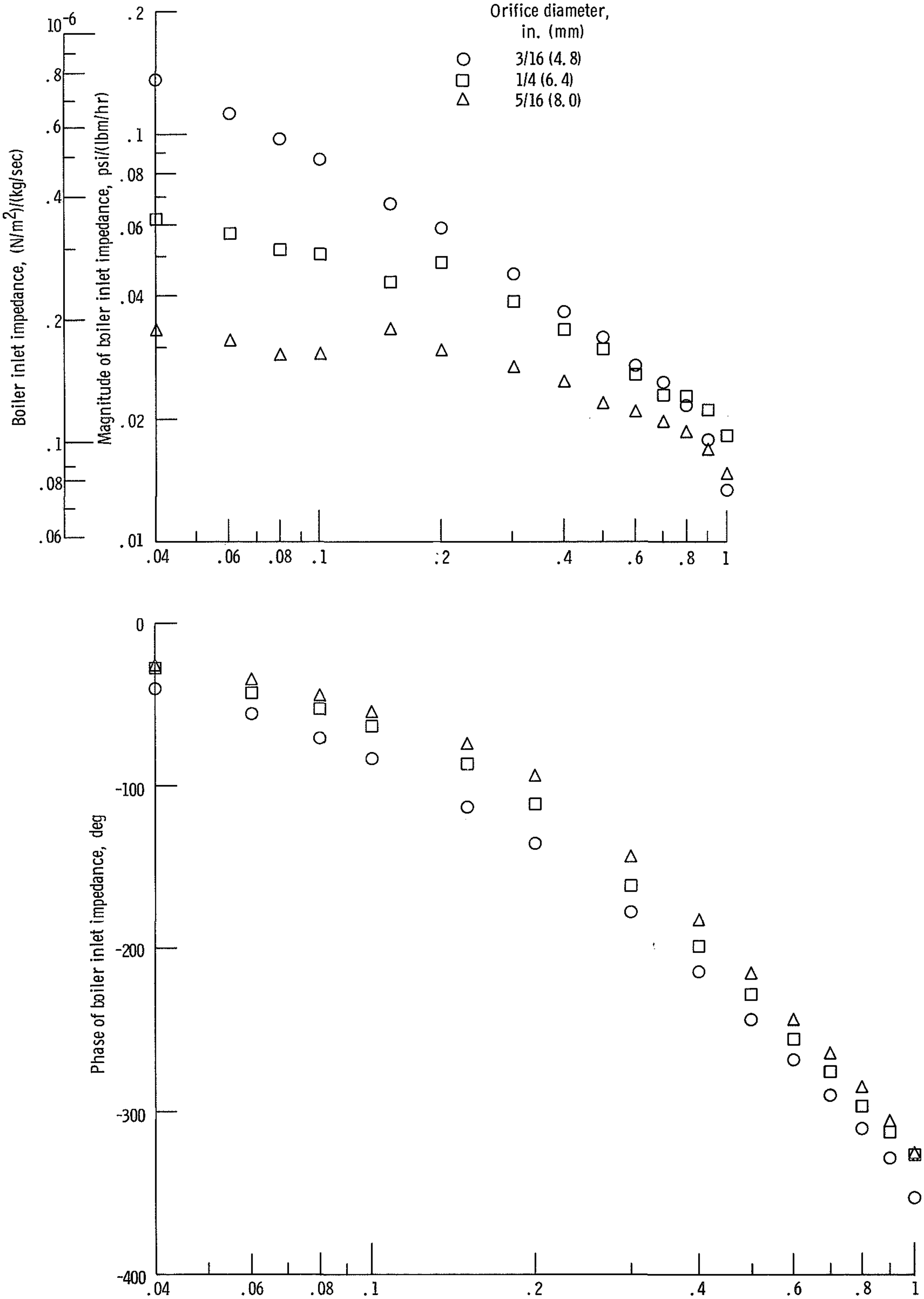


Figure 4. - Boiler inlet impedance as function of frequency with orifice diameter as parameter.

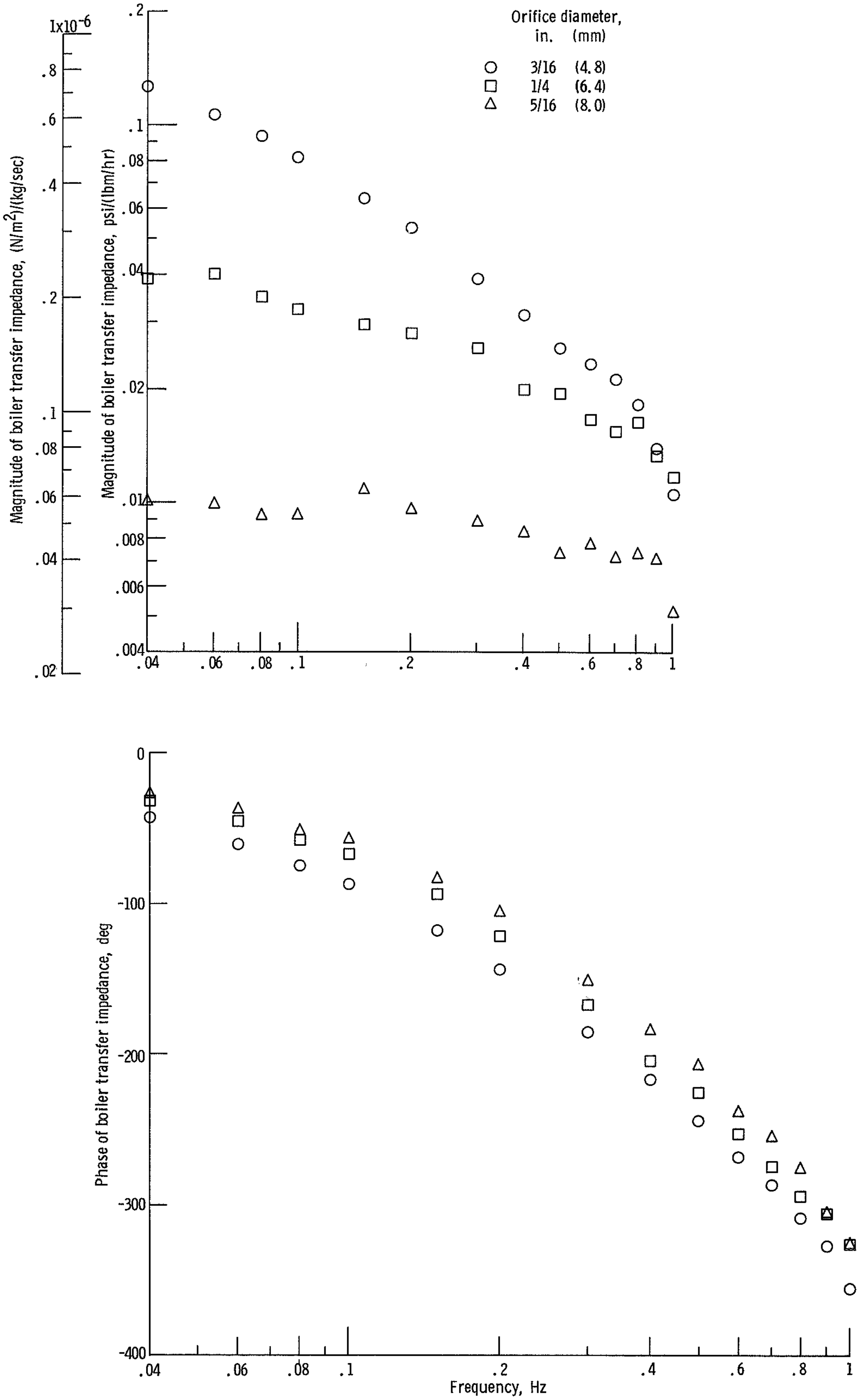


Figure 5. - Boiler transfer impedance as function of frequency with orifice diameter as parameter.

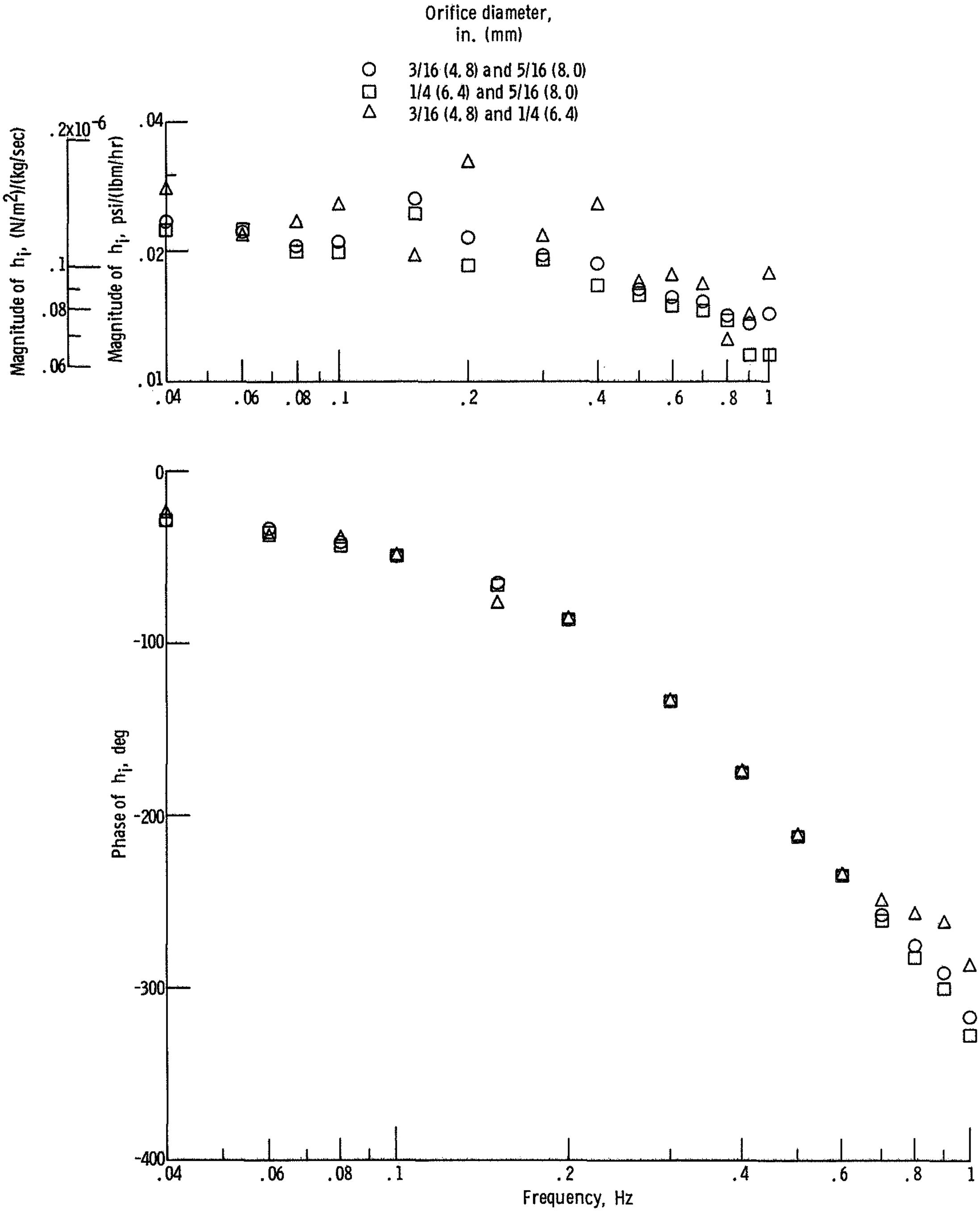


Figure 6. - Pressure-flow ratio with constant exit pressure h_i as function of frequency.

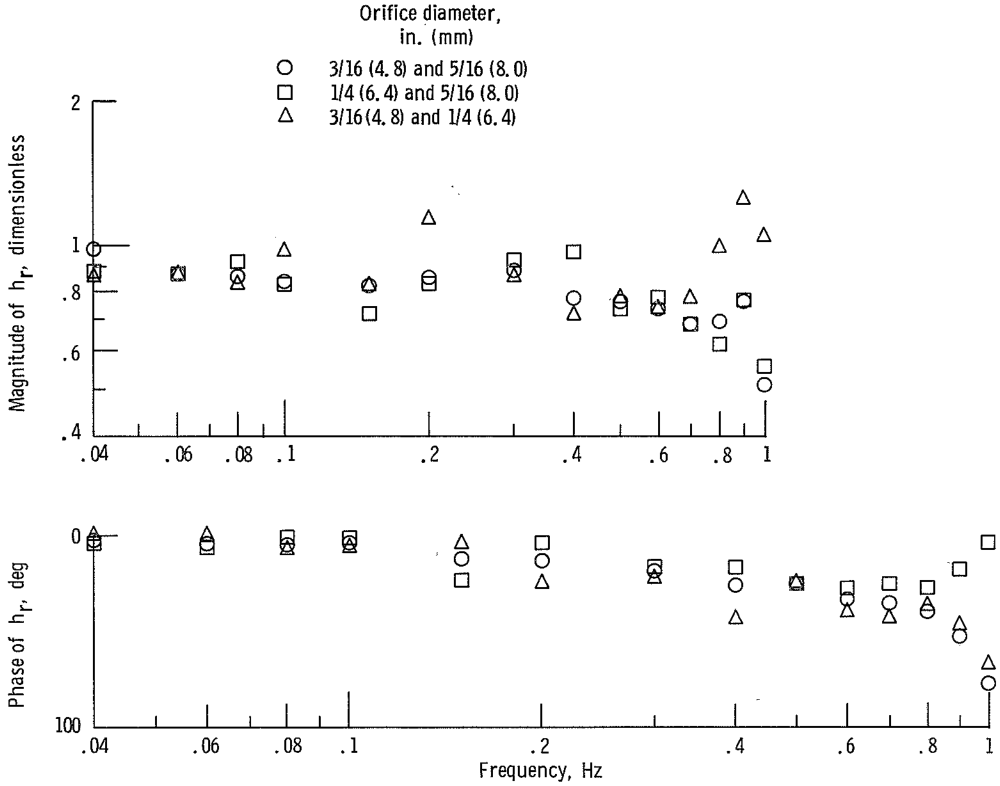


Figure 7. - Pressure ratio with constant inlet flow h_r as function of frequency.

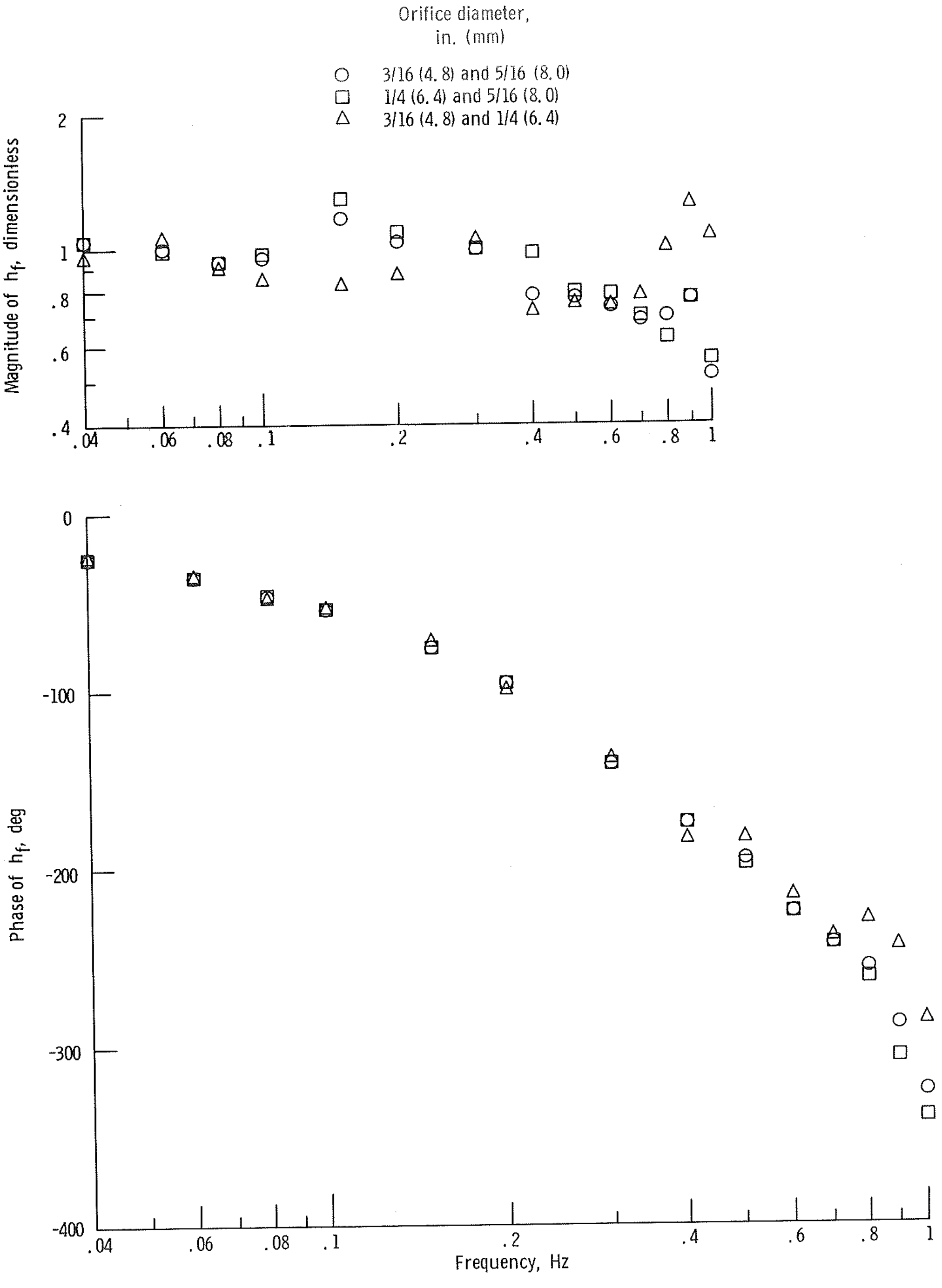


Figure 8. - Flow ratio with constant exit pressure h_f as function of frequency.

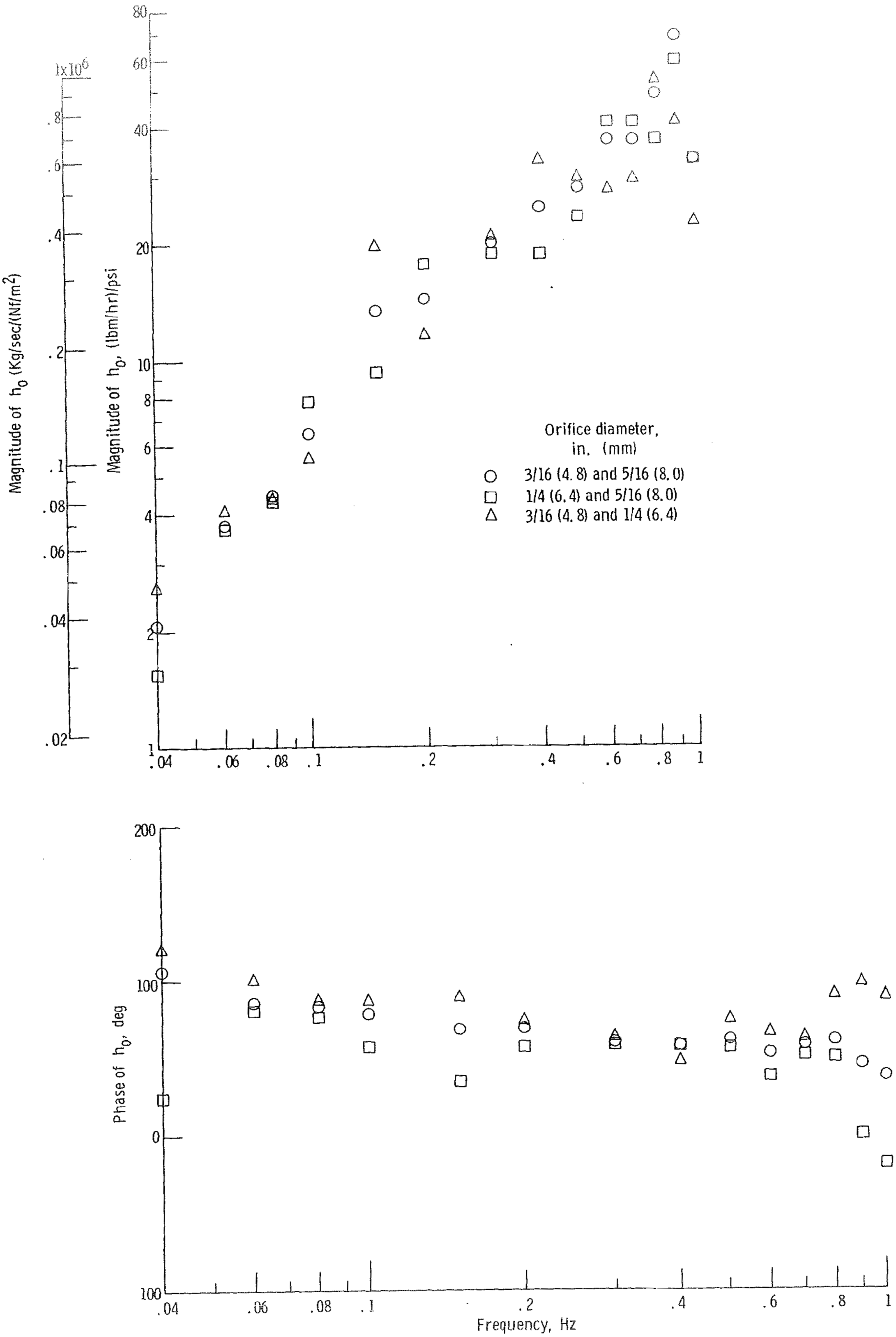


Figure 9. - Flow-pressure ratio with constant inlet flow h_0 as function of frequency.

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— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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