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UCRL-52271

METERING LOW-QUALITY STEAM-WATER FLOWS

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April 26, 1977

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Prepared for U.S. Energy Research & Development
Administration under contract No. W-7405-Eng-48

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Printed in the United States of America

Available from

National Technical Information Service

U.S. Department of Commerce

5285 Port Royal Road

Springfield, VA 22161

Price: Printed Copy \$; Microfiche \$3.00

Page Range	Domestic Price	Page Range	Domestic Price
001-025	\$ 3.50	326-350	10.00
026-050	4.00	351-375	10.50
051-075	4.50	376-400	10.75
076-100	5.00	401-425	11.00
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Distribution Category
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Nomenclature*

LATIN LETTERS

A_o	orifice area (m^2 , ft^2)
e	internal energy (ft-lbf/slug, J/kg)
h	enthalpy (ft-lbf/slug, J/kg)
K	flow coefficient
K_J	correlation factor for James' equation
K_E	correlation factor for energy equation
$\dot{m}$	mass flow rate (kg/s, slug/sec)
P	pressure (Pa, lbf/ ft^2)
u	velocity (m/s, ft/sec)
v	specific volume (m^3/kg , $ft^3/slug$)
x	quality
y	mass fraction of liquid
Y	compressibility factor

GREEK LETTERS

α	area ratio
β	ratio of constriction diameter to pipe diameter
ϕ	slip ratio
ρ	mass density (slug/ ft^3 , kg/m^3)

SUBSCRIPTS

f	liquid
g	gas or vapor
G	gas or vapor (Murdock correlation)
L	liquid (Murdock correlation)
m	mixture
o	orifice
TP	two-phase flow

* All dimensions are given in the fundamental units to be used in the equations presented in this report. The following conversion factors may be useful to the reader.

$$\begin{aligned}1 \text{ slug} &= 32.2 \text{ lbm} \\1 \text{ BTU} &= 778 \text{ ft-lbf}\end{aligned}$$

METERING LOW-QUALITY STEAM-WATER FLOWS

Abstract

The simultaneous measurement of mass flow rate and quality of low-quality steam-water flows is of primary interest in evaluating and monitoring the flow from geothermal resources. This report relates the experience acquired at LLL in attempting to perform such measurements with a double flash (meter-valve-

meter) arrangement using orifices and venturis. The mass flow correlations proposed in the literature are reviewed and a new correlation based on the energy equation is introduced. The data are presented and evaluated in light of these correlations. Directions for future research in this area are suggested.

Introduction

The goal of the Geothermal Energy Program at LLL¹ is to achieve maximum effective utilization of geothermal resources through an integrated program examining energy conversion, chemical treatment, and resource assessment. The high temperature, high salinity geothermal resources which are of most interest to the Program lie in the Salton Sea area of the Imperial Valley, California. The wellhead condition of the geothermal fluid is a mixture of liquid and vapor with a quality less than 20% (vapor fraction). Pressure and temperature may be as high as 400 psia (2.8 MPa) and 450°F (230°C), respectively.

To design conversion machinery and assess its efficiency, one must be able to measure the mass flow rate and the thermodynamic properties of the inlet and outlet fluid. This report describes a series of experiments performed at LLL to study the feasibility of using two orifices or two venturis to simultaneously measure mass flow rates and quality of geothermal sources. Previous studies²⁻⁵ show that the mass flow rate of a single-component two-phase fluid through an orifice depends on both the pressure drop and upstream quality. In the initial phases of this study, it was thought that the

use of two orifices or two venturis separated by a valve would provide sufficient data to yield both mass flow rate and quality. Murdock's equation² appeared most satisfactory for this application. However, analysis of the data indicated that Murdock's correla-

tion is inadequate for the flow conditions found in high temperature, high salinity geothermal resources. Other correlations also proved inadequate, so suggestions are made for different methods of obtaining the mass flow rate and quality simultaneously.

Test Description

A general schematic of the LLL geothermal test facility,⁶ used for these experiments, is shown in Fig. 1. The system, designed to evaluate the performance of nozzles, turbines, and other energy-conversion devices

operating in a two-phase working fluid, consists of a gas-fired hot water generator having an output of 7900 lb/hr at 5.5×10^6 Btu (3590 kg/h at 5.8 GJ). It can be operated as either a closed- or open-loop system.

Fig. 1. Geothermal test facility.

The range of thermal capabilities is shown in Fig. 2. Most of the investigations were carried out near the ~300-psia nominal pressure of the Salton Sea area.

In these experiments, the compressed liquid from the hot water generator was measured by an orifice, then flashed through a throttling valve prior to entering the test sec-

tion. Typical sketches of the piping system are shown in Figs. 3 and 4 and a photograph of the system is shown in Fig. 5. The piping is shown without insulation for clarification purposes only; the pipes were insulated during the testing program. The orifice plates were commercially obtained and ranged in β -ratio (pipe size/size of restriction) from 0.578

Fig. 2. Test facility capabilities.

Fig. 3. Typical piping for orifice test series.

Fig. 4. Typical piping for venturi test series.

Fig. 5. Test system.

to 0.783. They all satisfied the requirements of the ASME Fluid Meter Code. The venturis, also obtained commercially, were fabricated according to the ASME Fluid Meter Code. They had two β -ratios: 0.65 and 0.78.

The test series consisted of 24 tests which differed by β -ratio and type of meter (one or two orifices or venturis). A number of preliminary tests (Tests 1 through 10) were made before data collection instrumentation and techniques were perfected. During these tests, short calming

lengths, various differential pressure transducers, and temperature measurement devices were evaluated. All temperature measurements with two-phase flow were made with chromel-alumel thermocouples welded to the outside of the pipe. The pressure drops across orifices and venturis were measured using precalibrated differential pressure transducers. The data were collected and recorded on a data logger. The quality at each meter was calculated using the properties of the compressed liquid

and assuming the flashing sequence to be an isoenthalpic process. Some tests were done with straighteners as indicated in Table 1. Short calming lengths were used for Tests 23 and 24. Globe and gate valves were used upstream of the meters.

The raw data is provided in the Appendix. The pressure P_1 was calculated from the thermocouple reading T_1 . It was found that thermocouple data was more stable and the associated equipment more economical than pressure transducers in transmitting information to the data logger. More temperatures were recorded, as shown in Figs. 3 and 4, than indicated in the Appendix. These data were used to determine line, meter, and valve pressure drops.

In test series 12 and 15 through 24, a meter was located both upstream

and downstream of the gate valve. The original intent of throttling between meters was to determine mass flow rate and quality simultaneously by using an iterative technique based on the quality change between meters. The technique assumed an isoenthalpic process and used the measured temperatures and flow-meter pressure drops. A quality was assumed for the upstream orifice which then fixed the downstream quality. The mass flow was then calculated through each orifice and when they matched presumably a solution would be obtained. However, it was found that the Murdock model was too insensitive to small quality changes. The two meters were continued in service but attempts at solving for both quality and mass flow rate were discontinued.

Metering Correlations

PREVIOUS WORK

Because the venturi and the orifice are inexpensive, accurate, and reliable, they have been widely used by industry to meter single-phase flows. Their operation is based on a straightforward concept: constricting the area of a pipe leads to changes in velocity and pressure.

The pressure difference between the upstream and constricted portion relates directly to the mass flow rate. The commonly used expression relating mass flow rate ($\dot{m}$) and pressure differential (Δp) is

$$\dot{m} = KYA_o \sqrt{2\rho\Delta P}, \quad (1)$$

where K is the flow coefficient, Y

Table 1. Summary of experimental parameters.

Test No. ^a	Upstream meter					Downstream meter				
	Meter type ^b	β -ratio	Straightener	Valve ^c	Calming length (pipe diam)	Meter type ^b	β -ratio	Straightener	Valve ^c	Calming length (pipe diam)
11	V	0.78	No	G1	20	—	—	—	—	—
12	O	0.71	No	G1	20	O	0.78	No	Ga	20
13	O	0.71	Yes	G1	20	—	—	—	—	—
15	O	0.78	Yes	G1	20	O	0.71	Yes	Ga	20
16	O	0.78	No	G1	20	O	0.71	No	Ga	20
17	V	0.78	No	G1	20	V	0.65	No	G1	20
18	V	0.78	Yes	G1	20	V	0.65	Yes	G1	20
19	O	0.71	Yes	G1	20	O	0.76	Yes	Ga	20
20	O	0.76	Yes	G1	20	O	0.71	Yes	Ga	20
21	O	0.58	Yes	G1	20	O	0.76	Yes	Ga	20
22	O	0.58	No	G1	20	O	0.76	No	Ga	20
23	O	0.73	No	G1	20	O	0.76	No	Ga	6
24	O	0.73	No	G1	6	O	0.76	No	Ga	6

^aRuns — 1 through 10 were preliminary check out runs.

^bO — orifice, V — venturi.

^cG1 — globe valve, Ga — gate valve.

is a factor to correct for compressibility of the fluid, A_o is the orifice area (or venturi throat area), and ρ is the fluid density upstream of the meter. The flow coefficient K is a function of the β -ratio (orifice diameter/pipe diameter) and Reynolds number and can be found in ASME tables or most basic fluid mechanics texts. The compressibility factor Y is unity for liquids and somewhat less than unity for gases depending on the pressure drop across the meter. Empirical expressions for Y are available in standard references.

Some effort has also been devoted to assessing the utility of orifices and venturis in metering the flow rates of gas-droplet or steam-water mixtures. Both Murdock's and James' equations were examined in this work. Murdock² employs a separated flow model in developing an empirical equation for metering two-phase flow through an orifice. His development parallels that used by Chisholm.⁷ Murdock's correlation is based on a relationship between the pressures corresponding to flow of either the vapor or liquid alone through the orifice and the two-phase mixture. Using the standard orifice equation, Eq. (1), and equating the sum of the flow areas of each phase to the orifice area, Murdock finds

$$\sqrt{\frac{\Delta P_{TP}}{\Delta P_G}} = \frac{K_L}{(K_L)_{TP}} \sqrt{\frac{\Delta P_L}{\Delta P_G}} + \frac{K_G Y_G}{(K_G Y_G)_{TP}}, \quad (2)$$

where ΔP_G and ΔP_L are the differential pressures corresponding to vapor or liquid flowing alone through the orifice, and ΔP_{TP} corresponds to the pressure differential for the two-phase mixture. K_L and K_G are the flow coefficients corresponding to single-phase flow while $(K_L)_{TP}$ and $(K_G)_{TP}$ are flow coefficients for each phase taking the ΔP_{TP} as the pressure differential. By analyzing the available data, Murdock found a good correlation of the pressure data with

$$\sqrt{\frac{\Delta P_{TP}}{\Delta P_G}} = 1.26 \sqrt{\frac{\Delta P_L}{\Delta P_G}} + 1 \quad (3)$$

for the Martenelli-Lockhard parameter $(\sqrt{\Delta P_L/P_G})$ ranging between 0 and 0.28.* Finally, Murdock purposes the equation

$$\dot{m} = \frac{K_G Y_G A_o \sqrt{2\rho_G \Delta P_{TP}}}{(1-y) + 1.26 y \frac{K_G Y_G}{K_L} \sqrt{\frac{\rho_G}{\rho_L}}}, \quad (4)$$

* Chisholm pointed out, however, that considerable error can accrue with this empirical fit as ΔP_G approaches zero, following which Murdock cautioned the use of his results for vapor/liquid volume ratios less than 100. (See discussion in Murdock's paper.²)

where y is the mass fraction of the liquid.

James⁵ has proposed using the correlation for a single-phase fluid, [Eq. (1)], with a modified mixture density; namely,

$$\dot{m} = \frac{0.61 K_J Y A_o}{\sqrt{1 - \beta^4}} \sqrt{x^{1.5} (v_g - v_f) + v_f} \quad (5)$$

where x is the quality, and v_g and v_f are the specific volume of the vapor and liquid phases, respectively. The factor $0.61/\sqrt{1 - \beta^4}$ can be regarded as the flow coefficient. The factor K_J is used later in the report as a correlation factor for James' equation. One notes that if the exponent on the quality were unity, the specific volume would be that corresponding to a homogeneous fluid. Recent studies⁸ have shown that James' equation exhibits the highest degree of predictive capability for steam-water mixtures ($\pm 8\%$) compared to other equations available.

Some other equations^{9,10} have been proposed but will not be discussed here. A new equation developed at LLL and based on energy conservation is introduced below.

ENERGY EQUATION

The orifice equation, Eq. (1), which is commonly used for metering single-phase flows and which has been modified in various ways for

two-phase flows, is a specific application of the general energy equation for a flowing fluid. Neglecting the piezometric pressure, one can write the general energy equation for an adiabatic, quasi-one-dimensional flow in the form

$$h_1 + \frac{u_1^2}{2} = h_2 + \frac{u_2^2}{2}, \quad (6)$$

where the subscripts 1 and 2 specify two stations along the duct, and h and u are the specific enthalpy and velocity of the fluid, respectively. Writing the enthalpy as the sum of the internal energy and flow work (P/ρ), one finds that the energy equation becomes

$$e_1 + \frac{P_1}{\rho_1} + \frac{u_1^2}{2} = e_2 + \frac{P_2}{\rho_2} + \frac{u_2^2}{2}. \quad (7)$$

If the flow is incompressible ($\rho_1 = \rho_2$) and inviscid (no mechanism to change internal energy; $e_1 = e_2$), then the classic Bernoulli equation, which has served as the starting point for developing the orifice equations, is recovered. However, with low-quality steam-water flows it would appear that changes in internal energy may also contribute significantly to the velocity change through the orifice.

Assuming the flow is homogeneous, one can write an energy equation

between the pipe (1) and the vena contracta (2) (minimum area) as

$$u_2^2 - u_1^2 = 2(h_1 - h_2) \quad (8)$$

However, from the continuity equation, one has

$$\frac{u_1 A_1}{[xv_g + (1-x)v_f]_1} = \frac{u_2 A_2}{[xv_g + (1-x)v_f]_2} \quad (9)$$

Substituting Eq. (9) into Eq. (8) and solving for u_2 yields

$$u_2 = \sqrt{\frac{2(h_1 - h_2)}{1 - \frac{A_2^2 [xv_g + (1-x)v_f]_1^2}{A_1^2 [xv_g + (1-x)v_f]_2^2}}} = \sqrt{\frac{2(h_1 - h_2)}{1 - \frac{A_2^2 v_{m,1}^2}{A_1^2 v_{m,2}^2}}} \quad (10)$$

where v_m is the specific volume of the mixture. The mass flow rate is given by

$$\dot{m} = \frac{u_2 A_2}{v_{m,2}} \quad (11)$$

Realizing that the area of the vena contracta is proportional to the orifice (or throat) area and that the flow is not homogeneous, one can introduce an empirical correlation factor K_E .

$$\dot{m} = \frac{K_E A_o}{v_{m,2}} \sqrt{\frac{2(h_1 - h_2)}{1 - \frac{A_2^2 v_{m,1}^2}{A_1^2 v_{m,2}^2}}} \quad (12)$$

If the flow is incompressible, this equation reduces to the standard orifice equation.

To establish the state of the fluid at station (2), it is assumed that the process is isentropic. Of course, the process is not isentropic because of velocity and thermal non-equilibrium, but it is assumed that this can be accounted for by the empirical factor K_E .

Analysis of Experimental Data

The test conditions are summarized in Table 1. The data were analyzed according to Murdock's equation, James' equation, and the energy

equation developed at LLL. The following section discusses the trends observed using these equations.

MURDOCK'S EQUATION

The total mass flow rate was measured by the orifice in the compressed liquid line. The quality was determined by measuring the boiler pressure and temperature and the pressures upstream of the orifices (or venturis) and assuming isoenthalpic flow (data is given in Appendix). Thus the mass flow rate of each phase at the orifices could be determined. Using the ASME recommended flow coefficients for each phase and the measured "two-phase" pressure drop, one can establish

the pressure correlation fundamental to Murdock's model.

The Murdock correlation for the upstream orifices with a β -ratio of 0.71 is shown in Fig. 6. Here one notes a reasonably good correlation, but there is considerably more scatter than observed by Murdock. However, the data presented in Fig. 6 represent a much wider range of the Martinelli-Lockhart parameter (0.1-1.0) than correlated by Murdock (0.01-0.25). In fact, the upper limit of the Martinelli-Lockhart parameter for the steam-water data

used by Murdock was only 0.04. The fact that flow straighteners were used in Tests 13 and 19 and a gate valve (in lieu of a globe valve) in Test 13 is not readily apparent in the data which implies minimal effects. One also notes that the data is best fit by the linear relationship

$$\sqrt{\frac{\Delta P_{TP}}{\Delta P_G}} = 1.23 + \sqrt{\frac{\Delta P_L}{\Delta P_G}}, \quad (13)$$

which differs considerably from the correlation proposed by Murdock. Specifically, the slope is somewhat less and the y-intercept is not unity.

The Murdock correlation for the upstream orifices with a β -ratio of 0.73 is shown in Fig. 7. The calming length for Test 24 is only 6 as compared to the usual 20, and one notes a definite upward shift and a more pronounced scatter in the data. The data from Test 23 fit well with those shown on Fig. 6. These data suggest calming length does have an effect and 20 diameters should be maintained to reduce scatter in the data.

The Murdock correlation for upstream orifices with a β -ratio of 0.78 is shown in Fig. 8. The only difference between these two tests

Fig. 7. Murdock correlation for upstream orifice with β -ratio of 0.71.

Fig. 8. Murdock correlation for upstream orifice with β -ratio of 0.78.

is the use of a flow straightener in Test 15 for which the data exhibit considerable scatter. Although the use of flow straighteners appeared to have no significant effect on the data for the orifices with a β -ratio of 0.71, these data do imply that their effect may become more pronounced for large β -ratio orifices.

The smallest β -ratio orifice used in this experimental study was 0.58 and the corresponding data reduced according to the Murdock correlation are shown in Fig. 9. The correlation is reasonably good. Note that Test 22 had flow straighteners while none were used for Test 21. As with the data shown on Fig. 6 for the 0.71 β -

ratio orifice, the flow straighteners appear to have no effect. Also, note that the data are represented reasonably well by the linear relationship

$$\sqrt{\frac{\Delta P_{TP}}{\Delta P_G}} = 1 + 1.43 \sqrt{\frac{\Delta P_L}{\Delta P_G}} \quad (14)$$

which, like Murdock's, appears to have a y-intercept of unity but a slope of 1.43 as opposed to the 1.26 used by Murdock. However, the steam-water data used by Murdock represented a very limited range of the Martenelli-Lockhart parameter.

The Murdock correlation for orifices with a β -ratio of 0.71 located downstream of another orifice and

Fig. 9. Murdock correlation for upstream orifice with β -ratio of 0.58.

valve is shown in Fig. 10. The correlation is much poorer than that for a corresponding upstream orifice (Fig. 6). Also, there appear to be no significant trends associated with flow straighteners. Although the scatter in the data is unacceptably large, one might conclude the slope of the correlation is somewhat smaller and the y-intercept somewhat larger than those observed for the upstream orifice.

The data for a downstream orifice with a β -ratio of 0.76 reduced according to Murdock's correlation are

shown in Fig. 11. Once again sizable scatter in the data are observed.

Tests 23 and 24 were done with a calming length of only 6 diameters and as before (Fig. 7) one notes an upward shift of the correlation and considerable scatter in the data.

Finally, the Murdock correlation for the downstream orifice with a β -ratio of 0.78 is shown in Fig. 12. This test was done with no flow straighteners and, as with the upstream orifice of the same β -ratio, the scatter in the data is not excessive. Note that there is an upward

Fig. 10. Murdock correlation for downstream orifice with β -ratio of 0.71.

Fig. 11. Murdock correlation for downstream orifice with β -ratio of 0.76.

Fig. 12. Murdock correlation for downstream orifice with β -ratio of 0.78.

shift in the correlation compared to the data presented in Fig. 8.

Based on the data presented above, the following general observations can be made about the application of Murdock's equation to metering low-quality steam-water flows:

- (1) Flow straighteners produce scatter in the data for large β -ratio orifices so their use is not recommended.
- (2) A calming length of at least 20 pipe diameters should be maintained.
- (3) Downstream orifices provide less reliable data than upstream orifices.

- (4) There is a general increase of the y-intercept for Murdock's correlation for downstream orifices.

- (5) The smaller β -ratio orifices produce correlations which compare more favorably with Murdock's correlation.

The Murdock correlation for the venturi data appears in Fig. 13. Considerable scatter is observed for both the upstream and downstream data with no trends apparent for the effect of flow straighteners. The most striking feature of the data is the upward shift of the correlation for the downstream venturis. The

Fig. 13. Murdock correlation for venturi data.

same trend was apparent for the orifice data.

An explanation of the upward shift in the correlation for the downstream orifice might be gained by applying the energy equation between the pipe (1) and the venturi throat or the orifice vena contracta (2).

$$\begin{aligned} \dot{m}[xh_v + (1-x)h_f + u_v^2/2]_1 \\ = \dot{m}[xh_v + (1-x)h_f + xu_v^2/2 \\ + (1-x)u_f^2/2]_2, \end{aligned} \quad (15)$$

where $\dot{m}$ is the total mass flow rate and velocity equilibrium is assumed in the pipe. Assuming, also that there is little change in quality and vapor density in passing through the meter, one can write the continuity equation as

$$[u_v A]_1 = [A(xu_v + (1-x)u_f)]_2. \quad (16)$$

Also it is reasonable to assume little change in the enthalpy of the liquid in passing through the meter

so the energy equation can be simplified to

$$x(h_{v,1} - h_{v,2}) + u_{v,1}^2/2 = x[1 + \frac{1-x}{x} \phi^2]_2 u_{v,2}^2/2, \quad (17)$$

where ϕ is the slip ratio (u_f/u_v). Combining Eq. (17) with the continuity equation and solving for the vapor velocity at (2) yields

$$u_{v,2}^2 = \frac{2\Delta h_v}{(1 - \alpha^2) \left[1 + \frac{(1-x)}{x} \phi \frac{(\phi - \alpha^2)}{1 - \alpha^2} \right]} \quad (18)$$

where α is the area ratio A_2/A_1 .

In accordance with the derivation of the orifice equations, in which the internal energy change is neglected, one has

$$u_{v,2} = \sqrt{\frac{2(P_1 - P_2)}{\rho_v(1 - \alpha^2) \left[1 + \frac{(1-x)}{x} \phi \frac{(\phi - \alpha^2)}{(1 - \alpha^2)} \right]}}, \quad (19)$$

and the mass flow of the vapor is given by

$$\dot{m}_v = \rho_v A_2 u_{v,2} = \frac{A_2}{\sqrt{1 - \alpha^2}} \sqrt{\frac{2\Delta P \rho_v}{1 + \frac{1-x}{x} \phi \frac{(\phi - \alpha^2)}{(1 - \alpha^2)}}}, \quad (20)$$

where A_2 is the area of the throat or vena contracta. Incorporating the contraction ratio (A_2/A_o) and $(1 - \alpha^2)$ factor in the flow coefficient K yields*

$$\dot{m}_v = K A_o \sqrt{\frac{2\Delta P \rho_v}{1 + \left(\frac{1-x}{x} \right) \phi \frac{(\phi - \alpha^2)}{(1 - \alpha^2)}}}. \quad (21)$$

One notes that if the quality is unity, the orifice equation for a vapor is recovered and if the slip ratio is unity the equation for a homogeneous two-phase fluid is obtained.

Returning to Murdock's correlation, Eq. (2), one recognizes K_G as simply K in the above equation and $(K_G)_{TP}$ as

$$(K_G)_{TP} = \frac{K}{\left[1 + \frac{(1-x)}{x} \phi \frac{(\phi - \alpha^2)}{(1 - \alpha^2)} \right]^{1/2}}. \quad (22)$$

Thus, the ratio of flow coefficients is

$$\frac{K_G}{(K_G)_{TP}} = \left[1 + \frac{(1-x)}{x} \phi \frac{(\phi - \alpha^2)}{(1 - \alpha^2)} \right]^{1/2}. \quad (23)$$

* Actually the flow coefficient reflects somewhat more than just these two factors.

Neglecting compressibility effects ($Y = 1$), this ratio is the y-intercept for Murdock's correlation. The steam-water data used by Murdock represented qualities higher than 80%. Also, small β -ratio orifices were used ($\beta < 0.5$) which leads to small slip ratios. Both factors contribute to Murdock's correlation having a y-intercept of unity. However, with the large β -ratio orifices and lower qualities used in the present experiments, one would anticipate a higher y-intercept as observed. Also one would anticipate smaller droplets in the downstream orifice or venturi due to passage through a second valve which would lead to a larger ϕ and an upward shift of the correlation.

JAMES' EQUATION

James' equation is correlated by the factor K_J in Eq. (5). If James' equation is applicable, K_G is equal to unity. The data reduced according to James' equation is shown in Table 2 grouped according to orifice location and β -ratio. One notes that K_J is generally larger than unity indicating the nonuniversality of the factor 0.61 in James' equation. Other observations concerning the data trends agree with those discussed previously.

ENERGY EQUATION

The flow coefficients based on the energy correlation [K_E in Eq. (12)] are summarized in Table 3 where they are grouped according to the β -ratio of the orifices and venturis. For each result, standard deviations and test number are indicated. The data for the smallest orifice exhibits sizable scatter. However, an excellent correlation is noted for both the upstream and downstream orifices with a β -ratio of 0.71. As noted for the Murdock correlation, the short calming length (Tests 23 and 24) has an appreciable effect on the correlation and, therefore, should be avoided. For the large β -ratio orifices, it appears that the downstream orifices tend to have a smaller K_E whereas this trend is not observed for the smaller β -ratio orifices. This trend is probably due to droplet size being controlled by the orifice flow itself for small orifices whereas the intervening valve has some influence on droplet size for large orifices.

The venturi data are reasonably consistent although a generally higher standard deviation is noted.

Overall, the energy approach to correlating low-quality steam-water mass flow data appears to be promising. The standard deviation is

Table 2. James' correlation factor (K_J) grouped according to orifice β -ratio.

Orifice β -ratio	James' correlation factor (K_J)	
	Upstream ^a	Downstream ^a
0.58	1.11 $\pm$ 0.10 (21)	
	1.07 $\pm$ 0.08 (22)	
0.71	1.16 $\pm$ 0.03 (12)	1.15 $\pm$ 0.04 (15)
	1.39 $\pm$ 0.04 (13)	1.19 $\pm$ 0.03 (16)
	1.15 $\pm$ 0.05 (19)	1.14 $\pm$ 0.03 (20)
0.73	1.14 $\pm$ 0.03 (23)	
	0.96 $\pm$ 0.06 (24)	
0.76	1.28 $\pm$ 0.05 (20)	1.18 $\pm$ 0.07 (19)
		1.25 $\pm$ 0.05 (21)
		1.28 $\pm$ 0.05 (22)
		1.17 $\pm$ 0.12 (23)
		1.17 $\pm$ 0.08 (24)
0.78	1.30 $\pm$ 0.06 (15)	1.03 $\pm$ 0.05 (12)
	1.16 $\pm$ 0.06 (16)	

^aTest numbers are in parentheses.

generally smaller than that for James' equation which suggests the energy equation is more reliable. A dis-

advantage of this approach is the need to have enthalpy data in lieu of the more easily obtainable pressure data.

Conclusions

This study has resulted in the following conclusions concerning the utilization of orifices or venturis to meter low-quality steam-water flow.

- (1) The dependence of mass flow rate on quality in the orifice and venturi equations is too insensitive to pro-

vide a reliable measure of both mass flow rate and quality using a double flash (meter-valve-meter) arrangement.

- (2) The orifice and venturi provide a reasonably reliable measurement of the total mass

Table 3. Energy-correlation factor (K_E) grouped according to β -ratio.

	Energy correlation factor (K_E)	
	Upstream ^a	Downstream ^a
<u>Orifice β-ratio</u>		
0.58	1.09 $\pm$ 0.10 (21)	—
	1.04 $\pm$ 0.08 (22)	—
0.71	1.11 $\pm$ 0.02 (12)	1.11 $\pm$ 0.02 (15)
	1.10 $\pm$ 0.03 (13)	1.14 $\pm$ 0.02 (16)
	1.11 $\pm$ 0.04 (19)	1.12 $\pm$ 0.03 (20)
0.73	1.09 $\pm$ 0.03 (23)	—
	0.93 $\pm$ 0.05 (24)	—
0.76	1.22 $\pm$ 0.04 (20)	1.13 $\pm$ 0.05 (19)
		1.18 $\pm$ 0.05 (21)
		1.21 $\pm$ 0.05 (22)
		1.11 $\pm$ 0.10 (23)
		1.12 $\pm$ 0.06 (24)
0.78	1.23 $\pm$ 0.05 (15)	0.99 $\pm$ 0.04 (12)
	1.10 $\pm$ 0.04 (16)	
<u>Venturi β-ratio</u>		
0.78	1.30 $\pm$ 0.05 (11)	—
	1.28 $\pm$ 0.05 (17)	—
	1.35 $\pm$ 0.06 (18)	—
0.65	—	1.24 $\pm$ 0.03 (17)
		1.18 $\pm$ 0.09 (10)

^aTest numbers are in parentheses.

flow of a low-quality steam-water mixture provided the upstream quality is known.

- (3) The energy equation leads to better correlations than provided by Murdock's or James' equations. However,

equation-of-state information is needed before it can be utilized.

- (4) Using flow straighteners upstream of the meter is not recommended.

(5) A calming length of at least 20 pipe diameters upstream of the meter should be maintained.

(6) Small β -ratio meters give more reliable data at the expense of a higher pressure loss.

Suggestions for Further Study

The method described in this report for measuring total mass flow of a low-quality steam-water mixture requires that the upstream quality is known. However, if either the steam or water mass flow rate can be measured, then, the upstream quality need not be known because it can be determined simultaneously with the mass flow rate.

One method to independently measure the vapor mass flow rate is to ensure an annular or stratified flow by increasing the pipe area (decreasing the velocity) and using a pitot tube to measure the vapor velocity. Several spatial measurements might be needed to obtain sufficient data for a valid mass flow determination.

This technique, however, is not attractive from an industrial standpoint because of the delicate equipment and sensitive pressure transducers needed for pitot tube measurements.

Another possibility is using non-intrusive techniques such as sonic Doppler or tracer techniques. However, these probably lack the simplicity and durability required of industrial equipment.

A third possibility is using a vortex meter to measure the vapor velocity. However, the presence of liquid droplets may attenuate the vortex strength and affect the shedding frequency. This scheme may still have merit but requires further study.

Acknowledgments

The authors acknowledge the support of Jay Schall in laying out the experimental setup and of Glen Lathrop in setting up the experimental equip-

ment and helping with the data acquisition. The authors also acknowledge the helpful technical discussion with Terry Alger.

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Appendix

Flow Measurements Data

Upstream meter								Downstream meter					
Test-run ^a	Boiler conditions		P ₁ (psia)	Quality, X ₁	Flow rate (lbm/sec)	Differential pressure, ΔP_1 (in. of H ₂ O)	Meter type	Throat size (in.)	P ₂ (psia)	Quality, X ₂	Differential pressure, ΔP_2 (in. of H ₂ O)	Meter type	Throat size (in.)
	P ₀ (psia)	T ₀ (°C)											
11- 1	863	256.1	74.1	22.4	0.82	107.3	Vertical venturi	0.75	—	—	—	—	—
- 2	864	258.1	103.2	20.6	1.16	159.1			—	—	—	—	—
- 3	864	255.6	102.6	20.1	0.83	70.52			—	—	—	—	—
- 4	865	254.8	145.4	17.2	1.14	88.14			—	—	—	—	—
- 5	865	255.7	146.7	17.3	1.42	142.76			—	—	—	—	—
- 6	865	256.7	149.2	17.4	1.71	225.0			—	—	—	—	—
- 7	865	257.6	274.5	11.9	1.69	87.1			—	—	—	—	—
- 8	867	259.2	276.1	12.3	1.92	121.8			—	—	—	—	—
- 9	1047	262.1	280.1	12.9	2.21	181.3			—	—	—	—	—
-10	1045	258.6	278.2	12.1	1.30	47.2			—	—	—	—	—
-11	1051	258.1	118.2	19.6	1.31	175.8			—	—	—	—	—
-12	1049	257.8	117.4	19.6	1.00	98.1			—	—	—	—	—
-13	1049	258.0	116.6	19.9	0.77	46.7			—	—	—	—	—
12- 1	1031	261.4	66.1	24.4	0.51	148.0	Horizontal orifice	0.68	58.3	25.2	111.7	Horizontal orifice	0.75
- 2	1030	264.7	99.7	22.5	0.79	227.0			87.6	23.3	155.8		
- 3	1040	264.0	93.2	22.8	0.73	209.9			81.1	23.7	148.7		
- 4	1032	263.3	94.7	22.5	0.73	203.9			83.2	23.4	158.7		
- 5	1032	263.0	108.8	21.4	0.75	169.0			85.8	23.1	195.6		
- 6	1020	262.7	112.1	21.1	0.73	145.0			104.4	21.7	104.4		
- 7	1033	263.1	117.0	20.9	0.74	137.1			107.5	21.5	107.1		
- 8	1033	263.3	131.1	20.1	0.73	112.7			108.4	21.6	113.2		
- 9	1030	264.6	204.1	16.7	1.20	168.6			168.9	18.3	171.3		
-10	1035	265.1	184.5	17.7	1.24	215.9			173.3	18.4	162.8		
-11	1031	266.1	193.4	17.6	1.21	200.2			168.6	19.0	189.2		
-12	1031	266.4	170.0	18.8	1.41	335.8			151.5	19.7	284.4		
-13	1031	262.9	207.2	16.1	1.44	234.9			194.8	16.7	187.1		
-14	1035	262.1	210.5	15.8	1.45	231.2			195.5	16.4	195.5		
-15	1035	261.3	217.2	15.3	1.47	216.9			196.0	16.2	191.2		
-16	1037	260.7	265.2	13.1	1.45	161.6			250.7	13.7	127.1		
-17	1030	260.7	269.1	13.0	1.47	158.9			251.2	13.7	134.7		
-18	1030	260.6	259.3	13.3	1.45	169.1			250.7	13.7	126.7		
-19	1030	260.4	300.2	11.7	1.46	130.9			249.5	13.6	132.5		
-20	1032	260.7	333.3	10.6	1.47	110.4			249.5	13.8	136.8		
-21	1030	260.9	161.9	17.8	1.37	314.7			144.7	18.7	265.1		

^aTests 1 through 10 were preliminary check out runs.

Upstream meter

Downstream meter

Test-run	Boiler conditions		P ₁ (psia)	Quality, X ₁	Flow rate (lbm/sec)	Differential pressure, ΔP ₁ (in. of H ₂ O)	Meter type	Throat size (in.)	P ₂ (psia)	Quality, X ₂	Differential pressure, ΔP ₂ (in. of H ₂ O)	Meter type	Throat size (in.)
	P ₀ (psia)	T ₀ (°C)											
12-22	1032	260.5	140.5	18.9	1.17	287.2	Horizontal orifice	0.68	125.3	19.7	226.1	Horizontal orifice	0.75
-23	1035	260.4	139.6	19.9	1.15	282.3			124.3	20.7	232.7		
-24	1032	260.5	144.1	18.7	1.15	262.3			124.3	19.8	236.2		
-25	1032	260.6	165.8	17.5	1.15	207.6			127.6	19.6	295.6		
-26	1032	260.8	286.7	12.3	1.14	85.8			282.9	12.45	58.54		
-27	1032	260.6	261.4	13.2	1.14	95.1			251.2	13.7	79.5		
-28	1032	260.4	278.2	12.5	1.14	87.0			251.2	13.7	77.6		
13- 1	1061	251.2	104.5	18.9	0.88	200.5	Horizontal orifice	0.68	-	-	-	-	-
- 2	1061	255.2	107.1	19.7	0.84	191.8			-	-	-		
- 3	1060	257.3	154.6	17.3	0.82	103.4			-	-	-		
- 4	1060	257.9	254.1	12.8	0.80	48.5			-	-	-		
- 5	1061	258.7	316.9	10.6	0.79	35.2			-	-	-		
- 6	1061	259.3	226.6	14.3	0.82	60.0			-	-	-		
- 7	1061	259.4	316.9	10.8	0.78	33.8			-	-	-		
- 8	1061	260.3	326.2	10.7	0.79	33.5			-	-	-		
- 9	1057	260.9	232.1	14.5	1.23	143.5			-	-	-		
-10	1060	261.3	155.3	18.2	1.26	285.6			-	-	-		
-11	1058	261.2	331.5	10.8	1.19	75.1			-	-	-		
-12	1061	260.9	333.3	10.6	1.17	75.9			-	-	-		
-13	1061	261.3	160.3	18.0	1.27	278.7			-	-	-		
-14	1050	260.7	170.0	17.3	0.97	135.5			-	-	-		
-15	1055	260.2	159.3	17.8	0.90	128.0			-	-	-		
-16	1058	258.3	176.6	16.4	1.01	135.3			-	-	-		
15- 1	1026	257.2	216.7	14.2	0.81	25.0	Horizontal orifice	0.75	212.7	14.4	59.1	Horizontal orifice	0.68
- 2	1026	258.5	230.8	13.9	1.13	48.9			223.7	14.3	108.7		
- 3	1026	258.4	235.6	13.7	1.21	47.0			224.4	14.2	120.3		
- 4	1026	258.8	231.3	14.0	1.11	49.3			204.0	15.2	138.1		
- 5	1026	258.9	227.4	14.2	1.32	75.2			208.5	15.0	195.3		
- 6	1026	259.0	246.4	13.4	1.32	65.7			209.4	15.0	188.0		
- 7	1026	259.6	222.6	14.6	1.33	82.0			210.0	15.1	188.0		
- 8	1026	259.4	229.2	14.2	1.52	108.4			212.7	15.0	262.4		
- 9	1026	260.1	275.5	12.6	1.51	72.2			263.7	13.0	169.0		

Upstream meter								Downstream meter					
Test-run	Boiler conditions		P ₁ (psia)	Quality, X ₁	Flow rate (lbm/sec)	Differential pressure, ΔP ₁ (in. of H ₂ O)	Meter type	Throat size (in.)	P ₂ (psia)	Quality, X ₂	Differential pressure, ΔP ₂ (in. of H ₂ O)	Meter type	Throat size (in.)
	P ₀ (psia)	T ₀ (°C)											
15-10	1026	260.3	277.0	—	—	—	Horizontal orifice	0.75	—	—	—	Horizontal orifice	0.68
-11	1026	260.2	291.4	12.0	1.50	62.9			263.7	13.0	173.5		
-12	1026	260.2	278.2	12.5	1.51	71.0			248.7	13.6	195.5		
-13	1021	259.7	275.5	12.4	1.31	49.7			255.8	13.2	128.3		
-14	1021	259.6	286.7	12.0	1.32	45.1			255.8	13.2	133.3		
-15	1-21	259.6	280.1	12.2	1.30	47.7			247.2	13.5	143.6		
-16	1020	259.4	243.6	13.6	1.12	43.9			214.5	14.9	130.6		
-17	1020	259.2	277.3	12.2	1.09	34.0			254.7	13.1	91.9		
-18	1020	258.9	165.8	17.1	1.11	94.3			131.8	19.0	308.0		
-19	1020	258.7	108.5	20.4	0.75	74.5			90.3	21.7	204.0		
16- 1	1024	259.7	193.2	15.9	0.80	38.4	Horizontal orifice	0.75	189.2	16.1	69.2	Horizontal orifice	0.68
- 2	1024	259.8	211.2	15.1	0.82	37.7			207.4	15.3	69.4		
- 3	1024	257.9	221.8	14.2	0.84	35.4			207.7	14.8	62.2		
- 4	1024	258.5	275.2	12.1	0.82	28.4			265.2	12.5	40.9		
- 5	1021	263.3	272.4	13.5	1.10	51.0			251.2	14.3	94.6		
- 6	1021	261.5	259.0	13.6	1.12	55.1			252.3	13.8	102.2		
- 7	1021	260.6	260.5	13.3	1.12	46.0			251.8	13.6	97.3		
- 8	1021	260.2	259.9	13.3	1.11	54.8			251.2	13.6	97.6		
- 9	1021	260.1	259.9	13.2	1.12	54.4			251.2	13.5	97.0		
17- 1	1035	257.4	133.7	18.5	0.84	43.4	Horizontal venturi	0.75	94.3	21.1	279.2	Horizontal orifice	0.625
- 2	1035	258.7	173.6	16.4	0.83	39.1			150.1	17.9	137.9		
- 3	1035	259.7	188.6	16.2	0.84	35.7			152.0	18.0	135.8		
- 4	1035	260.7	228.9	14.6	0.83	26.3			203.3	15.7	87.3		
- 5	1035	260.9	219.8	15.0	0.81	28.3			203.3	15.8	90.7		
- 6	1035	262.2	217.5	15.5	1.10	49.3			181.6	17.1	203.3		
- 7	1035	262.2	223.7	15.2	1.10	48.0			182.5	17.1	210.6		
- 8	1035	262.8	218.0	15.6	1.11	49.3			183.2	17.2	216.2		
- 9	1035	262.7	276.7	13.2	1.10	34.4			254.7	14.0	124.1		
-10	1035	262.8	276.1	13.2	1.11	35.0			239.5	14.7	139.0		

Upstream meter								Downstream meter					
Test-run	Boiler conditions		P ₁ (psia)	Quality, X ₁	Flow rate (lbm/sec)	Differential pressure, ΔP ₁ (in. of H ₂ O)	Meter type	Throat size (in.)	P ₂ (psia)	Quality, X ₂	Differential pressure, ΔP ₂ (in. of H ₂ O)	Meter type	Throat size (in.)
	P ₀ (psia)	T ₀ (°C)											
17-11	1035	266.0	272.4	14.2	1.35	64.4	Horizontal venturi	0.75	198.1	17.3	304.8	Horizontal venturi	0.625
-12	1025	264.2	247.5	14.7	1.35	72.1			197.4	16.9	304.2		
-13	1025	261.1	273.3	12.9	1.27	47.6			242.0	14.1	175.2		
-14	1025	260.8	294.3	12.0	1.26	42.3			267.9	13.0	146.1		
-15	1025	260.5	293.7	12.0	1.45	61.7			255.8	13.4	219.3		
-16	1025	259.7	298.9	11.6	1.11	28.8			280.7	12.2	99.4		
18- 1	1034	258.1	120.0	19.5	0.73	41.8	Horizontal venturi	0.75	83.2	22.1	284.4	Horizontal venturi	0.625
- 2	1034	260.9	144.4	18.7	0.86	50.7			99.8	21.5	328.3		
- 3	1034	260.7	139.2	19.0	0.83	48.2			96.2	21.7	320.9		
- 4	1034	261.8	175.7	17.3	0.96	34.5			147.8	18.8	168.3		
- 5	1034	263.4	178.5	17.6	1.06	64.9			122.6	20.6	366.4		
- 6	1034	263.6	187.2	17.2	1.06	60.2			136.5	19.8	326.0		
- 7	1034	263.2	189.7	17.0	0.80	30.4			166.6	18.1	137.0		
- 8	1034	263.3	187.6	17.1	0.85	34.5			160.3	18.5	165.2		
- 9	1034	263.4	226.8	15.4	0.86	25.5			207.2	16.2	113.1		
-10	1034	259.9	223.2	14.6	1.09	42.2			188.1	16.2	213.8		
-11	1034	260.3	237.6	14.1	1.10	39.0			188.6	16.3	211.1		
-12	1034	260.1	275.5	12.6	1.09	30.6			252.0	13.5	133.5		
-13	1034	260.3	274.8	12.6	1.09	30.8			241.1	14.0	138.7		
-14	1034	260.1	271.9	12.7	1.34	48.0			225.5	14.6	243.0		
-15	1034	260.1	293.0	11.9	1.31	41.9			254.1	13.4	197.6		
-16	1034	260.0	289.5	12.0	1.12	28.7			263.7	13.0	197.5		
-17	1034	260.0	294.3	11.8	1.10	27.8			273.3	12.6	120.3		

Upstream meter										Downstream meter				
Test-run	Boiler conditions		P ₁ (psia)	Quality, X ₁	Flow rate (lbm/sec)	Differential pressure, ΔP ₁ (in. of H ₂ O)	Meter type	Throat size (in.)	P ₂ (psia)	Quality, X ₂	Differential pressure, ΔP ₂ (in. of H ₂ O)	Meter type	Throat size (in.)	
	P ₀ (psia)	T ₀ (°C)												
19- 1	1052	256.3	103.0	20.2	0.80	201.2	Horizontal orifice	0.68	86.0	21.5	160.3	Horizontal orifice	0.725	
- 2	1052	262.5	230.8	15.0	0.81	61.0			229.5	15.0	38.7			
- 3	1052	260.6	235.6	14.3	0.84	60.1			229.7	14.5	39.0			
- 4	1052	259.4	227.9	14.3	0.84	63.3			208.5	15.2	42.9			
- 5	1052	260.2	223.2	14.7	1.10	111.3			181.6	16.6	98.8			
- 6	1052	264.4	223.2	15.8	1.34	187.7			206.0	16.5	146.8			
- 7	1052	263.4	222.9	15.5	1.58	256.2			198.1	16.6	220.6			
- 8	1052	262.2	278.2	12.0	1.57	166.0			263.1	13.6	126.8			
- 9	1052	259.8	276.7	12.4	1.62	215.0			256.4	13.2	171.5			
-10	1052	260.8	280.1	12.6	1.32	108.3			270.6	12.9	80.0			
20- 1	1047	256.8	79.0	22.2	0.623	86.6	Horizontal orifice	0.725	68.3	23.1	186.7	Horizontal orifice	0.680	
- 2	1047	258.8	98.2	21.1	0.77	110.2			84.9	22.1	236.0			
- 3	1047	258.3	145.8	18.0	1.19	158.9			126.7	19.1	330.7			
- 4	1047	259.0	228.4	14.2	1.20	65.5			220.3	14.5	144.6			
- 5	1047	262.4	228.9	15.0	1.19	69.7			213.0	15.7	159.9			
- 6	1047	260.5	226.0	14.7	1.37	95.9			206.0	15.5	222.9			
- 7	1047	258.9	222.1	14.4	1.65	143.1			192.2	15.9	333.6			
- 8	1047	261.7	277.3	12.9	1.64	103.6			256.7	13.7	222.6			
- 9	1047	261.7	290.2	12.8	1.31	64.0			278.9	12.8	119.6			
-10	1047	261.1	276.1	12.8	1.31	67.3			263.7	13.3	131.0			
-11	1047	260.2	277.9	12.5	1.13	48.9			270.0	12.8	90.5			
-12	1047	259.9	292.4	11.9	1.14	47.8			285.7	12.1	82.3			
-13	1047	260.1	284.5	12.2	1.13	48.9			255.8	13.3	90.9			

Upstream meter										Downstream meter				
Test-run	Boiler conditions		P ₁ (psia)	Quality, X ₁	Flow rate (lbm/sec)	Differential pressure, ΔP ₁ (in. of H ₂ O)	Meter type	Throat size (in.)	P ₂ (psia)	Quality, X ₂	Differential pressure, ΔP ₂ (in. of H ₂ O)	Meter type	Throat size (in.)	
	P ₀ (psia)	T ₀ (°C)												
21- 1	1034	257.8	223.2	14.1	0.79	181.0	Horizontal orifice	0.5541	84.9	21.9	157.0	Horizontal orifice	0.725	
- 2	1034	258.4	119.9	19.6	0.81	348.9		83.6	22.2	150.7				
- 3	1034	259.2	184.9	16.2	0.80	234.6		171.9	16.9	48.3				
- 4	1034	259.8	227.4	14.4	0.80	181.9		218.5	14.8	36.4				
- 5	1034	260.3	280.1	12.4	0.78	134.6		273.9	12.7	27.5				
- 6	1034	260.2	292.1	11.9	0.78	123.0		286.3	12.2	25.9				
- 7	1034	260.7	187.0	16.5	1.11	344.3		144.4	18.7	141.6				
- 8	1034	260.9	225.0	14.8	1.12	345.2		201.1	12.7	79.3				
- 9	1034	260.9	277.8	12.7	1.11	261.6		262.5	13.3	52.1				
-10	1034	261.1	293.0	12.1	1.09	247.8		278.9	12.7	47.7				
22- 1	1052	258.6	108.7	20.4	0.74	349.1	Horizontal orifice	0.5541	77.6	22.7	143.4	Horizontal orifice	0.725	
- 2	1052	256.5	187.0	15.4	0.77	209.5		179.6	15.8	37.9				
- 3	1052	256.0	229.2	13.4	0.78	164.0		224.2	13.6	26.5				
- 4	1052	258.1	226.7	14.0	0.76	170.6		209.0	14.8	35.4				
- 5	1052	258.6	281.0	11.9	0.75	120.5		270.0	12.4	24.1				
- 6	1052	259.1	277.9	12.2	0.76	128.1		273.3	12.4	21.6				
- 7	1052	261.0	303.2	11.7	0.76	110.4		299.5	11.9	19.3				
- 8	1052	264.4	275.2	13.7	1.06	280.2		265.2	14.1	51.9				

Upstream meter									Downstream meter					
Test-run	Boiler conditions		P ₁ (psia)	Quality, X ₁	Flow rate (lbm/sec)	Differential pressure, ΔP ₁ (in. of H ₂ O)	Meter type	Throat size (in.)	P ₂ (psia)	Quality, X ₂	Differential pressure, ΔP ₂ (in. of H ₂ O)	Meter type	Throat size (in.)	
	P ₀ (psia)	T ₀ (°C)												
23- 1	1050	254.9	107.8	19.5	0.88	205.4	Horizontal orifice	0.70	89.0	20.9	145.6	Horizontal orifice	0.725	
- 2	1050	256.7	116.9	19.4	0.88	155.9			91.7	21.1	175.0			
- 3	1050	258.4	101.9	20.8	0.86	207.6			89.6	21.7	150.7			
- 4	1050	260.8	184.0	16.7	0.85	83.4			179.2	16.9	51.1			
- 5	1050	262.2	184.0	17.0	0.85	84.5			169.5	17.7	85.8			
- 6	1050	262.5	182.0	17.2	1.15	154.9			152.0	18.7	195.3			
- 7	1050	261.3	181.2	16.9	1.13	150.8			172.3	17.4	105.7			
- 8	1050	261.1	225.0	14.9	1.16	108.4			218.0	15.2	71.9			
- 9	1050	261.3	229.0	14.7	1.16	113.9			217.2	15.3	121.6			
-10	1050	261.4	224.5	15.0	1.15	112.2			193.2	16.4	128.9			
-11	1050	261.3	226.6	14.8	1.36	153.6			201.7	15.9	158.0			
-12	1050	261.6	227.9	14.9	1.36	149.7			184.9	16.8	204.9			
-13	1050	261.2	276.1	12.8	1.35	118.8			264.6	13.3	109.2			
-14	1050	260.4	275.1	12.6	1.37	120.8			237.0	14.2	130.6			
24- 1	1027	259.7	77.0	23.0	0.60	194.1	Horizontal orifice	0.70	67.0	23.9	115.0	Horizontal orifice	0.725	
- 2	1027	260.8	104.6	21.2	0.87	275.0			93.4	22.0	156.1			
- 3	1027	256.8	184.3	15.6	0.90	139.7			177.6	16.0	54.7			
- 4	1027	253.4	184.9	14.8	0.93	134.1			177.0	15.2	60.1			
- 5	1027	249.7	184.3	13.9	0.93	136.2			171.8	14.5	71.9			
- 6	1027	258.6	236.2	13.7	1.16	139.6			222.3	14.3	93.5			
- 7	1027	261.2	184.9	16.7	1.12	205.0			164.3	17.7	144.4			
- 8	1027	261.3	221.9	15.0	1.10	146.6			207.7	15.7	95.4			
- 9	1027	261.3	230.8	14.7	1.14	153.5			217.2	15.3	99.0			
-10	1027	261.2	230.8	14.6	1.13	158.9			216.2	15.3	98.0			
-11	1027	261.4	229.2	14.8	1.39	161.2			207.7	15.7	165.1			
-12	1027	261.3	272.4	13.0	1.37	160.7			257.3	13.6	106.9			
-13	1029	261.0	272.7	12.9	1.16	113.0			261.9	13.3	70.8			
-14	1029	260.7	273.3	12.8	0.92	72.7			267.0	13.1	42.1			