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EFFECTS OF ORIFICE GEOMETRY ON STEAM-WATER CRITICAL FLOW

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SUMMARY - Critical flow behavior of steam-water mixtures through orifices was investigated experimentally. As the steam quality increases, mass flow rates per unit orifice area rapidly decrease even at low pressure ratios. For the steani quality larger than 6 %, two-pliase flow shows critical flow behavior. Effects of the orifice diaineter on two-phase flow are sinall, while an increase in the plate thickness largely depresses the mass flow rate.

1. INTRODUCTION

The critical flow phenomenon in single component, two-phase, vapor-liquid mixtures occurs in various processes, such as blow-offs from boilers, draining of feed-water heaters, a burst of a boiling-water reactor. Earlier research work on this subject includes both experimental and theoretical studies of critical flow through pipes, ducts, nozzles, orifices, and other apertures. Extensive studies have been done on two-phase blowdown of a high pressure vessel, particularly a nuclear reactor system.

Hutcherson (1975), for instance, investigated the bubble growth mechanism within the vessel during the early period of the decompression, the two-phase flow behavior within the vessel, and the blowdown transient in a short duct. His results confirmed that transient two-phase critical flow in large ducts is essentially the same physical phenomena as steady-state two-phase critical flow in small ducts.

The flow of steam-water mixtures through orifices has been also investigated. Orifices are often installed in pipelines for metering a flow rate of single- or two-phase flow, and for throttling fluid flow. Benjamin and Miller (1941) conducted experiments of the flow of saturated water through sharp-edged thin-plate orifices. They concluded that no flashing occurs until after the saturated water is through the orifice, and no critical-pressure condition is evident, and that a change in steam quality between 0 and 0.04 has a considerable effect on the total weight of the mixture. Chisholm and Watson (1968) reported experimental results and correlations also for the flow of steam-water mixtures through sharp-edged orifices.

In geothermal engneering, two-phase critical flow can possibly occur in wellbores and pipes because of high flow rates and a wide range of steam qualities in a wellbore and surface facilities. The present study was initiated to obtain reliable data of single- and two-phase flow through orifices which are assumed to be set in a surface pipeline for throttling purposes. Data should be useful for instance to estimate the discharge flow rate in a blow-off process from a pipeline to atmosphere. Objectives of the study are to examine effects of the size and shape of orifices, and the thickness of plates on single- and two-phase flow, and to also test effects of steam quality on flow behavior.

2. EXPERIMENTS

Experiments were conducted by an apparatus as shown schematically in Fig. 1. Main parts of the apparatus are a tank, a flow line, an orifice plate and its mounting flanges, a flow rate measuring device, and heating-temperature controllers. The tank is of 0.48 m^3 capacity, and heated inside by mantled heaters and outside by heating tapes. A discharge flow line is of 2.54 cm (1 inch) inside diameter and 2 m length connecting the bottom of the tank and the orifice mounting flanges. Two valves, a ball-valve and a flow regulating valve, are placed in series on the flow line. The flow line is heated by heating tapes to bring the pipe walls approximately to the fluid temperature. SUS304 was used for all the parts which make contact with water.

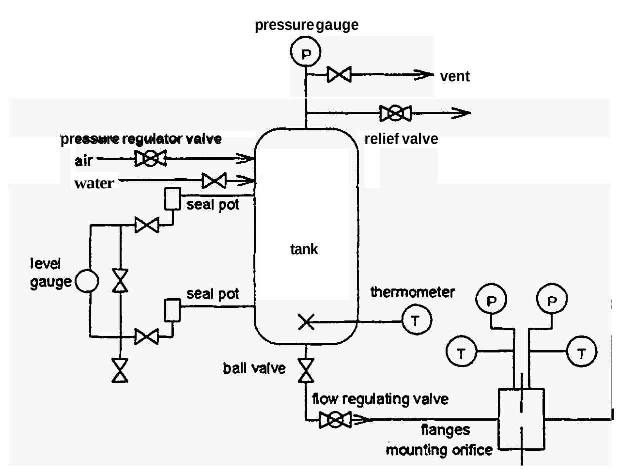

Figure 1 - Schematic layout of experimental apparatus

The **flow** rate is estimated by measuring the falling rate of water level in the tank. The water level is continuously monitored by a pressure-difference transducer connected to the lines from two pressure tappings at about one-tenth and nine-tenth of the tank height. **A** seal-pot is inserted between each tapping and the pressure transducer. **A** schematic drawing of the orifice mounting flanges is shown in Fig. **2.** The pressure and temperature tappings are placed immediately upstream and downstream of the orifice plate. The orifice plates used for the study are shown in Fig. **3.** Table 1 lists geometry and thicknesses of the orifice plates. Three different thicknesses of plates, 1.8 mm, **12.7** mm **(1/2** in), and **25.4** mm (1 in), were tested for the circular orifices of diameter **3.18** mm **(1/8** in) and **6.35 mm (1/4** in).

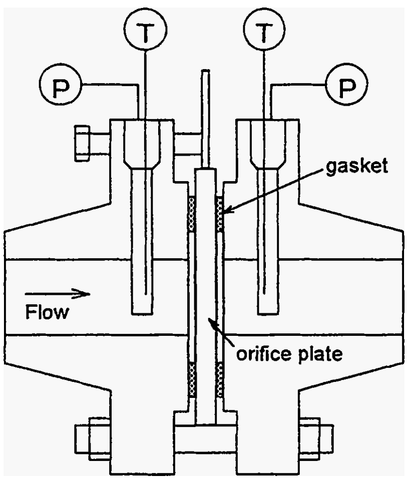

Figure 2 - Orifice mounting flanges

Table 1 - Orifice dimensions and test conditions for single-phase flow.

shape	size mm	thick. mm	temp. degC	mass rate kg/sec.m²	press. ratio
circle	3.18	1.80	25	9281-23235	1.95-6.95
circle	3.18	12.7	20	10085-23234	1.95-6.95
circle	3.18	25.4	24	10910-24058	1.85-6.95
circle	6.35	1.80	25	13742-19721	3.85-6.95
circle	6.35	12.7	24	11607-17217	2.35-6.75
circle	6.35	25.4	15	11722-20316	1.95-6.95
square	3.18	12.7	28	9235-21316	1.85-6.35
triangle	3.18	12.7	39	3794-23389	1.15-6.15
upper semicircle	3.18	12.7	32	3444-18821	1.15-5.75
lower semicircle	3.18	12.7	39	3175-19113	1.15-6.05

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The tank is fed with tap water after being filtered, and heated up to a required temperature. During heating, pressure is kept constant above the saturation pressure by pressurized air supplied into top of the tank from an air cylinder. The maximum temperature and pressure allowed for experiments are **190** ℃ and **1470** kPa, respectively. Pressure increases during heating are adjusted by a relief valve placed on a line from top of the tank. This initialization for an experimental run is continued unitl temperatures detected in tank water and on the flow line wall reach the target temperature.

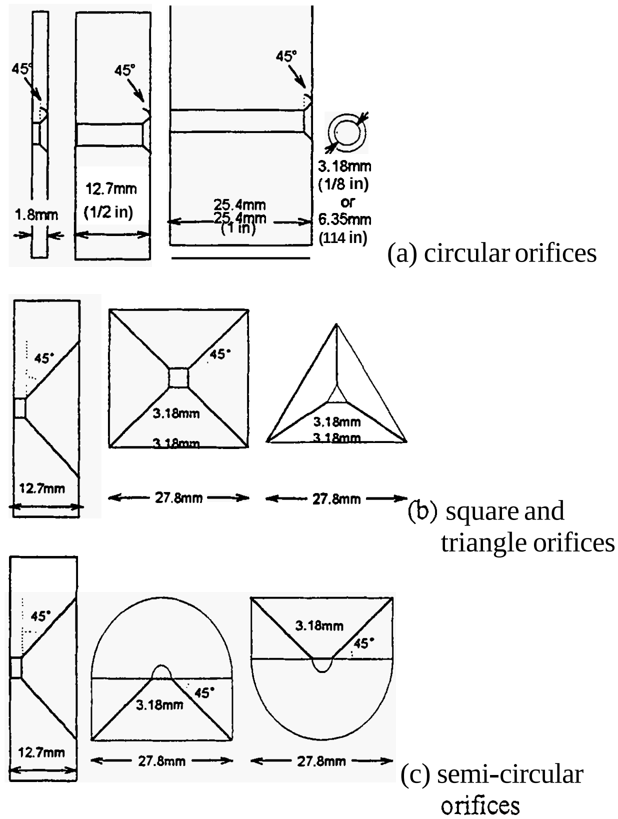

Figure 3 - Tested orifices

At a stabilized stage, electric power for heating water, the tank wall, and the line wall should be minimal. Making a computer ready for recording and displaying data, the ball-valve is opened to allow water discharge into the flow line. The flow rate is adjusted by the regulating valve. The flow line downstream of the orifice is of **2.54** cm inside diameter and **2** m length, and open to atmospheric pressure without back-pressure. During blowing down **the** tank, the pressure in the tank is maintained constant by feeding air through the pressure regulating valve. **A** set of data consisting of the water level in the tank, and pressures and temperatures upstream and downstream of the orifice plate are recorded every 1 **-** 4 seconds.

3. RESULTS AND ANALYSIS

3.1 Single-Phase Flow

Effects of three kinds of orifice parameters were examined, i.e. diameter of the circular orifice, thickness of the orifice plate, and shape **of** the orifice. Two different orifice diameters, **3.18** mm (1/8 in) and **6.35 mm (1/4** in), and three different thicknesses, **1.8** mm, **12.7** mm **(1/2** in), and **25.4** mm **(1** in) for each diameter, were tested. Flow conditions are seen in Table **1.** Figs. **3** and **5** show results for 3.18 and **6.35** mm diameters, respectively, graphed as mass flow rate per unit orifice area vs. **the** ratio of upstream pressure and downstream pressure.

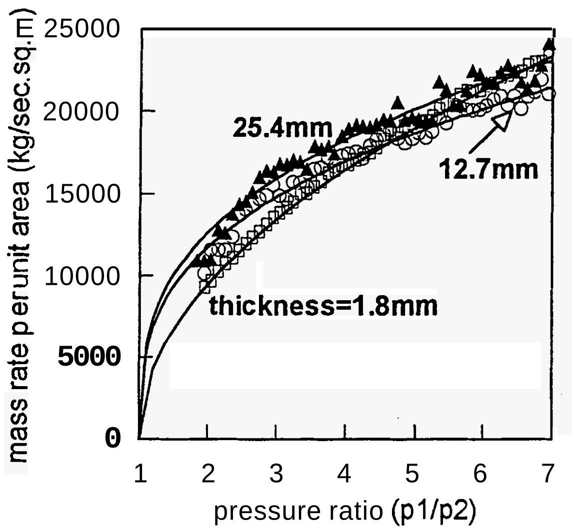

Figure 4 - Flow of water through circular orifice of 3.18 mm (1/8 in) diameter

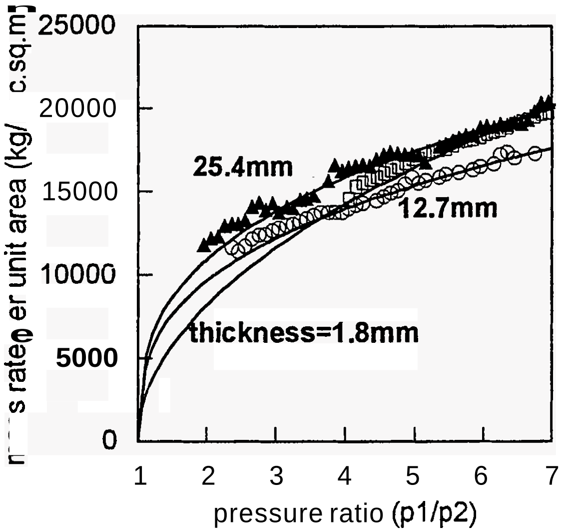

Figure 5 - Flow of water through circular orifice of 6.35 mm (1/4 in) diameter

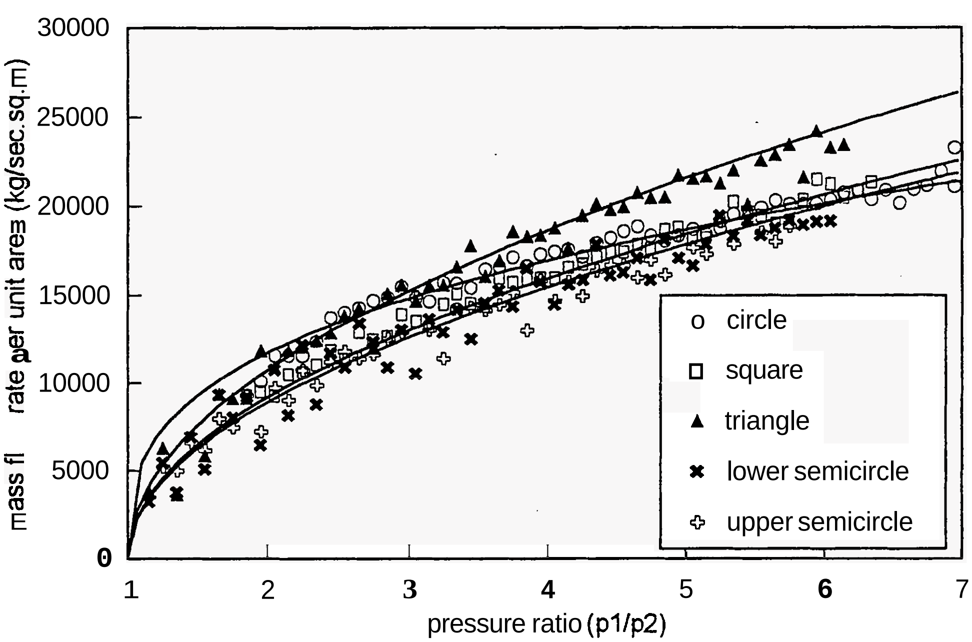

Figure 6 - Flow of water through various orifices

Several flow characteristics are observed in these graphs. For the thin (1.8 mm) plate of orifices, flow data can be correlated with the general equation for flow of 'cold water' (20°C) through orifices as

$$w = C\sqrt{2\rho p_2(p_1/p_2 - 1)} \qquad (1)$$

where w is mass flow rate per unit area, C is flow coefficient, p is density of water, p_1 is upstream pressure, and p_2 is downstream pressure. Tlie flow coefficients C's for the orifice diameters 3.18 mm and 6.35 mm are determined to be 0.68 and 0.58, respectively. The **mass** flow rate per unit orifice area for diameter 3.18 mm is much higher than that of diaiiieter 6.35 mm.

For both cases of the orifice diameters, behaviors of flow through the thicker plates are different from behavior of the 1.8 mm plate, in that mass flow rates of the thick plates are higher than that of the 1.8 mm plate for lower values of the p_1/p_2 ratio, and tend to bend down at higher values of the pressure ratio. These flow characteristics are caused by longer conduits in the thicker plates.

Fig. 6 shows flow behaviors for five different orifice geometries, i.e. circle of 3.18 mm diameter, square of 3.18 mm sides, triangle of 3.18 mm sides, upper and lower semi-circle of 3.18 mm diameter, all with 12.7 mm (1/2 in) plate thickness. Tlie data can be correlated by Eq. (1) with flow coefficients C's, 0.65, 0.76, and 0.63 for the square, triangle, and semi-circle cases, respectively. The data of the upper and lower semi-circles show similar distributions and scatterings. As seen in Fig. 6, effects of the plate thickness are exhibited only in the case of the circular orifice.

It is confirmed from Figs. 4 - 6 that no critical **flow** exists in single-phase flow through the tested sharp-edged and thicker orifices.

3.2 Two-Phase Flow

Measurements on two-phase flow of steam-water mixtures were conducted by changing the size of circular orifice and thickness of plate. Steam qualities upstream of the orifice are evaluated assuming the enthalpy of the mixtures to be equal to the enthalpy of water in the tank. Table **2** presents the dimensions and test conditions for each orifice. Figs. **7** - 9 present the results for the orifice of diameter **3.18** mm (**1/8** in), and Figs. **11** - **13** for the orifices of diameter 6.35 mm (**1/4** in). As expected, two-phase flow showed unstable behavior which is reflected in scattered **data.** particularly for steam quality **0.02.** The solid lines in these graphs represent correlation obtained by Eq. **(1)** with the averaged flow coefficients for each quality.

Table 2 - Orifice dimensions and test conditions for two-phase flow runs.

shape	size mm	thick. mm	temp. degC	quality range	mass rate kg/sec.m^2	press. ratio
circle	3.18	1.80	115-195	0.0017-0.160	130-26560	1.08-8.72
circle	3.18	12.7	115-185	0.0002-0.131	205-25736	1.18-8.92
circle	3.18	25.4	115-180	0.0004-0.135	570-24729	1.28-8.88
circle	6.35	1.80	145-185	0.0099-0.145	189-14522	1.15-3.75
circle	6.35	12.7	150-180	0.0014-0.142	143-7952	1.15-4.45
circle	6.35	25.4	115-185	0.0046-0.149	95-9532	1.05-4.65
square	3.18	12.7	155-185	0.0325-0.148	260-18294	1.05-5.35
triangle	3.18	12.7	155-185	0.0098-0.147	382-17805	1.15-5.85
semicirc-1	3.18	12.7	155-185	0.0527-0.127	297-5358	1.15-2.55
semicirc-2	3.18	12.7	155-185	0.0330-0.111	105-16060	1.21-7.12

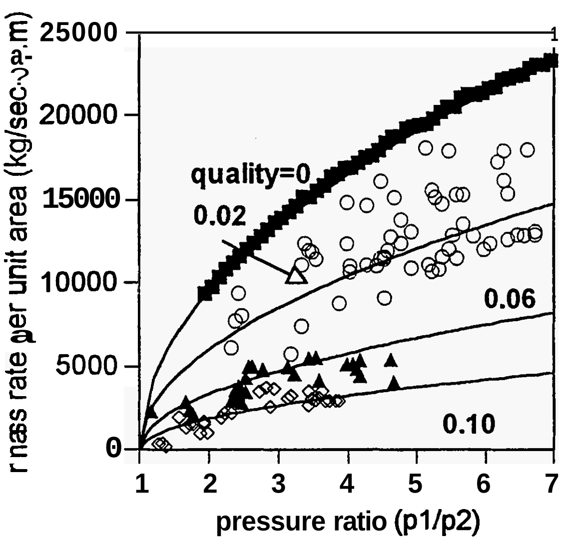

Figure 7 - Two-phase flow through orifice, diameter **3.18** mm, thickness **1.8** mm

Effects of quality - Figs. **7** - 9, and **11** - **13** show that as the steam quality increases, mass flow rates per unit area decrease largely regardless of the orifice diameter. Decrements become smaller when the steam quality is larger than 0.06. This feature is more pronounced for the plate thickness of **12.7** and **25.4 mm**. This is consistent with previous studies, and can be considered as one of the characteristics of two-phase flow through orifices.

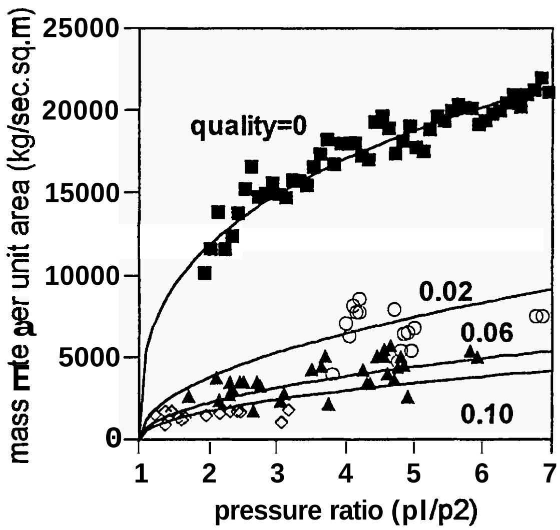

Figure 8 - Two-phase flow through orifice, diameter **3.18 mm**, thickness **12.7 mm**

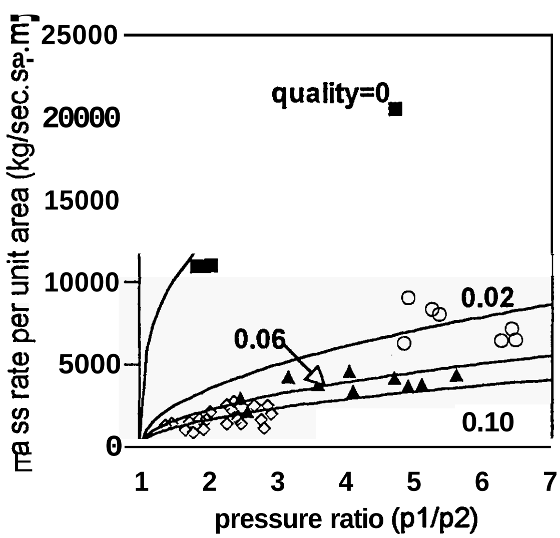

Figure 9 - Two-phase flow through orifice, diameter **3.18** mm, thickness **25.4 mm**

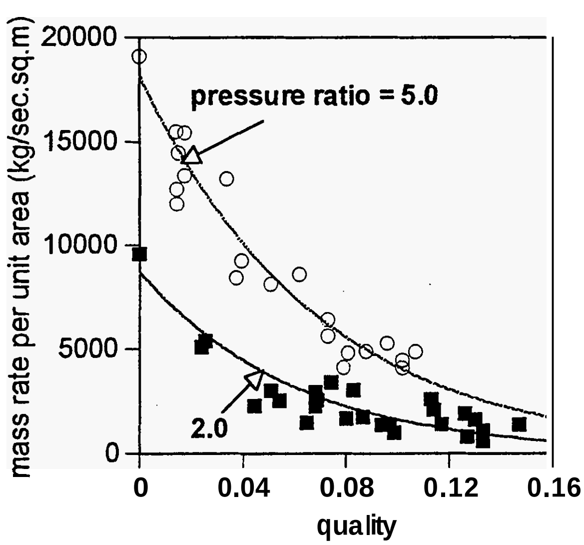

Figure 10 - Mass flow rate as a function of steam quality, orifice diameter **3.18** mm, thickness **1.8 mm**

Figure **10** shows tlie mass flow rate as a function of steam quality in the case of orifice diameter **3.18** mm, and thickness **1.8** mm

It is also important to note that two-phase flow appears to show critical flow behaviour for the steam qualities larger than 0.06. This can be clearly observed in flow through the **3.18** mm orifices as seen in Figs. **7** - 9.

Effects of orifice diameter - The orifice diameter affects strongly the mass flow of single-phase water as described above. For two-phase flow, however, effects of the orifice diameter on the mass flow rate per unit area appear to be minimal, as observed by comparing the data for two diameters of the saine plate thickness, i.e. Figs. **7** and **11,** Figs. **8** 'and 12, and Figs. 9 and **13.** This is considered to be caused by the compressible property of two-phase flow, but should be further examined by testing orifices of other sizes.

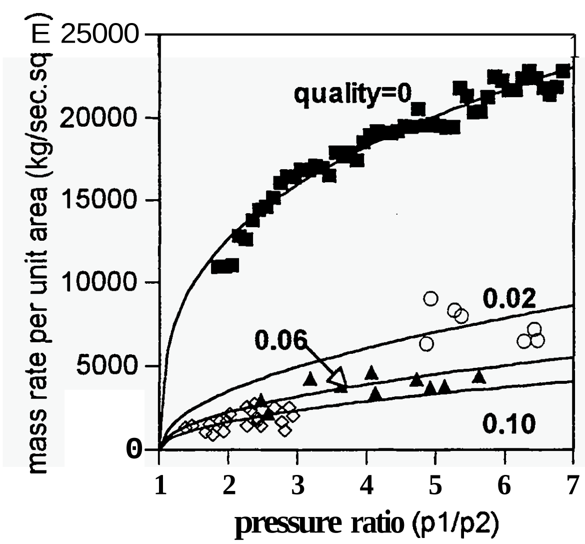

Figure 11 - Two-phase flow through orifice, diameter **6.35** nun, thickness **1.8** mm

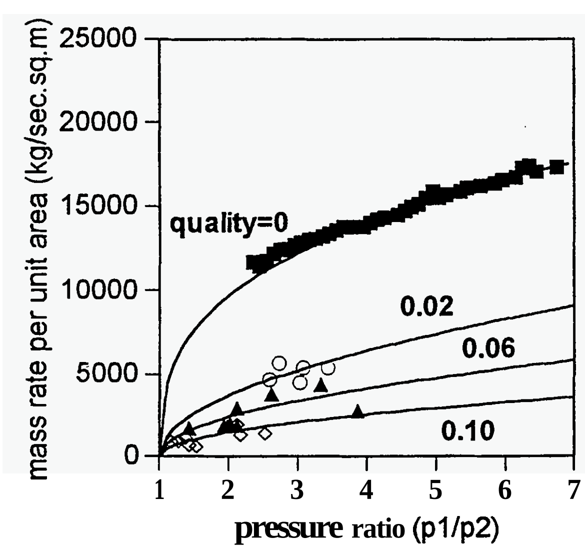

Figure 12 - Two-phase flow through orifice, diameter **6.35** mm, thickness **12.7** mm

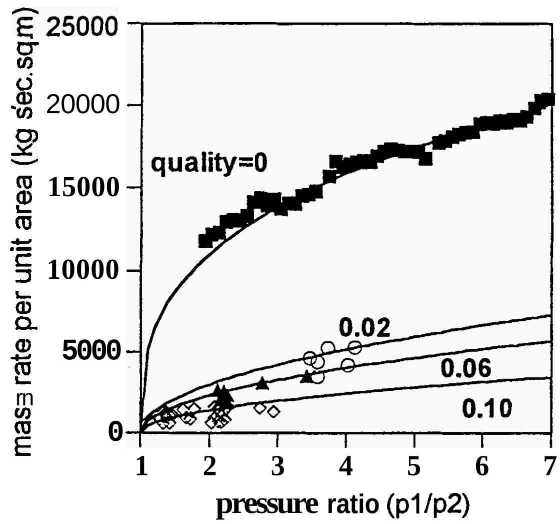

Figure 13 - Two-phase flow through orifice, diameter 6.35 mm, thickness 25.4 mm

Effects of plate thickness - Comparing the data for the same orifice diameter but for different plate thicknesses, it is observed that mass flow rates are strongly depressed as the plate thickness increases from **1.8** mm to **12.7** mm. A futher increase in thickness from **12.7** mm to 25.4 mm, however, does not much affect two -phase flow behavior.

4. CONCLUSIONS

1. Effects of three parameters on single-phase water flow were examined.
- Flow through thin-plate **(1.8** mm) orifices can be correlated by the general equation with the flow coefficient. The flow cofficient takes a lower value as tlie orifice diameter is increased.
- Flow through thick-plate **(12.7** and 25.4 mm) orifices deviates from the general equation.
- Flow through **the** thick-plate **(12.7** mm) orifices of non-circular shapes can be correlated by the general equation.

2. For two-phase flow, effects of the steam quality, orifice diameter, and plate thickness were evaluated.
- The mass flow rate per unit area decreases largely, as the steam quality increases. Decrements become smaller when the steam quality is larger than 0.06.
- The mass flow rate per unit area is not much affected by an increase in orifice diameter from **3.18** to **6.35** mm.
- Mass flow rates are strongly depressed as the plate thickness increases from **1.8** mm to **12.7** mm.

5. ACKNOWLEDGEMENTS

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