EXPERIMENTAL STUDY ON TRANSPORTATION OF TWO-PHASE MIXTURES THROUGH HORIZONTAL AND INCLINED PIPES

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INTRODUCTION

In a hot water type geothermal power plant, it is desirable for higher thermal efficiency and for economical advantages to adopt the double flash cycle with steam-water mixture transportation from wells to the power station site without wellhead separators. To realize the steam-water mixture transportation, some problems such as flow stability and increase of pressure drop, which are not encountered in the transportation of the single phase steam or water, should be clarified.

Therefore, steam-water test was carried out at actual geothermal fields to investigate the characteristics of the mixture transportation. And an air-water test have also been carried out in a wider range of the inclination of a pipe to investigate the effect of the inclination.

TEST EQUIPMENT

The steam-water tests were carried out at Otake(1) and Hatchobaru(2). The test section at Otake was composed of a horizontal pipe, an inclined pipe and three bends, connected in series. The inside diameter of the pipes is 200 mm and the overall length of the test section is approximately 70 m. The effective lengths of the horizontal and the inclined pipes are 23.85 m and 23.95 m, respectively. The slope angle of the inclined pipe was 7°25' from horizon. Both of the upward flow and the downward flow in the inclined pipe were tested by changing the flow direction.

In the test at Hatchobaru, a pipe of 300 mm in inside diameter, 162 m in effective length and approximately 7° downward inclination, was used as the test section. Two sight glasses were installed on the pipe for the observation of flow patterns.

In both tests, the mixtures of steam and hot water coming up from the wells were introduced into the test sections, and then into the separators where steam and water were separated from each other and discharged out. The flow rate of the steam-water mixture was adjusted with a valve at the inlet of the test section and the pressure in the pipe with a valve at the exit of that. The flow rates of steam and water were measured by an orifice and a weir, respectively, after their separation. Several pressure gauges and manometers for the measurement of the pressure drops were set on the test sections.

The air-water test was carried out under the atmospheric pressure and at room temperature using the equipment shown in Fig.1. Air supplied by the blower and water pumped from the storage tank were mixed in the mixer and then entered into the test section. The flow rates of air and water were measured by orifices before mixing. The test section was made of a transparent acrylate pipe, 100 mm in inside diameter and approximately 10 m in length. Two quick shut valves were installed at the positions of 5.8 m and 8.7 m from the inlet of the test section to measure the void fraction in the pipe by shutting these valves simultaneously with a link. The test section was provided with pressure taps at 1000 mm or 750 mm intervals except the parts of the quick shut valves. The mixture leaving the test section was led into the separator. The separated air was discharged out to the atmosphere while water was returned back into the storage tank.

The bypass line from the exit of the mixer to the separator was used to release the air water mixture when the quick shut valves were closed.

The inclination of the test section was changed to four angles, horizontal, 30° upward, 45° upward, and 30°

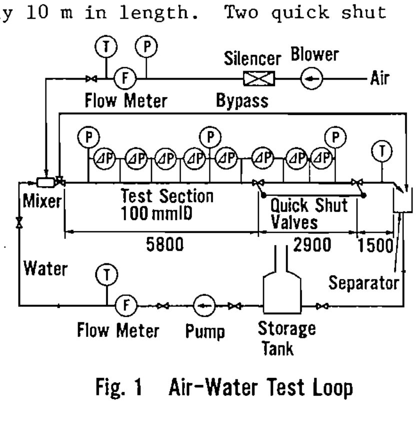

Fig. 1 Air-Water Test Loop

Table 1 Test Conditions in Steam-Water Test

Field	Test Series	Pressure MPa	Mixture Velocity m/s	Steam Weight Fraction %
Otake	Upward	0.21～0.25	13～39	7～10
	Downward	0.20～0.24	14～37	7～11
Hatcho-baru	Transient	0.24～0.60	6～58	6～26
	Steady	0.29～0.60	4～55	4～26
	Long-Run	0.40	50	22

Table 2 Test Conditions in Air-Water Test

Test Series	Air Velocity m/s	Air Weight Fraction %
Horizontal	7～50	5～50
30° Upward	7～50	5～75
45° Upward	10～50	10～75
30° Downward	10～50	10～50

TEST CONDITIONS

The flow conditions in the steam-water and the air-water tests are listed in Tables 1 and 2, respectively. The mixture velocity means the velocity of homogeneous mixture with no slip between steam and water. The present tests may cover almost the whole range of flow conditions for the mixture transportation in practical use.

FLOW PATTERNS

The flow conditions in the steam-water test at Hatchobaru are plotted on the Baker chart as shown in Fig.2. It is seen that the tests with the mixture velocity U_M higher than about 25 m/s are in the mist flow region, lower than 25 m/s in the annular flow, and at 4 m/s on the boundary between the annular and the slug flows, according to the Baker flow pattern map.

The typical flow patterns actually observed at Hatchobaru through the sight glasses are summarized in Fig.3, comparing with the Baker's patterns. The steam flow which occupied the greater part of the passage in the pipe was truly transparent when superficial steam velocity U_{SO} was very low. With increase in U_{SO}, the steam gradually contained more mist and became non-transparent. At the bottom of the passage, a water layer was always found. The thickness of the layer was presumed to be from 10 mm to 20 mm.

On the other hand, a very thin discontinuous water film appeared at the upper inside wall of the pipe only in some rare cases. Hence, this kind of flow pattern can be called a semi-annular mist flow.

Figure 4 is the comparison of the flow pattern observed in the horizontal air-water flow test with the Baker and the Mandhane boundaries. At 10 m/s in the superficial air velocity, the wavy flow was observed. At 20 m/s, the wavy water layer was still present at the bottom of the pipe, while the inside wall above the water layer was covered with water film, with an exception of higher water flow condition. This was regarded as the annular flow. At the air velocity of 30 m/s or more, the flow became the annular mist flow in which the air flow above the water level contained the water mist and the water layer was frothy with bubbles. The water layer became thinner with decrease in the water velocity and increase in the air velocity.

As seen from this figure, the flow pattern boundary in the air-water test agreed relatively well with the Mandhane's than with the Baker's. The flow patterns in the steam-water test shown in Figs. 2 and 3 can also be regarded as the wavy flow or the stratisfied flow in the region of the low steam velocity not more than 10 m/s.

The flow patterns of air-water and steam-water mixtures are similar to one another, and agreed relatively well with the Mandhane's chart.

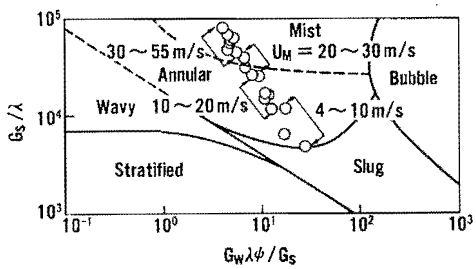

Fig. 2 Plot of Flow Conditions in Hatchobaru Test on Baker Chart

U_{SO} m/s	U_{WO} m/s	Baker's Pattern	Flow Pattern
4	0.22	Annular	Transparent Steam / Water Layer
22	0.35	Annular	Uneven Semi-Transparent Mist / Water Layer
43	0.51	Mist	Uneven Non-Transparent Mist / Water Layer
54	0.52	Mist	Dense Non-Transparent Mist / Water Layer

Fig. 3 Typical Flow Pattern in Hatchobaru Test

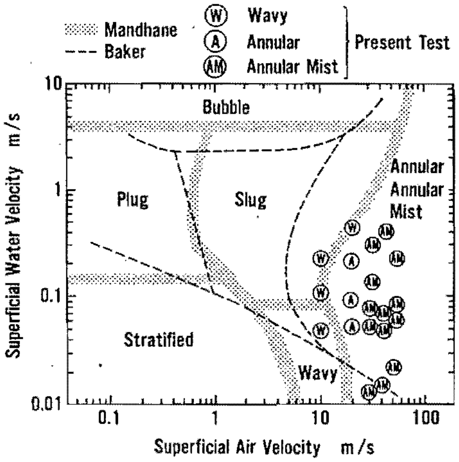

Fig. 4 Flow Pattern of Horizontal Air-Water Flow

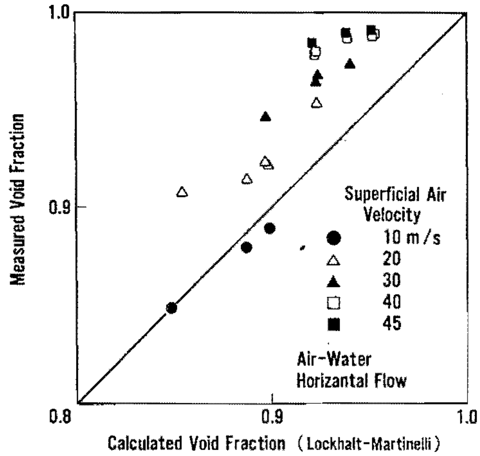

Fig. 5 Comparison of Measured Void Fraction with Calculation

VOID FRACTION

The void fractions measured by the quick shut method in the horizontal air-water flow test are given in Fig.5, comparing with the calculation based on the Lockhalt-Martinelli's method(3) (L-M method). The measured void fraction was higher than the calculation. The difference between the measurement and the calculation becomes larger with the increase in the air velocity and with the decrease in the air weight fraction.

The measured void fraction was also higher than the calculation in upward and downward flows. In upward flow, the differences between the measured and the calculated void fractions were smaller than that in the case of the horizontal flow. The tendency of the change of the void fraction with the air velocity and the air weight fraction was similar to that of the horizontal flow in upward flow, but was opposite to in downward flow.

PRESSURE DROP

The frictional pressure drop in the horizontal air-water flow test are correlated by the L-M method in Fig.6. The L-M curve for turbulent-turbulent flow and the data of other researchers(4),(5) are also shown in this figure. Although ϕ_G in this test is lower than the L-M curve, it is on the extrapolation of the results of Reid et al. and Chhabra et al., showing no inconsistency. Simpson et al.(6) mentioned that the value of ϕ_G changed according to the flow pattern and was smaller than that by the L-M method in the annular flow. The results of the present test show same tendency with this.

ϕ_G in the upward flow was somewhat lower than the L-M curve, rather near to it.

The pressure drop correlation in the 30° downard air-water flow and the 7° downward steam-water flow are shown in Fig.7. Both of them agreed relatively well with the L-M curve.

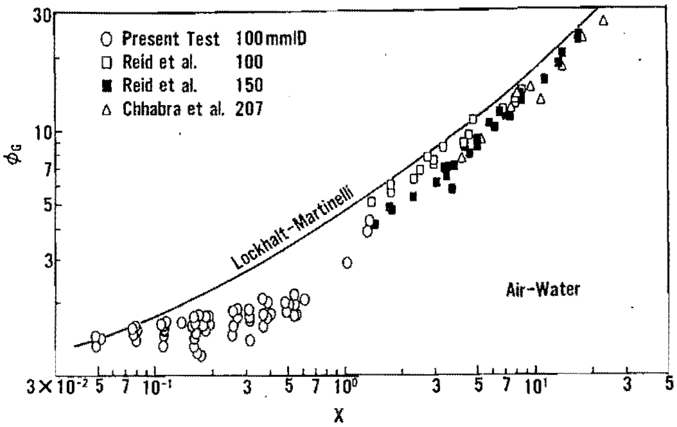

Fig. 6 Correlation of Frictional Pressure Drop in Horizontal Flow

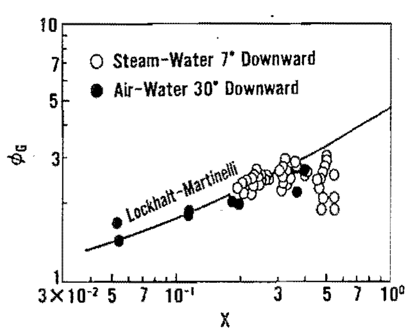

Fig. 7 Correlation of Frictional Pressure Drop in Downward Flow

FLOW STABILITY

During the tests at Otake and at Hatchobaru, no vibrations of pipes were experienced and it was verified that the flow of the steam-water mixture was stable enough under the pipe inclination tested.

In the air-water test, the horizontal flow and the 30° downward flow showed no instability in all the test ranges. Although the flows 30° upward and 45° upward showed some instability under the conditions of slower air velocity, the flows were sufficiently stable at velocities above certain levels.

CONCLUSION

(1) The flow patterns of the steam-water mixture and the air-water mixture approximately agreed with the Mandhane chart.
(2) The measured void fraction was higher than the calculation by the Lockhalt-Martinelli method.
(3) The frictional pressure drop can be predicted by the L-M method. Although this prediction gives slightly larger values, they are on the safety side in a design work.
(4) Horizontal and downward flows were stable enough. 30° and 45° upward flows were stable except in the region of low air velocity.

NOTATION

- G Mass velocity
- ΔL Length
- ΔP Pressure drop
- U Volumetric velocity
- X Martinelli paramiter

$$X \equiv \left(\frac{G_w}{G_s}\right)^{0.9} \left(\frac{\gamma_s}{\gamma_w}\right)^{0.5} \left(\frac{\mu_w}{\mu_s}\right)^{0.1}$$

- γ Specific weight
- λ Parameter in Baker chart
- μ Viscosity
- ϕ_G Nondimensional pressure drop

$$\phi_G \equiv \left[\left(\frac{\Delta P}{\Delta L}\right)_M / \left(\frac{\Delta P}{\Delta L}\right)_{so}\right]^{0.5}$$

- ψ Parameter in Baker chart

Suffix

- M Mixture
- s Steam or air
- so Superficial steam or air
- w Water
- wo Superficial water

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