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STEAM MASS FLOW RATE SOLUTION FOR CRITICAL FLOW USING NUMERICAL ANALYSIS

Jooned Hendrarsakti[1], Davy Febrynzki[1] and Ali Ashat[2]

[1]Faculty of Mechanical and Aerospace Engineering, Institut Teknologi Bandung, Bandung-Indonesia
[2]Geothermal Study Program, Institut Teknologi Bandung, Bandung-Indonesia
email: jooned2001@yahoo.com

ABSTRACT

A series of tests are carried out on the geothermal wells to obtain accurate information about the condition of a reservoir. One of well testing types is discharge test with pressure lip method which utilizes the critical flow phenomena to determine mass flow rate when the fluid flows out from the reservoir. Many current tests use the empirical equation proposed first by James (1962). This study developed new relation using numerical simulation and compared the results to James equation and to another empirical mass flow rate equation proposed by Chien and Schrodt (1995) for condition saturated and mixture steams. The simulation results showed a insignificant difference in the value of the mass flow rate from the results of James and Chien and Schrodt at different pressure and steam quality.

INTRODUCTION

Testing process on the geothermal well is very important in order to get information on reservoir condition and to forecast the potential capacity of power generation. One of the tests is the debit test method called lip pressure. The empirical relation that is mostly used at the field is the relation proposed by James (1962). Since the relation was found experimentally, there is a limitation in parameter range used, i.e pipe diameter, and pressure. The formula does not differ the formula for saturated steam from the formula for mixture steam. Other researchers, Chien and Schrodt (1995) proposed another empirical relation to the problem.

The objective of this research is to develop new relation for mass flow rate for saturated and mixture steam using numerical calculation. The relation is then compared to previous relations by James and Chien and Schrodt. The new relation is expected to have larger range of pipe diameter and pressure. The new relation can give alternative solution during the debit/mass flow rate test.

BASIC THEORY

Russell James Empirical Equation

James observed his experiment at one of geothermal well at New Zealand region. James used geothermal wells with 8-inch pipe diameter and separates each phase of fluid using a separator. Each phase was then measured its speed using orifice meter. The discharge pipes of 3,6, and 8 inches in diameter were used, and the critical lip pressure was measured at the exit of discharge pipe. James then developed the relation between mass flow rate, stagnation steam enthalpy, and critical lip pressure as show in Eq. (1).

$$\frac{Gh^{1.102}}{P_c^{0.96}} = 11400 \qquad (1)$$

where G is the mass flow rate per unit area (lb/sec.ft^2), h is the stagnation steam enthalpy (Btu/lb), and P_c is the critical lip pressure (psia).

Chien and Schrodt approach using King and Crocker Equation

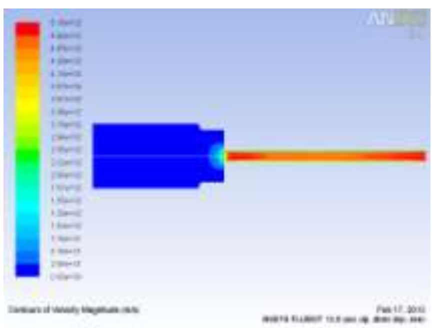
Chien and Schrodt conducted the experiment in lab-scale using the steam generator. They measured the choke condition inside pipe as critical flow meter and used the equation proposed by King and Crocker in measuring the critical mass flow rate as shown in Eq. (2).

$$w = 36.41\frac{d_c^2 P}{\left(\frac{x}{100}\right)^{0.42178}} \qquad (2)$$

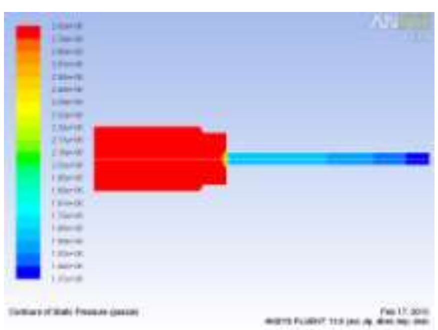
where w is the mass flow rate (lb/hr), d_c is the critical diameter (inc), P is the inlet pressure before chocke (psi), and x is steam quality (%).

NUMERICAL ANALYSIS

Numerical solution using Ansys 13.0 and comparison of mass flow rate using James and King and Crocker equation were conducted on James and Chien-Schrodt experimental condition. James used discharge pipe with critical diameter of 6-in in critical pressure of 20 to 60 psia. On the Chien and Schrodt experiment, choke was used with critical diameter of 0,3750-in and 4,5-in in the head pressure of 400 to 800 psia. Result example of numerical simulation is shown in Fig. 1. Results of the flow simulation are flow velocity, pressure, and mass flow rate.



(a)



(b)

(c)

Fig. 1. Sample simulation results for velocity (a) and static pressure (b) and mass flow rate report (c).

SATURATED STEAM MASS FLOW RATE COMPARISON

Figures 2 and 3 are the mass flow rate results for each condition of Chien and Schrodt and James experimental date. Figure 2 shows that all three methods give higher mass flow rate as the critical pressure increases. Figure 2 also show that the mass flow rate output from King and Crocker gives the highest value and that the current work using numerical simulation gives the lowest mass flow rate. The mass flow rate differences are also found to be lower at lower critical pressure.

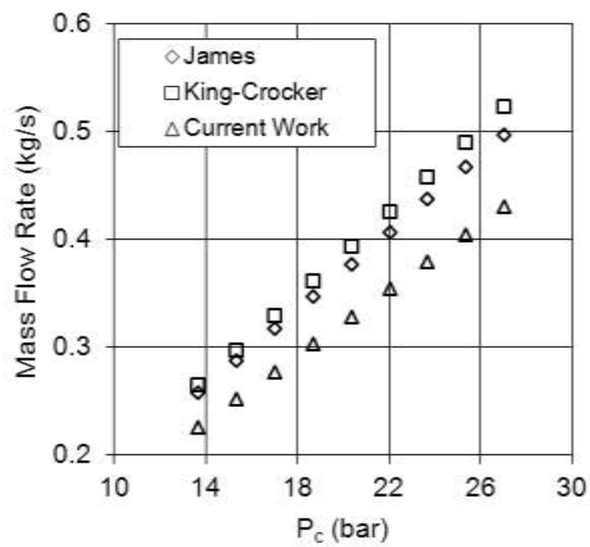


Figure 2. Mass flow rate for saturated steam using Chien and Schrodt experimental conditions with 0.375 inch pipe diameter.

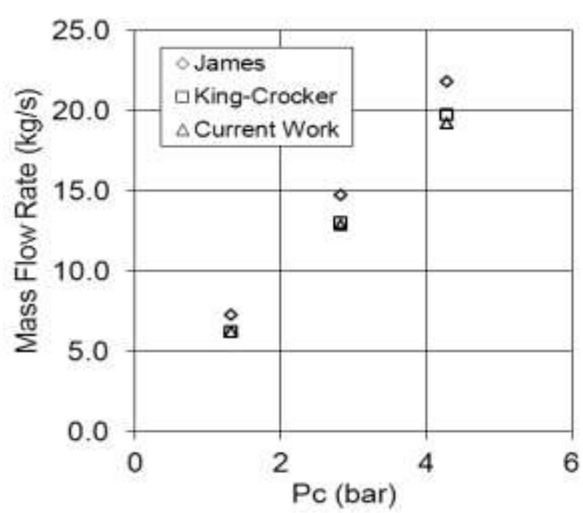


Figure 3. Mass flow rate for saturated steam using James experimental conditions with 6 inch pipe diameter.

Figure 3 shows that all three methods give higher mass flow rate as the critical pressure increases. Figure 3 shows that the mass flow rate output from James gives the highest value and that the current work using numerical simulation gives the lowest mass flow rate. The numerical simulation has very close results to the King and Crocker relation. Similar to Fig. 2, the mass flow rate differences among these three methods are also lower at lower critical pressure. Figure 3 shows the comparison of three relations using James experimental data gives closer results compared to when using Chien and Schrodt experimental data.

MIXTURE STEAM (TWO PHASE) MASS FLOW RATE COMPARISON

Similarly to the saturated steam case, the mass flow rate for mixture was also calculated using simulation with data from James and Chien and Schrodt experiments. Critical diameter dimension and pressure being used are similar with the saturated steam condition. For the two-phase condition, the steam quality parameter has a range of 20% to 90%.

Figures 4 and 5 show comparison of two-phase mass on experimental data of James and Chien and Schrodt, respectively. Figure 4 shows that in general, the mass flow rate is increasing with the decreasing of the steam quality. For the low steam quality, the mass flow rate from King and Crocker equation has no much different from the mass flow rate of the simulation result. With low steam quality, The James equation and King-Crocker give more similar mass flow rate value.

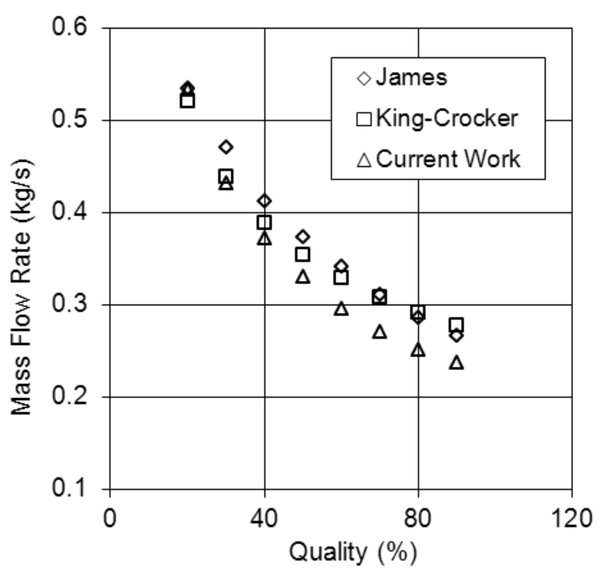


Figure 4. Two-phase mass flow rate using Chien and Schrodt experimental conditions with 0.375 inch pipe diameter.

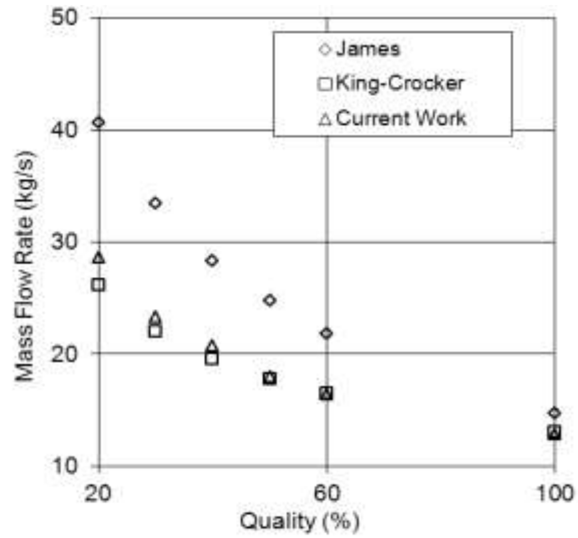


Figure 5. Two-phase mass flow rate using James experimental conditions with 6 inch pipe diameter.

Figure 5, on the other hand, shows a big discrepancies at lower steam quality. The numerical and Chien and Schrodt solutions have closer mass flow rate, while James solution overpredict most values.

NEW MASS FLOW RATE RELATION

Figures 2 to 5 show that while numerical simulation results underpredict the results of empirical equation by James and Chien and Schrodt, they give close results. The difference might come from the assumption in numerical simulation, piping condition is perfectly smooth leading to lower pressure drop. It can be seen from Fig. 2, for example, that at similar mass flow rate, the numerical solution has larger value of critical pressure. The numerical simulation results were then used to develop new mass flow rate relation for two conditions: saturated steam and mixture steam since there are difference in the mass velocity pattern at each condition. The relation is built based on regression analysis with trial and error process to obtain the related constants.

Equation for saturated steam flow

The equation for the saturated steam condition is formulated by plotting the parameter $\frac{w}{P_c^{0.1}\, d_c^{2.02}}$ against the upstream pressure. Figure 6 shows the plotting and regression result. The resulted equation for mass flow rate based on flow simulation result is as shown in Eq. 3.

$$w = \frac{P_c^{0.1} d_c^{2.02} P_u^{0.8473}}{9320.6} \qquad (3)$$

where w is the mass flow rate (kg/s), d_c is critical pipe diameter (mm), P_u is the upstream pressure (bar), and P_c is the critical lip pressure (bar).

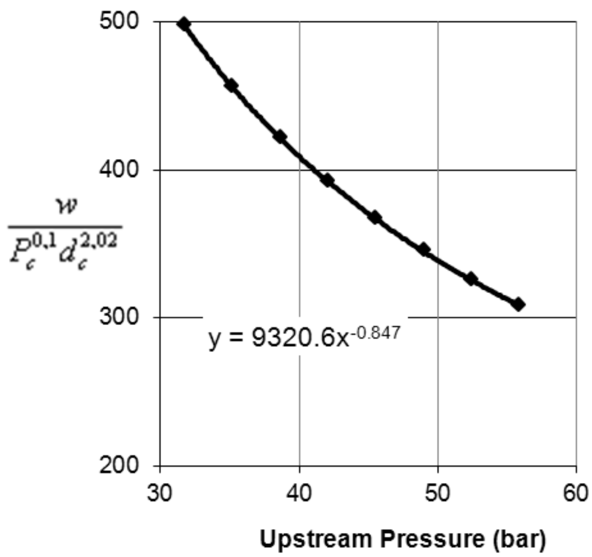


Figure 6. Equation for mass flow using numerical simulation for saturated steam regime.

Equation formula based on two-phase flow simulation result

The Equation for the two-phase condition is formulated by plotting the parameter $\frac{P_u^{0.94} d_c^2}{w}$ against the steam quality. Figure 7 shows the plotting and regression result. The resulted equation for mass flow rate based on flow simulation result is as follow:

$$w = 588 \frac{P_u^{0.94} d_c^2}{x^{0.554}} \qquad (4a)$$

where w is the mass flow rate (lb/hr), x is steam quality (%), P_u is the upstream pressure (psia), and d_c is critical pipe diameter (inc), or

$$w = 1{,}416 \cdot 10^{-3} \frac{P_u^{0,94} d_c^2}{x^{0,554}} \qquad (4b)$$

where w is the mass flow rate (kg/s), x is steam quality (%), P_u is the upstream pressure (bar), and d_c is critical pipe diameter (mm),

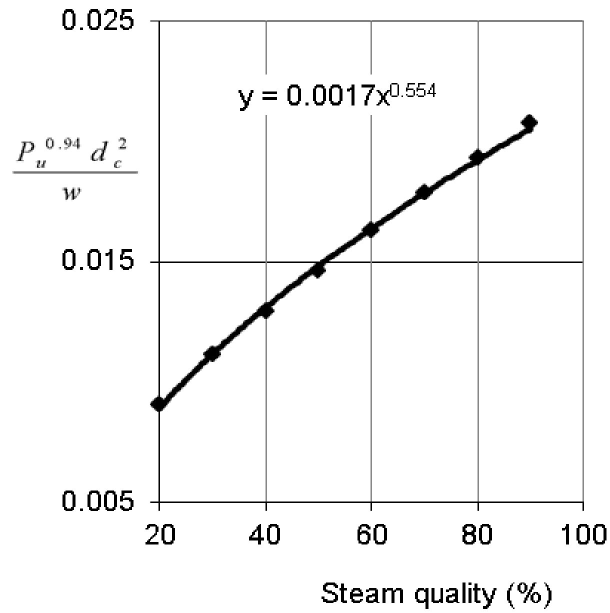


Figure 7. Equation for mass flow using numerical simulation for mixture regime.

CONCLUSION

1. On low enthalpy (saturated steam low pressure or two-phase low quality) the numerical simulation of mass flow rate result gives values which is similar to the mass flow rate resulted from King and Crocker equation
2. On High enthalpy (saturated steam high pressure or two-phase high quality) the velocity mass resulted from James equation gives mass flow rate which is similar with mass flow rate resulted from King-Crocker equation
3. The dimensional analysis has been done succesfully to define the mass flow rate based on numerical simulations which are shown on Equations (3) and (4).

REFERENCES

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