DISCHARGE OF BOILING WATER THROUGH HORIZONTAL BARE PIPELINES EXCEEDS THAT FOR INSULATED PIPES

RUSSEL JAMES
Geothermal Consultant
Taupo, New Zealand

SUMMARY

Pressurised hot water at boiling point can be transmitted overland for re-injection or other purposes either through insulated pipelines with progressive generation of steam or through bare pipelines where heat loss can suppress steam evolution. The avoidance of a vapour phase results in significantly greater discharge (typically 2 to 3 times) through the bare compared with the insulated alternative, with considerable economic advantage.

INTRODUCTION

It is now mandatory for most geothermal projects to dispose of their separated boiling water by means of injection wells. To accomplish this over a ground surface distance of several kilometres requires pumps close to the outlet of the separation plant in order to keep the water from flashing en route, or to overcome the resistance of "tight" injection wells. If the latter were highly permeable, pumps would not be necessary as steam generation within a horizontal boiling water pipeline creates no particular hazard and its only drawback is that it reduces the flow so that a larger pipeline would be needed. An economic optimisation procedure would almost certainly prefer the pump alternative because of the length of line usually required, but pumps are costly and troublesome, and if they break down can bring a whole power project to a standstill.

Another alternative presented in an earlier paper (James, 1979) and specific for injection wells of unrestricted permeability - thus avoiding pumps - was to transmit the incipient boiling water through bare pipe with the water velocity calculated so that the heat loss along the line exactly compensated for the frictional pressure-drop; under these conditions no steam would be generated. It was possible to accomplish this even for horizontal pipelines where it was found that water velocities were comparable to that for cold water flow; about 2 m/s for an average saturated vapour pressure of 7.5 bar.

Temperature fall along the bare pipeline was not excessive and approximated to about 4.25 deg C/km for pipe of 0.3048 m diameter with a throughput of 130 kg/s at the above line pressure. It would be of interest to compare this large flow with that within an insulated horizontal pipeline under the same pumpless conditions, with inevitable steam generation.

PURPOSE OF THE WORK

Two centuries of steam plant work has made it difficult for engineers to look favourably at unlagged pipelines transmitting hot fluid. Even if convinced that it is the best policy for the particular conditions under study, they may be faced by embarrassing questions from the uninformed when they consider neglecting a long tradition.

Up to the present there appears to have been no study made into comparing the flows through bare and insulated pipelines over horizontal distances of kilometres. As reinjection of hot brines is becoming increasingly common, long pipelines are required to dispose of the fluid at the peripheral injection wells, hence it should be of practical use to get the subject into perspective. At least we should get some practical figures from which an intelligent choice can be made into the type of pipeline preferred when cost, efficiency and aesthetics am balanced.

BARE PIPE TRANSMISSION

The greater the temperature - and associated pressure - of boiling water, the greater the heat loss from bare pipe and hence the greater the temperature decline along the flowing fluid. For small flows, this temperature fall dominates and no flashing can take place. For large flows the frictional pressure-drop dominates and flashing occurs. There is a unique flow velocity where the situation is in balance and the water falls in both temperature and pressure as it moves along the horizontal line, but remains at the boiling point throughout, without, however, generating steam. The water velocity at this point is given by the following equation (James, 1979) with units given at the end of the paper.

$$U = 0.89 P^{0.4} \text{ m/s for } 1.4 < P < 14 \text{ bar} \quad \text{.... (1)}$$

To determine the flowrate we employ the inside diameter of the pipe and the specific volume of the water at its boiling pressure which when plotted from Steam Tables (Keenan et al, 1969) gives the relationship:

$$V_w = 1.0432\, P^{0.0337} \text{ litre/kg for } 1.0 < P < 20 \quad \text{.... (2)}$$

$$W_w = \frac{U}{V_w} \left(\frac{\pi}{4}\right) d^2 \; 1\,000$$

$$W_w = 670\, d^2\, P^{0.366} \text{ kg/s for } 1.4 < P < 14 \text{ bar} \quad \text{... (3)}$$

To evaluate the frictional pressure-drop, the following formula is applicable:

$$\Delta P = \frac{f}{50} \left(\frac{L}{d}\right) \frac{U^2}{V_w} \quad \text{.... (4)}$$

Substituting for U and V_w and letting length L = 1 000 m

$$\Delta P/km = 15.186 \frac{f\, P^{0.766}}{d} \text{ bar/km} \quad \text{.... (5)}$$

The Reynold's number R_n is required to determine the Fanning friction factor f as follows:

$$R_n = \frac{U\; d\; 10^6}{V_w \quad \mu_w} \quad \text{.... (6)}$$

The viscosity of boiling water μ_w can be calculated from the following equation which is derived from the steam-water viscosity chart of James (1970).

$$\mu_w = \frac{0.3025}{P^{0.286}} \text{ centipoise for } 1 < P < 70 \quad \text{....(7)}$$

Substituting U, V_w and μ_w in (6), we have:

$$R_n = 2.82 \;\; 10^6 \;\; d \;\; P^{0.65} \quad \text{.... (8)}$$

For typical values of P = 6.0 bar and d = 0.3048 m R_n = 2.75 10^6 which when used in conjunction with a Moody chart as given by Perry (1963), gives f = 0.0033, with little variation over a range of "typical" values. Employing this value of f in (5), we have:

$$\Delta P/km = \frac{P^{0.766}}{20 \;\; d} \text{ bar/km for } 1.4 < P < 14 \quad \text{....(9)}$$

Equations (3) and (9) are the only relevant ones determining flow and pressure-drop for horizontal transmission of boiling water through bare (uninsulated) pipes. It should be noted that the pressure used is the average value based on the arithmetic mean of the inlet and outlet pressures to the pipeline.

Although temperature-drop/km can be indirectly estimated from equation (9), a more direct approach is useful. The ratio of temperature change to pressure change at boiling point is estimated from Steam Tables and the following formula derived:

$$\Delta t/\Delta P = \frac{26.392}{P^{0.778}} \text{ degC/bar for } 1.4 < P < 140 \quad \text{....(10)}$$

$$\Delta t/km = \left(\frac{26.392}{P^{0.778}}\right)\left(\frac{P^{0.776}}{20 \;\; d}\right)$$

$$\Delta t/km = \frac{1.319}{P^{0.012}\; d} \quad \text{.... (11)}$$

As the above equation is not sensitive to pressure because of the small index, and because of the imprecise nature of fluid flow through pipes, we may take the following relationship as adequate:

$$\Delta t/km = \frac{1.30}{d} \quad \text{.... (12)}$$

Illustrated Example I

Boiling water of average pressure 6 bar has to be transmitted along 3 000 m of bare horizontal pipeline 0.3048 m in diameter. Determine the inlet and outlet pressures and temperatures as well as the flowrate.

From equation (3), flowrate

$$W_w = 670(0.3048)^2\, 6^{0.366} = 120 \text{ kg/s}$$

From equation (9),

$$\Delta P/km = \frac{6^{0.766}}{20(0.3048)} = 0.647 \text{ bar/km}$$

Overall pressure-drop for 3 km = 3 (0.647) = 1.94 bar difference.

Inlet pressure $= 6.0 + \frac{1.94}{2} = 6.97$ bar

Outlet pressure $= 6.0 - \frac{1.94}{2} = 5.03$ bar

As the water is at boiling point throughout its length, the inlet and outlet temperatures can be interpolated from Steam Tables at the above pressures.

Inlet temperature = 164.97 °C
Outlet temperature = 152.08 °C

Temperature decline along 3 km pipeline
= 164.97 - 152.08 = 12.89 °C.

Alternatively, the temperature drop along the line can be estimated from equation (12), as:

$$(3.0)\left(\frac{1.30}{0.3048}\right) = 12.79°C$$

which is sufficiently close to the above value to be acceptable.

INSULATED PIPE TRANSMISSION

For comparison purposes, the inlet and outlet pressures (and hence temperatures) for insulated horizontal pipelines are assumed identical to that far bare pipe transmission and, in fact, it would not be easy to determine from a superficial examinati'on any difference in the physical state of the fluid being carried.

An alternative to equation (4) for pressure-drop is employed here with subscripts "w" *applied* to bare pipe transmission while subscript "sw" is for insulated pipe (as *steam* is present).

The pressure-drop is the same for the two modes of transmission so we have:

$$\Delta P = \frac{f_w\ L\ W_w^2\ V_w}{3.084\ (10)^7\ d^5} = \frac{f_{sw}\ L\ W_{sw}^2\ V_{sw}}{3.084\ (10)^7\ d^5} \quad .... (13)$$

Calculations indicate little significant difference between the friction factors for this type of comparison, and L and d are identical, hence:

$$\frac{\textit{Flow through bare pipe}}{\textit{Flow through insulated pipe}} = \frac{W_w}{W_{sw}} = \sqrt{\frac{V_{sw}}{V_w}} \quad .... (14)$$

$$\frac{W_w}{W_{sw}} = \sqrt{q\left(\frac{V_s}{V_w} - 1\right) + 1} \quad .... (15)$$

where the dryness fraction is:

$$q = \frac{h_o - h_f}{h_{fg}} \quad .... (16)$$

Sensible heat h_f and latent heat h_{fg} together with specific volumes V_s and V_w are derived from Steam Tables at the average line pressure (arithmetic mean of the inlet and outlet pressures).

The enthalpy h_o is that of the hot water entering the pipeline and is considered to remain *constant* along the pipe with insulation assumed as perfect.

It was found that the most effective method was to graph $\frac{W_w}{W_{sw}}$ *against* pipeline length for a specific diameter and over a range of average line pressures, then to repeat using other pipe diameters. Lengths up to *6* km were used with diameters of 0.2032, 0.3048 and 0.4572 m with average pipeline pressures of 3, 6, 12 and 24 bar. Although the 24 bar pressure is higher than normal for geothermal pipelines and outside the range of accuracy of some of the equations used, it was found reasonably close far interpolation when pressures greater than 12 bar were being considered.

Illustrated Example 2

Determine the flowrate for the conditions of Illustrated Example 1 but where the horizontal pipeline is insulated. All parameters identical except flowrate.

The boiling water at inlet to the pipeline was calculated as 6.97 bar which from Steam Tables has a water enthalpy of *696.46* kJ/kg and far insulated pipe is constant along the length. At the average line pressure of *6* bar, h_f = 670.56 h_{fg} = 2086.3 kJ/kg, V_s = 315.7, V_w = 1.1006 litres/kg.

From equation (16),

$$q = \frac{696.46 - 670.56}{2086.3} = 0.012413$$

From equation (15),

$$\frac{W_w}{W_{sw}} = \sqrt{0.012413\left(\frac{315.7}{1.1006} - 1\right) + 1}$$

Hence

$$\frac{W_w}{W_{sw}} = 2.1326$$

(This value is shown plotted on Figure 2 at L = 3 000m and P = *6.0* bar).

Bare pipe flow was calculated as 120 kg/s in the previous example, thus

$$W_{sw} = \frac{120}{2.1326} = 56.3\ kg/s,$$

flow through insulated pipeline.

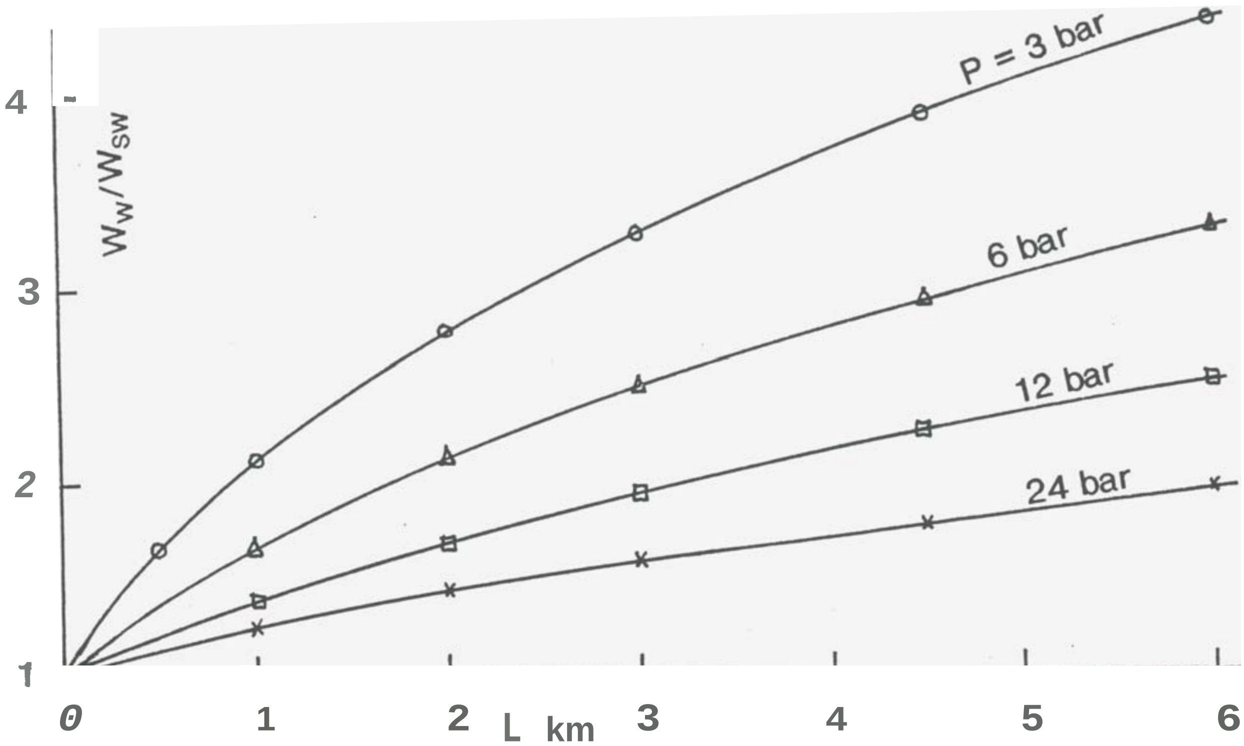

Figure 1. Flow ratios for d = 0.2032 m

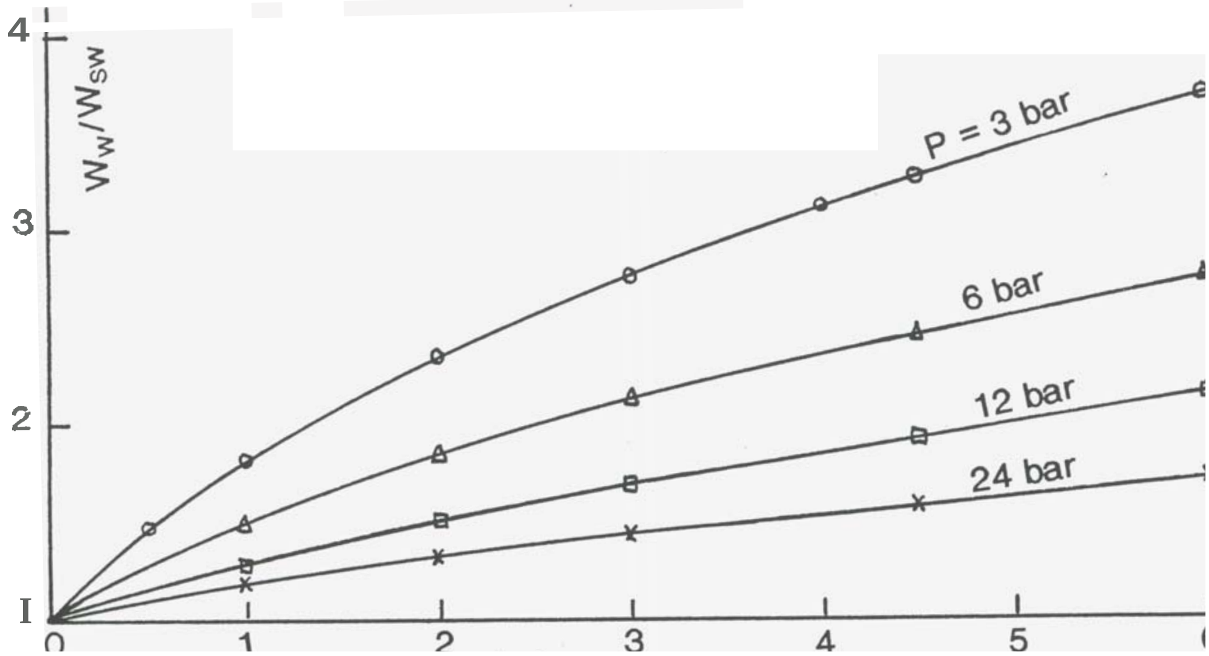

Figure 2. Flow ratios for d= 0.3048 m

Plotting the figures

Each point was plotted on the figures employing calculations demonstrated in the two illustrated examples.

COMMENTS

It is clear from an examination of the figures that the flow through bare pipes is significantly greater than in insulated for identical conditions. Three times the flow passes through 5 km of 0.2032 m diameter pipe at an average pressure of 6 bar, as shown on Figure 1, while twice as much flows along 1.3 km of 0.3048 m diameter pipe at 3 bar, from Figure 2.

Obviously, unless other factors control the choice, it would be much cheaper to employ bare pipe rather than the insulated alternative. To get costs into perspective, present prices (1991) indicate that a 0.3048 diameter boiling water pipeline which is insulated and strongly supported could be installed for roughly 0.75 million dollars/km. If one bare pipe performed the same duty as two insulated, there would be considerable savings, and the longer the pipelines the greater the economic advantage, as shown on the figures.

From the point of view of calcite or silica scaling, neither system would appear to have an advantage, as pressures and temperatures fall equally for both, although the absence of flashing in bare pipe transmission with retention of carbon dioxide in solution would appear to favour this mode in avoiding the former scale. Especially as the laminar sub-layer would be at a slightly lower temperature in the bare pipe and would tend to inhibit calcium carbonate deposition (which has retrograde solubility).

Either type of scale may be removed during the annual maintenance shutdown by filling the pipeline with the highest pressure steam available. No mineral carryover water is permitted in this steam and a high gas content is preferred as the dissolution medium is the "pure" acidic carbonated condensate coalescing on the internal pipe surfaces and constantly being flushed and replaced with the operation of a few vent valves along the line.

The traditional objection to uninsulated hot pipes is partly based on the concept of thermal efficiency which does not apply here where the concept of economic efficiency is of much greater importance.

Another objection is that bare pipelines may be potentially dangerous in causing bums to staff or tourists. This has little validity as no record of such accidents exists over the 35 years of geothermal projects in New Zealand. Evidently the ordinary household kitchen is a much more dangerous location than that posed by a long unlagged geothermal pipeline.

CONCLUSIONS

Whether bare pipe is preferable to insulated pipe transmission will depend on a number of factors such as the ultimate purpose of the hot water. Most likely it will be used for re-injection but other possibilities are for district heating or use in a Binary Power Plant.

The heat loss from the bare pipeline is not likely to be significant unless very long lines are being considered of 5 to 6 km; this is because it would only normally amount to a few percent/km and is proportional to the temperature decline along the line. The quantities of heat being transported are so large that the heat loss is probably irrelevant to its ultimate purpose. In the examples given, a flow of 120 kg/s reaches its destination at 152°C and delivers 77 MW (thermal) even after losing about 8% of its original heat over 3 km of bare pipeline of diameter 0.3048 m.

Of course, if relatively impermeable wells are relegated to the duty of injection wells, then pumps will undoubtedly be required but this does not require pipeline insulation unless cogent geo-chemical reasons dictate otherwise.

Whatever the reasons, bare pipe transportation of water at the boiling point will always reduce the volume of steam that might be generated and hence result in significantly greater flows with the avoidance of vapour-lock.

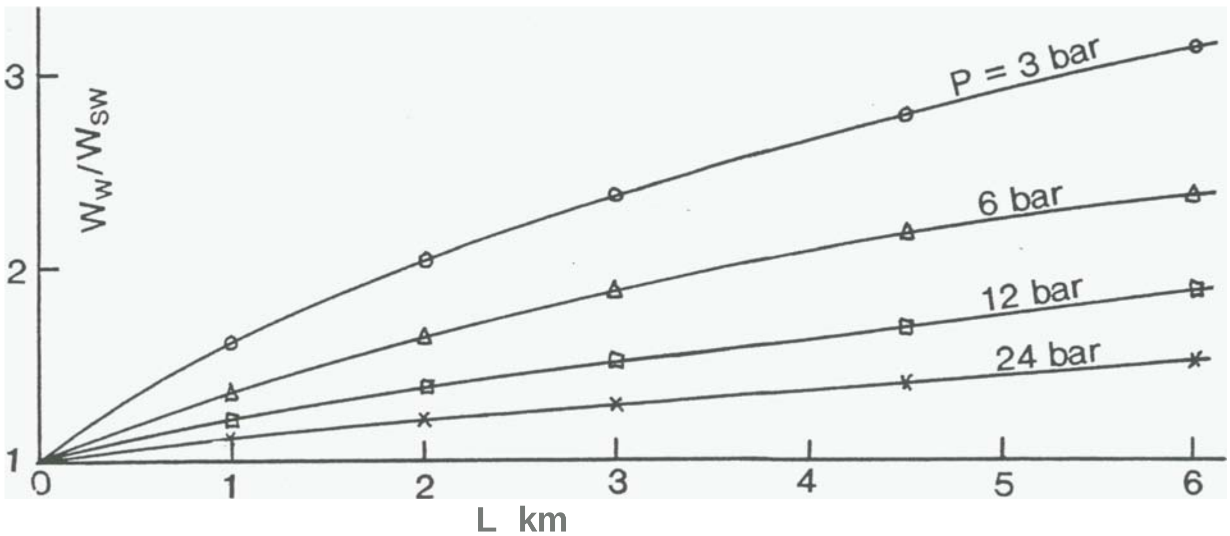

Figure 3. Flow ratios for d = 0.4572 m

NOTATION

d	Pipe diameter, m
f	Fanning friction factor
h_f	Enthalpy of saturated hot water, kJ/kg
h_{fg}	Latent heat of steam, kJ/kg
h_g	Enthalpy of dry saturated steam, kJ/kg
h_o	Enthalpy of water entering pipeline, kJ/kg
L	Pipe length, m
P	Average pipeline pressure, bar
R_n	Reynold's number
U	Velocity of water at the boiling point, m/s
V_w	Specific volume of water, litre/kg
V_s	Specific volume of steam, litre/kg
W_w	Flow of water at the boiling point in bare pipe, kg/s
W_{sw}	Flow of flashing water in insulated pipe, kg/s
ΔP	Pressure-drop, bar
Δt	Temperature-drop, deg C
μ_w	Viscosity of water at the boiling point, centipoise

REFERENCES

James, R (1970): Factors controlling Borehole Performance. *Geothermics Special Issue*, V01.2 Pt 2, 1502-1515.

James, R (1979): Transmission of Pressurised Hot Water at the Boiling Point. *Proceedings NZ Geothermal Workshop*, Pt 1, 166-170.

Keenan, J H; Keyes, F G, Hill, P G; and Moore, J G (1969): *Steam Tables.* Wiley, New York.

Peny, J H (1963): *Chemical Engineers' Handbook* McGraw-Hill, New York.