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THE PROCESS DESIGN OF STEAMFIELD PIPELINE SYSTEMS FOR TRANSIENT OPERATION FROM LIQUID DOMINATED RESERVOIRS

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SUMMARY- Geothermal plant designed for base load operation nevertheless experiences transients that need to be designed for. The water flowing from separators to reinjection wells is at saturation temperature, and is liable to boil. This feature is the most significant in transient considerations. Bubble growth in the reinjection lines may cause separator flooding and turbine damage. Bubble collapse may cause pipe and valve failure. The paper derives a simple allowable rate of change of separator pressure to avoid reinjection line boiling. The paper describes a general approach and a simplified method of calculating the separator pressure transients for any design, for comparison with the allowable rates.

1. INTRODUCTION

The demand for electricity is not constant in time but varies above a minimum. Some electricity generating plant must therefore operate as base load, some with varying load and others in an "on-off" mode. For large coal and oil fired power plant, the annual fuel costs are a significant proportion of the capital costs, so there may be financial benefit in operating with varying load, depending on the tariff structure. Fossil fuelled boilers and steam turbines are designed to operate at varying load. Geothermal power plant is usually considered for base load operation because the majority of the costs are incurred at the beginning of the project life, and base load operation is required to avoid financial loss.

However it would be safe to say that all geothermal power stations operate at varying load sometimes. Some stations in remote locations have an installed capacity much larger than the local demand, yet no transmission grid, so the power station is forced to suffer some daily load variations. Resource consent restrictions in New Zealand can make variable load operations attractive. Bringing production and reinjection wells on and off-line for reservoir management is a normal operation that subjects the steamfield to pressure variations. Finally, power station trips due to plant failures have the same effect.

Steam turbines can cope with load variations successfully; there are allowable rates of change to avoid thermal stressing problems, but since the steam turbine has been developed for fossil fuelled operation which is more demanding, these are not too restrictive for geothermal use.

This paper identifies the events that can occur in the steamfield under transient conditions, and the problems that these can cause. The primary process control variable is identified. A method of analysis, of the reservoir-steamfield-powerstation system transients is discussed, and a simplified process design method for single flash systems is outlined.

2. AN ALLOWABLE RATE OF CHANGE OF SEPARATOR PRESSURE

Consider a single flash system. The separators accept two-phase fluid from the wells, the steam passes to the power station and the separated water is delivered to the reinjection wells through pipelines. The separated water leaves the separator at saturation temperature corresponding to the separator pressure. If the reinjection lines are long and the water velocity is restricted to the usual order of 3m/s, then the transit time for a 1.5km line is 8.3 minutes. During this period some event may take place that reduces the separator pressure. Any reduction in separator pressure is transmitted through the pipeline at the velocity of sound in the water (about 1500m/s) which is relatively instantaneous. If the reinjection lines are insulated so that the water temperature remains virtually constant, and if the pipeline runs downhill, the water will have an increasing margin of temperature difference between its actual temperature and the saturation temperature at the local pressure. Nevertheless, a large enough reduction in separator pressure could result in water boiling before it reaches the reinjection wells. The resulting increase in specific volume of the mixture may cause reverse flow and separator flooding, with the result that water will carry over into the steam lines. This may be a significant cause of silica scaling on turbine blades, and repeated occurrences, say from reservoir management well changes, will result in early plant outages with economic penalties. A more dangerous occurrence is the recovery of separator pressure after water in the reinjection lines has boiled; the bubble collapse can generate very large pressures indeed, and can burst the reinjection lines.

The flow of saturated water in long pipelines has received attention in relation to fossil fuelled power stations, notably the classic paper by Gage (1952) which is the basis of de-aerator to feed pump pipeline design optimisation. Wilkinson and Dartnell (1980) list 9 catastrophic failures of valves or pipes due to bubble collapse in UK thermal power stations over a period of 20 years. There have been incidents of reinjection line damage in geothermal power plant, but these are not well documented.

Consider the system shown in Fig 1, comprising a separator with steam and separated water lines.

Under steady conditions the pressure at the reinjection wellhead is given as :-

$$P_R = P_{So} + \rho g z - \Delta P_f \quad (1)$$

If the transit time of the water is τ, and if the separator pressure is changing linearly at a rate $(dP/dt)_S$, the pressure at the reinjection wellhead, P_R' will be :-

$$P_R' = P_{So} + \rho g z - \Delta P_f - (dP/dt)_S \cdot \tau \quad (2)$$

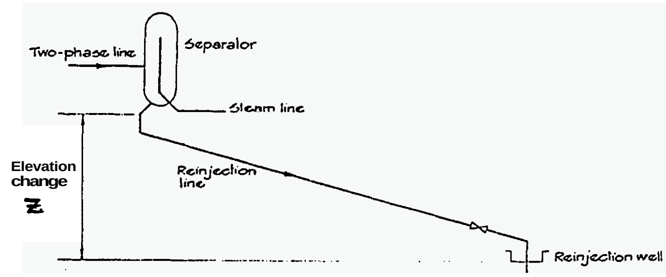

Fig. 1 Simple separator and reinjection line system

If the line is thermally insulated, and if boiling in transit is to be avoided, P_R' must not be less than P_{So}. Setting the difference as zero gives an allowable rate of change of separator pressure :-

$$(dP/dt)_S = (1/\tau)(\rho g z - \Delta P_f) \quad (3)$$

Using f as the friction factor for the line :-

$$\Delta P_f = (2 f L/\rho d)(m/A)^2 \quad (4)$$

then

$$(dP/dt)_S = g (z/L)(m/A)^2 - (2 f/\rho^2 d)(m/A)^3 \quad (5)$$

It is possible to choose a reinjection line diameter that will maximise the allowable rate of change of separator pressure.

The above is an idealised case; reinjection lines do not necessarily always fall in elevation, and separator pressure may not vary linearly, so the element of water at most risk of boiling may not be the one farthest from the separator.

3. A GENERAL APPROACH TO STEAMFIELD DESIGN FOR SAFE TRANSIENT OPERATION

In principle, the proposed steamfield design would be set out based on the steady state operating criteria. The allowable rate of change of separator pressure would then be calculated. The design would then be analysed to find the possible separator pressure transients induced by any events such as:-

- sudden loss of turbine load
- linear change in turbine load (increase or decrease)
- failure of mechanical gas extractors and startup of reserve steam jet ejectors
- bringing on line or closing a particularly powerful well
- bursting disk failure in a two-phase line
- steam line rupture
- reinjection line rupture

The design might then be modified to ensure that without the involvement of a control system, the possible rates of change of separator pressure are a reasonable minimum. There may be limited scope to arrange this, bearing in mind the many other considerations involved in the design trade off, so finally a control system must be designed to control rate of change of separator pressure.

The relevant equations are continuity of mass flow and conservation of energy together with the equation of state for water.

The analysis may be either finite difference or a coarse (lumped parameter) form of the same. An equation for dP/dt in each lump can be produced and solved using 4th order Runge Kutta. The equations contain some non-linear terms.

Whilst the full analysis is worth considering to give some perspective, satisfactory results for a single flash system can be obtained with a simplified approach, bearing in mind that the dynamics of the steamfield are relatively slow.

4. A SIMPLIFIED APPROACH

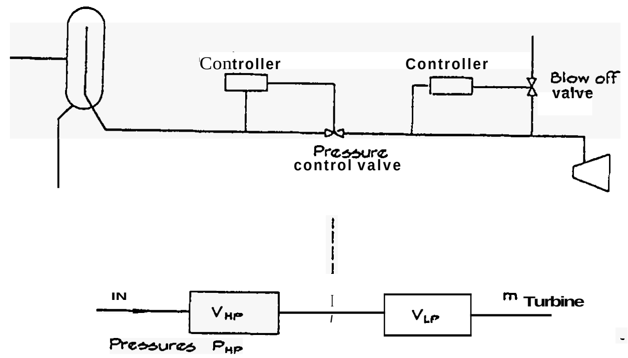

Fig. 2 Simplified single flash system

Consider the single flash system shown as Fig 2, supplying steam to a condensing turbine. A throttling control valve is situated partway along the steam line. The analysis can be confined to several components with particular characteristics (turbine, well and control valve) and two sections of steam line.

The objective is to protect the turbine against water in the steam lines, and the reinjection lines against boiling and hence potential damage from bubble collapse, using the pressure control valve to moderate rate of change of separator pressure.

4.1 Steam turbine characteristics

The speed of rotation of a turbine ensures that for the order of transients that we are interested in here, the steady state characteristics can be used. Assuming throttling control, the characteristics are the Willans Line (Fig 3) and the steam swallowing capacity (Fig 4). These are both linear and allow a linear equation relating MWe output to inlet pressure. In a simple first stage analysis, the pressure drop in the steam lines can be neglected, so the turbine inlet pressure is then equal to the downstream valve pressure. The steam line pressure drop can easily be included if necessary.

The turbine has its own control system to protect it against local problems; this is entirely separate from the steamfield control system and is not part of this analysis.

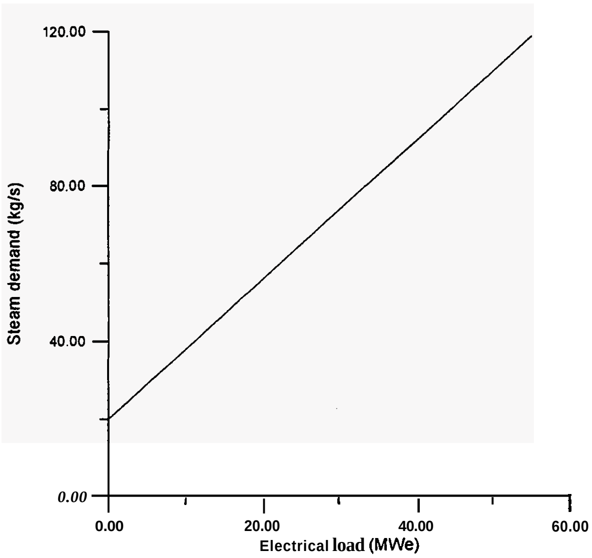

Fig. 3 Turbine Willans line

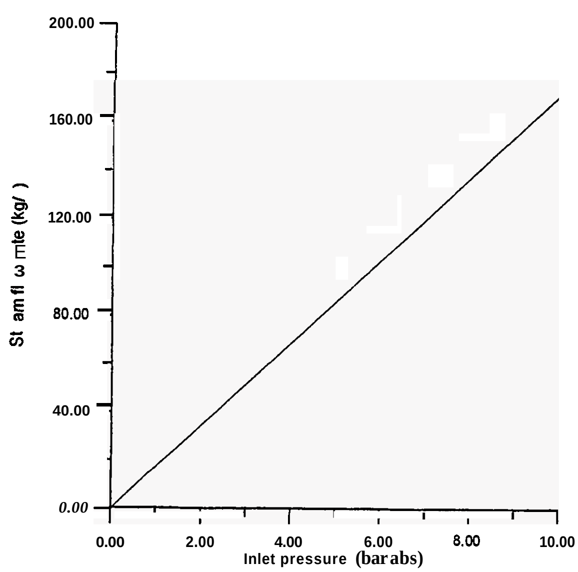

Fig. 4 Turbine swallowing capacity

4.2 The well and reservoir

Free from geometrical constraints, a two-phase mixture is capable of expanding or contracting almost instantaneously in response to pressure changes, by water flashing or steam condensing. Because the volume is in the form of a well, a long narrow tube, the response time to pressure changes at the separator is of the same order as the changes that we are analysing. In reservoir engineering terms, the well response is in the wellbore storage regime.

The two-phase line to the separator similarly represents a store of two-phase fluid that can expand or contract to damp any tendency for separator pressure to change. For a simplified analysis, the two-phase flow to the separator can be considered to be constant, although it can be represented by a given function of time to represent wellhead valve opening or closing times if required.

4.3 Pressure control valve

The pressure control valve has a characteristic of mass flow rate passed versus pressure drop that for Fisher valves has the form :-

$$Q = k_1 \sqrt{P_{HP}} \sin \{(k_2/C) \sqrt{(P_{HP}-P_{LP})/P_{HP}}\} \quad (6)$$

where the **k** values are constants and C is shown in Fig **5**.

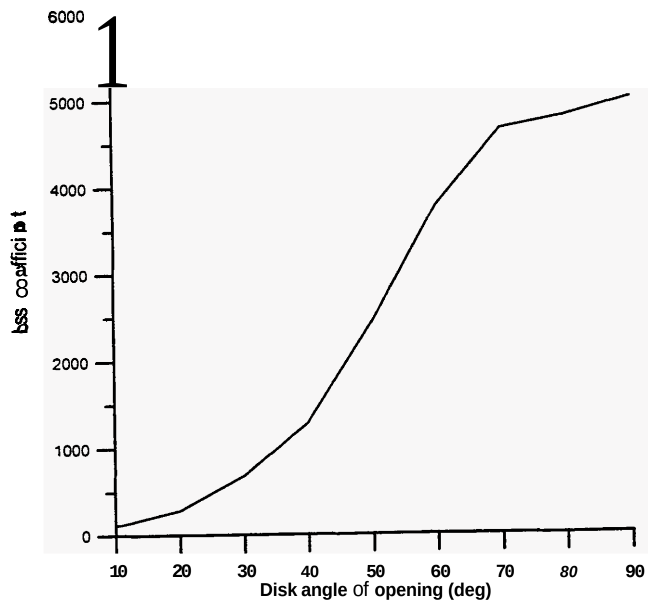

Fig. 5 Typical butterfly valve characteristic

The speed of response of the valve must be considered. **As** with the turbine, the steady state characteristics of Fig **5** can be used while the valve is moving. The valve position, θ_i at any time t_i can be calculated as

$$\theta_i = \theta_{i-1} + (d\theta/dt) . \delta t \quad (7)$$

assuming that valve angle is driven at uniform speed by the actuator. The required direction of travel of the valve must be determined at each time step.

4.4 Separator and reinjection line

The relevant characteristics are represented by the allowable rate of change of separator pressure, and these components play no further part in the simplified approach, except in the case of the separator, to provide a steam volume to add to the steamline upstream of the control valve. This is often small.

4.5 Steamline upstream of the control valve

This has volume V_{HP} and has an effective pressure P_{HP} which is the separator pressure. For the range of pressures of interest, the energy balance has a negligible part to play and conservation of mass dominates. Considering this section as a control volume, the equation is :-

$$V_{HP}\, d\rho_{HP}/dt = m_{in} - m_{out} \qquad (8)$$

Mass flow rate in, m_{in} ,is from the well and separator, as discussed above, and m_{out} is a function of P_{HP} and P_{LP} (the pressure in the downstream section) and the valve characteristic, ie. the mass flow rate through the valve depends on its angle of opening , the upstream pressure and the downstream pressure.

The steam density can then be represented as a function of pressure, by whatever level of simplicity is acceptable - since there is no energy balance consideration, it can be assumed that P/ρ is constant.

In making these assumptions, the level of accuracy required of the analysis needs to be borne in mind. The simple analysis being discussed is to determine responses to various occurrences, and there is the opportunity to modify the design to "improve" the response. If the response is still not sufficiently fast to avoid difficulties, then either a more detailed analysis would be carried out, or a faster control valve plus a control system would be speacified.

Bursting disks on the two-phase line or separator can be represented by an additional pressure dependent mass flow rate from the control volume, which is simply added into the above equation.

4.6 Steam line downstream of the control valve

Conservation of mass again gives :-

$$V_{LP} d\rho_{LP}/dt = m_{in} - m_{out} \qquad (9)$$

Here, m_{in} is m_{out} from the upstream steam line volume, and is expressed in terms of P_{HP} P_{LP} and θ, and m_{out} is the flow to the turbine.

Safety valves on this line can be represented by an additional pressure dependent mass flow rate from the control volume.

4.7 Solution procedure

Despite the simplicity of the set of equations, we used a 4th order Runge Kutta procedure. After each timestep δt, the valve position (angle) is recalculated for the next step, and the coefficient relating pressure drop to mass flow rate is taken from the valve characteristic, Fig 5. The instantaneous rate of change of separator pressure is compared to the allowable, and the required valve direction of travel is determined. The location of the valve is a design variable since volumes of the steam lines up and downstream influence the solutions.

Note that although the allowable separator pressure is dictated by the pipeline between separator and reinjection well, the actual rate of change that will be experienced is quite independent of it and is governed by the other components such as steam line, valves and turbine.

5. SAMPLE SOLUTION

Fig. 6 shows the maximum possible turbine output following a failure of the mechanical gas extractors and the start of auxiliary steam jet ejectors for a 55MWe turbine. The latter have a high steam demand that cause the pressure control valves to close partially to keep (dP/dt) at the separator within the limit. The result is a decrease in turbine output from the steady full output of 55MWe to a final output of 35.5 MWe, as shown in Fig 6.

6. CONCLUSIONS

This paper shows that an allowable rate of change of separator pressure can be defined, to avoid separator flooding and carryover of water to the turbine or the potential for damage from bubble collapse. An expression is derived for the allowable rate, for a single flash system. A simplified method of designing the steamfield layout and calculating the response to various transients is outlined. This response can be adjusted by changing design parameters, to give a rate of change of separator pressure less than the allowable.

Nomenclature

A reinjection line cross sectional area
d reinjection line diameter
f friction factor (Fanning)
g gravitational acceleration
L reinjection line length
m mass flow rate
P pressure
t time
δt calculation time step
z elevation difference between separator and reinjection wellhead
ρ density of separated water
Δ P frictional pressure drop
τ transit time of water in reinjection line

Suffixes

R pressure at reinjection well
S separator
So separator at steady state
HP upstream of control valve
LP downstream of control valve

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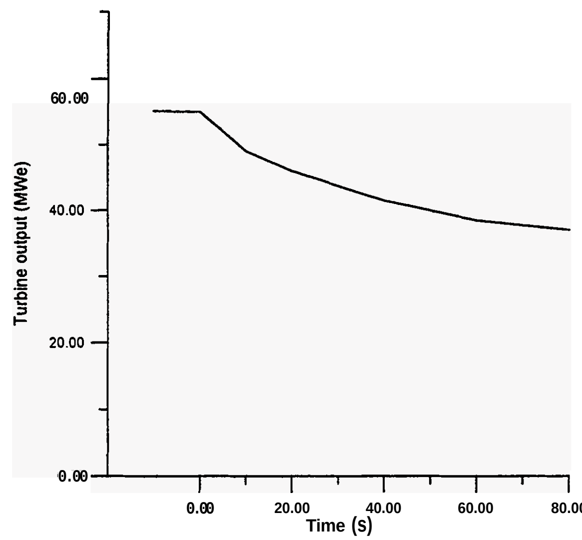

Fig. 6 Results of **mechanical gas extractor trip**