The Discharging Well

8

Once discharge is achieved, the discharge flow rate and its temperature, pressure and specific enthalpy can be measured; several methods are available. The main parameters are presented as "discharge characteristics", which are required for power station control but also contain information about the producing formations. The chemical constituents of the discharge are measured at the same time as the discharge characteristics and provide further clues as to conditions in the producing formations. Some wells discharge at a steady flow rate, with perhaps a long-term decline as the formation pressure declines, but some have a periodic flow or even a regular intermittent discharge like a geyser. It is sometimes useful to have a means of predicting the details of the flow during discharge, and numerical discharge prediction methods have been developed. All of these matters are discussed in this Chapter.

8.1 The Discharge Characteristic

8.1.1 The Form of the Discharge Characteristic

The discharge from a well is equivalent to the discharge from a pump, and the well responds in a similar manner, the flow rate increasing as the wellhead control valve or pump outlet valve is opened. Pumps are selected for a task according to their characteristic, a graph of pressure difference over the pump plotted on the vertical axis versus the mass flow rate discharged plotted on the horizontal axis. This plot is useful because the resistance to flow in a piping system increases with the square of mass flow rate and can be calculated for a range of flows; a graph of resistance versus mass flow rate can be plotted on top of the characteristic. The intersection of the two curves marks the mass flow rate and pressure difference that will occur if the two are coupled together.

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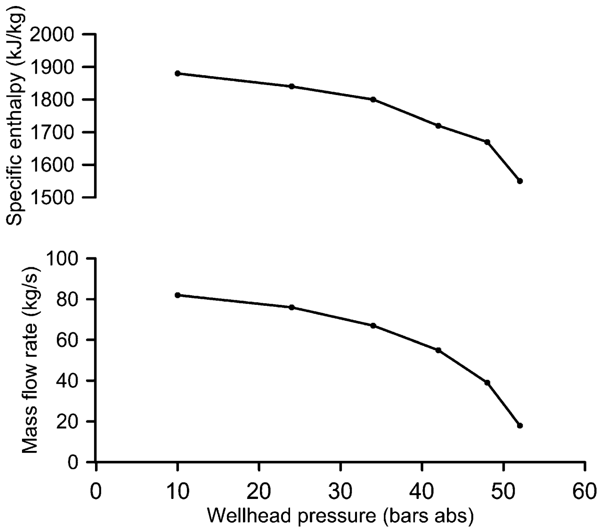

Fig. 8.1 Typical well discharge characteristics

For geothermal wells a different convention has been adopted. Perhaps because the wellhead pressure is the controlled variable, it is plotted horizontally and the mass flow rate discharged is the vertical axis. Also, however, the discharge from a geothermal well needs two parameters to define it, mass flow rate and specific enthalpy, so two characteristic curves are necessary and are conveniently plotted as shown in Fig. 8.1 (which shows actual measurements and scatter). Like pumps, some mass flow rate characteristics have a maximum in wellhead pressure at low mass flow rates, curving back on themselves as zero mass flow rate is approached. A common practice is to fully open the well first until its discharge stabilises and then progressively throttle it to see if there is a clear maximum discharge pressure, which was not found in the well of Fig. 8.1.

Wells may be discharged for periods of weeks to determine production capability and resource characteristics such as geothermal gases and chemical species in solution. If the discharge rate is controlled by the wellhead control valve (never the master valve), the gate edges become very abraded and eventually will not seal. For long-term discharge it is common practice to place a less expensive restriction in the delivery pipe, usually a disc with a hole in it sufficient to pass the required flow rate, so the control valve can be fully opened, leaving the gates clear of the flow to avoid damage. A set of discs is made covering the range of flow rates to be tested, a trial and error exercise. Lovelock and Baltasar [1983], in discussing geochemical analysis of discharge samples, explain that PNOC-EDC (now EDC) discharge testing lasts for 4–6 weeks.

Because the pressure in the producing formations may fall gradually as the discharge continues, it is best not to change the wellhead pressure in uniform steps from high to low during the tests, but to randomise the sequence. By gradually opening the well so that the points on the characteristic form a regular sequence in time, any simultaneous reduction in formation pressure is hidden.

For a well discharging two-phase fluid at wellhead pressure P_{wh}, the specific enthalpy and mass flow rate of the discharge for a particular wellhead pressure can be read from Fig. 8.1. The dryness fraction can be calculated according to the equations given in Chap. 3 and in this way a third graph showing the mass flow rate of saturated steam versus wellhead pressure could be added to Fig. 8.1. Assuming a steam rate for the turbine, say 2.4 kg/s/MWe, a graph of power output versus wellhead pressure could also be added and also a graph showing the amount of separated water and condensate to be disposed of.

The measurement of the discharge characteristic is likely to be the first occasion on which the well has been discharged for a lengthy period, and it will be tested immediately afterwards to check for any damage. A calliper will be lowered into the well with the aim of checking that the production casing is still of uniform diameter, has not developed any holes and shows no evidence of solids deposition or acid attack from the aqueous solutions discharged. The calliper is a cylindrical instrument with several arms which make contact with the production casing and move in or out to follow any undulations in the casing wall, as already discussed in Chap. 5. The signal is recorded at the surface.

Before discussing how the discharge characteristics are measured, some more information about their use is appropriate.

8.1.2 Interpretation of Resource Behaviour from the Discharge Characteristics

The maximum wellhead pressure is a function of the resource and the fluid composition. The shape of the discharge characteristics together with the downhole measurements described in Chap. 6 can provide more information about the physics of the flow in the formations. In making this assessment the heat loss from the flow as it passes up the well can be ignored as a first estimate, as can the reduction in specific enthalpy by work done against gravity. Several circumstances can occur:

(a) The well produces from only one liquid-filled formation at a temperature significantly below saturation. The flow flashes on its way up the well, and this takes place over the whole range of wellhead pressures obtainable. The specific enthalpy of the discharge remains constant with wellhead pressure.

(b) The well produces from a formation at or only just below saturation temperature, so the fluid flashes in the formation as a result of the pressure reduction. The pressure reduction works its way radially outwards from the well, and as it does so the saturation temperature in the fluid falls. Whereas before production began the rock and fluid were at the same temperature, the fluid is now cooler, so there is the potential for the fluid to gain heat from the formation. The temperature difference driving this heat transfer is greatest at the sandface, where the pressure is the lowest. The specific enthalpy of the discharge will increase if heat transfer takes place, which accounts for the term "flowing enthalpy" to describe discharge specific enthalpy, a reminder that it may not be the specific enthalpy of the undisturbed fluid in the formation. Under these circumstances the well is said to produce "excess enthalpy", which is expected to be highest at low wellhead pressure.

(c) The fluid in the formation flashes as in (b), but the steam is able to move towards the well faster than the water—the steam (strictly, the combination of formation and steam) is said to have a higher relative permeability than the liquid water. The discharge has a higher specific enthalpy than the downhole pre-discharge measurements indicated for the producing formation and the well again has excess enthalpy.

Examples of wells exhibiting excess enthalpy were given by Menzies et al. [1982] and by Lovelock et al. [1982].

When the well has two or more production zones, the discharge characteristics are more difficult to interpret because the proportion of flow coming from each zone is a variable. The flow from each is governed by the pressure in the well at the zone. But these pressures are not independent; they form part of a non-linear distribution up the well which is linked to the specific enthalpy and mass flow rate of the discharge from the zones. This distribution changes in a complicated way with these four variables. Grant et al. [1979] give an example of a well penetrating two production zones, the upper one producing dry steam and the lower one being liquid filled. Suppose the lower zone has a high temperature and is capable of producing a high flow rate. The well stands shut with the upper section steam or gas filled because it is connected to the steam zone; below that depth the well is liquid filled. When the well is opened only enough to allow a small discharge rate, the pressure gradient in the well below the steam zone is unaffected—to enable the lower zone to discharge the liquid column must flash and reduce its density and hence the sandface pressure, and this calls for a major reduction in wellhead pressure. At low flow rates (wellhead pressure just a little below the shut value) the discharge will thus be from the steam zone only and the discharge specific enthalpy will be that of steam at the formation pressure. When the well is fully opened and the lower zone begins to produce, the discharge specific enthalpy will tend towards that of the lower zone liquid. The specific enthalpy discharge characteristic will change accordingly. This emphasises the importance of good well measurements and interpretation prior to discharge. In passing, note that in some wells of this type, the wellhead pressure cannot be lowered sufficiently to make the lower zone discharge by simply opening the valve without some encouragement of the type described in Sect. 6.5.

If some formations are steam filled, the question arises whether the flow from the formation or at the wellhead will be superheated. The thermal boundary conditions of the flow up the well need to be considered (wellbore heat loss) as well as the loss of specific enthalpy in the form of work done against gravity; in other words, if the exact degree of superheat is an issue, then greater precision in the analysis is needed.

8.2 Measuring the Discharge Characteristics

Several measuring methods are available to choose from, depending on the thermodynamic state of the fluid discharged and wider project issues. The alternatives are set out as a chart later in this section. Most methods combine several individual measurements made using equipment that is easy to describe and has been left until Sect. 8.3. The James lip pressure pipe is a more complicated "instrument" which is introduced first.

8.2.1 The James Lip Pressure Pipe

The lip pressure pipe was invented by James [1962, 1966], during the exploration and development of New Zealand resources in the late 1950s. James carried out experiments in which a two-phase flow was created by mixing two separate streams of water and steam at known rates and then discharging the mixture through a "lip pressure pipe", a piece of plain round pipe about 1 m long or less, flanged so that it can be fitted to the pipe delivering the flow. The discharge end is open to atmosphere and is cut off very precisely, normal to the axis, leaving sharp, right-angled edges. It has a pressure tapping fitted close to the end as shown in Fig. 8.2. James [1966] gave the results of experiments with the dimensions of the pressure tapping, which should be taken into account when designing a tube.

James recognised that so long as the emerging jet is supersonic, a simple correlation relates the lip pressure pipe reading to the mass flow rate and the specific enthalpy of the discharge. The correlation is

$$\frac{G h_D^{1.102}}{{P_{lip}}^{0.96}} = 22106 \tag{8.1}$$

$$\text{for } 400 < h_D < 2800 \text{ kJ/kg}$$

where

$G = \dot{m}/A(\text{kg/m}^2\text{s})$ is the mass velocity for a mass flow rate $\dot{m}(\text{kg/s})$ in a pipe of cross-sectional area $A(\text{m}^2)$

h_D = specific enthalpy of the discharge (kJ/kg)

P_{lip} = lip pressure (kPa abs)

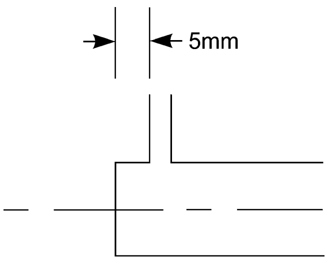

Fig. 8.2 Dimensions of the James lip pressure pipe

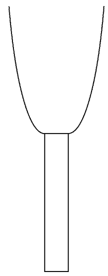

Fig. 8.3 Sketch of James lip pressure pipe flared supersonic flow

The constant on the right-hand side of the equation is experimentally determined and its value depends on the units used for the parameters in the equation. Constants for other units can be found in the literature. If the measurements are made using different units to those used in the formula, it is safer to change them to the formula units, carry out the calculation and convert the answer back to the required units. There is a further problem with this correlation; it is implicit in the variables to be determined, with one of them (specific enthalpy) raised to a power, so it cannot be solved simply. An example of its use is given below.

When testing a new well, the pipe diameter giving supersonic flow at maximum discharge is found by trial and error by watching the shape of the discharge, which has a characteristic flared shape when it is supersonic, as shown in Fig. 8.3. The velocity of sound in a two-phase mixture is lower than in either phase, see, for example, Kieffer [1977], so supersonic discharge can usually be achieved.

Measuring the complete discharge characteristic may take weeks and requires a good deal of equipment to be set up, so an initial estimate is often made with a lip pressure pipe attached directly to the wellhead. Used by itself, the lip pressure pipe provides insufficient information to determine mass flow rate, and an estimate of the specific enthalpy of the discharge from downhole measurements is necessary, which then allows mass flow rate to be determined.

There are practical problems with this method in terms of the disposal of the discharged fluid. In NZ, permits are usually obtainable to allow a short discharge vertically through a pipe attached directly to the wellhead and inclined at a slight angle to direct the flow away from the well but still having it fall within the drilling pad. The discharge is limited to an hour or so, on the grounds of noise and contamination. Wells are often in areas with natural surface discharge, so the extra contamination is tolerable.

8.2.2 The Available Methods of Measurement

The chart (Fig. 8.4) shows the main measurement methods available, characterising the state of the discharge as steam, two-phase or liquid, which dictates the level of complexity of the measurement method. One method has been left out of this diagram, namely, the calorimeter, which is only suitable for wells with a small discharge rate compared to that required for major power station projects.

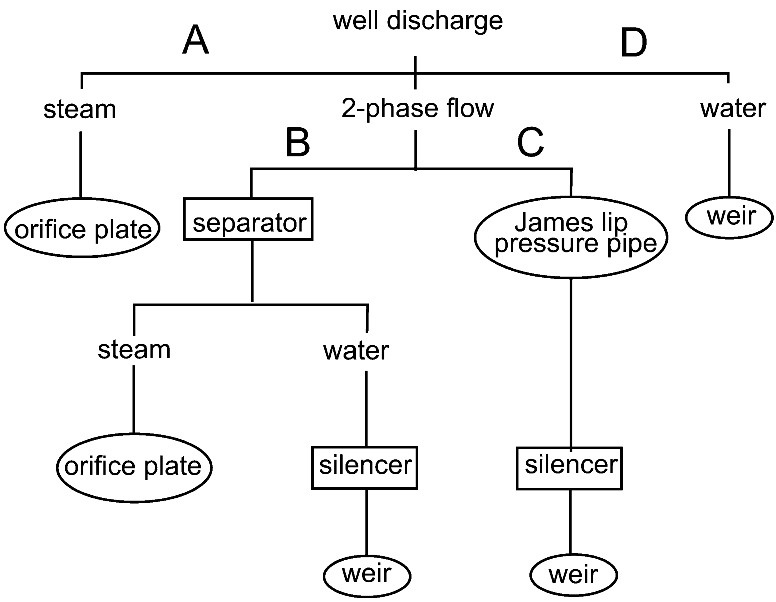

Fig. 8.4 Diagram showing method options

It consists of a thermally insulated tank of known volume, partially filled with a known volume of cold water at known temperature. The well is discharged into the tank for a measured length of time and the total volume and temperature of the mixed water are measured. Any steam discharged must be condensed in the tank, and the entry is submerged to encourage this. The mass flow rate of the well and the specific enthalpy of its discharge can be deduced from simple algebraic equations written for a mass and heat balance. The method is most often used for small diameter wells such as those supplying heat for domestic or small commercial use.

In the diagram are three measurement devices, namely, a single-phase orifice plate, a weir and the James lip pressure pipe, and these are used in combinations. The flow may have to be processed using a separator or an atmospheric pressure separator (otherwise known as a silencer), also shown in the diagram. Four routes through the diagram have been identified as A, B, C and D, of which route D requires only an explanation of the measurement weir, which is given in Sect. 8.3.

8.2.3 Route A: A Well Discharging Steam Only (Dry Steam)

The flow from a well producing steam only can be measured by directing it through a single-phase orifice plate, which is a regular obstruction in the form of a disc with a hole in it through which the flow passes, creating a small pressure drop—see Fig. 8.5. The disc must be manufactured and installed according to a standard, after which the mass flow rate can be calculated from the measured pressure drop and the

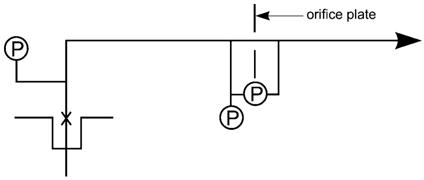

Fig. 8.5 Well discharging steam through an orifice plate—Route A of Fig. 8.4

pressure in the pipe just upstream of the orifice plate; it is described in detail in Sect. 8.3.1. The specific enthalpy of the well discharge can be found from the steam tables using the measured wellhead pressure. The flow through the pipe and orifice plate must be well below sonic velocity.

As a check on the wellhead pressure gauge and that the discharge is in fact saturated steam, a good estimate of the temperature of the flow can be found by attaching a thermocouple to the outside of the production casing or discharge pipe, making sure that it is thermally insulated over a circle around the thermocouple, perhaps 10 pipe wall thicknesses in radius.

8.2.4 Route B: A Well Discharging a Two-Phase Mixture

Route B is the most difficult (expensive) to set up in the field as a temporary arrangement during exploration, as it requires a separator and a silencer, but it should provide higher accuracy than Route C. The separator is essentially a closed vertical cylinder, higher than its diameter, in which water and steam are rotated at high enough speed that they separate under the centrifugal acceleration; a steel structure is needed to support it rigidly. A silencer is an atmospheric separator (essentially a separator vessel with no top) which may be as tall as the separator but is on a bigger base, so is more stable, and skid mounted moveable silencers are used during early exploration. On completed fields permanent separators and silencers are constructed. For the present purposes both separator and silencer can be assumed to separate the entering two-phase fluid into flows of saturated water and saturated steam, at the separator pressure and atmospheric pressure, respectively.

Figure 8.6 shows the arrangement and the relevant parameters. The specific enthalpies at the separator pressure and at atmospheric pressure are found from the steam tables at the measured pressures.

Recall that a two-phase flow has a dryness fraction X, the proportion of the total mass flow rate which is steam, which relates to specific enthalpy according to Eq. (3.18):

$$h = h_f + Xh_{fg} \tag{3.18}$$

There are two stages in Fig. 8.6 at which a two-phase flow separates into water and steam: in the separator, which receives the two-phase discharge from the well, and in the silencer, which receives separated water at separator pressure and flashes

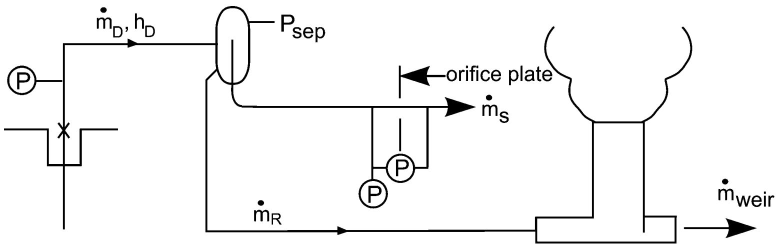

Fig. 8.6 Arrangement of equipment for Route B of Fig. 8.4

it to atmospheric pressure. Thus continuity of mass flow rate (a mass balance) can be written for the separator and reorganised, as follows:

$$\dot{m}_D = \dot{m}_R + \dot{m}_S \tag{8.2}$$

$$1 = \frac{\dot{m}_R}{\dot{m}_D} + \frac{\dot{m}_S}{\dot{m}_D} = \frac{\dot{m}_R}{\dot{m}_D} + X_{sep} \tag{8.3}$$

and similarly for the silencer,

$$\dot{m}_R = \dot{m}_{weir} + \dot{m}_{Satmos} \tag{8.4}$$

$$1 = \frac{\dot{m}_{weir}}{\dot{m}_R} + \frac{\dot{m}_{Satmos}}{\dot{m}_R} = \frac{\dot{m}_{weir}}{\dot{m}_R} + X_{sil} \tag{8.5}$$

The steam discharged from the silencer at atmospheric pressure is not measured, but the specific enthalpy of the mass flow rate $\dot{m}_R$ is known from the steam tables because the separator pressure P_{sep} is measured. Thus using Eq. (3.18) above,

$$h_R = (h_f)_{Psep} = (h_f + X_{sil}.h_{fg})_{atmos} \tag{8.6}$$

The atmospheric pressure is also measured, so X_{sil} for the silencer can be found. The mass flow rate of atmospheric pressure water is measured using the weir, which allows the mass flow rate of water entering the silencer, $\dot{m}_R$, to be found from Eq. (8.5). Equation (8.2) then allows the total discharge from the well to be found, since the mass flow rate of steam leaving the separator is measured, and also the separator dryness fraction. Continuity of energy (an energy balance) finally allows the specific enthalpy of the discharge to be calculated:

$$\dot{m}_D.h_D = (\dot{m}_R.h_f + \dot{m}_S.h_g)_{Psep} \tag{8.7}$$

The calculation proceeds upstream from the silencer, using the key fact that the flow entering the silencer is saturated water at a known pressure.

Example

- The measured parameters are the following:
  Separator pressure = 6.0 bar abs.
  Atmospheric pressure = 1 bar abs.
  Steam discharge rate from the separator, $\dot{m}_S = 6.2$ kg/s.
  Atmospheric pressure water flowing over the weir, $\dot{m}_{weir} = 35.3$ kg/s.
- Collect the properties required.

P (bar abs)	h_f (kJ/kg)	h_{fg} (kJ/kg)	h_g (kJ/kg)
6.0	670.5	2085.6	2756.1
1.0	417.4	2257.5	2675.0

- Apply the equations.

From Eq. (8.6)	$670.5 = 417.4 + X_{sil}.\ 2257.5$ (kJ/kg) giving $X_{sil} = 0.1121$ (it is advisable to carry four significant figures)
From Eq. (8.5)	$\dot{m}_R = 35.3/(1 - 0.1121) = 39.76$ kg/s
From Eq. (8.2)	$\dot{m}_D = 39.76 + 6.2 = 45.96$ kg/s
From Eq. (8.7)	$45.96\ .\ h_D = 39.76.\ 670.5 + 6.2\ .\ 2756.1$ giving $h_D = 951.85$ kJ/kg

8.2.5 Route C: An Alternative for a Well Discharging a Two-Phase Mixture

Route C addresses the same problem as Route B but avoids the use of a separator. Instead, a James lip pressure pipe is fitted where the fluid from the wellhead enters the silencer and the separated liquid passes over a measurement weir.

As before, the liquid flow rate over the weir is not the mass flow rate entering the silencer, as some of the discharged liquid is lost to atmosphere as steam. There is enough information to allow for this in the calculation.

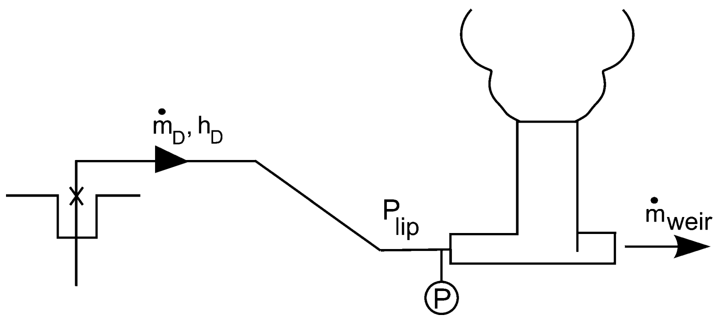

Fig. 8.7 Arrangement of equipment for Route C of Fig. 8.4

This time, the mass balance equation is

$$\dot{m}_D = \dot{m}_{Satmos} + \dot{m}_{weir} \tag{8.8}$$

and

$$\dot{m}_D = \frac{\dot{m}_{weir}}{(1 - X_{atmos})} \tag{8.9}$$

Equation (8.1) for the James lip pressure pipe is to be used:

$$\frac{G h_D^{1.102}}{P_{lip}{}^{0.96}} = 22106 \tag{8.1}$$

so the discharge mass flow rate must be written in terms of G:

$$G = \frac{4\dot{m}_D}{\pi d^2} = \frac{4\dot{m}_{weir}}{\pi d^2 (1 - X_{sil})} \tag{8.10}$$

The dryness fraction for the silencer, X_{sil}, is inconvenient and can be eliminated as follows:

$$(1 - X_{sil}) = \left(1 - \frac{(h_D - h_{fatmos})}{h_{fgatmos}}\right) = \frac{(h_{gatmos} - h_D)}{h_{fgatmos}} \tag{8.11}$$

With these substitutions, the correlation becomes

$$\frac{4\dot{m}_{weir} . h_{fgatmos} . h_D^{1.102}}{\pi d^2 . P_{lip}^{0.96} (h_{fgatmos} - h_D)} = 22106 \tag{8.12}$$

This equation has only one unknown, h_D, but it appears twice. A simple approach for field work is to rearrange the equation so that the unknown appears on both sides:

$$\left(\frac{4\dot{m}_{weir} . h_{fgatmos}}{22106 . \pi d^2 . P_{lip}^{0.96}}\right) . h_D^{1.102} = (h_{fgatmos} - h_D) \tag{8.13}$$

Then calculate the left-hand side and right-hand side and plot these on a graph against h_D repeating for a range of values until the two lines cross. The value of h_D at which they cross is the specific enthalpy of the discharge, from which the dryness fraction can be calculated, then G and finally $\dot{m}_D$. Iterative methods are available.

8.3 Further Details of the Measurement Equipment

8.3.1 The Single-Phase Orifice Plate

Several standards are available for orifice plates, ASME, ISO and BSI. The British Standard BS 1042 is used for the description here; it gives several options for construction. That referred to as the "D and D/2 version" shown in Fig. 8.7 and 8.8 is most often used with the flow from left to right.

The orifice plate is made with its edges accurately machined as shown. It is mounted between two flanges in a straight length of pipe of diameter D. The upstream pressure is measured at a wall tapping a distance D upstream of the plate and is an absolute pressure measurement used to determine the density of the fluid; call this location 1.

The other pressure of interest is where the cross-sectional area for the flow as it passes through the orifice is the smallest—call this location 2. Surprisingly, it turns out that the best position for location 2 is a distance D/2 downstream of the plate, so a wall tapping is placed there.

The formula relating pressure difference to mass flow rate is an empirical modification of Bernoulli's equation (4.28), which is for an ideal frictionless fluid (viscosity $= 0$). The equation can be reduced to

$$\frac{P_2}{\rho_2} + \frac{u_2^2}{2} = \frac{P_1}{\rho_1} + \frac{u_1^2}{2} \tag{8.14}$$

because gravitational effects are negligible over such a small arrangement, which is usually horizontal in any case. Rearranging,

$$u_1^2 - u_2^2 = 2\left(\frac{P_2}{\rho_2} - \frac{P_1}{\rho_1}\right) \tag{8.15}$$

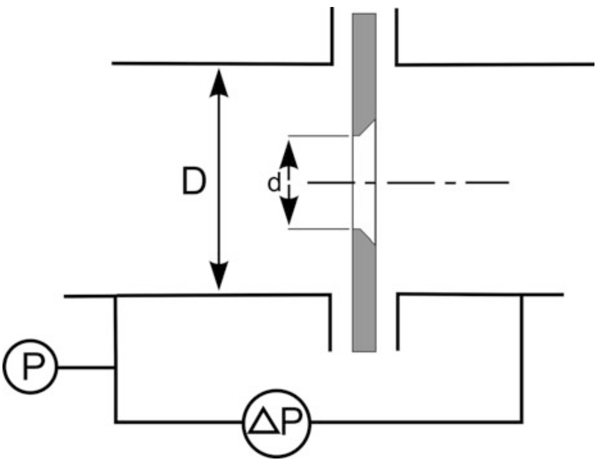

Fig. 8.8 Cross section of a single-phase orifice plate to BS 1042

Since $\dot{m} = \rho u A$ by definition, the left-hand side of the equation can be juggled to become

$$\frac{\dot{m}^2}{(\rho_2 A_2)^2}\left[\left(\frac{\rho_2 A_2}{\rho_1 A_1}\right)^2 - 1\right] = 2\left(\frac{P_2}{\rho_2} - \frac{P_1}{\rho_1}\right) \tag{8.16}$$

giving an expression for mass flow rate in terms of pressures and areas, which can be measured, and densities, which can be calculated if the fluid temperature is known. Despite the sites chosen for the pressure tappings, the areas A_1 and A_2 are for the pipe and orifice plate, respectively. For a steam flow the pipe could be thermally insulated and the temperature measured near the orifice plate by a thermocouple attached to the insulated pipe wall or a thermometer pocket. Equation (8.15) can be rearranged as

$$\dot{m} = (\rho_2 A_2)\sqrt{\frac{2\left(\frac{P_1}{\rho_1} - \frac{P_2}{\rho_2}\right)}{\left(1 - \left(\frac{\rho_2 A_2}{\rho_1 A_1}\right)^2\right)}} \tag{8.17}$$

The equation used by BS 1042 for real fluids is

$$\dot{m} = C.\frac{\pi d^2}{4}\sqrt{\frac{2(P_1 - P_2)\rho_1}{\left(1 - \left(\frac{d}{D}\right)^4\right)}} \tag{8.18}$$

where C is called the discharge coefficient

The equations can be made more similar. If the pressure drop over the plate is small so that $\rho_1 \approx \rho_2$ and the value ρ_1 is used for both, and if the areas are expressed in terms of their diameters, then the equations differ only by the BS1042 form containing the discharge coefficient C. The discharge coefficient is necessary because of two real fluid effects. Firstly, the neck of the flow is not at the orifice plate but further downstream—the neck is referred to as the vena contracta and it is smaller in diameter than the hole in the plate. Secondly, there is a small energy loss between the upstream location and the neck because of eddies formed in the corners of the plate. These are illustrated in Fig. 8.9 which compares streamlines for an ideal (non-viscous) fluid and a real fluid.

The pressure is fairly uniform over the eddy formed after the plate, and the downstream tapping position has been chosen so that it is in this uniform pressure region. The value of C is of the order of 0.6 but is sensitive to a number of factors which BS 1042 takes account of, for example, it depends slightly on mass flow rate. The standard contains rules governing the required upstream length of straight pipe, the proximity to bends, etc., and these must be followed exactly if the measurement

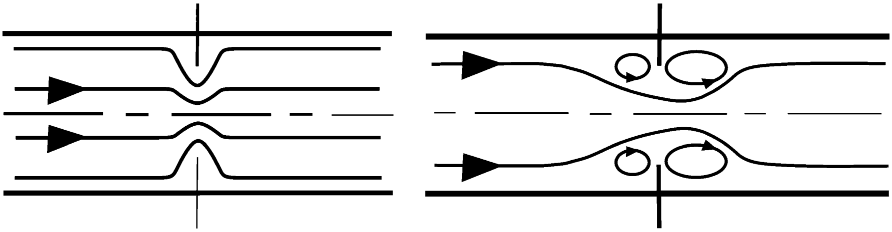

Fig. 8.9 Streamlines for ideal and real flow through an orifice plate

is to be to the prescribed precision. The plate itself must be accurately machined and free from burrs and defects along its sharp edge. (It should not be hung on a nail by its hole!) In addition, any pressure tappings made through the pipe must be of small diameter compared to the pipe wall thickness, say 1 mm diameter, and must have drilling burrs polished off on the inside leaving a square edged hole. Tappings welded on on-site are most unlikely to produce good results—the orifice plate is a laboratory technique and needs very careful attention to detail.

8.3.2 The Two-Phase Orifice Plate

The simplicity of placing an orifice plate in a flow attracted attention to its use for two-phase flows in various industrial sectors many years ago. It represents a very attractive option since the equipment arrangement shown in Figs. 8.6 and 8.7 would reduce to that of Fig. 8.5.

The problem of making predictions about the behaviour of any two-phase flow has already been explained in Sect. 7.7—experimental data is essential. A large number of parameters is required to define a two-phase flow, so a very large number of permutations must be examined in experiments if they are to provide data for a comprehensive correlation for any particular flow property of interest (in this case the pressure drop over an orifice). Adding to the problem is the uncertainty in knowing that the list of parameters is complete. Early empirical correlations were produced by Murdock [1962] and James [1965], the latter specifically for geothermal applications. Helbig and Zarrouk [2012] have reviewed them and others and have proposed a new correlation which they tested against field data. They note that the specific enthalpy of the flow is not an output of the orifice plate measurements and must be found separately.

8.3.3 The Thin-Plate Sharp-Edged Weir

There are even more standards governing weir flow measurement than orifice plates—ASME, ASTM, AWWA, BSI, ISO and so on; British Standard 3680 is used for this description. Like the orifice plate, which is an obstruction in a pipe flow,

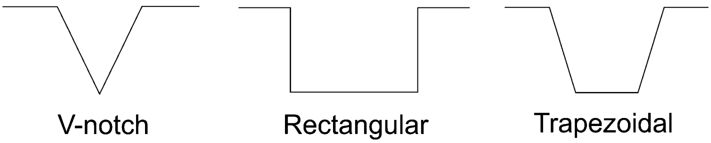

Fig. 8.10 Patterns of weir notches often used for geothermal measurements

the thin-plate weir is an obstruction in an open channel flow, and the fluid flow is disturbed in a controlled way to create a measurable effect that can be related to the mass flow rate. Weirs for measurement were developed extensively in the nineteenth century by hydraulics engineers, and many interesting details of their use can be found in older fluid mechanics textbooks.

British Standard 3680: part 4A sets out precise rules for the construction and installation of thin-plate weirs in the same manner as BS1042 does for orifice plates, although less manufacturing precision is required. For geothermal engineering, the hole, or "notch" in the weir, is usually shaped as either a V notch, a rectangular notch or a trapezoidal notch—Fig. 8.10.

A Cipolletti weir, sometimes used in geothermal well measurements, is a trapezoidal notch of particular shape, with a side slope of 1:4. The various notches have characteristics that influence the choice of which to use, but the differences are not complex. The plate must be vertical and the main measurement required is the water level above the bottom of the notch, although it is practically easier to deduce it by measuring below the top edge. The V-notch weir widens with height above the point, allowing increasing flow without a proportional increase in depth. This helps to keep the accuracy of the measurement uniform over the range of flow rates, whereas with the rectangular weir, low flow rates give a very small wide flow, the height of which is difficult to measure accurately. The trapezoidal weir is an alternative to the rectangular weir giving a smaller variation of depth measurement with flow rate.

Whichever notch is chosen, it will be accurate only if it is kept free of debris and chemical deposition (calcite and silica), is installed vertically and normal to the flow, and if the water flows over it correctly. The stream of water flowing over the weir is supposed to emerge as a jet—referred to as the "nappe"—which must make no contact with the downstream face of the weir plate. When the water forms a jet with clear air beneath it (Fig. 8.11) the nappe is said to be aerated and this is the requirement; a "drowned nappe" will not provide accurate measurements.

8.3.4 The Separator

Separators or, more precisely, cyclone separators are a normal part of steamfield equipment and are discussed in Chap. 13. Small units suitable for well testing can be constructed.

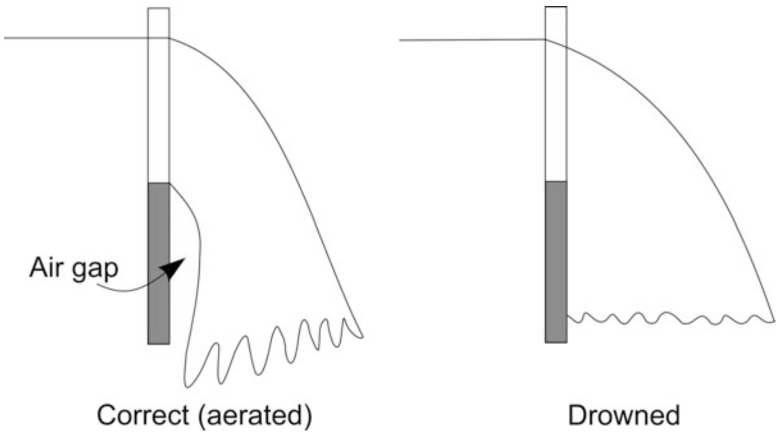

Fig. 8.11 Correct and incorrect flow patterns over notched weirs

8.3.5 The Silencer

A silencer is effectively a separator which has had its upper end dome removed, leaving it open to atmosphere. It works in precisely the same way as a separator, with a tangential entry that rotates the flow within the cylinder, but the steam and gas are allowed to discharge to atmosphere through the open top. Its purpose is to separate the water so that it can be measured and also to reduce the noise of the discharge. Many silencers are built as twin stack, with a single entry causing spinning in opposite directions and a single liquid exit—see, for example, Thain and Carey [2009] where it is referred to as an atmospheric separator. The water exits the bottom at the saturation temperature corresponding to the atmospheric pressure for the aqueous solution produced, but the difference between this and the properties of pure water are neglected and pure water properties are used. The mass flow rate of the water is measured with a simple weir; the mass flow rate of steam from the top of the silencer does not need to be measured, as already demonstrated in the examples given. The weir has already been explained, and usually the only problem, particularly in portable silencers, is arranging for the required length of undisturbed upstream flow. Some silencers are made as permanent concrete structures within easy piping distance of several wells, others from steel and some with wooden slat cylinders.

Most of the noise from a silencer is generated at the inlet nozzle, and the duct directing the flow into the silencer barrel (the tall cylinder) is often a thick-walled concrete construction to help reduce the noise level. The annular gap between the concrete pipe and the nozzle may be many cm wide, and air is dragged in, which also helps, but nevertheless these are noisy devices. The annular gap is usually covered by a loose-fitting steel plate, since the air entrained in the jet creates a suction that may be a hazard to operators.

8.4 Chemical Measurements During Discharge

Although it is not dealt with in any detail in this book, an understanding of the chemistry of the resource fluids is an important key to understanding the behaviour of the resource as a whole as an actively convecting, chemically reacting system. Sufficient understanding cannot be gained by examining the thermo-fluid dynamics of the resource in isolation. By adding the geochemistry it is possible to understand how the resource functions in the natural state and thus what to expect when fluid is removed by discharging wells and replaced (or not) with separated water at a lower temperature containing higher concentrations of the dissolved species in the original discharge, without the gas. The various large-scale effects that can result are discussed in Chaps. 13 and 14; their detection comes as a result of several types of geoscientific measurements, including geophysics (e.g. gravity changes), but perhaps most importantly, sampling of discharged fluids. Wells provide the only direct access to the resource, and by documenting changes in chemical species in the discharge, changes in the resource as a whole can be deduced.

From a purely mechanical engineering point of view, the gas present in the well discharge is important to the power station operation, as it is non-condensable and must eventually be pumped from the condenser at the cost of some power that could otherwise be sold as electricity. Some of the dissolved chemical species are also important, in particular silica, which often comes out of solution to form scale deposits in the pipelines and on the turbine blades. Various other chemical species may deposit in the well production casing, on first flashing, a phenomenon which is resource specific.

8.4.1 Sampling Arrangements During Discharge Measurements

Chemical samples are usually taken between the wellhead and the discharge measurement equipment and from just upstream of the weir attached to the separator. Ellis and Mahon [1977] state that water samples are best taken where the discharge is still at wellhead pressure, so that the volume of steam present is at its smallest, and a wellhead side valve is often used. Samples for gas content are best taken close to the silencer, downstream of any pressure restriction, where the water content is at its minimum. Geothermal gases do not all partition into the steam and their solubility in water cannot be ignored.

The samples are taken using a hand-carried cyclone separator, identified by those in the industry as a “Weber” separator (although Weber was responsible for the development of cyclone separators in general, which includes any separator used at a geothermal resource). The handheld device has a cooling system to condense the steam sampled.

8.4.2 Discharge from a Well Producing from Several Formations containing Chemically Different Fluids

Consider a well penetrating two producing formations, A and B, each with different chemical compositions, identified by different concentrations of a chemical species C and different specific enthalpy. Three balance equations can be written, for mass, energy and chemical species, in terms of mass flow rate $\dot{m}$, specific enthalpy h and species concentration C, as follows:

$$\dot{m}_A + \dot{m}_B = \dot{m}_D \tag{8.19}$$

$$\dot{m}_A.h_A + \dot{m}_B.h_B = \dot{m}_D.h_D \tag{8.20}$$

$$\dot{m}_A.C_A + \dot{m}_B.C_B = \dot{m}_D.C_D \tag{8.21}$$

where the suffixes refer to formations A and B and the total discharge D.

These form a set of linear algebraic equations, and the result of mixing the two sources in various proportions appears as a straight line on a graph of h versus C, for example. This is the basis of mixing models; h and C can be regarded as tracers provided they are passive. This approach was used by Pinder and Jones [1969] in examining the chemical composition of the total runoff of groundwater in terms of its individual sources and has been formalised as "endmember mixing analysis (EMMA)" according to Durand and Torres [1996]. The same approach was used by Fournier [1977], less formally in mathematical terms but with clear physical explanations, to demonstrate the use of geothermometers and mixing models to the examination of springs. These linear relationships provide a means of examining variations in total discharge composition with time and total discharge rate. Glover et al. [1981] used the approach to interpret the gas content in the total discharge of wells, citing examples from Krafla (Iceland) and Tongonan (Philippines) and drawing conclusions about the source of excess enthalpy. Lovelock and Baltasar [1983] illustrated the same general approach using a variety of examples from discharge tests in which the measurement method of Fig. 8.7 was used. The measurement uncertainty is a problem, as the uncertainty range as represented by an uncertainty bar on a point tends to lie along the mixing line that is the result, reinforcing the conclusions. However, a greater issue is that the parameters in the equations are not always passive, specific enthalpy varies with pressure and temperature, some species deposit when they reach saturation concentration and the concentration of species is increased as a result of flashing, the latter being the most significant.

8.4.3 Changes in Concentration of Dissolved Species as a Result of Flashing

The discharged fluid is likely to have a sufficiently high specific enthalpy to cause it to flash in the discharge measurement equipment, with the result that the concentration of dissolved solids increases; for the present purposes the concentration of silica (SiO_2) is the main interest. Silica dissolved in steam is of concern in fossil-fuelled power stations operating with high purity water at very high temperatures and pressures (550 °C and supercritical pressures), but in the range of pressures experienced by discharging wells it has negligible solubility in steam so is assumed to remain with the liquid phase. The dryness fraction, which defines the proportion of an original liquid which flashes and forms steam, can be used to calculate the concentration of the species in the remaining water. Thus Eq. (3.17),

$$h = (1 - X)h_f + Xh_g \tag{3.17}$$

states that the specific enthalpy of the original liquid is shared between the water and steam and shows that the mass flow rate of water is reduced to $\frac{1}{(1-X)}$ of the original. The chemical mass balance is

$$\dot{m}_D.C_D = \dot{m}_g.C_g + \dot{m}_f.C_f \tag{8.22}$$

where C is the species concentration, in the total discharge, and in steam and in water, respectively, reading from the left, and since the concentration in the steam is zero, the concentration in the remaining water is

$$C_w = \left[\frac{\dot{m}_D}{\dot{m}_f}\right].C_D = \frac{C_D}{(1 - X)} \tag{8.23}$$

The concentration measured in a liquid sample must be modified in this way according to how much of the original liquid remains after the flashing processes. The concentration increases as the liquid mass diminishes and may reach saturation, or supersaturation for a period of time until it deposits. Silica will be found to be a significant factor in steamfield design (Chap. 12).

8.4.4 Mass Flow Rate Measurement by Chemical Tracers

The same simple mixing algebra can be used to measure the mass flow rate of the two phases in a pipe carrying a two-phase mixture, and a measurement method using it was originally patented by Chevron Corporation [1988]. Lovelock [2006] explains that a tracer substance, isopropanol, is injected into the flow, and at some distance downstream sufficient for it to have become well mixed, it will have become distributed between the liquid and steam. At 180 °C the distribution is quoted as being about 5 % remaining in the liquid. The tracer is injected near the wellhead of a discharging well, and then at some distance downstream, samples of water and steam are taken. The steam is condensed and laboratory analysis can determine the concentration of the tracer in each phase. The mass flow rate of each phase is thus determined. Lovelock [2006] also describes the same technique but using sulphur hexafluoride (SF_6). He gives the results of tests using dry steam wells where the flow rate was already being measured with an orifice plate (see Fig. 8.5) and found an average difference between the two methods of only 1.2 %. A comprehensive set of test results is provided for two-phase flows comparing the two tracers. The distance from injection to sampling point was quoted as 10–15 m to obtain good results.

8.5 Surveying Wells During Steady-State Discharge and Predicting Pressure and Temperature Distributions

The downhole instruments described in Chap. 6 may be used while the well is discharging. The instruments partially block the flow in the liner, and particularly in the casing, which is transmitting the full flow, and an upward drag force is produced, capable of lifting the instrument up to the surface, damaging it and producing a tangle of steel wireline. Weights must be added to the instrument to counteract this. Measurements during discharge are helpful in locating production zones and the temperature of the fluid emerging from them. Measurements in the production casing are helpful in designing calculation procedures to predict details of the flow in the well

It is sometimes helpful to be able to predict the steady-state pressure and temperature distributions in the flowing well. For example, these would show the depth at which flashing first occurs in a liquid flow, which might be important in a discharge which deposits calcite. For a well with any type of axial tubular insert in the upper sections, it might be helpful to know how the discharge characteristics would be modified. The mixture produced at wellhead when more than one formation is producing depends on the flow from each, which is bound up with the sandface pressure of each, which both results from and partly controls the axial pressure distribution. A combined analysis of flow in the well and the formations could in principle be carried out. As a final example, the production casing diameter might be chosen based on pressure drop from formation to wellhead; King et al. [1995] presented a cost–benefit analysis of using different-sized production casings, using the commercial wellbore "simulator" WELSIM. For some reason, numerical predictions of this type have become known as wellbore simulation, despite "simulation" being almost universally reserved to describe the prediction of transients. Elmi and Axelsson [2009] show the application of a more recent simulator known as HOLA.

For single-phase flows the standard pipe flow solutions can be applied, with friction factor–Reynolds number correlations chosen for an appropriate wall roughness (see Sect. 4.3.4). For example, Leaver and Freeston [1987] produced a correlation from which the discharge characteristic of a steam-producing well could be determined.

Predicting heat loss from the flow is a problem because the thermal boundary condition on the production casing is ill-defined, and an average for the well must be used. Flow through the slotted liner can be reasonably represented by using an equivalent diameter, but an effective roughness is also needed and this is empirical and specific to each well, since rubble may obstruct the annular passage in places.

This problem was studied for geothermal wells at least as early as 1964 (Ryley [1964]—see Kestin [1980]) and earlier for petroleum wells. Research on two-phase flow for the nuclear industry started in roughly the same era. All calculations of pressure gradient in pipes carrying two-phase flow are essentially similar, using the approach described in Chap. 7. The explanation offered here uses a calculation procedure based on an ESDU compilation [1978] for water–air and water–steam mixtures; it was developed for application to geothermal wells by Brennand and Watson [1987] and later rewritten for teaching purposes. It has shortcomings as discussed by Karaalioglu and Watson [1999], which could be avoided by using a more recently available collection of two-phase correlations, ESDU [2008].

Equation (7.14) is the basis of the calculation, rearranged as

$$dz = \frac{dP}{\left(\left(\frac{dP}{dz}\right)_{grav} + \left(\frac{dP}{dz}\right)_{accel} + \left(\frac{dP}{dz}\right)_{fric}\right)} \tag{8.24}$$

The calculation proceeds by starting at a known level in the well, z, and calculating the pressure reduction over a short element, dz. The starting point can be either the top or bottom of the well, so the calculation steps down or up. However, instead of specifying dz, the pressure difference dP across the element is specified, leaving dz as the unknown. This approach allows the fluid properties at each end of the element to be calculated (pressure, temperature, and liquid and gas densities and viscosities), so the axial variation of properties, which produces variations in the flow via the correlations, is taken account of. Single-phase correlations are used if the flow is single phase; otherwise, two-phase correlations are used, which depend on parameters such as mass velocity G and volumetric flux j (defined in Sect. 7.7.2). The correlations provide a pressure gradient for each of the terms, gravity, acceleration and friction, one at each end of the element, allowing an average gradient to be determined. Thus using Eq. (8.24) the step length dz is the outcome of the calculation. The two-phase correlations used were based on homogenous flow, with the seven gravitational correlations and six frictional ones given in the ESDU compilation, and the acceleration component based on either homogenous or separated flow models.

The calculation procedure was tested against some data from Rotorua wells. These have small diameter production casing occupying almost the full drilled depth, so their measured mass discharge characteristics provide a valuable test because the flow through the casing is known at all depths and there are no step changes of diameter, slotted liner or increases in flow from several formations that require assumptions which would cloud the comparison. Furthermore, the producing formation was virtually at saturation point so there is a long length of two-phase flow. The details are given in Table 8.1 below.

The measured discharge characteristics represent the extreme right, low mass flow rate, high-wellhead pressure part of the characteristics shown in Fig. 8.1. They show a wellhead pressure maximum which, if it were a pump characteristic, would lead to flow instability—two mass flow rates corresponding to a single-wellhead

Table 8.1 Dimensions of the Rotorua wells for Figs. 8.12 and 8.13

Well no.	Depth (m)	Cased depth (m)	Formation temperature (°C)	Sp. enthalpy (kJ/kg)
715	122	100	165	610–720
901	149	129	183	730–790
703	206	193	199	860–900

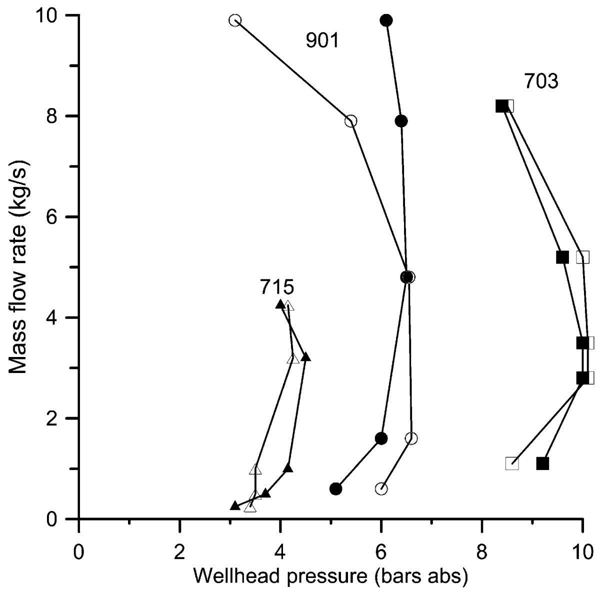

Fig. 8.12 Discharge characteristics of Rotorua wells of Table 8.1 showing measurements (*solid symbols*) and predictions (*hollow symbols*)

pressure—although the flow was apparently steady. The measurement data were given in the report of the NZ Ministry of Energy [1985] and are replotted in Fig. 8.12 together with the predictions of Brennand and Watson [1987].

For one of the points on the characteristic for well 703, the contributions to total pressure drop made by the three components are shown in Fig. 8.12. The frictional gradient makes the biggest contribution at the top of the well, because the mean density of the flow is least there, and the mean velocity highest—friction is generally proportional to kinetic head. The fluid is most dense near the bottom of the well, so the gravitational gradient is highest there. The acceleration component is small everywhere but increases up the well as the fluid is expanding.

For the comparisons of measurement and prediction shown, the roughness height was assumed to be 0.0003 m, which is much rougher than new commercial steel pipe, and the heat loss from the well was assumed to be zero because they had been in continuous use for a long time and the surrounding ground was warm. These assumptions were obviously suitable for well 703, based on Fig. 8.12, but not for well 901; to obtain a good match, the roughness height can be varied by trial and error, and this needs to be done for every well individually (it has not been

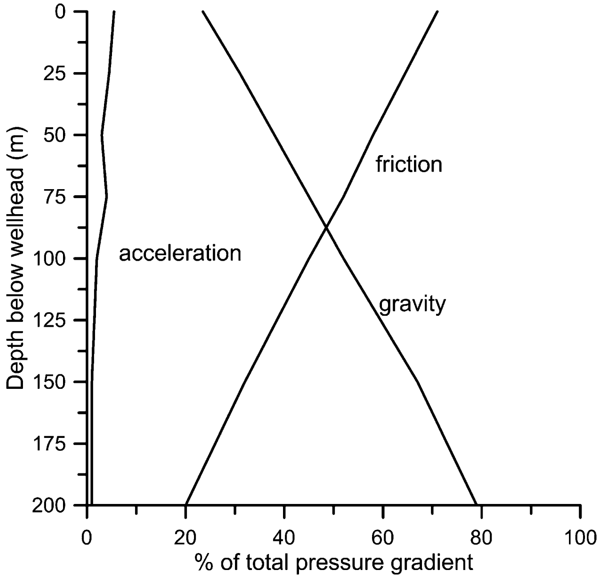

Fig. 8.13 Percentage contributions to total pressure drop made by friction, gravity and acceleration for Rotorua well 703

done here, to illustrate the point). Once a good match is obtained, then the effects of a modification to the well, such as inserting a sleeve to patch a hole in the casing, can be assessed by introducing the appropriate changes in diameter.

No provision was made for more than one production zone in the calculation procedure, because there are then too many degrees of freedom available which makes a match less reliable; the difficulties of specifying parameters for the slotted liner have already been explained. Thus the Brennand and Watson procedure is best suited to examining flow in the production casing only. Finally, the correlations used are not appropriate for near-sonic flows (choked flows).

Karaalioglu and Watson [1999] made comparisons of predictions and measurements for large diameter wells using the same procedure and noted the problem with using the ESDU [1978] correlations, which included heated flows. The acceleration component is greatly increased for the high heat flux situations of interest to fossil and nuclear boilers, for which the correlations were produced. More recently, a compilation of experimental data and correlations have been produced for adiabatic vertical flows, ESDU [2008], which would be applicable to geothermal wells.

8.6 Transient Discharge Measurements and Predictions

There are at least two different physical processes that lead to a periodically varying well discharge, which is what the title of this section refers to. The discharge is transient when the well is first opened and is being closed, but there has been little incentive to try to predict this for geothermal wells although it is an important research topic in the nuclear industry in relation to the rate at which water escapes through a break in the pressure vessel or pipes of a water cooled reactor.

One physical process involves two (or more) producing formations in a well. The interaction of drawdown of a zone with the phase distribution in the well offers the possibility of a major shift in wellbore pressure at the deeper zone. Consider a lower zone producing a fairly dry two-phase mixture but with low permeability which draws down, leaving the discharge from an upper good producer of liquid continuing. When the discharge from the lower zone reaches some particular low rate, the two-phase regime in the well collapses and becomes denser at the lower zone, halting or at least severely reducing the flow there and allowing the formation pressure to recover towards the undisturbed condition. The process repeats. This is entirely speculative of course, and Menzies [1979] offers a slightly different explanation for an impressive set of measurements of a Tongonan (Philippines) well with very regular periodic variations in discharge rate. Lovelock and Baltasar [1983] present convincing evidence of this type of behaviour in a Tongonan well, by chemically sampling the output at frequent intervals during the discharge, which had a period of 4 h, sufficiently long to allow sampling. The results were plotted on a graph of two components of the discharge, chloride and CO_2, and a mixing line of the type discussed in Sect. 8.4.2 above was obtained. The two formations were a high-chloride liquid-filled zone and a high-gas zone (presumably a shallower steam zone).

A different physical process occurs in some geysers. Geysers and geysering wells produce an extreme flow variation, an intermittent flow. Lu [2004] (see also Lu et al. [2005, 2006]) reviewed the history of investigation of geysers, which began in Iceland (the word is Icelandic), and also the occurrence of geyser-like behaviour in engineering equipment. Although natural geysers have been explained in terms very similar to those offered above for wells with multiple producing formations, geysering in engineered equipment is clearly not of this type. There exist a number of wells worldwide which exhibit the behaviour, and that at Te Aroha, New Zealand, was the subject of Lu's experiments. Like the Rotorua wells used for steady-state calculation comparisons, the Te Aroha well was cased to within a few metres of the bottom with a single 100 mm diameter steel tube; the well is 70 m deep so a long length of test section was available. It has a maximum temperature at the bottom of 83 °C and discharges at 70–75 °C, producing water with a high concentration of dissolved CO_2. Clearly, flashing of water to steam does not drive the phenomenon, and in this respect, it differs from natural geothermal geysers like those at Yellowstone and Rotorua. When shut it exhibits a wellhead pressure of 1.5–2.5 bars abs, depending on recent rainfall, and although it will discharge steadily when the discharge is restricted to a low flow rate, when fully opened, it discharges intermittently for approximately 120 s with a period of 700 s. The discharge is eruptive, with large amounts of gas produced with the water. Measurements were made by placing piezometric pressure transducers at various depths in the well. The void fraction was measured by placing two transducers a distance of 2–3 m apart and calculating the density between them.

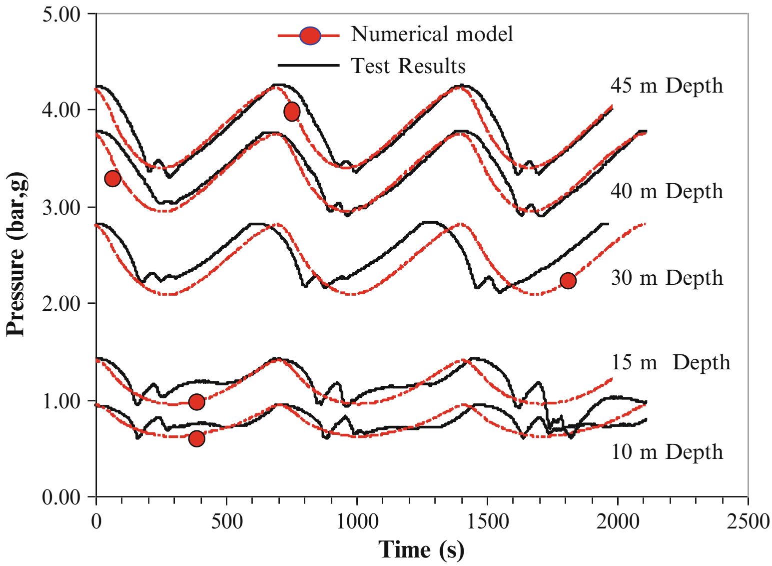

Fig. 8.14 Showing the cycling pressure variations (reproduced by permission of X.Lu [2004])

The equations governing the flow were continuity, expressed as one each for water and gas, with a source term representing the CO_2 coming out of solution, and also momentum in the form developed earlier as Eq. (7.14):

$$\frac{dP}{dz} = \left(\frac{dP}{dz}\right)_{grav} + \left(\frac{dP}{dz}\right)_{accel} + \left(\frac{dP}{dz}\right)_{fric} \tag{7.14}$$

The heat loss from the well was small so the energy equation was ignored on the grounds that energy exchanges did not significantly affect the flow. The solubility of CO_2 was described by Henry's law.

In the calculations (which represent a true simulation since they follow a time-dependent process), the gravitational term in the momentum equation was found using the calculated local mean density, and the frictional component assumed the homogenous model. Adopting separate conservation equations allowed the phases to have different velocities which in turn allowed the drift flux model to be used for the acceleration term in the momentum equation—despite homogenous flow being assumed for the frictional term. This was essentially based on an intuitive understanding of which component of pressure drop was having the greatest influence, gained from the experimental measurements. The process is accompanied by a periodic rise and fall of the bubble formation level (flash level) in the well, as Lu et al. [2006] demonstrated. The agreement between measurements and calculations is illustrated by Fig. 8.14.

The predictions compare very well with the measurements; those shown are for depths from 10 to 45 m. The agreement is good for period and amplitude of the main disturbance. Secondary measured regular disturbances, small at 45 m but quite large near the surface, are not represented by the calculations. It seems likely that a similar calculation approach incorporating the energy equation could be developed for application to natural geysers, but definition of the flow channel would present a problem.

References

Brennand AW, Watson, A (1987) Use of the ESDU compilation of two-phase flow correlations for the prediction of well discharge characteristics. In: Proceedings of 9th NZ Geothermal Workshop, University of Auckland

Chevron Corporation (1988) US Patent No 4788848

Durand P, Juan Torres JL (1996) Solute transfer in agricultural catchments; the interest and limits of mixing models. J Hydrol 181:1–22

Ellis AJ, Mahon WAJ (1977) Chemistry and geothermal systems. Academic, New York

Elmi D, Axelsson G (2009) Application of a transient wellbore simulator to wells HE-06 and HE-20 in the Hellisheidi geothermal system, SW-Iceland. In: Proceedings of 34th Workshop on Geothermal Reservoir Engineering, Stanford

ESDU (1978) Guide to calculation procedures for solving typical problems related to pressure drop in two-phase systems, ESDU 780018

ESDU (2008) Pressure gradient in upward adiabatic flows of gas–liquid mixtures in vertical pipes, ESDU 04006

Fournier RO (1977) Chemical geothermometers and mixing models for geothermal systems. Geothermics 5:41–50

Glover RB, Lovelock BG, Ruaya JR (1981) A novel way of using gas and enthalpy data. In: Proceedings of 3rd NZ Geothermal Workshop, University of Auckland

Grant, MA (1979) Interpretation of downhole measurements in geothermal wells, Report No. 88, Applied Maths Division, Department of Scientific and Industrial Research, NZ

Helbig S, Zarrouk SJ (2012) Measuring two-phase flow in geothermal pipelines using sharp-edged orifice plates. Geothermics 44:52–64

James R (1962) Steam-water critical flow through pipes. Proc Inst Mech Eng 176(26):741

James R (1965) Metering of steam-water two-phase flow by sharp edged orifices. Proc Inst Mech Eng 180:549–566

James R (1966) Measurement of steam-water mixtures discharging at the speed of sound to the atmosphere. NZ Eng 21(10):27

Karaalioglu H, Watson A (1999) A comparison of two wellbore simulators using field measurements. In: Proceedings of 21st NZ Geothermal Workshop, University of Auckland

Kestin J (ed) (1980) Sourcebook on the production of electricity from geothermal energy, US DoE, Contract No EY-76-S-4051.A002

Kieffer S (1977) Sound speed in liquid–gas mixtures: water-air and water-steam. J Geophys Res 82(10):2895

King TR, Freeston DH, Winmill RL (1995) A case study of wide diameter casing for geothermal systems. In: Proceedings of 17th NZ Geothermal Workshop, University of Auckland

Leaver JD, Freeston DH (1987) Simplified prediction of output curves for steam wells. In: Proceedings of 9th NZ Geothermal Workshop, University of Auckland

Lovelock B (2006) Flow testing in Indonesia using alcohol tracers. In: Proceedings of 31st Workshop on Geothermal Reservoir Engineering, Stanford University

Lovelock BG, Baltasar SJ (1983) Geochemical techniques applied to medium term discharge tests in Tongonan. In: Proceedings of 5th NZ Geothermal Workshop, University of Auckland

Lovelock BG, Cope DM, Baltasar AJ (1982) A hydrogeochemical model of the Tongonan geothermal field, Philippines. In: Proceedings of Pacific Geothermal Conference incorporating the 4th NZ Geothermal Workshop, University of Auckland

Lu X (2004) An investigation of transient two-phase flow in vertical pipes with particular reference to geysering PhD thesis, Department of Mechanical Engineering, University of Auckland, New Zealand

Lu X, Watson A, Gorin AV, Deans J (2005) Measurements in a low temperature CO2 driven geysering well, viewed in relation to natural geysers. Geothermics 34:389–410

Lu X, Watson A, Gorin AV, Deans J (2006) Experimental investigation and numerical modeling of transient two-phase flow in a geysering well. Geothermics 35:409–427

Menzies AJ (1979) Transient pressure testing. In: Proceedings of NZ Geothermal Workshop, University of Auckland

Menzies AJ, Gudmundsson JS, Horne RN (1982) Flashing flow in fractured geothermal reservoirs. In: Proceedings of 8th Workshop on Geothermal Reservoir Engineering, Stanford

Murdock JW (1962) Two-phase flow measurement with orifices. J Basic Eng 84:419

New Zealand Ministry of Energy (1985) The Rotorua geothermal field; technical report of the Rotorua Geothermal Task Force

Pinder GF, Jones JF (1969) Determination of the groundwater component of peak discharge from the chemistry of total runoff water. Water Resour Res 5:438–445

Ryley DJ (1964) Two-phase critical flow in geothermal steam wells. Int J Mech Sci 6(4):273

Thain IA, Carey B (2009) 50 years of geothermal power generation at Wairakei. Geothermics 38:48