Proc. 5th NZ Geothermal Workshop 1983

SEPARATED OR TOTAL FLOW HEAT EXCHANGER PLANTS

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ABSTRACT

Use of the total flow (well-head two-phase mixture) in heat exchanger plants for geothermal direct heat applications in New Zealand is not a new idea - this approach has been adopted successfully in Rotorua on low enthalpy steam/water mixtures for many decades. However now that field test data on two-phase heat transfer and fouling is available, it is possible to consider the commercial implications in using the total flow in heat exchanger plants from higher pressure production wells. A case study for process steam generation is presented to discuss the possible thermal efficiency and environmental impact advantages of this approach.

INTRODUCTION

Until now, geothermal direct-heat applications in New Zealand have utilised both separated steam and the total flow (the well-head steam/water mixture) in heat exchanger plants. The separated flow approach is characterised by separation of the steam/water mixture in flash plants, transmission of the geothermal steam to the end-user and then partial condensation of the steam/non-condensible gas mixture in specially designed heat exchangers. The total flow type of recovery system, takes the well-head two-phase mixture directly into a heat exchanger where the steam fraction is condensed before the water fraction and gas are subcooled.

The best known example of the separated flow approach is at Kawerau where the geothermal steam is taken to the Tasman Pulp and Paper mill for both process heating and power generation in an atmospheric pass-out turbine. The geothermal resource enthalpy is 1100 kJ/kg which at 8 bar produces a 19% steam fraction in the steam/water mixture. Single flash plants at 15 bar and 8 bar provide the steam containing 1.2% mole fraction (3% w/w) gas, predominantly CO_2. Up to 200 t/h geothermal steam is currently used. The main process heating application is clean steam generation in kettle boilers operating at an effective temperature difference driving force of 20°C. Consequently the 8 bar geothermal steam at 170°C produces process steam at 150°C and 4.8 bar.[1] These boilers condense between 90 and 95% of the steam fraction in the geothermal steam/gas mixture although a new unit (number 5) with a preheater should be capable of condensing 99% of the available steam. The main loss in thermal efficiency of this type of system is in the separated water which is currently flashed from 170°C to atmospheric pressure for surface disposal in the local river.

In Rotorua, the total flow from low enthalpy wells, typically 500 to 900 kJ/kg is used in a variety of types of tubular heat exchangers to heat water for domestic and commercial space and water heating. In most cases the heat exchangers have been generously overdesigned as the design method assumed water only on the geothermal side and there is a lack of actual performance data. However the heat exchangers have given few operating problems and have needed cleaning only infrequently. The main fouling problem is due to calcite deposition and silica deposition is not observed. The subcooled geothermal two-phase (water/gas) mixture is let down to atmospheric pressure at the soak bore where the gas is vented. If the discharge temperature exceeds 100°C before the soak bore, steam will separate with the gas vit. the many visible steam plumes.

HEAT EXCHANGER DESIGN

The availability of process design methods for geothermal and other heat exchangers in New Zealand took a major step forward when DSIR became a member in Heat Transfer Research, Inc. (HTRI) in 1981. The process design of shell-and-tube heat exchangers for steam generation or water heating and banks of high-finned tubing for air heating can be carried out using the HTRI computer programs.

Both the ST (single-phase) and the CST (condenser) programs have since been used extensively to design and rate geothermal heat exchangers at Kawerau, Broadlands, Rotorua and Wairakei. Actual performance data has compared well with the predictions made by the computer programs. The HTRI methods can now be supplemented by performance data on two-phase heat transfer and on fouling from the field test work at Broadlands. This work confirmed that design fouling factors for geothermal fluids are low and that carbon steel tubes can be cleaned effectively. For heat exchanger design purposes, the different features of each type of flow-separated steam, separated water and total flow can be summarised in Table 1.

Table 1 Summary of Available Heat Exchanger Design Methods

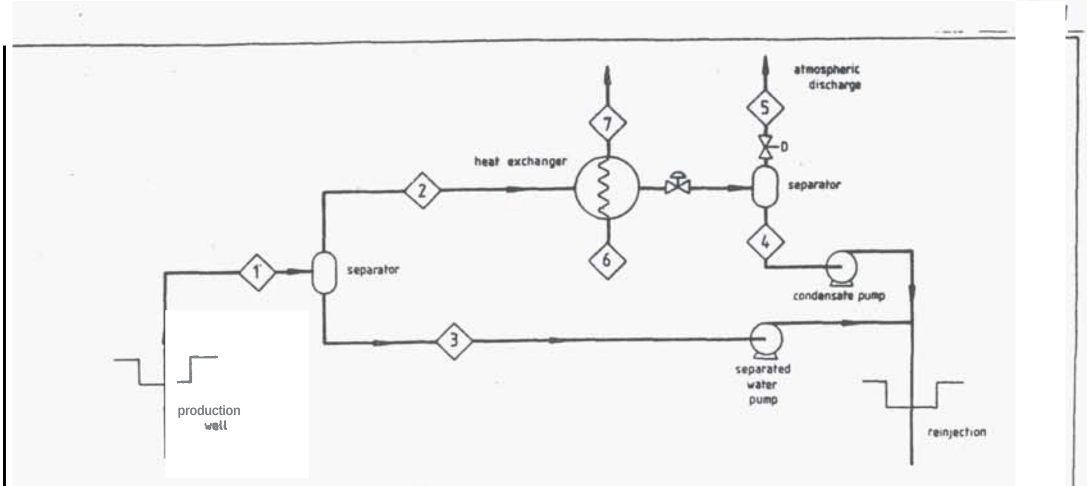
	Separated Steam		
Basis	partial condenser	heat exchanger designed for cleaning	partial condenser
Film coefficient	CST program	ST program	CST program
Pressure drop	CST program	ST program	CST program
Fouling factor	Low Corrosion fouling	Low Silica deposition fouling	Low Corrosion + Precipitation fouling
Cleaning	Chemical	Mechanical + chemical	Chemical
Problems	Care at shutdown	Limited life out of CS tubes due to cleaning	Maldistribution in header
Confidence	High	High	Moderate

Separated Steam

Partial condensers for the condensation of the steam/non-condensible gas mixture can be designed adequately using the 'incremental CST program and assuming a steam/CO_2 mixture. Both tubeside and shellside (with a variable baffle spacing) condensation can be handled. Condensing heat transfer coefficients will usually be high at around 20,000 to 10,000 W/m^2°C at moderate gas concentrations, 1 to 5% molefraction, for the shew condensing regime and will decline quite rapidly after 80 to 90% of the steam fraction has condensed. Carbon steel is the primary material of construction and passivation due to the formation of iron sulphides and iron oxides in the presence of the dissolved H_2S in the condensate occurs quite rapidly. The geothermal fouling resistance is due to this corrosion product layer. The field test work confirmed that this fouling resistance is extremely low and can be taken at 0.0001 m^2°C/W which is probably conservative. The presence of over 10 ppm SiO_2 from any carry-over water appears to assist the formation of this stable film. A test with SiO_2 at less than 1 ppm in geothermal steam, also formed passivating sulphide films but required a much longer time to do so. Low and acceptable corrosion rates were observed. At shutdown when the tube-bundle is opened to the atmosphere for inspection and cleaning, the passivating iron sulphides can be damaged by thermal stress and if geothermal condensate is allowed to form further corrosion can occur. There should be some benefits in shutting down the heat exchanger hot to avoid the contact of geothermal condensate and oxygen. Cleaning the iron sulphide deposits if they are allowed to accumulate after many years of operation can be achieved by washing out the tubes with a dilute inhibited acid, followed by a fluid flushing of mechanically dislodged solids.

Separated Water

Heat recovery from separated water involves sensible heat transfer on the tubeside to facilitate easier cleaning of the hard and adherent silica layer. The ST program can be used for the heat exchanger design and it will optimise the number of shells required in series to satisfy the desired temperature profile and available pressure drop. A high water heat transfer coefficient of around 10,000 W/m^2°C can be obtained with a water velocity of 2 m/s at 100°C in 19 mm tubes - the Reynolds number is 10^5 i.e. good turbulent flow conditions. Fouling is due to the deposition of silica as supersaturation occurs with cooling. Test data has shown that the rate of deposition is extremely slow if the separated water is taken directly from the wellhead or flashplant and flows under turbulent flow.[2] Again carbon steel would be the primary material of construction. The mill scale initially present on the tubes appears to be partially transformed to iron sulphides and gradually a layer of silica is superimposed over these. After 3 months deposition at Broadlands well BR22 this silica layer was still not continuous over the scales present on the heat exchanger tubes. Silica deposition rates were of the order of 0.1 mm/yr. A fouling resistance for an annual cleaning frequency corresponds to less than 0.0001 m^2°C/W which permits sensible designs. The deposited silica also increases the surface roughness and a small increase in pressure drop can be expected.



Assumptions : (1) 99% steam fraction is condensed in the heat exchangers

	Two-phase geothermal supply	Separated steam	Separated water	Condensate	Gas and steam	Treated water	Process steam
	1	2	3	4	5	6	7
Flow (t/h)	170	32	138	30	2	30	30
Temp (°C)	170	170	170	140	140	120	148
Pressure (bar)	8·0	8·0	8·0	6·0	1·0	5·0	4·5
Enthalpy (kJ/kg)	1100	2690	719	590	1100	506	2744

D.S.I.R., INDUSTRIAL PROCE[SS] DIVISION
EQUIP'T FLOW SHEET/MATL'S B[ALANCE]
PLANT SIZE 30 t/h LP Steam
DRAWN BY S. R. Drew
DATE Sept '83
APPROVED
TITLE SEPARA[TED] STEA[M]
PROJECT Geothermal Workshop

FIGURE 1

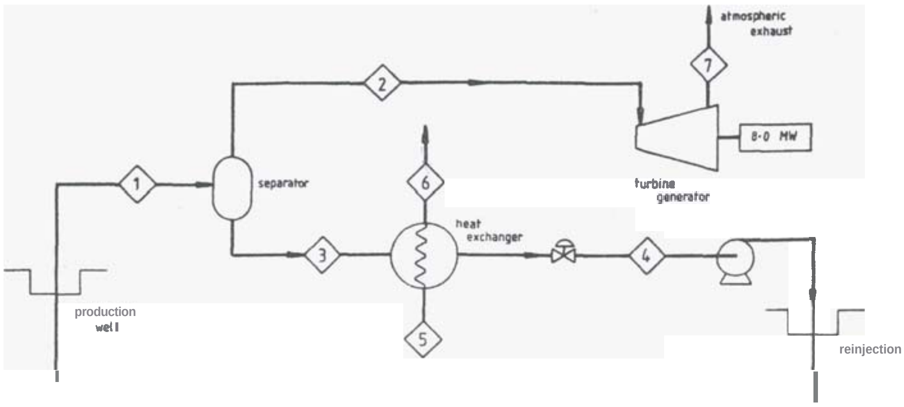
Strong acjd cleaning (a mixture of HCl and HF) was effective in removing the silica layer, presumably due to the preferential attack on the iron based scale deposits embedded in the silica layer. A fully continuous silica layer is unlikely to be removed so easily and both mechanical and chemical cleaning methods may have to be used as part of the cleaning procedure. A hardened steel cleaning tool going once through the tube should be sufficient to breakdown the hard silica layer before washing out with dilute acid.

Total Flow

The CST program can handle a partiall condensed feed (a two-phase steam/water mixture! with CO_2 as the non-condensible gas and so the program can be used to rate and design a total flow geothermal heat exchanger. The first stage in the desi n procedure is to plot the heat release curve ?temperature of both 'streams versus heat release) and to identify the minimum temperature difference driving force to ensure that a temperature difference pinch (when $\Delta T \leq 0$) is not occurring. If necessary a series of designs should be prepared at different AT minimums so that a design optimisation can be carried out. A AT minimum = 10°C is probably a sensible design temperature difference. If the selected design with two or more tube-passes is posing a problem with a temperature pinch then it should be designed out by considering a pure counter-current 1:1 exchanger. Even though the heat exchangers will be long (heat exchangers on a binary plant in the Imperial Valley have 18.3m tubes), these should not usually present any problem-with layout constraints for a new geothermal plant.

There are two zones in the total flow heat exchanger - condensing and subcooling. In the condensing zone, the condensing coefficients are high. The field test work showed condensing coefficients around 20,000 to 10,000 W/m²°C for two-phase condensation in the shear regime inside tubes. Whereas, in the subcooling zone, sensible heat transfer predominates in the water/gas flow. The heat transfer coefficients are higher than if the water phase were flowing alone owing to better turbulence induced by the two-phase flow. Excellent heat transfer was found in the test work for the water/gas mixtures and this ties in with the results predicted by an approximate method in the ST program. Pressure drops can be predicted by the programs but the confidence in the results is low. This should not be a problem as there is usually ample pressure drop available for the geothermal flow. Actual pressure drop data is sketchy because of difficulties in obtaining reliable pressure measurements when the flow regime was slug or high velocity slug. Even though the flow regimes in the test exchange went from annular to slug, with sometimes quite high oscillations in the local static pressures, the flow remained stable and could be controlled.

Fouling changed along the heat exchanger due to cooling and a changing chemistry in the water phase. The pH of the water phase decreased quite markedly



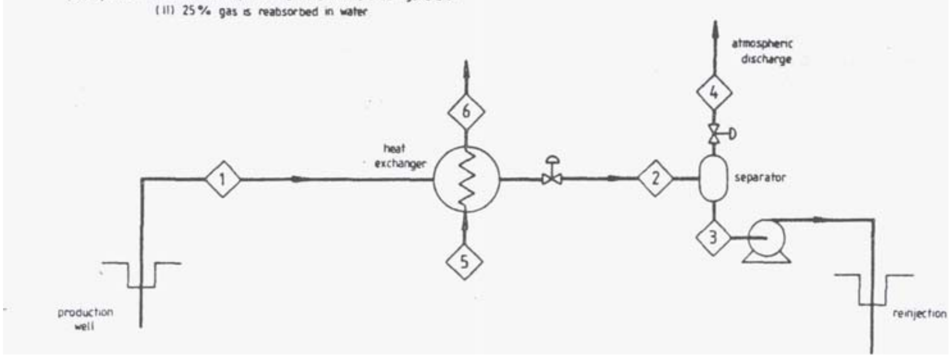
Assumptions 1) An outlet AT = 10 °C is used for the steam generator

	Two-phase geothermal supply	Separated Steam	Separated water	Separated water	Treated water	Process steam	Atmospheric exhaust
	1	2	3	4	5	6	7
Flow (t/h)	730	120	610	610	30	30	120
Temp (°C)	182	182	182	157	120	148	100
Pressure (bar)	11·0	11·0	11·0	8·0	5·0	4·5	1·0
Enthalpy (kJ/kg)	1100	2780	773	662	506	2744	2540

D.S.I.R., INDUSTRIAL PROCESSING DIVISION
EQUIP.T FLOW SHEET/MATLS BALANCE
PLANT SIZE 30 t/h LP Steam
DRAWN BY S.R. Drew
TITLE SEPARATED WATER
DATE Sept '83
APPROVED
PROJECT Geothermal workshop

FIGURE 2.

Assumptions :- (I) The minimum ΔT is 10°C in the steam generator
(II) 25% gas is reabsorbed in water



	Two-phase geothermal supply	Two-phase geothermal effluent	Separated water	Gas and steam	Treated water	Process steam
	1	2	3	4	5	6
low (t/h)	150	150	148	2	30	30
emperature (°C)	182	154	154	154	120	148
ressure (bar)	11·0	8·0	8·0	8·0	4·5	4·5
nthalpy (kJ/kg)	1100	654	634	1100	506	2744

D.S.I.R., INDUSTRIAL PROCESSING DIVISION
EQUIP.T FLOW SHEET/MATLS BALANCE
PLANT SIZE 30 t/h LP steam
DRAWN BY S.R. Drew
TITLE Total flow
DATE Sept'83
APPROVED
PROJECT GEOTHERMAL WORKSHOP

Figure 3

(in the tests at Broadlands the ambient pH declined from the inlet pH = 6.9 to outlet pH = 5.5) due to absorption of the CO and H_2S as cooling and condensation took place fincrease in gas partial pressure). The silica concentration in the water phase also declined during condensation. The condensing zone exhibited corrosion fouling, forming predominantly iron sulphides with a low fouling resistance. In the subcooling zone, a soft red precipitate of arsenic and antimony sulphides was deposited due to the extremely low solubility of these sulphides at low pH. The inlet concentrations of the arsenic and antimony in the water were 3 ppm and 0.1 ppm respectively. Other constituents in the precipitate in significant concentrations were thallium 20,000 to 40,000 ppm, silver 1000 to 1500 ppm and gold 7 ppm. There was no silica detected and the precipitate could be easily wiped clean. In fact no cleaning problems are envisaged in total flow if the deposition of hard and adherent silica can be avoided in this way.

One design problem with horizontal two-phase heat exchangers is to ensure that uniform distribution occurs in the inlet header. Maldistribution in horizontal two-phase flow can cause poarer heat transfer and higher pressure drops than anticipated. Instead of uniformly mixing, the steam and water phase stratify. The problem could be overcome by a vertical orientation, an axial inlet nozzle or feeding the steam and water phases coaxially. There may also be possibilities in using an eccentric design of header. This may be an area where further field test work is required.

CASE STUDY

Flowsheets have been prepared for the three types of geothermal flow generating low pressure process steam at 148°C, 4.5 bar (50 psig). This duty has been chosen as it is appropriate to most industries. The design basis is for 30 t/h of process steam using standard shell-and-tube heat exchangers. A horizontal kettle boiler and preheater are needed even though only one heat exchanger is shown on the flowsheets.

The high pressure geothermal resource produces a two-phase mixture with the following characteristics:-

Enthalpy = 1100 kJ/kg
Gas content in the separated steam = 1.2% mole fraction (3% w/w)

Minimum reinjection temperature = 150°C

A few notes will help explain each flowsheet given in Figures 1 to 3.

Separated Steam - Figure 1

In order to maximise heat recovery in the separated steam, a flash pressure at 8 bar is used to obtain an effective AT of 20°C in the steam generator. The outlet and minimum temperature difference is 10°C. It is assumed that 99% of the steam fraction is condensed in the steam generator and preheater with a geothermal outlet temperature at 140°C. A separator operating under a positive pressure vents the gas and both the condensate and the separated water can be combined for reinjection at a temperature 162°C. If the scaling characteristics of the combined condensate/separated water mixture is unacceptable for reinjection well life then these fluids can be reinjected in separate wells.

Separated Water - Figure 2

Separation at the wellhead pressure of 11 bar is suggested to maximise the heat recovery to the separated water. The separated steam is let down through a non-condensing turbine generator. An outlet temperature difference of 10°C is chosen for the steam generator. After the preheater, the separated water at 157°C is available for reinjection.

Total Flow - figure 3

The total flow at the well-head pressure 11 bar is transmitted directly into the steam generator and preheater where the two-phase mixture is subcooled to 154°C. The minimum AT is 10°C at the outlet of the steam generator. Up to 25% of the CO_2 and 50% of the H_2S will be reabsorbed by the water phase. The remaining gas is vented from a pressurised separator and the water is available for reinjection at 154°C. Again the chemistry of this water may need to be altered to limit or avoid scaling due to precipitate formation (arsenic/antimony sulphides) to ensure long reinjection well lifetimes.

Results Analysis

1. Thermal efficiency - (process heat/geothermal drawoff) of the total flow plant is 13% higher than for the single-flash separated steam plant. There would be little difference between the thermal efficiency between a total flow and multi-flash system down to the reinjection temperature as long as commercial use could be made of the lower pressure separated steam with the latter, This is often the major problem. Obviously heat recovery from the separated water requires far more (nearly five times) geothermal draw-off but there is the advantage of power generation using the separated steam.

2. Environmental impact - Figure 4 shows the equilibrium solubilities of CO_2 and H_2S in the water phase for the total flow example at a reinjection temperature of 150°C. The initial gas composition has been taken as (BR22 data):-

CO_2	=	0.002 molefraction
H_2S	=	0.00004 molefraction
NH_3	=	0.000007 molefraction
Residuals	=	0.00003 molefraction

The Henry's law and dissociation constants used by the calculation method were taken from reference 3.

Operating the production well and hence the geothermal plant at a higher pressure could allow

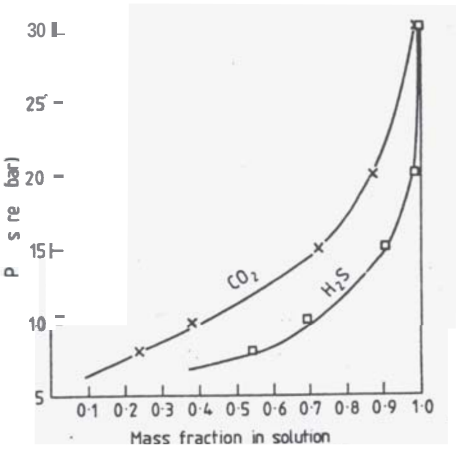


Figure 4. Equilibrium solubility of CO_2 and H_2S at 150°C for the gas composition given in the text.

the bulk (say 95%) of the H_2S to be reinjected with the separated water by the total flow approach. An operating pressure at 17.5 bar is quite feasible. Also equilibrium solubility conditions are likely to be met with the turbulent flow in long pipelines. The separated flow system would require expensive compression equipment to achieve the same result.

3. Heat exchanger design - As the geothermal film heat transfer coefficients are high (design 10,000 $W/m^2{}^oC$) and the anticipated fouling is low, both the boiler and preheater have similar overall heat transfer coefficients for each scheme viz.

Boiler U = 1600 $W/m^2{}^oC$ with the geothermal
R_F = 0.0001 $m^2{}^oC/W$

Preheater U = 1300 $W/m^2{}^oC$ with the geothermal
R_F = 0.0002 $m^2{}^oC/W$

The respective heat loads are:-

Boiler Q = 17.6 MW
Preheater Q = 1.0 MW

The size of the heat exchangers is determined by the respective effective temperature difference driving forces which as it happens are similar for both exchangers :-

	ΔT effective (°C)	Boiler Surface Area(m^2)	Preheater Surface Area(m^2)
1.Separated steam	20	550	39
2.Separated water	22	500	35
3.Total flow.	30	370	26

The total flow plant has the smallest heat exchangers as the well-head pressure has been chosen above the separation pressure of the geothermal steam system. Obviously, the same sized heat exchangers could be used for the separated steam at 13 bar but there would, of course., be a further penalty in mass draw-off.

4. Commercial Implications - The total flow approach appears to offer the advantages of smaller, less complex plant at the minimum draw-off for direct-heat use of a geothermal resource. This is especially relevant to lower enthalpy systems where it will make less sense to utilise only the separated steam. New plants must be designed to maximise energy conservation and minimise draw-off.

The other possible advantage of the total flow system is the optimisation of operating pressure and reinjection temperature inorder to return the bulk of the H_2S back to the reservoir, This could be an important step forward in process design for self-flowing well systems and is in essence what is done overseas where a moderate temperature resource is pumped above the saturation pressure inorder to keep the gases in solution. H_2S abatement is strictly enforced in the USA where H_2S recovery systems have been installed on a number of power projects. If this happens in New Zealand, a total flow heat exchanger approach could be one solution for the major direct-heat users, provided the resultant fluids are suitable for reinjection.

Economic advantages of each scheme are not obvious and a detailed cost study has nat been completed as the costs will be very site specific and each case will have to be considered on its own merits. However, the total flow plant should be the cheapest as it is sensible to maximise the available geothermal temperature for heat recovery not minimise the energy supply temperature by flashing for steam production, Table 2 compares the three schemes:

Table 2: A comparison of the three schemes for 30 t/h LP process steam

	Mass Drawoff (t/h)	H_2S reinjection	Heat exchangers(total m^2)	Notes
1.Separated steam	170	No	590	
2.Separated water	730	No	540	t 8 MW electrical
3.Total flow	150	Yes	400	

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ACKNOWLEDGEMENT

The author wishes to express his thanks to the Industrial Processing Division and Chemistry Division scientists and technicians who have assisted with this work.