GEOTHERMAL HEAT TRANSFER - FIELD TESTS AT BROADLANDS

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ABSTRACT

A pilot scale heat exchanger, designed to generate basic heat transfer and pressure drop data for the turbulent flow of geothermal fluids in carbon steel tubes, has been operated at Broadlands since 1981.

Results are given for operation with separated water flowing alone and with gas, and for separated steam and steam/water mixtures. These show enhancement of heat transfer rates when gas flows with the separated water, and high heat transfer rates for steam/water mixtures.

The decline in performance during a three-month test using separated water, cooled from 175°C to approximately 90°C, shows a low silica deposition rate and thus a low annual fouling rate. Three commercial cleaning methods removed this silica scale with varying degrees of success. Fouling tests with two other geothermal fluids are planned.

Operating problems with the test rig are noted.

INTRODUCTION

An engineering project team was formed in 1980 to collect basic data on the heat transfer and pressure drop performance of geothermal fluids in heat exchangers. A test rig was built at Broadlands (BR22) to generate some of the required performance data.

The typical composition of separated fluids from BR22 (for normal operation at a separator pressure of 11 bar absolute) is shown in Table 1. The noncondensible gas concentration in the steam can be increased by bleeding in additional gas from BR3.

The test heat exchanger was designed for flexibility so that it could operate with all geothermal fluids (water, steam, total flow) in standard carbon steel heat exchanger tubes. Automatic logging and control was incorporated to allow continuous operation without supervision. The design basis for the unit has been described previously (1).

Two types of experiment can be carried out on the plant:

1. Short-term tests with clean tubes. The heat exchanger reaches a steady state and performance data (heat transfer coefficients and pressure drops) are obtained.

2. Long-term tests to measure decline in performance. The heat exchanger is run under steady conditions to determine the change in heat transfer (fouling factor) and pressure drop (friction factor).

This paper summarises the important results from the short-term tests. Results from a long-term fouling test using separated water are also given. In connection with the fouling test, three commercial cleaning methods were evaluated for removing the silica scale from the tubes. The ability to clean these hard silica deposits from the tube surface is crucial to commercial development of heat exchangers for separated water or total flow use.

TABLE 1: Composition of BR22 Separated Flows

STEAM		WATER	
Component	Concentration/ppm	Component	Concentration/ppm
CO_2	24900	SiO_2 (actual)	720
H_2S	390	SiO_2 (at saturation) inlet	780
NH_3	37	outlet	300
Other noncondensibles	225	pH	6.9

PLANT DESCRIPTION

The pilot plant flowsheet is shown in Fig. 1. The plant consists of three loops: geothermal fluid, treated cooling water, and cooling tower water. The experimental heat exchanger transfers heat from the geothermal fluid to the treated water. This treated water, pressurised with nitrogen and containing hydrazine to minimise corrosion, circulates through secondary heat exchangers; the heat is dissipated in a cooling tower. Resistance-type corrosion probes are used in the treated water loop to monitor the corrosivity of the water.

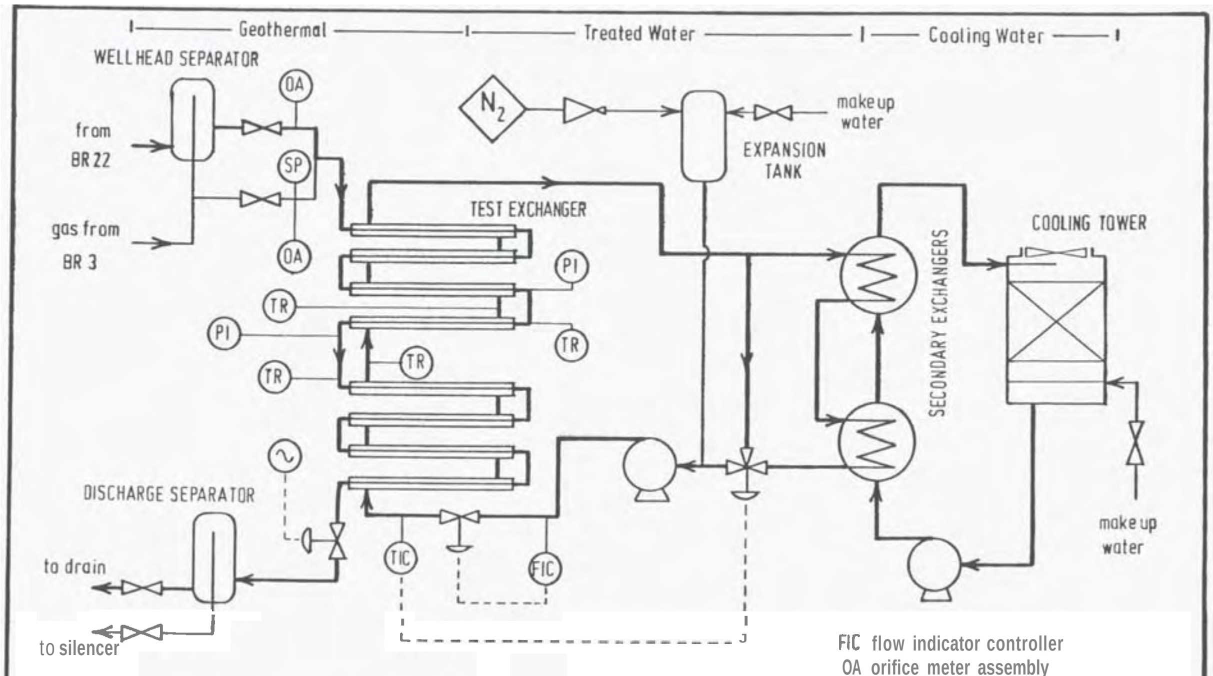


Fig. 1 Pilot Plant Flowsheet

FIC flow indicator controller
OA orifice meter assembly
PI pressure indicator
SP sample point
TIC temperature indicator controller
TR temperature recorder

Test exchanger — Instrumentation shown for Section 4 only

TABLE 2: Pilot Plant Programme

Data	Activity	Fluid	Runs	Conditions	Notes
1981	Commissioning	Separated water			Check that plant meets desiqn. No start-up problems.
	Calibration	Separated water	201-223	Process and geothermal flows varied	Development of correlationfor process-side coefficient
	Short-term test	Separated water	various	cooled from 175-85°C, 11 bar	Heat transfer coefficients and pressure drops determined.
		Separated steam	401-430 431-444	175-65°C, F = 0.05-0.16 kg/s 175-65°C, additional gas up to 30%w/w	
		Water + Gas	613,614	160-70°C, gas 4-8% w/w	
		Steam + Water	502-510 601-611	175-70°C, y_s = 0.0 - 0.5	
1982	Brig-term tests	Separated water	-	175-90°C, 1900 hours	New tubes used for each run.
		Separated steam	-	175-65°C	Fouling factors and friction factors determined.
		Steam + water	-	175-70°C, y_s = 0.21	Cleaning trials on fouled tubes, with retesting for foulingand friction factors

The test heat exchanger consists of eight horizontal tubes through which the geothermal fluid passes in series. Each tube is cooled by treated water running in counterflow through an annular water jacket.

Geothermal water and steam from the wellhead separator are metered using orifice plates and manometers before passing through the test exchanger. Two-phase mixtures are obtained by recombining the phases in the desired ratios. Supplementary gas from BR3, when required, is cooled and metered with a rotameter before being bled into the steam line.

Temperatures are measured with type T thermocouples, automatically scanned by a data-logger. Static pressures are measured with gauges, recalibrated as required. Pressure drops through the tube sections are measured with a manometer where possible, but when they exceed 0.6 bar, pressure gauges must be used.

Temperature, pressure, and flowrate data are stored on magnetic disc for subsequent computer analysis.

TEST PROGRAMME

The test programme is shown in Table 2. Currently the short-term tests and one long-term fouling test (on separated water) have been completed. A further long-term test, on steam, is now in progress and another, on a steam-water mixture, is planned.

The results are analysed using a Fortran program developed for this work.

At the conclusion of the fouling test on separated water, three of the tubes were cleaned using different commercial methods:

1. Dissolution of the scale using a cold, corrosion-inhibited solution of hydrochloric and hydrofluoric acid which was circulated through the tube for several hours.

2. High-pressure water blasting at 600 bar.

3. Use of a mechanical tool which removes scale by a combined cutting and hammering action.

To simulate a cleaning procedure which would be practicable on a large industrial heat exchanger, repeated passes of the cleaning device were not made in methods 2 and 3. The effectiveness of each cleaning method was estimated by retesting the tube to determine the heat transfer coefficient and pressure drop after treatment. A fourth tube was retested without cleaning as a control.

OPERATION PROBLEMS

A number of problems have occurred during this work:

1. Services

A temporary electrical supply line has led to power cuts and consequent reliability problems with the cooling tower fan and instrument air compressor.

The available cooling water at times contains suspended solids which can cause fouling of heat transfer surfaces.

2. Instrumentation

Temperature measurement with the thermocouple/data logger system used has an accuracy of $\pm 0.7\,^{\circ}C$. When a small temperature difference occurs over a section of the test exchanger (generally sections 6 to 8) a heat balance over that section cannot be calculated to the desired accuracy of $\pm 10\%$. For substantial heat loads (generally sections 1 to 5) this accuracy is achieved.

3. Plant Design

The PTFE tube sealing rings originally used suffered creep due to temperature cycling resulting in severe leakage. Stainless steel packing rings have proved satisfactory.

RESULTS

Calibration

Results from 23 runs using different water flowrates inside and outside clean tubes were used to evaluate the annulus side heat transfer coefficient. A correlation was derived from these to predict the annulus side performance, so that the tubeside (geothermal) performance could be extracted from the measured overall heat transfer coefficient (1).

Short-Term Tests

Approximately 90 runs have been made using the four types of geothermal fluid in the tubes; separated water, water/gas mixtures, separated

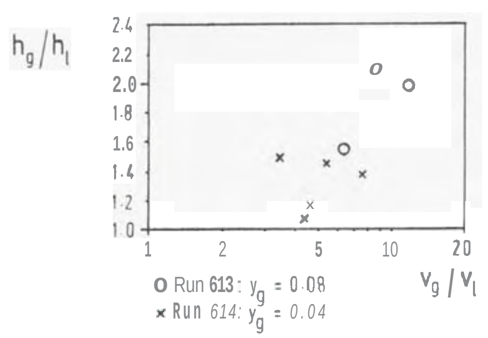


Fig. 2 Effect of Gas on Heat Transfer

TABLE 3: Geothermal-Side Performance for Selected Short-Term Runs

	T_{in}	T_{out}	F	y_s	y_g	Q	U *	h_g *	Re	ΔP	f
	°C	°C	kg/s			kW	kW/m² °C	kW/m² °C		bar	
WATER											
Run 511	175	92	0.83	0.0	0.0	293	3.9	13.4	335,000	1.5	0.019
Run 512	173	100	0.73	0.0	0.0	270	3.7	12.0	-	1.1	-
Run 205	174	72	0.52	0.0	0.0	223	4.2	11.3	199,000	0.6	0.026
WATER/GAS											
Run 613	147	64	0.21	0.0	0.08	88	3.8	9.7	55,000	0.8	-
Run 614	159	75	0.50	0.0	0.04	218	4.6	13.5	167,000	3.1	-
STEAM											
Run 414	175	69	0.15	0.98	0.02	380	5.4	36.5		3.2	-
Run 607	174	64	0.12	0.98	0.02	296	5.8	25.8		1.7	-
STEAM/WATER											
Run 603	175	71	0.27	0.32	0.007	290	5.6	22.7	84,000	1.5	-
Run 608	174	69	0.23	0.43	0.01	295	5.7	24.2	61,000	1.8	-

* for steam-containing fluids, coefficients given for initial condensing region only.

steam, and steam/water mixtures (total flow). Two runs for each of these cases are shown in Table 3. For simplicity the terminal conditions only are given, although the performance has been measured for each of the eight sections. The clean tubeside heat transfer coefficient (h_g) is, given in the table for conditions near the inlet of the exchangex, to allow comparison between different inlet compositions.

Figure 2 indicates the results of adding a gas phase to separated water flowing in the tubes. The heat transfer coefficient for the mixture is compared with a calculated film coefficient (h_1) for the liquid flowing alone at the same mass flowrate. This enhancement of the heat transfer by gas is plotted against the ratio of the phase superficial velocities.

The heat transfer rates in these runs are increased by the gas phase; pressure drops are also increased (compare run 205 with run 614 in Table 3).

Variations due to slugging flow made pressure drop measurement over individual tube sections unreliable, but the total pressure drop was recorded.

In Figure 3, the geothermal fluid temperature is plotted against heat released for four of the short-term runs. Separated water (run 512) is characterised by a straight line as only sensible heat is removed. Where a steam phase is present (runs 603, 608, and 607) there is an almost isothermal region in which the bulk of the steam is condensed, followed by a more rapid, nearly linear, drop in temperature as sensible heat is removed from the liquid and gas. The film coefficient (h_g) given in Table 3 refers to the condensation region.

Pressure drops in the condensing region are high due to the high vapour-phase velocities used. In the subcooling zone, pressure drop measurement is again unreliable due to slug flow.

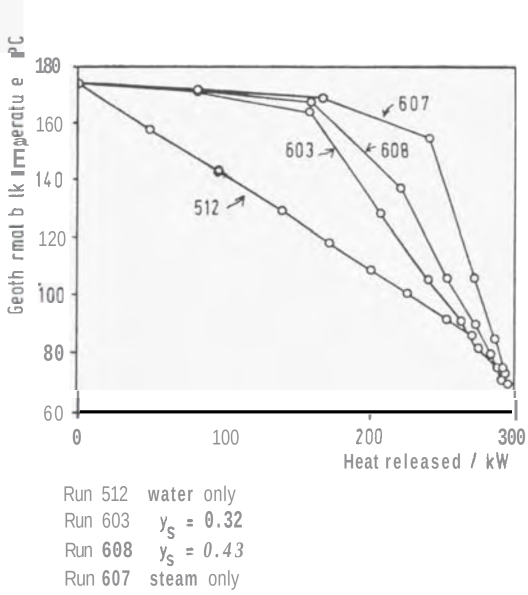
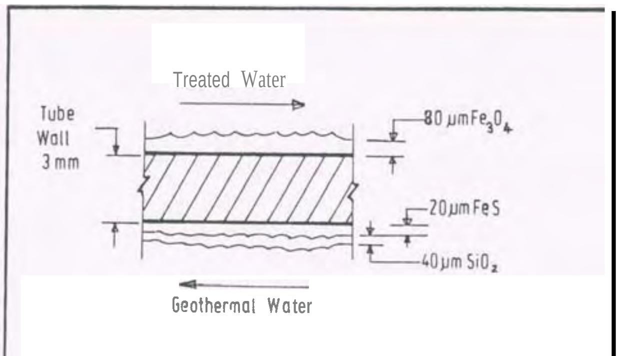


Fig. 3 Temperature Profiles

TABLE 4: Overall Results of Fouling Test - Separated Water

	Temperature Range	Q	U	R_{FI}	ΔP
	°C	kW	kW/m^2 °C	m^2 °C/kW	bar
Clean Performance	175-85	325	4.9	0.0	1.65
After 1900 hours	175-100	290	3.8	0.055	1.8



TUBE WALL SECTION-DEPOSITS

TABLE 5: Summary of Cleaning results

Tube No.	Method	Estimated Effectiveness * %
3	Cold acid wash HCl/HF	90
4	High-pressure water blasting	30
6	Rotary mechanical tool	45

$$* \text{ Effectiveness } = 100 \times \frac{R_{FI}(\text{fouled}) - R_{FI}(\text{cleaned})}{R_{FI}(\text{fouled})}$$

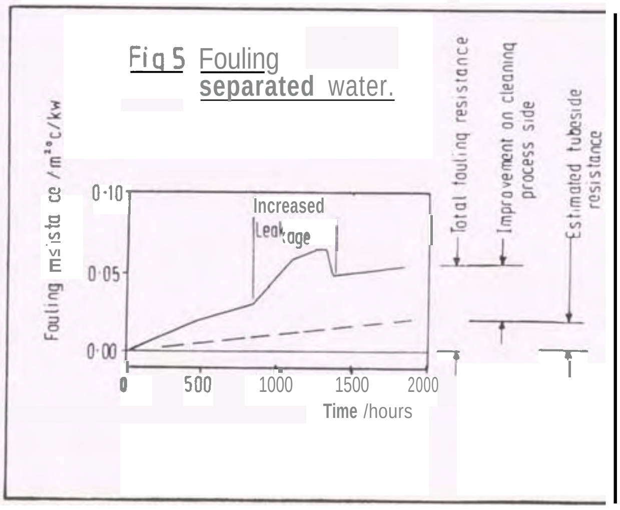


Fig 5 Fouling separated water.

Long-Term Test

Initially the separated water was cooled from 175 to 85 °C in clean tubes. The plant was operated for a total of 1900 hours over a 3-month period. There were many short outages during this time but the tubes were kept full of geothermal water at all times. The heat transfer rate declined slowly and at the end of the run the water discharge temperature had risen to 100 °C. The pressure drop had also increased slightly (Table 4).

The heat exchanger was then shut down for cleaning trials, and the cleaned tubes retested for heat transfer coefficient. Table 5 shows the effectiveness of each cleaning method, estimated as the percentage reduction achieved in that part of the total fouling factor due to silica scale.

Removal of the tubes revealed a deposited layer of magnetite, with a small amount of pumice, on the outside surfaces (Fig. 4). This fouling material had been introduced with the make-up treated water which had to be added regularly to replace leakage from the pump gland. The contribution of this process-side fouling to the total was determined by cleaning it from two tubes and retesting them. Figure 5 shows the development of the total fouling resistance and indicates the contribution of geothermal and process sides.

Examination of both fouling layers by scanning electron microscope indicated typical thicknesses (Fig. 4). The silica layer was discontinuous and contained small areas of corrosion products.

DISCUSSION

The pilot plant has been used to produce basic performance data for the different types of geothermal flow in carbon steel heat exchanger tubes. This information will support improved design methods for geothermal heat exchangers. The operational problems are also important, in order to deal with them in future field test work.

Separated Water

For water flowing alone in clean tubes, the film coefficients and pressure drops obtained (Table 3) compare well with those calculated using standard design methods. For run 512, a correlation (2) gives h_g = 16.6 kW/m^2 °C which is reasonable agreement considering experimental errors.

The observed friction factor of 0.03 is typical of commercially rough tubing (3).

The fouling resistance caused by silica deposition from separated water was partially masked by the process side resistance. The results do show that the geothermal-side fouling factor is very low. If extrapolated to an annual basis it gives R_{FI} = 0.08 m^2 °C/kW which in most applications will be lower than the process-side resistance. Extrapolating the observed thickness of the silica layer to an annual basis gives 0.12 mm/y, which is also acceptable as cleaning has been successfully performed.

Cold acid treatment was the most effective cleaning method tested. It is thought that *this* treatment was successful because the silica scale contained some corrosion products (iron sulphides) which were rapidly attacked by the acid. A pure, continuous silica layer may not be removed as easily and further test work is required. It may be necessary to use a combination of mechanical cleaning, to attack the silica, followed by chemical cleaning to dissolve the corrosion products.

Water/Gas Mixtures

This type of two-phase mixture is encountered in the fluid produced by low-enthalpy wells. An increase in heat transfer rates, over the water phase flowing alone, has been demonstrated (Fig. 2). Further data would be required to fit this enhancement to a correlation.

Separated Steam

The results compare well with theoretical predictions for condensation of a steam/CO_2 mixture. Distinct condensing and subcooling zones are observed in the heat release profiles. A small reduction in heat transfer in the first tube section is also seen, due to slightly superheated steam.

Film coefficients are high in the condensing zone (Table 3), and drop to about 5.0 kW/m^2 °C in the condensate/gas subcooling zone. Pressure drops are also high in the condensing zone, and very low in the subcooling zone, where velocities are low and the flow regime is gravity-controlled. Virtually all of the geothermal steam fraction is condensed, with only condensate and gas leaving.

Results for the long-term test using separated steam are not yet available. The main potential source of a fouling resistance with steam is corrosion of the tube surface by the condensate which typically has a pH of 5.6 at exit conditions.

Steam/Water Mixtures

The heat release profiles (Figure 3) also show distinct condensing and subcooling regions. Film coefficients in the condensing region are high and compare well with the case of steam only (Table 3). Pressure drops were not excessive although again the individual pressure drops could not be measured accurately in the subcooling zone. No serious flow instabilities, or consequent difficulties in control, were encountered.

Silica deposition rates have yet to be measured in a long-term test.

Operational Problems

For any future field test work, greater consideration should be given to services and instrumentation requirements.

Reliable services are essential; in particular frequent electrical supply interrqptions are not acceptable. Water quality is also critical, and should not be too variable. Magnetite deposition from cooling water streams is a common occurrence (4). It should be noted that if once-through cooling water was used, this deposition would make a heat exchanger unusable in less than the 3 months run.

Reliable and accurate instrumentation is also critical. Future pilot plants should use more accurate methods to measure temperature differences, flowrates, and pressure drops in two-phase flows. Instrument technology is available to do this and also record and evaluate results continuously.

NOMENCLATURE

F	total geothermal mass flowrate	kg/s
f	friction factor	-
h_g	tubeside (geothermal) heat transfer coefficient	kW/m^2 °C
h_l	tubeside heat transfer coefficient for liquid flowing alone	kW/m^2 °C
ΔP	total tubeside pressure drop	bar
Q	heat load	kW
Re	Reynolds number for liquid flowing alone	-
R_{FI}	fouling factor, inside-area basis	m2 °C/kW
T_{in}	geothermal inlet temperature	°C
T_{out}	geothermal discharge temperature	°C
U	overall heat transfer coefficient	kW/m^2 °C
v_g	gas/vapour superficial velocity	m/s
v_l	liquid superficial velocity	m/s
y_g	noncondensible gas mass fraction in total flow	
y_s	water vapour mass fraction in total flow.	

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