Proc. 5th NZ Geothermal Workshop 1983

DESIGN, DEVELOPMENT AND TEST OF A 500 kW ORGANIC RANKINE CYCLE PLANT

A. Dal Secco, B. Salucci,
L. Centemeri, G. Caniato

FRANCO TOSI INDUSTRIALE S.p.A.
Legnano, Italy

ABSTRACT

The paper describes design criteria of an ORC plant for low temperature geothermal water utilization with electric energy production. Mechanical and thermal problems arisen during the development stage are discussed. Results of full scale tests at manufacturer workshop are presented.

1.0 INTRODUCTION

For the exploitation of liquid dominated geothermal resources the use of binary cycles or Organic Rankine Cycles is becoming nowadays more and more attractive. Such plants present some definite advantages over the plants utilizing directly the steam generated by flashing geothermal hot brine (Refer to Salucci et al., 1982).

In ORC systems hot water is used to vaporize a law boiling point fluid which drives a turbine. The present pilot plant, rated 500 kWe net power, is based on a saturated Rankine cycle, using R114 a8 working fluid. Refrigerant R114 is a chlorofluorocarbon compound, nonpoisonous, nonirritating, non flammable, thermally stable and non corrosive toward ordinary construction materials; furthermore it is available at reasonably low cost and in great quantities.

ORC plants may also find an interesting field of application in recovering heat from industrial waste effluents either liquid or gaseous.

The plant has been designed and manufactured by Franco Tosi in collaboration with Ansaldo. F. Tosi was responsible of the project and of the supply of the therm-mechanical portion of the equipment, Ansaldo supplied the electrical, instrumentation and control equipment.

2.0 PLANT DESCRIPTION

2.1 General

Fig. 2.1 shows cycle flow diagram and design heat balance. Geothermal water at 140°C preheats the organic, fluid in the liquid heater up to a temperature near the boiling point and then vaporizes it in the evaporator. The generated vapor drives the turbine and exhausts into the condenser. The condensate from the receivers, that act as the condenser hotwell, is pumped back to the liquid heater. The receivers are sized to hold the process liquid in case of opening for maintenance.

The system is designed for unattended fully automatic operation. Direct control of the hot source is not deemed necessary, since R114 vapor pressure is controlled through the turbine bypass, that relieves the excess energy to the condenser. The evaporator liquid level is controlled directly via a valve located between the evaporator and the liquid heater. A low load recirculation line to the receivers is provided to protect the feedpumps.

In order to minimize site erection cost, the plant is made up from four skid-mounted modules pre-assembled and prewired: power module, that contains 'turbogenerator, heat exchangers and ancillary equipment; feedpump module; control cab module; instrument air system module (see Fig. 2.2).

2.2 Workshop Testing Facilities

The plant was tested in the workshops of F. Tosi in Legnano, from February to June 1983.

The bench test simulated conditions similar to the site:

- Water was heated by steam in a direct contact heat exchanger and circulated by a pump through the exchangers. The hot water system was kept pressur-

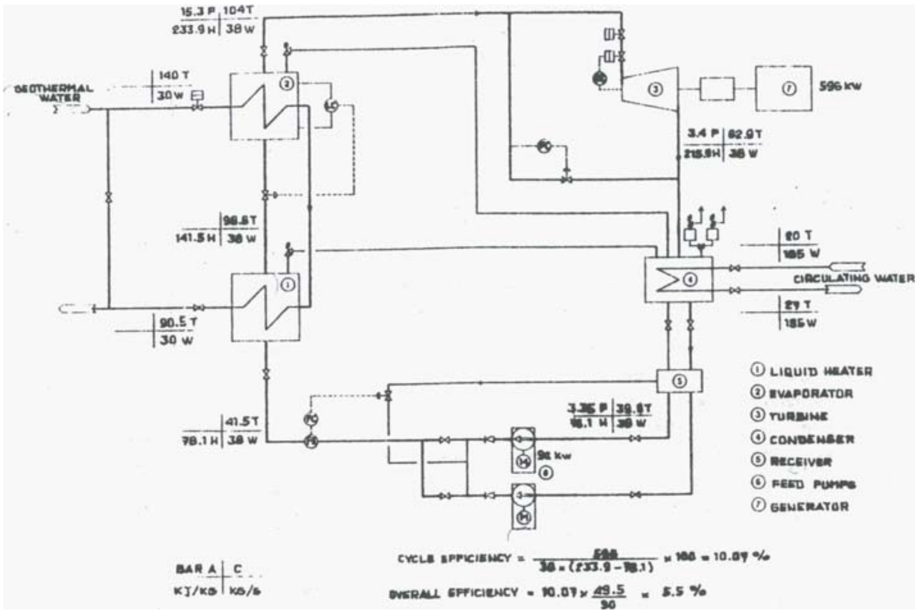


Fig. 2.1 -Heat balance

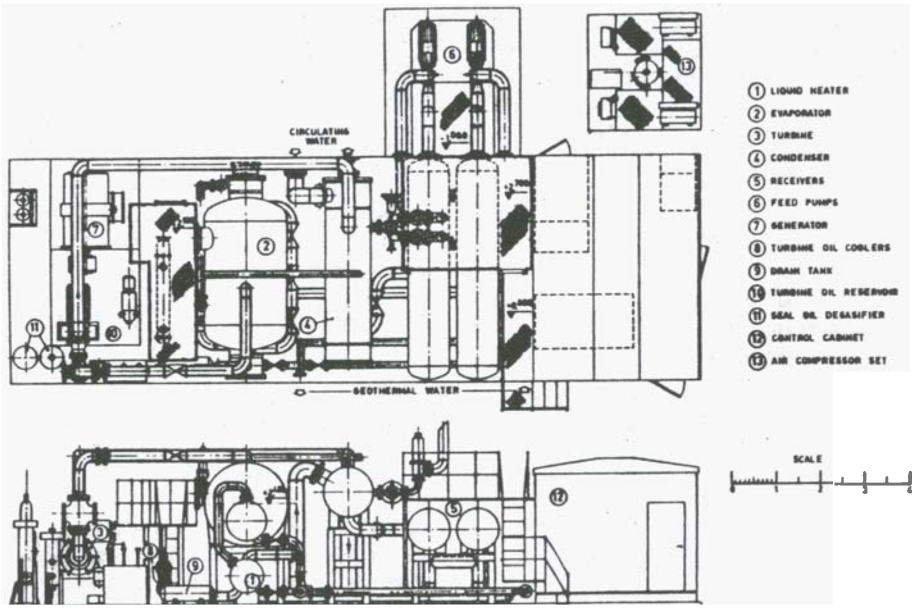


Fig. 2.1 General layout

ized with nitrogen and the excess condensate was discharged through a level control system.

- Cooling water for condenser, turbine and generator coolers was provided by existing cooling towers.

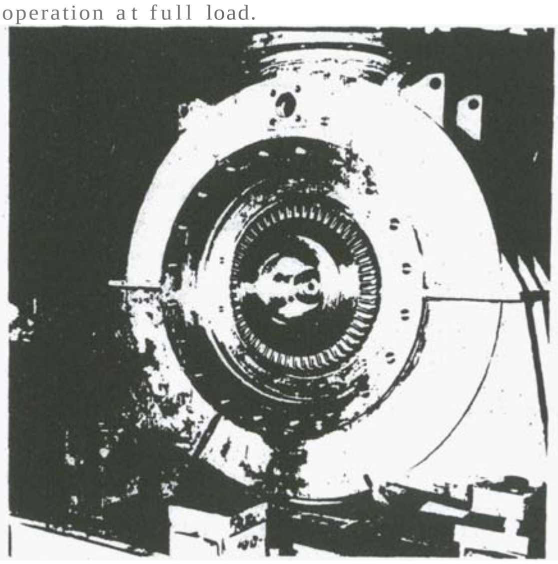
- Generated electric power was dissipated in a tank by means of load resistances submerged in water.

3.0 COMPONENT DESIGN

From the point of view of the turbine design, R114 differs from conventional fluids such as steam or air for some characteristics, mainly higher density, higher pressure at the same temperature level; lower enthalpy drops; lower sonic velocity. These characteristics lead to a turbine of limited size notwithstanding the rather high mass flow; peripheral speed also is quite low in comparison to conventional expanders.

The selection of the most suitable turbine type has favored the axial, single stage, reaction turbine; main reasons for this were the possible future extension of the turbine size and the aim to a better efficiency. From the mechanical point of view, the main features are the overhung rotor, in order to have a single end seal, the PTFE lining of the parts likely to be exposed to rubbing in order to avoid high contact temperature with the consequent fluid decomposition, Fig. 3.1 shows a picture of the turbine under assembly taken from in the inlet side.

Load control is accomplished by throttling as it is peculiar to reaction turbines, bearing in mind that a recovery plant is designed for continuous operation at full load.



- Fig. 3.1 View of the turbine during assembly

For the heat transfer equipment, among several possibilities, conventional shell and tube heat exchangers were preferred. The fluid more liable to scaling, i. e. geothermal brine and circulating water, were arranged inside the tubes; the arrangement allowed the use of externally finned tubes on the side of R114, which has lower heat transfer characteristics.

For further design details and data refer to Salucci et al. (1982).

4. ANALYSIS OF THE PROBLEMS EXPERIENCED DURING THE TEST. HINTS FOR POSSIBLE IMPROVEMENTS.

4.1 Introduction

The plant has been operated during the bench tests for 250 hrs approx. During the initial operation phase were experienced some troubles, that are outlined in the following paragraphs, together with the changes made and the possible improvements.

4.2 Turbine Sealing System

The turbine is equipped with a double seal with buffering fluid (see Fig. 4.1); at the turbine side

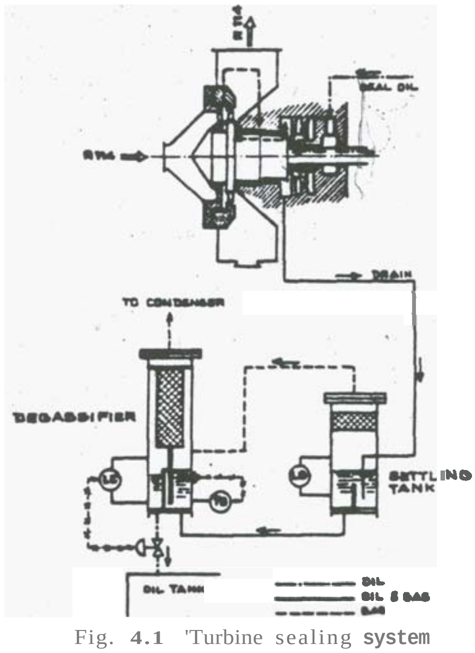


Fig. 4.1 Turbine sealing system

the seals are of the labyrinth type with central injection of R114, bled at a intermediate pressure between the inlet and the exhaust of the turbine; at the atmosphere side they are of the oil film type. The escaping mixture of oil and gas is collected in a settling tank where the organic fluid not dissolved in the oil is separated; the mixture is then transferred through a demister to a degassifier tank.

The degassing is performed by heating the oil with an electric resistance up to 85°C. The separated oil is fed back to the turbine oil tank and the organic fluid to the condenser through a demister. It is necessary to keep hot the outside surfaces of both tanks in order to avoid condensation of the organic fluid on separating tank walls and stratification with oil (the organic fluid is heavier than oil). For the heating it is convenient to use the water discharged from the liquid heater at a temperature of approx 90°C.

During the operation an oil sample from the degassifier has been tested in laboratory. The organic fluid content was found to be 15% with an oil temperature of 85°C. Increasing the oil temperature to 120°C, the organic fluid content would decrease down to a more acceptable value of 5%. The test on a sample of organic fluid discharged to the condenser from the degassifier has shown that the oil content is negligible.

4.3 Turbine Control Valves.

The turbine load is controlled by throttling. The flow/stroke characteristics curve of the turbine control valve can be assimilated to two lines having different slope; the first line up to *70%* of the stroke has a slope or valve gain of 1.5 to 1; for higher opening values the valve is saturated and the gain drops to a value of 0.3 to 1. The normal startup procedure consists in taking up to load the vapour system operating with the turbine bypass; then start the turbine, synchronize, and increase gradually the load; at the same time the bypass valve closes, controlled by the steam pressure. For the performance tests it is necessary that the bypass valve is completely closed. The electric load is dissipated in a tank, in which load resistances are submerged in water. With the tank level control available for the tests, it was not possible to make small load changes. In balancing the thermal load with the electric load, it was then necessary to proceed by trial and error, introducing a disturbance in the system. Due to the turbine valve characteristic, the control system was able to compensate the disturbances up to a 70% opening of the control valve; for higher values, due to the insensibility corresponding to the low gain of the valve, the turbine started hunting in a way that no performance tests could be carried out. For this reason during the tests the vapour pressure was kept to a value higher than the nominal in order to operate with the valve in the range where the control system insensibility was reduced to the minimum. For the same reason it was not possible to carry out the test at the maximum rating (596 kW), but it was performed only the test at the highest stable load (550 kW).

The above said problems would not have been occurred if it had been possible to operate connected to the external grid or if, for the load dissipation, a finer load control system had been available. An improvement could be achieved modifying the valve plug to a profile with linear characteristic.

4.4 Feed Pump

The pump delivery head, was insufficient. In fact during the test at the supplier works the actual head was found to be 3% lower than the design value. Furthermore as it was required to operate at a pressure higher than the nominal, for feed flows higher than 115 t/h (design value 137 t/h), it was necessary to operate with two feed pumps in parallel. This fact can be noted from the auxiliary power consumption, measured during the test (see Fig. 4.3), which presents an abrupt step for power values higher than 450 kW.

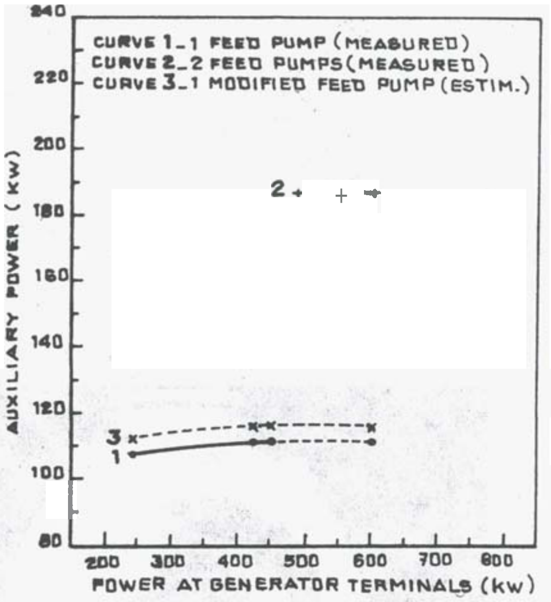


Fig. 4.3 Power absorbed from electric auxiliaries

To overcome this, it is possible to change the pump impeller, increasing the diameter to 300 mm. The absorbed power increases of 5%, still within the margin of the electric motor.

4.5 Evaporator

The evaporator is of the pool-boiling type without dome; the shell diameter is 1800 mm. The heat exchange surface, with finned straight tubes, is located in the lower side; the tube bundle diameter is 665 mm. The hot water inlet is on the lower side. On the shell top, mesh type demisters were provided, having a free volume of 98.4% and thickness of 150 mm. The distance from normal operation level to demister inlet was 415 mm. During the initial operation it was found that for flows higher than 120 t/h, the vapour quality dropped down to 0.75-0.8. Furthermore the quality value was not constant during the operation. It was gathered that the cause of the problem was the heavy turbolence of the boiling with consequent flooding of the demister. A first action on the evaporator was to mount a baffle plate between liquid surface and demister. The subsequent tests showed that the quality was improved up to a 0.9 value and that it remained constant during the operation. It was then decided to modify again the evaporator, changing the demister configuration and increasing the distance from the liquid level to the demister up to 715 mm. The new demister is composed of a first layer of high flooding limit mash (free volume 98.75%) 50 mm thick and a second layer 100 mm thick having higher filling (97.5% free volume). During the tests the quality value was around 0.99 for organic fluid flows higher than 120 t/h. From the measures taken at various loads, it can be inferred anyhow that is particularly important to maintain low liquid levels to get high quality values.

4.6 Comments on Plant Operation

The prototype, after an initial operation phase, has demonstrated his ability to operate steadily and safely in automatic control. The turbine vibrations were lower than 10 u (double amplitude) on the high speed shaft. The turbine bearing temperature were down to very conservative values (75°C for the axial bearing and 55°C for the journal bearings). No failure was experienced during the initial operation, demonstrating the soundness of the adopted design criteria.

5.0 PERFORMANCES MEASURED DURING THE TESTS

For the performance test, a computer-based automatic data acquisition system was used. During each measuring cycle, were recorded the readings of 17 thermocouples, 14 pressure transducers and 3 flow transmitters.

5.1 Turbine Efficiencies

Blading Isoentropic Efficiency η_{ip}

It is defined as the ratio of the actual enthalpy drop, calculated from the conditions upstream the turbine nozzles and the corresponding isoentropic drop.

Turbine Mechanical Efficiency η_{ot}

It is as the ratio of the power at the coupling turbine-generator to the power at turbine blading.

The value of η_{ip} and η_{ot}, as measured, are plotted in Fig. 5.1; the figure shows also the design value

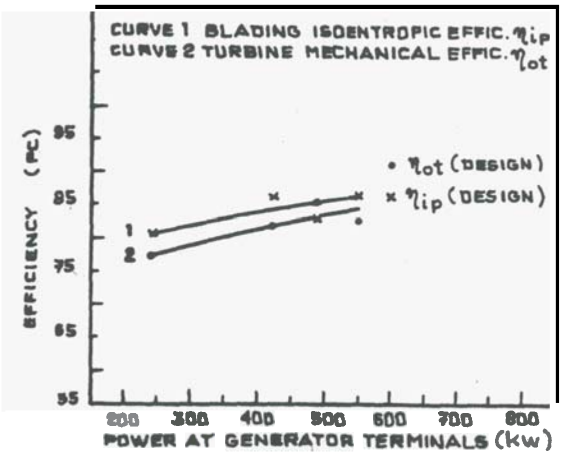


Fig. 5.1 Turbine efficiencies

at the maximum rating. Fig. 5.2 shows the turbine vapor rate, as resulting from the test.

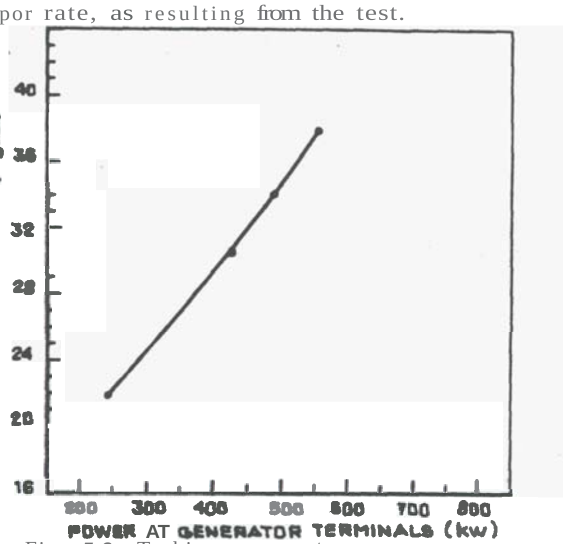


Fig. 5.2 Turbine vapor rate

The comparison with the design values shows that the blading efficiency at the load of 550 kW is slightly higher than the design value. On the contrary the mechanical losses are higher. As a consequence, the turbine vapour rate, at the maximum rating, is 5% higher than the design value.

5.2 Plant Efficiencies

- Net Maximum Power

It is defined as the difference between the electric power at generator terminals and the power absorbed from electric auxiliaries at the maximum rating.

For the reasons outlined in § 4.3, it was not possible to test the plant at the maximum load; but is was only carried out the test at the highest stable load; furthermore (see § 4.4) it was necessary to operate with two feed pumps instead of one, with a consequent 70% increase of the power absorbed from the auxiliaries. The highest value of net power obtained during the performance test has been 370 kW with two feed pumps. Using the value of auxiliary power estimated taking into account only one modified feed pump operating (see Fig. 4.31, the corrected net power would be 435 kW. Anyhow it is our opinion based on the test results, that the plant could give the maximum design power, if the external conditions could allow a finer control of load changes (see § 4.31, as, for instance, the group was connected to the external grid.

- Gross Cycle Efficiency η_{cl}

It is defined as the ratio of the electric power at generator terminals to the thermal power supplied from the hot source.

- Net Cycle Efficiency η_{cn}

It is defined as the ratio of the net power to the thermal power supplied from the hot source.

- Gross Overally Efficiency η_{gl}

It is defined as the gross cycle efficiency times the ratio of the thermal power extracted to the thermal power available from the hot source. The available thermal power is computed taking into account a minimum temperature 10°C higher than the bottom temperature of the cycle.

- Net Overall Efficiency η_{gn}

It is defined in the same way as the gross overall efficiency, but referred to the net cycle efficiency.

The values of η_{cl}, η_{cn}, η_{gl} and η_{gn}, as resulting from the performance tests, are plotted in Fig. 5.3. The Figure shows also the design values. Comparing the measured value with the design one the gross cycle efficiency results 7% lower than the design efficiency. This is due to the turbine vapor rate, that resulted higher than calculated in the design stage. The value of gross overall efficiency, as resulting from the test, is slightly higher than the design one. This is due to the fact that the heat exchange surfaces were clean, while in the design a fouling factor was taken into account. For loads higher than 420 kW, the efficiency values are negatively affected from the fact that it was necessary to operate with two feed pumps. Using the value of auxiliary power estimated taking into account only one modified feed pump operating, it has been calculated and plotted in

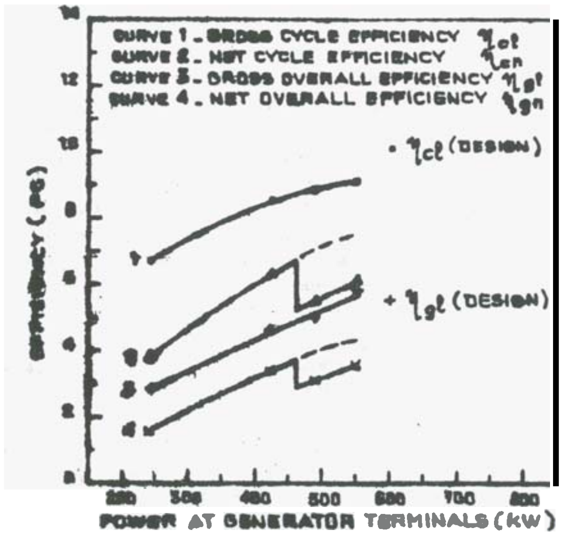


Fig. 5.3 Plant efficiencies

Fig. 5.3 (dotted line) a more reliable value of net cycle and overall efficiency for power higher than 420 kW. At the maximum load the net cycle efficiency would be 7.5% and the net overall efficiency 4.5%.

6.0 CONCLUSIONS

From the analysis of the test findings, it can be inferred that the research has been successfully concluded as:

- the prototype plant has demonstrated its capacity to operate steadily and safely under automatic control .
- The performances, as resulting from the test, are in line with the design values
- from the experience were extracted useful hints for further improvement of the design criteria and performances

7.0 ACKNOWLEDGMENTS

The research has been carried out with the contribution of CNR (National Research Council) during the construction stage and EEC (European Economic Community) during the tests. Montefluos has supplied the organic fluid.

8.0 REFERENCES

Salucci, B., Centemeri, L., Caniato, G., 1982, A 500 kWe ORC plant for the recovery of heat from geothermal water, International Conference on Geothermal Energy, Florence, Italy, May 11-14, 1982, Paper H5.