Recent trends in the development of heat exchangers for geothermal systems

A Franco and M Vaccaro
Department of Energy, Systems, Territory and Constructions Engineering (DESTEC), University of Pisa, Largo Lucio Lazzarino, 56126 PISA (ITALY).

E-mail: alessandro.franco@unipi.it

Abstract. The potential use of geothermal resources has been a remarkable driver for market players and companies operating in the field of geothermal energy conversion. For this reason, medium to low temperature geothermal resources have been the object of recent rise in consideration, with strong reference to the perspectives of development of Organic Rankine Cycle (ORC) technology.

The main components of geothermal plants based on ORC cycle are surely the heat exchangers. A lot of different heat exchangers are required for the operation of ORC plants. Among those it is surely of major importance the Recovery Heat Exchanger (RHE, typically an evaporator), in which the operating fluid is evaporated. Also the Recuperator, in regenerative Organic Rankine Cycle, is of major interest in technology. Another important application of the heat exchangers is connected to the condensation, according to the possibility of liquid or air cooling media availability. The paper analyzes the importance of heat exchangers sizing and the connection with the operation of ORC power plants putting in evidence the real element of innovation: the consideration of the heat exchangers as central element for the optimum design of ORC systems.

1. Introduction
ORC plants have been identified since the beginning of the 1990s as the basic reference technology for increasing the use of medium to low temperature geothermal resources for electricity production purposes. In fact, as it has been largely addressed in the scientific literature in the last twenty years, the medium to low temperature reservoirs, with temperature in the range between 70 °C and 150 °C, are the most diffused all around the world [1, 2].

The potential use of geothermal resources has been a remarkable driver for market players and industry operating in the field of geothermal energy in the last ten years. For this reason, medium to low temperature geothermal resources have been the object of recent rise in consideration, driven by the growth of the geothermal market around the world due to subsidies to ORC applications by the national and local Institutions, mainly in the European Union, together with the development of the geothermal industrial branch in emerging countries of Central America, Africa and Asia.

In recent years, a significant attention to the ORC development and utilization has been addressed by the scientific community and academic researchers and by the companies involved in geothermal industry. Both theoretical and practical solutions based on the optimum matching among geothermal resource characteristics, ORC working fluid, and thermodynamic cycle arrangement have been largely proposed in the last 15 years [3-5].
Notwithstanding the diffused debate, the industrial applications of ORC plants in geothermal energy field seems to be limited only to some specific technologies, and in specific cases the economic results after some years of exercise are not always positive or anyway a they need to be deeply analyzed.

The performance of ORC systems is strongly influenced by heat exchangers design, strongly dependant on external thermophysical parameters (reservoir potential, ambient temperature variation). In practical applications, the space limitation in which the heat exchanger will be installed is also an important constraint. Therefore, the heat exchanger size must also be more compact to satisfy this condition by an enhancement in its thermal design.

Since there are competing effects of increased heat transfer with increased hot-side and cold-side frictional pressure drop, this makes the optimization design of heat exchanger a complex and difficult task. Two efforts are then significant: the evaluation of the optimal trade-off between fluid friction and heat transfer irreversibility and the analysis of augmentation techniques to decrease frontal area at a specified thermal capacity, without causing a damaging increase in pumping power.

It is found that the capital cost of heat exchanger accounts for a large proportion of ORC, and even reaches about 80% in case of air cooled condenser [6]. Therefore, the selection of heat exchanger in ORC is extremely important.

Considering this, the objective of the present paper is to define a kind of balance about the recent diffusion of ORC power plants and the perspectives of future development of geothermal ORCs, analyzing the different perspectives coming from industrial and academic research, mainly in connection with modular small power solutions (often in the range between 200 kW and 10 MW).

When power is recovered from low temperature heat sources, due to the quite low value of the First Law efficiency, large heat exchanger areas and circulation mass flow rates (geofluid, working fluid and cooling media) are necessary. This impacts in particular on heat transfer devices such as condenser, preheater and evaporator, and the cost of those largely contributes to the total power plant cost increase. The importance of the correct sizing of the heat exchangers is well recognized.

This is mainly true for the condenser surface in case of dry type cooling towers. They usually consume much electricity than wet cooling towers, regarding auxiliary power consumption, leading to a reduced power output of the plant. Moreover, due to the need of higher heat exchange surface and of a large volume of air that has to be moved through them, the condenser section can cost about 5-10 times as much as a wet type one, depending on the condensing temperature of the turbine, in particular when low condensing temperatures are considered (as minimum approach against environmental temperature decreases). So a suitable selection of operating conditions (condenser temperature and ambient temperature) of the plant and an optimum thermal design of the heat transfer surfaces is necessary in order to solve the relative optimum design problem. Scaling and solid deposition have a strong impact on the heat exchangers operation too.

Considering the previous elements, the aim of this paper is to analyze the status of the development of heat exchangers with special attention to the development of ORC for geothermal energy use, analysing the negative influence determined on the operation of the plant of an incorrect sizing of the heat exchangers. Also a focus on the design methods is reported including the idea that heat exchangers are not only components of the systems but important elements for an optimum design.

2. ORC Power Plants: state of the art
The binary power plants have a small environmental impact due to the “confinement” of the geofluid respect to atmosphere and soil. In a binary cycle power plant the heat of the geothermal water is transferred to a secondary working fluid, usually an organic fluid that has a low boiling point and high vapor pressure when compared to water at a given temperature. The cooled geothermal water is then returned to the ground by the re-injection well to recharge the reservoir [2].

As clearly evidenced in Fig. 1, the plant comprises two separate sections: the geothermal fluid loop and the power cycle. Geothermal fluid loop and power cycle are completely separated. The connection point is represented by recovery heat exchanger (RHE).
In this way “Nearly zero emission” plants (mainly for all-liquid geofluid) can be conceived. Moreover, this kind of plant is suitable for integration with other energy sources (solar, biomass, or other waste heat recovery).

Binary technology allows the use of medium to low temperature water dominant reservoirs and makes geothermal power production feasible even in countries where high enthalpy resources at shallow depth are not available. Moreover, geothermal resources at temperatures below 150 °C can be available resources at lower depths than high enthalpy geothermal fields. The availability of the resource at a quite low deep (e.g. 1000-1500 m below the ground level instead of 3000-4000 m) permits interesting reduction of the costs connected to exploration and the drilling phase.

Figure 1. ORC power plant, typical configuration

The geothermal binary plants currently in operation can be divided according to different classifications: the first and more meaningful is surely the dichotomy between “stand-alone” or “bottoming cycles”. Another difference is related to the power output. Binary plants can also be classified basing on the cooling system used: plants with a wet cooling system (the working fluid is condensed by cooling water) and plants with a dry cooling system (heat is rejected directly to air). Relevant differences can be evidenced in the operating fluid and in the thermodynamic variables. [7]

The worldwide installed geothermal power plants reach approximately 13 GW and ORC plants (or steam/ORC combined cycles) are about 1800 MW, namely 280 power plants about 14% of the total. The diffusion of such kind of plants has increased in a meaningful way in the last ten years, as clearly discussed in the next section. It is possible to estimate that about 1050 MW have been installed in the last ten years, mainly under the impulse of some manufacturers, [8].

Mainly in the last ten years the perspective of installation of new binary cycle power plants has driven in a significant way the geothermal energy branch. More than 1050 MW of binary plants, corresponding to about 78 new power plants have been installed between 2005 and 2015 increasing the installed capacity from 738.9 MW up to 1790 MW (Table 1).

Table 1. Binary cycle power plants installed.

| Period       | Plants installed (n) | Cumulative power (MW) |
|--------------|----------------------|-----------------------|
| Before 2005  | ~200                 | 738.9                 |
| 2005-2009    | 27                   | 465.8                 |
| 2010-2014    | 51                   | 585.3                 |
| Total        | ~280                 | 1790.0                |
Even if geothermal power plants have the characteristics of operating for a lot of time (up to 8500 hours in a year), the total amount of installed power generation considering geothermal energy is well below the level of the other renewables. Considering the same period, a less remarkable installed capacity of flash-steam plants has been observed and few hundreds additional MW of dry steam power plants have been installed.

In the industrial practice, the power production capability is impacted by practical issues and by constraints individuated by Institutions, customers, and all of these are case specific. These constraints are apparently contrasting with the necessity of standardization (e.g. size, equipment selection, environmental issues). In the technical field of ORC technology, the recent evolution of the research, slightly evidenced in this paper, mainly deal with a lot of topics, summarized in the following lines:

- Working fluid chemical studies and stability;
- Plants layout and compact configuration;
- Combined plants optimization;
- Thermal cycle definition;
- Supercritical cycles configuration;
- Machinery optimization;
- Exergetic analysis;
- Thermoeconomic and Exergonomic analysis;
- Optimization engineering;
- Dynamic analysis;
- Plant equipment design.

The interest of the researchers in the field of the binary cycle power plants and ORC technology is clearly identified by the large amount of scientific contributions in this field. About 1300 papers can be found in the most used research journal collector (www.sciencedirect.com), and about 200 are produced in the first months of 2017. While the papers dealing with geothermal heat exchangers, both for power conversion and direct use, are about 7400, and about 600 are dated 2017.

3. ORC Plant Technology: technical solutions, design problems and role of heat exchangers

One key point to understand ORCs development along history of geothermal branch is that since the beginning and for a quite long time, each installation has been designed for the conditions at a given location and the different systems have been tailored to specific geothermal fluid characteristics. Fig. 1 provides a typical scheme of the most common schematization of a ORC power systems in which the role of the different exchangers is well evident: the recovery heat exchanger (RHE), the Recuperator, in which the temperature of the fluid at the outlet from the turbine is used for preheating the same fluid before entering in the RHE, and the cooling system (condenser).

Mainly in the last years, some attempts have been made by manufacturers to design “standard machinery”. Some manufacturers have proposed the use of standard sizes and systems, and this approach could be a key driving factor for a larger diffusion of small size geothermal plants. Unfortunately, it is very difficult to pursue this standardization in practical design purpose, for different reasons dealing with the nature of the geothermal resources and the environmental conditions (that have importance for the definition of the condensation temperature).

The temperature of the condenser in geothermal power plants may have different values depending on its location in the world. Indeed, the climate around a geothermal power plant dictates the outdoor temperature, which then impacts on the nominal temperature in the condenser. This value fixes the turbine discharge pressure, due to the environmental air design temperature, leading to cut the possibility of exploiting a wider useful enthalpy range in the expansion machinery.

3.1. Working fluids and thermodynamic optimization of the heat recovery cycle

The thermodynamic properties of the working fluids are considered as key parameters. The selection of suitable fluids for use in binary cycle plant is a quite complex problem and cannot be disjointed by the heat recovery cycle selected. In general, the working fluids deserve the following characteristics: low critical temperature and pressure, small specific volume, low viscosity and surface tension, quite high thermal conductivity, suitable thermal stability and environmental acceptability. A desirable thermodynamic property of the fluid is a near vertical saturated liquid and vapor line for the possibility of “carnotizing the cycle” but this is a quite complex question. The saturation vapor curve is the most
crucial characteristic of a working fluid in an ORC. This characteristic affects the fluid applicability, cycle efficiency, and arrangement of associated equipment in a power-generation system.

Working fluid selection for geothermal ORCs has been largely addressed in scientific literature, also by one of the authors in [5] and it deals with thermodynamic issues respect to more practical heat transfer issues and feasibility and industrial questions.

There are two types of vapor saturation curves in the temperature-entropy (T-s) diagram: “dry fluids” with positive slopes ($dT/ds$), “wet fluids” with negative slopes. In the second case, since the vapor expands along a quite vertical line on the T-S diagram, vapor saturated at the turbine inlet will remain vapor phase throughout the turbine exhaust duct, then it seems not particularly convenient to resort to Rankine cycle with superheater. In some cases the superheating of “dry fluids” (with positive slope of the vapor saturation curve) is done, but this to increase the specific enthalpy content of the expanding stream and to make sure that the vapor is dry also in transient conditions (e.g. start-up).

The minimization of the exergy losses must be performed to perform the optimization of a certain ORC arrangement. It is mainly related to the recovery heat exchanger (RHE), this can be obtained theoretically by increasing the number of pressure levels (PL) of the thermodynamic cycle, in order to keep close the temperature profiles of the two exchanging fluids. A complete analysis of the system involves the evaluation of exergy losses in the working fluid turbine as well as the residual exergy of the auxiliary working fluid at the end of expansion. The residual exergy of the geothermal brine at reinjection temperature are important element too, but it is usually kept higher than a controlling value depending on the scaling threshold due to the chemical composition of the geofluid.

Different types of ORCs exist in the literature and in commercial application. The investigated cycles can be of the simple or recuperated type, be subcritical or supercritical and can have one or two pressure levels. Different examples are illustrated in Fig. 2, in which the scheme of single-pressure with or without superheat ORC, a double-pressure ORC and supercritical ORC, using two different operating fluids, are shown. A great number of heat exchangers (economizer, evaporator, superheater, desuperheater, condenser and recuperator) are necessary.

**Figure 2.** Thermodynamic cycles for binary plant
A critical point in the design of the binary cycle power plants is the design of the Recovery Heat Exchanger (RHE). Anyway, it is possible to state that a good match between thermodynamic cycle and working fluid can be obtained for each kind of combination, so that the influence of the working fluid could be considered marginal for the optimization of ORC performances. For this reason, as it will be discussed in the further section, in some cases the working fluid choice is driven by economic or supply-oriented evaluations, mainly driven by end-users.

3.2. Turbine (expander) efficiency and new turbine concept

Increase in the turbine efficiency (through continuous improvements in thermo-fluid-dynamic, finite element and vibration analysis) is object of the research too. Titanium blades have been developed by some leading manufacturers in the industry, displaying improved corrosion resistance. However, these have not gained widespread acceptance due to concerns about their performance in relation to erosion resistance. At the opposite end of the spectrum, there is reputedly intriguing ongoing work to develop small, 'high speed' turbine wheels that rotate at tens of thousands of RPM a concentrated power extraction. Clearly the benefits here would be reductions in materials usage, although questions remain about use of such devices with wet steam that would cause erosion, and also about gearbox coupling and efficiency. Recently, within the indirect geothermal market (i.e. non-flash) such turbo-expanders are commonly used with binary fluids.

3.3. Heat exchangers and auxiliary systems

The heat exchangers technology for power production, although well-known, also deserves some attention, particularly in light of equipment sizing and selection and integration into ORC systems. Heat exchangers represent a major share of the total cost. Their design should therefore be carefully performed. Key characteristics regarding heat exchangers design are the efficiency (or pinch point) and pressure drops. Different types of heat exchangers can be used, the most common are: shell & tube; and plate (or plate and shell) heat exchangers (mainly in small-scale systems, due to their compactness), [13]. Some basic configurations of the heat exchangers are provided in Fig. 3.

Concerning the various components of ORC plants, a critical heat exchanger is surely the one installed directly on the heat source, with the purpose or energy recovery form geothermal fluid.

![Typical heat exchangers for geothermal energy systems application](image)

Figure 3. Typical heat exchangers for geothermal energy systems application

This particular heat exchanger (transferring heat from the geofluid to the working fluid) is the critical equipment of the whole plant, as it is affected both by strict pinch point and from chemical aggressiveness of the geofluid. Depending on its nature, this heat exchanger operates with a fluid at a quite high temperature and with a not simply defined chemical composition.

Preliminary evaluation of the global heat transfer coefficient (U) is important in order to perform cycle calculation: this is not always a simple task due to the fact that it depends on the following terms: inside and outside convective heat transfer coefficients, wall thermal resistance and fouling factors. The presence of an organic working fluid made sometimes difficult the estimation of the heat transfer coefficient mainly with respect to operating conditions different from the nominal values.
RHE can be often subject to fouling and corrosion, due to the presence of acids in the geothermal fluid, and/or reactants. Scaling and solid deposition can reduce the efficiency of this equipment, leading to critical area reduction or catastrophic rupture, if not prevented or mitigated with chemical cleaning and inhibitors injection. The cost of these devices largely contributes to the total power plant cost increase. This is particularly true for the condenser surface in case of dry type cooling towers, as they consume much more electricity than wet cooling towers (reducing the global power output of the plant). Moreover, due to the need of higher heat exchange surface and of a large volume of air flow, the condenser section costs about 5-10 times as much as a wet type one, depending on the condensing temperature of the turbine, mainly if low condensing temperatures are considered (as minimum approach against environmental temperature decreases). A suitable selection of operating conditions (condenser temperature and ambient temperature) of the plant and an optimum thermal design of the heat transfer surfaces is necessary for optimum design problem.

4. Heat exchangers design and development with respect to geothermal ORC industry

As it has been underlined in the previous section, the heat exchangers are the most critical components of a geothermal ORC power plant. A lot of issues and technical problems (thermodynamic, corrosion, scaling, heat transfer, huge mass flow rates) are concentrated into these exchangers because both geofluid and working fluid are processed. The design of a heat exchanger is really linked to the analysis of the whole system. The preliminary sizing and the optimum design of the heat exchangers used in the ORC plants is a problem with a great number of variables.

The three main heat exchangers can be treated. The most important role is surely played by the Evaporator or Regenerative Heat Exchanger (RHE). The Recuperator (REC), necessary in case of regenerative cycle, is less impacted by geofluid side issues, but it can be critical for the whole plant efficiency and in transient operative conditions. The largest heat exchanger area used in a geothermal ORC is then the condenser surface, mainly if dry cooling must be performed. Not always it is possible to use a liquid heat source (that would give significant benefit on the condenser equipment sizing and auto consumption). The typical ORC location does not allow reaching water bodies for condensation.

Air cooled condenser could be also critical when the plant facility is located close to inhabited areas, as the fans release noise. Low-noise fans can also be proposed but it increases the cost of the equipment. Considering the recent studies about ORC systems, the real innovation element is the proposal of including the heat exchangers and the connected variable in the optimum design process of ORC. The optimum design of ORC system can arranged considering two steps, as represented in Fig. 4. A system optimization of an ORC is taken by including the heat exchangers in the optimum design. The heat exchangers can be modelled with the methods available in the literature that can be used for single-phase flow, condensing and evaporation.

4.1. Heat exchanger configurations

The type of heat exchangers that can be used in ORC plants are basically two: plate heat exchangers and shell-and-tube heat exchangers. The use of different heat exchangers and heat exchanger configuration is argument of some interesting papers, like [14-16]. In general, considering the two main types of heat exchangers, the following dimensions can be considered.

| Table 2. Typical values of the variables for the shell and tube heat exchangers in ORC application. |
|---|---|---|
| Variable | Lower boundary | Upper boundary |
| Shell diameter (D) | 0.3 m | 2 m |
| Tube outside diameter (d) | 5 mm | 50 mm |
| Relative tube pitch (p/d) | 1.2 | 2.5 |
| Ratio length/shell diameter (L/D) | 6 | 10 |
| Ratio of tube diameter to shell diameter | 0.001 | 0.1 |
4.2. Recovery Heat Exchanger (evaporator): critical elements and perspectives

The evaporation of the working fluid (and/or superheating, in case of both “wet fluids” and “dry fluids”) is possible because of the heat given by the hot geofluid. Shell and tube heat exchanger type can be used achieving standard cost structure. The source fluid outlet temperature is critical as it is linked to scaling phenomena. This temperature must be kept sufficiently high to avoid scaling on the source fluid side of the exchanger. Cleaning of the source fluid side may be necessary, so the vaporizer design must take this into account. Any geothermal fluid may be corrosive, so an appropriate material must be identified (e.g. also special steels) to be used for the vaporizer.

As the evaporation of a low-boiling point fluid (respect to water) is to be performed, two types of heat exchanger can be proposed: kettle type boilers and once-through heat exchangers. The first type is more traditional, belonging to the more experienced practice of combined cycle plants (see Fig. 5). The second type (see Fig. 3-a) leads to a different path of flow arrangement (particularly for the working fluid), as a tidy liquid-vapor interface is not identified or observed along the heat exchanger. This second typology often implies longer heat exchangers (with geofluid passing through the tube side), with reduced shell diameter.

One possible perspective for standardization and development from manufacturer is truly given by these aspects, trying to match clearly identified and modular typology of heat exchanger, mainly for the RHE. As for machinery manufacturing, for which standardized sizes of turbines and expanders
should be a perspective, also in case of geothermal heat exchangers modular equipment could be an enhancement. Reinjection temperature (usually in the range between 70 °C and 100 °C) is often a driven factor, as the scaling phenomena. Another operating problem is surely represented by non-condensable gases (NCG). When vapor phase geofluid is used instead of liquid phase, then NCG must be removed by the geofluid side of the equipment. This operation impacts on the efficiency of the RHE and a careful design of the NCG removal system must be performed. A small compressor could be used for this purpose, increasing the auxiliary consumption of the plant and also the noise level emission.

4.3. Recuperator design

The regenerative heat exchanger, as clearly illustrated in Fig. 1, is the heat exchanger between the hot exhaust vapor from the turbine and the liquid being pumped from the condenser. The objective of this component is the heat transfer from the exhaust vapor exiting the turbine to the cold liquid from the condenser. The fluid behavior is usually close to linear, so it is normally not necessary to divide the regenerator into sections. The Recuperator is not impacted by geofluid issues, but it contributes to the whole energy recovery arrangement of the cycle. Its sizing is then also important, as it could lead to reduce the size of the RHE.

4.4. ORC condenser design

The condenser may be either water or air cooled. Three different schemes of condensers are available as illustrated in Fig. 6. The calculations for the condenser are roughly the same in both cases, as the cooling fluid (air or water) is very close to have a thermally linear behavior. In a typical ORC plant the condenser is a heat exchanger between the hot vapor from the regenerator/turbine and a cooling medium. The temperature of the hot fluid is higher than the one of the cold fluid throughout the condenser, but this difference is not so marked. As well it must be kept in mind that the relation between the enthalpy and the temperature is non-linear, requiring that the vaporizer is divided into appropriate sections for the calculation. This is especially valid for Kalina cycles, in the ORC cycle there is only a property change at the dew point, where de-superheat ends and condensation begins.

4.5. Scaling and material selection

As it has been addressed from research and technical applications, scaling is one the more impacting problems in the design of binary cycle power plants. Scaling (usually silica or other typology of deposition) is directly connected with the chemical composition of the fluid. Its peculiarity is that it can only be analyzed basing on manufacturer experience and geothermal exploration (it depends on the chemical composition of the geofluid extracted), which are lacking when facing a new developing reservoir, with no drilling historical data. Its real impact can be measured only when the wells are drilled and a dedicated analysis is performed. Scaling and deposition problem are currently being faced through experience and background of operators and it is one of the sectors in this field less involved in technology transfer. Material selection is an obvious criticality, being strongly influenced by the geofluid chemical composition and aggressiveness.
The RHE must resist to both aggressiveness and potential scaling, and a periodic chemical cleaning should be planned. For small application also particular plate type heat exchanger could be used, however the correct design and chemical issues must be treated in a more severe way, as the small channels could be impacted in a more critical way.

5. Conclusions
The design of ORC systems is a challenging task in energy systems engineering. Many design alternatives are available at each level of design, from working fluid selection via cycle optimization and control through to the efficient integration of the various components of the system.

An important role is covered by heat exchangers and heat transfer sections optimum design. The problem concerns the thermal and fluid dynamic elements as well as the materials.

Significant possible approaches moving from systematic strategies to detailed design issue have emerged over the past years with the aim at supporting the designer in making optimal choices at each level of ORC development.

The paper has analyzed a state-of-the-art of the application of the heat exchangers in the ORC plants considering both conventional and emerging studies with a particular emphasis on the optimum design of the system that have to consider the heat exchangers.

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