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The First Geothermal Organic Radial Outflow Turbines

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ABSTRACT

In the last years a new turbine technology for geothermal energy exploitation has been developed, engineered, manufactured and tested by Exergy : the organic radial outflow turbine.

The radial outflow turbine technology has several unique characteristics which qualify this innovative configuration as advantageous for many geothermal applications, as it ideally matches the process conditions typical for geothermal organic binary power plants.

The purpose of the present article is to analyze the performances encountered in the first installation of the organic radial outflow turbine in a geothermal field, the Bagnore power plant of ENEL Green Power, and the current and future development of such turbine configuration for multi pressure level cycles.

1. INTRODUCTION

It is well documented that for binary geothermal power plants axial turbines with an overhung configuration have traditionally been the selected design. In fact, despite other configurations having been proposed in the market, such as the radial inflow turbine, the overhung axial arrangement is the reference configuration in the geothermal field, having been developed since more than 50 years and representing nowadays the most common turbine technology (Di Pippo, 2005).

Recently a different solution has been reconsidered as a suitable turbine technology for expanding organic vapor in geothermal binary power plants: the radial outflow turbine.

This technology has been developed in the early 20th century by Ljungstrom (counterrotating) and Parsons to expand steam (Dixon,1998).

The expansion of a working fluid vapor in a radial outflow turbine is shown in Fig. 1 : the fluid enters the turbine disk axially in its center and expands radially through a series of stages mounted on the single disk. At the discharge of the last rotor the flow go through a radial diffuser and is then conveyed to the recuperator and/or condensation section of the system, through the discharge volute.

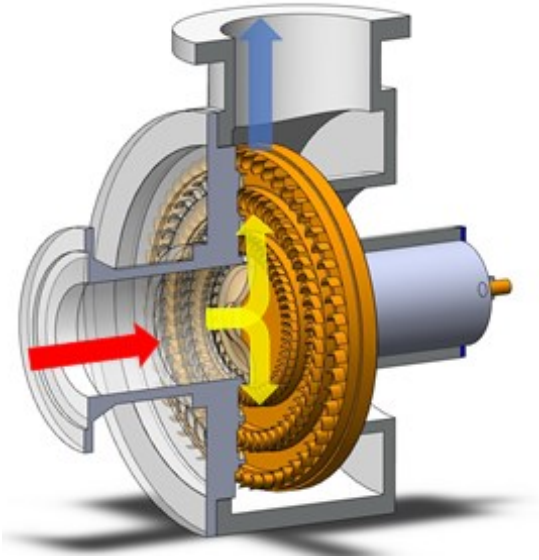

Figure 1: 3D cross section of the radial outflow turbine.

To better understand the particular feature of the radial outflow turbine some considerations about turbomachinery fluid dynamics and about thermodynamics are necessary.

It is known that for turbo machinery the general Euler equation, ignoring minor negligible losses, provides a formulation of the specific work for a single stage as (Dixon, 1998 – Lakshminarayana, 1986):

$$l = u_1 c_{t1} - u_2 c_2 \tag{1}$$

where

u is the Peripheral velocity

c_t is the Tangential component of the absolute velocity

1 is the Inlet section of the turbine

2 is the Outlet section of the turbine

As a result of Equation (1) in order to maximize the specific work of a single stage, the first term should be significantly higher than the second: assuming that in a turbine C_{t1} is bigger than C_{t2}, the highest specific work of a single stage is thus achieved by the radial inflow configuration, which has intrinsically an higher peripheral velocity at the inlet and a lower one at the outlet.

The radial outflow configuration has instead a low specific work per stage due to the reduction of the peripheral velocity while expanding the vapor ($U_1 < U_2$).

Furthermore from thermodynamics it is known that the expansion of fluids with low molecular weight, like water, at operative conditions which are typical for power production, is characterised by high enthalpy drops, high volumetric flows and high volumetric ratios (Poling et al., 2000).

Thus the choice of the radial outflow turbine with water steam faces a serious limit : a significant number of stages is mandatory to convert the enthalpy drop of the fluid into mechanical energy. Owing to this reason Ljungstrom developed his counter rotating radial outflow turbine configuration,in order to reduce the number of the turbine stages by increasing their specific work.

Furthermore, due to the remarkable volumetric flow and its ratio between the inlet and outlet section (considerable for steam), the turbine blades would necessarily have a large height even for small power output turbines.

Thus for the very large diameter disk necessary to accommodate all the required stages and for the too long blades, the radial outflow turbine configuration demonstrated serious limitations while processing steam and was therefore deemed not suitable.

These issues meant no significant development of the such type of turbines, which were phased out for steam applications by axial turbines.

2. THE RADIAL OUTFLOW TURBINE BY EXERGY

At the operative conditions which are typical for geothermal power production, fluids with high molecular weight lead to significantly lower enthalpy drops, volumetric flows and volumetric ratios than steam (Poling et al., 2000): this made possible for Exergy to reconsider the radial outflow turbine configuration for geothermal application on binary power plants, as the intrinsic limits of this type of technology are no longer relevant.

If compared to traditional organic turbines, meaning overhung axial turbines, the Exergy overhung radial outflow turbine demonstrates several mechanical and fluid dynamics differences hereby summarized.

Mechanical analysis

Axial turbines are characterized by having only a stage mounted on a single disk (in future called single-disk/single stage configuration). This arrangement in overhung axial turbines limits the number of stages, for rotordynamics reasons, to up to 3 stages.

The radial outflow turbine allows instead to have several stages (up to 7) arranged on the same disk (see Figure 1).

The single-disk / multi stage configuration has thus the advantage to minimize vibrations and static and dynamic loads on the bearings, due to the reduced distance between bearings and the turbine center of gravity. These makes possible to decrease the maintenance and extended the useful life of the rotating components (see Figure 2).

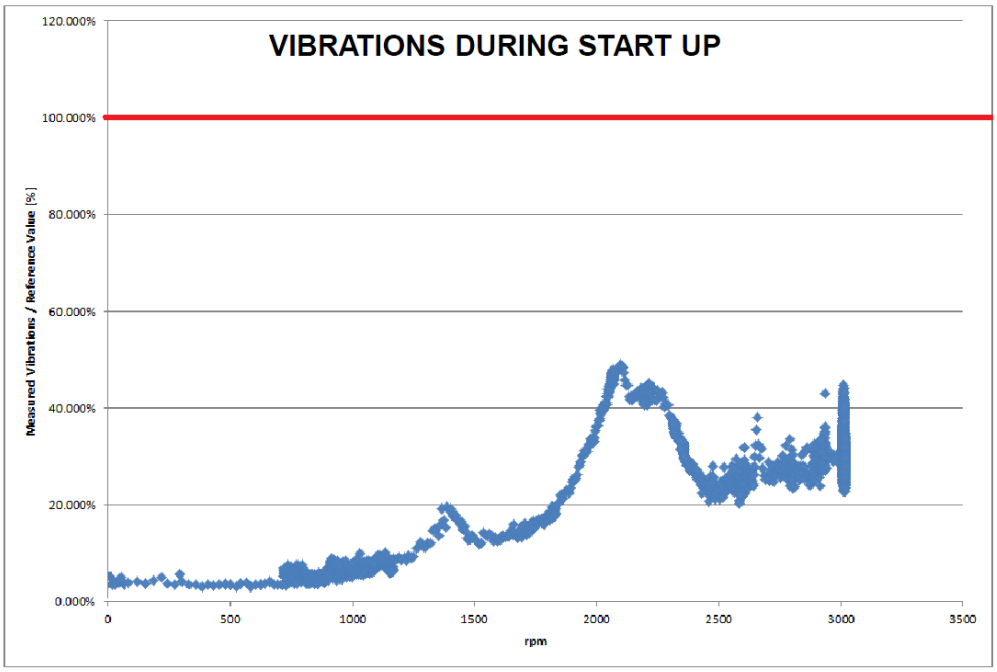

Figure 2: Vibrations during start up.

Finally being the peripheral velocity constant along the blade span, the velocity triangles are constant and the blades should be prismatic instead of twisted.

Fluid dynamics analysis

Having a cross section increasing proportionally to the radius, during the expansion, the radial outflow turbine matches the volumetric flow behavior better than the axial turbines which usually require high flaring angles. This means that it is possible to have lower blade at the last stage, leading to evident mechanical advantages, and higher blades at the first stages, thus to reduce the secondary and leakage losses.

For this reason, as initial stages have a better aspect ratio, they do not need partial admission, avoiding additional losses related to this aspect.

As a consequence, the possibility to manage higher volumetric flow ratio allows to have an higher pressure at turbine inlet while keeping the same condensing pressure and so giving the possibility to increase the thermodynamic cycle efficiency.

Finally, as the enthalpy drop of the fluid is divided on several stages for the single-disk/multi stage configuration, the radial outflow turbine is characterized by subsonic or transonic stages (instead of supersonic ones typical of the other configuration, because of the low speed of sound of organic fluids) having a lower work coefficient resulting in an higher fluid dynamics efficiency both in nominal and off-design conditions (see Figure 3).

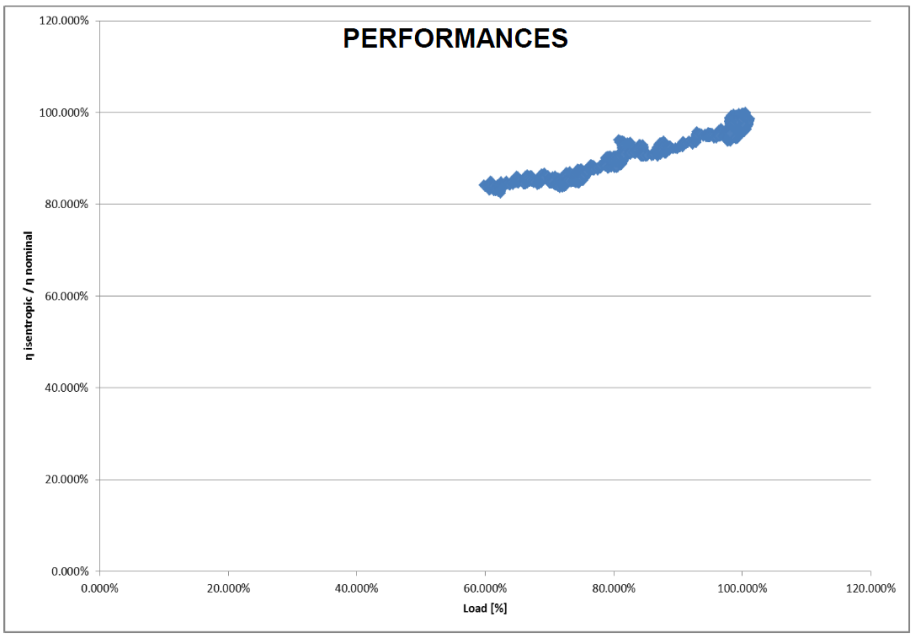

Figure 3: On-field measured performances.

These theoretical advantages have been confirmed in the first installation of the organic radial outflow turbine in a geothermal binary power plant, the Bagnore power plant, and the future installations will foresee an important development for the multi pressure level cycles

3. THE BAGNORE ORGANIC RADIAL OUTFLOW TURBINE

The Bagnore power plant represents the first installation of the organic radial outflow turbine in the geothermal field and it has been operational since early 2013 (Di Pippo, 2005).

Despite other experimental ORC units tested in Italy previously, the Bagnore radial outflow turbine represents the first commercial geothermal organic turbine operating in Italy.

The turbine was delivered to ENEL Green Power and installed in the Bagnore geothermal site at Monte Amiata, Tuscany (Italy).

The Bagnore field belongs to the Monte Amiata geothermal reservoir, which is a typically water dominated field with high temperature and pressure (Bertini et al, 1995). These field was already exploited in the past, by flashing the geothermal fluid and expanding the steam in steam turbines in the units Bagnore 1 and Bagnore 2 of a total power of 40 MW and delivering the brine to the district heating.

To implement a technology flexible enough to accommodate the variations in the resource over the lifecycle, binary technology has been considered to be the preferred solution and the radial outflow turbine the most efficient and cost effective turbine.

The ORC binary unit has been installed in parallel to the steam turbines and is exploiting steam at 150 °C.

In order to maximize the thermal energy recover from the steam, thus to minimize the irreversibility associated to the heat exchange, a single pressure level cycle with Pentane has been selected as the most appropriate combination between working cycle and fluid.

Furthermore the unit condensing system is water cooled and no recuperator installed due to the low amount of energy recoverable after the expansion of the organic fluid.

The process flow diagram of the Bagnore binary power plant is shown in Figure 4.

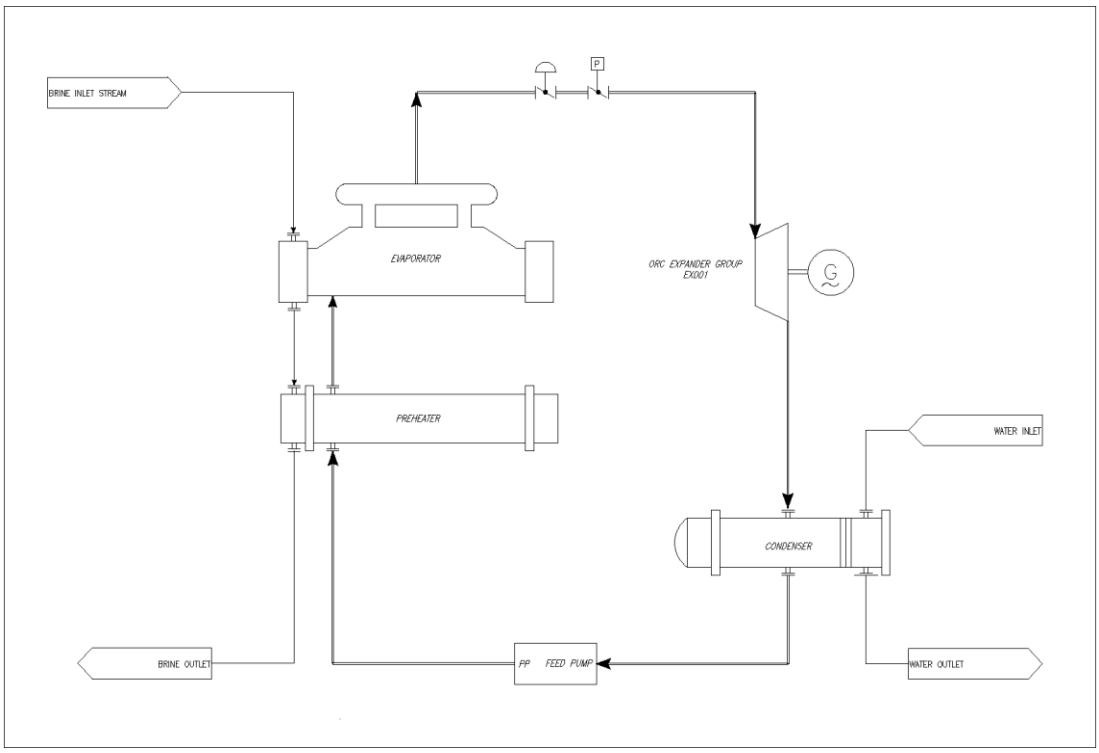

Figure 4: Process flow diagram of the Bagnore binary power plant.

The Bagnore plant is shown in Figure 5, where the principal components are highlighted.

Figure 5: Bagnore binary power plant.

Working in the above conditions, a comparison between the expected design efficiency of an axial turbine and a radial outflow turbine has been performed.

The main thermodynamic parameters, affecting the turbine design, for the optimized working cycle are presented in Table 1.

Table 1: Principal parameters affecting the turbine design for the Bagnore ORC binary power plant.

Parameter	Unit of measure	Value
Inlet vapor quality	-	1.00
Mass flow	[kg/s]	18.6
Inlet temperature	[°C]	115.6
Inlet pressure	[bar a]	8.0
Discharge static pressure	[bar a]	1.1
Isoentropic enthalpy head	[kJ/kg]	75.4
Volumetric expansion ratio	-	7.7
Pressure expansion ratio	-	7.27

Based on the inputs of Table 1, the main mechanical parameters of the optimized axial and a radial outflow turbines, with an overhung configuration, are presented in Table 2.

Table 2: Main mechanical parameters of the optimized axial and radial outflow turbines.

Parameter	Unit of measure	Axial turbine	Radial outflow turbine
Rotational speed	[rpm]	3000	3000
Number of stages	-	2	4
Shaft length	[mm]	940	800
Disks diameter	[mm]	886-910	740
Blade height	[mm]	min 13; max 44	min 36; max 54

For what above the efficiency of the turbines are as shown in Table 3.

Table 3: Expected design turbine efficiency of the optimized axial and radial outflow turbines for the Bagnore binary power plant.

Parameter	Unit of measure	Axial turbine	Radial outflow turbine
Expected design turbine efficiency	-	80 %	84.5 % [6]

The expected efficiency of the turbines is calculated to be higher for the radial outflow turbine, which is thus perfectly suited for the Bagnore site. The Bagnore turbine is presented in Figure 6.

Figure 6: Rotor disk of the Bagnore radial outflow turbine.

4. THE MULTI PRESSURE RADIAL OUTFLOW TURBINE BY EXERGY

It is well documented that binary geothermal power plants have the possibility to be developed as multi pressure level cycle systems and for many geothermal resources, a system designed in this way can deliver a significant increase in the power output, in comparison to a single pressure level system (Di Pippo, 2005). In fact these cycle configuration enable the recovery of heat from the geothermal source by vaporizing the organic fluid at multiple pressure and usually reduce both the thermal irreversibility associated to such heat exchange and increase the cycle efficiency. The concept recalls the GT combined cycles.

As represented in Figure 7 and Figure 8, a single pressure level cycle is intrinsically simpler and usually less expensive than a multi pressure level system. However the advantage in the efficiency offered by the latter gives a favorable payback, thus making it the preferred option in the geothermal field.

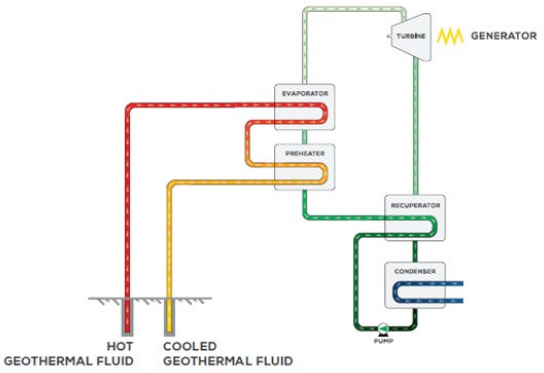

Figure 7: Process flow diagram of a regenerative 1 pressure level cycle.

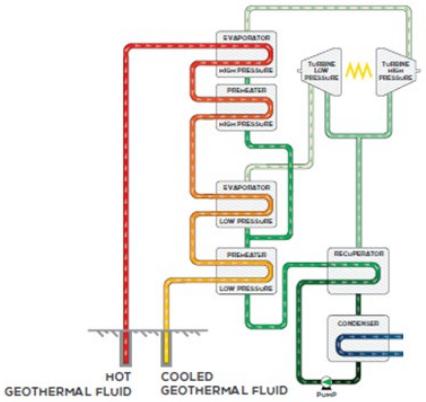

Figure 8: Process flow diagram of a regenerative 2 pressure level cycle.

The state of the art indicates that the technologically advanced multi pressure level geothermal binary systems require at least one turbine per pressure level, to expand the organic vapor, and these turbines are normally installed with an overhung configuration (Di Pippo, 2005).

The radial outflow turbine gives the possibility to employ a different solution.

In fact, in order to expand multi pressure flows in the same axial turbine, it would be necessary to enlarge the space between the disks, allowing a second flow to be inserted to mix with the primary flow; the mixed flow will be then expanded in the remaining stages.

As a consequence the shaft length of the axial turbine must increase, resulting in several rotordynamics problems for the overhung configuration, as the distance between the center of gravity of the turbine disks and the bearings consequently increases.

As a matter of fact actually it appears not possible to design such a turbine.

At the same time, having a single-disk / single stage configuration, the radial inflow turbine does not allow multiple pressure entries.

A different scenario is instead provided by the radial outflow turbine: its unique single disk / multi-stage configuration makes it possible to enlarge the spacing between the stages (see Figure 9), allowing a low pressure flow to enter the turbine, whilst still maintaining an overhung configuration without any negative rotordynamic consequences.

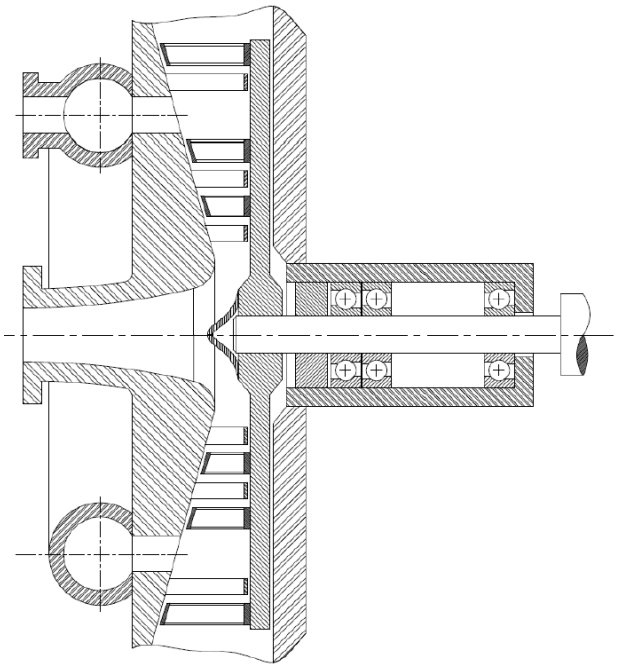

Figure 9: Schematic drawing of the multi-pressure radial outflow turbine.

The radial outflow turbine can therefore allow multiple pressure levels cycles to be expanded over a single turbine.

The major advantages related to this configuration are the techno-economical savings associated with a lower number of turbines to be installed per plant. This minimizes the plant overall costs, and reduces the amount of rotating equipment, spare parts and maintenance.. Furthermore the plant layout is more compact, reducing the amount of foundations, control equipment and control complexity.

4.1 The Denizli-Tosunlar Multi Pressure Organic Radial Outflow Turbine

EXERGY have applied this unique and new configuration in the Denizli-Tosunlar geothermal field in Turkey, for Akca Enerji.

The Denizli-Tosunlar is of water dominated type and geothermal plant has the following design characteristics (Yaldrim):

- Geothermal mass flow per productive well 350 ton/hr
- Geothermal fluid temperature 105 °C
- Geothermal fluid reinjection temperature 60 °C
- Cooling water inlet temperature 15 °C
- Cooling water outlet temperature 20 °C
- Number of productive and reinjection wells 4

In order to evaluate the performances of different combinations of thermodynamic cycles and organic working fluids, a thermodynamic analysis have been performed based on the above conditions. Four different combinations have been investigated : single pressure level cycle with IsoButane, single pressure level cycle with R134a, two pressure level with IsoPentane and 2 pressure level with R245fa.

In the comparison, the hypothesis considered are presented in Table 4.

Table 4: Hypothesis of the thermo dynamic comparison for the Denizli-Tosunlar ORC binary power plant.

Parameter	Unit of measure	Value
Geothermal fluid temperature at ORC plant input	[°C]	105
Geothermal fluid temperature at ORC plant reinjection	[°C]	≥60
Pinch point in the heat exchangers	[°C]	5.0
Turbine mechanical efficiency	-	82.0 %
Organic fluid Feed Pump mechanical efficiency	-	70.0 %
Electric Generator efficiency	-	97.0 %
Organic fluid Feed Pump electric motor efficiency	-	95.0 %

The results of the analysis are shown in Table 5 where is compared the power output of the four combinations, having put as basis the outputs realized adopting worst combination, thus the 1 pressure level cycle and Isobutane.

Table 5: Outputs of four possible different combinations of working cycle and fluid, adoptable in the Denizli Tosunlar geothermal field.

Working cycle	Working fluid	Gross Power	Net Power
1 pressure level	IsoButane	1.00	1.00
	R134a	1.08	1.03
2 pressure level	IsoPentane	1.15	1.18
	R245fa	1.17	1.19

In such conditions a two pressure level optimized cycle delivers up to 20% higher power output than an optimized saturated or superheated single pressure level system.

Such an increase is made possible by significantly reducing the thermal irreversibility associated to the heat exchange between the geothermal source and the organic fluid.

As shown in the process flow Figure 10, the Denizli-Tosunlar ORC binary geothermal power plant designed by EXERGY is exploiting a geothermal source with a saturated two pressure level cycle and is water cooled by the water channeled from the Menderes river. A recuperator was not installed due to the low amount of energy recoverable after the expansion of the organic fluid R245fa.

The unique feature of the Denizli-Tosunlar plant is related to the turbine, able to expand the 2 pressure level flows on a single radial outflow turbine.

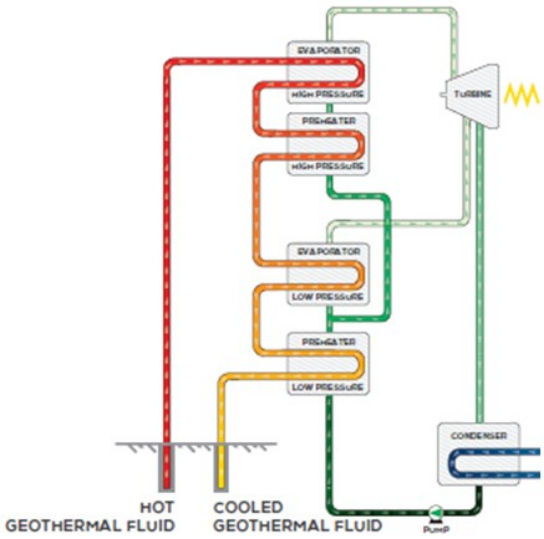

Figure 10: Process flow diagram of two pressure level cycle with radial outflow turbine.

In order to expand the two flows at different pressure levels, EXERGY has designed the multi pressure level radial outflow turbine with the following characteristics:

- Power at shaft 4.00 MW
- Total number of stages 3
- High pressure stages 1
- Low pressure stages 2
- Rotational speed 1500 rpm
- Disk diameter 1450 mm

5. CONCLUSIONS

This paper has presented a new turbine technology for geothermal energy exploitation: the Exergy organic radial outflow turbine.

The mechanical and fluid dynamics advantages of the overhung radial outflow turbine has been explained in detail, having as reference the overhung axial turbine which is the reference turbine for the geothermal binary power plants.

The above advantages have been demonstrated in the first installations of the organic radial outflow turbine in a geothermal field, the Bagnore power plant of ENEL Green, where the expected design efficiency has been modeled and calculated to be significantly higher (+4.5%) than the reference binary turbine.

The current and future development of such turbine configuration for multi pressure level cycles have then been presented where the multi pressure radial outflow turbine has been modeled and comprehensive thermodynamic analysis has been conducted.

The multi pressure radial outflow turbine is clearly an important innovation for the geothermal field, particularly for small size and low temperature geothermal applications, ie. less than 5 MWe with a resource < 120 °C, where the volumetric flows and enthalpy heads are thus limited.

For all the above, the following can be concluded:

1. The EXERGY radial outflow turbine has an higher efficiency compared to traditional organic turbines and this is well documented from first experimental results;

2. The EXERGY radial outflow turbine has been demonstrated to have very low vibrations compared with the ISO Standard values;

3. The EXERGY radial outflow turbine, thanks to its single disk multi-stages unique design, makes possible to expand multi pressure flows with a single turbine.

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