TEST PROCEDURE, MEASUREMENTS AND CALCULATION METHODS FOR THE TURBINE EFFICIENCY AND POWER CYCLE PERFORMANCE

INTRODUCTION

In recent years, the ORC market expanded rapidly in terms of installed plants, power and number of ORC manufacturers. New markets, like the waste heat recovery from industrial process or endothermic engines, are growing very fast, but the biomass combustion and the exploitation of geothermal brines have been confirmed as the two main fields of application. Regarding the latter, the presence of monetary subsidies is making attractive the exploitation of geothermal brines with temperatures as low as 100°C, but it is mandatory to maximize the plant efficiency in order to payback the relevant cost of exploration and drilling. Efficiency of low-medium temperature geothermal plants can be enhanced: (i) by realizing a two evaporation level cycle able to reduce the irreversibilities in the heat introduction process, (ii) by lowering the condensation temperature and (iii) by increasing the turbine efficiency. Exergy Spa has recently installed a number of geothermal plants in Turkey where the three aforementioned precautions are considered in the system design. In addition, Exergy has introduced in the ORC market an interesting innovation by developing a radial outflow turbine that has several unique characteristics qualifying this unconventional configuration as advantageous for many ORC applications.

Compared to axial and centripetal turbines radial outflow turbines can accommodate many stages on the same disk allowing for a lower stage loading and a high expansion efficiency without incurring in rotor-dynamics issues. Moreover, their particular design allows to easily handling very high volume flow ratio thanks to the increase of stage radius along the expansion: blade height offers lower variation over the radius, resulting in higher blades in the first stages and lower blades in the last ones, with beneficial effects on expansion efficiency. A further interesting feature is the constant peripheral speed on the blade, allowing of the us of prismatic blades.

In spite of the rising interest in this configuration, nowadays only few experimental data are publicly available. This paper provides some experimental results on the performance of the radial outflow turbine in two different geothermal plants which have been in operation for several thousands of hours (> 10.000 h).

Nomenclature and acronyms

η	efficiency
PH	pre-heater; it can be on High Pressure Cycle (PH_{HP}) or on Low Pressure Cycle (PH_{LP})
EVA	evaporator; it can be on High Pressure Cycle (EVA_{HP}) or on Low Pressure Cycle (EVA_{LP})
TUR	turbine; it can be on High Pressure Cycle (TUR_{HP}) or on Low Pressure Cycle (TUR_{LP})

PLANT DESCRIPTION

Both the plants investigated in this paper have double evaporation levels cycles. Figure 1 depicts their layouts and the instrumentation installed. The first plant (named GREENECO) exploits a geothermal brine flow at 140 °C, producing 13 MW of electrical power. It is designed with two independent saturated cycles working with isopentane at two different evaporation pressures. The high pressure cycle is recuperative and has two preheaters in series (PH1HP and PH2HP) where the working fluid is heated cooling down the geothermal brine. On the contrary the low pressure cycle is non-recuperative and has a single preheater (PHLP). The geothermal brine flows through the high pressure evaporator (EVAHP), the high temperature preheater of the high pressure cycle (PH1HP) and the low pressure evaporator (EVALP); finally it is split in two parallel streams flowing in the low temperature preheater of the high pressure cycle (PH2HP) and the preheater of the low pressure cycle (PHLP). Saturated vapor is expanded in both cycles by a radial outflow turbine (TURHP and TURLP). Both turbines are mounted on the same line shaft connected to a single generator in a double-ended configuration. Both cycles are condensed by a loop of cooling water connected to wet cooling towers for the heat rejection to the ambient.

The second plant (named AKCA) is designed to produce 3.6 MW cooling a low temperature geothermal brine from 105°C down to 60°C. This plant fully exploits the capability of a radial outflow turbine having a double admission: this configuration allows for a clear advantage compared to an overhung axial configuration because it does not require two separate turbines, having all the stages mounted on the same disk. R245fa is firstly pumped up to the maximum cycle pressure, then after a first preheating (PH1) the mass flow rate is split in two streams, one is laminated down to the low pressure and evaporates (EVALP), the other is further heated in a high temperature preheater (PH2) and then it evaporates at high pressure (EVAHP). A fraction of the geothermal brine is derived just before the reinjection and it is heated up by a stream of a CO_2 rich geothermal steam and then mixed before the low temperature preheater (PH1). The cycle is water cooled condensed.

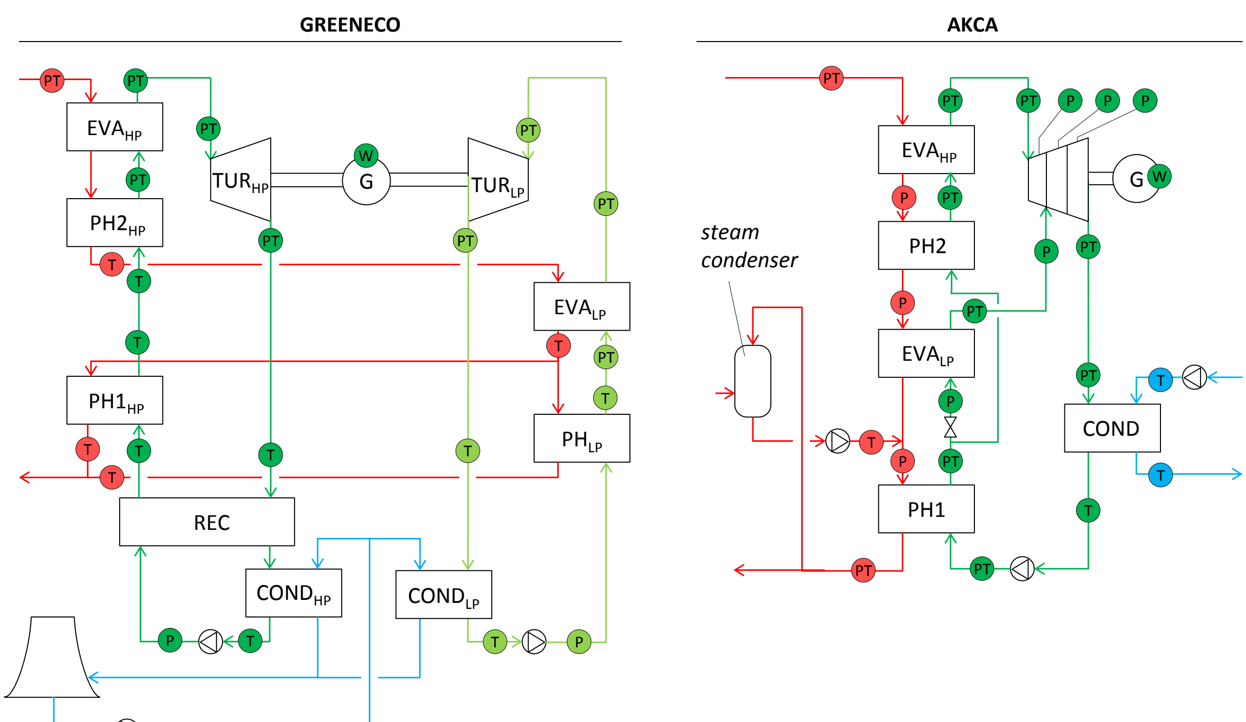


Figure1. Plant schemes of GREENECO plant (left) and of the AKCA plant (right) with information about the field instrumentation

Figure 2 depicts the aerial view of the two plants: in both case preheaters are shell&tubes heat exchangers while evaporators are kettle reboilers. Condensers are common shell&tubes with cooling water in the tubes, while the recuperator is arranged as a bundle of finned tubes enclosed in a vessel.

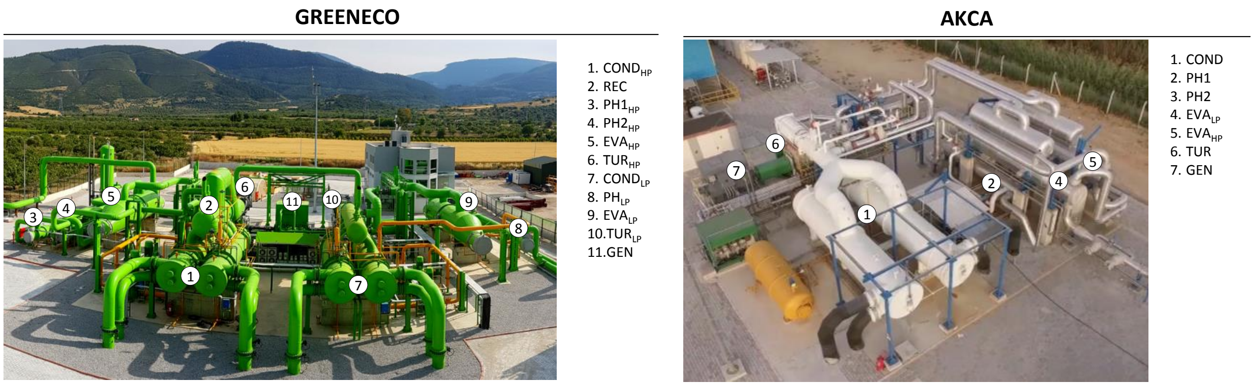


Figure 2. Aerial view of GREENECO and AKCA plants

EXPERIMENTAL CAMPAIGN AND DATA SET DEFINITION

As shown in Figure 1, the two plants are provided by adequate field instrumentation for temperature and pressure measurements both on brine and organic fluid streams. Thermodynamic state can be evaluated for most of the streams and energy balances can be verified for most of the components. Moreover, a high accuracy measure of produced electrical power is available. To increase precision of measurement of data acquisition, some measures are redundant.

For both plants, a 20 minutes interval in stable condition has been selected and data are sampled every second for GREENECO plant and every 5 seconds for AKCA plant.

Figure 3 depicts the trend of some quantities during the experimental campaign in GREENECO and AKCA plants. For the latter there is also a comparison between data from field instrumentation and from the instruments with higher accuracy, in order to expand the statistical samples and to reduce possible systematic errors of measurement. Moreover, for AKCA plant, the energy production in the sampling period has been checked comparing the measurements from a field watt-meter and by an energy-meter at grid input point. The relative difference is 0.274% showing a high reliability of the power output measured by field instrument.

DATA SET DEFINITION AND PRELIMINARY CHECK

For the calculations the average value of each measured quantity is used; for some redundant measurements the mean value between the two reference ones is used. In GREENECO plant it is found a small superheating at both high pressure and low pressure evaporators outlet, while for AKCA plant no superheating is observed at both levels, in accordance with the use of a demister. Same check is done at condenser hotwell comparing the measured temperature with the saturation temperature at condenser inlet pressure. In all the cases small subcooling temperatures were found.

METHODOLOGY

Both for GREENECO and AKCA case, the lack of some point of measurement and the absence of direct measures of mass flow rate do not allow the validation of the complete energy balance. For this reason, a number of assumptions and the use of additional data related to turbine and heat exchangers design are required in order to validate the experimental dataset and to calculate the performance of the components. The methodology adopted for each plant is described below.

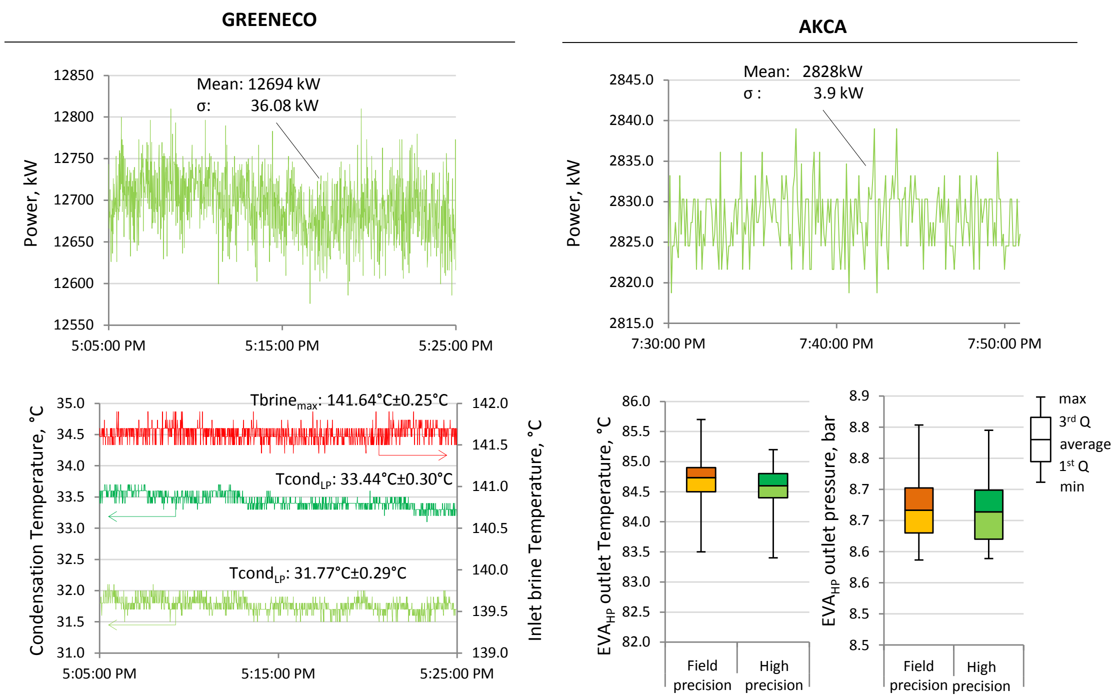


Figure 3. Trend of data set collected in the experimental campaign. GREENECO is close to nominal point while for AKCA plant power production is lower than the nominal because of a lower brine mass flow rate and temperature.

For GREENECO plant the following procedure is used:

- Missing values of brine pressure are evaluated assuming an homogeneous repartition of the overall pressure drop among the heat exchangers. Same approach is followed for HP fluid where the total pressure drop between pump outlet and evaporator inlet is assumed equally divided between REC, $PH1_{HP}$ and $PH2_{HP}$. Organic fluid pump efficiency is set equal to 0.75 and we verified that the effect of different assumed values is negligible on the overall energy balance[1].
- HP and LP fluid mass flow rate is calculated from the TUR inlet condition and considering chocked flow in the outlet section of the 1st stator vanes. Geometrical data of turbine (row radius, number of blades, gauging ratio, fillet factor) were measured by Exergy during turbine manufacturing. The calculated value of mass flow rate is in good agreement with the result of an independent 3D CFD calculation made by Exergy on the same turbine.
- The overall energy balance of EVA_{HP} and $PH2_{HP}$ components is imposed: neglecting heat losses a first value of the brine mass flow rate is calculated.
- Energy balance of EVA_{LP} is imposed finding a second value of brine mass flow rate.
- Energy balances of $PH1_{HP}$ e PH_{LP} are imposed and a third value of brine mass flow rate is obtained.
- Turbine shaft power is computed by two alternate methods: (i) from electrical power output of generator considering shaft mechanical losses measured by Exergy in test bench and generator efficiency provided by generator manufacturer and (ii) from the product of mass flow rate and enthalpy drop across turbine.

A minimization process is then applied: the objective function is the sum of the percentage differences among the three mass flow rates and between the two power output and the optimizing variables are the measured temperatures used in the calculations. It is found that changing brine and isopentane measured temperatures from the instrumentation, within a range of ±0.25°C, it is possible to reduce all differences down to less than 0.1%. Turbine efficiencies are equal to 85.5% and 88.4% for high and low pressure machine respectively.

[1] Varying the value of pump efficiency by ±10% leads to variation lower than 0.15% on the overall heat balance

For AKCA plant the following procedure is used:

- The high pressure mass flow rate is calculated as previously explained for GREENECO plant knowing the inlet conditions and the geometrical data of the first stator.
- Thanks to the use of additional high precision temperature probes, the energy balance of EVA_{HP} component is imposed and the brine mass flow rate is calculated
- Energy balance of PH2 is evaluated and the error for the heat balance is calculated
- A tentative value of the efficiency of the first turbine stage is assumed to calculate the thermodynamic state of the discharged flow from first stage. Since brine temperature ad EVA_{LP} outlet is not measured because the lack of the thermowell in the piping a pinch point temperature difference (ΔT_{pp}) is assumed and a first value of low pressure mass flow rate is calculated through the energy balance of EVA_{LP}. The mixing between the low pressure vapor from EVA_{LP} and the fluid expanded from turbine first stage allows calculating the second stage inlet thermodynamic conditions. Total mass flow rate expanded by low pressure stages is calculated as in the previous cases allowing to calculate a second value of low pressure mass flow rate. The two values are compared and the error is set to zero by varying the assumption on ΔT_{pp}.
- The mass and energy balance of brine mixing process after EVA_{LP} is imposed allowing to calculate the mass flow rate of the brine coming from the steam condenser and the mass flow rate of brine entering in the PH1 component
- Energy balance of PH1 is evaluated and the error for the heat balance is calculated
- Generator electrical power output is then computed considering mechanical losses measured by Exergy in test bench and generator efficiency provided by generator manufacturer. The error between the calculated and the measured values of power output is finally calculated.

In the validation process, three errors are calculated: two for the energy balance of PH1 and PH2 components and the third between the calculated and the measured electrical power. These errors are minimized by changing the assumed value for turbine efficiency. It is found that with an efficiency of 92% the convergence of all the errors is reached. The efficiency value in this case is particularly high and the turbine over performs respect to the design.


OPEN
CLOSE

RESULTS AND DISCUSSION

For both plants the experimental data are validated with an iterative procedure aiming at reducing all the errors related to energy balance in components and produced electrical power. It is found that in both cases the experimental data set is consistent and it allows to calculate the missing values by means of the energy balance and of the geometrical data for the turbines 1st stator. Figure 4 depicts the temperature-heat diagrams for the heat introduction process in both plants with the repartition of the heat introduced between the different components. Very low pinch point temperatures differences are obtained highlighting the choice to adopt very large heat exchanger surface in order to increase system efficiency.

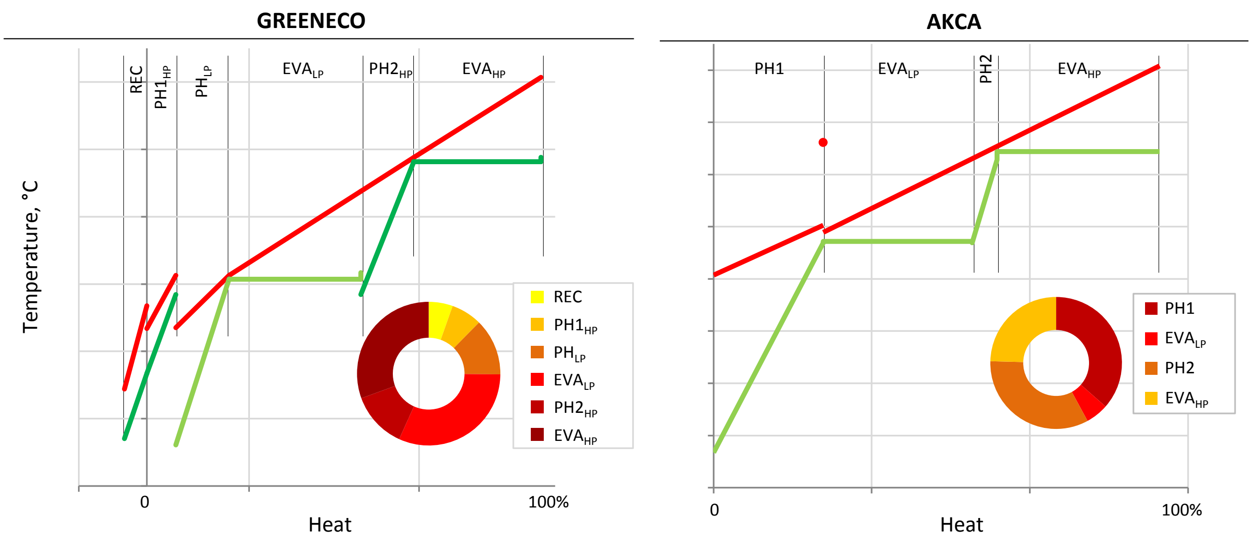
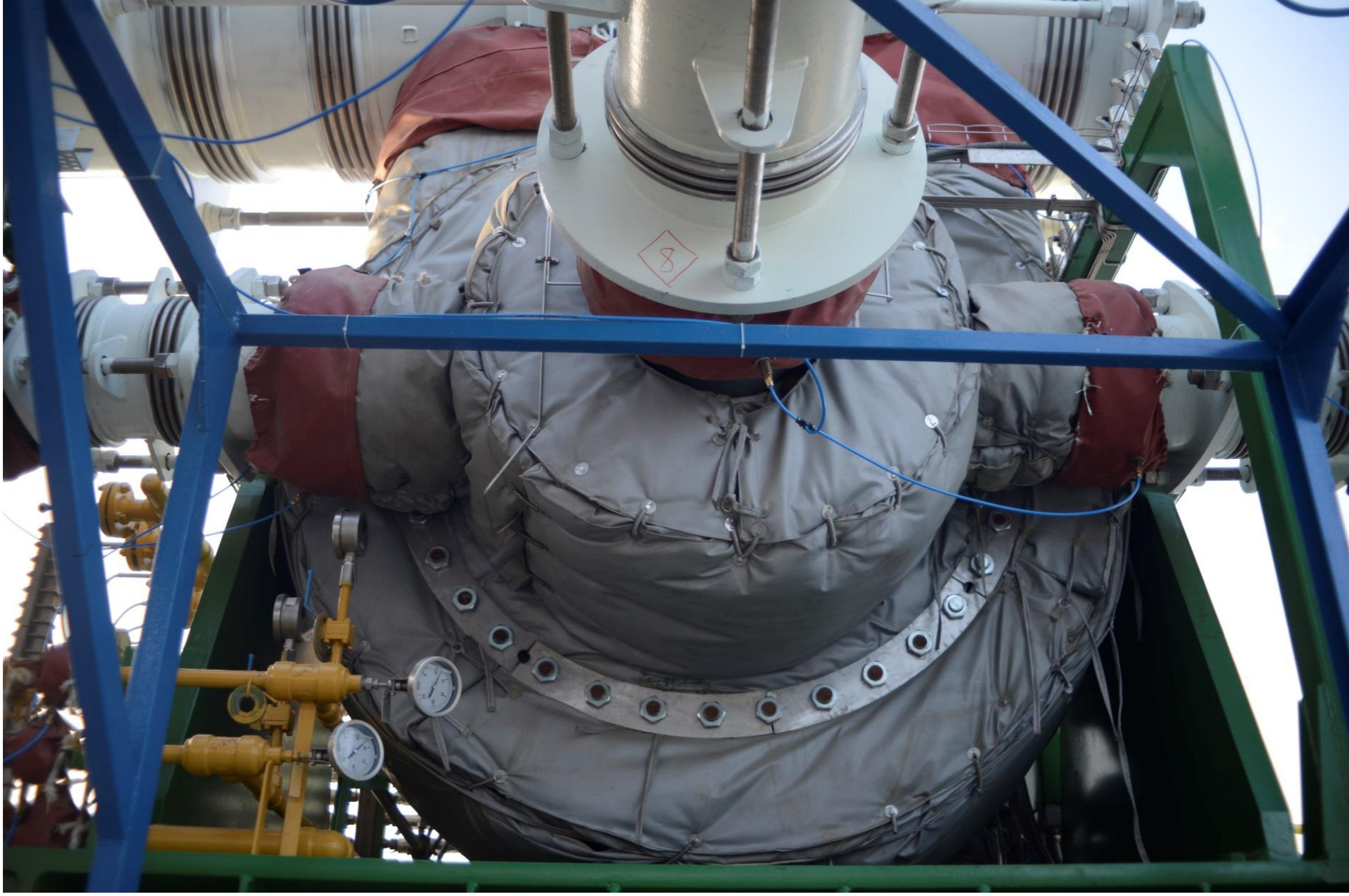


Figure 4. T-Q diagrams for the introduction process for GREENECO and AKCA plants

CONCLUSIONS

The turbine isentropic efficiency could be simply computed from values of inlet and outlet thermodynamic conditions of the working fluid. However, this procedure cannot be applied for steam turbines, since the expansion usually ends inside the saturation line and is not possible to measure the steam quality at outlet conditions. Also in open cycle gas turbines the procedure is not possible, since inlet turbine temperature are too high for temperature probes and the expansion is far from adiabatic, being strongly cooled. In ORC turbines the procedure is possible, but the small temperature drop across the turbine can leave uncertainties about the precision of the calculated value.

With the procedure adopted in this paper, the found values of isentropic efficiency are guaranteed on the basis of the validation of a large set of experimental data, including direct electrical power measurement.



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