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Radial Inflow Turbines for Kalina and Organic Rankine Cycles

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ABSTRACT

Cryostar has been a world leader in radial inflow turbine technology for more than 30 years but is a relative newcomer in the geothermal business.

Experience gained during the design and production of two turbo-expanders coupled to a generator for binary cycles has shown that standard expanders can easily be used for geothermal or heat recovery applications.

The Main concern of the corrosion resistance of turbine elements against a corrosive working fluid like ammonia-water mixture can be solved with a rigorous selection of materials.

The other concern is about sealing gas management in a close cycle loop. The Dry Gas Seal solution allows the seal gas flow to be decreased to very low values. The recompression of the leaking gas back into the cycle offers a zero leakage system.

Process data for binary cycles are ideal for radial inflow turbines: pressure ratios, flows and temperatures ensure an operation very close to the maximum achievable isentropic efficiency. Other losses in gear boxes, generator and bearings typically do not exceed in total 10% of the total isentropic enthalpy drop. For this reason the larger units can recover almost 85% electricity compared to the total isentropic enthalpy drop.

Another benefit in using radial inflow turbine in standard execution with variable inlet nozzles is the ability to smooth seasonal variations inherent to geothermal process. In fact, this device can be used to control the flow widely through the expander without wasteful throttling. All the expansion energy in the nozzles and wheel is recovered almost at constant isentropic efficiency throughout the year.

The advantages of operating at higher pressure levels and with lighter organic fluid than usual are explained. It increases the recovered electrical power, whilst decreasing the expander frame size and its price.

In most of the cases there is a large benefit to optimise the binary cycle process data together with the turbine design to offer the best net cycle efficiency.

1 INTRODUCTION

The need to produce energy which does not negatively influence the environment is now widely recognised. Geothermal energy is one of the rare means to produce carbon-dioxide-free electricity.

Today most of the geothermal power plants built are of binary type (Di Pippo, 2005). In a binary power plant, the geothermal water is passed through one side of a heat exchanger, where its heat is transferred to a second (binary) liquid, called a working fluid. The working fluid boils to vapor which is expanded through the turbine coupled to generator. It is then condensed back against ambient air or cooling water to a liquid and pumped back to the inlet of the evaporator. The geothermal water passes only through the heat exchanger and is immediately recycled back into the reservoir.

The working fluid can be either a hydrocarbon like isobutane, isopentane, propane or a mixture of these components.

The so called Kalina cycle using ammonia/water mixtures has been developed to attain higher thermal efficiency than Rankine cycle. The variable boiling point nature of this binary fluid at a specified pressure enables more heat to be extracted especially for a low enthalpy geothermal source (Borgert & Velásquez , 2004).

Cryostar has been a world leader in radial inflow turbine technology for more than 30 years. Its installed base of generator loaded turbines comprises over 130 units and more than 60 MW installed, including 20 machines on natural gas distribution networks. The natural gas installations have so far provided customers with more than 1000 GWh of recovered electricity.

Cryostar is a relatively newcomer in the geothermal activity, but is the selected supplier of turboexpanders for some European on-going projects based on both Kalina and Organic Rankine cycle technologies.

2 MAIN FEATURES OF A TURBOEXPANDER

Designing and building turboexpanders for binary cycles like Organic Rankine or Kalina did not required special developments. Standard equipment can be used as long as the compatibility between materials and working fluid is taken into account.

E.g. for Kalina cycle with Ammonia/water mixture, the use of copper and aluminum is prohibited. Therefore an expander wheel in Titanium is chosen to avoid any corrosion problems.

Description of the main features of a turboexpander coupled to a generator is outlined hereafter.

2.1 General

The turboexpander/generator system can be split into the following functional subsystems / modules:

(1) Turbine protection

(2) Turboexpander and associated auxiliaries

(3) Seal gas system

(4) Generator

(5) Connection to the grid

(6) Control System

(7) Isolation, inerting, purging

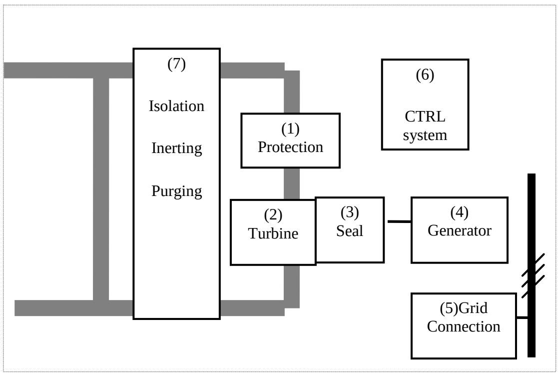

Figure 1: Simplified scheme of main modules of a turbo-expander coupled with a generator

2.2 Turbine protection

2.2.1 Quick closing valve

In case of critical condition that may lead to turbine or generator damage (such as generator trip, expander over-speed, low lube oil pressure, etc.), the unit has to be shut-down in an emergency. This is performed by closing the inlet quick closing valve (QCV) in about 500 ms.

The QCV is fail closed by loss of electrical signal as well as by lack of pneumatic supply.

This valve is equipped with a positionner to avoid overspeed by controlling the opening of the valve at turbine start up.

2.2.2 Expander inlet strainer

The Expander inlet strainer protects the machine from any damage coming from debris or particles.

2.3 Turboexpander and associated auxiliaries

2.3.1 Turboexpander

The turboexpander is a proven cartridge conception which allows quick replacement of the machinery capsule including the rotating parts without interfering with the process pipes. The turboexpander is of radial inflow type.

2.3.2 Lube oil system

The lube oil (LO) system is essential for the proper operation of the turboexpander.
It provides common lubrication for the expander and the gear box. It is a closed loop with a vented lube oil sump. The generator LO system is independent (self lubricated bearings or dedicated lube oil loop).

The main components of the lube oil systems are:

- oil tank with electric immersion heater - The lube oil tank constitutes a lube oil provision and allows correct lube oil recycling. The oil tank can withstand a slight over pressure induced by seal gas leakage which comes from the turbine & gearbox bearings.
- two circulating oil pumps - One is driven by the speed reduction gear and is used as the main operation pump, the second one is an electrical auxiliary pump. This pump is a start up and a standby pump. For start-up and emergency cases, the electric motor driven pump will operate in parallel with the mechanical driven pump.
- one oil cooler and temperature control valve - The oil / water exchanger cools the lubricating oil which is heated by the bearings and gears frictions. The oil temperature at the turbine inlet is regulated by a temperature control valve.
- dual oil filter
- differential pressure control valve - The pump's discharge pressure is controlled by a differential pressure control valve to maintain a constant pressure difference across the turbine & gearbox bearings.
- pressure safety devices (transmitter, relief valves…). The relief valves ensure the pressure limitation in the whole lube oil system.

The Operation pressure level is maintained by a small compressor which recompresses the ORC working fluid back into the cycle.

Protection against overpressure in the lube oil tank is ensured by several pieces of equipment calibrated according to different operation levels:

- First level: alarm generated by pressure transmitter ensuring a constant pressure measurement
- Second level: solenoid valve opening
- Third level: pressure safety valve setting
- Final level: burst disk cracking. This safety device is used only in case of catastrophic failure of the system, as it vents gas to the atmosphere.

2.3.3 Nozzles

A system of vanes (adjustable nozzles) is located around the expander wheel and is used to control the working gas flow and the power of the generator by changing the flow area.

The nozzle vanes offer a simple construction, with shock free flow acceleration and provide the widest possible flow range.

Vanes are pivoted around one of its mounting bolts in clockwise and counterclockwise directions.

This adjustment is done by means of a lever system operated by a pneumatic actuator with I/P transmitter.

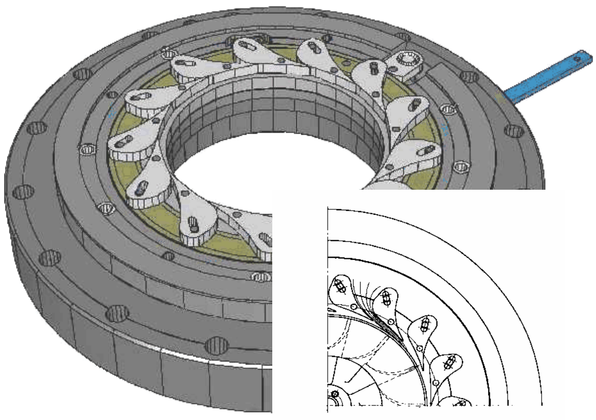

Figure 2 : 3D and 2D views of nozzles mounting

The variable nozzles, from a control point of view, act just as a throttle valve does, but without throttling losses. Conventional flow control instrumentation can be used to operate them.

As emphasized in § 4.2., the variable nozzles allow an optimization of the working gas flow through the expander thus the ability to run the expander at a good efficiency level whatever the process conditions.

2.3.4 Seal gas system

The seal gas is applied between the expander wheel and the bearing, so that no lube oil mist migrates into the process stream and no process gas is lost.

For binary cycles, the seal gas arrangement is usually a Dry Gas Seal system.

The sealing mechanism consists of two rings: a stationary (plain face) and a shaft-mounted rotating face with grooves. On rotation, the groove continuously pumps the seal gas into the reducing cavity. Based on the seal groove geometry, the working gas film thickness between rotating and stationary seal faces typically varies from 3 to 8 µ.

Generally the source of the seal gas is the working fluid at the inlet of the expander. Two flows are necessary: a small flow of process gas to feed the dry gas seal and a higher flow (separation gas) to avoid contamination of the dry gas seal by the oil. Figure 3 depicts such arrangement with isobutane as the Organic Rankine fluid.

Both seal gas flows are regulated by:

- the differential pressure between expander back wheel pressure and the injection pressure by means of a differential pressure control valve.

- the differential pressure between leakage recovery line pressure and the injection pressure by means of a differential pressure control valve.

The seal gas leakage must be evacuated from the lube oil tank.
Oil traces are removed using a coalescent filter and the clean gas is recompressed to be re-injected in the cycle at the lower pressure which is the inlet of the condenser.

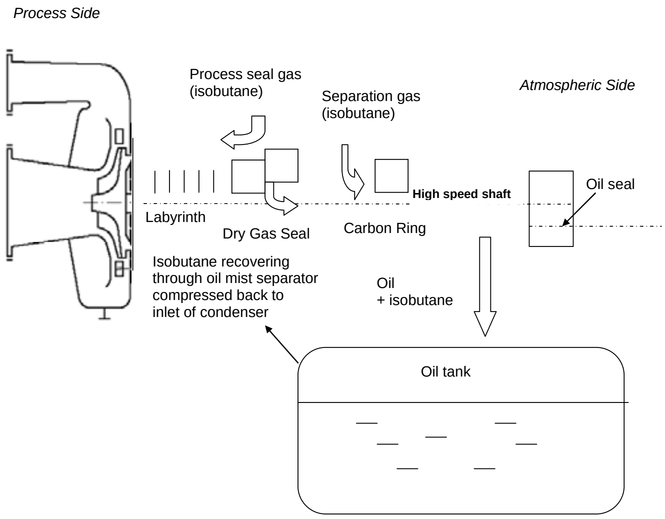

Figure 3 : Schematic view of the sealing gas system

2.3.5 Gear box

The expander rotates at a higher speed than that of the generator. Therefore it is mandatory to reduce the shaft speed to respectively 1500 or 3000 rpm for 4 poles or 2 poles 50 Hz generator (1800 or 3600 rpm for 4 poles or 2 poles 60 Hz generator).

An epicyclic or planetary gear box is usually the preferred option.

The input and output shafts of these gears are coaxial, allowing compact turbine packages. Since power is transmitted via three or more planet gears, epicyclic gears use less space (up to 20% less) and are lower in overall weight (up to 50% less) than parallel shaft gears.

The performances are better for planetary gears especially for high gear ratio (ratio of rotational speed of high speed shaft and low speed shaft). The lack of high-speed bearings contributes to higher efficiencies. These bearings are the main contributors to power losses in parallel shaft gears.

Generally the losses of such gear boxes are in the range of 1.5 to 2 % of the shaft power.

2.4 Generator and connection to the grid

2.4.1 Principle

The generator can be either synchronous or asynchronous type. The synchronous generator rotates at synchronous speed and needs electrical excitation to produce electricity. The asynchronous or induction generator rotates faster than the synchronous speed and generates electrical power by electrical induction.

2.4.2 Synchronizing of induction generator

As there is no voltage at the generator terminals when the turbine is started, the generator accelerates power free. The connection to the grid is performed at the end of the acceleration phase at a frequency slightly below the synchronous frequency (generator is operated for a very short time as a motor). In this case the inrush current when the circuit breaker is closed is limited, below the generator nominal current.

2.4.3 Loading

The loading of the generator is performed by the turbine mechanical power given to the generator when the generator is connected to the grid (the frequency of the generator is fixed mainly by the grid).

The turbine mechanical power is controlled by acting on the variable nozzle of the expander at a given process state (inlet/outlet pressure, etc.). The more the inlet guide vanes are open, the more electrical power is produced by the generator.

The asynchronous generator consumes reactive power when it produces electrical power. The amount of consumed reactive power depends on the machine construction and varies with the electrical power produced by the generator.

2.4.4 Protection

The electrical protection of the generator is achieved by a numerical multifunction protective relay. Furthermore, the generator is equipped with windings and bearing temperature sensors that give an alarm and trip information in case of excessively high temperature.

In case of fault detection, the turbine will trip.

2.5 Control System

The primary objective of the turboexpander control system is to ensure the generated power of the ORC or Kalina cycle.

The optimized power generation is controlled indirectly by controlling the expander inlet pressure under normal conditions by the opening of the expander inlet nozzles.

A by-pass valve has been provided to prepare the correct process conditions for expander start-up and to pick-up load from the expander in case expander trip during normal operation. In this case the by-pass valve will prevent process upsets.

2.6 Isolation, inerting, purging

2.6.1 Turbine isolation

During the normal stop or emergency shut down of the turbine, the expander inlet shall be isolated.

This operation is done by using an automatic quick closing valve.

Isolation of the expander outlet has to be done by an automatic isolation valve to stop the constant seal gas leakage and thus, progressively depressurize the machine.

Moreover, for maintenance purposes, process manual isolation valves have to be implemented on suction and discharge lines of the turbine.

2.6.2 Inerting, Purging

During the first start up of the expander and after a long stop of the machine, inert gas (such as nitrogen) shall be used for purging the turbine and the gear box.

For this operation the quick closing valve and the variable nozzles are set closed. The process isolation valves (customer scope) are set closed too.

A dedicated purge valve connected to machine and gearbox casings is provided for this purpose. The purge gas can be evacuated through the vent line to the top of the oil tank.

3 BASICS OF EXPANDER DESIGN

3.1 Elements of radial inflow turbines

A Radial inflow turbine is a robust design which is a standard in air separation plants, recovery of condensables from natural gas, liquefaction of gases and power recovery.

Expanders are used because they are in an advanced state of development and have proven reliability for high efficiency, Perry (1999).

The main components of such radial inflow turbine are described in figure 4.

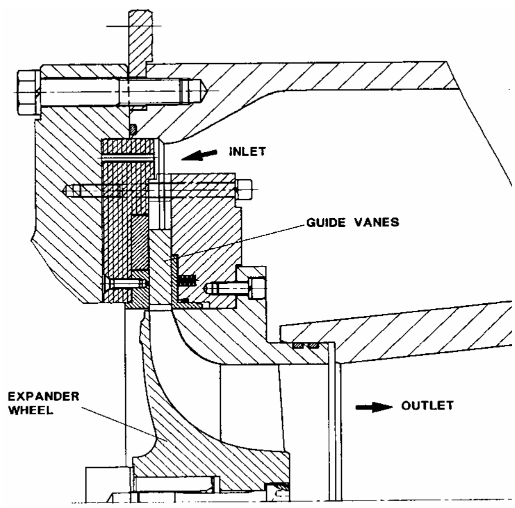

Figure 4: Cross section of expander wheel of radial inflow turbine showing the flow passages from inlet to outlet.

1/ A high pressure barrel housing from which the gas first expands through **guide vane or nozzles** arrangement that is located in the circumference of the wheel.

2/ The gas is accelerated in the guide vanes and enters the **turbine wheel**. It converts the kinetic portion of energy contained in the gas by means of deflection into mechanical energy.

3/ The gas leaves the wheel axially at the low pressure level and subsequently passes through the **discharge diffuser** where velocities are converted into pressure and reduced to normal pipeline velocities.

4/ The power generated by the wheel is given to a **shaft** which runs in high speed **bearings**. This power can be recovered by driving a compressor or a generator.

3.2 Designing for the best efficiency

3.2.1 Optimum velocity ratio

The expander wheel must be designed at optimum ratio of blade tip speed and spouting velocity U/C_0 which represents the shape of the velocity triangle in the inter-space between nozzle exit and rotor inlet

U = tip speed (m/s) is the rotating speed of the blades at the furthest extremity from the rotating axe

C_0 = spouting velocity (m/s) is the magnitude of the absolute velocity vector at nozzle exit under isentropic conditions (*i.e.* no losses in the nozzle passage)

$$C_0 = \sqrt{2000.\Delta H_{is}} \qquad (1)$$

With ΔH_{is} isentropic enthalpy drop in kJ/kg

The velocity ratio is mainly used to show the off-design performance of an expander.

Figure 5 shows a typical expander performance curve for different expansion ratios and nozzle openings.

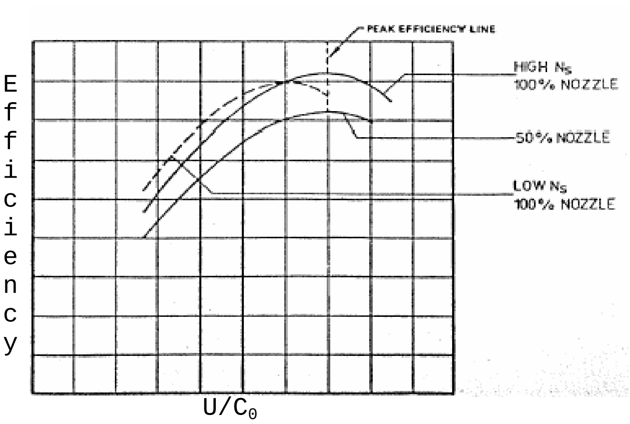

Figure 5: Efficiency as a function of velocity ratio

3.2.2 Optimum specific speed

The expander wheel must be designed at optimum specific speed N_s which represents a shape factor for the passage of the wheel

$$N_s = \frac{76.N}{1000} . \sqrt{\frac{Q_{out}}{\sqrt{\Delta H_{is}{}^3}}} \qquad (2)$$

With N the rotational wheel speed in rpm and Q_{out} the volumetric flow rate at the outlet of the expander in m^3/s.

Figure 6 below from Balje (1980) describes the range of specific speeds for different expander types.

For radial inflow type, the design is always performed in the dotted area rectangle where the efficiency is the highest.

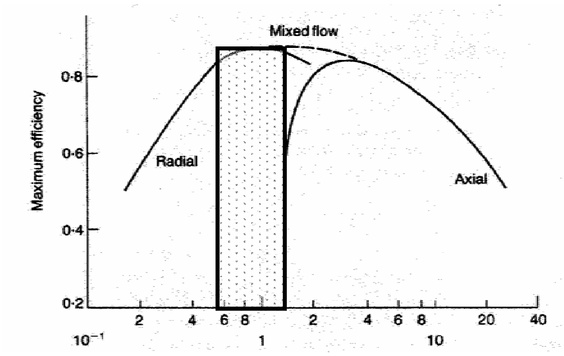

Figure 6: Efficiency as a function of a dimensional n_s (n_s = 0.18892 x N_s) for radial, mixed flow and axial turbines.

3.2.3 Determination of wheel diameter and speed

The turbine is designed for an optimum value of the specific speed and velocity ratio.

When process data is known (expander inlet and outlet pressures, flow and inlet or outlet temperatures) it is possible to calculate the ideal wheel diameter and speed to give the optimum velocity ratio and specific speed which lead to the best efficiency.

For Organic Rankine and Kalina cycles, process data (pressure ratio and flow) ensure, most of the time, that the design of the expander can be performed to offer the best efficiency.

Figure 7 describes the efficiency obtained for some of turboexpanders coupled to a generator offered by Cryostar. The rectangle focuses on the expanders only dedicated to Organic Rankine and Kalina cycles.

It is clear that the isentropic efficiency is in the range 0.82-0.90.

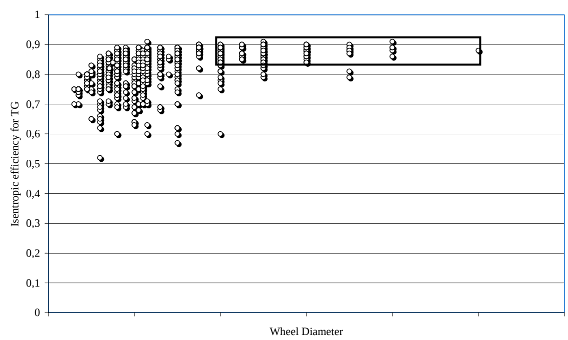

Figure 7: Wheel isentropic efficiency *vs* wheel diameter for different expanders, rectangle located on the expanders designed for Organic Rankine or Kalina cycles.

3.3 Total efficiency: electricity recovered

The losses of the expander wheel have been described above. But other losses must also be taken into account, to calculate the total electricity which can be recovered by the expander.

3.3.1 Bearing losses

High speed machinery operating under low to medium loads like turboexpanders use tiling pad type for journal bearings. They offer the optimum in rotor stability (due to their exceptional stiffness and damping characteristics) and provide the solution to the problem of oil film instability.

The losses of such bearings are in the range 40-100 kW for 1000-8000 kW expander shaft power.

3.3.2 Gear box losses

As described in § 2.2.1, they are in the range 1.5 to 2% of the shaft power.

3.3.3 Generator efficiency

It is dependant on many parameters like: atmospheric conditions, asynchronous or synchronous type, power output, number of poles…

It can be generally said that, at rated power, the efficiency is in the order of 0.95 to 0.9~~8~~7.

3.3.4 Total electricity recovered

Like for all mechanical equipment, the larger the size or the power of the expander, the lower the specific losses.

Figure 8 describes the recovered electricity from the isentropic expansion (total electrical efficiency) for two expander frame sizes.

These values are only typical and may vary depending on the process data and the working fluid chosen.

The order of magnitude is between 0.75 and 0.85 of the total isentropic enthalpy drop through the expander.

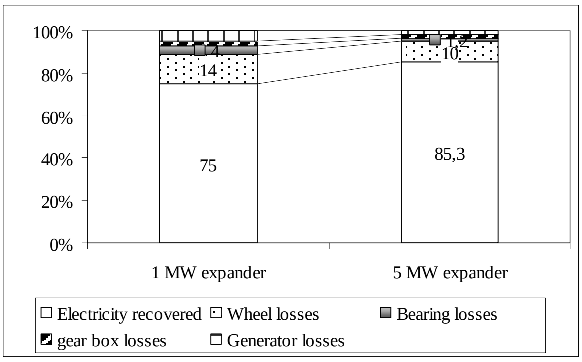

Figure 8: Typical percentage of electricity recovered and losses of a turbogenerator (basis 100% = isentropic enthalpy drop through the expander)

4 ADVANTAGES OF RADIAL INFLOW TURBINES FOR GEOTHERMAL CYCLES

4.1 Off design points – seasonal variations

Calculations and estimations of total efficiency as described above are only valid for the design point. When studying off-design process data, the performances of the expander must be recalculated.

This is often the case for geothermal projects where winter and summer conditions must be taken into account. For such projects, most of the time, air cooled condensers are used, because there is not enough cooling water available on site.

Therefore in summer, the temperature is high in the northern hemisphere, leading thus to a high condensing pressure then to a low pressure ratio over the expander and finally to a lower electrical output than in Winter.

There are different means to smooth the seasonal variations by using variable speed process pump on the binary cycle as well as a variable speed aero-cooler.

Nevertheless it is almost impossible to keep constant process conditions, mainly pressure ratio and mass flow, through the expander throughout the year.

In this case there is a big benefit in using radial inflow turbines fitted as standard with variable inlet nozzles. In fact, this device can be used to control the flow widely through the expander without wasteful throttling. All the expansion energy in the nozzles and wheel is recovered almost at constant isentropic efficiency throughout the year.

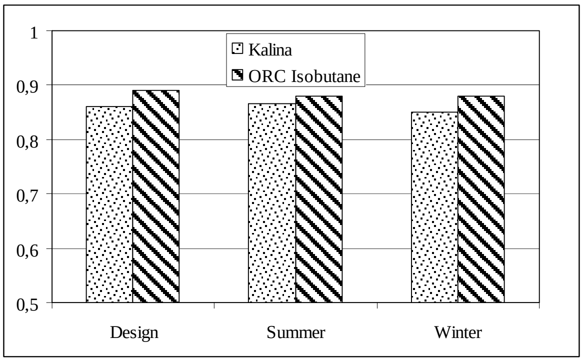

Figure 9: Isentropic efficiency for off-design cases of expanders used in Kalina or Organic Rankine cycles

As shown in the figure above it is possible to run the whole cycle to almost the design maximum efficiency thanks to the expander inlet nozzles and variable speed equipments (working fluid pump and aero-condensers) used in the closed cycle.

4.2 Increasing power recovery with high pressure operation

Historically turbines used for binary cycles were axial type turbines derived from steam turbine design. They expand high molecular weight working fluid like isopentane which condense at atmospheric pressure. Thus pressure ratio is limited across the turbine if a single stage design is considered.

With radial inflow turbine, there is a big benefit in operating the cycle as close as possible to the critical pressure of the working fluid as shown in table below.

Calculations are made for constant geothermal brine mass flow and temperatures

Working fluid	Inlet pressure (bara)	Outlet Pressure (bara)	Frame size	Cycle Net Power (MW)
Isopentane	9	1.1	700	2.1
Isobutane	35	3.6	500	3.2
Propane	42	8.7	300	3.5

There is always a gain in operating at a high inlet expander pressure. Of course the balance should be made between the capital cost and electricity recovered.

With high pressure operation, piping diameters as well as expander frame size are reduced. The main heat exchanger offers better heat transfer which allows the increase of working fluid superheating after the evaporator with a limited increase in heat exchange surface area.

The motive fluid pump size and power also increases as does the cycle net power as shown in table above.

The process engineer should make sure to maintain the pressure below *ca* 44 bar to stay in “reasonable” piping class like 300 lbs for carbon steel. This will help to limit the piping cost.

It should be noted the high pressure is not a problem for the expander. As an example more than 50% of the turbines quoted by Cryostar had an inlet pressure above 35 bar.

5 CONCLUSION

A review of the main features of a turbo-expander has shown that their use for binary cycles did not require special developments and that standard radial inflow turbines can be used with minor modifications for both Kalina and Organic Rankine cycles.

Operating the expander at pressure close to critical pressure with light hydrocarbons allows to the recovered electrical power to be maximized the expander frame size to be decreased.

In most of the cases there is a large benefit to optimise the binary cycle process data together with the turbine to offer the best net cycle efficiency.

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