Kalina & Organic Rankine Cycles: How to Choose the Best Expansion Turbine ?

Dr Frédéric Marcuccilli, Senior Process Engineer

Hervé Mathiasin, Sales Engineer

Electricity generation from Enhanced Geothermal Systems

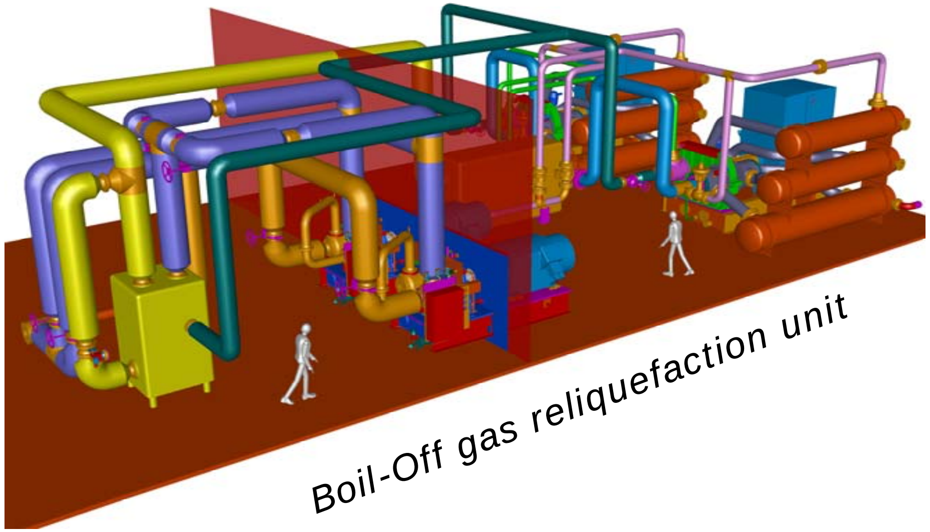
Strasbourg 14-16th of September, 2006

www.cryostar.com frederic.marcuccilli@cryostar.com

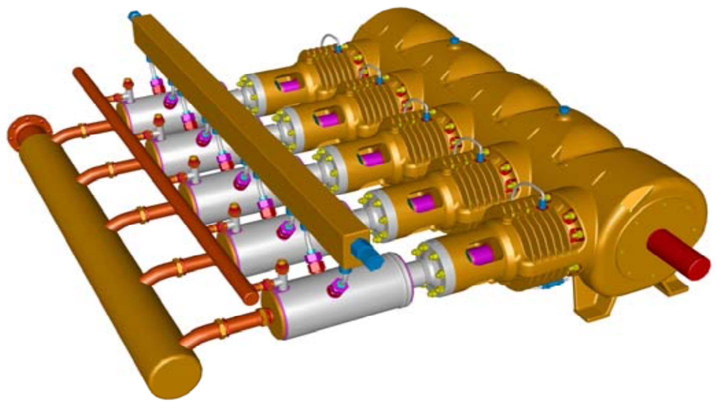
Contents

- ★ 350 employees
- ★ 145 Million € turnover in FY 2006
- ★ 90 % export
- ★ 15 Million € investments in 2005-07
- ★ Part of the new THE LINDE GROUP

Skid mounted HC turboexpanders



Boil-Off gas reliquefaction unit



High pressure reciprocating pump

Recognised as worldwide experts in the following areas:

★ Industrial gases

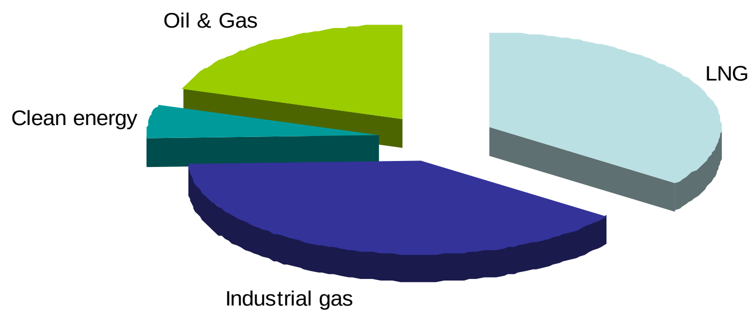
No.1 in the application of cryogenic and industrial gas pump sectors

★ Oil & Gas

One major supplier of turbo-expander/compressors in oil & gas treatment (HC dewpointing, ethylene plants)

★ LNG carriers

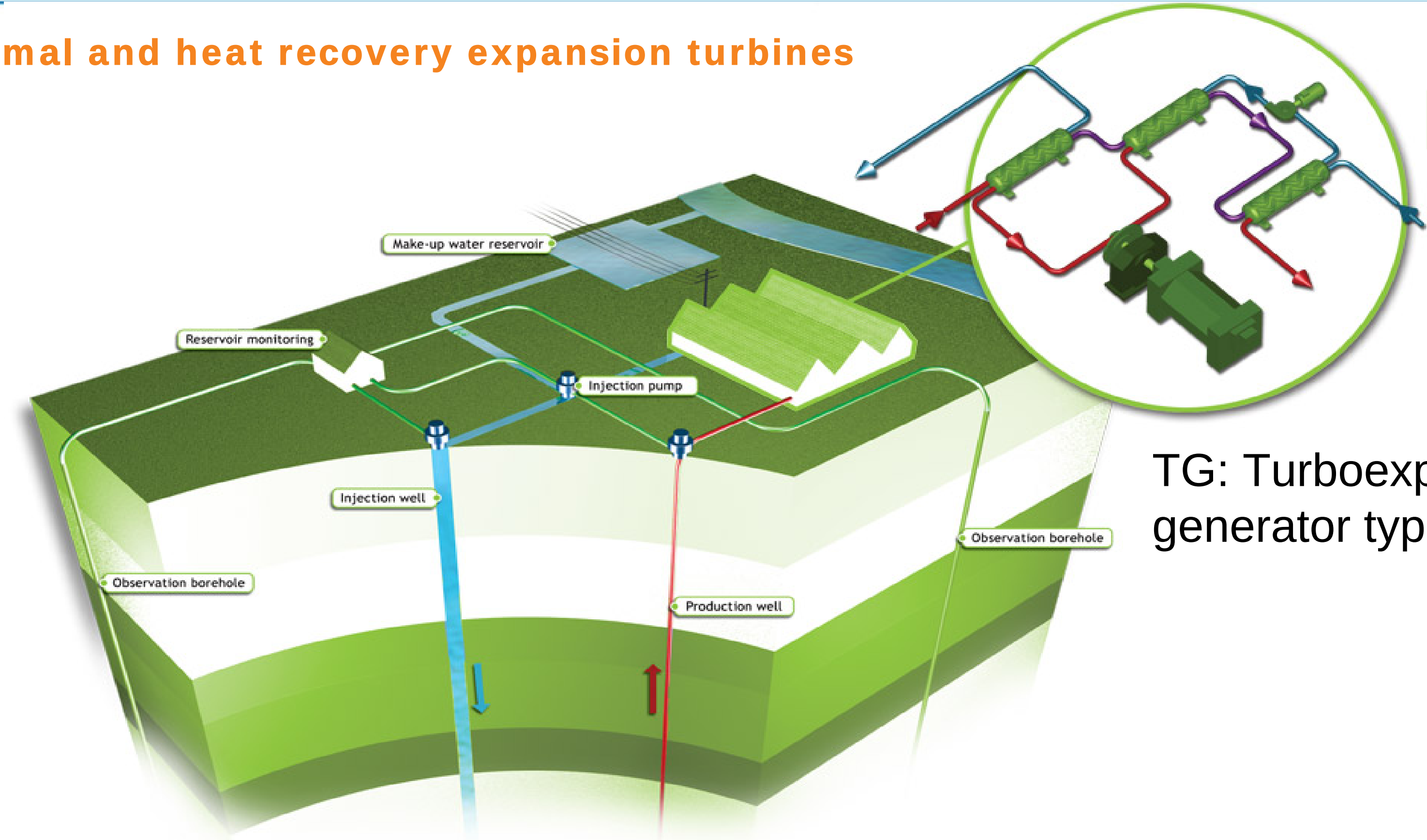
No.1 in « boil-off » gas handling and recovery (90% market share)



★ Energy recovery

Principal supplier of energy recovery expanders for « geo-pressure » application on natural gas grids (30 MW installed in Europe in the last 20 years plus North America ongoing)

★ **Geothermal and heat recovery expansion turbines**



TG: Turboexpander generator type

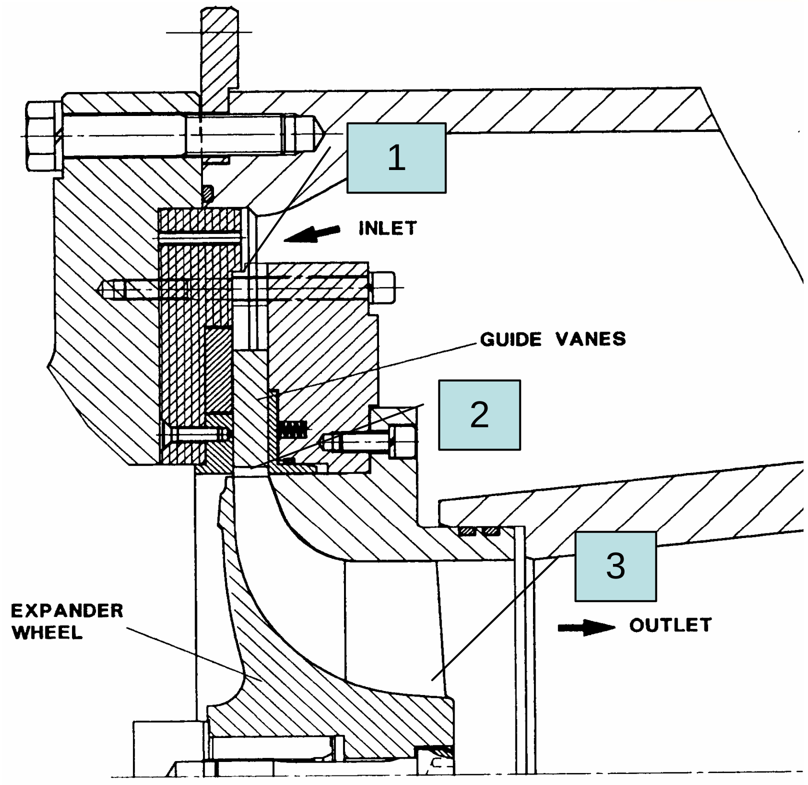
- ★ In construction: one TG500 delivering *ca* 3.3 MWelec for Siemens Kalina cycle in Unterhaching (Bavaria/Germany)
- ★ Ongoing project: other TG500 for Siemens Kalina cycle in Offenbach/Bellheim
- ★ Pre-selected for Soultz Hot Dry Rock ORC Project
- ★ Pre-selected for Innamincka Kalina Project

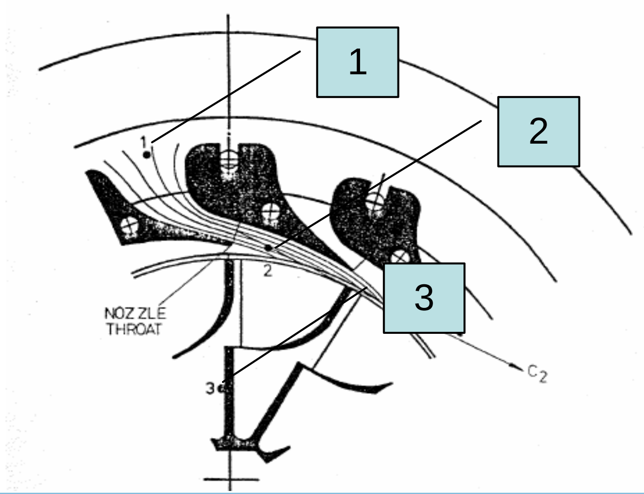
Main elements:

1.A high pressure barrel from which the gas first expands through **guide vane** 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 is passing afterwards through the **discharge diffuser** where velocities are reduced to normal pipeline velocities.



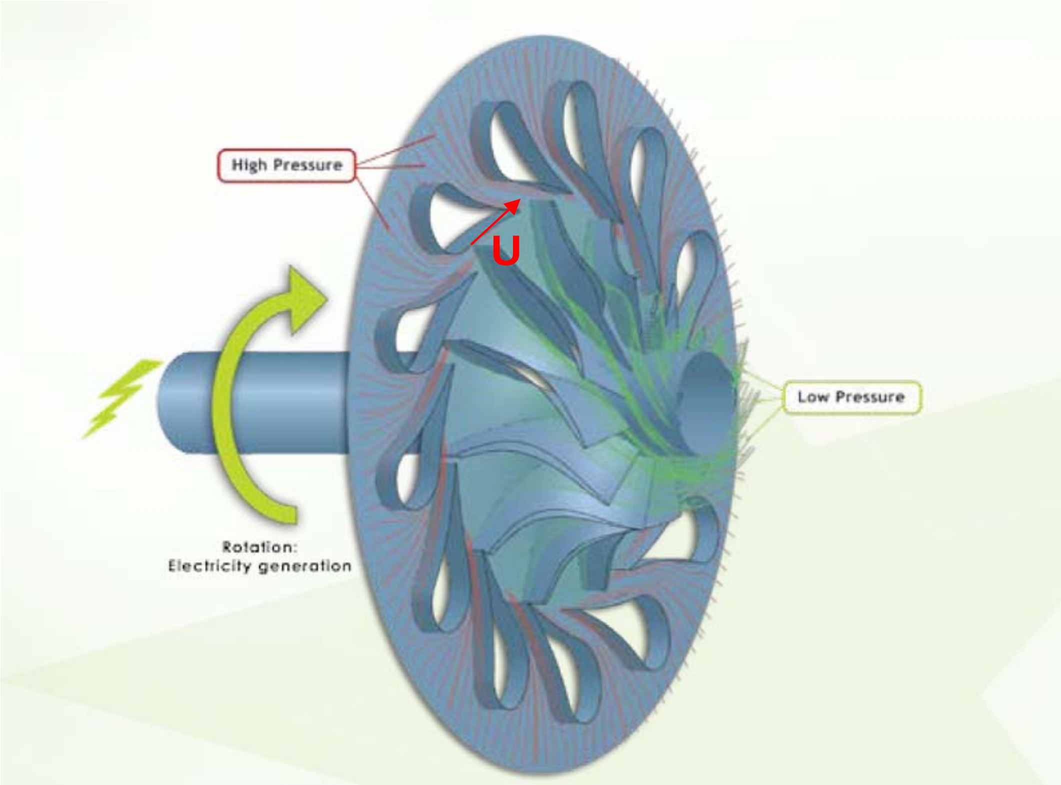


4. The power generated by the wheel is given to a **shaft** which runs in high speed **bearings**. This power can be recovered by driving a compressor or a generator.

The expander wheel must be designed at optimum ratio of blade tip speed and spouting velocity = U/C_0

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

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



$$c_0 = \sqrt{2000 . \Delta H_{is}} \quad \textit{Spouting velocity}$$

$$\Delta H_{is} \quad \textit{Isentropic enthalpy drop} \ (kJ/kg)$$

U/C_0 is a measure of the shape of the velocity triangle in the inter-space between nozzle exit and rotor inlet

The expander wheel must be designed at optimum specific speed Ns

Ns = specific speed

Links main sizing variables: flow, speed, head

Ns is shape factor for the passage of the wheel

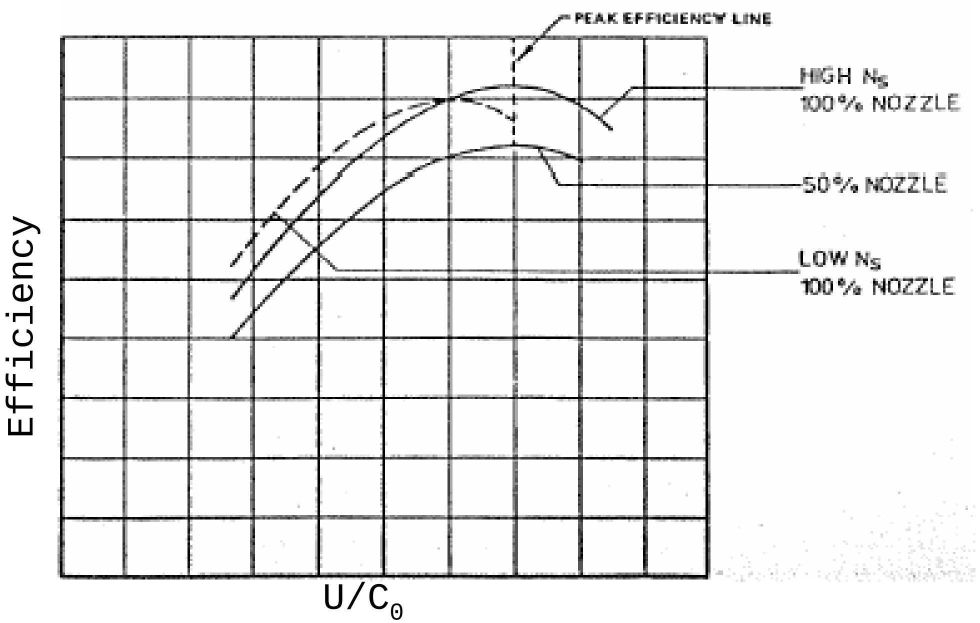
$$N_s = \frac{76.N}{1000} \cdot \sqrt{\frac{Q_{out}}{\sqrt{\Delta H_{is}^{3}}}} \quad \text{Specific Speed}$$

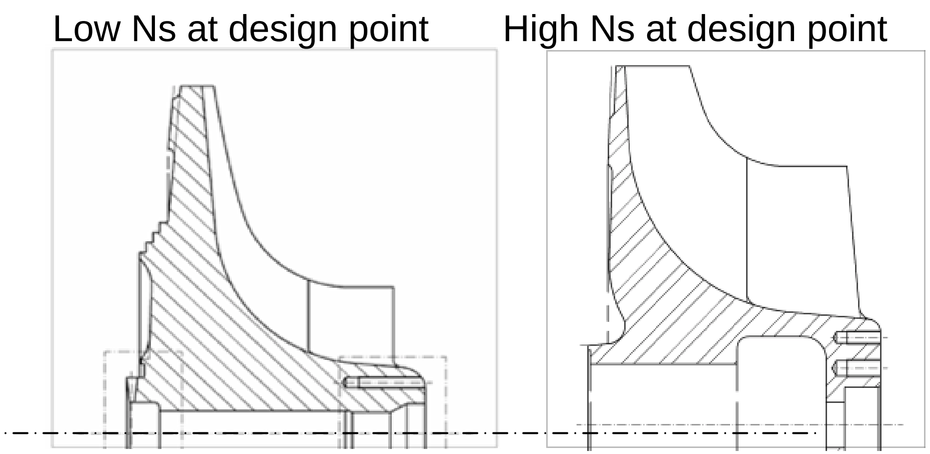
with:

ΔH_{is} Isentropic enthalpy drop (kJ/kg)

N Wheel speed (rpm)

Q_{out} Vol. Flow Rate (m^3/s)





Axis of rotation

CRYO STAR

★ Designing for the best efficiency

Optimum Ns for known process data

Calculation of angular velocity

$$\omega = \frac{(N_s)_{optimum} \cdot \sqrt{\dot{Q}out}}{\Delta h_{is}^{3/4}}$$

ω too high ?

Yes → Decrease Q_{exit}, Machines in //

No ↓

Optimum wheel speed

Optimum U/C_0
C_0 given by process data

Calculation of tip (wheel) speed

$$U_{tip} = \left(\frac{U}{C_0}\right)_{optimum} \times C_0$$

U_{tip} too high ?

Yes → Decrease C_0, Machines in serie

No ↓

Optimum wheel diameter

$$d_{tip} = \frac{2}{\omega} \cdot \left(\frac{U}{C_0}\right)_{optimum} \cdot \sqrt{2 \cdot \Delta h_{is}}$$

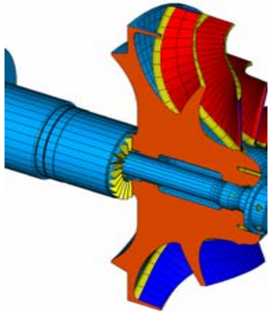
★ Expander limitations:

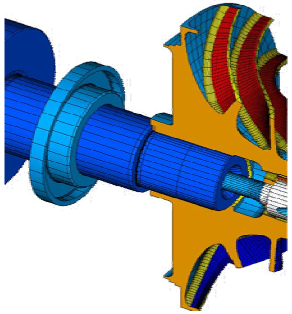
Circumferential (Tip) wheel speed

Depending on material Ti alloy > Al 7 Series > Stainless Steel

Depending on wheel type (open or closed)

Depending on shaft connection type (Hirth or Polygon)





Speed corresponding to max Tensile and Yield stresses admissible related to wheel geometry

★ Expander limitations:

Power Density

Usually expressed in Horse Power per Square Inch [hp/in2]

Defined the load admissible per unit of wheel surface area

Depending on material:

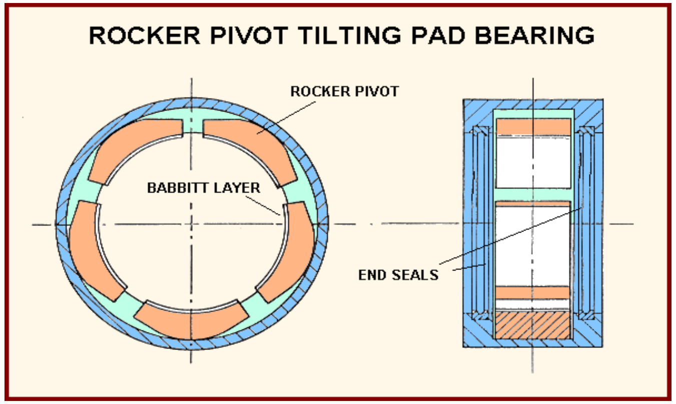
Ti alloy > Stainless Steel > Al 7 Series

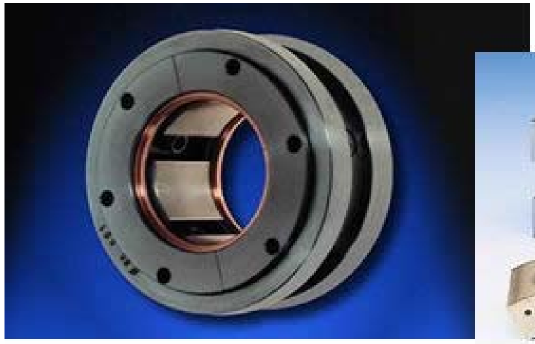
★ Expander limitations:

Bearing (sliding speed) speed

Most of the time, tilting pad (also called Michell) bearings are used

Maximum sliding speed defined by bearing manufacturer





★ Expander limitations:

Sound velocity or Mach Number

At wheel discharge, Ma =1 causes shock

At throat of the guide vanes, flow is limited to Ma= 1

Further downstream, Ma > 1 can give flow distortion, a cause for loss on efficiency

★ Expander limitations:

Application to turboexpanders for binary cycle

★ **Most of the time Titanium alloy wheels must be used because of:**

Inlet Temperature higher than 100-120 degC

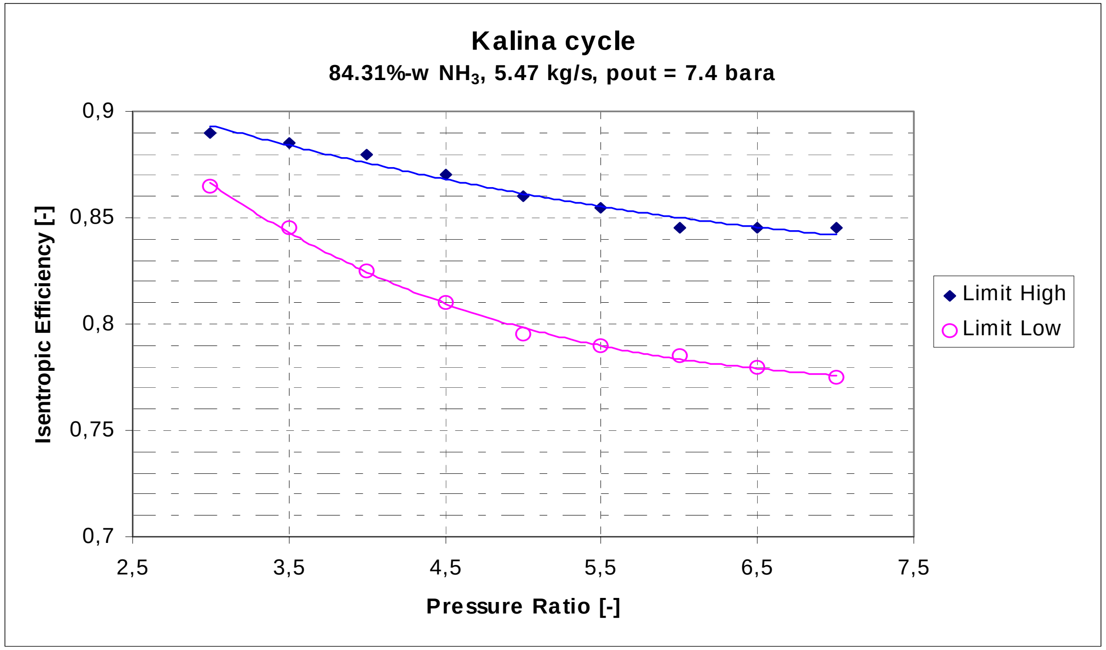
“Aggressive” working fluid like ammonia-water mixture

★ **Consequently it gives higher margin for:**

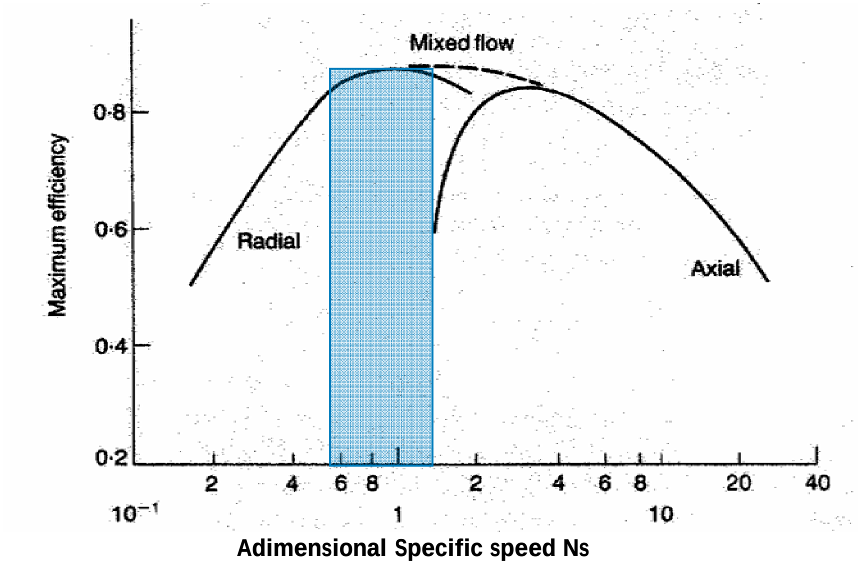
Wheel tip speed

Power Density

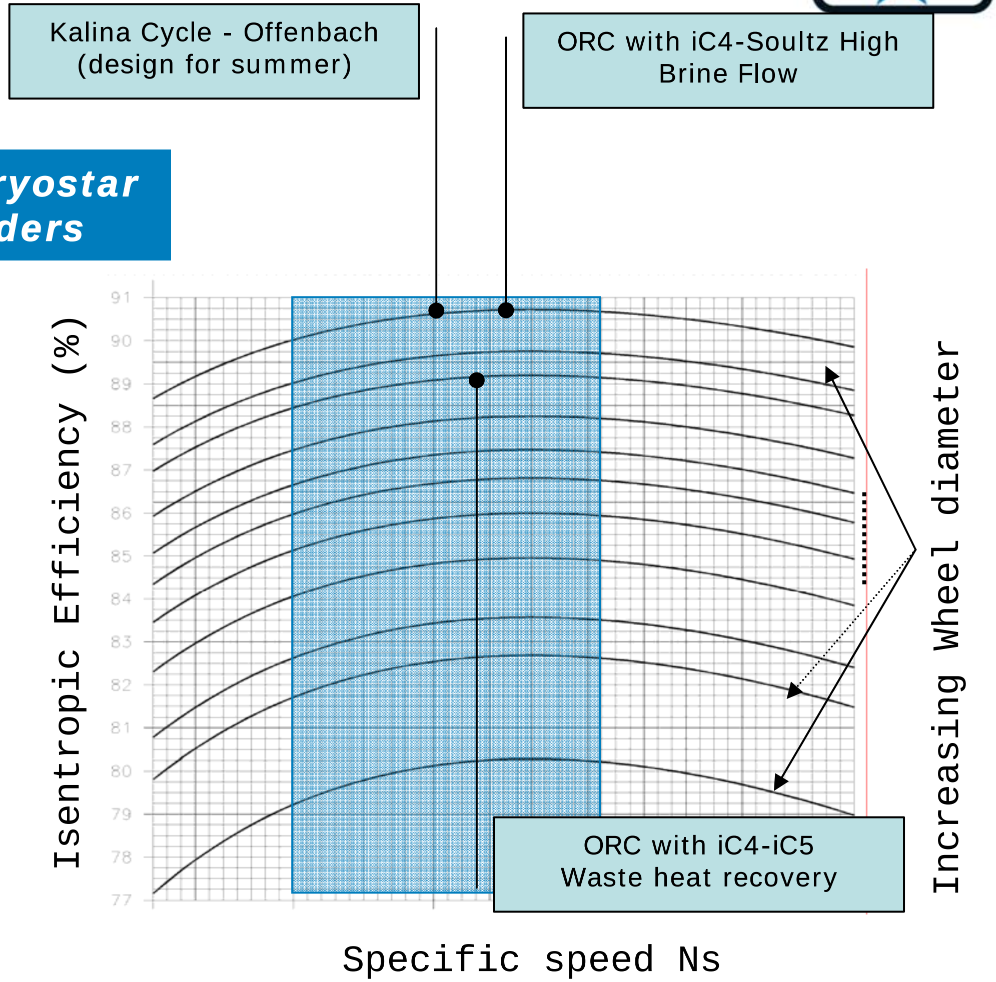
★ **… so higher efficiency**



Operating range for Cryostar binary cycle expanders



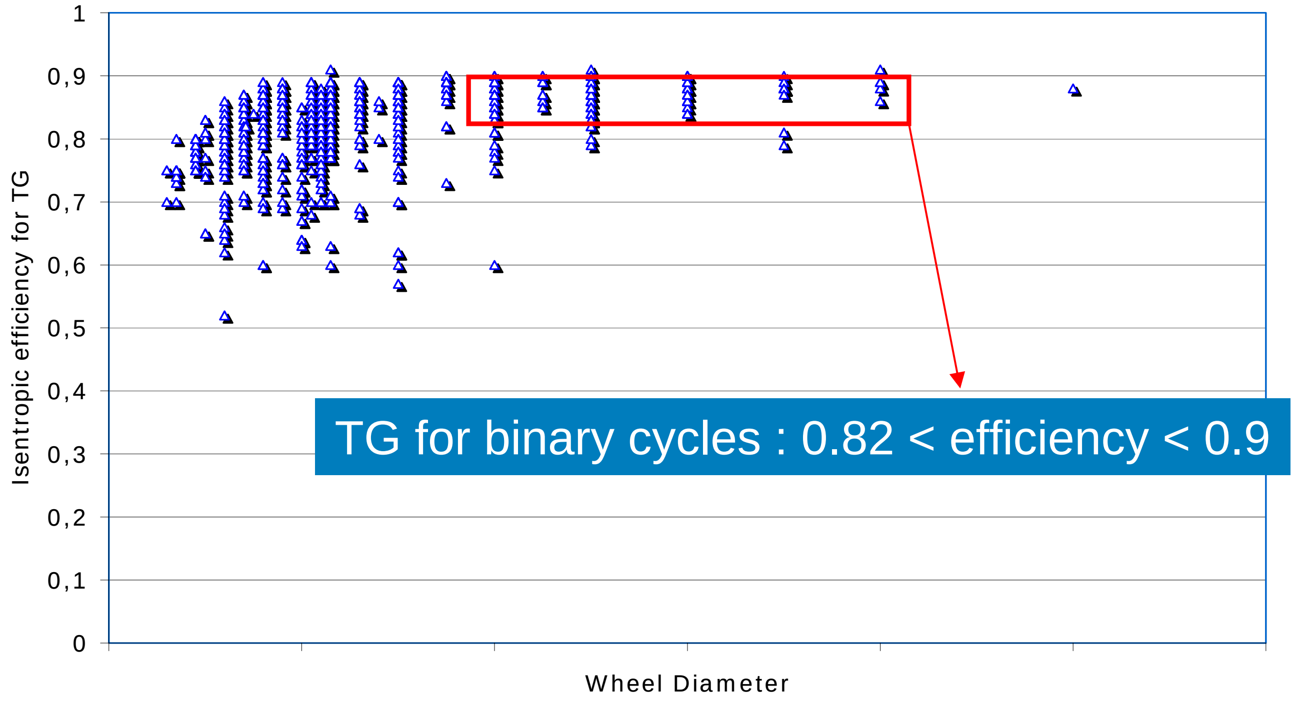
From Balje O.E., "Turbomachines, A Guide to…and theory" 1980



★ **Experience shows that efficiency decreases when:**

- Pressure ratio increases
- % liquid at outlet of expander increases

★ **Expander efficiency of Turboexpander-Generators (TG) at design points**



Up to 200°C inlet temperature
Up to 12 MWelec

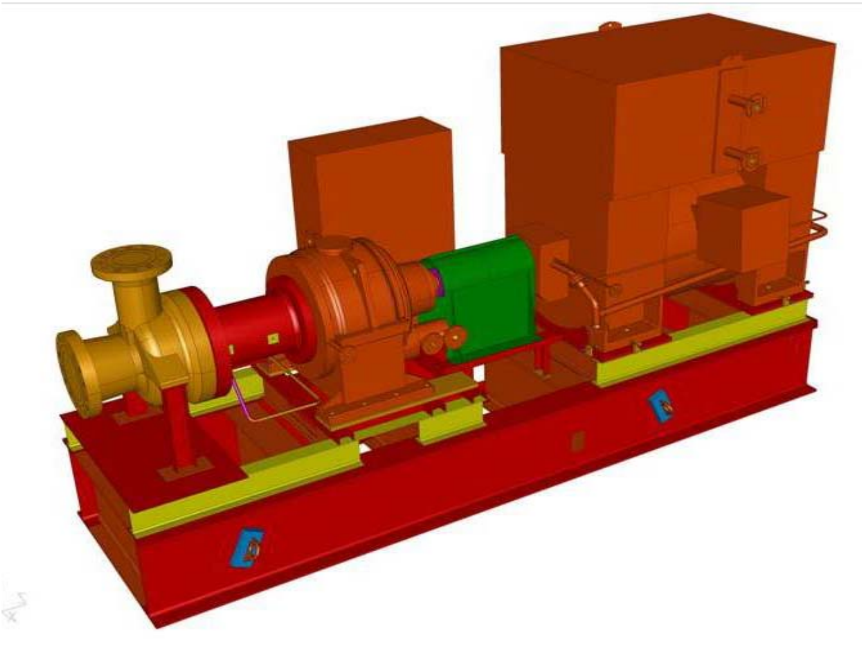
radial inflow turbines for binary cycles are …

…Standard machines for CRYOSTAR

Installed base :

- More than 1600 turbo-expanders & -compressors in operation
- *ca* 150 TG machines generating more than 80 MW electricity

★ TG machines



TG300/60 delivering 4MWe

Challenge: Sealing gas for closed cycle.

Role of the seal gas:

- ★ **prevent contamination of process gas by the lubricant**
- ★ **Limit or eliminate gas leakage around the shaft**

★ Kalina cycle:

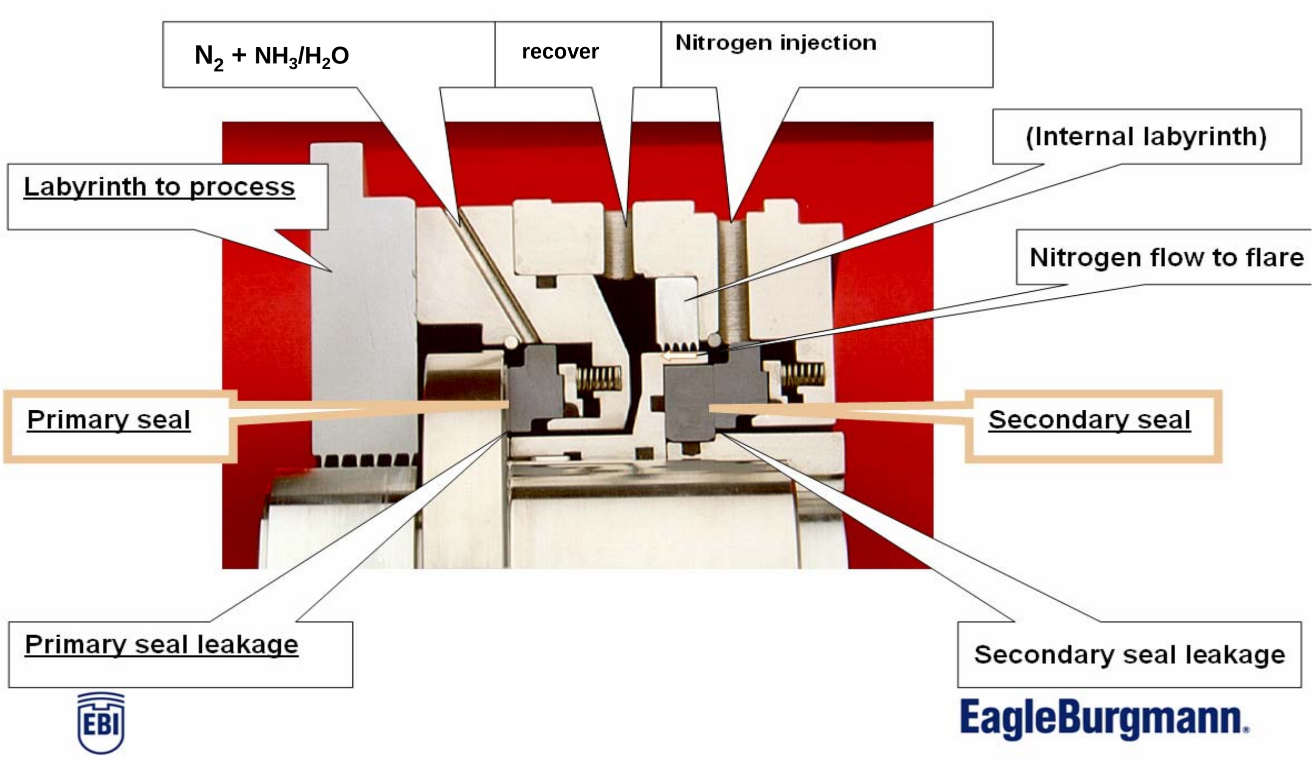
- ★ Use of process fluid impossible: NH_3 / $H_2$0 leads to liquid formation and corrosion problems;
- ★ Inert Nitrogen is often chosen;
- ★ Needs to limit the flow of N_2 which is lost afterwards;
- ★ « Dry Gas Seal » system;
- ★ Little losses of process gas unavoidable.

★ ORC cycle:

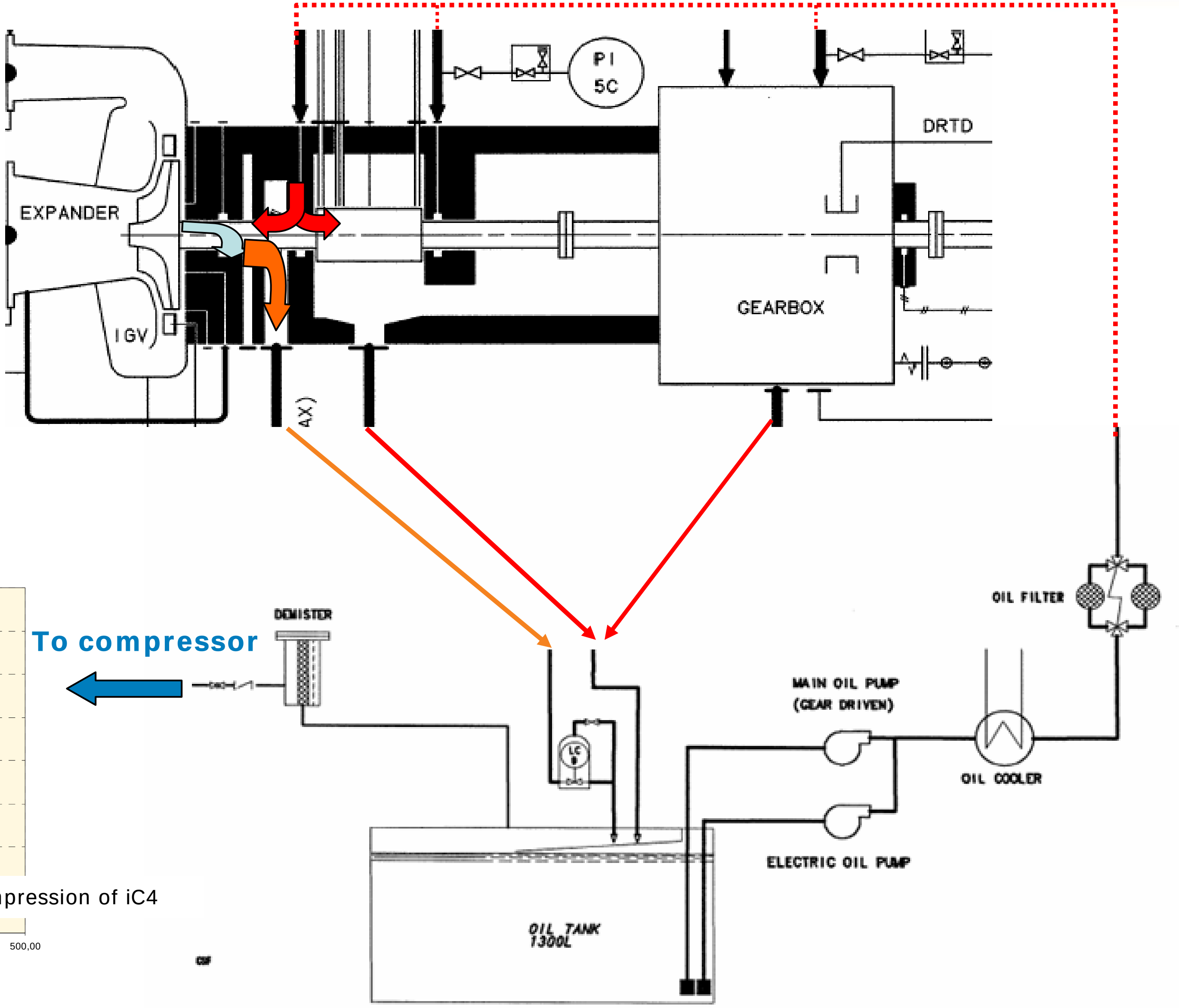
- ★ Use of ORC fluid possible: clean & dry iC4, iC5, R134A… used as seal gas;
- ★ Oil sealing system with drainer or Dry Gas Seal is used;
- ★ Seal gas migrating into oil system is cleaned from oil (coalescing filter);
- ★ Cleaned seal gas is recovered by recompression to inlet of condenser;
- ★ No losses of the process gas.

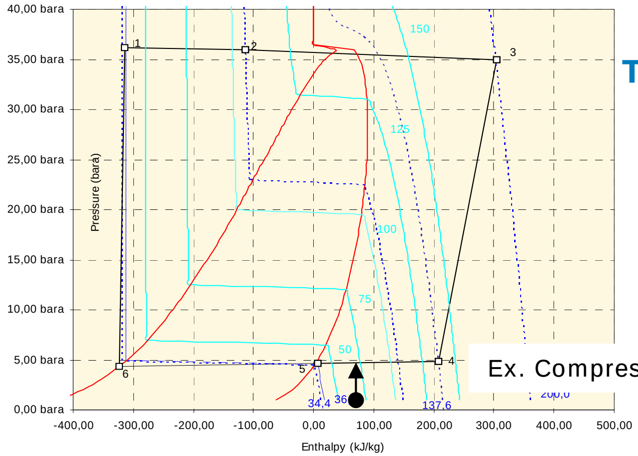
★ Kalina cycle: Dry Gas seal

- ★ Need of external source of Nitrogen;
- ★ Low flow is necesssary 1-2 m3/h;
- ★ Polluted N_2 by NH_3 & H_2O needs to be stored before treatment;
- ★ Possibility to « wash » the NH_3 gas to recover in the storage tank.



ORC cycle:
Solution for sealing
Oil seal + drainer
+ recompression





Ex. Compression of iC4

3. ORC Cycle Optimisation

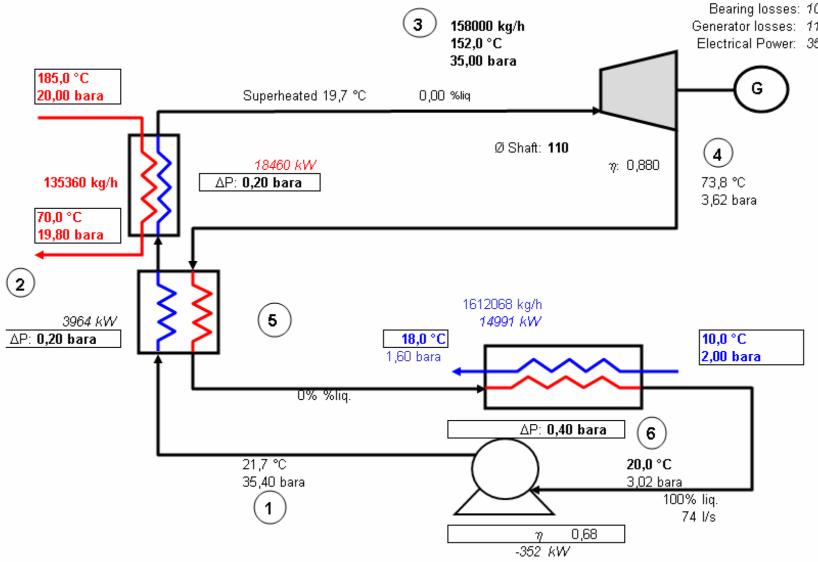
★ Ability to fit ORC process data and the expander at the same time

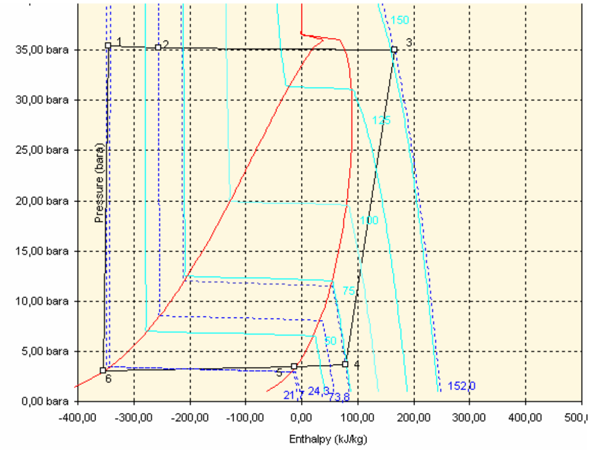
Organic Fluid Composition		P crit (bara)
PROPANE	0	42,5
TOLUENE	0	41,0
R134A	0	40,6
ISOBUTANE	1	36,4
ISOPENTANE	0	33,8

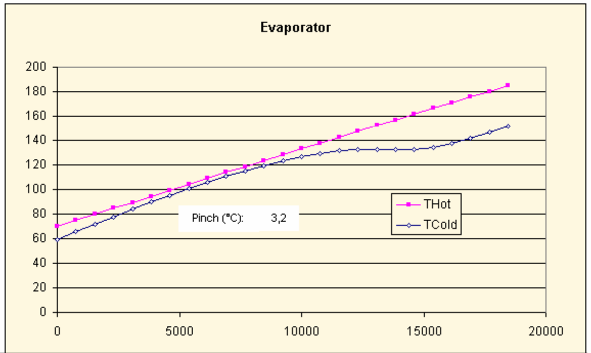
ORC design 1

Electrical efficiency:	***17,2%***
Generated Power (w/o pump):	***3536 kW***
Generated Power (with pump):	***3184 kW***

Cold Power:	*3821 kW*
Gear Box Losses:	*64 kW*
Bearing losses:	*106 kW*
Generator losses:	*115 kW*
Electrical Power:	*3536 kW*

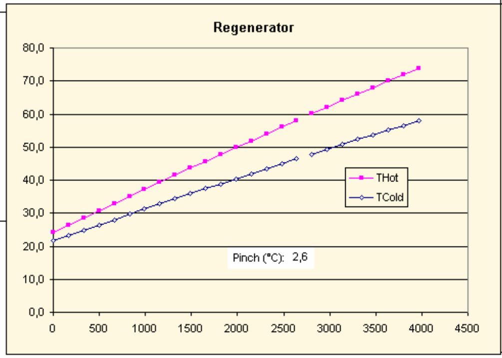


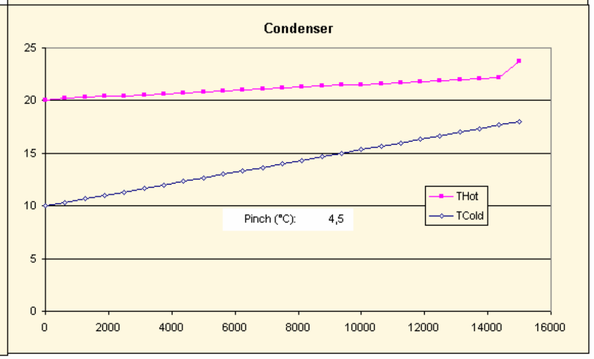




Expander		*Pump*	
Wheel Diameter [mm]:	400	Head (m):	553
Specific speed Ns [-]:		Speed (rpm):	3000
Δhis [kJ/kg]:	98,92	Ns [-]:	7,18
U/c0 [-]:		η (non corr):	0,830
Radial Speed [rpm]:	15300	% correc:	0,180
Power Density [hp/in2]:	20,66	η (corr):	0,68
Pratio [-]:	9,67	Stages nb [-]:	4
Nozzle Area [mm^2]			

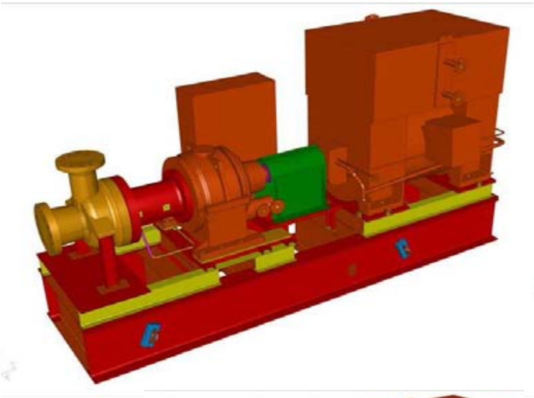
ref. 1150



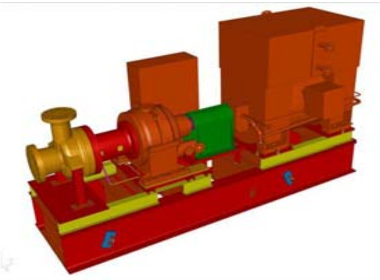


★ **Goal : expander frame size downsizing**

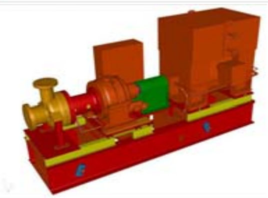
For the same brine flow & temperature data:



★ **Isopentane**
★ **Expansion from 9 to 1.1 bara**
★ **Optimal machine TG700**
★ **Net Cycle Power = 2.1 MW**



★ **Isobutane**
★ **Expansion from 35 to 3.6 bara**
★ **Optimal machine TG500**
★ **Net Cycle Power = 3.2 MW**



★ **Propane**
★ **Expansion from 42 to 8.7 bara**
★ **Optimal machine TG300**
★ **Net Cycle Power = 3.5 MW**

★ **Radial inflow turbines for binary cycles are standard machines:**

Flexible design with high efficiency

Kalina & Organic Rankine Cycle:

how to choose the best expansion turbine ?

Buy a Cryostar one !!!