



Optimized geothermal binary power cycles

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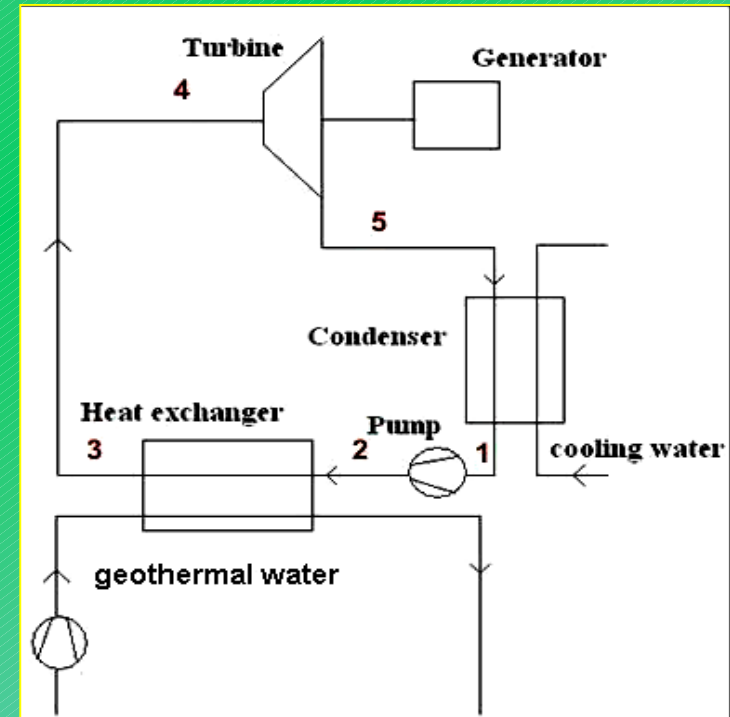
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LOW-BIN project

- ORC power plant for 65-90°C geothermal water
- ORC heat & power cogeneration plant for 120-150°C geo-water and 60/80°C district heating

Industrial partner: TURBODEN

Supported by DG-TREN (FP6)



Isobutane (R600a) and R134a as working fluids

- widely used with excellent results in the heat pumps and cooling/refrigeration industry
- available in the market
- The necessary parts for a Rankine cycle machine are available in the market
- CARRIER, lately developed low cost 200 kWe ORC units using R134a. Two units commenced operation in August-December 2006 in “Chena”, Alaska, USA, utilizing 74°C water

Shell & tubes condenser

Overall heat transfer:

$$U_o = \frac{1}{\frac{A_o}{A_i} \frac{1}{h_i} + \frac{A_o \ln(r_o / r_i)}{2\pi k L} + \frac{1}{h_o}}$$

Laminar condensation
on tubes surface:

$$h_o = 0.725 \left[\frac{\rho(\rho - \rho_v) g h_{fg} k_f^3}{\mu_f d (T_g - T_w)} \right]^{0.25}$$

Turbulent flow in tubes:

$$h_i = \frac{Nu k}{D}$$

$$Nu = 0.023 Re^{0.8} Pr^{0.4}$$

$$Re = \frac{u \cdot D \cdot \rho}{\mu}$$

Plate H.E. as evaporator

One side: Geothermal water

Second side: working fluid
Liquid \Rightarrow Two Phase \Rightarrow Vapor

$$U_{total} = \frac{1}{\frac{1}{U_{sp/l}} + \frac{1}{U_{tp}} + \frac{1}{U_{sp/g}}}$$

$$U_{sp/l} = \frac{1}{\frac{1}{h_{sp/l}} + \frac{\Delta x}{ktit} + \frac{1}{h_{gw}}}, U_{tp} = \frac{1}{\frac{1}{h_{tp}} + \frac{\Delta x}{ktit} + \frac{1}{h_{gw}}}, U_{sp/g} = \frac{1}{\frac{1}{h_{sp/g}} + \frac{\Delta x}{ktit} + \frac{1}{h_{gw}}}$$

Evaporation heat transfer

$$h_{tp} = C \left(\frac{k_l}{D_e} \right) \left[\frac{Re_l^2 h_{fg}}{L_p} \right]^{0.4124} \left(\frac{p}{p_{cr}} \right)^{0.12} \left(\frac{65}{\beta} \right)^{0.35}$$

Single phase heat transfer

$$Re = \frac{u \cdot L \cdot \rho}{\mu}$$

$$c_f = \frac{0.074}{Re^{0.2}} - \frac{1050}{Re}$$

$$St = \frac{c_f}{2} \cdot \frac{1}{Pr^{\frac{2}{3}}}$$

$$Nu = St \cdot Re \cdot Pr$$

$$h_{sp/l,g} = \frac{Nu \cdot k}{L}$$

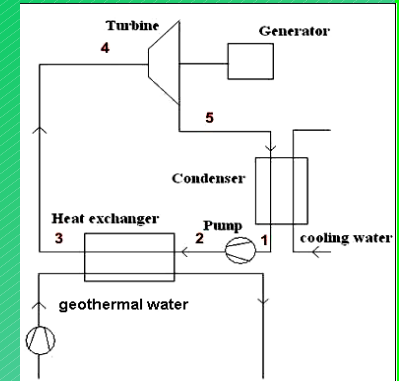
Rankine cycle optimisation

Objectives:

- Maximize overall net conversion efficiency of the plant

$$\eta_{cycle} = \frac{W_{turbine} - N_{pump}}{Q_{heatexch}} = \frac{(h_4 - h_5) \cdot m_{wf} - N_{pump}}{(h_3 - h_2) \cdot m_{wf}}$$

- Minimize the cost of the plant
→ Minimize both Heat Exchangers surface



Variables:

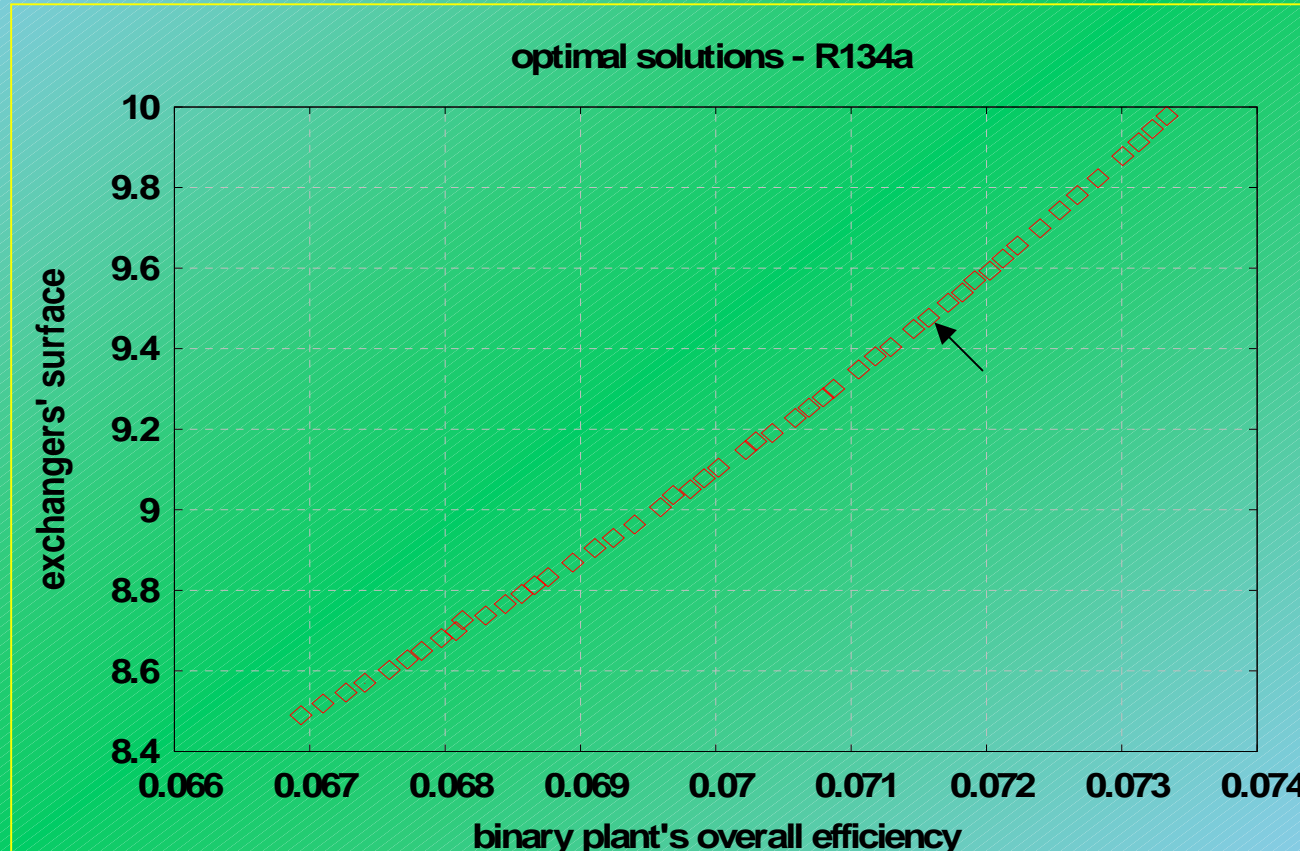
$P_2, m_{gr}, m_{wf}, \Delta T_H, \Delta T_C$

Constraints:

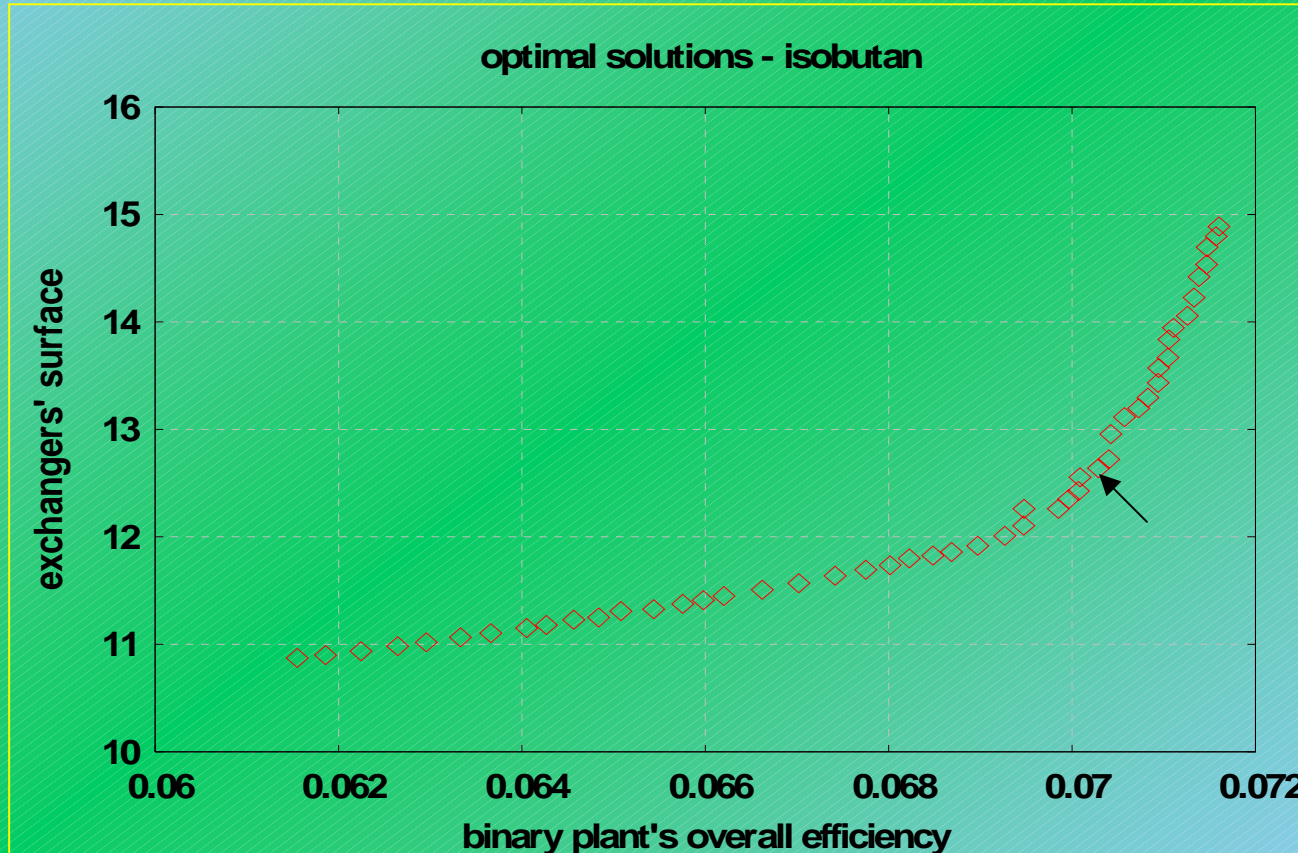
Net Power Output
 $200 \text{ kW}_e \pm 5 \text{ kW}_e$

using the EASY software code (Evolutionary Algorithm System)
by National Technical University of Athens, ref. <http://velos0.ltt.mech.ntua.gr/EASY>

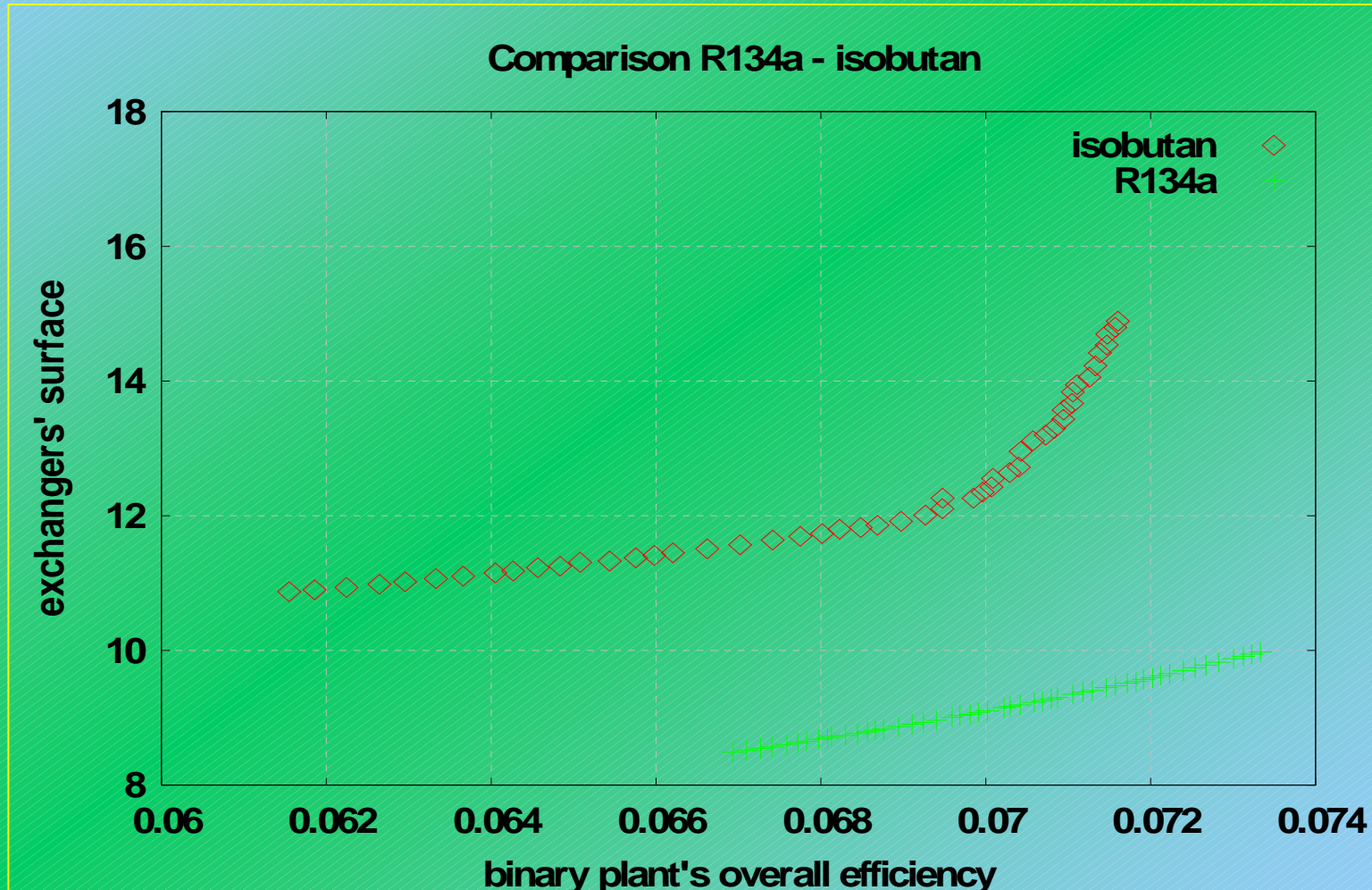
ORC machine for 65°C: R134a



ORC machine for 65°C: R600a



ORC machine for 65°C: R134a vs Isobutane

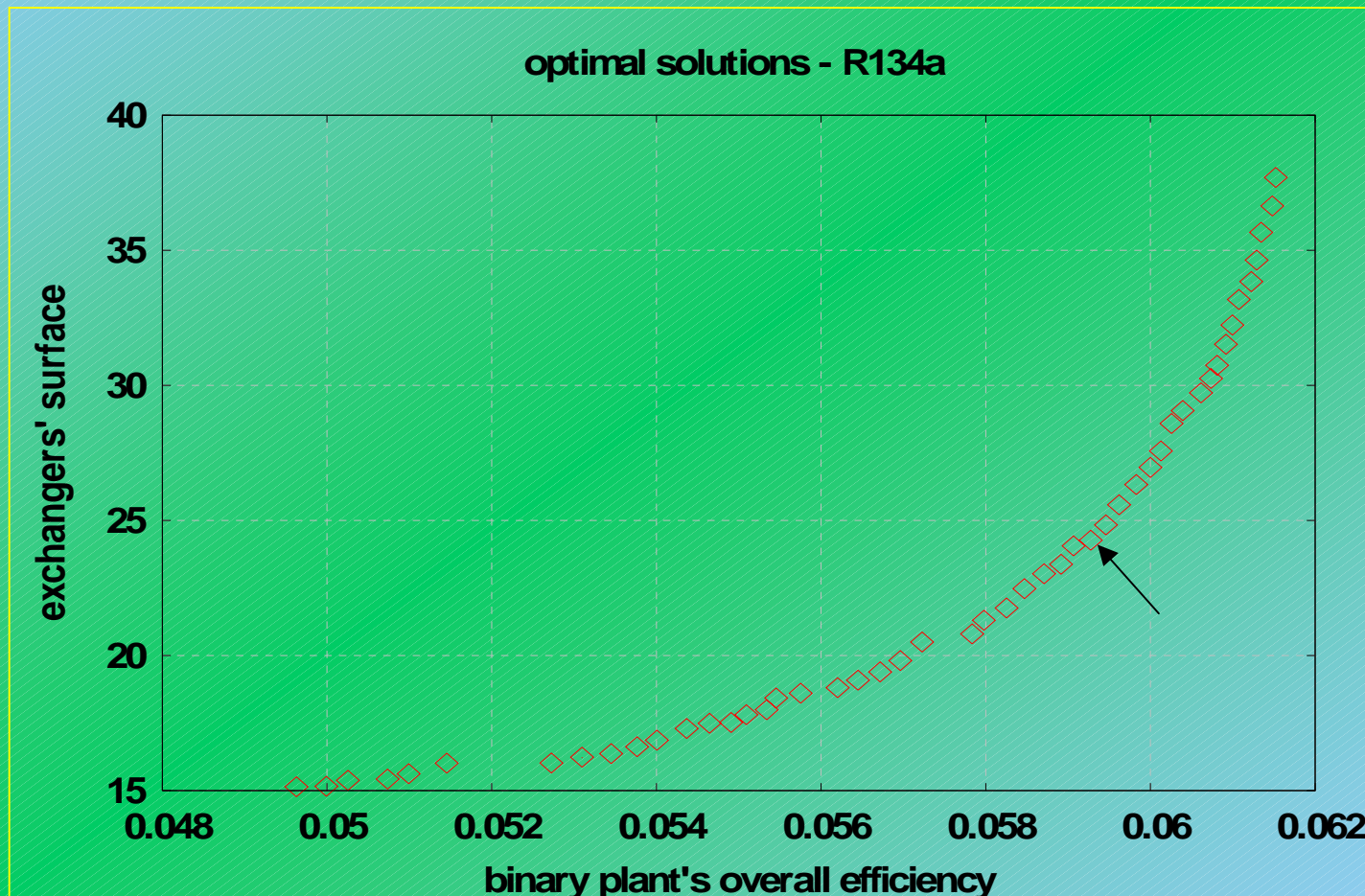


ORC machine for 65°C: R134a vs Isobutane

Variable	Isobutane	R134a
P_2 (bar)	6.19	11.99
$m_{\text{geothermal water}}$ (kg/sec)	46	51.2
$m_{\text{working fluid}}$ (kg/sec)	10.2	17.5
ΔT_H (°C)	21.8	18.6
ΔT_C (°C)	7.5	7.5
pump power (kW)	3.9	13.4
cooling water flow (kg/sec)	119	116
surface of the condenser (m ²)	7.0	5.5
surface of the heat exchanger (m ²)	5.7	4.0
total H.E. surface (m ²)	12.7	9.5
net conversion efficiency	7.04	7.16

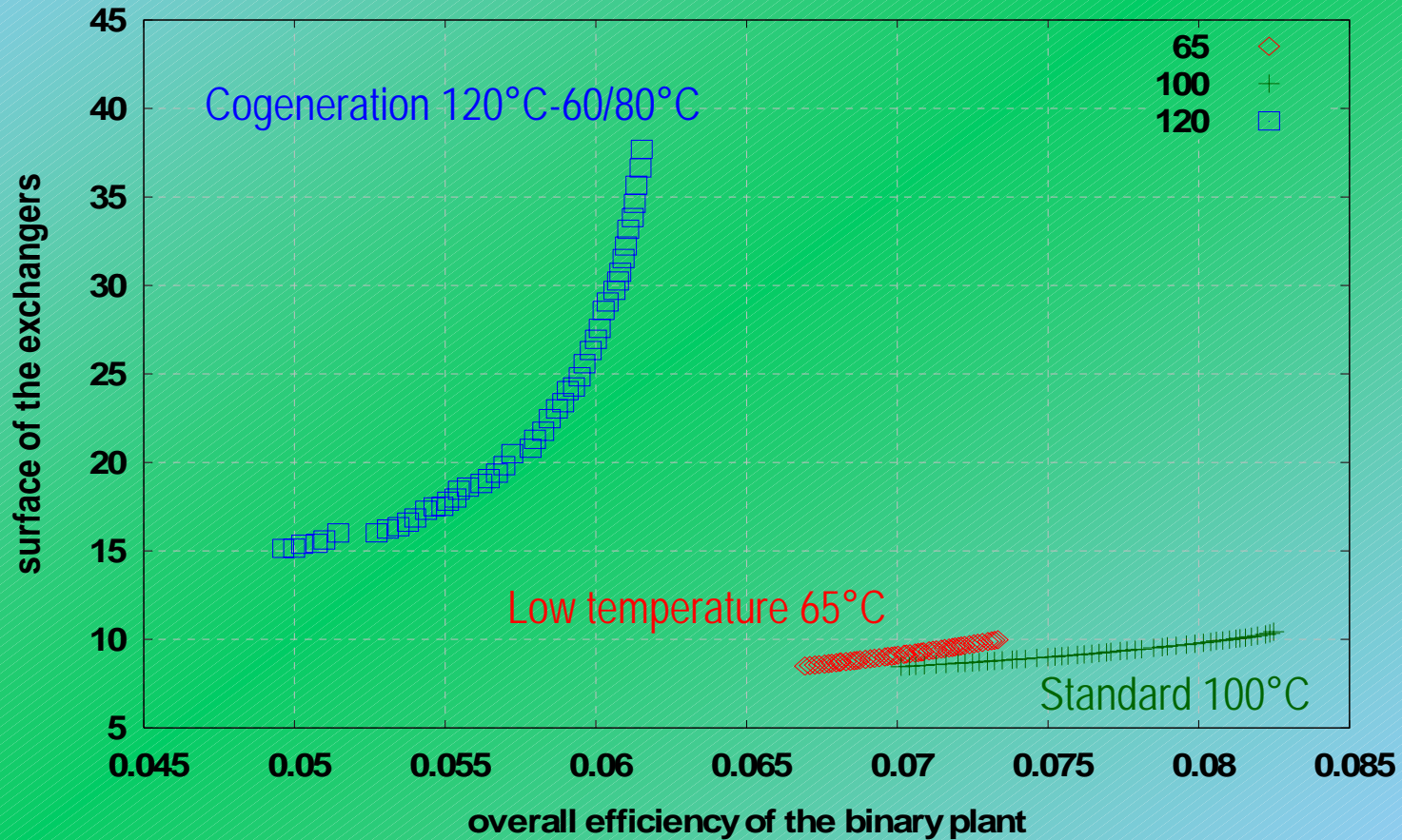
ORC heat & power cogeneration

source: 120°C, cooling: 60/80°C



R134a ORC plants

R134a - temperature threshold at 65,100,120



R134a ORC plants

Variable	Heat & power cogeneration 120°C	Power generation 65°C	Standard binary power plant, 100°C
P_2 (bar)	34.99	11.99	15.52
$m_{\text{geothermal}}$ (kg/sec)	52	51.2	45
m_{R134a} (kg/sec)	35	17.5	17.8
ΔT_H (°C)	26	18.6	20.0
ΔT_C (°C)	20	7.5	7.5
Cooling Temp (°C)	60	10	10
Condensing Temp (°C)	80	30	27
R134a pump power (kW)	58	13.4	18.5
cooling water flow (kg/sec)	66	116	110
Condenser surface (m ²)	22.0	5.5	4.6
Surface of the PHE (m ²)	2.0	4.0	5.4
Total H.E. surface (m²)	24.0	9.5	10
Net conversion efficiency	5.93	7.16	7.7
Net electrical Power (kW)	207	202	204