Optimized geothermal binary power cycles

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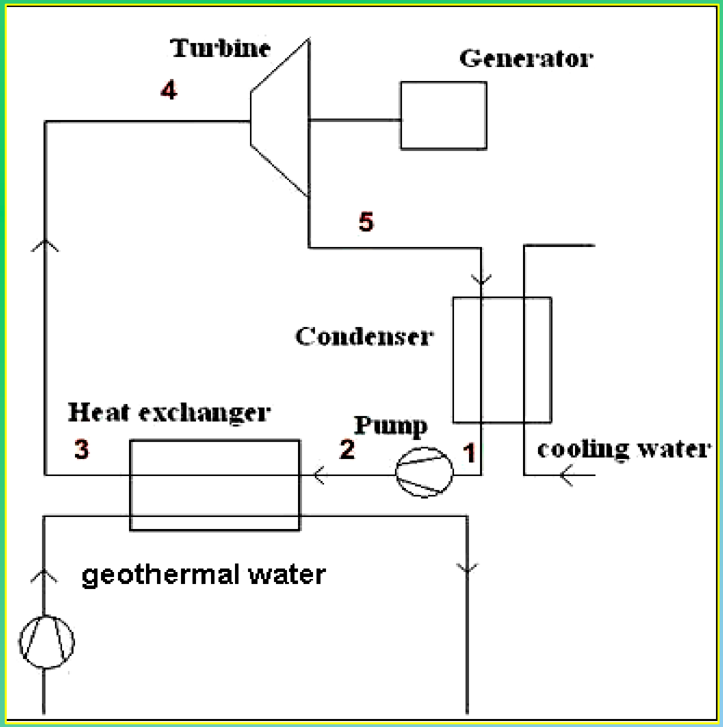
LOW-BIN project

- 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:

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

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:

$$h_i = \frac{Nuk}{D}$$

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}$$

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

Plate H.E. as evaporator

One side: Geothermal water

Second side: working fluid
Liquid ⇒ Two Phase ⇒ 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

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

Single phase heat transfer

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

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

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

$$Nu = St \cdot \mathrm{Re} \cdot \mathrm{Pr}$$

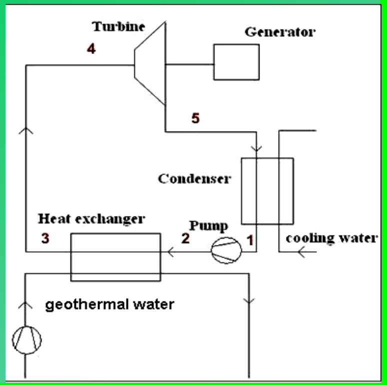
$$h_{sp/l,g} = \frac{Nu \cdot k}{L}$$

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}, ΔT_H, ΔT_C

Constraints:

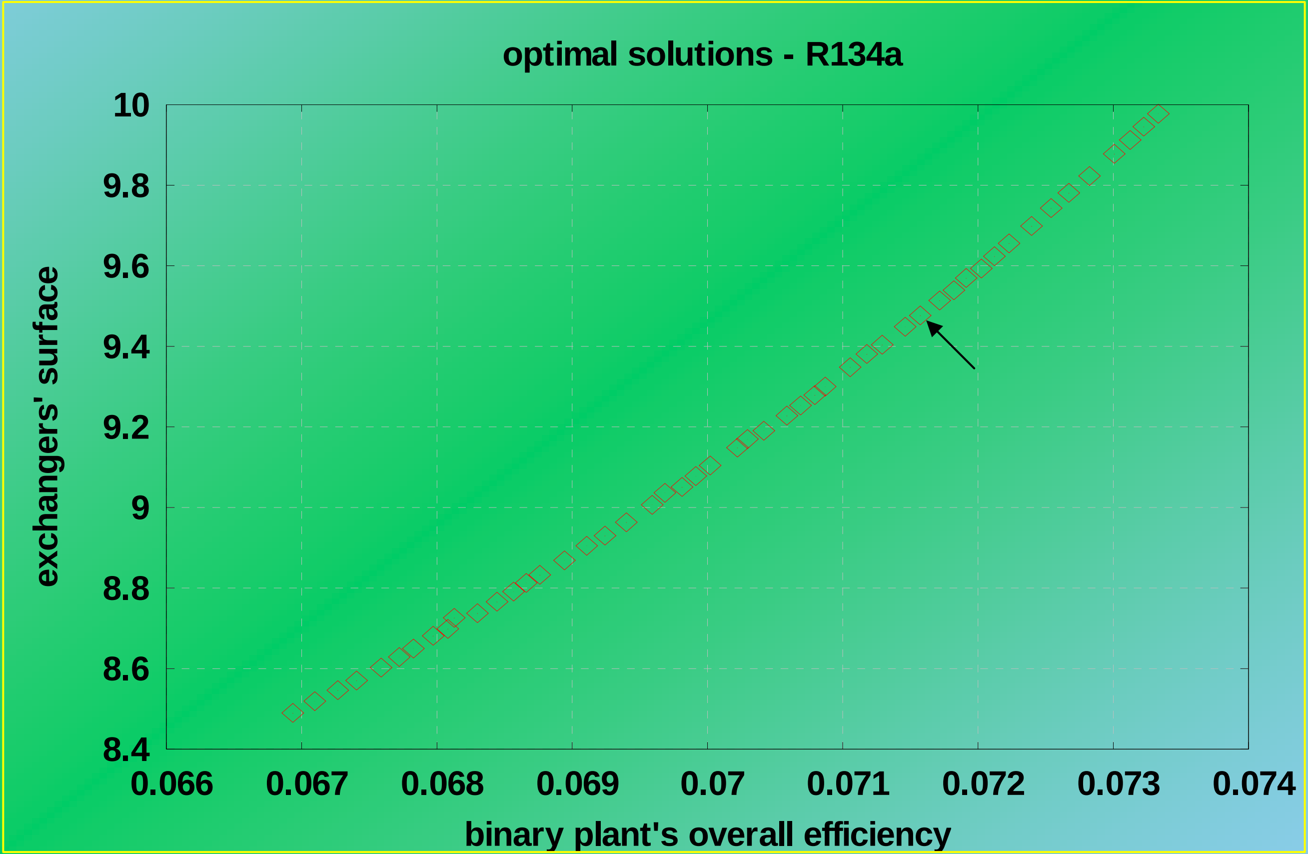
Net Power Output

200 $kW_e \pm 5kW_e$

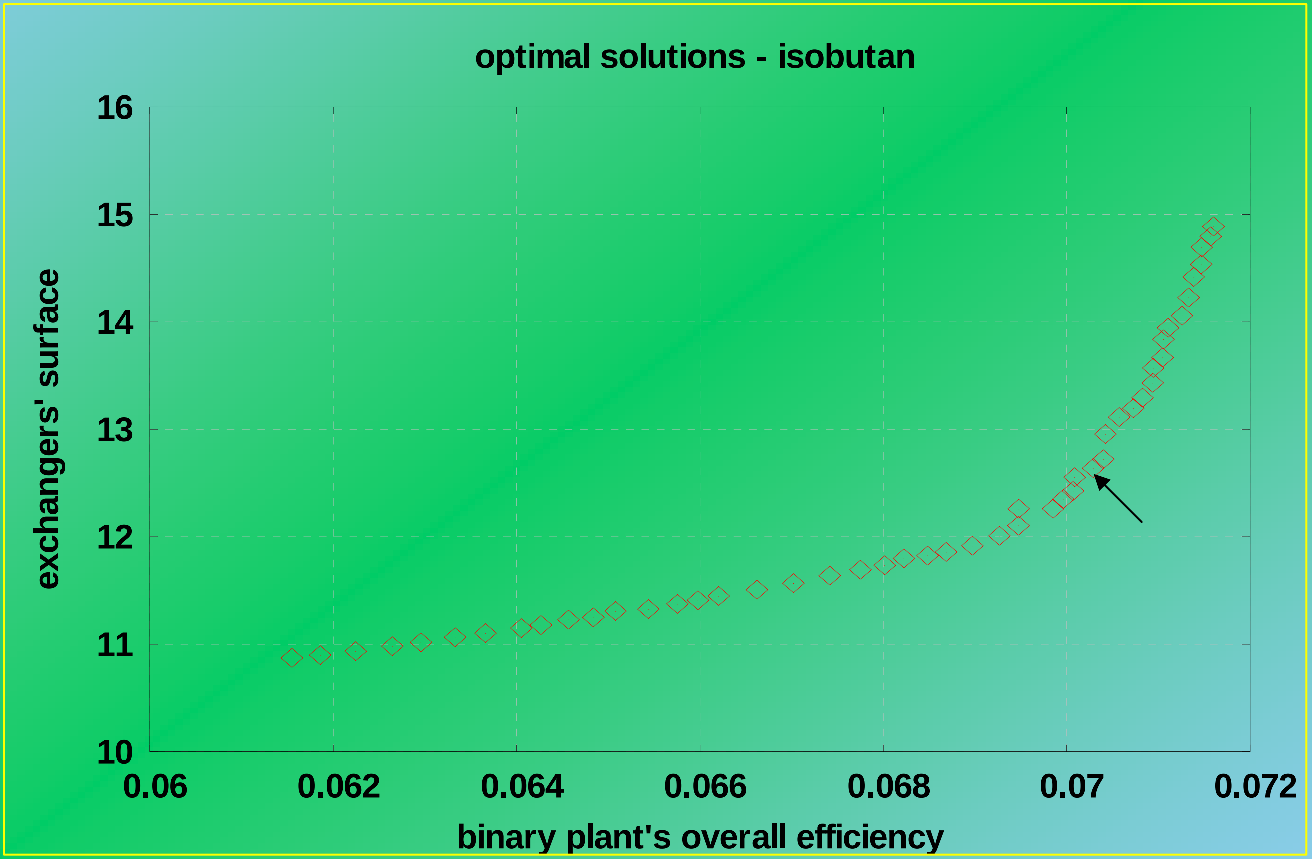
using the EASY software code (Evolutionary Algorithm System)

by National Technical University of Athens, ref. http://velos0.ltt.mech.ntua.gr/EASY

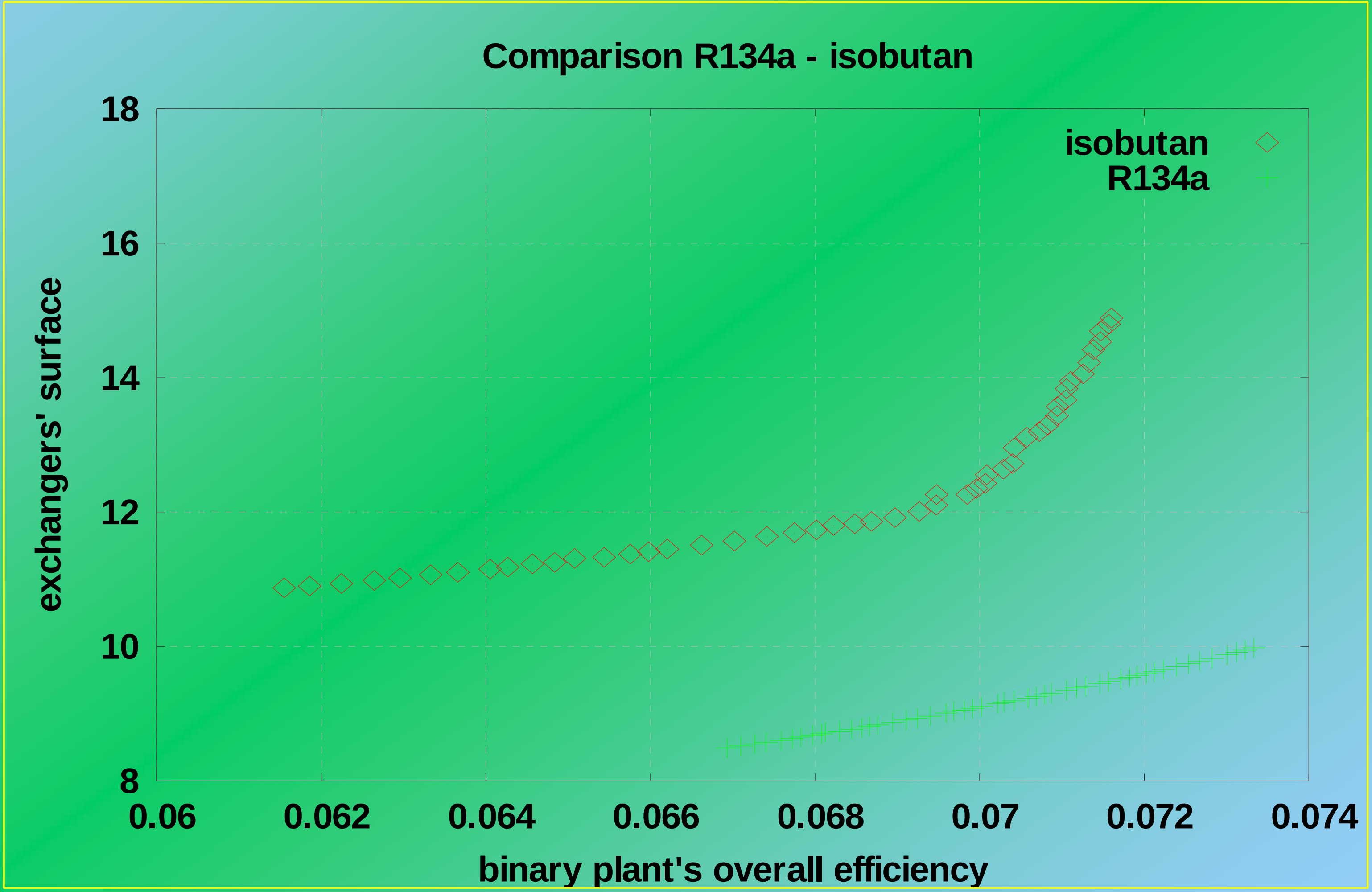
ORC machine for 65°C: R134a



ORC machine for 65°C: R600a



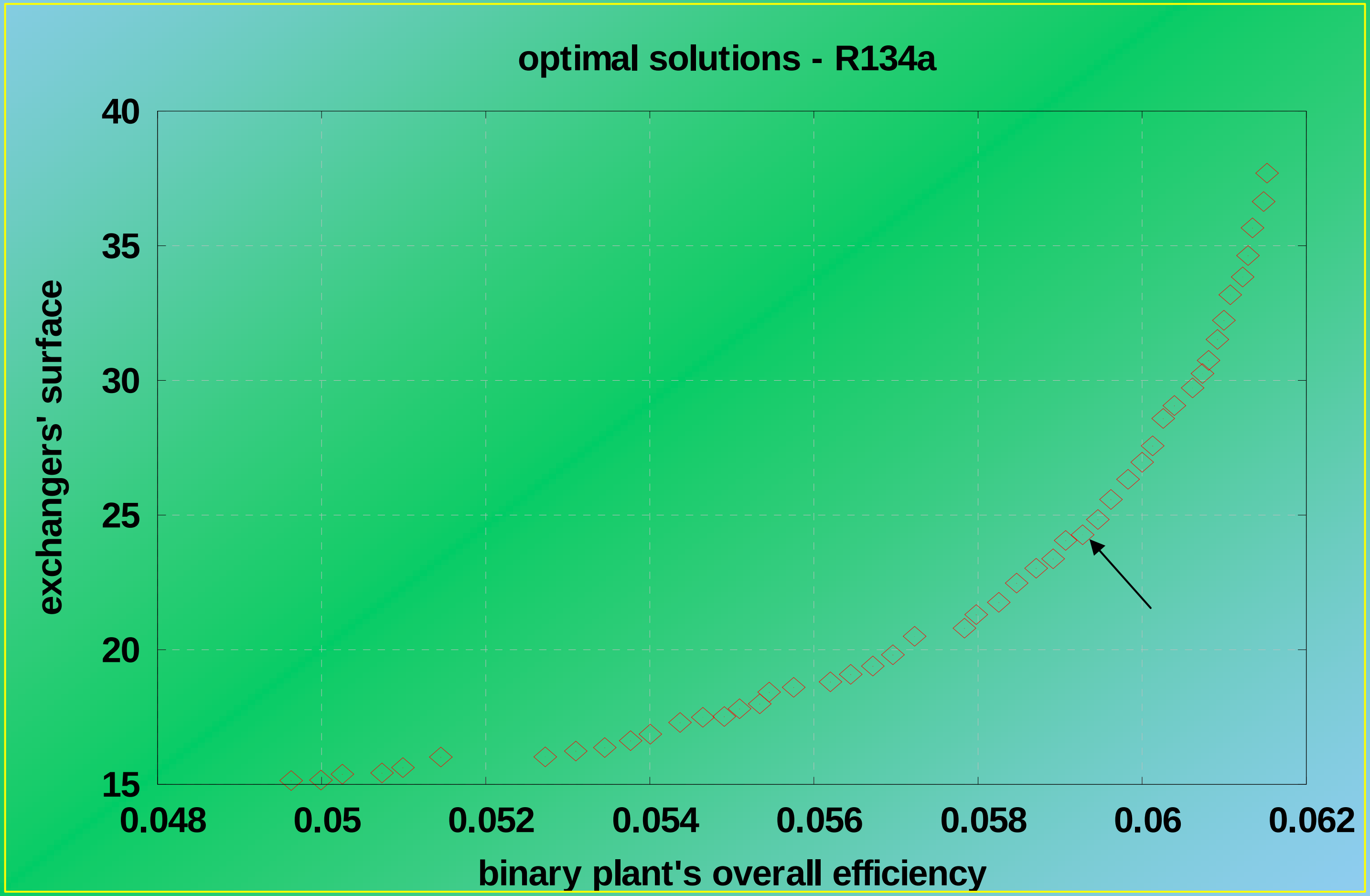
ORC machine for 65°C: R134a vs Isobutane



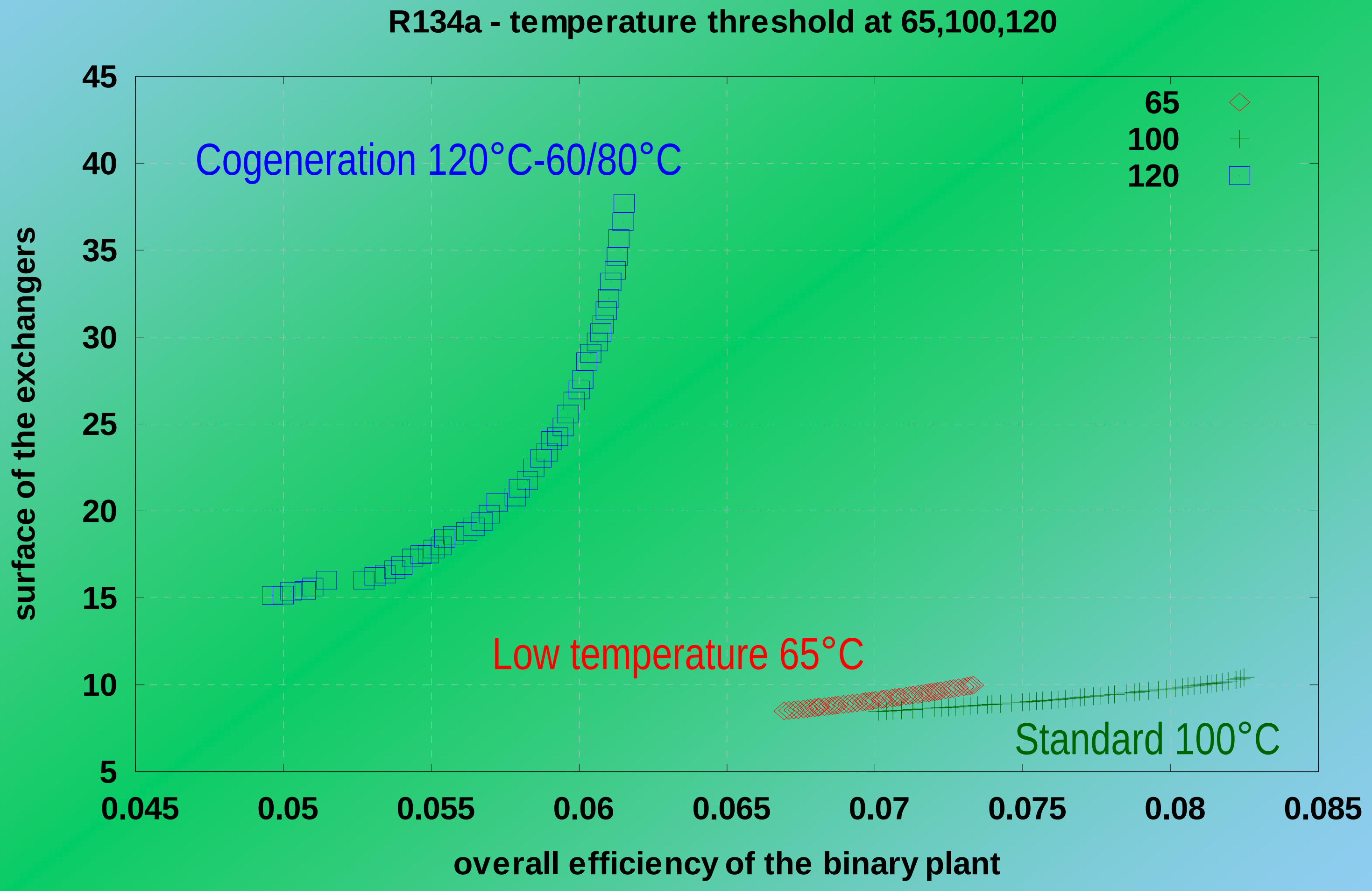
ORC machine for 65°C: R134a vs Isobutane

Variable	Isobutane	R134a
P_2 (bar)	6.19	11.99
$m_{geothermal\ water}$ (kg/sec)	46	51.2
$m_{working\ fluid}$ (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 ORC plants

Variable	Heat & power cogeneration 120^{o}C	Power generation 65^{o}C	Standard binary power plant, 100^{o}C
P_2 (bar)	**34.99**	**11.99**	**15.52**
$m_{geothermal}$ (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 (m^2)	**24.0**	**9.5**	**10**
Net conversion efficiency	**5.93**	**7.16**	**7.7**
Net electrical Power (kW)	207	202	204