Technische Universität Berlin

Institute for Energy Engineering

Study of a tri-generation system based on a supercritical CO_2 cycle

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Introduction

Research focuses on the application of exergy-based methods to improve the thermodynamic, economic and environmental performance of:

…

alternative power generation and refrigeration processes for sustainable industrial and commercial applications (including CO_2 as working fluid)

…

Exergy-Based Methods

Exergy-based methods **is a general term that includes the conventional and advanced *exergetic*, *exergoeconomic*, and *exergoenvironmental analyses* and evaluations.**

The *concept of exergy* complements and enhances an energetic analysis by calculating

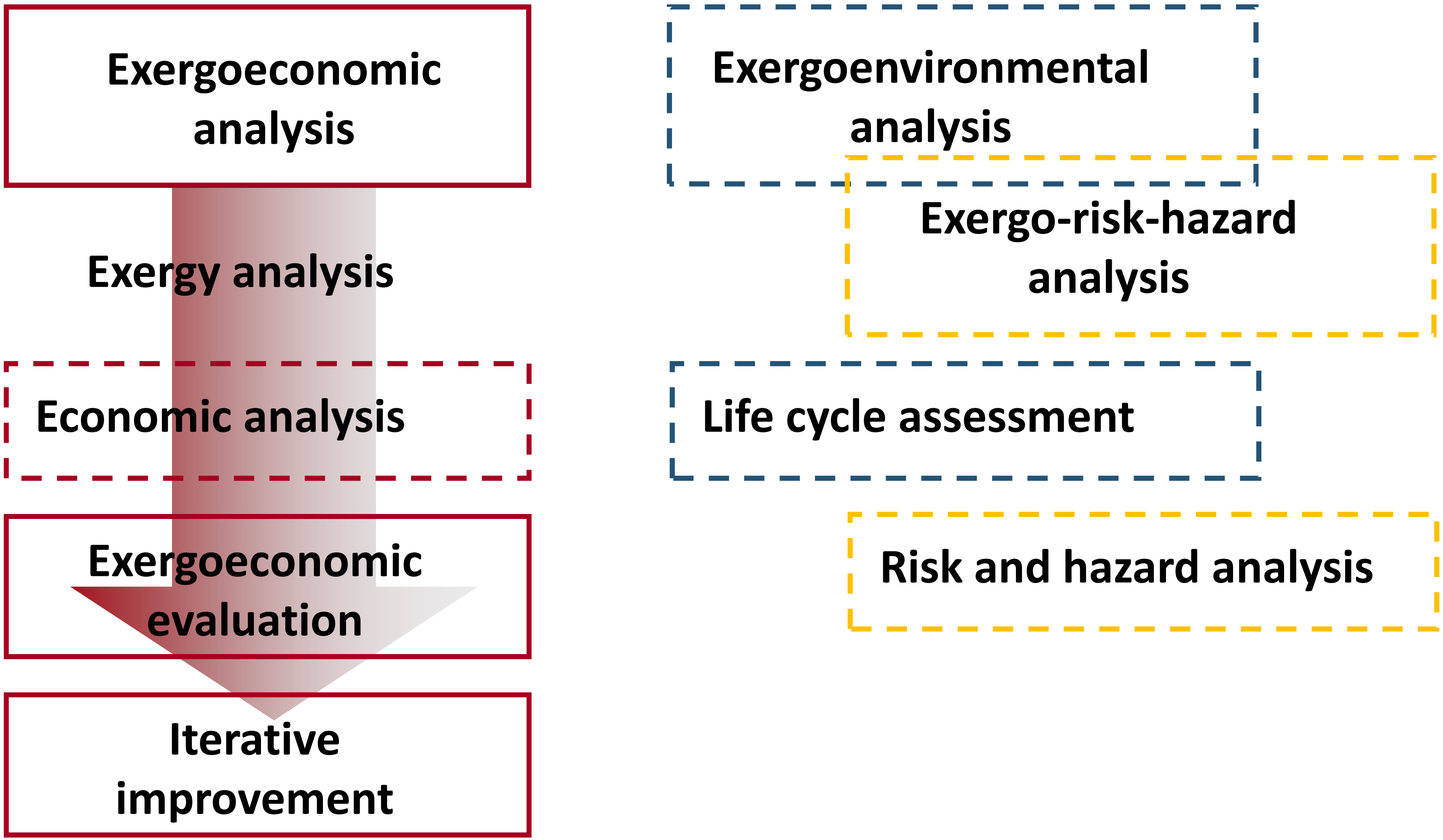
(a) **the true thermodynamic value of an energy carrier,**
(b) **the real thermodynamic inefficiencies in a system, and**
(c) **variables that unambiguously characterize the performance of a system (or one of its components) from the thermodynamic viewpoint.**

Why Exergy-Based Methods? - 1

The objective evaluation and the improvement of an energy conversion system from the viewpoints of *thermodynamics*, *economics*, and *environmental impact* require a deep understanding of

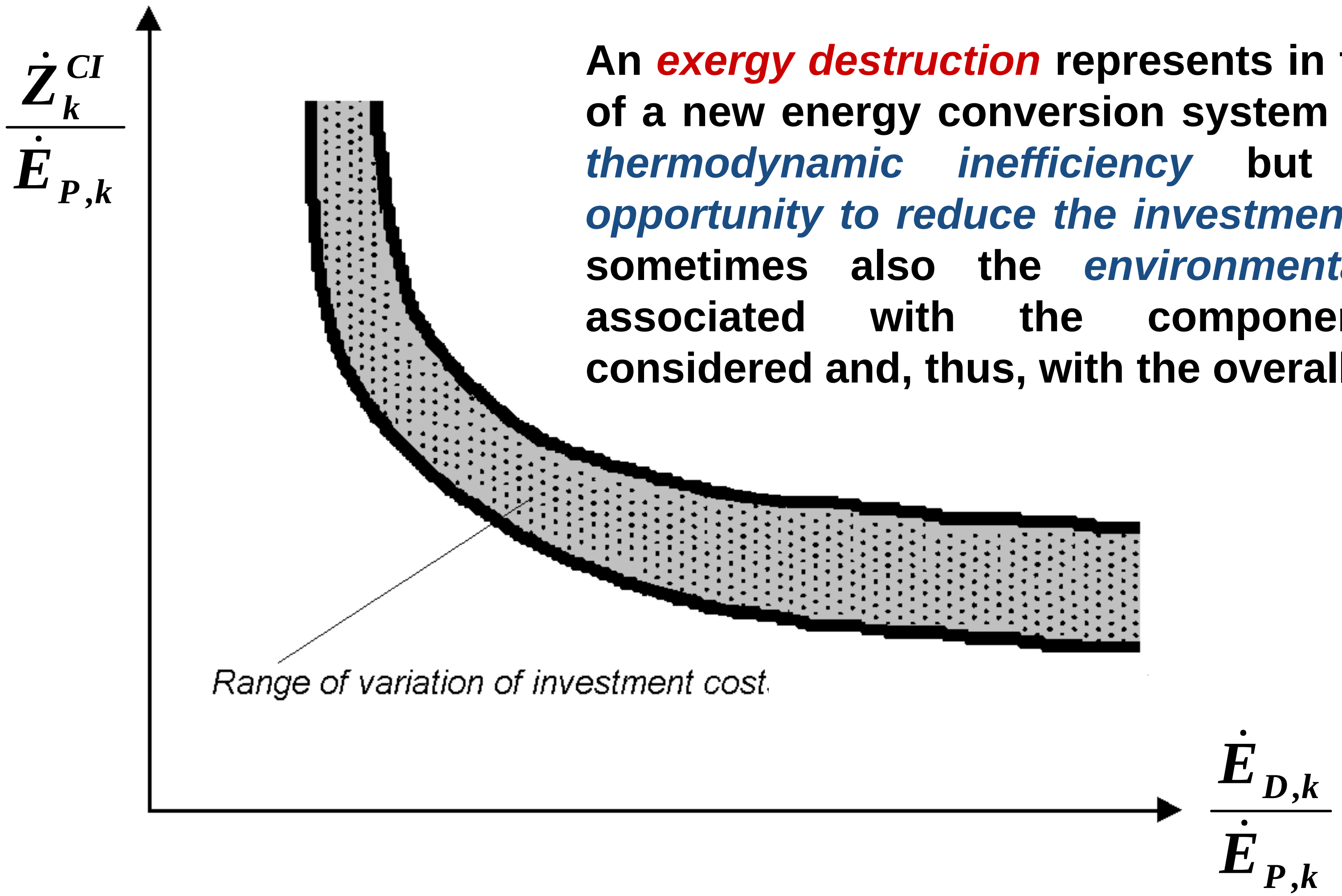
- **the *real thermodynamic inefficiencies* and the processes that cause them,**
- **the *costs associated with equipment and thermodynamic inefficiencies* as well as the connection between these two important factors,**
- **the *environmental impact associated with equipment and thermodynamic inefficiencies* as well as the connection between these two sources of environmental impact, and**
- **the *interconnections among efficiency, investment cost and component-related environmental impact* associated with the selection of specific system components**

Exergy-based methods



Basic Principle of Exergoeconomics

An *exergy destruction* represents in the design of a new energy conversion system not only a *thermodynamic inefficiency* but also an *opportunity to reduce the investment cost* and sometimes also the *environmental impact* associated with the component being considered and, thus, with the overall system.



Introduction – sCO2

The idea of developing supercritical CO_2 power cycles and applying them to industrial processes became increasingly popular in the last decade.

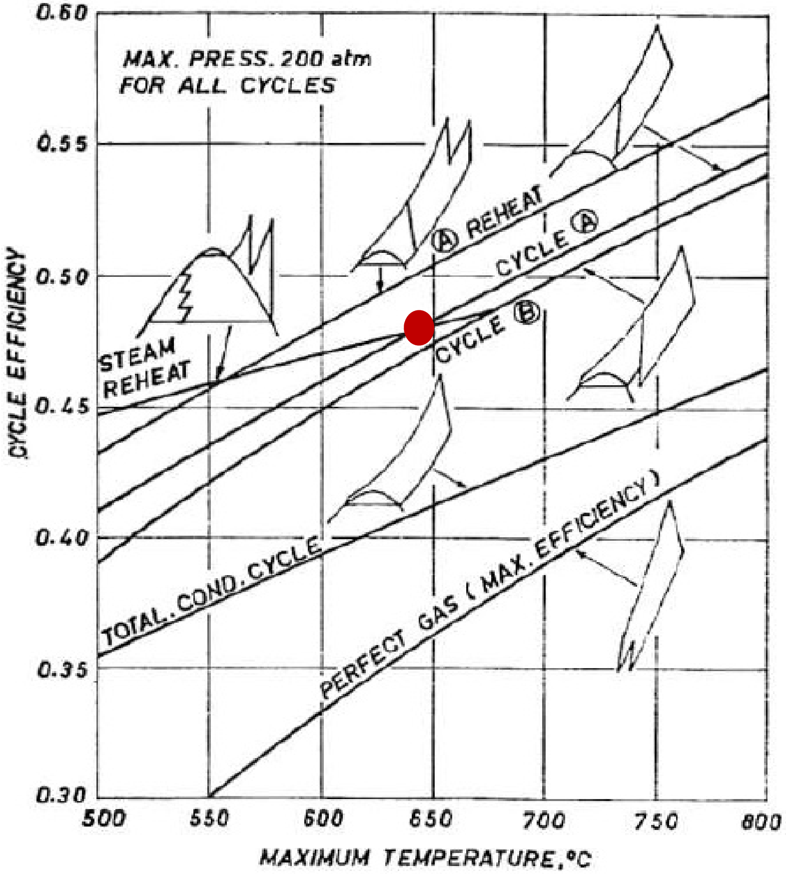
The potential for the application of supercritical CO_2 cycles is high for both *power generation systems* (Angelino, 1968) and *refrigeration systems* (Lorentzen, 1994) .

***Significant research* has been done in this field, including**

- **the development of new thermodynamic cycles,**
- **investigation of specific equipment, and**
- **parametric optimization of power systems.**

Case Study – Power Cycles

T_0=15^{o}C



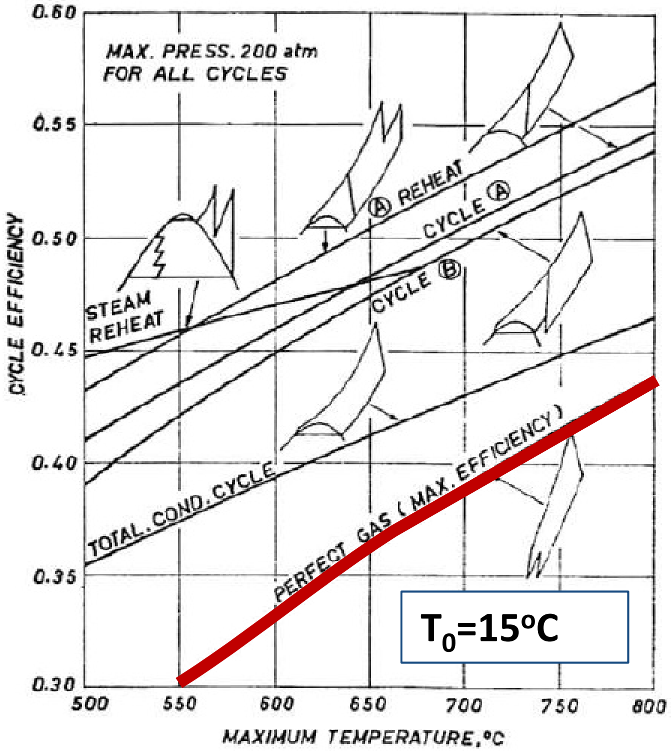
Angelino, 1968

New Challenges

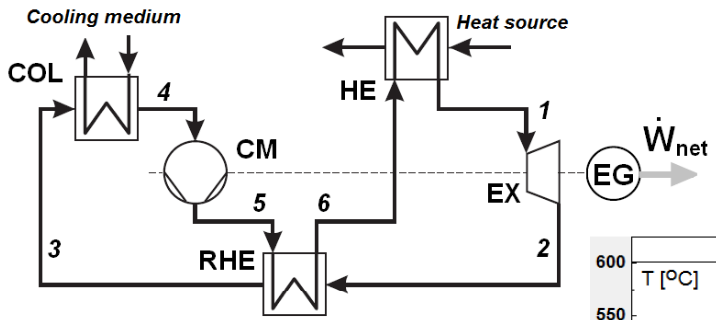
The present paper deals with the demonstration of the application of advanced exergy-based methods to supercritical CO_2 power cycles.

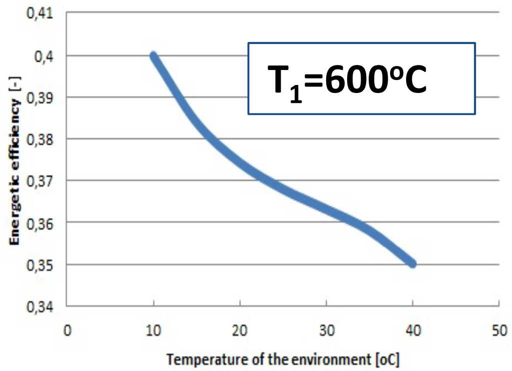
The examples used here assume power generation *when the temperature of the environment is high enough, so that a simple CO_2 cycle must operate above the critical temperature* of CO_2 (i.e., >31.1 °C).

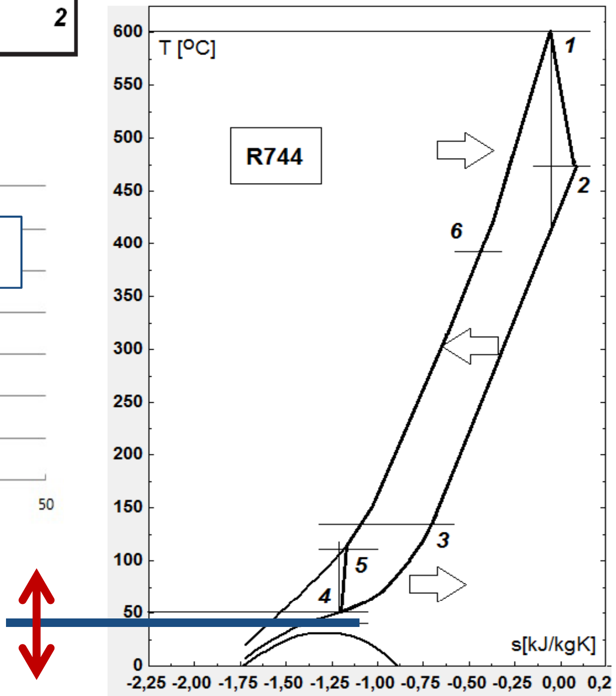
Then none of the known condensation cycles can be applied.

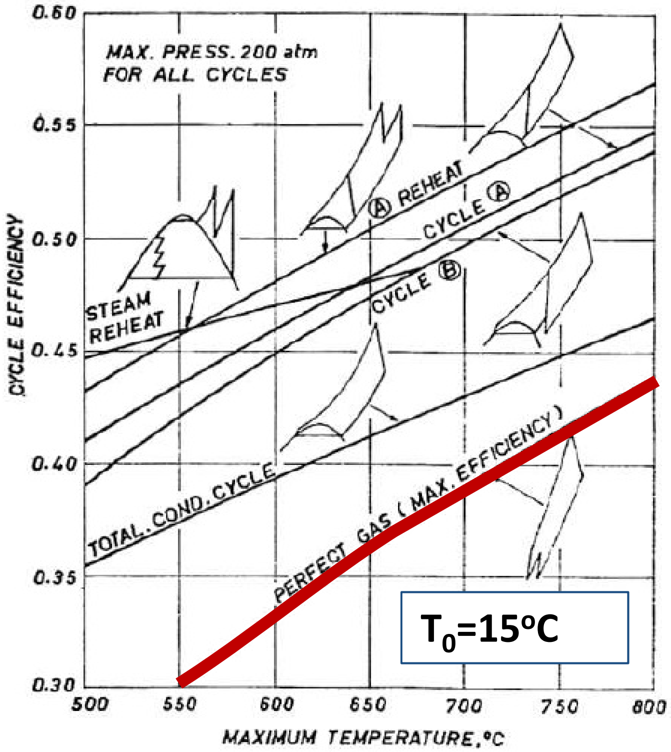


Case Study



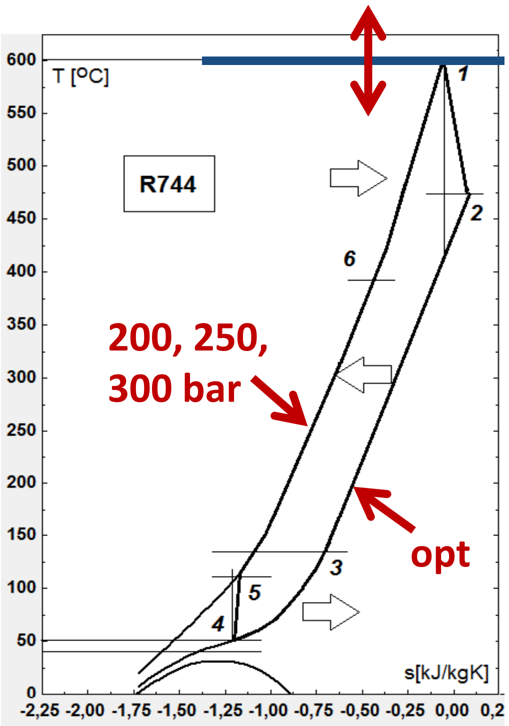


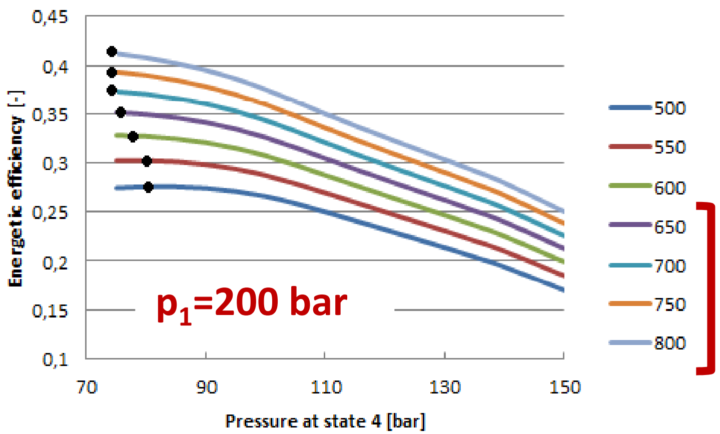


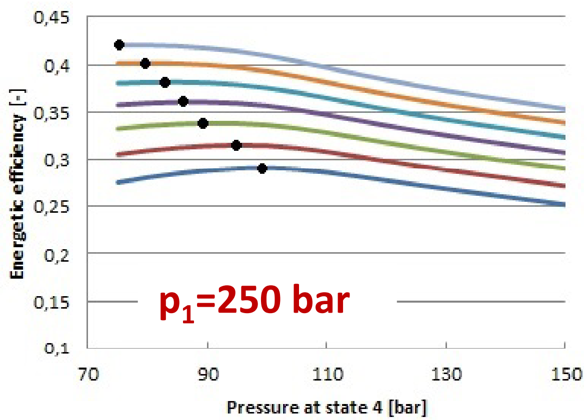


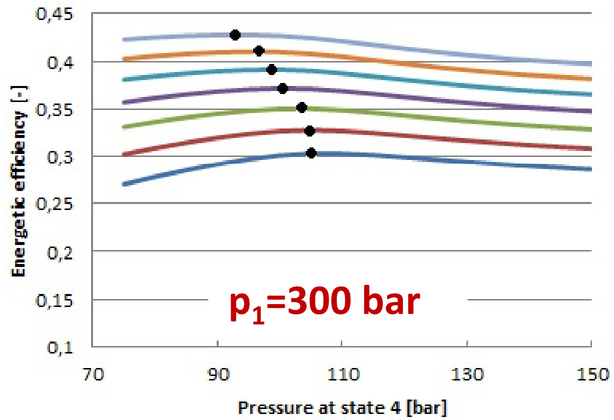
The temperature of the environment is high enough, so that a simple CO_2 cycle must operate above the critical temperature **of CO_2 (i.e., >31.1 °C)**

Case Study: Sensitivity Analysis

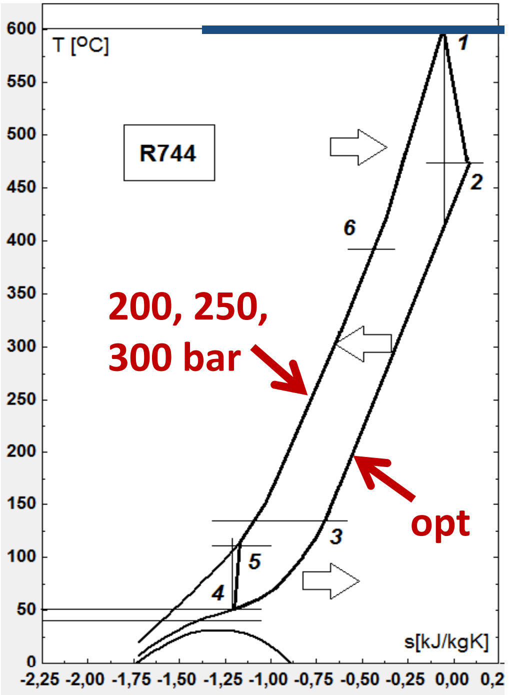








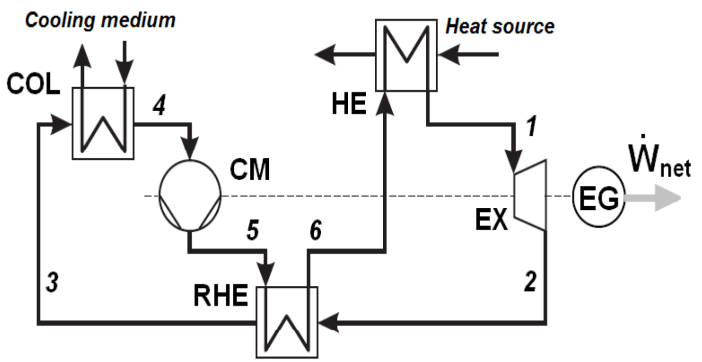
Case Study: Base Case

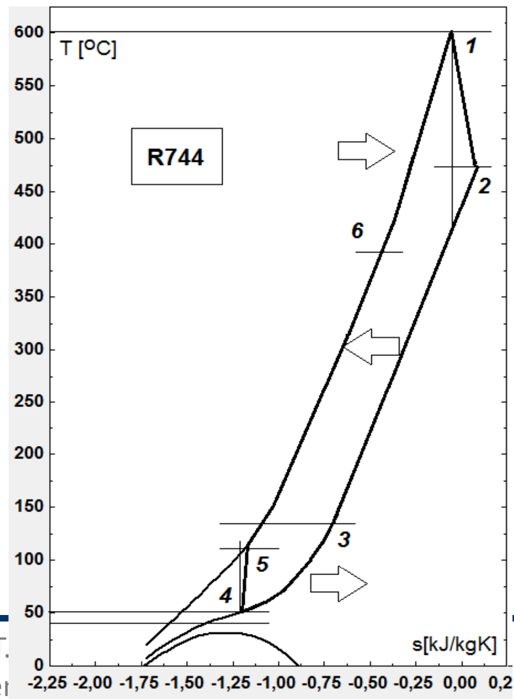


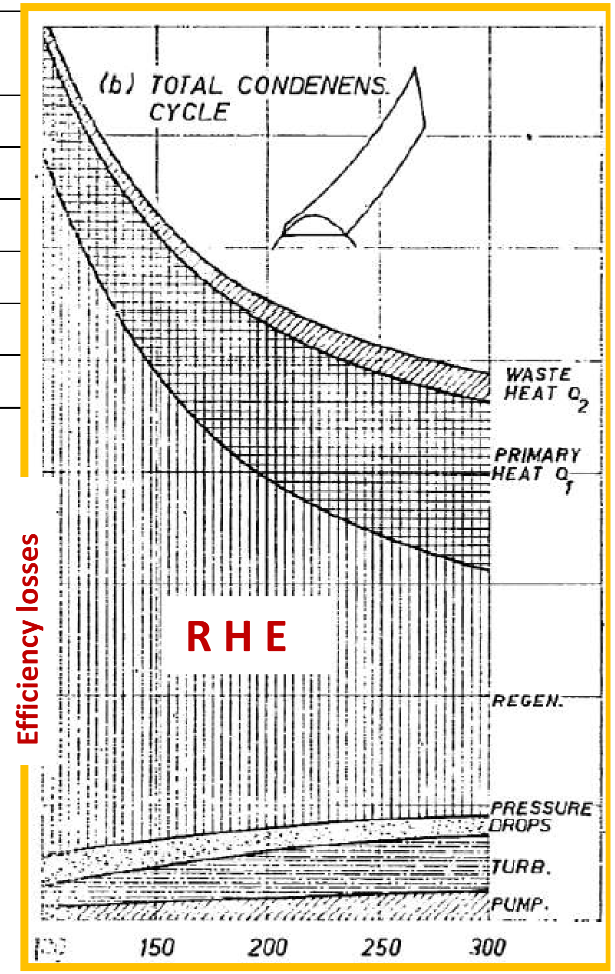
p_1 [bar]	p_4^{opt} [bar]	η [-]	w_{net} [kJ/kg]	$\dot{m}_{cycle}$ [kg/s]
200	75	0.33	73.15	136.7
250	90	0.34	83.95	119.1
300	105	0.35	94.97	105.3

Conventional Exergetic analysis: Results

Component	$\dot{E}_{F,k}$ [kW]	$\dot{E}_{P,k}$ [kW]	$\dot{E}_{D,k}$ [kW]
CM	4,688	4,114	574
COL	2,215	1,249	966
EX	15,377	14,689	688
HE	16,939	16,623	316
RHE	19,036	15,891	3,145
Overall system	16,939	10,000	5,689





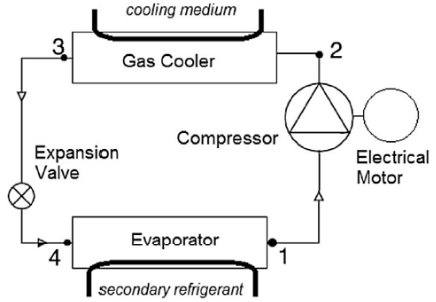


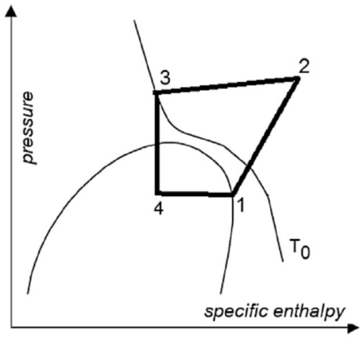
Conclusions – Power Cycles

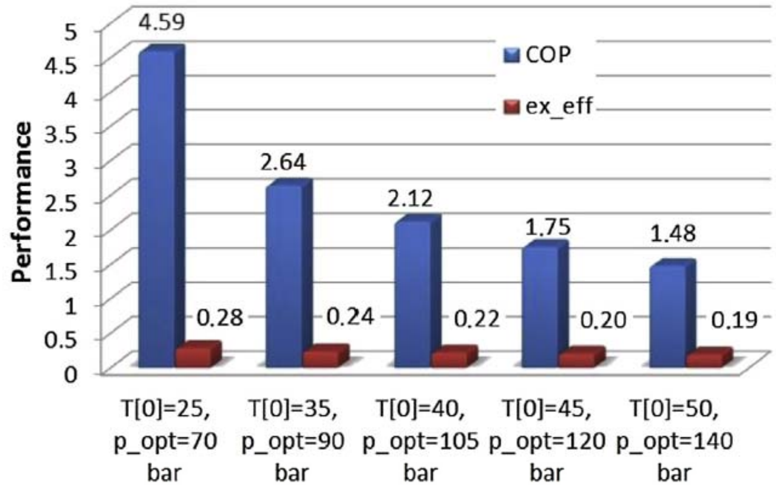
The application of an advanced exergetic analysis to a simple supercritical CO_2 cycle was demonstrated. This system can be improved by improving the components in isolation, because the *avoidable* inefficiencies caused by the components interconnections are relatively low.

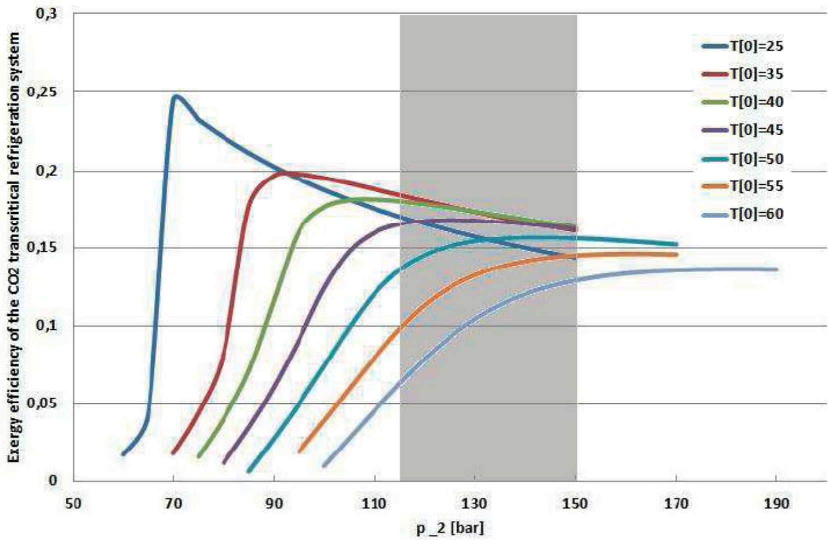
The most important component from the thermodynamic viewpoint is the regenerative heat exchanger. System designers should focus on this component.

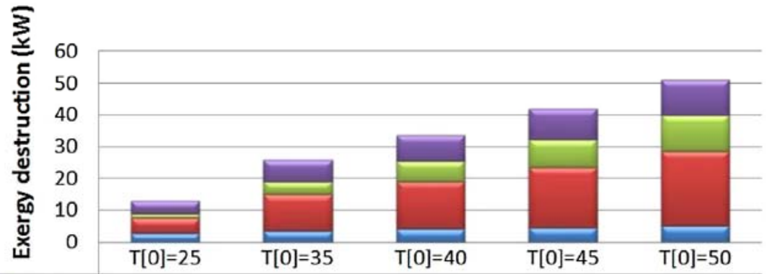
Refrigeration Applications – Exergy Analysis





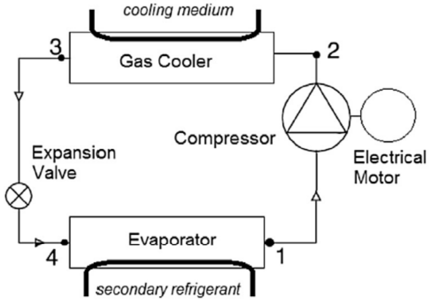


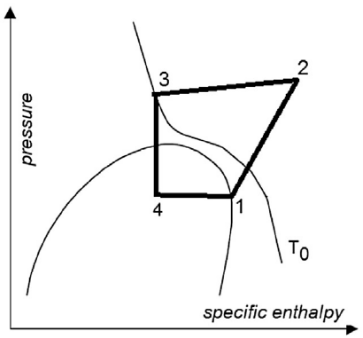


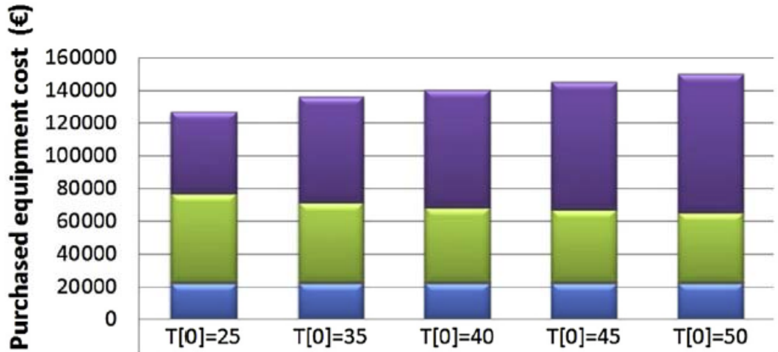


	T[0]=25	T[0]=35	T[0]=40	T[0]=45	T[0]=50
E_D_CM	3.96	6.69	8.14	9.69	11.26
E_D_GC	1.37	4.22	6.59	8.74	11.47
E_D_EXV	4.75	11.27	14.75	18.95	23.27
E_D_EV	2.97	3.76	4.20	4.69	5.21

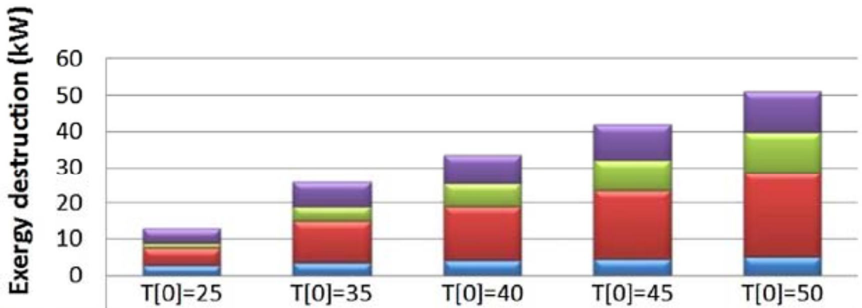
Refrigeration Applications – Cost Analysis







	T[0]=25	T[0]=35	T[0]=40	T[0]=45	T[0]=50
PEC_CM	50150	64700	71530	78080	84460
PEC_GC	54200	48800	45700	44400	42700
PEC_EXV	115	115	115	115	115
PEC_EV	22600	22600	22600	22600	22600



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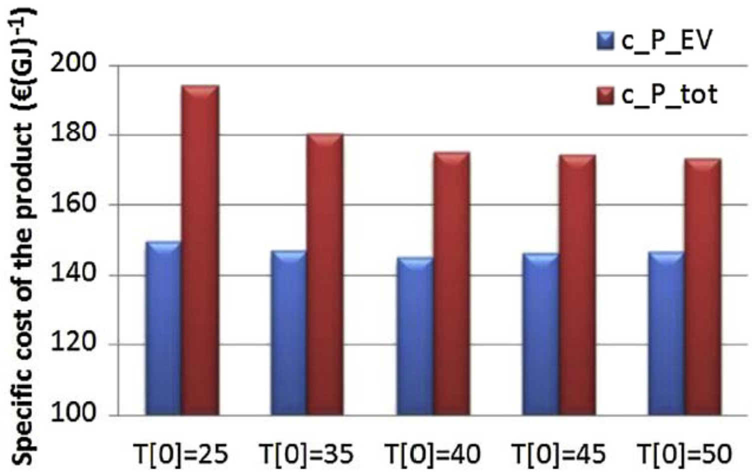
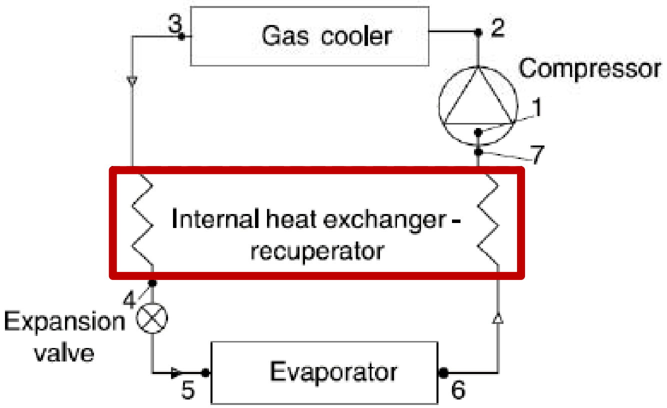
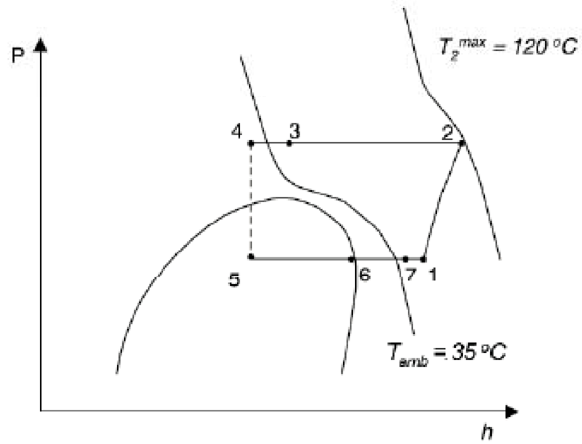
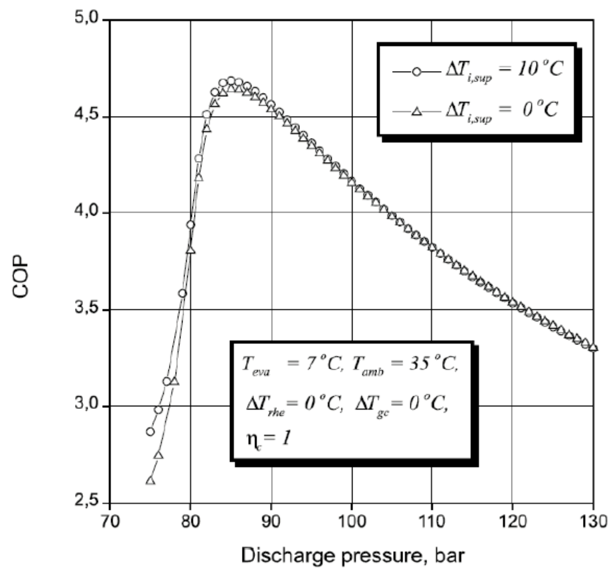


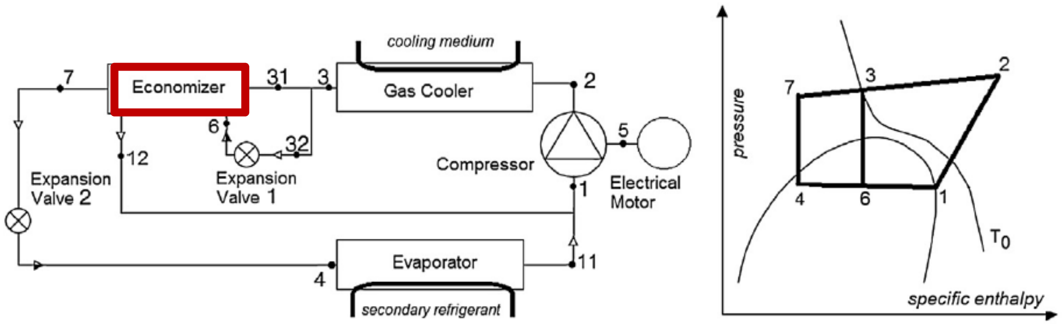
Refrigeration Applications – Improvements

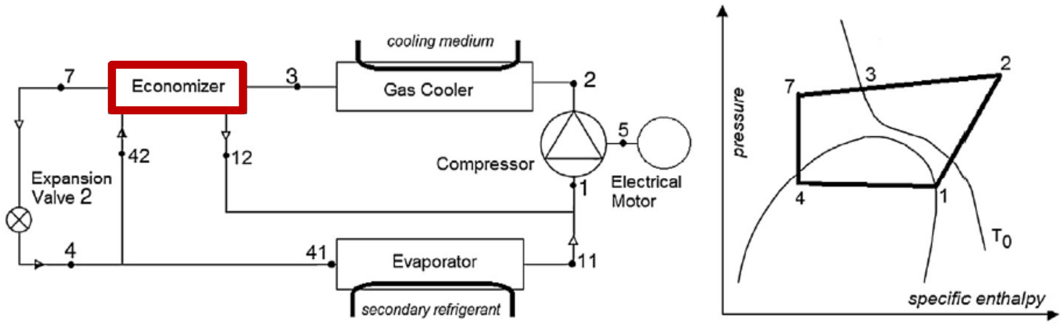






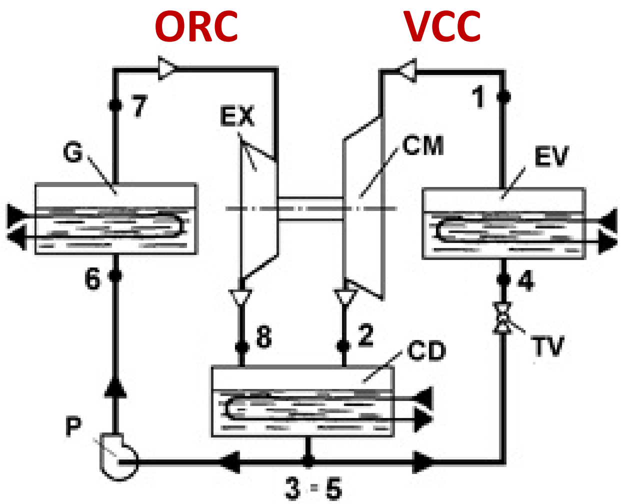
Refrigeration Applications – Improvements

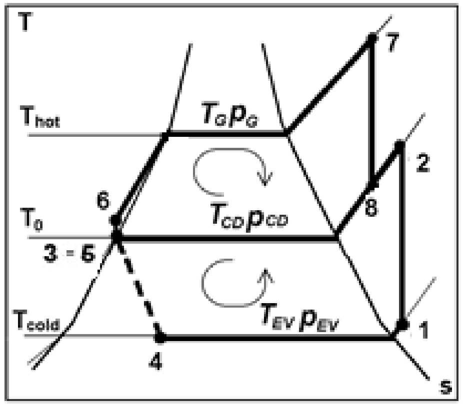




The advantage of economizer was discovered through the exergy-based evaluation. Using both options, the *purchased equipment costs of the overall machine increases by 4-5%,* while the *total cost of the final product decreases for 13-14%.* Based on conducted evaluation we can conclude that for countries with hot climates, the one-stage sCO2 refrigeration machine should include the economizer as an auxiliary component.

Refrigeration Applications – Heat-driven Machine



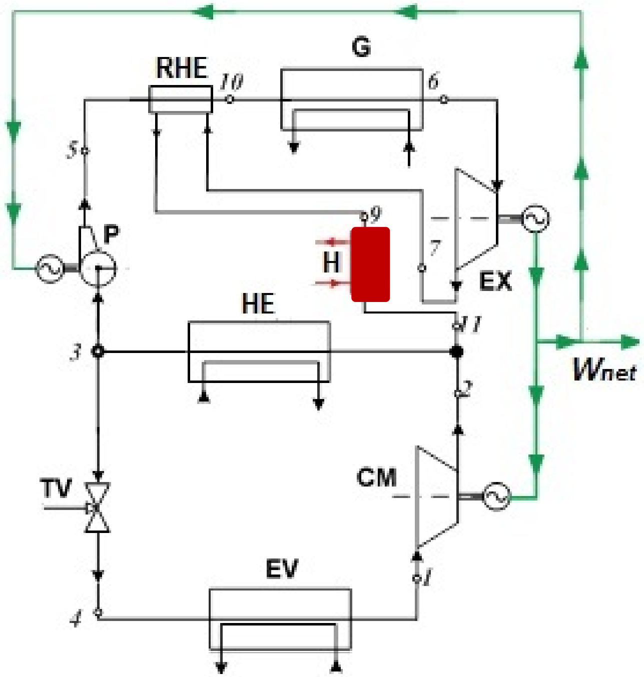


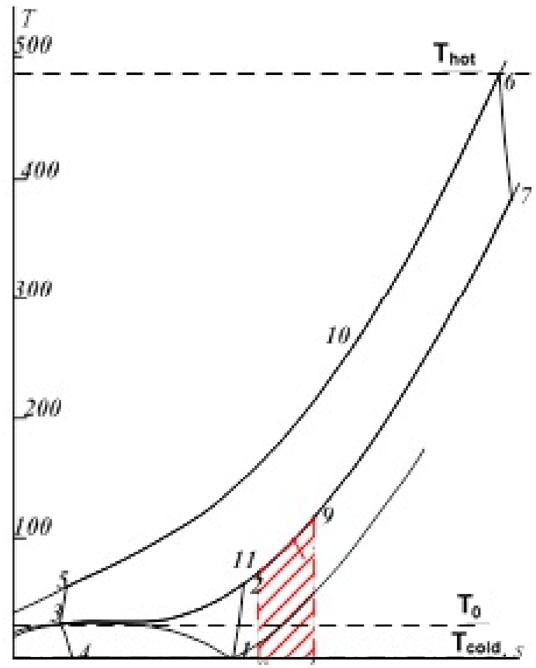
Chistiakov-Plotnikov refrigeration machine, Patent USSR 1952

In the concept to be presented here deals with the extended idea of the Chistiakov-Plotnikov refrigeration machine that includes the following:

- **CO_2 is the working fluid,**
- **VCC is replaced with a Supercritical Refrigeration Cycle (SRC), and**
- **ORC is replaced with a closed-cycle gas turbine system.**

Refrigeration Applications – Heat-driven Machine



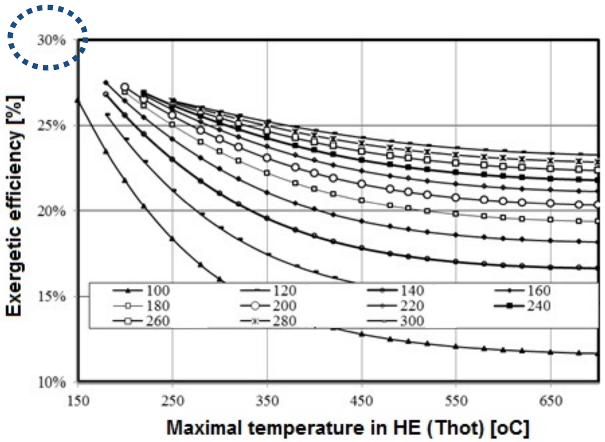


- The excess power $\dot{W}_{net}$ is generated because $\dot{W}_{\substack{direct\\cycle}} > \dot{W}_{\substack{ref\\cycle}}$;

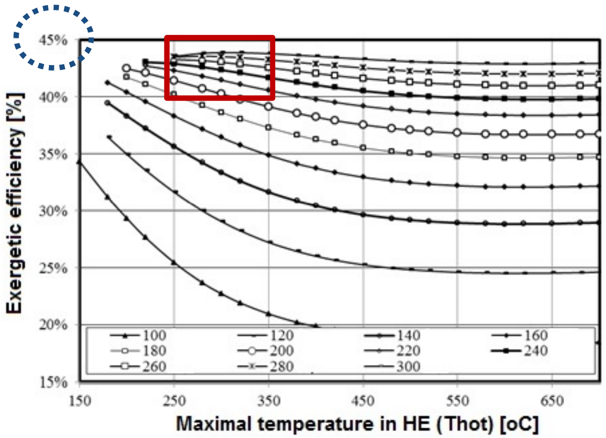
  $\dot{W}_{net}$ is the first product stream (positive effect), and
- The heat produced within the heater (H) represents the second thermal product (effect) of the machine, in addition to the refrigeration capacity

Refrigeration Applications – Heat-driven Machine

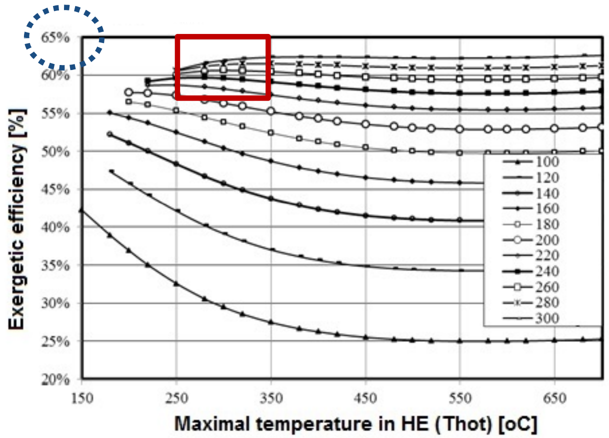
The values of $\dot{Q}_{cold}$ and $\dot{W}_{net}$ depend on the maximal temperature within the generator (T_{hot}) and pressure, but the ratio $z = \dot{W}_{net} / \dot{Q}_{cold}$ can be easily varied depends on the demand.



z=0.1



z=0.5



z=0.9

Conclusions

A novel tri-generation concept of a combined cycle coupled with ORC and SRC with R744 as working fluid has been introduced and evaluated using exergy analysis.

Future investigations will include the evaluation of more complex configurations and the application of economic and exergoeconomic analyses in order to identify the configurations and the system parameters that will lead to a lower cost of the generated products.

Thank you

for your attention

Exergetic Variables: E_P and E_F

Exergy of product: $\dot{E}_P$

The desired result, expressed in exergy terms, achieved by the system (the *k*-th component) being considered.

Exergy of fuel: $\dot{E}_F$

The exergetic resources expended to generate the exergy of the product.

The concepts of product and fuel are used in a consistent way not only in *exergetic analyses* but also in the *exergoeconomic* and *exergoenvironmental* analyses.

Exergetic Variables: E_D and E_L

Exergy destruction: $\dot{E}_D$

Exergy destroyed due to irreversibilities within a system (the k-th component).

Exergy loss: $\dot{E}_L$

Exergy transfer to the system surroundings. This exergy transfer is not further used in the installation being considered or in another one.

Exergy balance:

$$\dot{E}_F = \dot{E}_P + \dot{E}_D \left(+ \dot{E}_L \right)$$

$\dot{E}_D$ and $\dot{E}_L$ are absolute measures of

the thermodynamic inefficiencies.

Exergetic Variables: ε and $y_{D,k}$

Relative measures of the thermodynamic inefficiencies:

Exergetic efficiency: **The ratio between exergy of product and exergy of fuel**

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}}$$

Exergy destruction ratio **for the *k*-th component**

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}}$$