



SOCIÉTÉ FRANÇAISE DE THERMIQUE
Journée Thématique
Paris, 22 Novembre 2013



Modélisation et optimisation des technologies de récupération de chaleur : Exemple de l'ORC*

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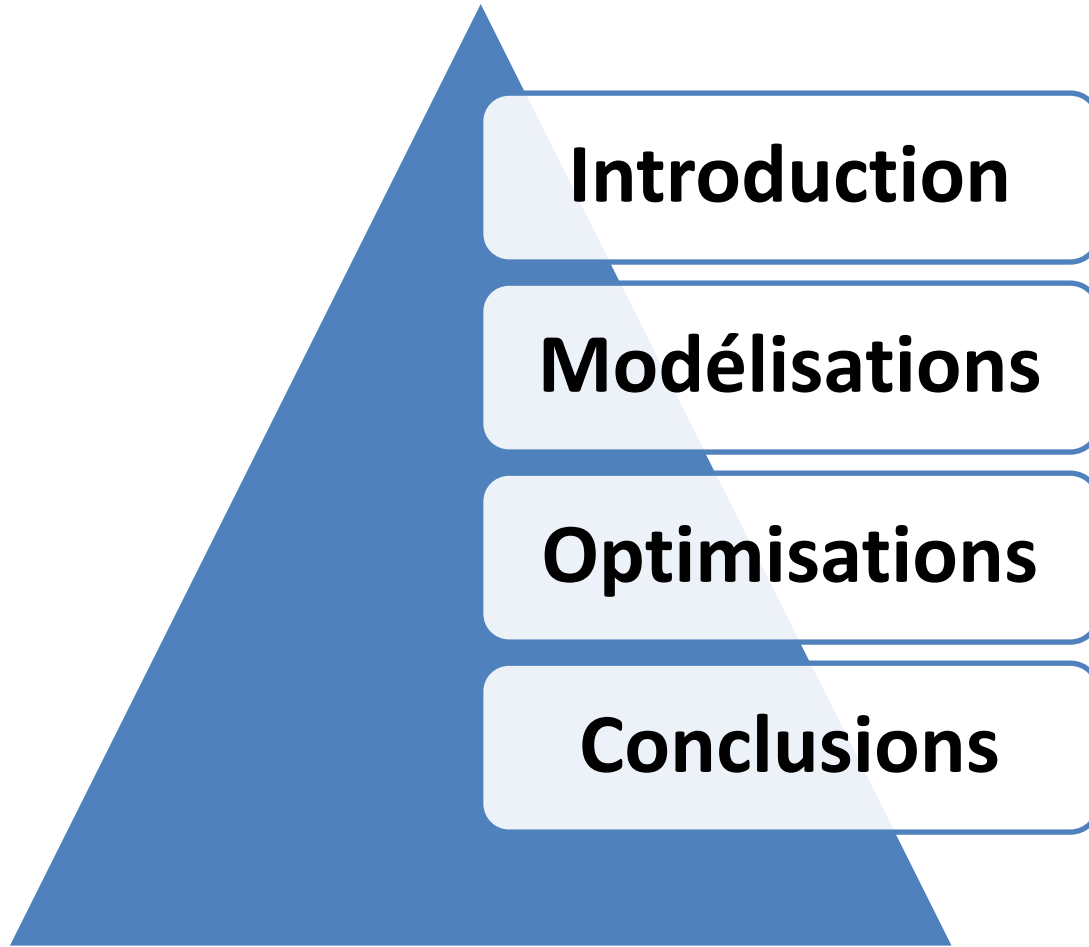
**Organic Rankine Cycle*



*Chemins Énergétiques pour la Récupération
d'Énergie dans les Systèmes industriels*



Sommaire



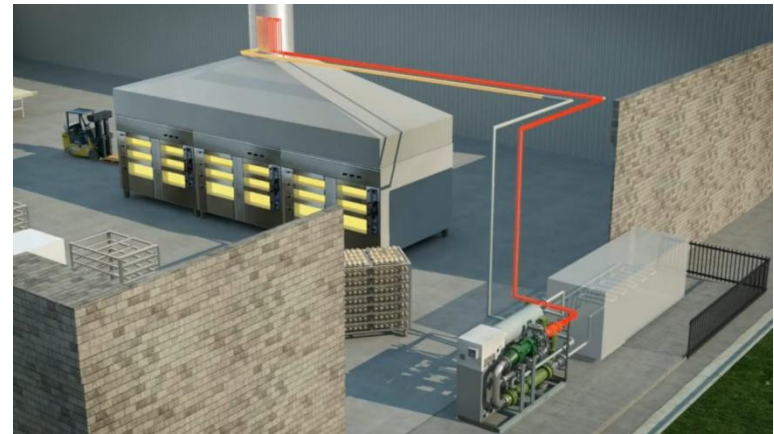
Introduction

Rejets thermiques industriels



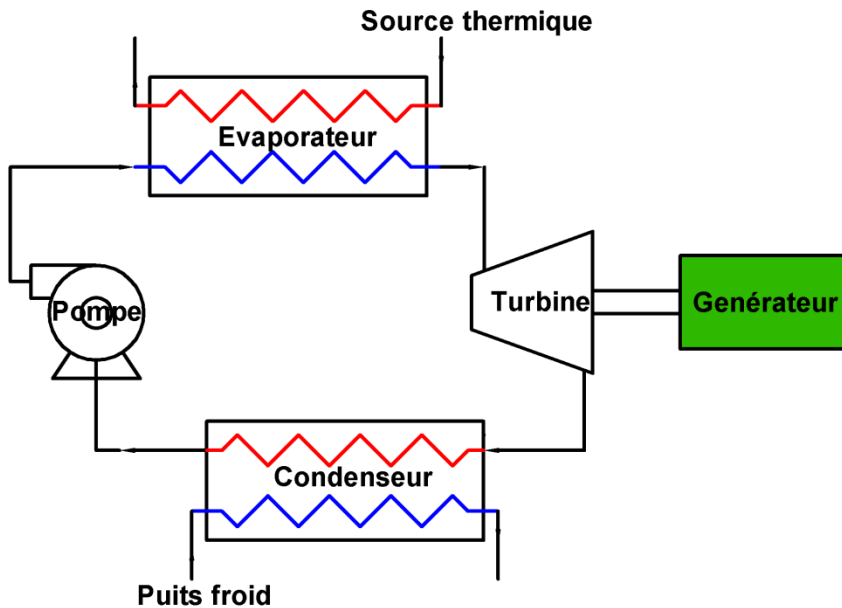
20 – 50 % d'énergie d'alimentation
60 % chaleur perdue $T < 230 \text{ }^{\circ}\text{C}$
90 % chaleur perdue $T < 316 \text{ }^{\circ}\text{C}$

Récupération de chaleur



Amélioration d'efficacité
énergétique: 10 – 50 %
Réduction de pollution thermique

Introduction



Cycle simple de Rankine

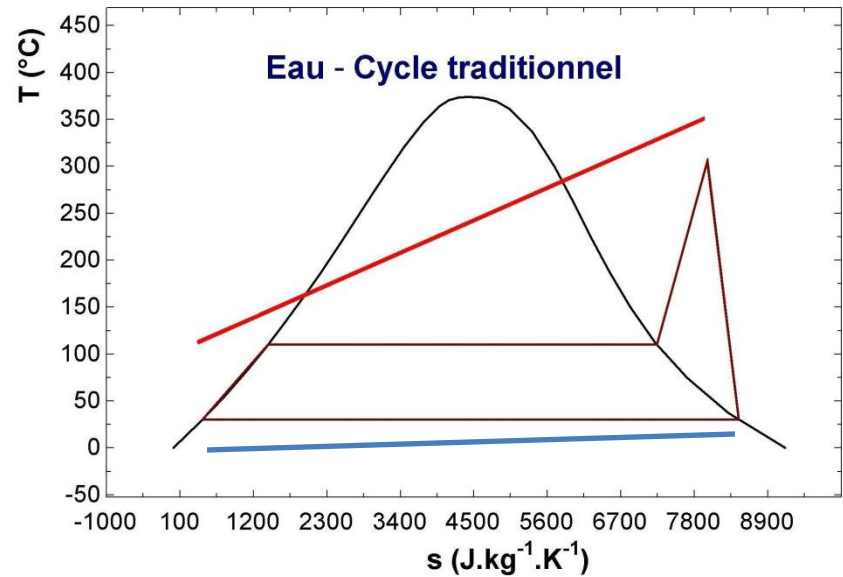


Diagramme T-s de l'eau

Introduction

$T_b = 100 \text{ }^\circ\text{C}$

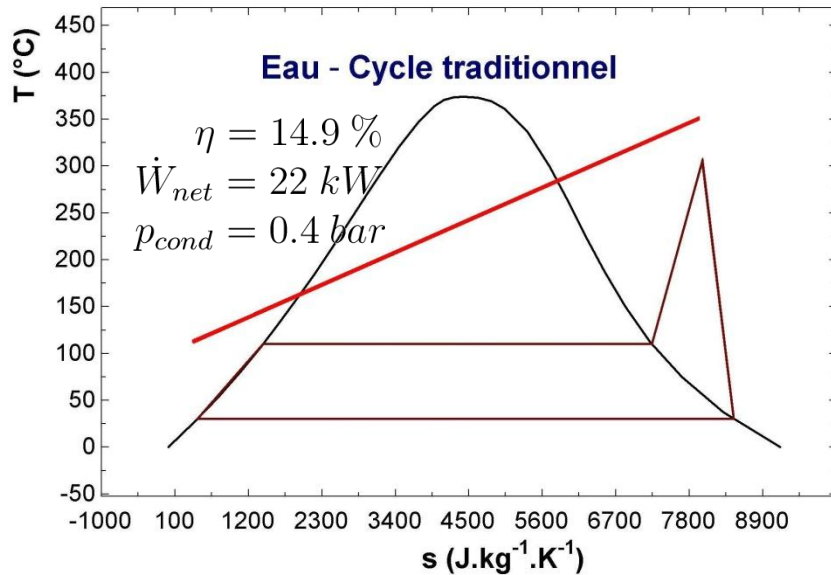


Diagramme T-s de l'eau

$T_b = 15.1 \text{ }^\circ\text{C}$

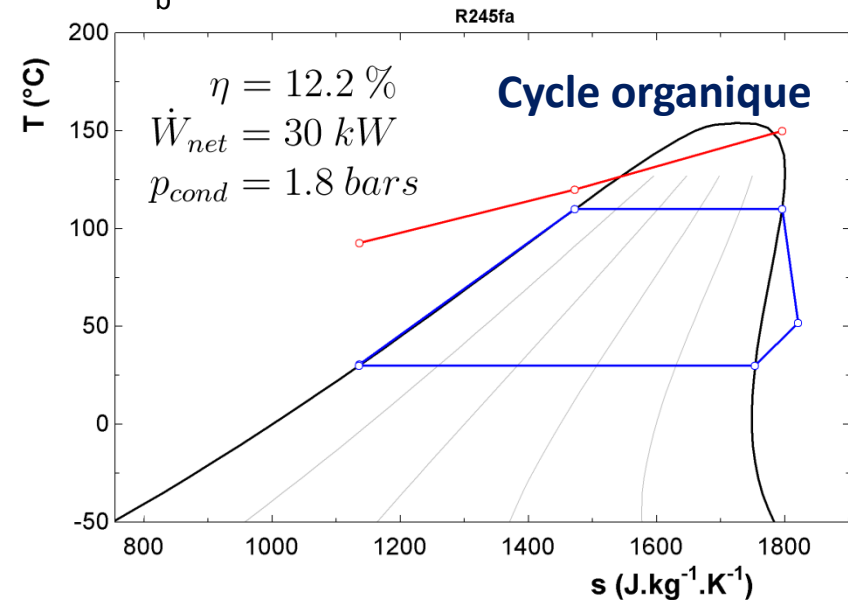
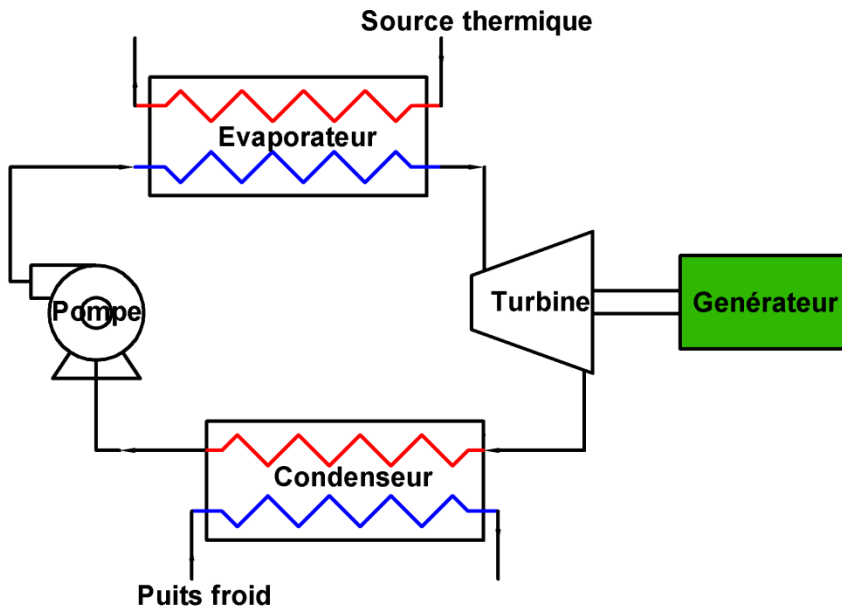
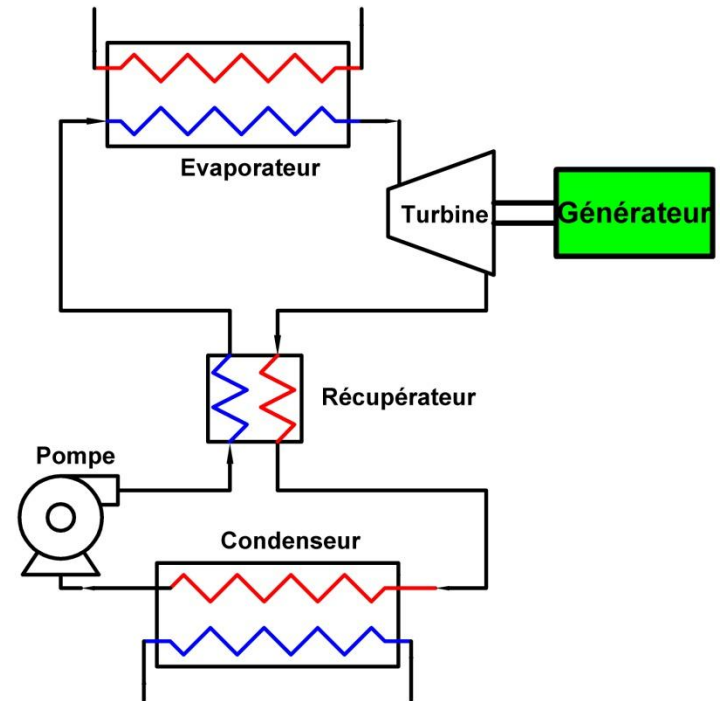


Diagramme T-s du R245fa

Introduction



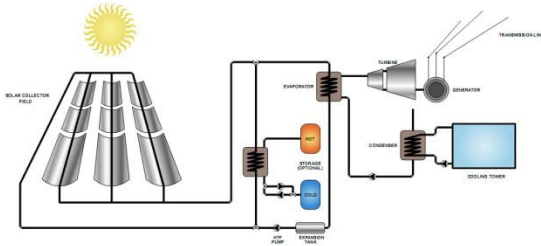
Cycle simple de Rankine



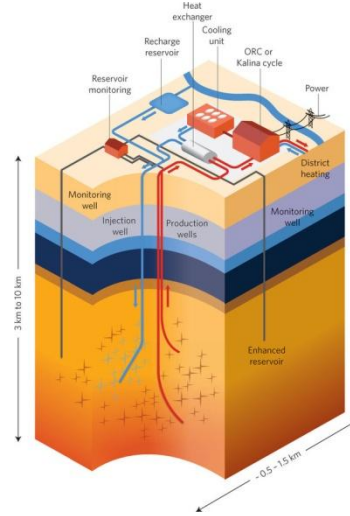
Cycle de Rankine avec récupérateur

Introduction

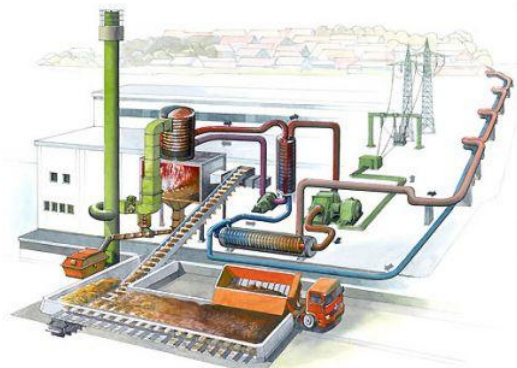
Applications



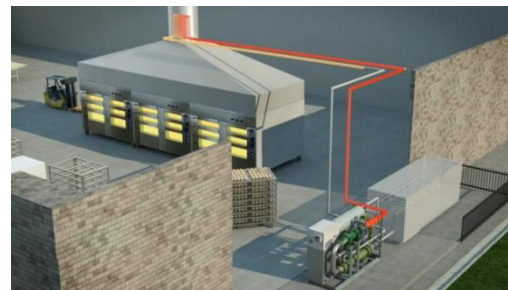
Solaire



Géothermie



Biomasse



Récupération de chaleur

Fournisseurs



Modélisation

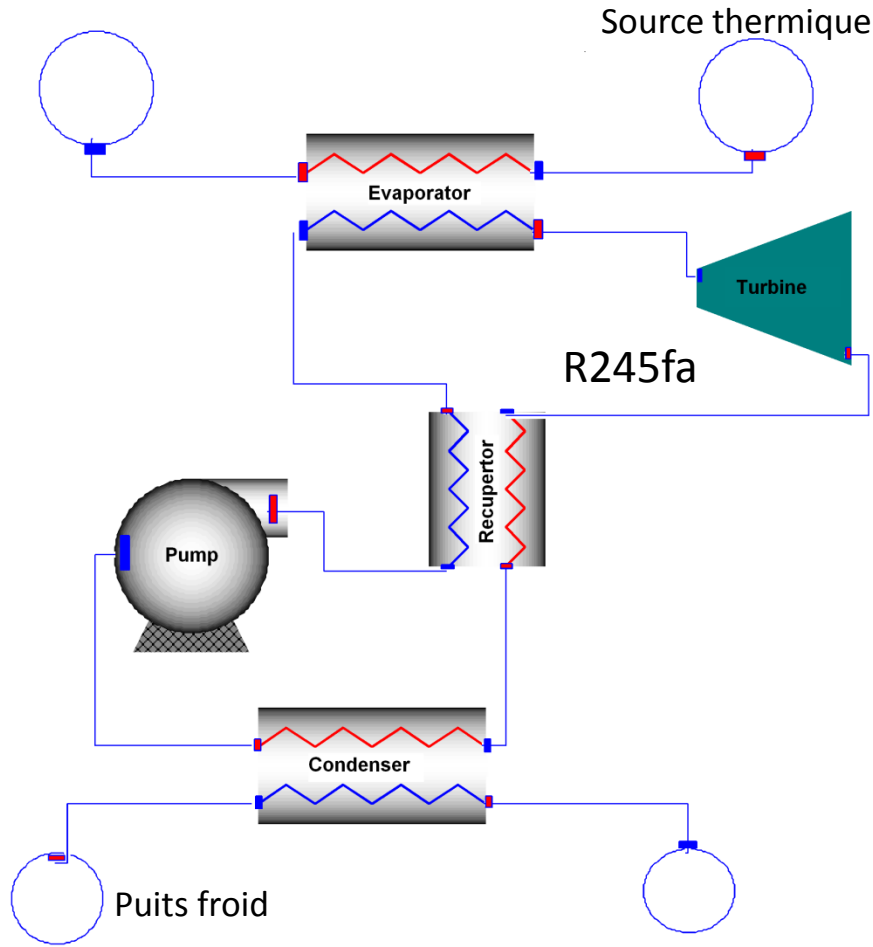
Browser

Diagram

Modelica Text

Browser

- Packages
 - ORC_New
 - ORC1
 - ORC2
 - Components
 - Stream
 - Stream_generic
 - HEX
 - Pump
 - Evaporator
 - Expander
 - Condenser
 - Recuperator
 - HeatSink
 - Models
 - SimuORC1
 - SimuORC2
 - ORC_Simple
 - ORC_IHE**
 - EvapTest
 - CondTest
 - PumpTest
 - Nusselt
 - Quality
 - hc_boiling
 - hc_cond
 - Dp_sp
 - hc_boiling_EES
 - Cost_p
 - F_BM
 - Dp_frictp
 - Dp_mom
 - Sigma
 - TestFunction
 - TestFunction2
 - TestFunction3
 - Icons



```

model ORC_IHE "ORC with Internal Heat Exchanger"

/*Module cost*/
parameter Real InvestCost = 1350 "Investment Cost - Euro per kWe";
parameter Real LifeSpan = 10 "Return on Investment - Years";
parameter Real OperatingHours = 8000 "Annual Operating Hours - h";
parameter Real ElecCost = 0.07 "Electricity Feed-In Tariff - Euro per kWh";
parameter Real Maintenance = 0.02;

Modelica.SIunits.Power W_flow "mechanical power output";
Modelica.SIunits.Power W_elec "electrical power output";
Real eta_I "first-law efficiency";
Real eta_Carnot "Carnot efficiency";
Real eta_II "second-law efficiency";
Real eta_Ex "exergy efficiency";
Real Cost_BM "bare modult cost";
Real Cost "purchased equipment cost";
Real Cost_kW "purchased equipment cost per kW";

end ORC_IHE
    
```

```

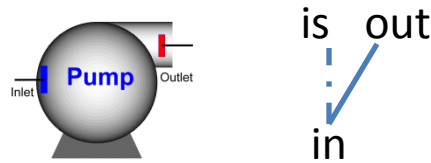
evaporator.P_evap = pump.P_evap;
evaporator.T_cond = condenser.T_cond;
expander.T_cond = condenser.T_cond;
/* cycle performance*/
W_flow = expander.W_flow - pump.W_flow;
W_elec = expander.W_elec - pump.W_elec;
eta_I = W_flow/evaporator.Q_flow;
eta_Carnot = 1-heatSink.T/heatSource.T;
eta_II = eta_I/eta_Carnot;
eta_Ex = W_flow/evaporator.Ex_flow_h;
// Cost
Cost_BM = condenser.Cost_BM + expander.Cost_BM + evaporator.Cost_BM + pump.Cost_BM;
Cost = condenser.Cost + expander.Cost_p + evaporator.Cost + pump.Cost;
Cost_kW = Cost/W_elec;

/*EIGroup definition*/
ORC_IHE.FactMin = 0;
ORC_IHE.FactMax = 100;
(ORC_IHE.CostFix,ORC_IHE.CostMult)=CERESInfo.Indicators.Economic.AnnualCost(0,InvestCost,
ORC_IHE.FactVariable = true;

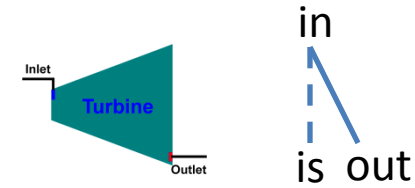
/*EStream definition*/
cold_Stream.Tin = evaporator.wf_In.Info.T;
cold_Stream.Tout = evaporator.wf_Out.Info.T;
cold_Stream.DTmin = 2 "to verify";
cold_Stream.QFlow = evaporator.Q_flow;
cold_Stream.htc = 1;
cold_Stream.massFlow = evaporator.m;

hot_Stream.Tin = condenser.wf_Out.Info.T;
hot_Stream.Tout = condenser.wf_In.Info.T;
hot_Stream.DTmin = 2 "to verify";
hot_Stream.QFlow = condenser.Q_flow;
hot_Stream.htc = 1;
hot_Stream.massFlow = condenser.m;
    
```


Pompe & turbine



Pompe à pistons



Turbine à vapeur

Rendement isentropique

$$\eta_{is,p} = \frac{\dot{W}_{is}}{\dot{W}_{real}} = \frac{h_{out,is} - h_{in}}{h_{out} - h_{in}}$$

Puissance hydraulique

$$\dot{W}_p = \dot{m}_{wf}(h_{out} - h_{in})$$

Puissance électrique

$$\dot{W}_{elec} = \dot{W}_p / \eta_{motor}$$

Flux d'exergie

$$\dot{E}x_p = \dot{m}_{wf}(h_{out} - h_{in} - T_0(s_{out} - s_{in}))$$

Exergie détruite

$$\dot{I}_p = \dot{m}_{wf}T_0(s_{out} - s_{in})$$

$$\eta_{is,t} = \frac{\dot{W}_{real}}{\dot{W}_{is}} = \frac{h_{in} - h_{out}}{h_{in} - h_{out,is}}$$

$$\dot{W}_t = \dot{m}_{wf}(h_{in} - h_{out})$$

$$\dot{W}_{elec} = \eta_{gen}\dot{W}_t$$

$$\dot{E}x_t = \dot{m}_{wf}(h_{in} - h_{out} - T_0(s_{in} - s_{out}))$$

$$\dot{I}_t = \dot{m}_{wf}T_0(s_{out} - s_{in})$$

Récupérateur

$$\dot{Q} = \epsilon \cdot \dot{C}_{min}(T_{hot,in} - T_{cold,in})$$

$$\dot{I} = T_0[\dot{m}_{wf}(s_{cold,out} - s_{cold,in}) - \dot{m}_{ex}(s_{hot,in} - s_{hot,out})]$$

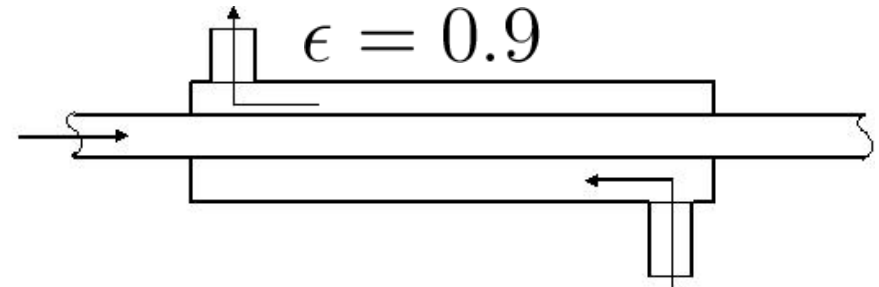
$$\Delta_{LMTD} = \frac{(\Delta T_1 - \Delta T_2)}{\ln \frac{\Delta T_1}{\Delta T_2}}$$

$$\dot{Q} = UA\Delta_{LMTD}$$

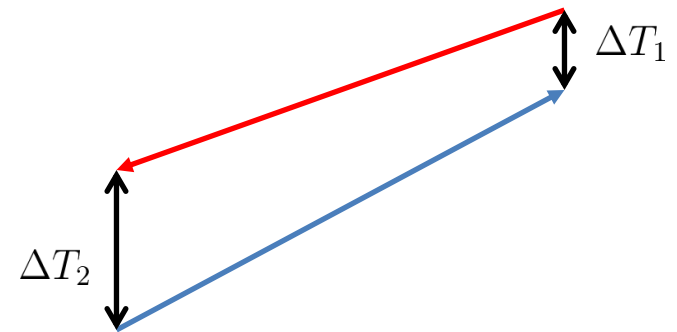
$$U = \left(\frac{1}{h_o} + R_{f,o} + \frac{d_o \ln\left(\frac{d_o}{d_i}\right)}{2k_{tube}} + \frac{d_o}{h_i d_i} + \frac{d_o R_{f,i}}{d_o} \right)^{-1}$$

$$h = \frac{Nu \cdot k}{D_e}$$

$$\Delta P = \frac{f L \rho V^2}{2D_h}$$



Échangeur bitubes



Évaporateur

$$\dot{Q} = \dot{m}_{wf}(h_{wf,out} - h_{wf,in})$$

$$\dot{E}x_h = \dot{m}_{ex}[h_{ex,in} - h_{ex,out} - T_0(s_{ex,in} - s_{ex,out})]$$

$$\dot{I} = T_0[\dot{m}_{wf}(s_{wf,out} - s_{wf,in}) - \dot{m}_{ex}(s_{ex,in} - s_{ex,out})]$$

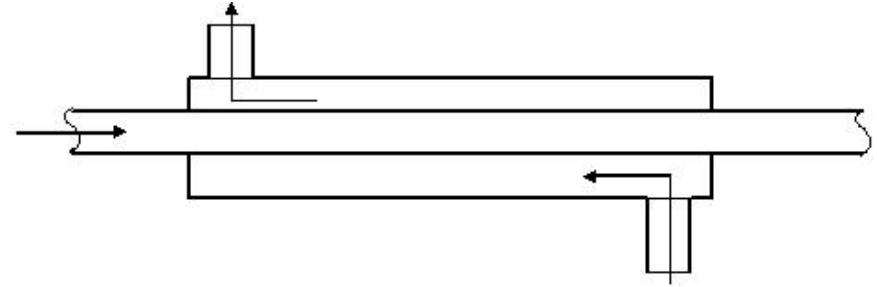
Transfert de chaleur avec changement de phase

Corrélation de Shah (1976)*

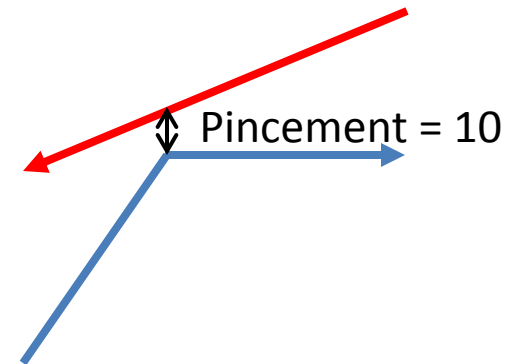
$$h_l = 0.023 \left[\frac{GD(1-x)}{\mu_{l,sat}} \right]^{0.8} Pr_{l,sat}^{0.4} \frac{k_{l,sat}}{D}$$

$$h = h_l \psi$$

ψ : facteur d'accroissement de transfert thermique



Échangeur bitubes



*Shah, M. M., "A new correlation for heat transfer during boiling flow through pipes" *ASHRAE Trans.*, Vol. 82(2), pp. 66-86, (1976)

Condenseur

$$\dot{Q} = \dot{m}_{wf}(h_{wf,in} - h_{wf,out})$$

$$\dot{I} = T_0[\dot{m}_{wf}(s_{wf,out} - s_{wf,in}) - \dot{m}_{ex}(s_{ex,in} - s_{ex,out})]$$

Transfert de chaleur avec changement de phase

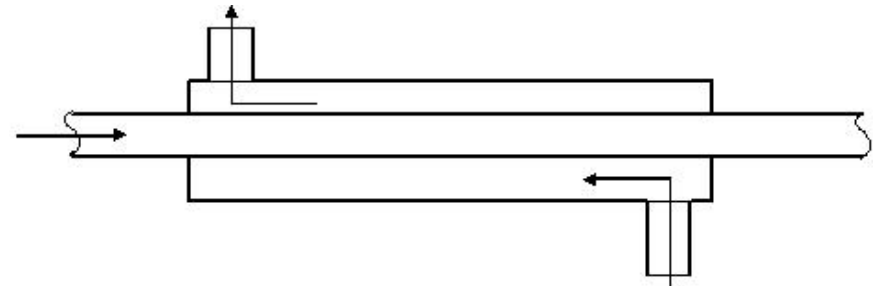
Corrélation de Dobson et Chato (1998)*

$$G > 500 \text{ kg}/(\text{s.m}^2) \text{ ou } Fr_{mod} > 20$$

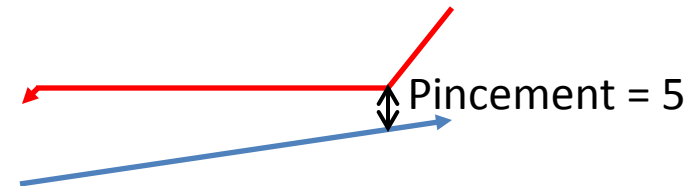
$$h = \frac{k_{l,sat}}{D} 0.023 Re_l^{0.8} Pr_{l,sat}^{0.4} \left(1 + \frac{2.22}{X_{tt}^{0.89}}\right)$$

$$G < 500 \text{ kg}/(\text{s.m}^2) \text{ et } Fr_{mod} < 20$$

$$h = \frac{k_{l,sat}}{D} \left[\frac{0.23}{1 + 1.11 X_{tt}^{0.58}} \left(\frac{GD}{\mu_{v,sat}}\right)^{0.12} \left(\frac{\Delta H_{vap}}{c_{l,sat}(T_{sat} - T_s)}\right)^{0.25} Ga^{0.25} Pr_{l,sat}^{0.25} + ANu_{fc} \right]$$



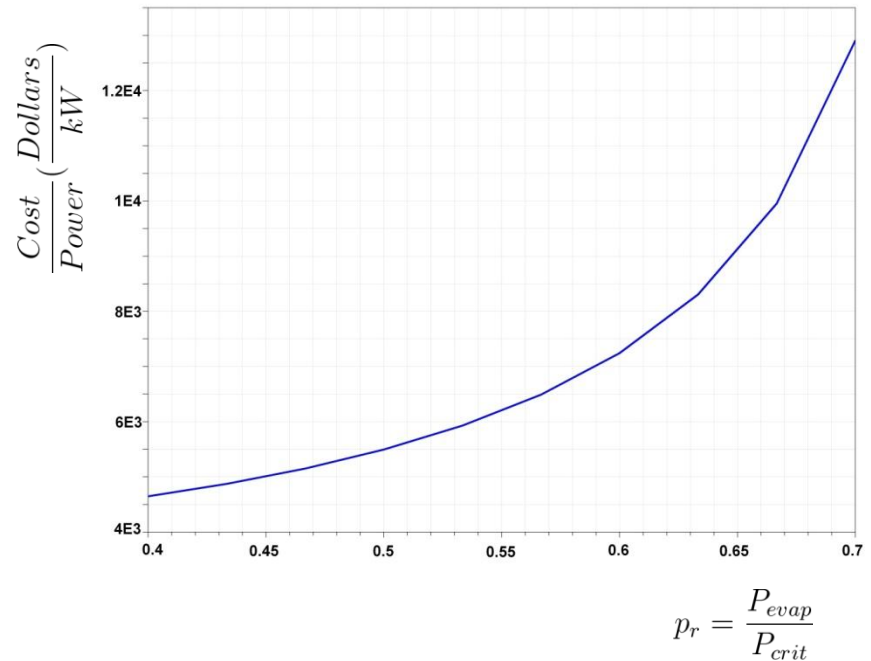
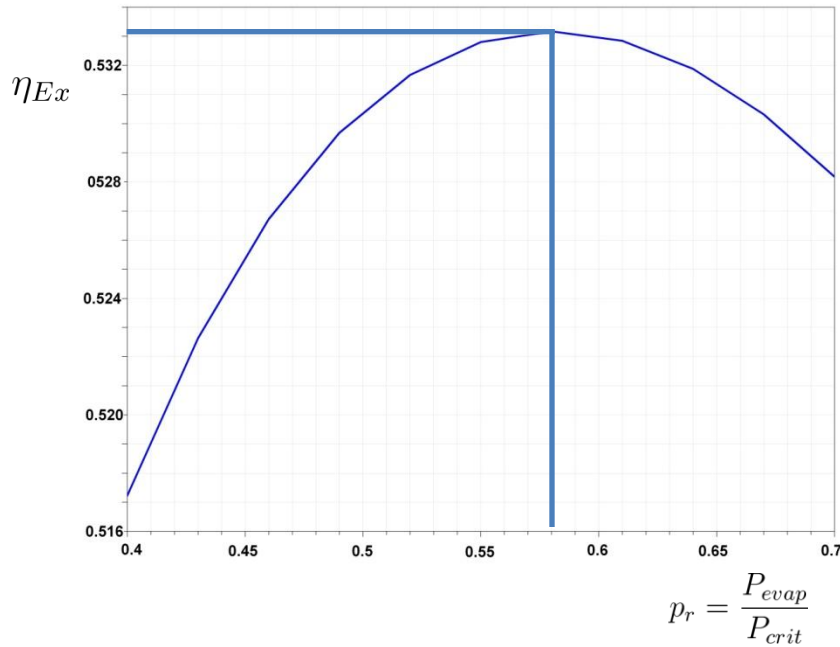
Échangeur bitubes



*Dobson, M. K. and J. C. Chato, "Condensation in smooth horizontal tubes" *Journal of Heat Transfer*, Vol. 120, pp. 193-213, (1998)

Résultats

Cycle ORC avec un récupérateur



$$\eta_{Ex} = \frac{Ex_{utile}}{Ex_{depensee}} = \frac{\dot{W}_t - \dot{W}_p}{\dot{E}x_h}$$

$$\frac{Cost}{Power} = \frac{\Sigma Cost_{equipement}}{\dot{W}_{elec}}$$

$$\dot{W}_{elec} = \dot{W}_{elec,t} - \dot{W}_{elec,p}$$

Coût d'achat à la condition basique: $\log_{10}(Cost_p^0) = K_1 + K_2 \log_{10}(A) + K_3 (\log_{10}(A))^2$

Facteur de la pression: $\log_{10}(F_p) = C_1 + C_2 \log_{10}(P) + C_3 (\log_{10}(P))^2$

Facteur de matériaux: F_m (données)

Coût d'achat d'équipement: $Cost_{equipement} = Cost_p^0 F_m F_P$

Sans vs. Avec récupérateur

	Avec récupérateur		Sans récupérateur
<i>Puissance</i> (kW)	8.9	10.1	9.8
η_I (%)	14.95	14.7	13.5
η_{Ex} (%)	53.3	53.2	49.2
<i>Coût/Puissance</i> (\$/kW)	6495.5	5924.2	5456.6
P_{evap} (bars)	20.6*	19.4	19.4*
\dot{m}_c (kg/s)	2.6	3.0	2.9
\dot{m}_{wf} (kg/s)	0.29	0.33	0.32
$T_{hs,out}$ (°C)	118.8	113.9	111.8
T_{evap} (°C)	123.6	120.5	120.5

*Rendement exergetique maximum

Optimisation

Variable optimisée	p_r $0.4 - 0.7$
Fonctions objectives	η_I η_{Ex} \dot{W}

The screenshot shows the Ceres - TravailORC software interface. The 'Optimized variables' table is as follows:

Name	Model	Value	Description	Data type	Causality	Opt Minimu
oRC_Simple.pump.p_r	CERESTotal.Utilities.ORB.Simulations.SimuORC2	0.6	reduced pressure	Real	Input	0,4

The 'Objectives' table is as follows:

Name	Model	Description	Direction	Minimum	Maximum	lg Fl.
oRC_Simple.eta_I	CERESTotal.Utilities.ORB.Simulations.SimuORC2	first-law efficiency	Maximize	-	-	N...
oRC_Simple.Wdot	CERESTotal.Utilities.ORB.Simulations.SimuORC2	ORC net power output [W]	Maximize	-	-	N...
oRC_Simple.eta_Ex	CERESTotal.Utilities.ORB.Simulations.SimuORC2	exergetic efficiency	Maximize	-	-	-

Optimisation

Algorithme « SPEA2Adapt » : un algorithme auto-adaptatif issu des algorithmes génétiques (SPEA: **S**trength **P**areto **E**volutionary **A**lgorithm)

The screenshot shows a software window titled "CERES" with a blue header bar. At the top left, there is a dropdown menu for "Algorithm" set to "SPEA2Adapt" and a "Parameters..." button. The main area contains several settings:

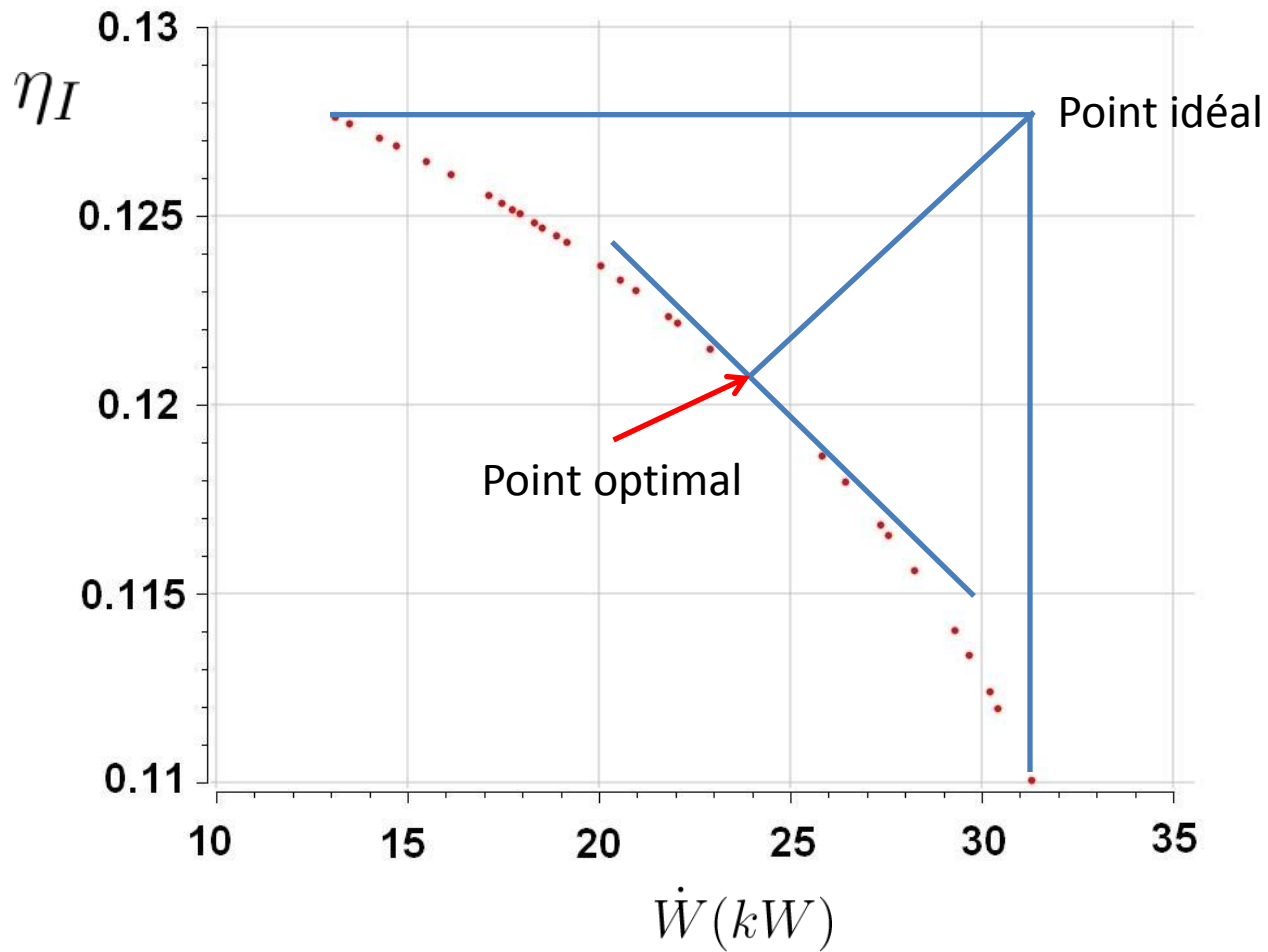
- Population size: 5
- OffSpring size/PopulationSize: 3
- Max Generations: 5
- Population saving frequency (# generations, 0 = save only final state): 1

Below these is a section titled "Pursue computation" with the following options:

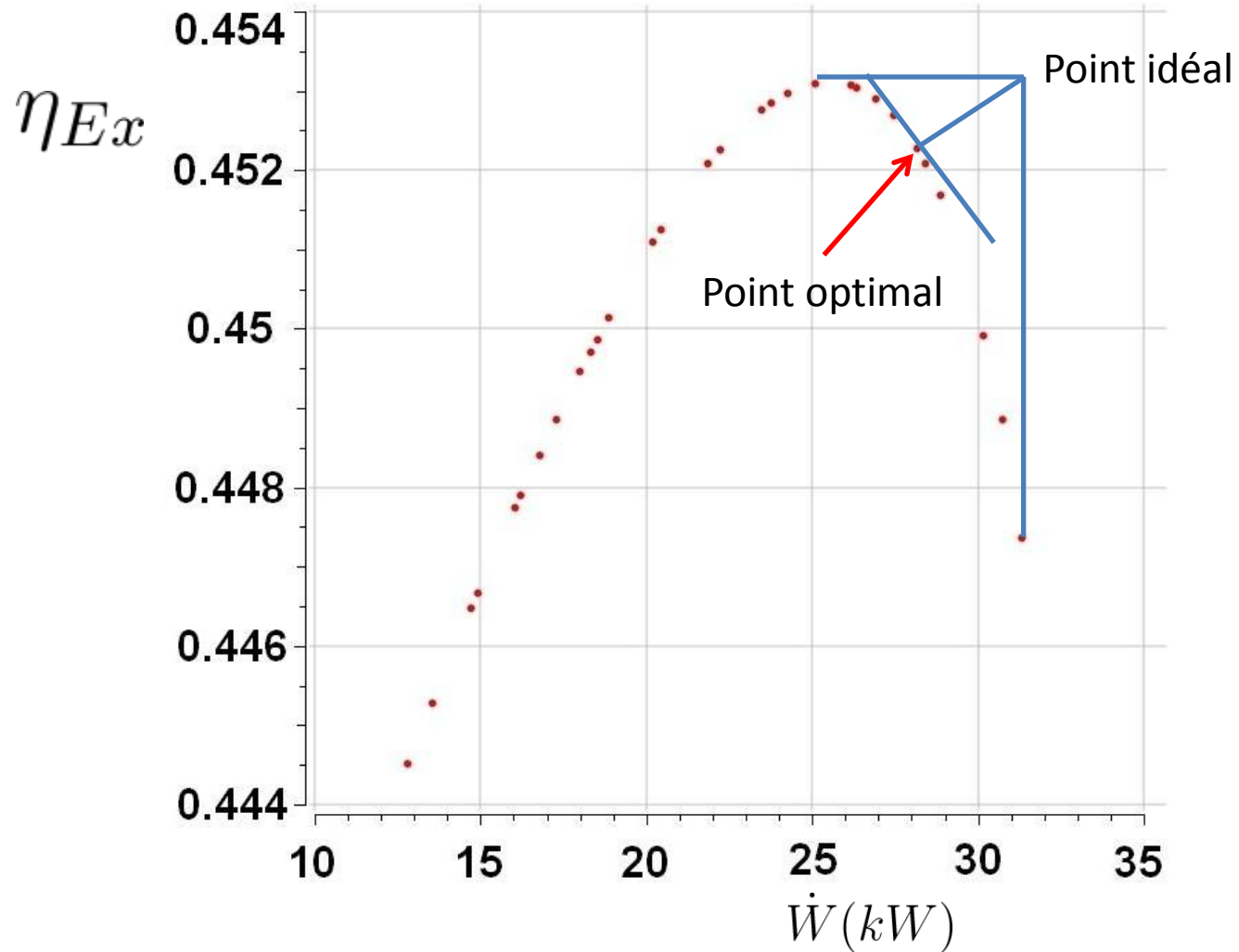
- Use start file (restart from previous result):
- Start file path (only if Use start file is checked): [text box] [Browse button (...)]
- Reinitialize StdDeviation (for pursuing optimization only):

At the bottom right, there are three buttons: "Ok", "Restore default", and "Cancel".

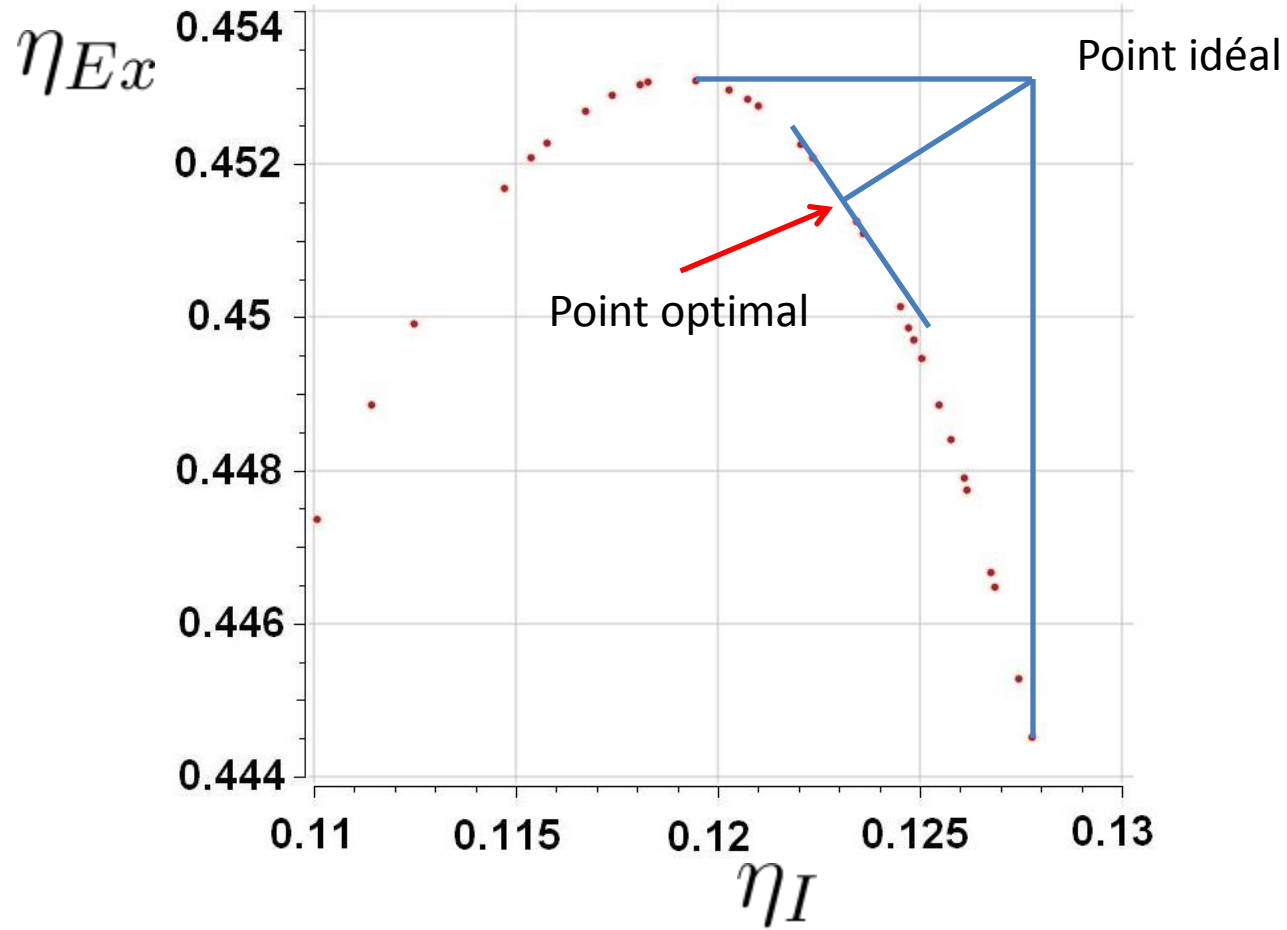
η_I vs. \dot{W}



η_{Ex} vs. \dot{W}



η_{Ex} VS. η_I



Conclusions

- Le Cycle ORC présente un intérêt certain pour la récupération de chaleur fatale à basse température.
- L'utilisation d'un récupérateur dans le cycle ORC améliore la performance globale du cycle mais augmente le coût d'investissement.
- Nous avons développé les modèles du cycle ORC et nous les avons codés en langage Modelica pour la plateforme CERES.
- La plateforme CERES, grâce aux utilitaires qu'elle contient, permet une optimisation multi-objectifs du cycle par des algorithmes génétiques.



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Merci de votre attention!
Questions?



*Chemins Energétiques pour la Récupération
d'Énergie dans les Systèmes industriels*

