Final GREC Presentation

Michael Peyrony-Rapatout
Pierre Le Provost

Table of Contents

Similar Sytems to GREC

Similar Systems

KEOS Module by Ananke:
Recovers industrial waste heat at high temperatures (450°C), based on the Ericsson engine principle.

Power output ⇒ **40 kW par module.** Module volume 5,985 m³
Power density ⇒ **~6.7 kW/m³**
Thermo mechanical efficiency **28%**

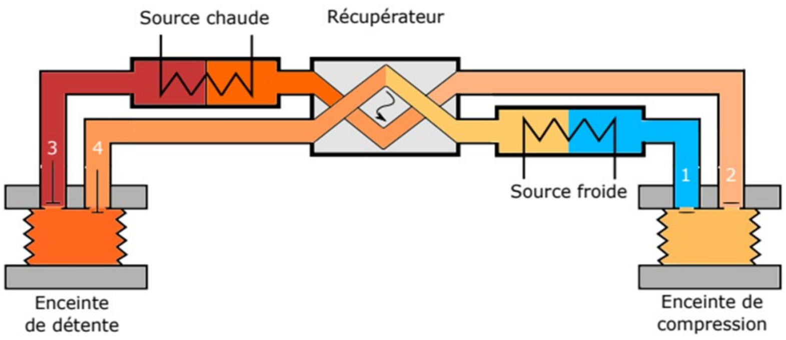


FIGURE 2.3 – Schéma de principe d'un moteur Ericsson avec récupérateur à cycle fermé.

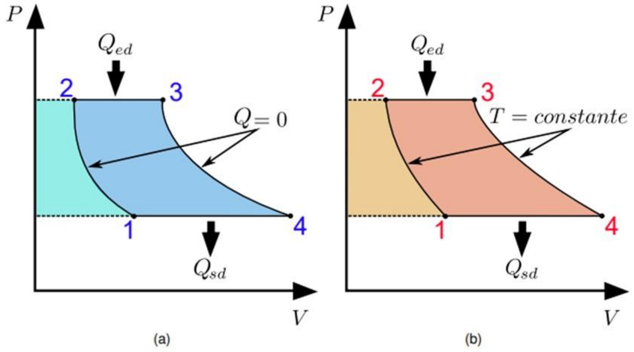


FIGURE 2.4 – Diagramme indicateur des cycles théoriques (a) de Joule / Brayton (b) d'Ericsson.

Ranc, P. (2019). *Contribution au développement d'un Moteur à Apport de Chaleur Externe à soufflets métalliques. Étude théorique, conception, réalisation et caractérisation expérimentale* (Doctoral dissertation, Université Bourgogne Franche-Comté).

Similar Systems

Technology Based on the Rankine Cycle, two-phase cycle (liquid/vapor)
SRC : Water as the working fluid, adapted for high temperatures (>350°C)
ORC : Organic fluid, more suitable for low to medium temperatures

Power output ⇒ from 10 kWe to over 1 MWe
Power density ⇒ ~ **5,787 kW/m³**
ORC efficiency **between 10% and 20 %**

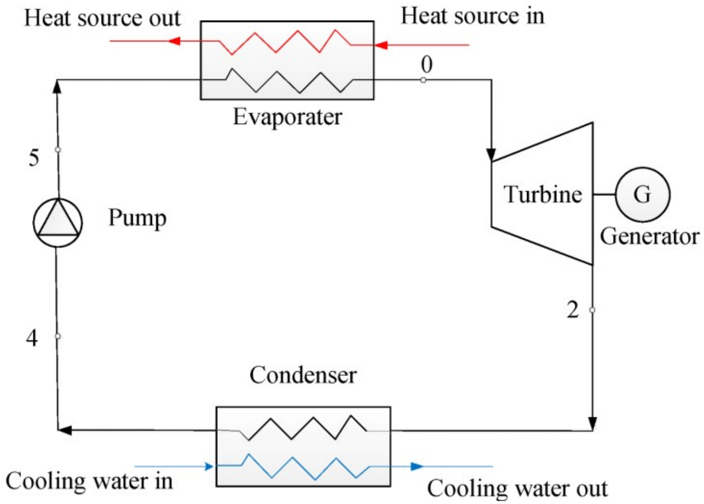


Figure : Diagram of a Rankine cycle working principle

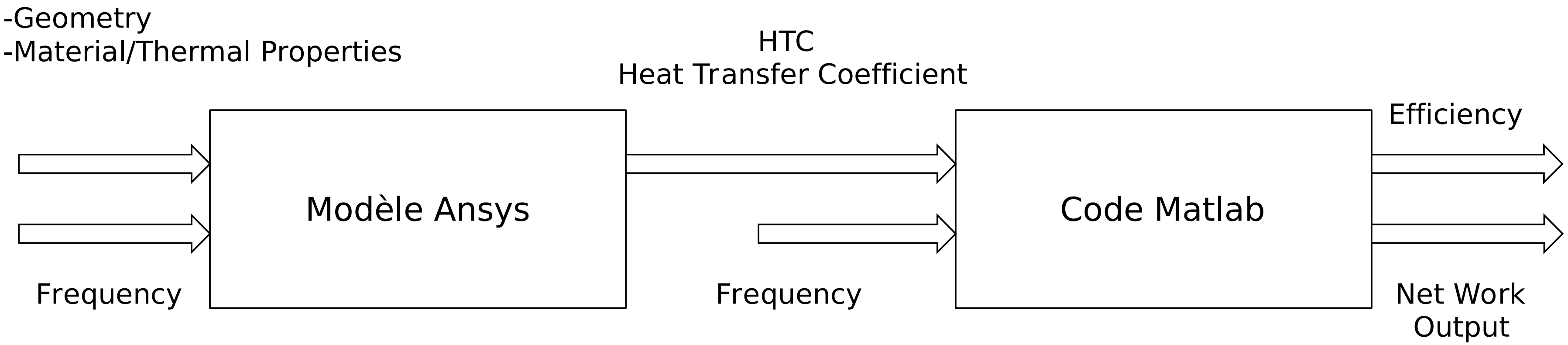
enogia.com
ORC industrialisation)

https://direns.minesparis.psl.eu/Sites/Thopt/fr/co/cycles-orc.html (travail sur les cycles ORC)

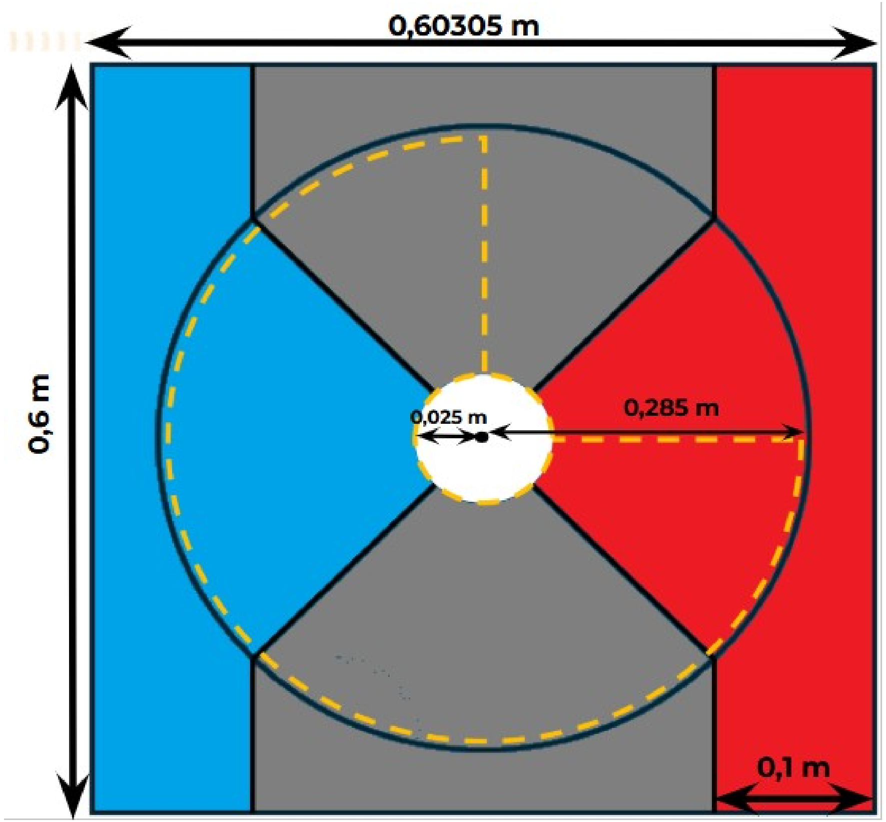
Approach and models

Approach

Combination of two models : Thermal Model + Thermodynamic Model
→ Conclusions drawn from Swedish reports



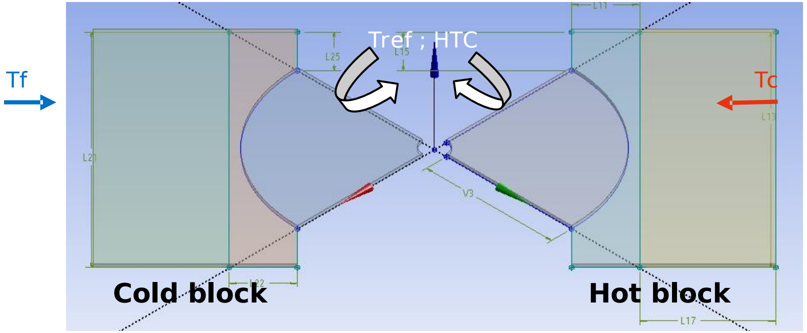
GREC Top View Section



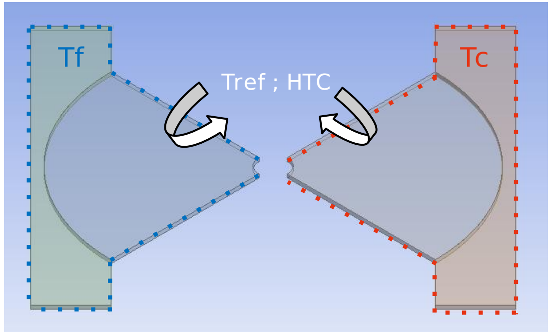
Ansys Model

Model Evolution (1 Layer, Transient Analysis)

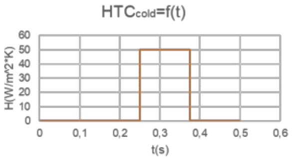
frequency : 2 Hz

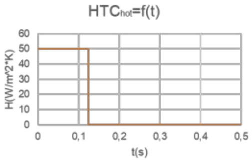


Modeling of hot and cold blocks



Removal of plates =>represent ideal model with homogeneous temperature distribution over the entire fin (imposed)

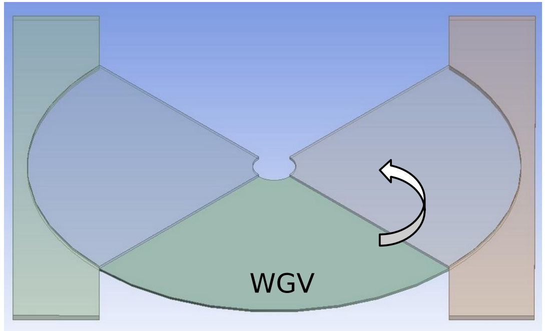




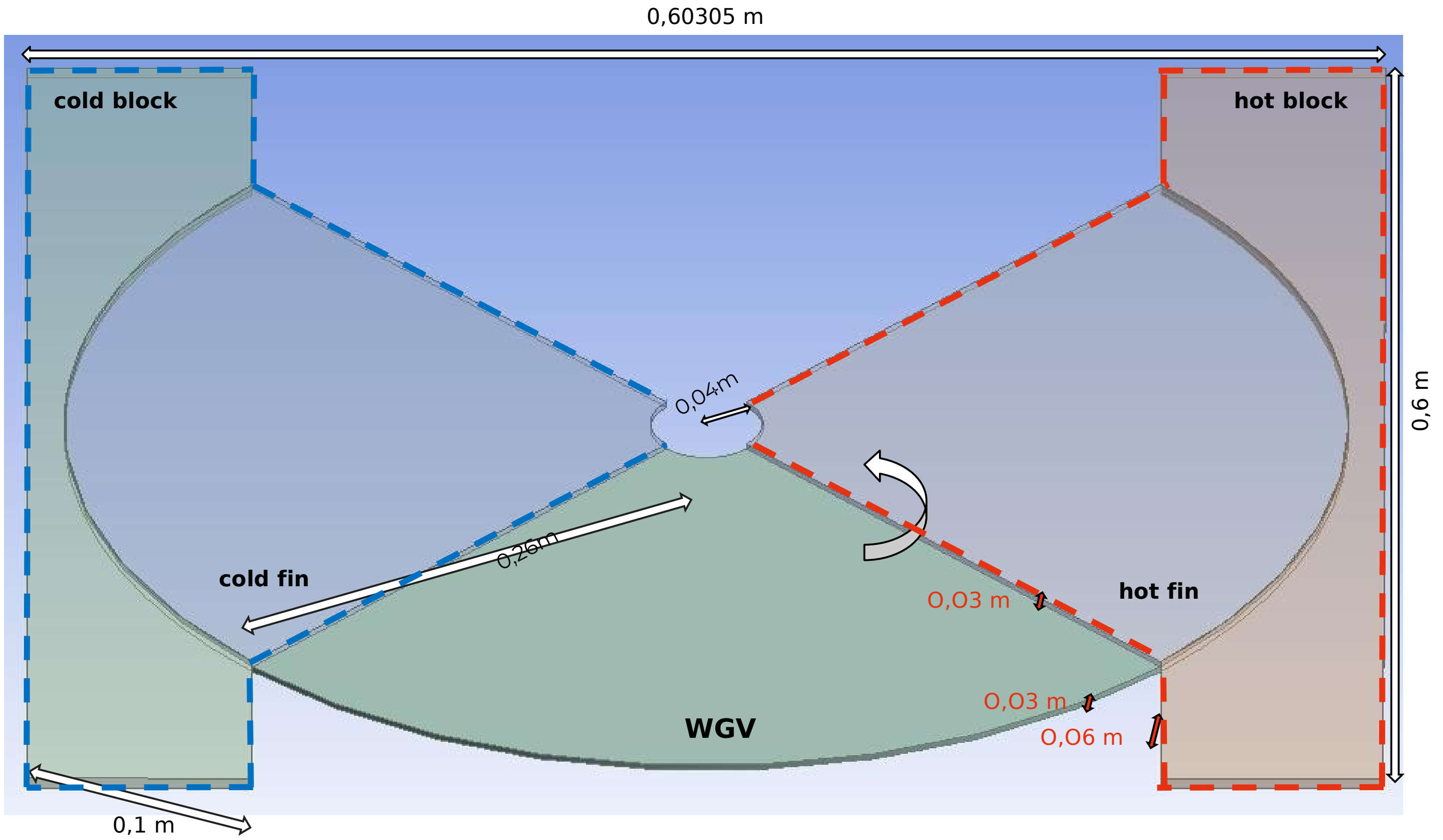
Hot temperature ”chaude” (**Tc**) = **150°C**
Cold temperature ”froide” (**Tf**) = **10°C**

Air temperature (**Tair**) = (Tc+Tf)/2 = **80 °C**

Adding the Work Generating Volume (WGV) and implementing rotation using the “mesh interface” function for the thermal transfer with the fins



Ideal Model


0,60305 m
cold block
hot block
0,04m
0,6 m
0,26m
cold fin
hot fin
0,03 m
0,03 m
0,06 m
WGV
0,1 m

Model parameters and hypothesis

- Optimized model (light mesh)

- Optimized for minimal losses

no air leaks, no friction, neglects dead zones, adiabatic insulating blocks adiabatiques

- Imposed temperatures across all fins

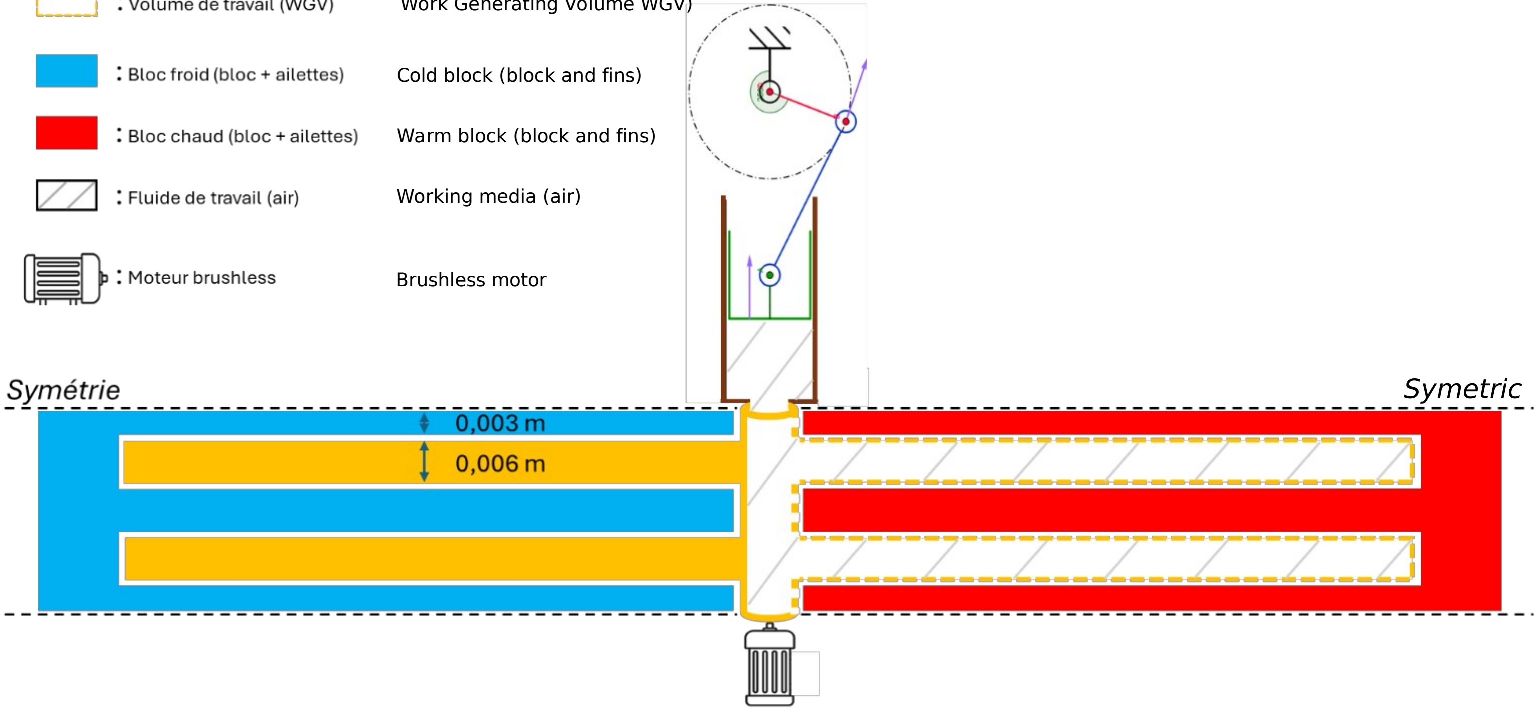
hot temperature ”chaude= $_c$ ” (T_c) and cold temperature ”froide= $_f$ ” (T_f)

- Initialised in a semi-steady-state regime (*“hybrid initialization”*)

Matlab Model

GREC with piston/crankshaft system

: Cylindre du Piston	Cylinder for piston
: Volet tournant (RS)	Revolving Shutter (RS)
: Volume de travail (WGV)	Work Generating Volume WGV)
: Bloc froid (bloc + ailettes)	Cold block (block and fins)
: Bloc chaud (bloc + ailettes)	Warm block (block and fins)
: Fluide de travail (air)	Working media (air)
: Moteur brushless	Brushless motor



Matlab code: efficiency and work calculations

Thermodynamic Model $\Rightarrow$ **Determines the potential extractable energy**

Reference case: T_c = 150 °C *(observe: T_c is "Temperature chaud" = hot)*

Input parameters and geometry : h, ρ_{air}, c_{vair}, T_{hot}, T_{cold}, T_{ref}, f, m_{air}, $S_{échange}$

First Law of Thermodynamics : dU = dW + dQ (1)

Ideal Gas Law : PV=nRT (2)

Internal Energy Change : $dU = m_{air} * c_v * dT$ (3)

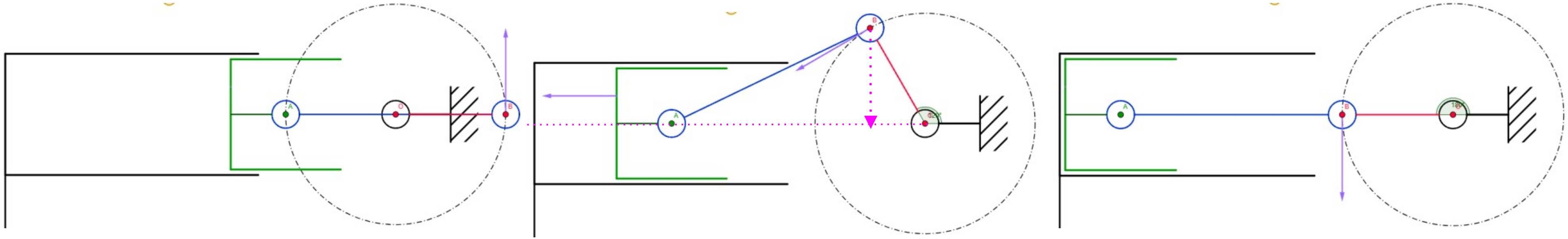
$dQ = d\Phi_{conv} = h * S * (Tref-Tair)dt$ (4)

$dW = -P_{ext}dV = -PdV = -(nRT)*dV/V$ (piston idéal $P_{ext} = P$) (5)

(3),(4),(5) => (1) : $m_{air} * c_v *dT = -(nRT)*dV/V + h*S*(T_{ref} - T_{air})dt$ (6)

=> differential equation with two unknowns : T et V

Equation V(t) (piston/crankshaft system)



$\omega t=0 \Rightarrow V(t)=V_0+\Delta V$ $V(t)=V_0+(\Delta V/2)*(1+\sin(\omega T+\pi/2))$ $\omega t=\pi \Rightarrow V(t)=V_0$

Cylinder volume (V) follows a sinusoidal function relative to the piston displacement.
Equation : $V(t)=V_0+\Delta V\cdot\sin(\omega t+\phi)$
In our case : $V(t)=V_0+(\Delta V/2)*(1+\sin(\omega t+\pi/2))$ with :

- V_0 : minimum cylinder volume
- ΔV : amplitude of the volume variation (divided by 2 because sin is between -1 et 1)
- $\sin(\omega t+\pi/2)$: sine function is offset to start at $V_0+\Delta V$

Matlab Code : efficiency and work calculations

Determination of $V(t)= V_0+(\Delta V/2)*(1+\sin(\omega t+(\pi/2))$ → more than one variable (T)

$m_{air}*c_v*dT = -(nRT)*dV/V + h*S*(T_{ref} - T_{air})dt$ (6)

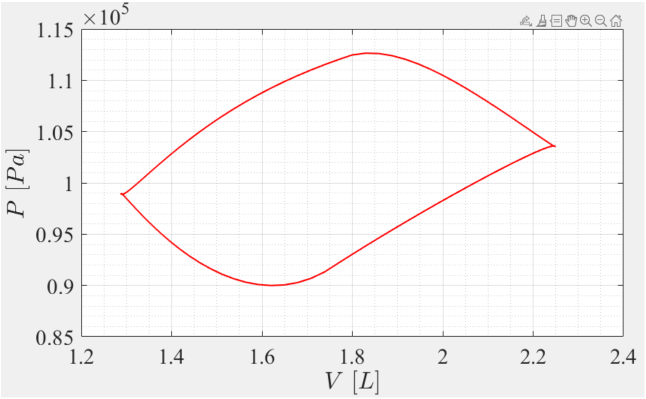
=> differential equation with one unknown, T(t), solved numerically.

T(t) and V(t) known → P(t) known → plot of the PV cycle

$W_{net} = - W_{expansion} - W_{compression}$ (cycle area)

$\eta= W_{net} /Q_c$

$\Phi_{net} = W_{net}*f$



f= 2Hz HTC= 27,2 W/(m²·K)

Determination of HTC

Revolving in time steps

→ Half-cycle study (exchange with The hot side ”côte chaud”)

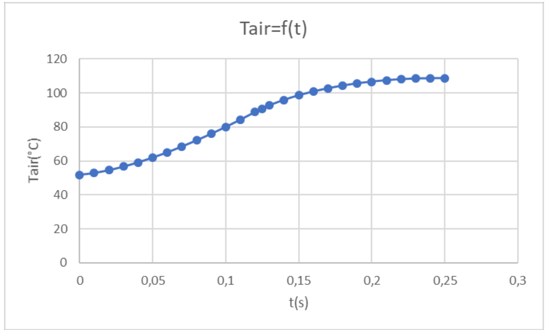
⇒HTC (t) = ϕ(t) / (S(t) * ΔT(t))

S : area of the WGV in contact with the fin

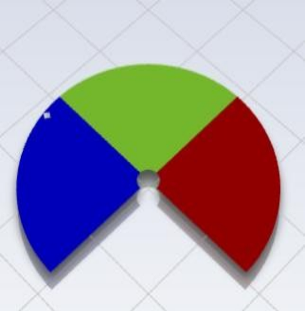
ϕ : flow between the hot fin and the WGV

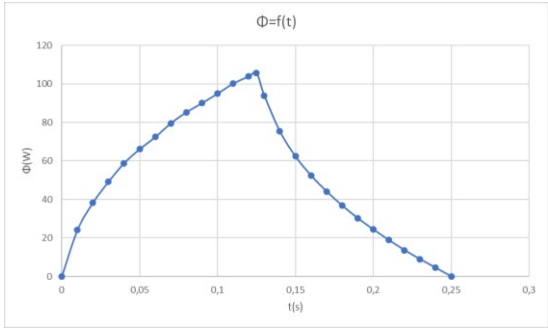
ΔT : T_c - $T_{air}(t)$

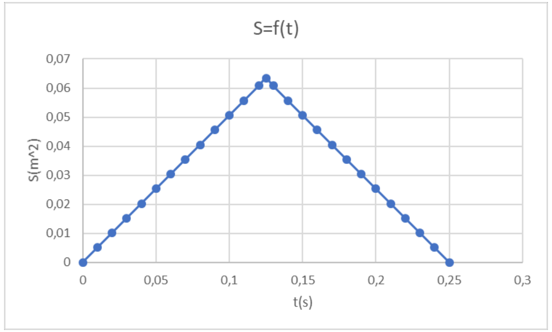
T_{air}(t) and ϕ(t) retrieved from Ansys
⇒ **HTC (t)**



Start (t=0) **End (t=period/2)**







f= 2 Hz

HTC Gradient

At time t, heterogeneous HTC in the WGV $\Rightarrow$ gradient as a function of radius

→ velocity gradient → Reynolds gradient → different flow regime within the WGV itself

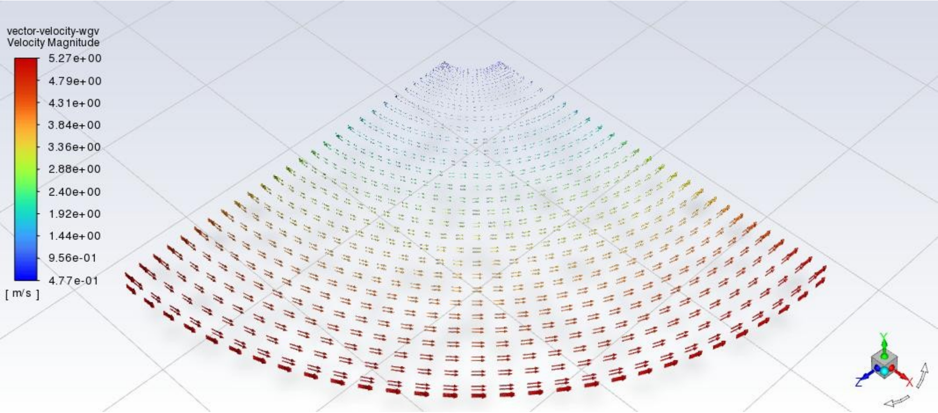


Figure : Velocity vectors within the WGV at 3 Hz

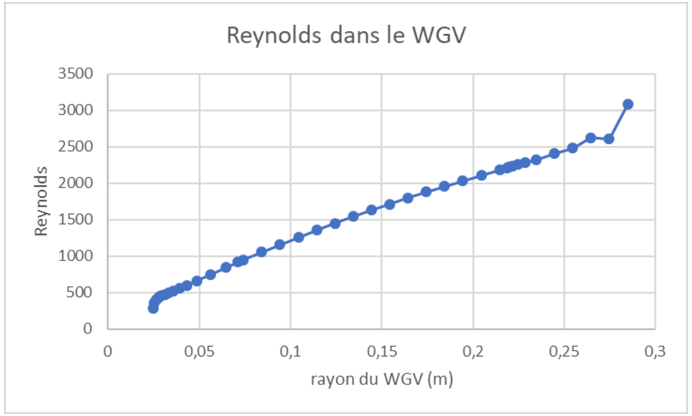


Figure : Reynolds number as a function of the radius of the WGV at 3 Hz

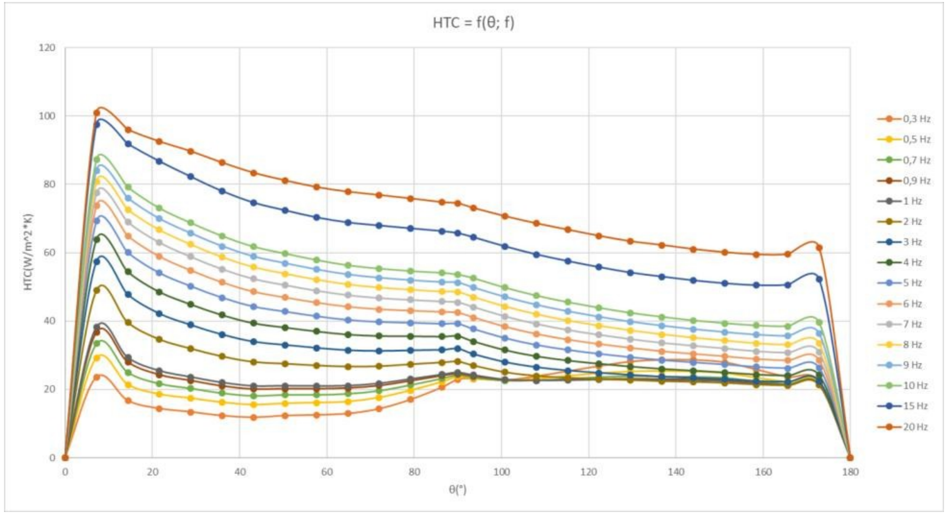
Reynolds (Re) $= (\rho * V * Dh) / \eta$

with
ρ : density
V : velocity
η : dynamic viscosity
$Dh = (4A/p) = 2e$
$= 0{,}012m$

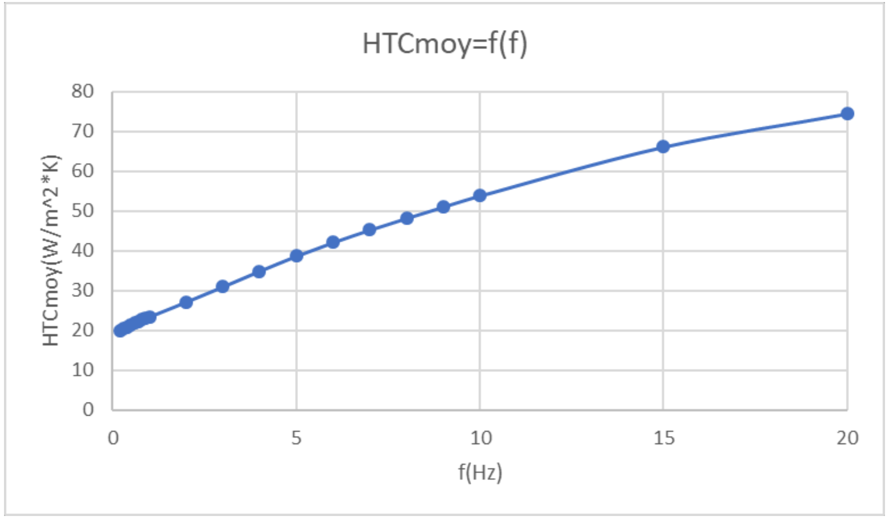
Results reference case

Results : HTC (Ansys)

Tc = 150°C   Tf = 10°C



Best HTC at high frequencies

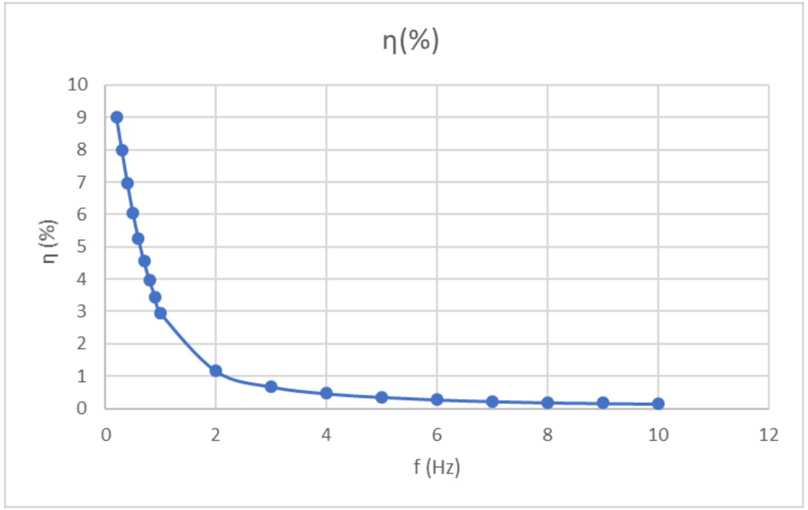


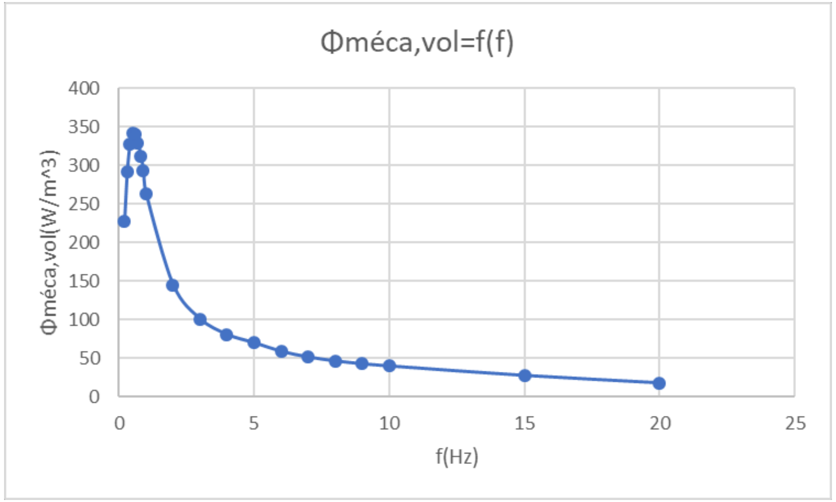
Matlab code input data

Calculated with the average of all points for each frequency in the chart

Results : Flows and efficiencies (Matlab)

Tc= 150°C   Tf= 10°C



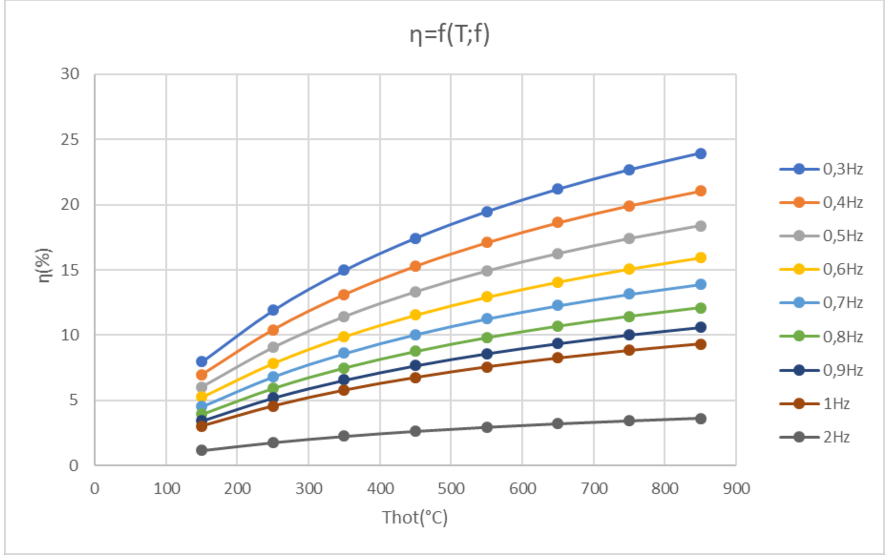


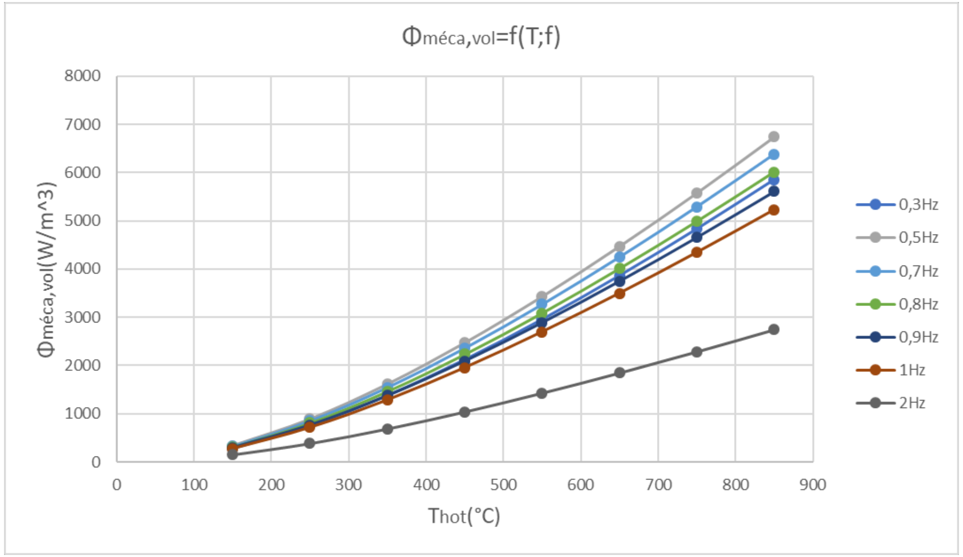
$\eta = W_{net}/Q_c$

$\Phi_{méca,vol} = (W_{net} * f)/V_{prototype}$

Optimised case results

Results : Influence of ΔT at a constant HTC



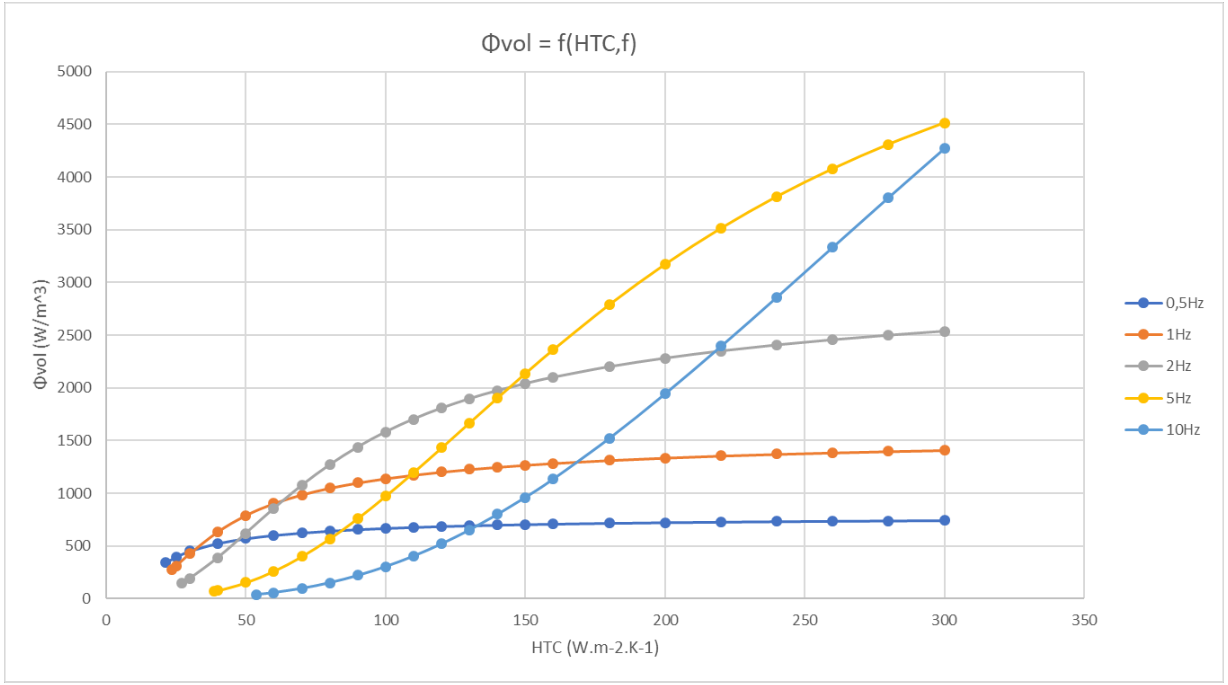


→Better performance at low frequencies and high temperatures

→Optimal flux at 0,5 Hz and high temperature

air properties (and therefor HTC) assumed to be constant at all temperatures => idealised results

Results : Influence of HTC at constant ΔT

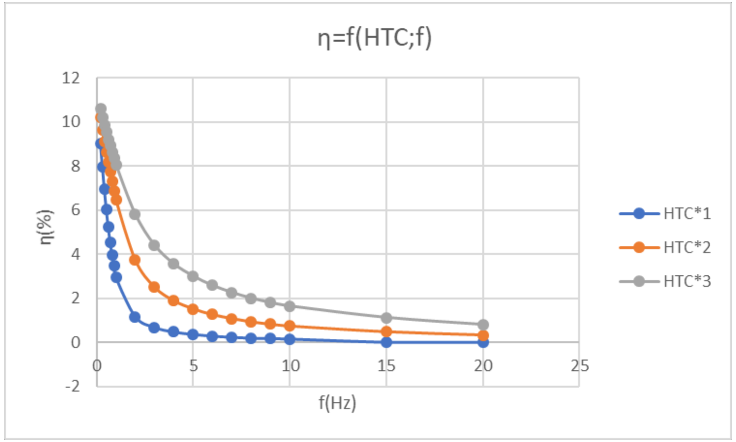


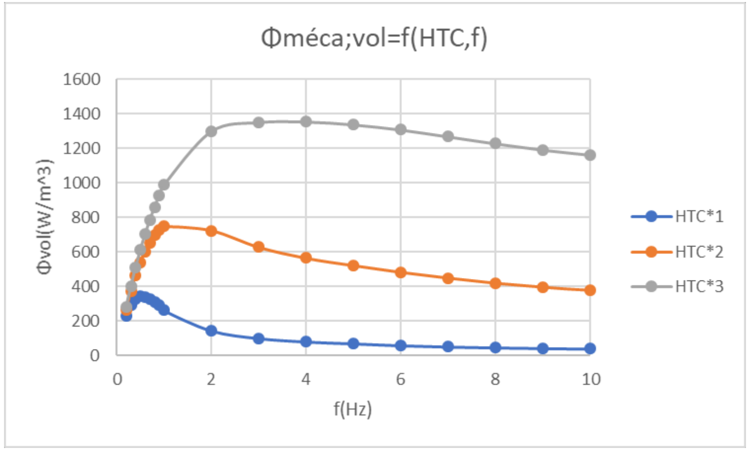
Tc = 150°C
Tf = 10°C

→ Sharp increase, then reaches a plateau that shifts depending on the frequency

Results : Optimum and Relationship f/HTC

Tc= 150°C ; Tf= 10°C ; Reference HTC calculated by Ansys
Results at HTC*2 and HTC*3 :

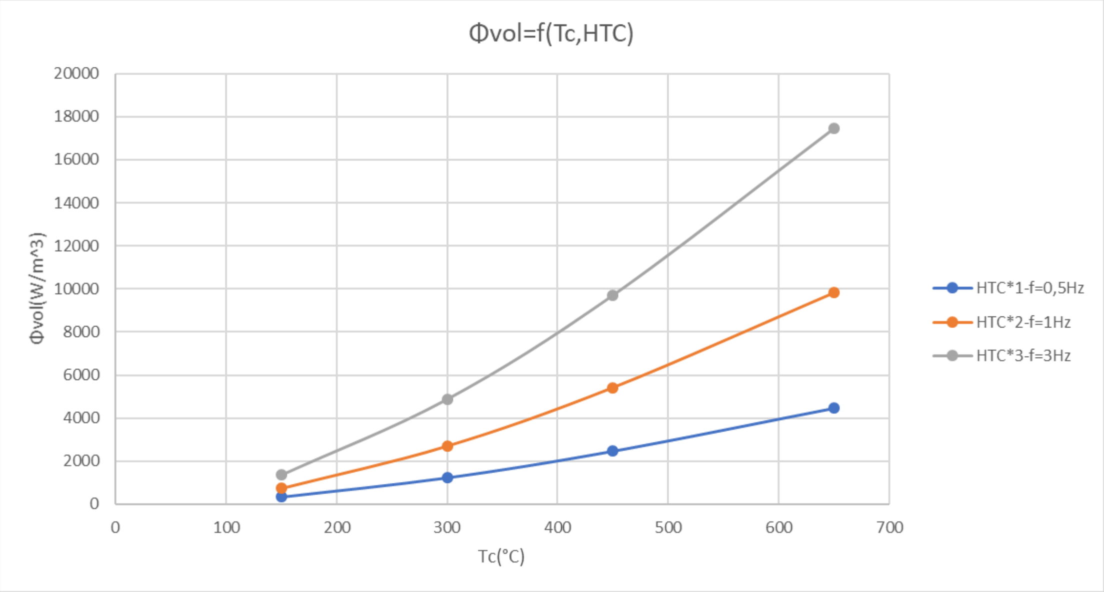




HTC increases -> optimum shifted towards high frequencies
HTC and frequency linked (time and exchange efficieny) => tune together

Results : Optimised case

→ Optimal case results : Higher T°, HTC*2 or HTC*3, frequency adjusted to optimal value



Ideal values ⇒ Shows the potential of GREC
→ **Interesting power levels**

In reality :
Frequency set by user
Hot source depends on the application
Remaining parameter : **HTC**

→ **Real challenge lies in its optimisation**

Useful energie

Energy Consumption Assessment

Motor required to rotate the Revolving Shutter (RS) ⇒ Energy consumption

$E_{consumed} < E_{produced}$

Brushless motor selected → More control, suited for GREC

$C_{motor} > C_{resistive}$

If no mechanical friction ⇒ Only air resistance ⇒ Due to its viscosity

Starting torque ($C_{inertia}$) exists only at start-up so it is not taken into account

→ The viscous torque (Cv) depends on the radius:

$$\mathbf{Cv} = \int_{ro}^{R} r * dFv = (2 * \pi * \mu * f)/e * \int_{ro}^{R} r^2 * 3/2 * \pi * r * dr = \frac{3 * \pi^2 * \mu * f}{4 * e} * (R^4 - R_0^4)$$

μ (air viscosity) = 0,0000228 Pa.s *R = 0,285 m*

e (dead zones) = 0,00025 m *R0 = 0,025 m*

f (frequency)

Motor power density

Reference case ; f = 0,5 Hz (optimal frequency)

$\Rightarrow$ Cv = 0,0022 Nm

$\Rightarrow P_{motor} > Cv * \omega = 0,007$ W $\Rightarrow$ **$P_{motor\_volumetric} > 0,81 \ W/m^3$**

$\Rightarrow E_{motor / cycle} > P_{motor} / f = 0,014$ J/cycle

Very low energy required → Very minimal impact

Due to the frictionless model assumption → Not the case in a real prototype

Useful work (non-optimised case)

$E_{useful} = E_{produced} - E_{consumed}$

Reference case : f=0,5 Hz

- $W_{produced/cycle}$ = 5,93 J /cycle ; $P_{vol\_produced}$ = 341,7 W/m^3

⇒ $E_{useful/cycle}$ = 5,93 - 0,014 = 5,916 J /cycle

⇒ P_{vol_useful} = 341,7 - 0,81 = 340,89 W/m^3

⇒ η : 6,05 % → 6,04 % (energy consumed taken into account)

$E_{motor/cycle}$ <<< $W_{produced/cycle}$ → Minimal impact → **Convincing results**

Conclusion

Conclusion

- Influential parameters : frequency, HTC and ΔT.
- Frequency and HTC related parameters adjusted properly =>improve GREC performance.
- En reality : fixed frequency, temperature too (case of application) => maximum optimisation of HTC but remaining low cost
- Assuming an optimised HTC, performance close to existing systems => **Real benefit**

Perspectives

Future perspectives

- Optimising the HTC to improve performance (new grooved model)

- Pipe model with heat transfer fluid

- Study of geometric parameters and impact of dead zones

- Construction of a low temperature prototype (200°C => limited by laboratory resources) upstream planning phase and downstream instrumentation phase

Thank you for your attention

Appendix

Appendix

Starting torque : $C_{inertia} = I_{total} \cdot \alpha$

$I_{total} = n \cdot I_{disk} + I_{shaft}$

$\alpha = \omega / Td = (2 \cdot \pi \cdot f) / Td$

I : Inertia ($kg \cdot m^2$)

α : angular acceleration (rad/s^2)

n : number of disks = 2 (*DNC*)

ω : pulsation (rad/s)

f : frequency (Hz) =2 (*DNC*)

Td : start-up time (s) = 2 (*DNC*)

DNC : Dans Notre Cas - in our case