

Comparison between thermomagnetic and thermoelectric generators

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Nowadays, the supply of waste heat is sufficiently abundant to make it a key target for technology development. So far, thermal energy harvesting of low-grade heat has been mainly associated to thermoelectric generator (TEG) technology. However, recent advances on magnetocaloric materials (MCM) aimed to applications in room temperature magnetic refrigeration, could pave the way for a new generation of thermogenerators (TMG). We propose to study the efficiencies and the power density of TMG and TEG at maximum power in the framework of the finite time thermodynamic [1]. The performance will be discussed as a function of the temperature difference between the reservoirs and of the efficiency of the heat exchangers.

Finite time thermodynamic applied on TMG reveals that as long as the adiabatic temperature change reaches half of the temperature difference of the reservoir ΔT_{res} , the TMG reaches the optimum cycle as confirmed in the simulation [2]. However, when this condition is not feasible due to field limitation, the optimum cycle is no longer reached and the efficiency relative to the Carnot efficiency, η_{rel} , decreases (Fig. 1). Our approach based on the work of Curzon and Ahlborn [1] gives a general method to estimate the performance achievable by TMG. Comparisons with the power density measured in some prototypes [3] show a good accordance with our results.

On the other side, TEG have already been well optimized [4] and even if the optimum is far from the Curzon and Ahlborn, its relative efficiency does not strongly decrease when the ΔT_{res} increases like TMG (Fig.2). Even if these primary results need to be confirmed, they show a potential benefit for TMG at low ΔT_{res} . Staging thermodynamic cycles could be seen as a possible improvement of the TMG, but our finite time thermodynamic analysis shows no gain. We, therefore, put our attention on the potential use of TMG in microsystem.

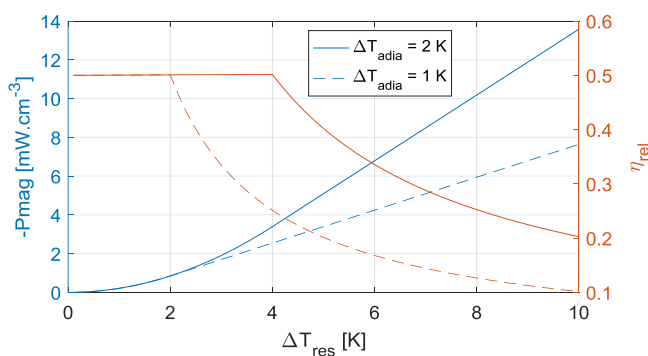


Figure 1. Power – Efficiency of thermogenerator

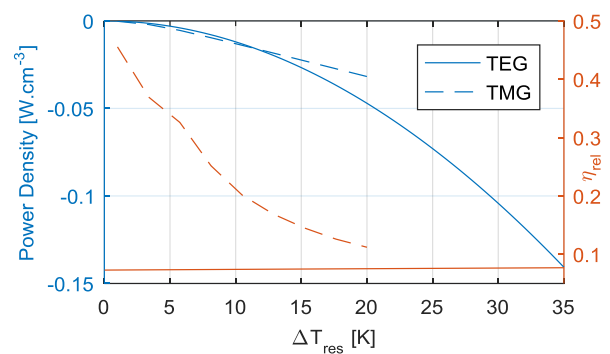


Figure 2. Comparison between TEG and TMG

- [1] F. L. Curzon, "Efficiency of a Carnot engine at maximum power output," *Am. J. Phys.*, vol. 43, no. 1, p. 22, 1975.
- [2] M. Almanza, A. Pasko, F. Mazaleyrat, and M. LoBue, "Numerical study of thermomagnetic cycle," *J. Magn. Magn. Mater.*, vol. 426, pp. 64–69, Mar. 2017.
- [3] M. Gueltig *et al.*, "High Frequency Thermal Energy Harvesting Using Magnetic Shape Memory Films," *Adv. Energy Mater.*, vol. 4, no. 17, p. n/a-n/a, Dec. 2014.
- [4] Y. Apertet, H. Ouerdane, O. Glavatskaya, C. Goupil, and P. Lecoeur, "Optimal working conditions for thermoelectric generators with realistic thermal coupling," *EPL Europhys. Lett.*, vol. 97, no. 2, p. 28001, Jan. 2012.



Thermomagnetic generators

Time line

Study of thermomagnetic generator efficiency and power density for adiabatic and isothermperature cycle and for isofield and isothermperature cycle

Numerical study of thermomagnetic cycle," J. Magn. Magn. Mater., vol. 426, pp. 64–69, Mar. 2017.

Effect of the first or second order magnetocaloric material in thermomagnetic generator

First vs second order magnetocaloric material for thermomagnetic energy conversion. IEEE Transactions on Magnetics, 2017

Comparison with thermoelectric generators

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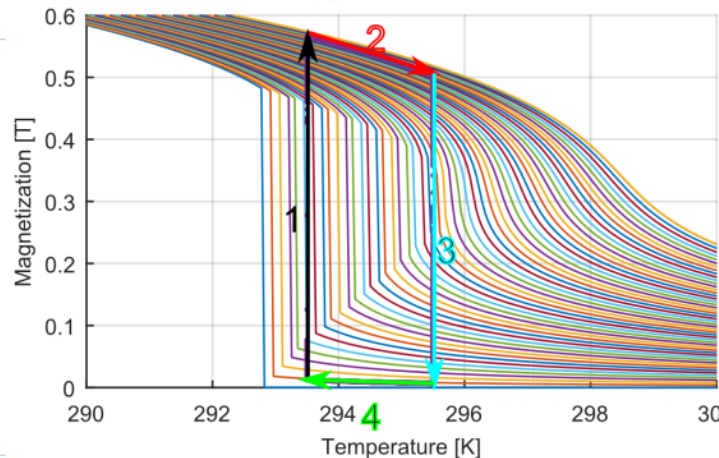
Introduction

Concept of thermomagnetic generator

- Successive thermal contact between the hot and the cold reservoir

- Temperature change of magnetocaloric material

- Induce magnetization changes

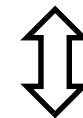


- Harvested through with magnetic force or Faraday's

Thermal effect



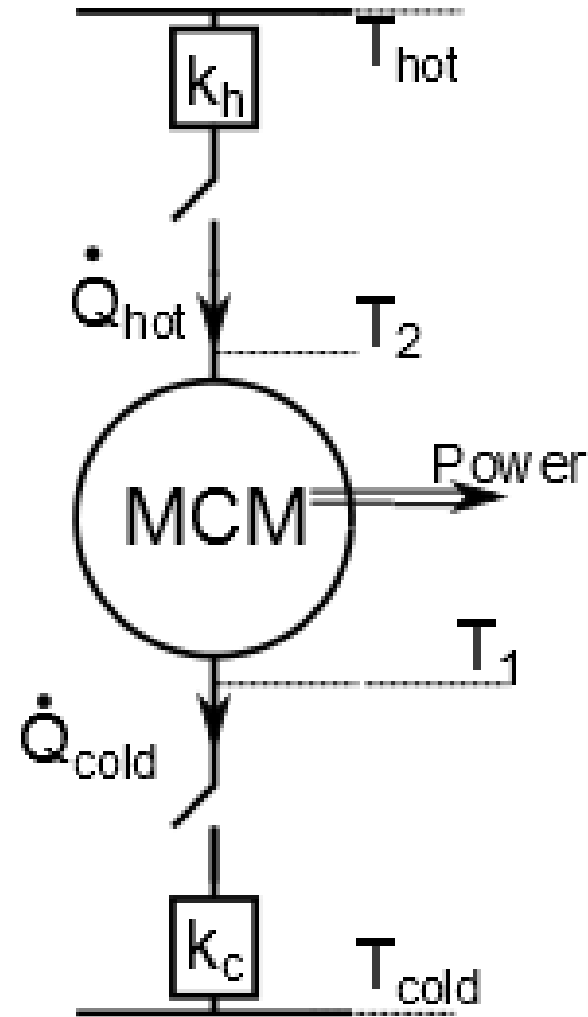
Equation of state



Magnetic Effect



Electricity

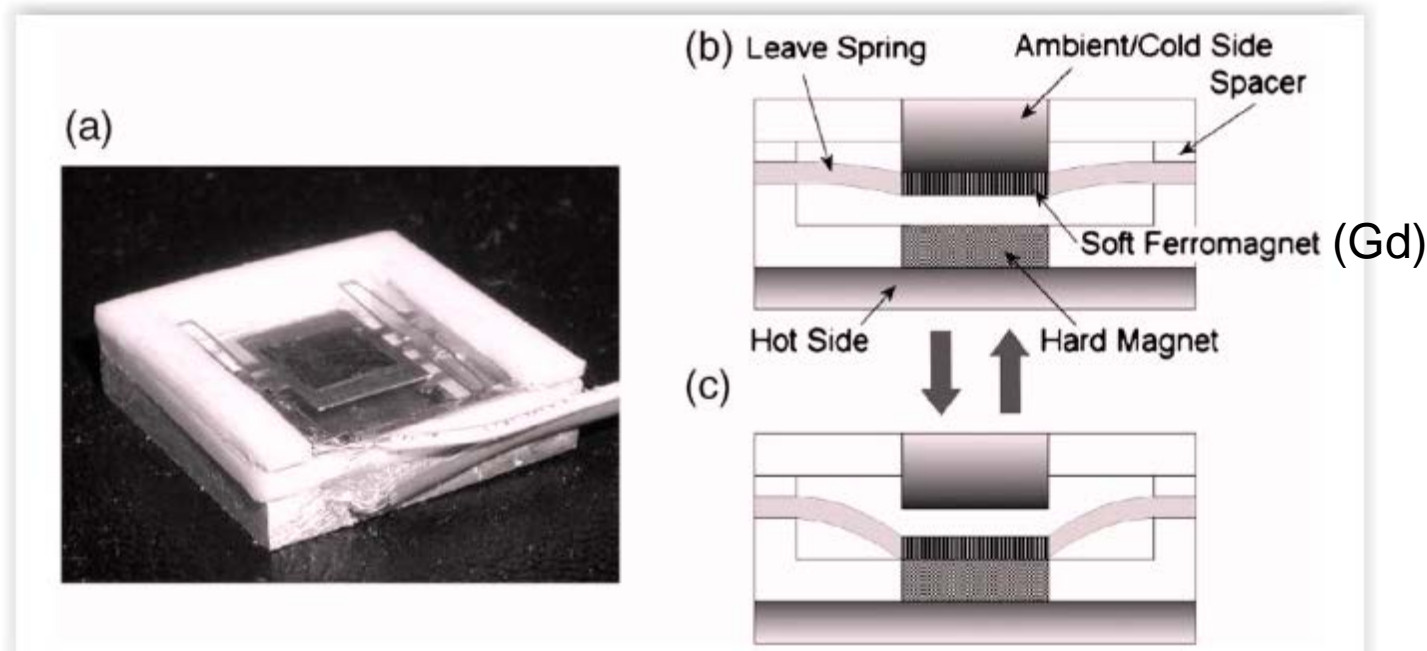


Thermomagnetic generator: devices

Introduction

Device based on magnetic force

M. Ujihara, G. P. Carman, et D. G. Lee, « Thermal energy harvesting device using ferromagnetic materials », *Applied Physics Letters*, août 2007.

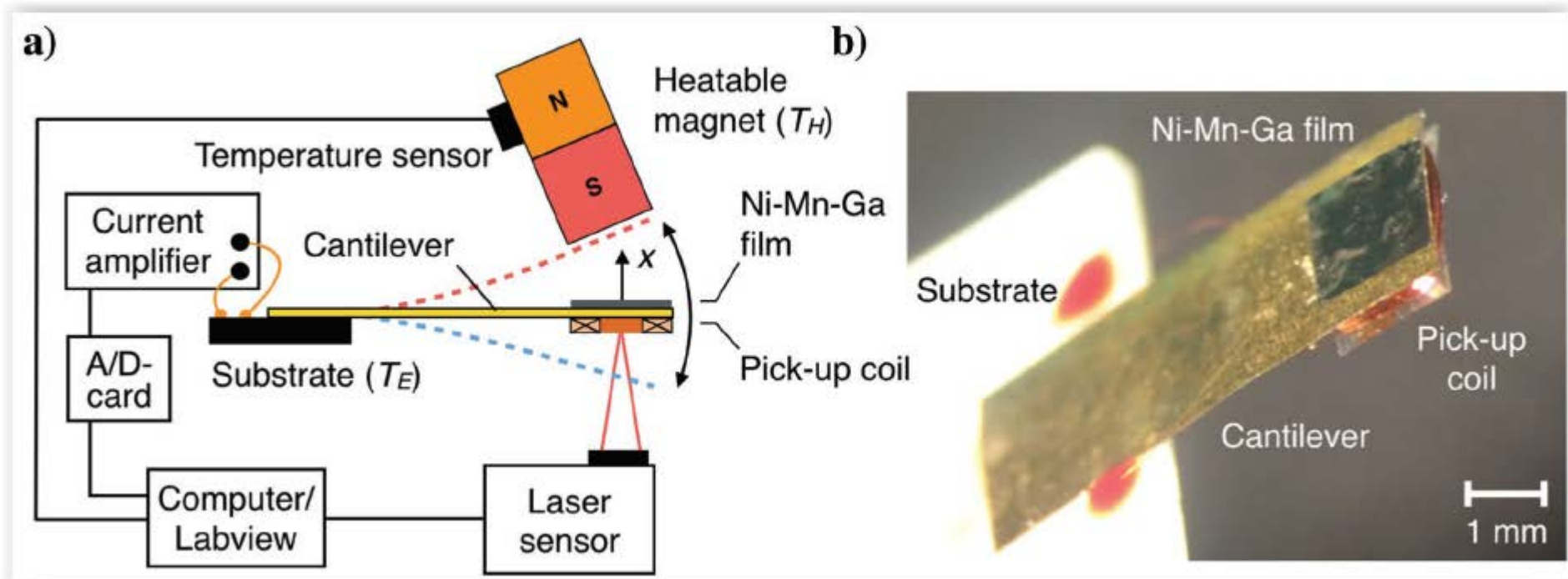


Thermomagnetic generator: devices

Introduction

Device based on induction

M. Gueltig *et al.*, « High-Performance Thermomagnetic Generators Based on Heusler Alloy Films », *Adv. Energy Mater.*, vol. 7, n° 5, p. 1601879, mars 2017..





Estimation of the maximum power of thermomagnetic and thermoelectric generator

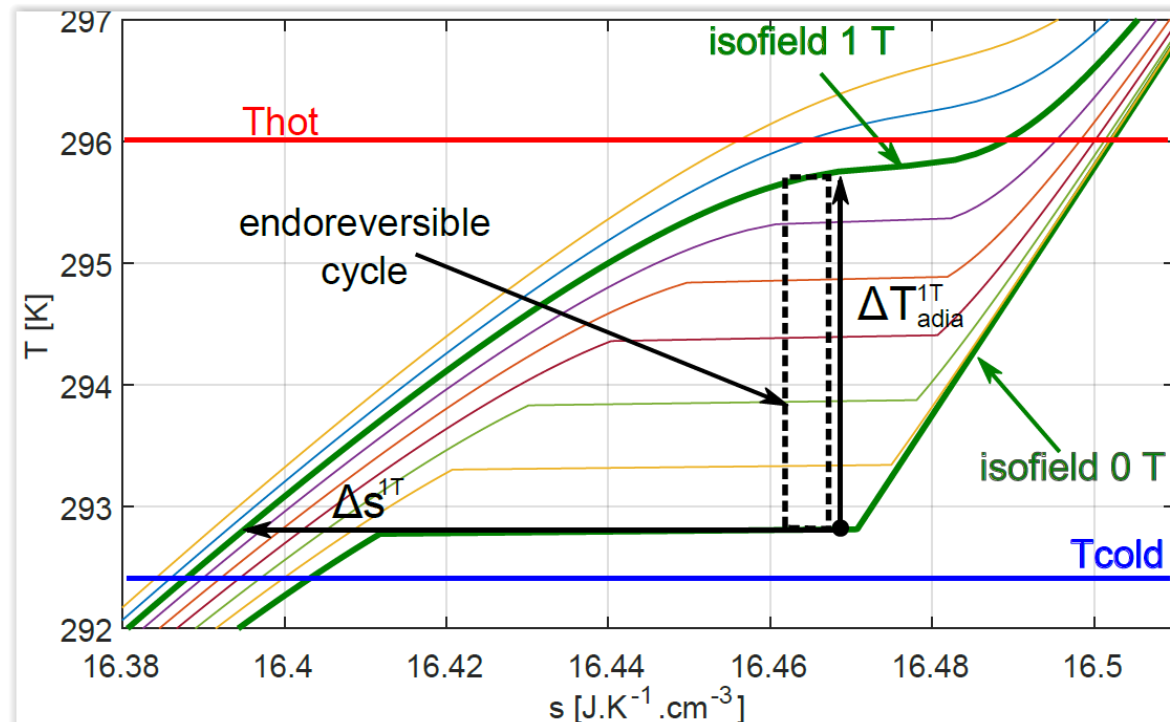
- Endoreversible cycle (two isothermatures – two adiabatics transforms)
- Finite time thermodynamic (consideration of the heat exchanger)
- The conversion from magnetic to electric energy is not considered

I. Single stage/ Multi stage thermomagnetic cycle

II. Comparison with the thermoelectric

Equation of state

- With endoreversible cycle => main parameter is ΔT_{adia}^{1T}
- (magnetic entropy change ΔS^{1T} is link to the frequency)

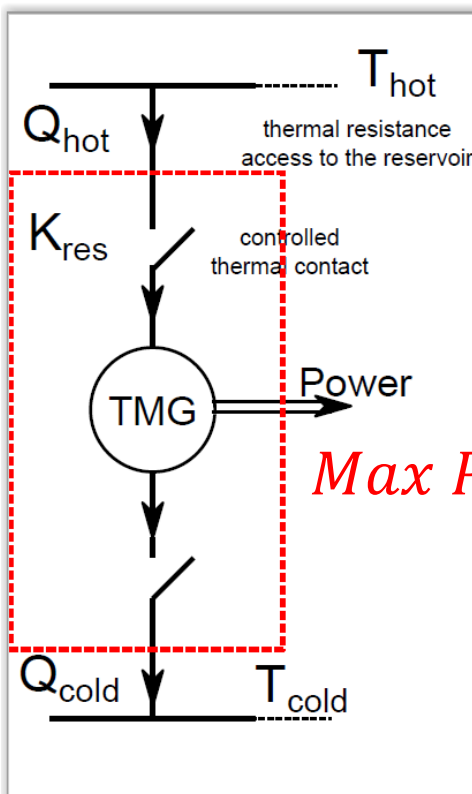


Model

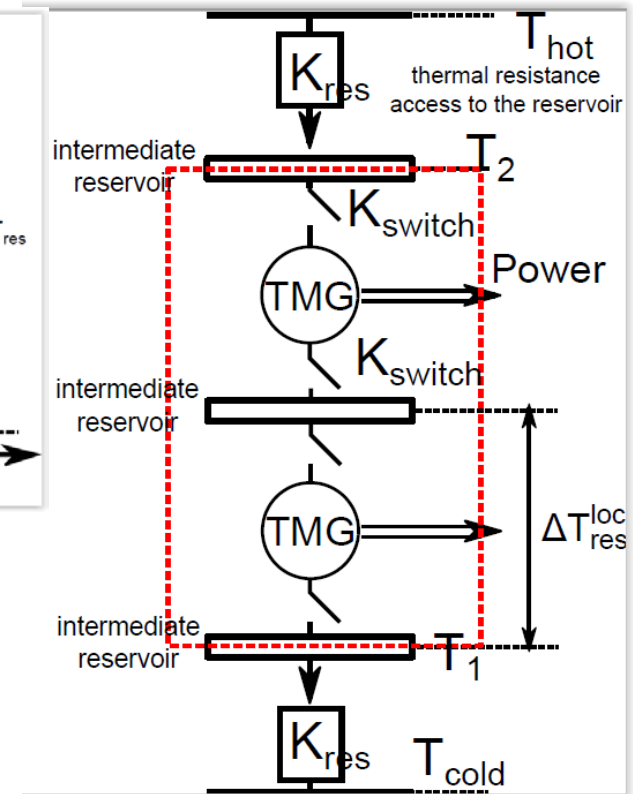
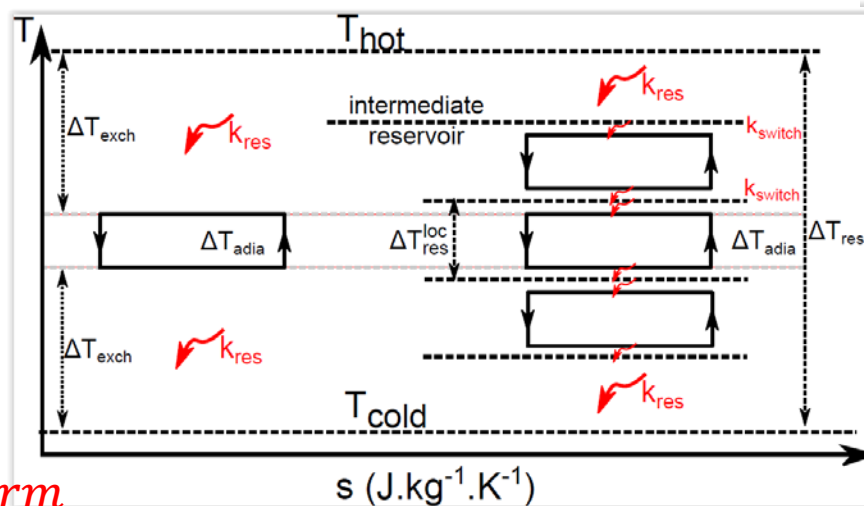
Part I

Thermal model

- Thermal conductance of the heat reservoir K_{res}
- Thermal conductance of the switch between K_{switch} and 0



Max P_{norm}



- Intermediate reservoirs
- Multistage cycles

Power versus relative efficiency

Part I

Finite time thermodynamic approach => Power

$$P(W) = \frac{K_{res}(T_{hot} - T_{cold})^2}{16T} \cdot \eta_{rel}(1 - \eta_{rel}) \cdot \frac{8R}{(1 + R)}$$

Working condition Working point

P_{norm}

Efficient thermal switch $R = \frac{K_{switch}}{n2K_{res}} \rightarrow \infty \rightarrow 8$

Relative efficiency (relative to Carnot) $\eta_{rel} = \frac{n\Delta T_{adia}}{T_{hot} - T_{cold}}$
 n number of stage

Maximum $\eta_{rel}(1 - \eta_{rel}) \Rightarrow \eta_{rel} = 0.5$

Not always reached => Increase the number of stages allows to overcome the limited ΔT_{adia}

One stage

Part I

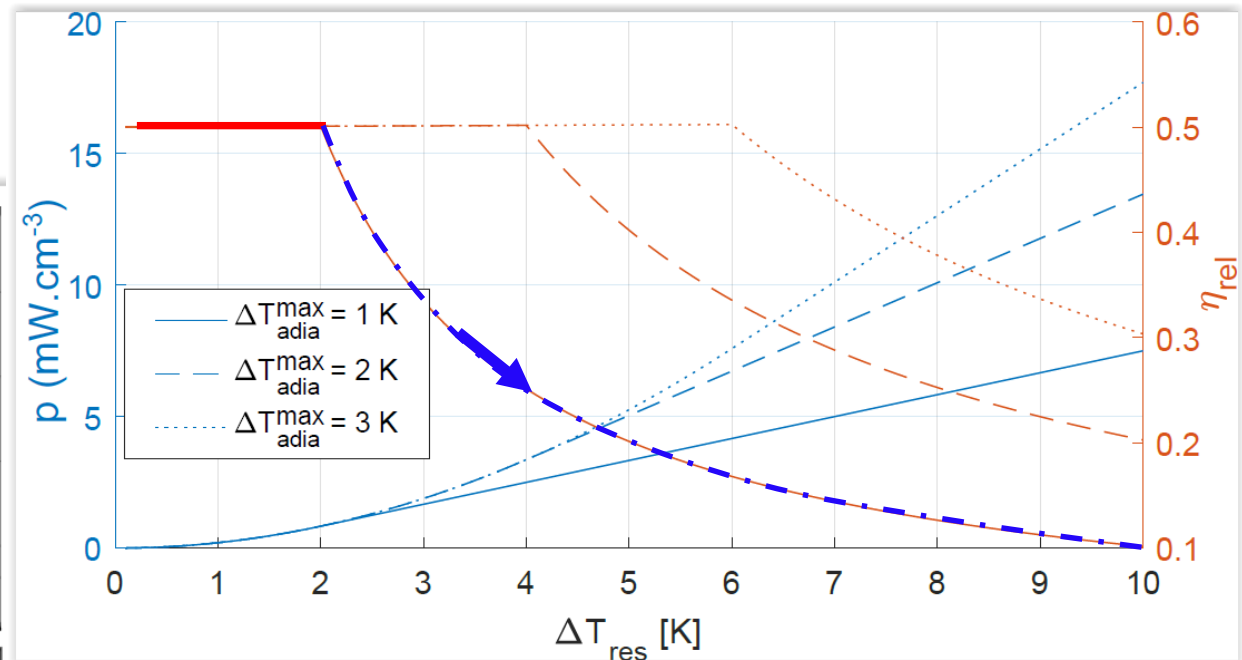
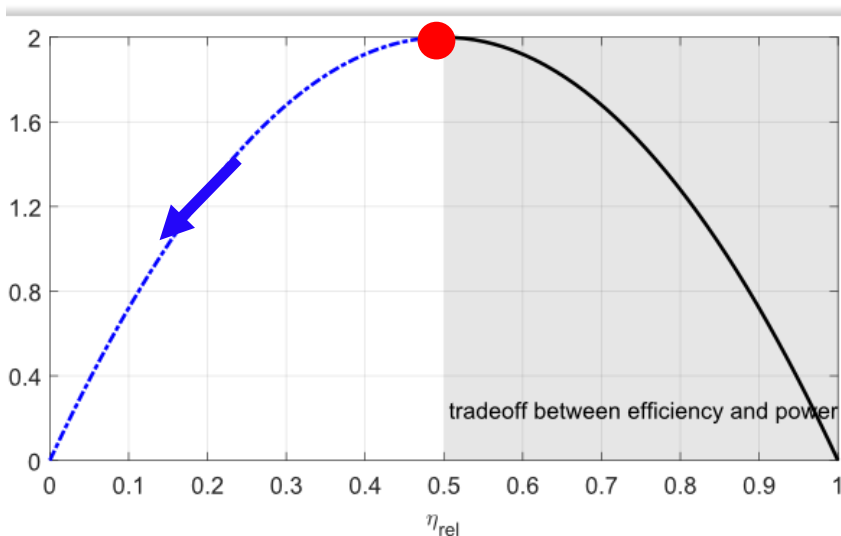
Effect of limited ΔT_{adia}

- The relative efficiency is different from the optimum $\eta_{rel} = 0,5$

$$P = P_{norm} \eta_{rel} (1 - \eta_{rel})$$

$$\eta_{rel} = \frac{\Delta T_{adia}}{T_{hot} - T_{cold}}$$

$P/P_{norm} (\eta_{rel})$



$T_{hot} - T_{cold}$

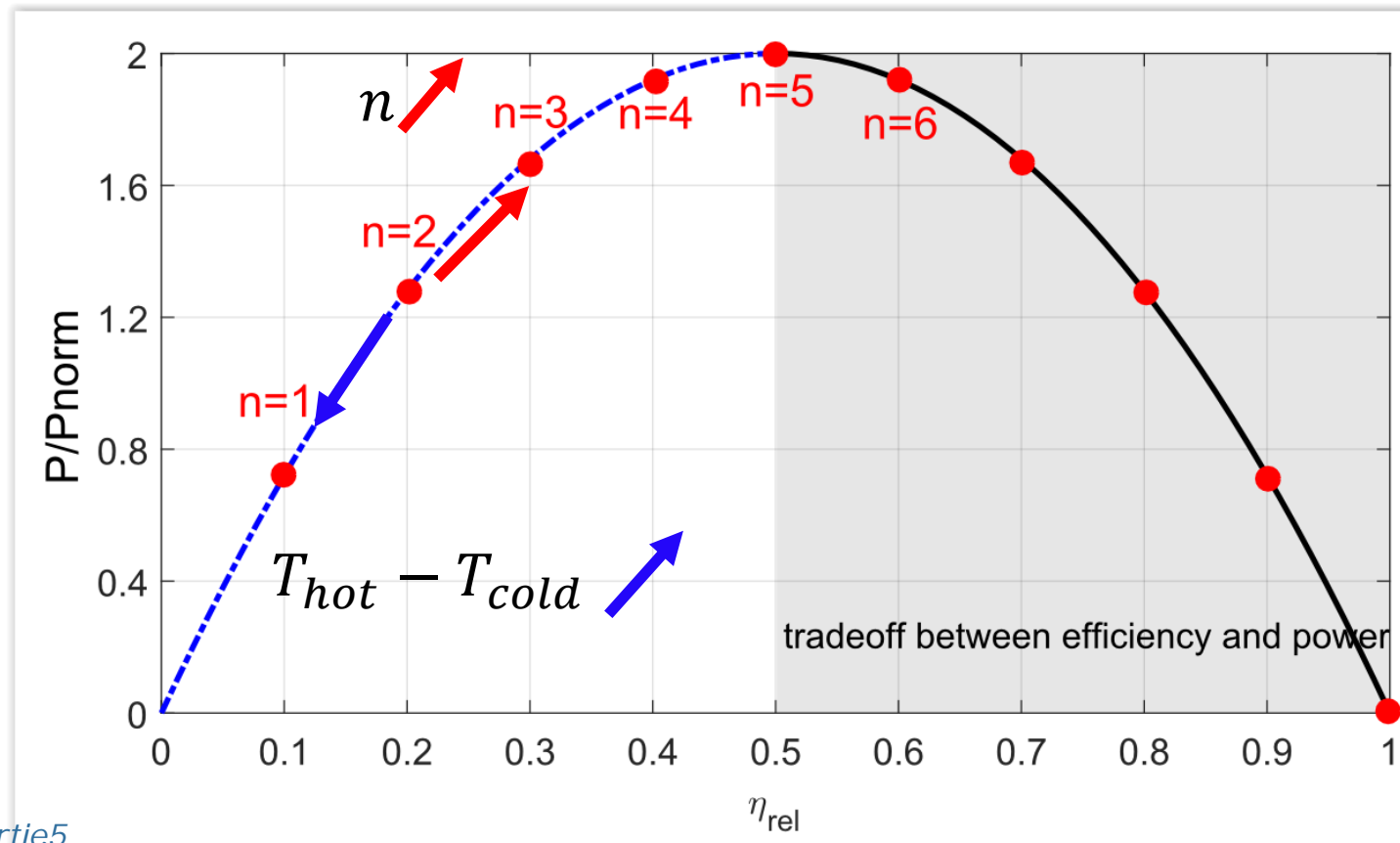
Multistage—Overcome the limited ΔT_{adia}

Part I

Overcome the limited ΔT_{adia} by staging

- The quantity of active substance increases as n

$$\eta_{rel} = \frac{n\Delta T_{adia}}{T_{hot} - T_{cold}}$$



Part I

TMG at maximum power

$$P(W) = \frac{K_{res}(T_{hot} - T_{cold})^2}{16T} \cdot 2$$

$$\eta_{rel} = 0.5$$

TMG when limited ΔT_{adia} is predominant

$$P(W) = \frac{K_{res}(T_{hot} - T_{cold})^2}{16T} \cdot \frac{8n\Delta T_{adia}}{T_{hot} - T_{cold}} \quad \eta_{rel} = \frac{n\Delta T_{adia}}{T_{hot} - T_{cold}}$$

Upper bound

- The magnetic to electric conversion is not taking into account
- Ideal behavior of the MCM

■ Finite time thermodynamic approach for TEG

- From the work of

Y. Apertet, H. Ouerdane, O. Glavatskaya, C. Goupil, et P. Lecoœur, « Optimal working conditions for thermoelectric generators with realistic thermal coupling », *EPL Europhys. Lett.*, vol. 97, n° 2, p. 28001, 2012.

- Power at optimal working condition (upper bound for thermoelectric)

$$P(W) = \frac{K_{res}(T_{hot} - T_{cold})^2}{16T} 0,34 \quad \text{with figure of merit } ZT = 1$$

■ Difference between TMG and TEG

- At maximum power the TMG shows a power ~ 6 (5.8) times higher
- At maximum ΔT_{adia} (2 K) TMG presents higher power for $T_{hot} - T_{cold} < 23$ K

Conclusion

- The power produced is always limited by the efficiency of the thermal conductance of the reservoir

$$\frac{K_{res}(T_{hot} - T_{cold})^2}{16T}$$

- Without staging, we have to work with

$$T_{hot} - T_{cold} < 23K$$

- If we have efficient thermal switch (regenerator), staging is an interesting alternative to work at higher temperature difference
- A factor 6 of improvement but we still need to study the magnetic to electric energy conversion

Thank for your attention