Analysis of thermal energy harvesting using ferromagnetic materials

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Harvest thermal energy with **ferromagnetic materials**

? **How**

Around its Curie Temperature $\boldsymbol{T_C}$, the permeability of ferromagnetic materials varies significantly

Coupling

Electric

Magnetic

Application of a magnetic field

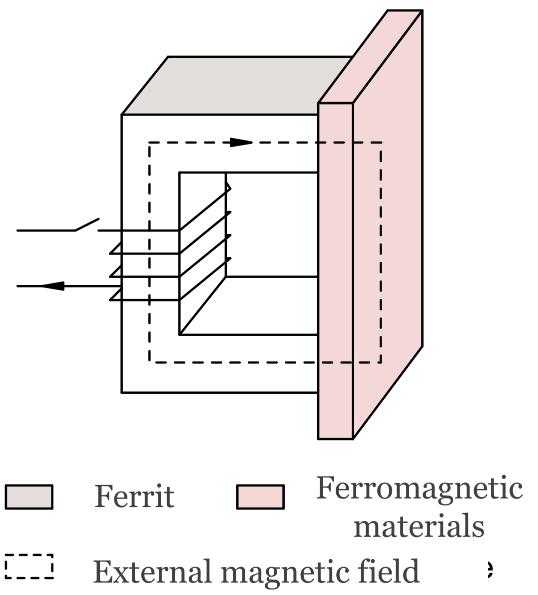
Magnetic

Coupling

Thermal

Thermoelectric coupling

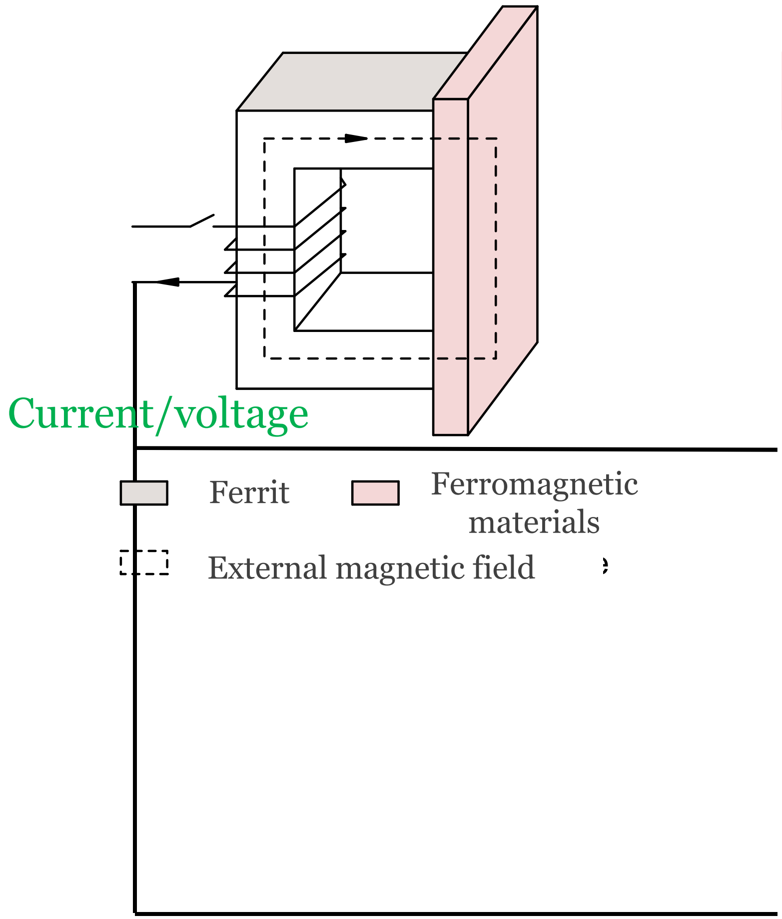
Setup



To combine these two couplings

- A piece of ferromagnetic material is attached to a U-shape ferrite
- U-shape ferrite is the magnetic core of a coil
- This system is placed in an external magnetic field

Analysis



Increase from $T< T_C$ to $T> T_C$

The thermal fluctuation will decrease the internal interactions → The ferromagnetic materials becomes disordered

↓

Significant decrease of μ → Variation in magnetic flux

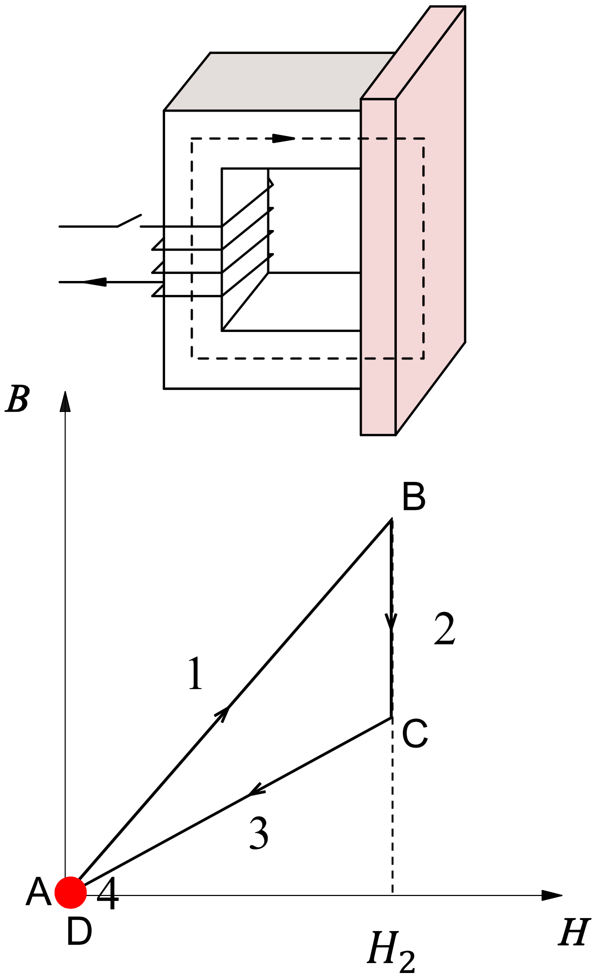
Decrease from $T > T_C$ to $T< T_C$

Thermal fluctuation is largely reduced → The ferromagnetic material reestablishes its order

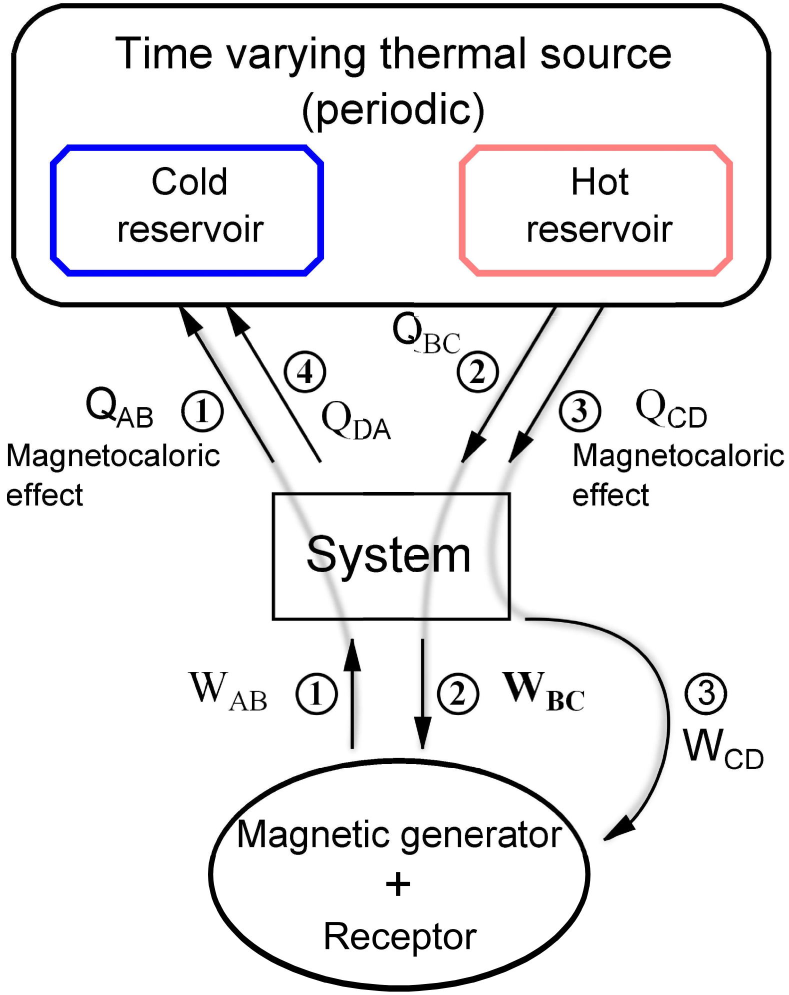
↓

Significant increase of μ → Variation in magnetic flux

Analysis Harvesting cycle



Energy flow



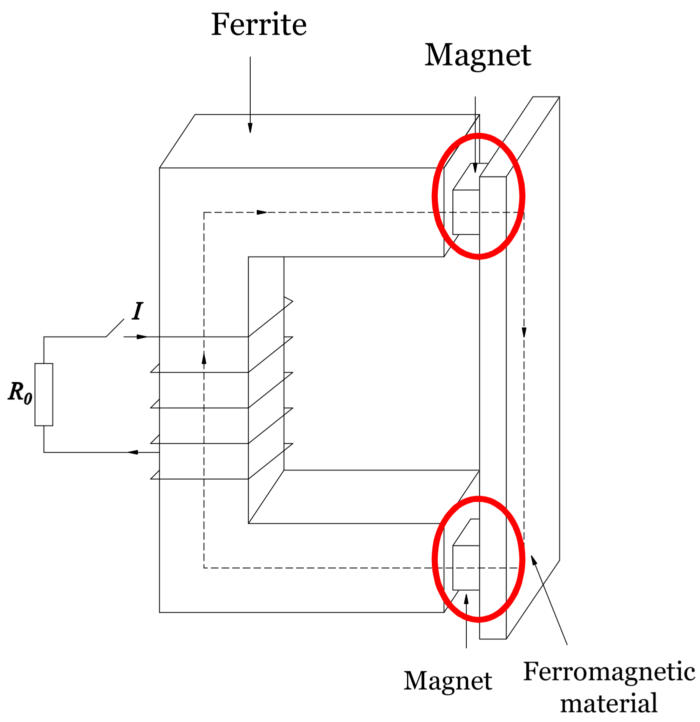
Analysis

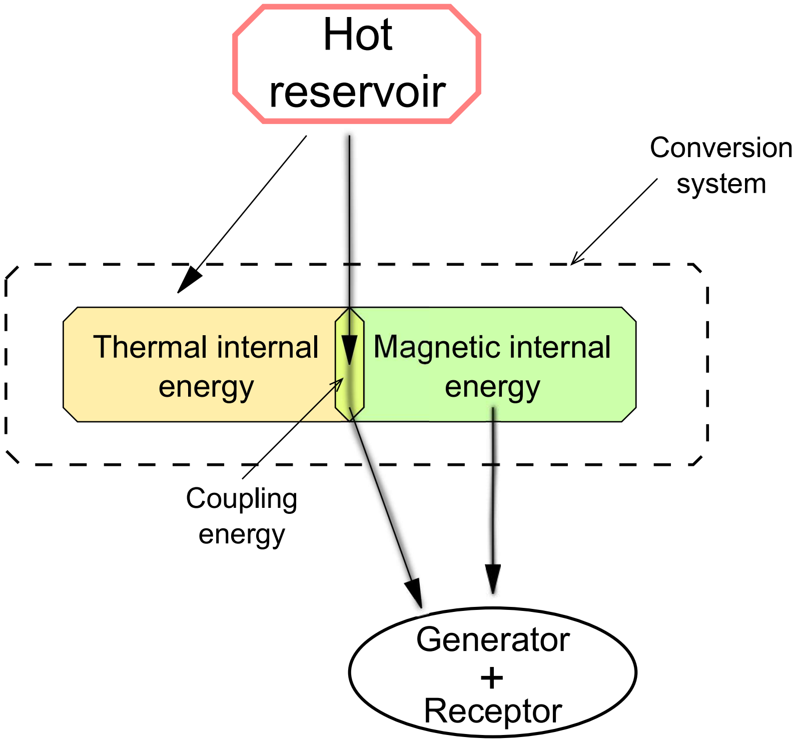
Harvesting cycle

Field – permanent magnet

External magnetic field is provided by permanent magnets

When the ferromagnetic material is **heated**

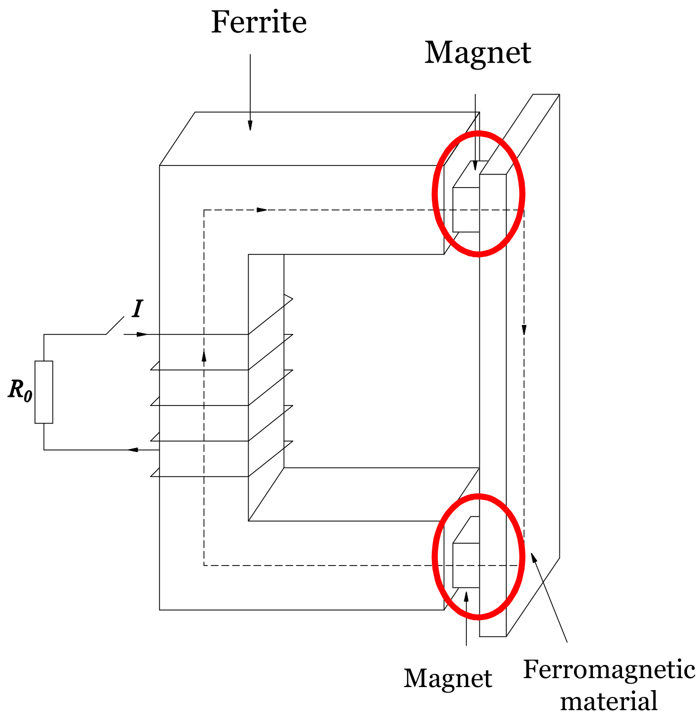


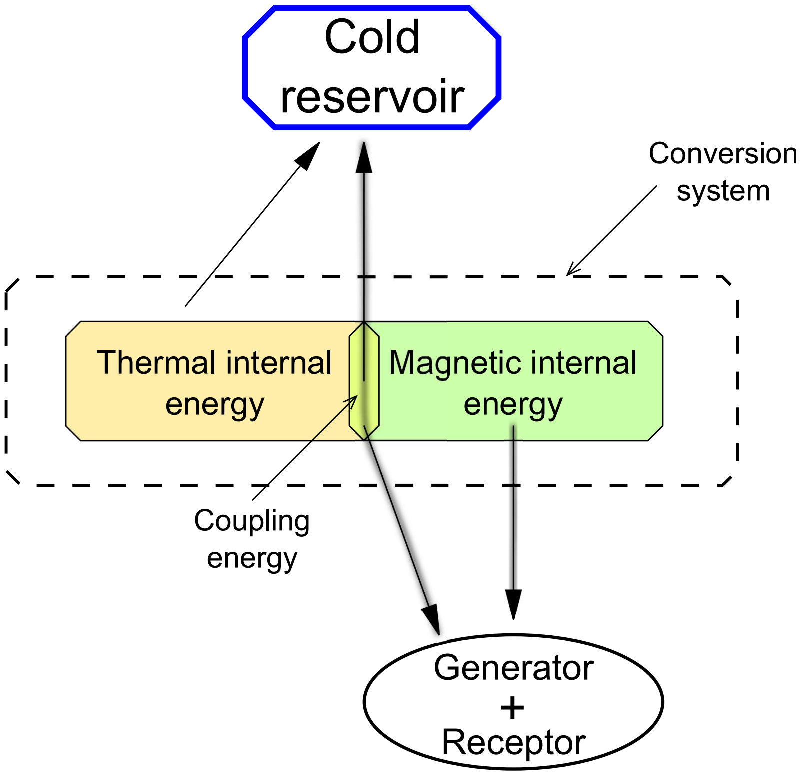


Analysis Harvesting cycle

Field – permanent magnet

When the ferromagnetic material is **cooled down**

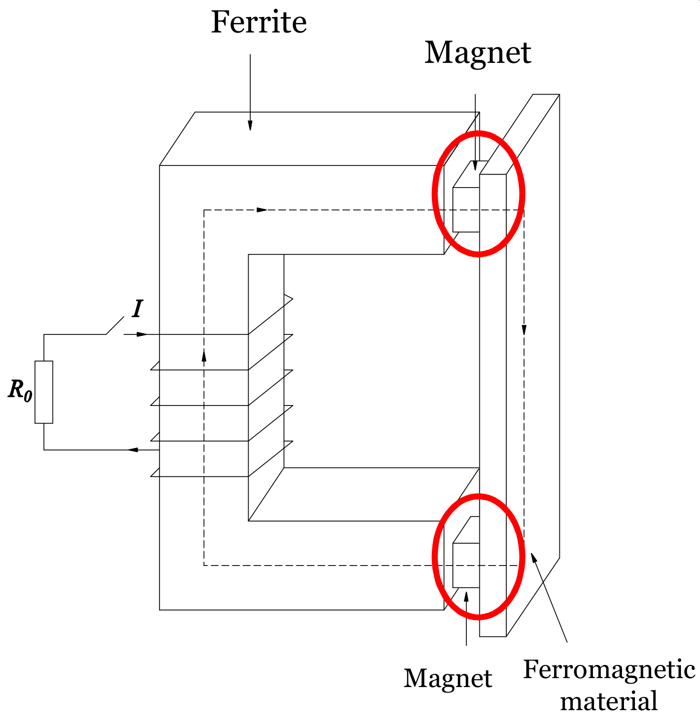




Analysis

Harvesting cycle

Field – permanent magnet



Voltage generated by variation of T:

$$\frac{dV}{dt} = \left[\frac{1}{\mathcal{R}(T)}\frac{d\mathcal{R}(T)}{dt} - \frac{R_0\mathcal{R}(T)}{N^2}\right]V + \frac{l_a R_0}{N\mu_a}\frac{1}{\mathcal{R}(T)}\frac{d\mathcal{R}(T)}{dt}$$

$$L\frac{dI}{dt} + R_0 I = -\beta\frac{dT}{dt}$$

Voltage generation

L: Pure inductance
R_0: Resistive load
β: Thermoelectric coupling factor

Analysis

Influence of $\frac{dT}{dt}$ on generated voltage

The generated voltage is proportional to variation velocity of the temperature

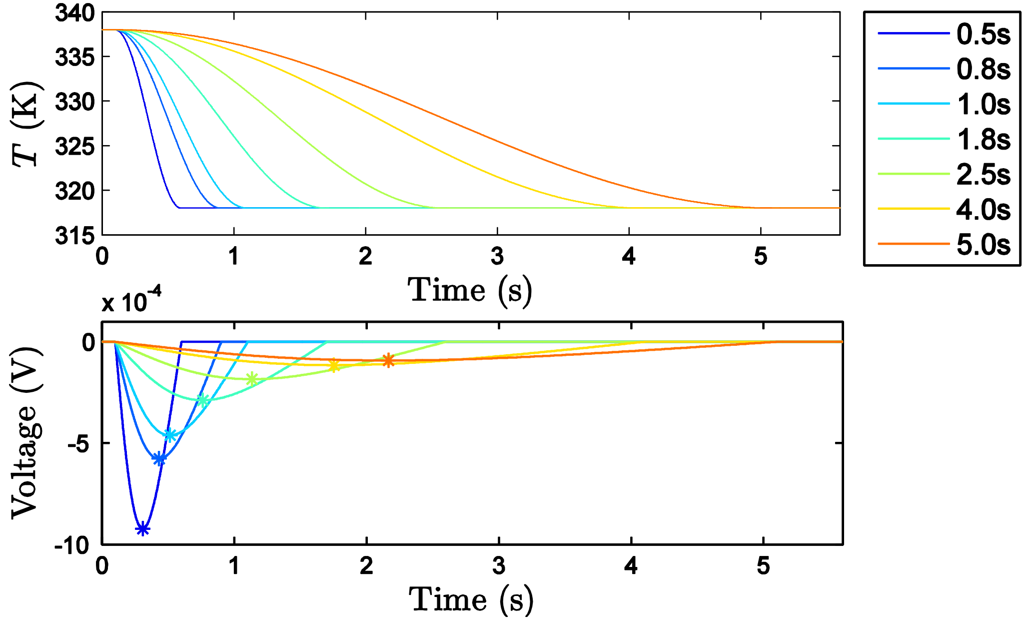
Same temperature decrease
in 0.5 s, 0.8 s,…,5 s

Approximately the same change in magnetic flux

For different variation velocity

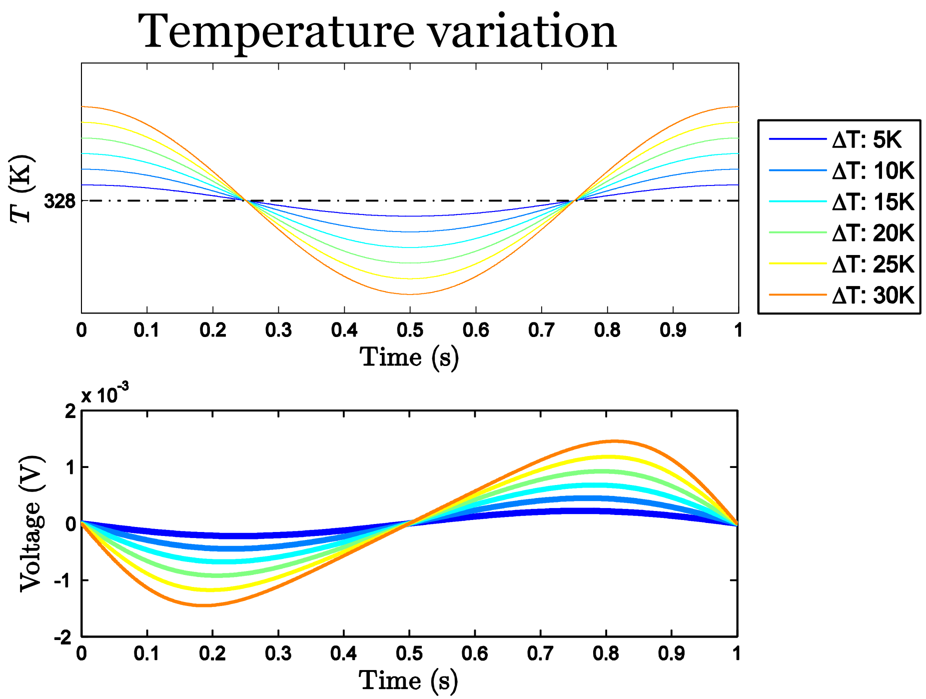
$$V = -\frac{d\phi}{dt}$$

The faster the temperature decreases, the higher the voltage is generated



Analysis

Influence of ΔT on generated voltage



The generated voltage is proportional to temperature variation $\Delta T = T_{max} - T_{min}$

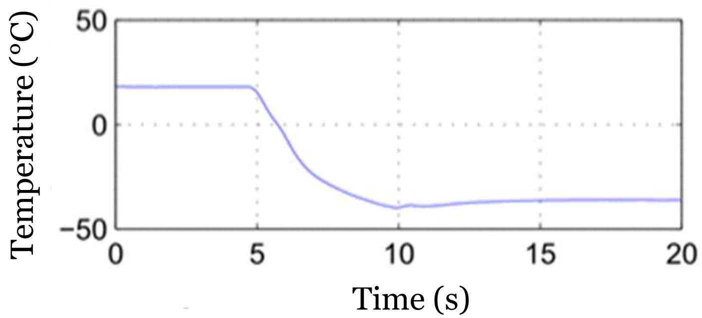
Large **temperature variation**

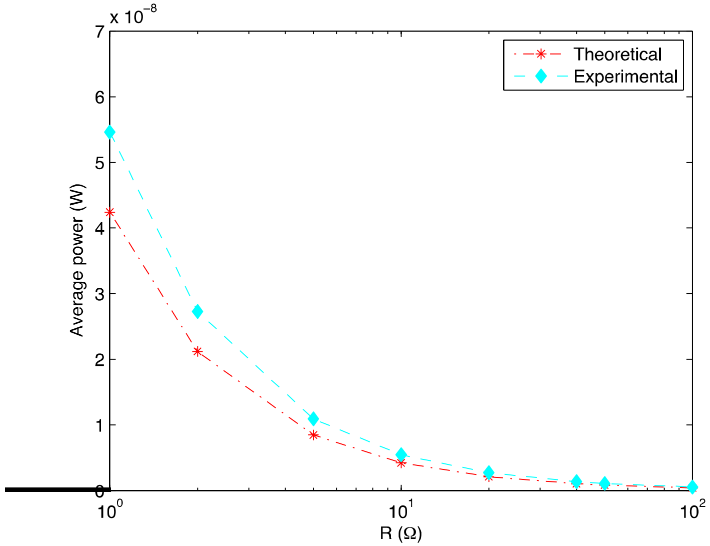
Large **permeability variation**

Significant **magnetic flux variation**

High generated voltage

Results





Temperature decreased **from 20°C to -40°C in 1~3 s**

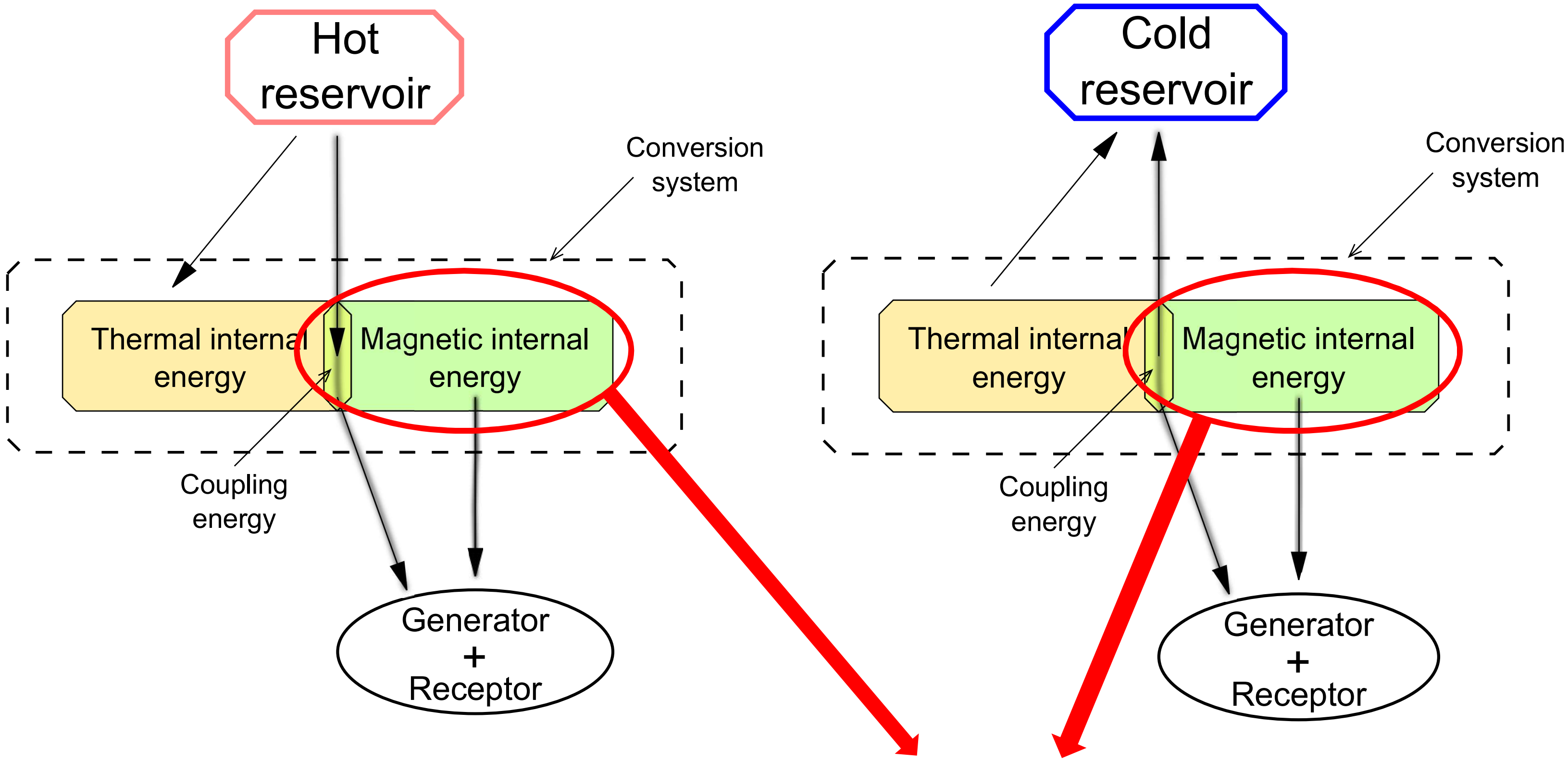
For a set of resistive loads from 1 to 100 MΩ

The maximum power is approximately $\mathbf{7 \times 10^{-7}}$ **W**

- Theoretically, there is an optimal resistance R_{opt} – quite small to optimize the power.
- In experiment, we did not succeed as the internal losses are already more than this optimal value

<u>However, even with this optimal resistance</u>, the harvested power is <u>less than 10^{-5} W</u>

Discussion



No matter how the temperature varies, the harvested energy is from **the coupling energy** and **internal magnetic energy.**

Discussion

↗ **Internal magnetic energy** ← Magnetization of external field

↗ **Coupling energy**

↑

Thermomagnetic coupling

Remanent field of permanent magnet

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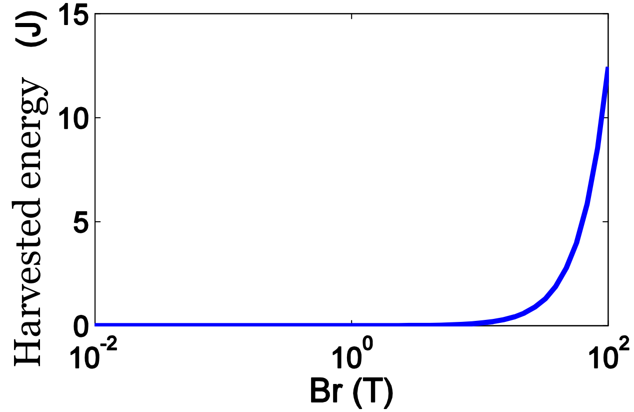
Choose a ferromagnetic material with high permeability variation around T_C

Choose magnets with high remanent field B_r (e.g. rare-earth magnets)



Summary

To harvest **thermal** energy with **ferromagnetic** materials

Characteristics

Permeability variation around T_C

\+ Ferrite + Coil + Application of an external magnetic field

Thermoelectric coupling

Permanent magnet

Harvest energy

Coupling energy and internal magnetic energy

Increase

Low power

Improve

Choices of magnets and materisl