Measurement of Thermomagnetic Convection Effect in a Cooling Process

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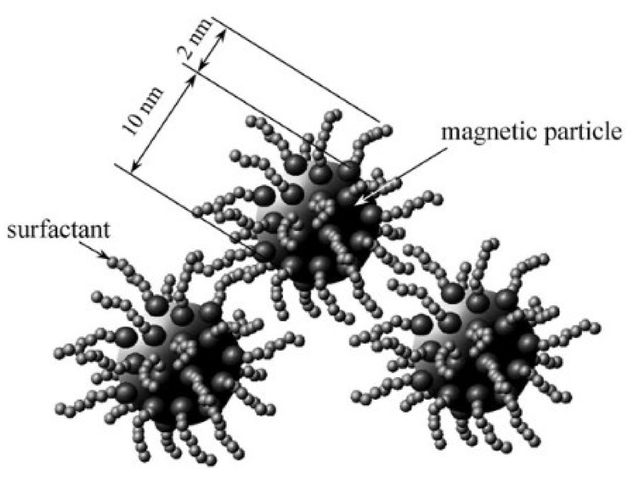
Context & Motivation

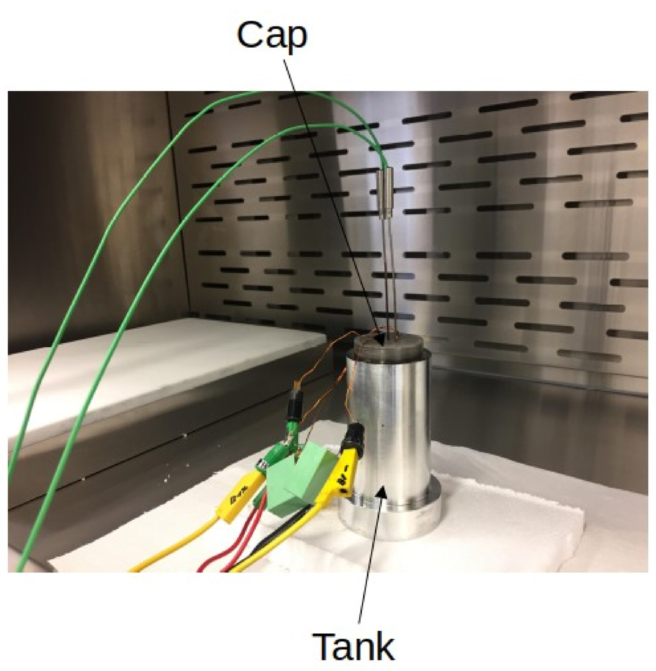
Cooling of electromagnetic systems (e.g. transformers) using ferrofluids, i.e. suspensions of magnetic nanoparticles in a liquid carrier, is studied at GeePs and LIMSI labs.

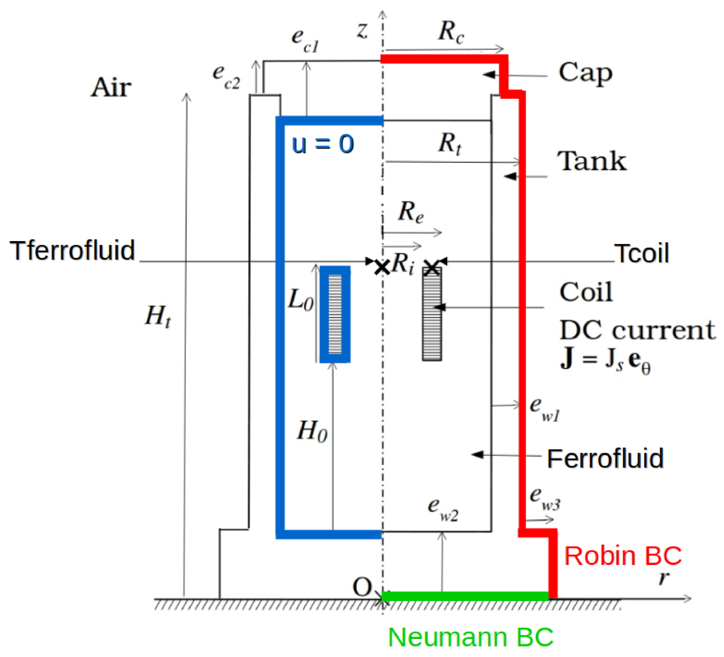


The objective is to understand the effect of the nanoparticles on heat transfers using both experimental and numerical approaches.

Experimental & Numerical Setup

An experimental setup uses a coil immersed in a cylinder filled with a cobalt-based surfactant ferrofluid (5% volume fraction of nanoparticles), carrier liquid is a vegetable oil





Setup model

Langevin's theory for linear magnetic material is used for the M-H relation:

$$M=\chi(T)H \qquad \chi(T)=\frac{\phi\mu_0\pi d^3 M_{s,p}(T)^2}{18K_B T}$$

Navier-Stokes, energy and magnetostatic equations are solved using Boussinesq approximation and an incompressible Newtonian fluid.

$$\begin{cases} \rho_l\frac{D\boldsymbol{u}}{Dt}+\nabla p-\eta\Delta\boldsymbol{u} = \rho_l\beta g(T-T_0)\boldsymbol{e}_z-\mu_0\frac{\boldsymbol{H}^2}{2}\nabla\chi(T) & \text{in }\Omega_f\\ \nabla\cdot\boldsymbol{u}=0 & \text{in }\Omega_f\\ \boldsymbol{u}=\boldsymbol{0} & \text{on }\partial\Omega_f\\ \boldsymbol{u}_{t=0}=\boldsymbol{0} & \text{in }\Omega_f \end{cases}$$

Buoyancy force

Helmholtz force

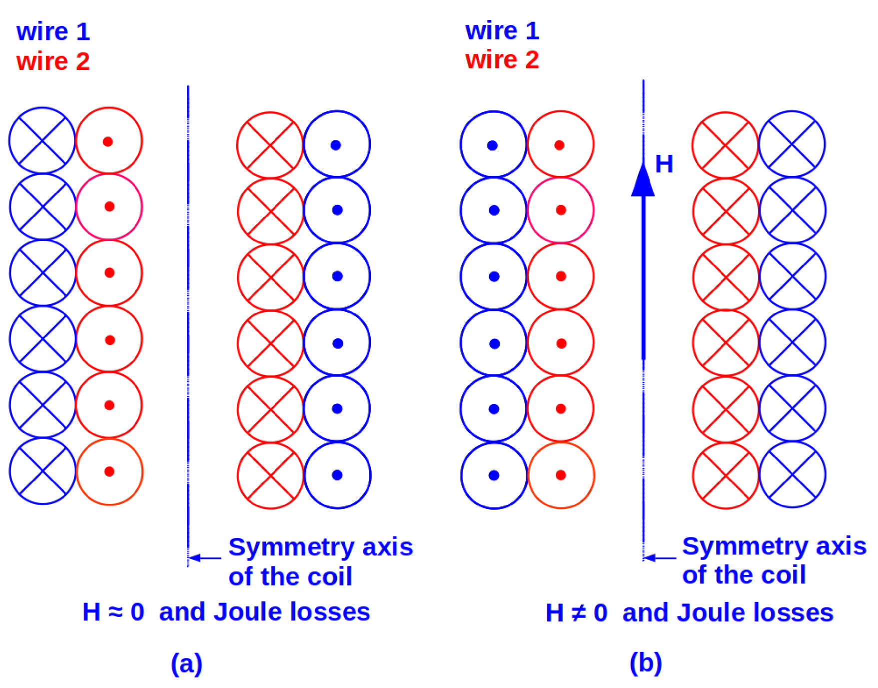
$$\begin{cases} \nabla\times\boldsymbol{H}=\boldsymbol{J} & \text{in }\Omega\\ \nabla\cdot(\mu\boldsymbol{H})=0 & \text{in }\Omega\\ \boldsymbol{H}\times\boldsymbol{n}=\boldsymbol{0} & \text{on }\partial\Omega \end{cases}$$

$$\begin{cases} \rho_l c_p\frac{DT}{Dt}-\nabla\cdot(\lambda\nabla T)=\frac{\boldsymbol{J}^2}{\sigma} & \text{in }\Omega\\ -(\lambda\nabla T)\boldsymbol{n}=h(T-T_0)\boldsymbol{n} & \text{on }\partial\Omega_R\\ -(\lambda\nabla T)\boldsymbol{n}=\boldsymbol{0} & \text{on }\partial\Omega_N\\ T_{t=0}=T_0 & \text{in }\Omega \end{cases}$$

The thermophysical properties of the ferrofluid are calculated using mixed laws.

Activation Method

The solenoid consists of a copper coil, in the form of a two-wire conductor as below:



(a) Currents directions in the two wires are opposite: Thermomagnetic convection deactivated

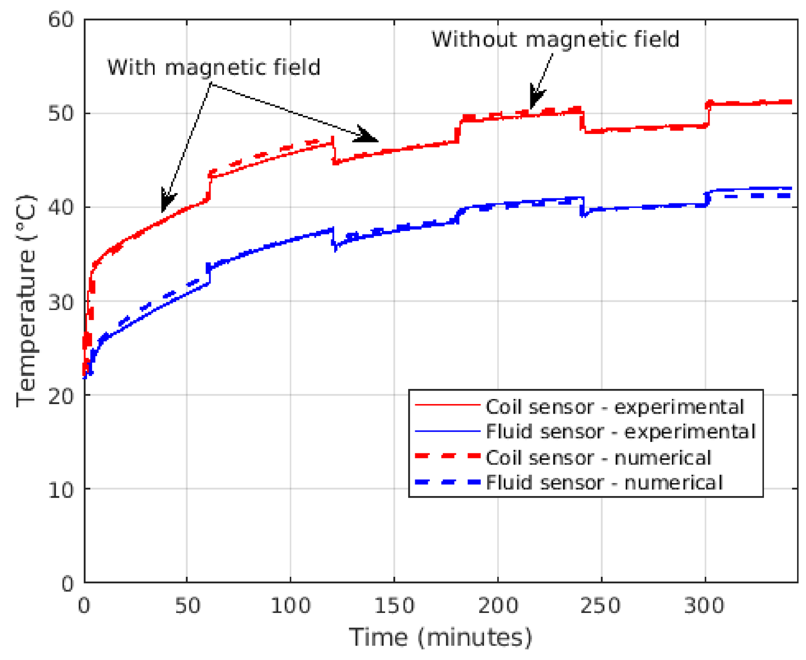
(b) Currents directions in the two wires are identical: Thermomagnetic convection activated

Results

Thermomagnetic Convection Effect

Two sensors record temperature in the fluid and at the coil.

The current direction in each resistor is initially the same, then it reverses every 60 minutes to activate/deactivate the thermomagnetic convection in the experiment and the computation.



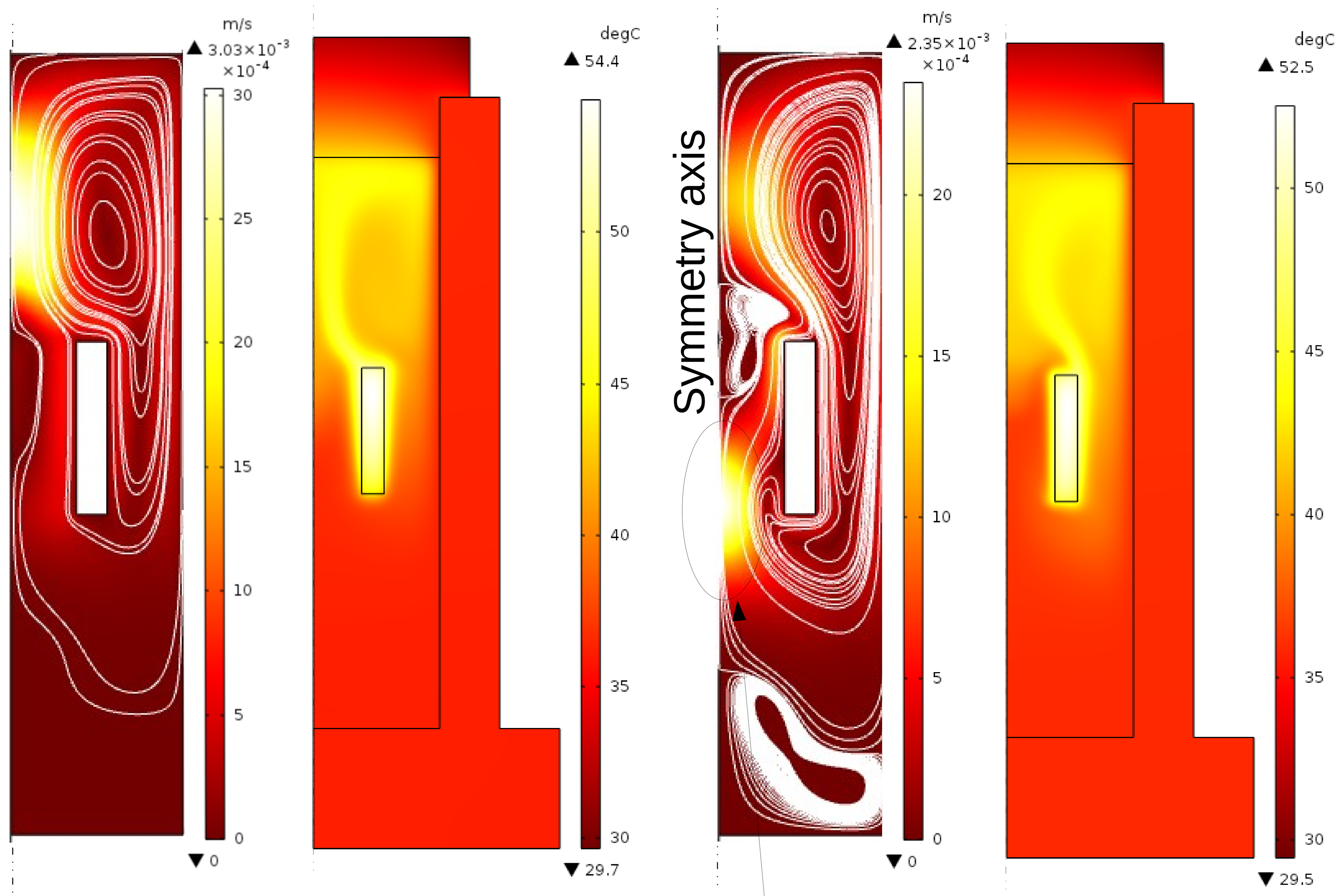
Crenellations with equal amplitude of 2,2 °C are approximately reproduced.

When the thermomagnetic convection is active, the coil temperature decreases.

Impact on velocity and temperature

The fluid flow around the coil is modified by the Helmholtz magnetic force. The temperature decrease is 1.9 °C.

Velocity magnitude U (m/s), streamlines (u,w) and temperature (°C) at t = 280 min and t = 330 min respectively:



Without Helmholtz force

With Helmholtz force

New convection cell

Conclusion

An experimental setup is developed to study the heat transfer of an electromagnetic system cooled by a ferrofluid.
The modeling assumptions lead to numerical results in agreement with the measurements.
The thermomagnetic convection leads to a decrease of coil temperature. Further developments will turn to more realistic devices with different types of load.

References

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