Analytical and Numerical Study of Heat Transfer Enhancement in Liquid Metal by Rotating Magnetic Field

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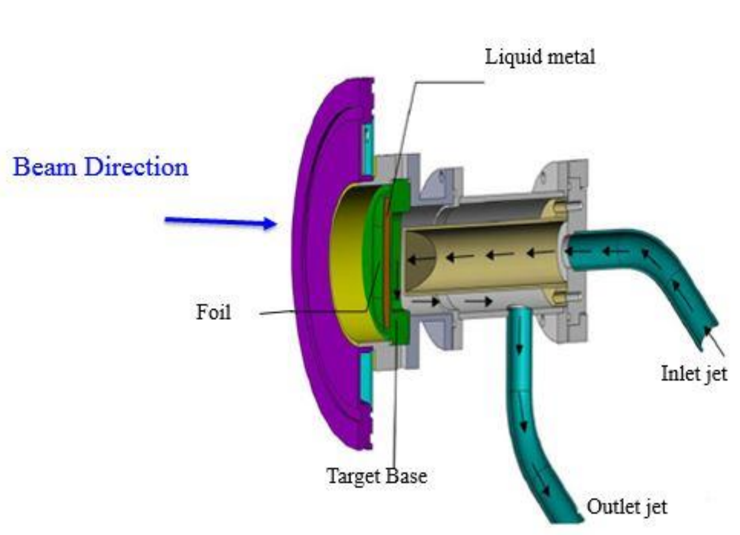
Abstract

Rotating Magnetic Field (RMF) was used to improve heat transfer in liquid metal (LM) targets exposed to high heat fluxes. Semi-analytical approximate solutions for the RMF and the flow field were developed and used for parametric study and optimization of the RMF inductor design. Additionally, the RMF was computed by commercial code ANSYS MAXWELL and plugged into ANSYS FLUENT code as a user defined function. Different simulations were conducted in order to test the dependency of the LM flow and the temperature distribution on the RMF parameters. The main goal was to obtain maximal flow circulation in the region exposed to high heat flux and maximal reduction of the fluid temperature.

Motivation

- ❑ To enhance heat transfer in LM target exposed to high heat fluxes.
- ❑ Circulation of LM by invasive means is prohibited.
- ❑ Rotating Magnetic Field (RMF) is chosen to force convection.



Cross section view of typical radio-isotope target

External RMF stirs the LM and generates forced convection. The radioactive material inside the target remains well isolated from environment.

Governing equation for full numerical simulation

$$\begin{cases} \dfrac{\partial \vec{b}}{\partial t} + (\vec{u}\cdot\nabla)\vec{b} = \dfrac{1}{\mu\sigma}\nabla^2\vec{b} + (\vec{B}\cdot\nabla)\vec{u} - (\vec{u}\cdot\nabla)\vec{B}_0 - \dfrac{\partial \vec{B}_0}{\partial t} \\ \mu\vec{j} = \nabla\times\vec{b} \rightarrow \vec{F} = \vec{j}\times\vec{B} \end{cases}$$

$$\begin{cases} \dfrac{\partial \vec{u}}{\partial t} + (\vec{u}\cdot\nabla)\vec{u} = -\dfrac{1}{\rho}\nabla p + \nu\nabla^2\vec{u} + \dfrac{1}{\rho}\vec{j}\times\vec{B} \\ \nabla\cdot\vec{u} = 0 \end{cases}$$

$$\frac{\partial(\rho E)}{\partial t} + \nabla\cdot\big(\vec{u}(\rho E + p)\big) = \nabla(k\nabla T) + S$$

Computational steps

Solve Maxwell's equations for the magnetic field generated by inductor

↓

Solve the induction and Ampere's equations to compute b, j and F.

↓

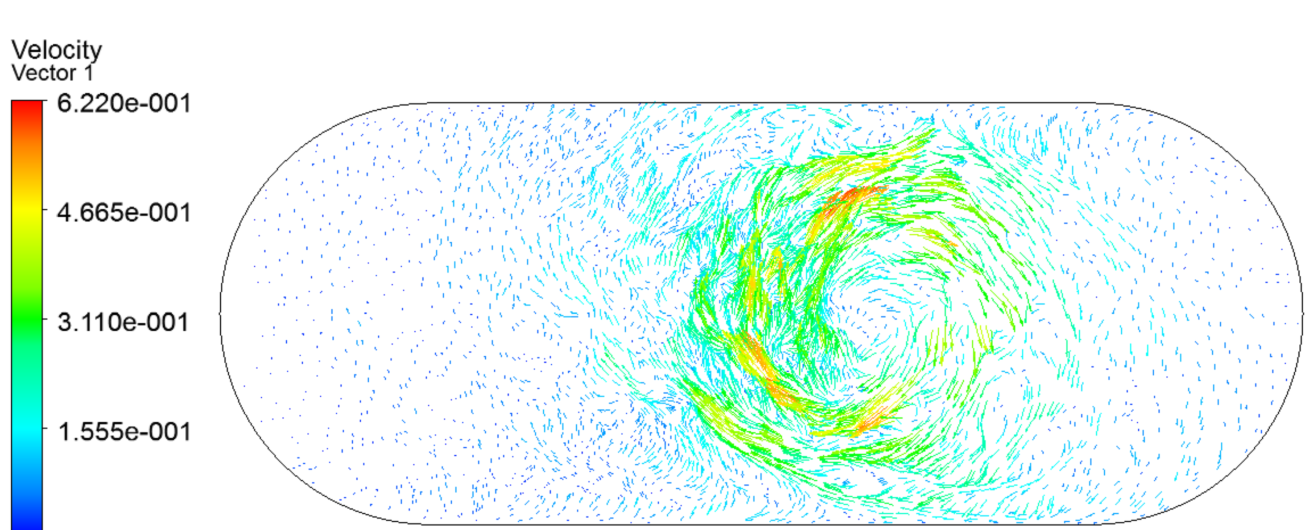
Solve the flow field driven by the Lorentz force F

↓

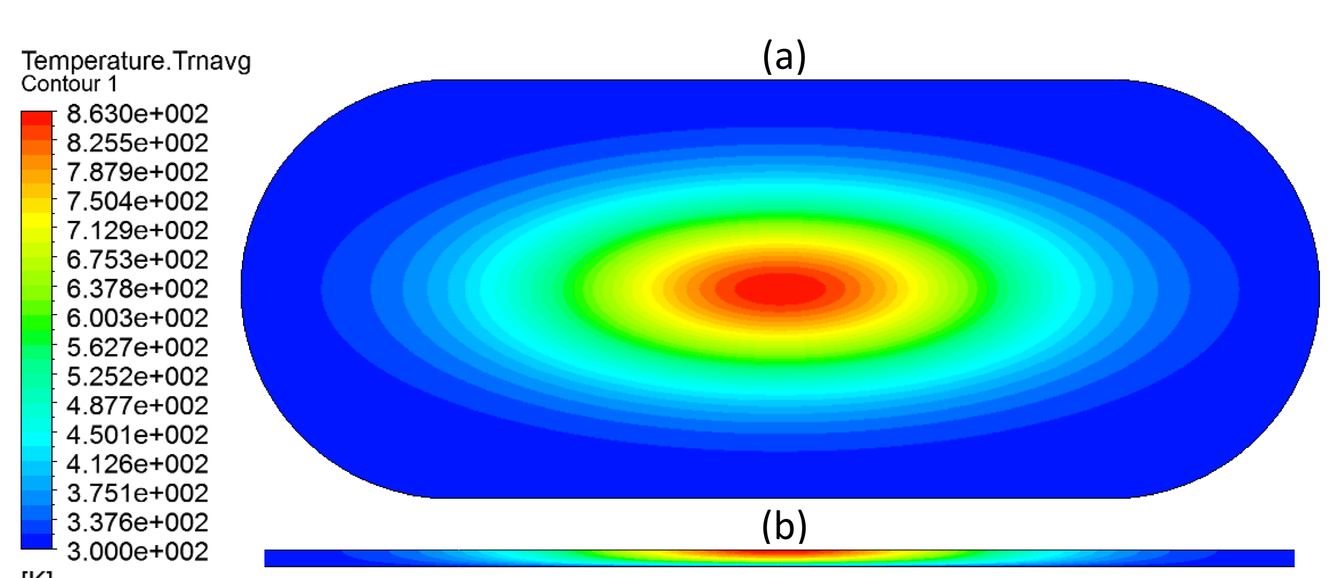
Solve the temperature of the LM target exposed to Gaussian volumetric heat source

Numerical simulation

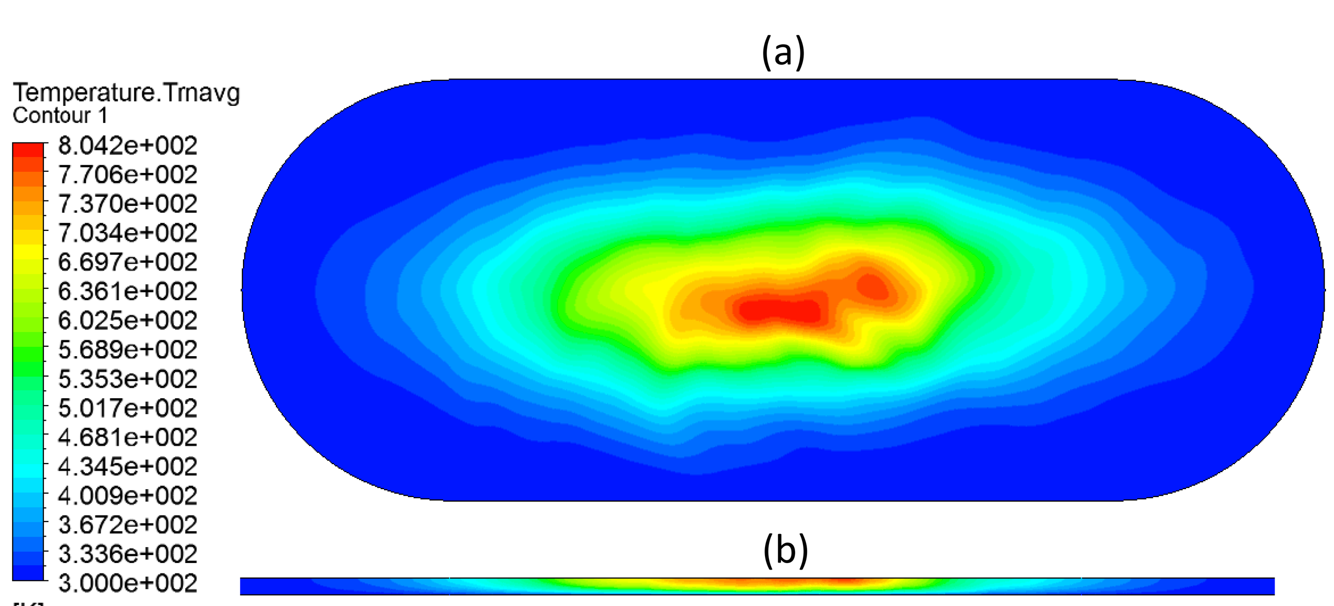
- ❑ Numerical simulation of the magnetic field was performed by ANSYS MAXWELL code.
- ❑ The magnetic field is plugged into ANSYS FLUENT as User Defend Function.
- ❑ Commercial code ANSYS FLUENT was used to simulate the flow and the temperature fields.
- ❑ In order to maximize the heat transfer enhancement, magnetic field parameters were adjusted by computational results.



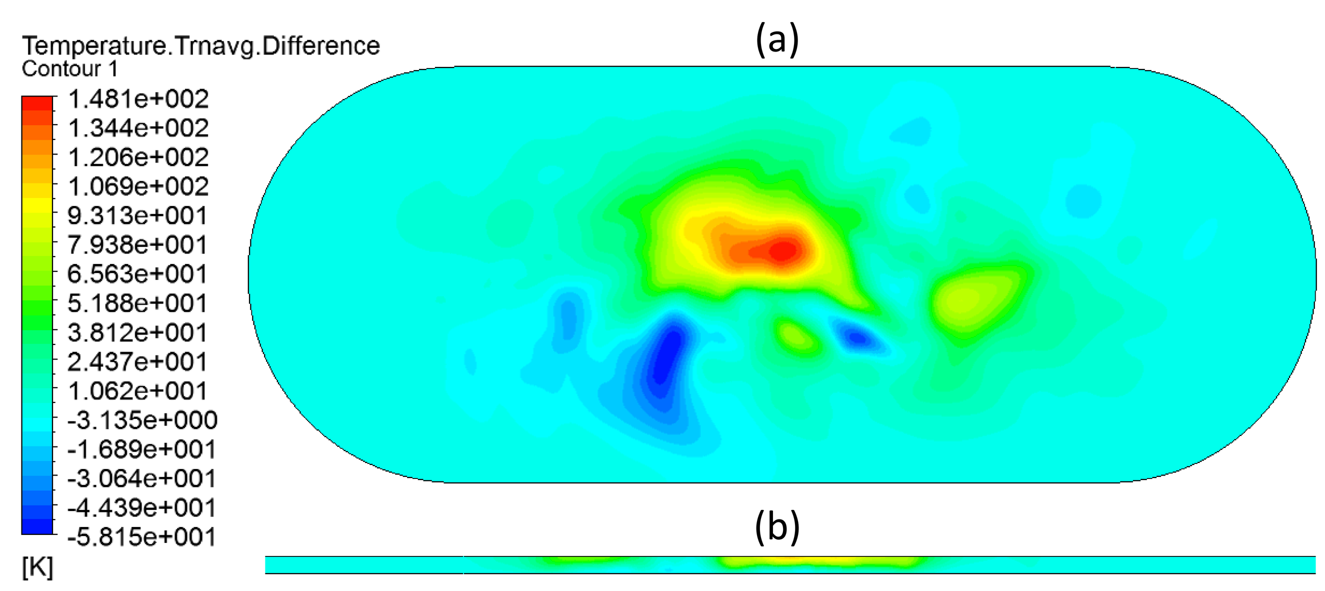
Velocity field in x-y plane



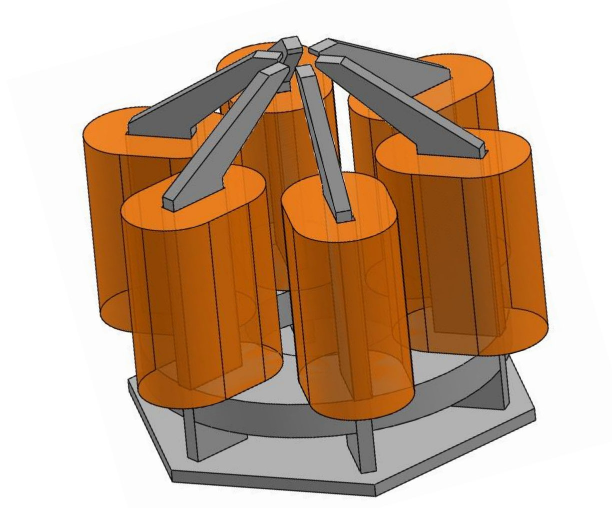
Temperature distribution without RMF, (a) x-y plane, (b) x-z plane



Temperature distribution with RMF, (a) x-y plane, (b) x-z plane



Temperature differences without and with RMF, (a) x-y plane, (b) x-z plane



Six poles inductor used to generate the RMF

$$f = 400\ \text{Hz}$$

$$I_0 = 10 sin(2\pi f t + \phi)\ \text{A}$$

$$\rho = 890\ \text{kg}/m^3$$

$$C_p = 1300\,\frac{\text{J}}{\text{kg K}}$$

$$k = 50\,\frac{\text{W}}{\text{m K}}$$

$$\mu = 4\cdot 10^{-4}\,\frac{\text{kg}}{\text{m s}}$$

$$\sigma = 1.68\cdot 10^{6}\,\frac{1}{\Omega\,\text{m}}$$

$$\mu_0 = 1.257\cdot 10^{-6}\,\frac{\text{H}}{\text{m}}$$

$$q''_{max} = 42\,\frac{\text{MW}}{\text{m}^2}$$

Conclusions

- The maximal flow temperature is reduced by as much as 50 K.
- In some regions the high flow velocity leads to temperature drop by 150 K!
- **The main goal is achieved by using RMF.**

Acknowledgments

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