A Computational Study on Thermal Conductivity Measurement of High Temperature Liquid Materials

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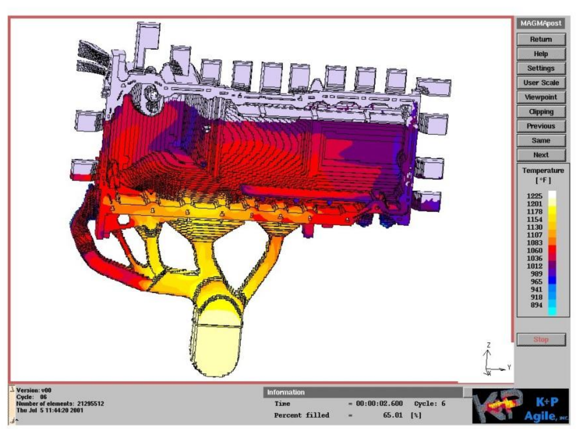
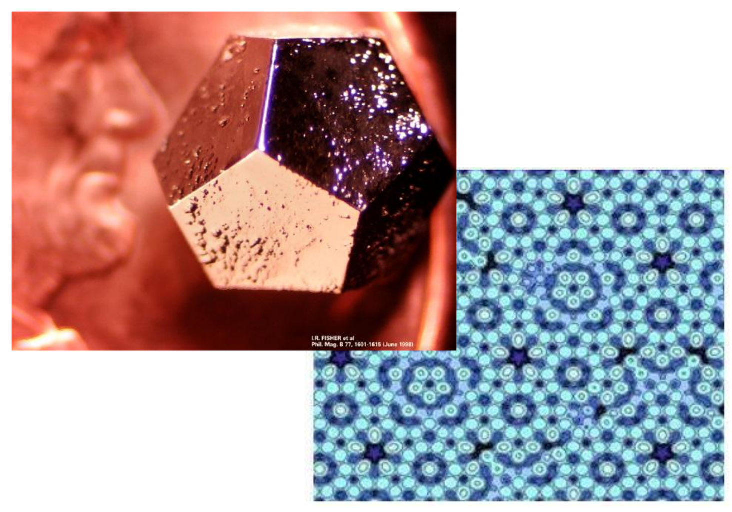
Motivation

- Accurate thermal conductivity (k) data of liquid metallic materials at high temperatures are desired for both industrial and scientific purposes.





(a) (b)

Figure 1. (a) simulation of the casting process of car engine [1] and, (b) study of the solidification kinetics of Zr-based bulk metallic glass-forming alloy.

- Traditional methods fall short due to:
  Environmental contamination + Uncontrolled heat transfer

Background

- Electromagnetic Levitation based Modulation Calorimetry (EML-MC)
  Noncontact processing + No external contamination

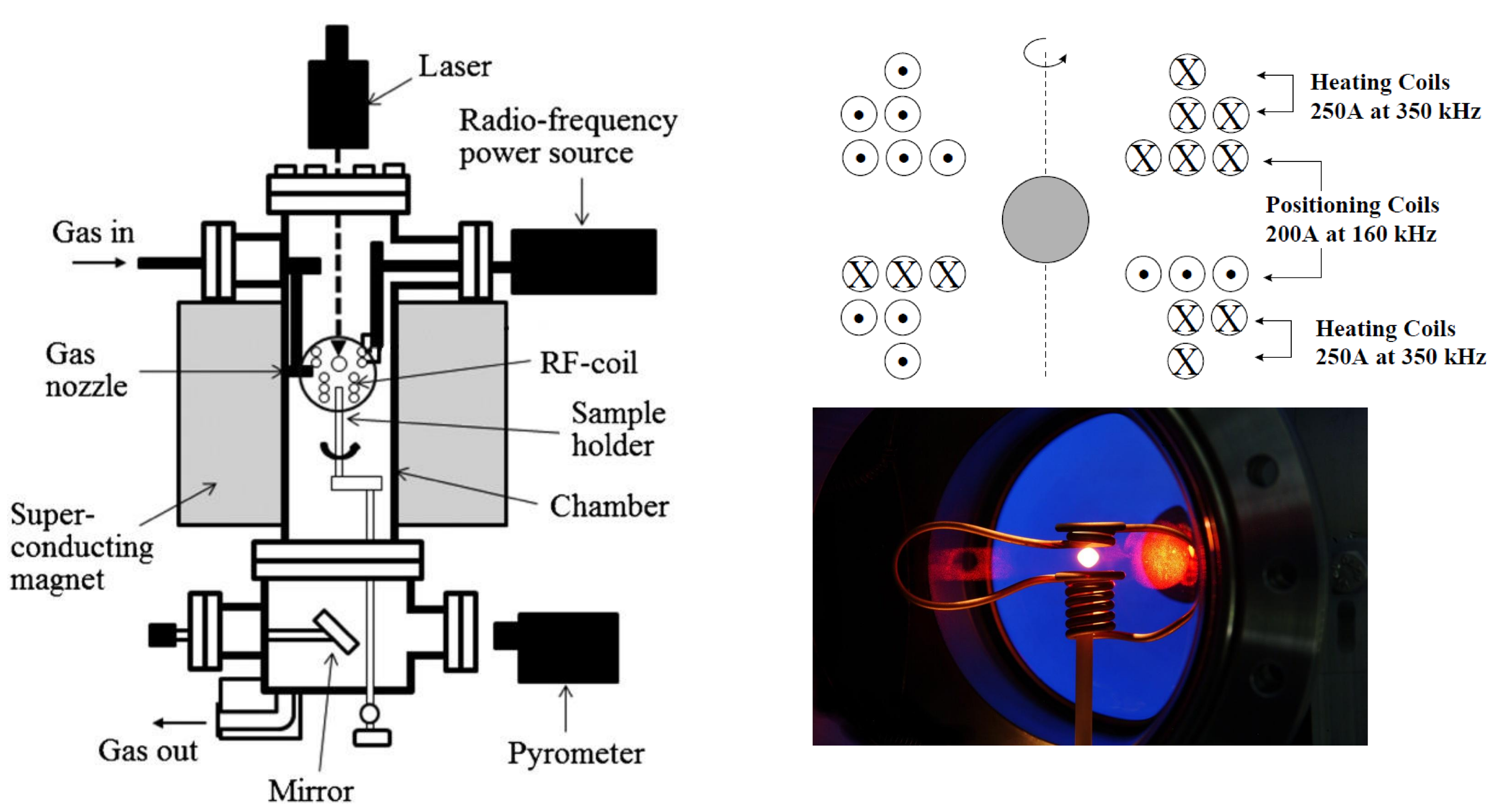


Figure 2. Left is an EML apparatus developed by Japanese scientists[2]. Sample is levitated using EML and heated via laser. Top right is the coil design for EML apparatus TEMPUS[3], which was flown in MSL-1 Spacelab mission. Bottom right is a sample under EML process.

- Principle (for solids):

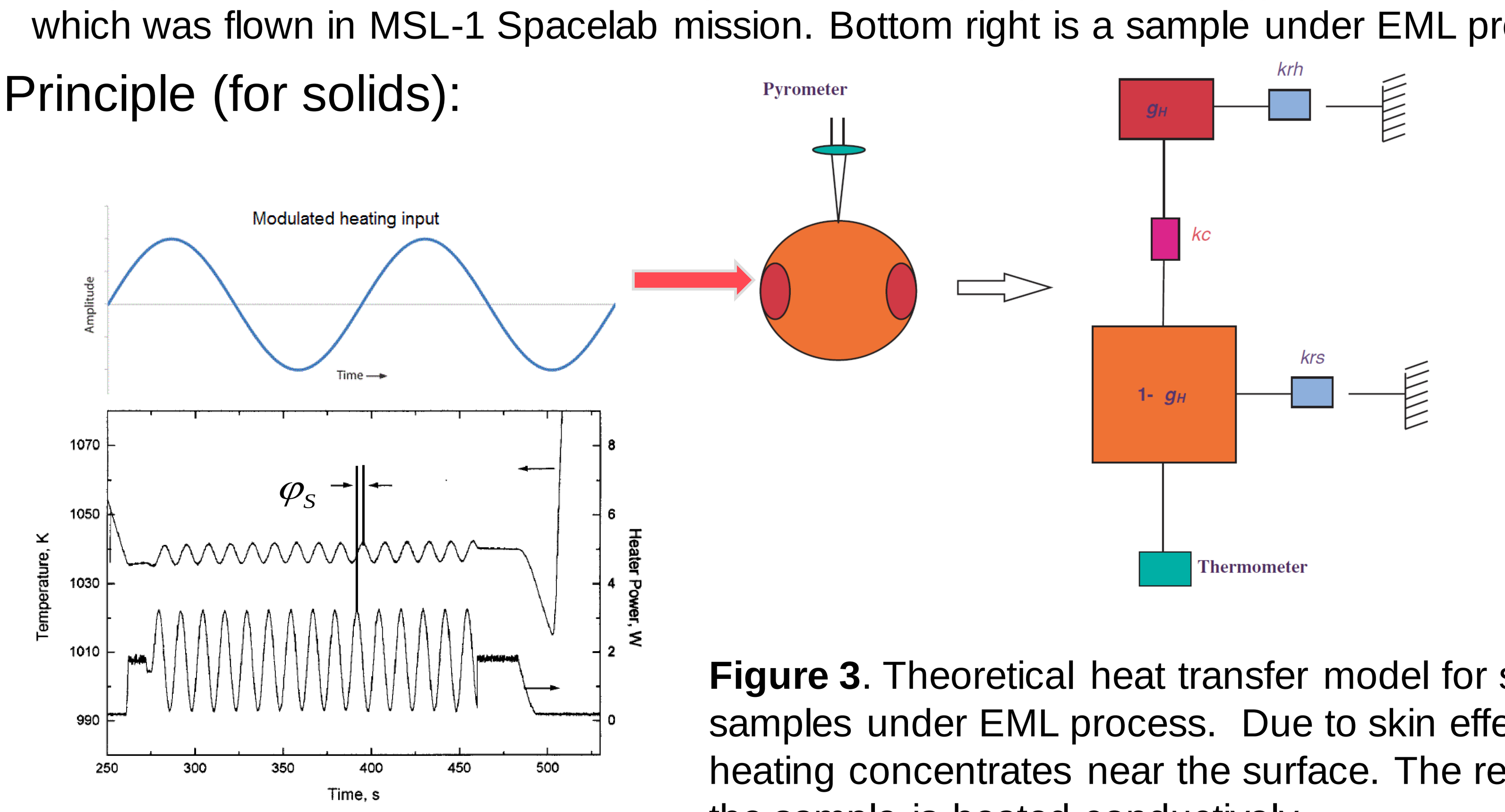


Figure 3. Theoretical heat transfer model for solid samples under EML process. Due to skin effect, EM heating concentrates near the surface. The rest of the sample is heated conductively.

1. Measure phase lag φ_S
2. Solve for $\lambda_2 = \frac{k_c}{c_p \cdot m}$ use: $\cos(\varphi_S) = (\lambda_1\lambda_2 - \omega^2)\left[(\omega^2+\lambda_1^2)(\omega^2+\lambda_2^2)\right]^{-1/2}$
3. Solve k use analytical solution: $k_c = \frac{4}{3}\pi^3 Rk$

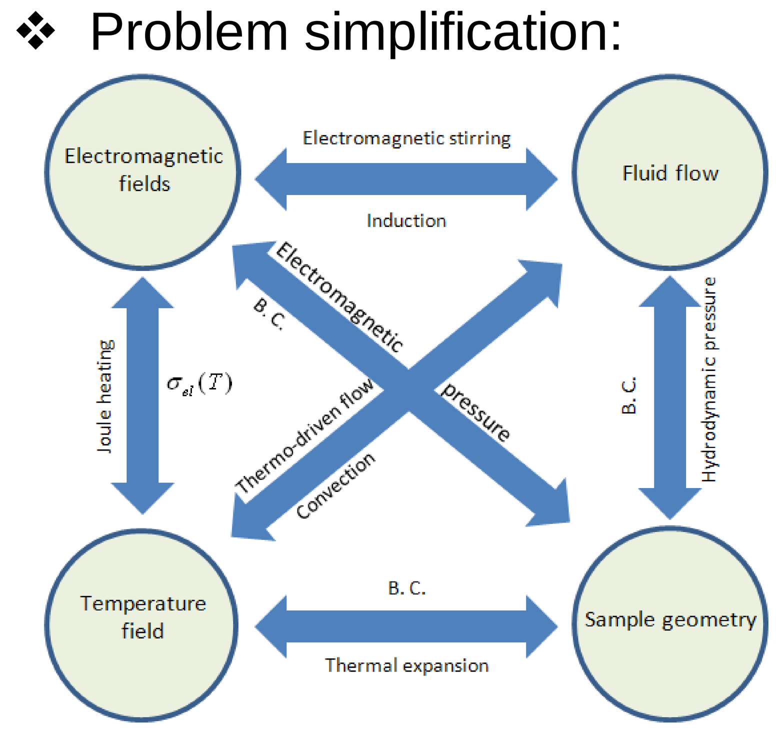
- For liquids: Convection results into overestimation of k!

Research Objective

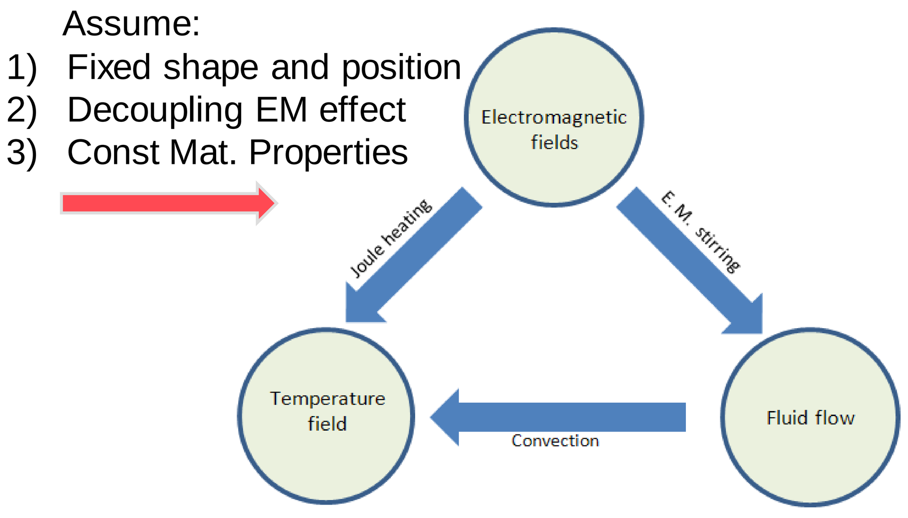
- Determine true k of liquid materials use numerical simulation;
- Understand the dependence of convective error on experimental parameters;
- Provide guidance to future k measurements.0

Modeling

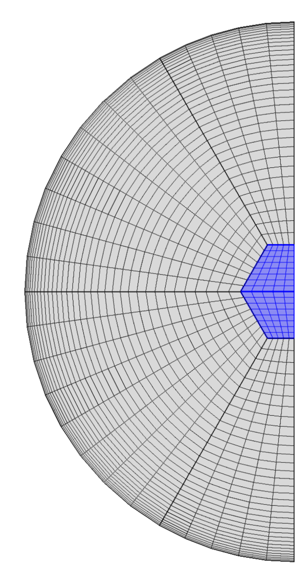
- Problem simplification:



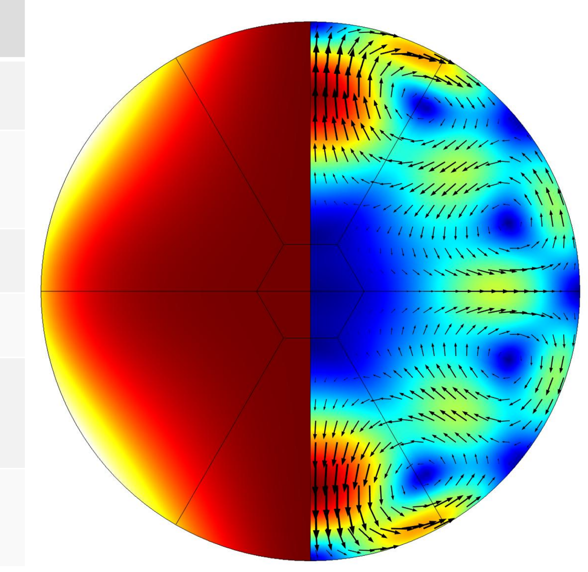
Assume:
1) Fixed shape and position
2) Decoupling EM effect
3) Const Mat. Properties



- Meshing: - Validation:

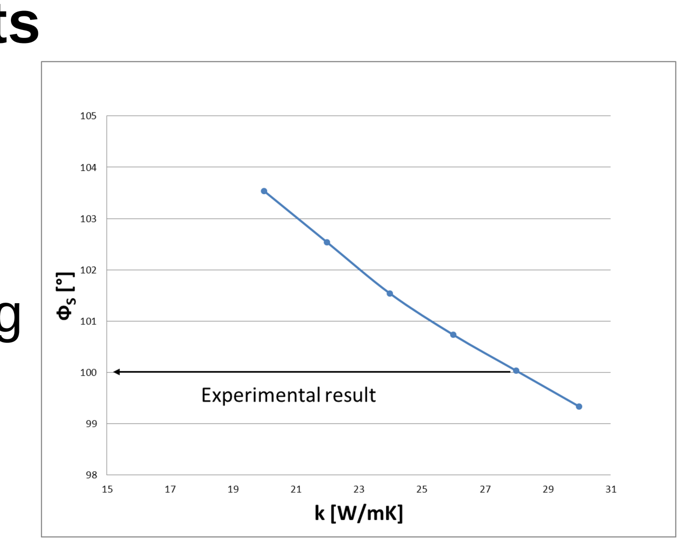


FeCrNi Alloy (@1540K)	
Density	7040 (Kg/m^3)
Thermal Conductivity	28.4 (W/mK)
Specific heat	830 (J/Kg-K)
Viscosity	5.59E-3 (Pa-s)
Electrical Conductivity	6.63E5 (ohm-m)^(-1)
Total hemi. Emissivity	0.33

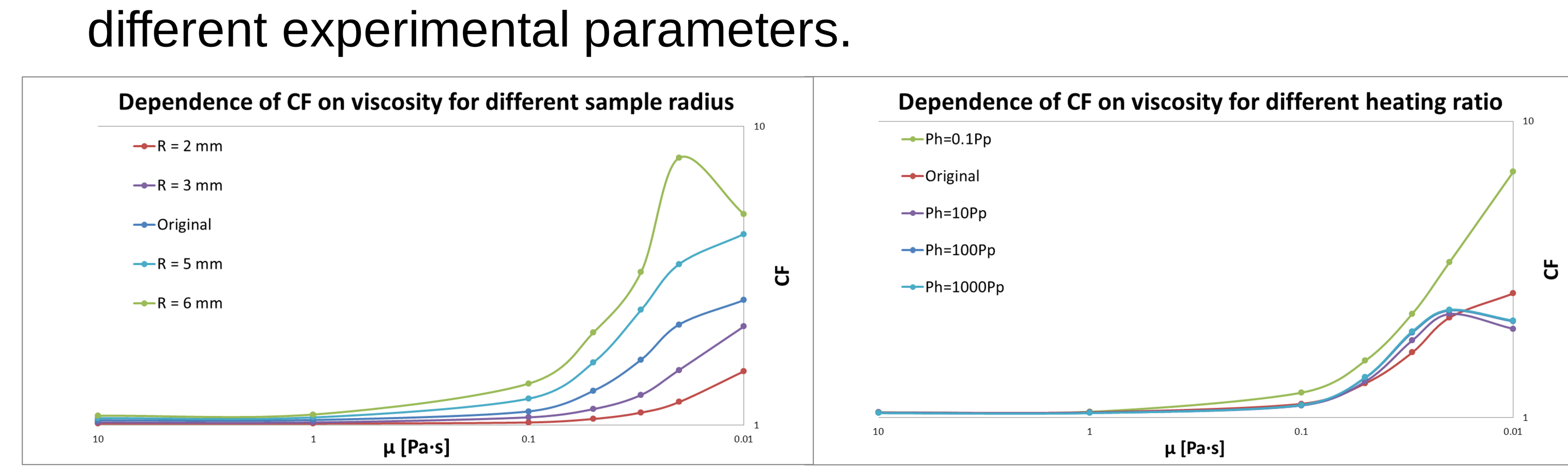


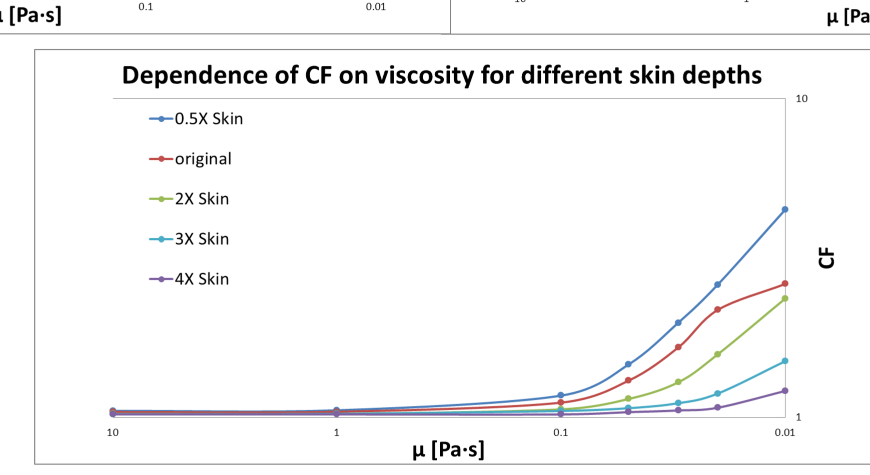
Results

- For liquid ZrAlCuNi alloy at 1024K. Ture k is determined to be 28W/mK, which is very close to the reported value 31.2 W/mK, indicating that convective error is small at this viscosity.



- Dependence of convective error (CF = measured k/ true k) on different experimental parameters.





- Uncertainty Analysis

		Uncertainty in CF at different viscosities			
	Uncertainty	10	1	0.1	0.05
Emissivity	6%	-6% to 6%	-6% to 6%	-6% to 6%	-6% to 6%
Viscosity	25%	-0.06% to 0.06%	-0.4% to 0.3%	-1.5% to 4%	-7% to 13%
Temperature	0.1K	-5% to inf	-10% to inf.	-15% to inf.	-20% to inf.

Table 1. Uncertainty analysis for CF at different viscosities. Uncertainty in emissivity needs to be addressed in high viscosity range. Uncertainty in viscosity has little impact on CF. Most importantly, measurement precision in T needs to be improved!

Conclusions

- CFD + EML-MC is a viable method for k measurement of high temperature liquid metallic materials.
- CFD simulation could be used to guide future experimental designs.

[1] Hepp, E., and S. Neves, I. Egry. Modeling of Casting, Welding and Advanced Solidification Processes IX. Shaker Verlag Aachen, 2000.
[2] Baba, YuyaThermal conductivity measurement of molten copper using an electromagnetic levitator superimposed with a static magnetic field. Measurement Science and Technology 23 (2012), 045103.
[3] Hyers, Robert W. *Modeling of and experiments on electromagnetic levitation for materials processing. PhD thesis, Massachusetts Institute of Technology,* MA, 1998.