Measurement of Coatings Thermal Properties via Induction Phase Radiometry

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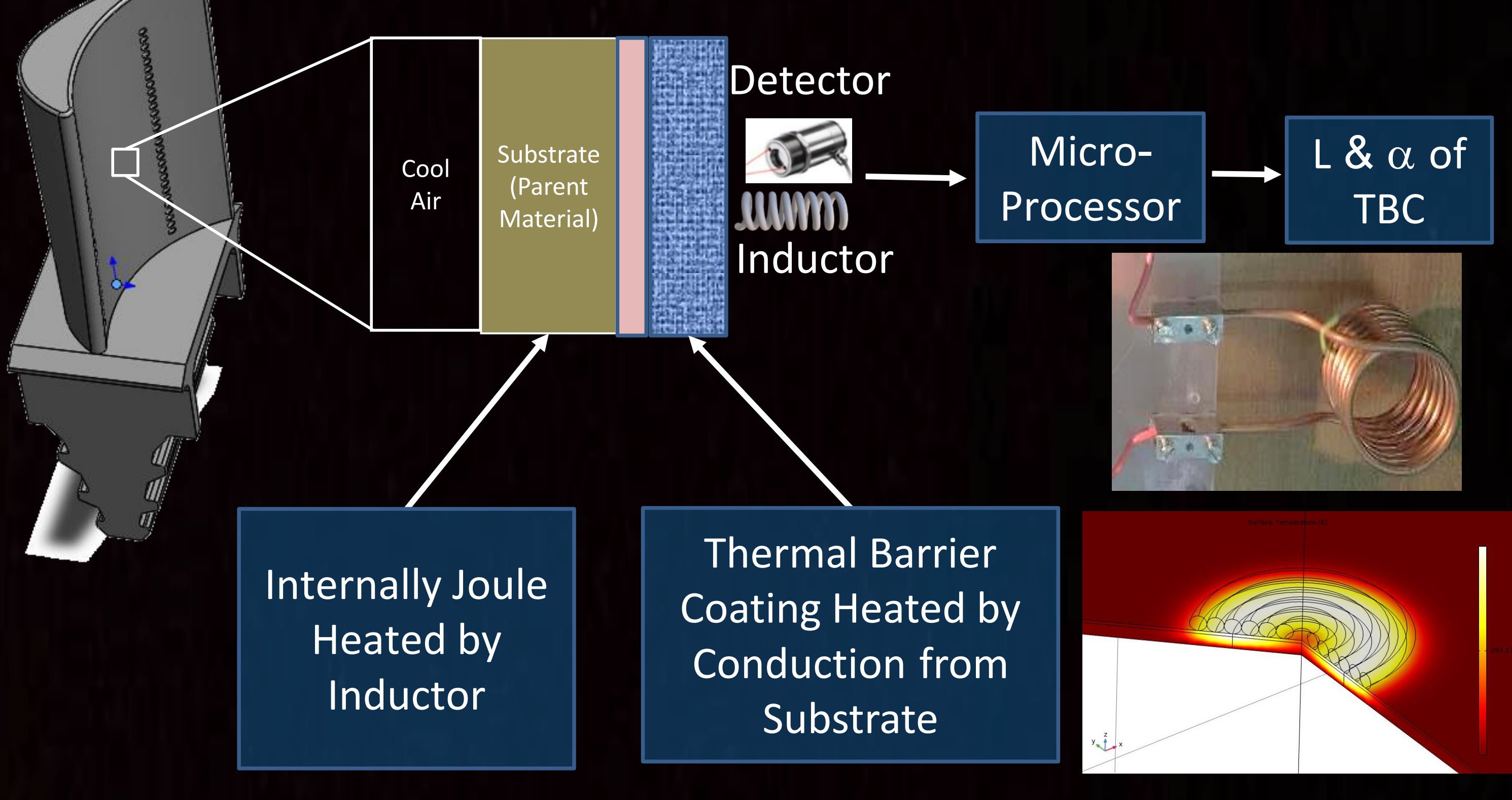
MOTIVATION & BACKGROUND

Novel methodology of measuring thermal properties of thin thermal barrier coatings (i.e., thermal diffusivity, layer thickness) is proposed in the research scope. This technique uses new approach which allows in-situ inspection of coated parts.

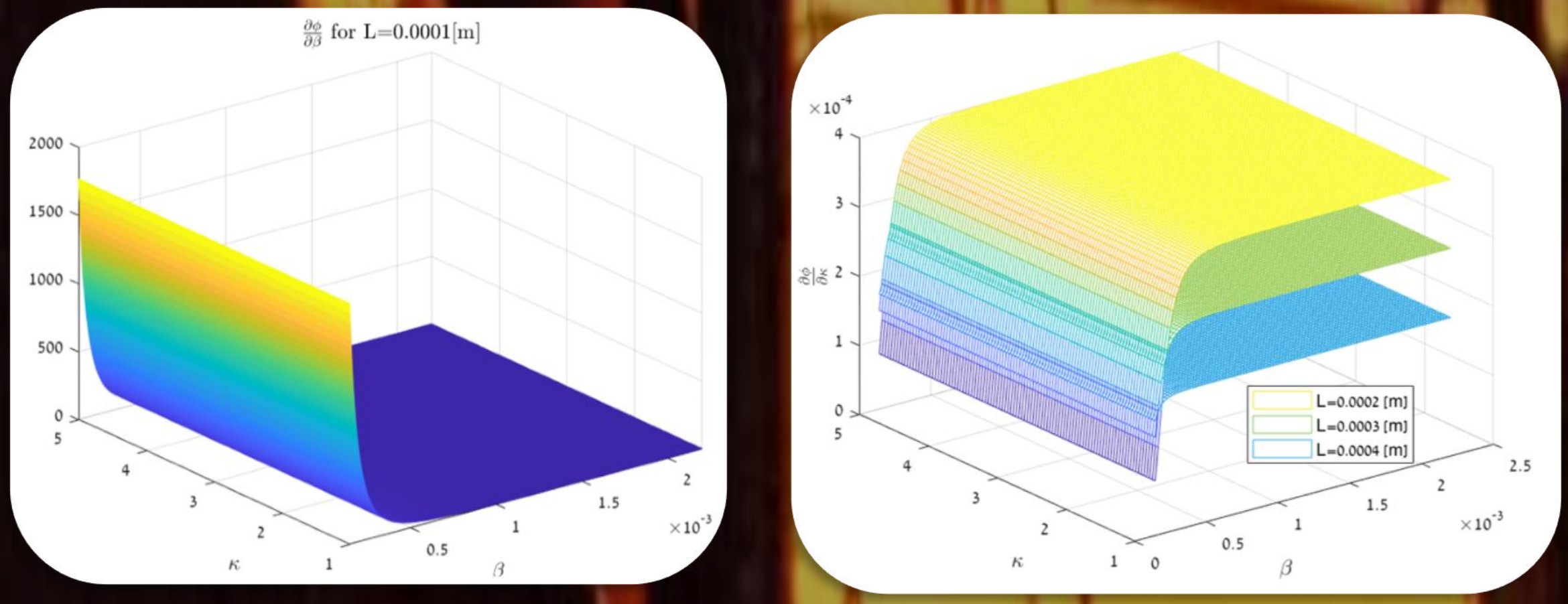
Measuring thermal properties of a part without removing it from the engine towards assessment in specially equipped lab, is of high demand. It potentially enables assessment of coating condition in a more convenient way than other currently available methods, thus reduces cost of unnecessary engine removals.



General diagram of research concept - measurement of TBC thermal properties by induction radiometry

METHODOLOGY DESCRIPTION

The methodology includes generating internal heat inside the parent material via induction. In following, external coating temperature is continuously recorded, and analyzed. Phase between external temperature and internal induction power is used to calculate thermal properties. 1D unsteady heat conduction equations are developed to recover properties by decoupling the relationship between surface temperature phase and TBC properties.


Phase and its partial derivatives, identify conductivity as negligible, allowing to develop optimization recovery scheme for diffusivity and thickness by doing a frequency sweep

DIRECT PHASE SOLUTION

Due to skin effect, the bulk of energy generation is close to the backside of TBC film. Therefore, we assume that the temperature distribution on the backside of the TBC film has the same phase as the generation.

Using this assumption, a simplified 1-layer domain phase expression is developed and solved.

Phase is found to be multivariable function (dependent on diffusivity, conductivity, thickness and frequency) therefore sensitivity analysis is carried out to identify bounds of potential neglection to enable optimization thermal properties recovery scheme.

MATHEMATICAL FORMULATION & EXACT SOLUTION

1D transient heat conduction problem was formulated and solved for a 2-layer domain including heat generation term representing oscillating induction power with skin effect, using Green's function method.

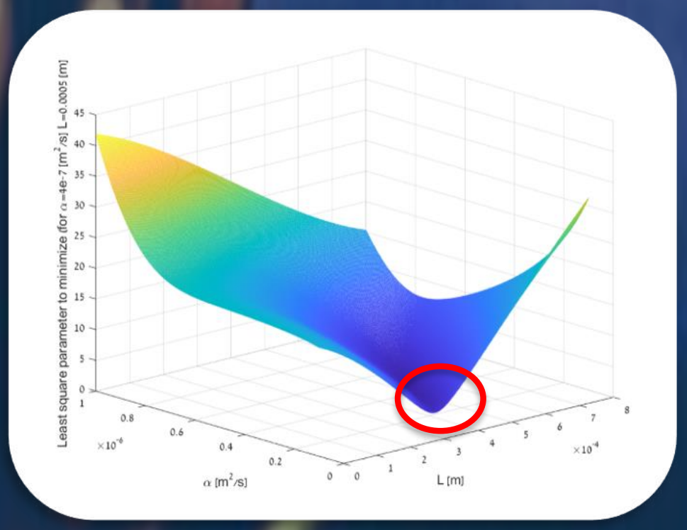
Solution of temporal behavior of surface temperature response yields appropriate required exciting frequencies to measure input/output phase change.

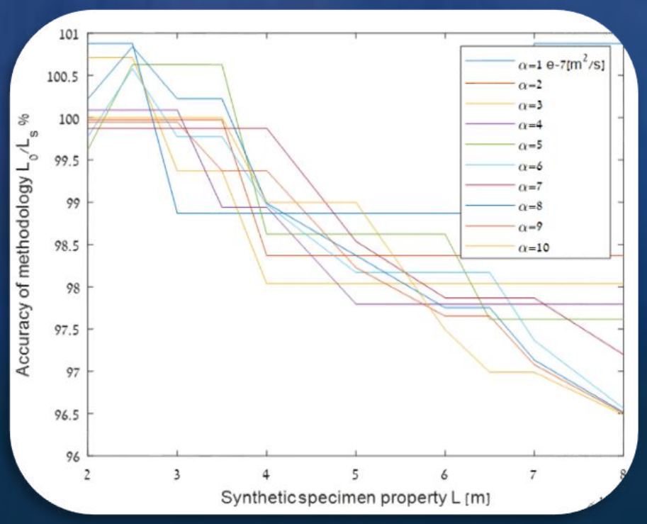
$$\alpha_1 \frac{\partial^2 T_1}{\partial x^2} + \frac{\alpha_1}{k_1} g(x,t) = \frac{\partial T_1(x,t)}{\partial t}$$

$$\alpha_2 \frac{\partial^2 T_2}{\partial x^2} = \frac{\partial T_2(x,t)}{\partial t}$$

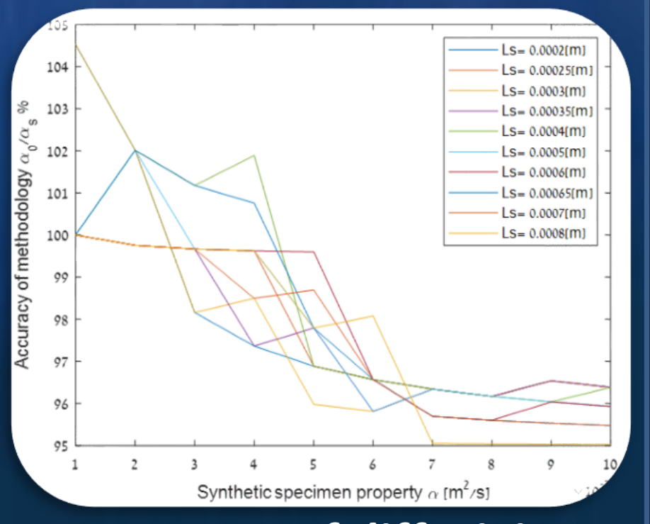
$$g(x,t) = \frac{\rho l}{A} I_0^2 e^{-2(a-x)/503\sqrt{\frac{\rho}{\mu_r F}}} \sin^2(2\pi F t)$$

$$\begin{aligned} T_i(x,t) = & \int_{x'=0}^{a} \left[G_{i1}(x,t|x',\tau)\right]_{\tau=0} F_1(x')dx' + \\ & + \int_{x'=a}^{b} \left[G_{i2}(x,t|x',\tau)\right]_{\tau=0} F_2(x')dx' + \qquad , i=1,2 \\ & + \int_{\tau=0}^{t}\int_{x'=0}^{a} G_{i1}(x,t|x',\tau)\frac{\alpha_1}{k_1} g(x',\tau)dx'd\tau \end{aligned}$$


LSPM minimum - recovers properties

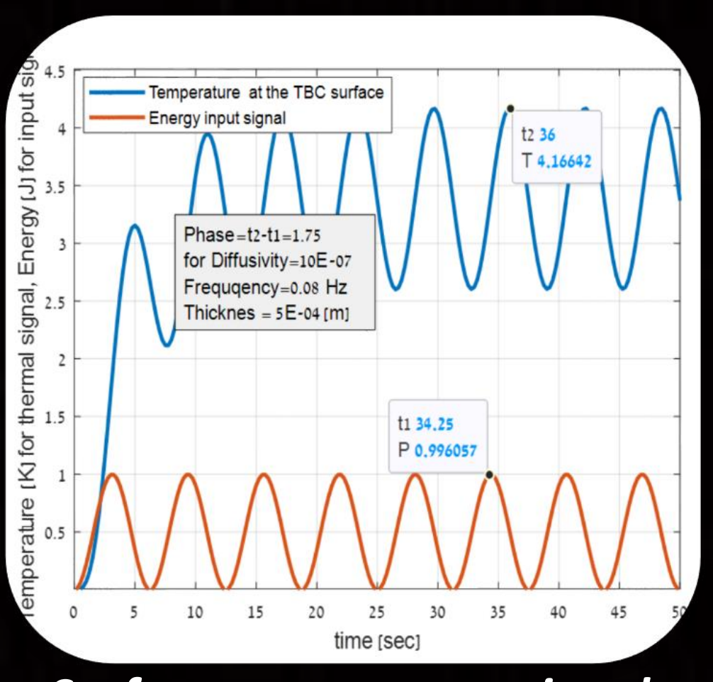


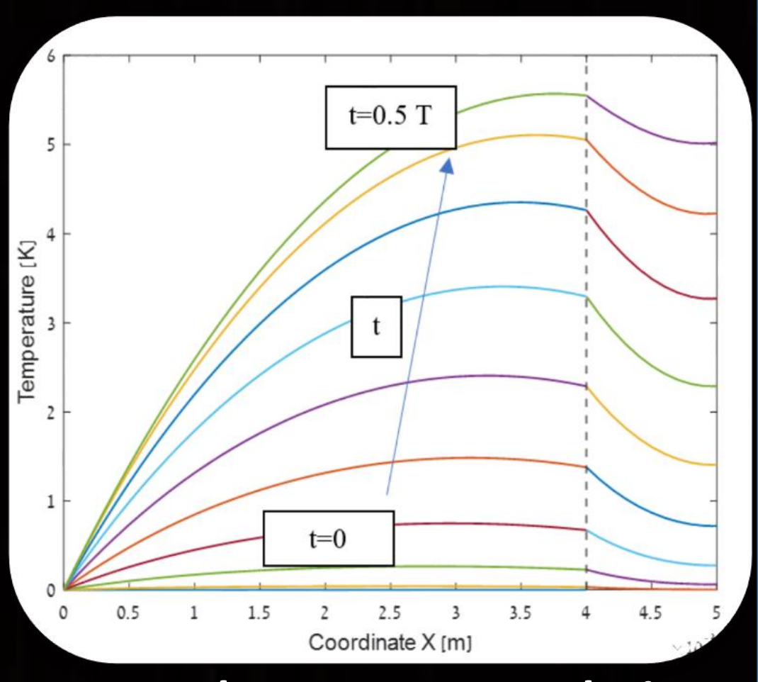
Accuracy of thickness recovery



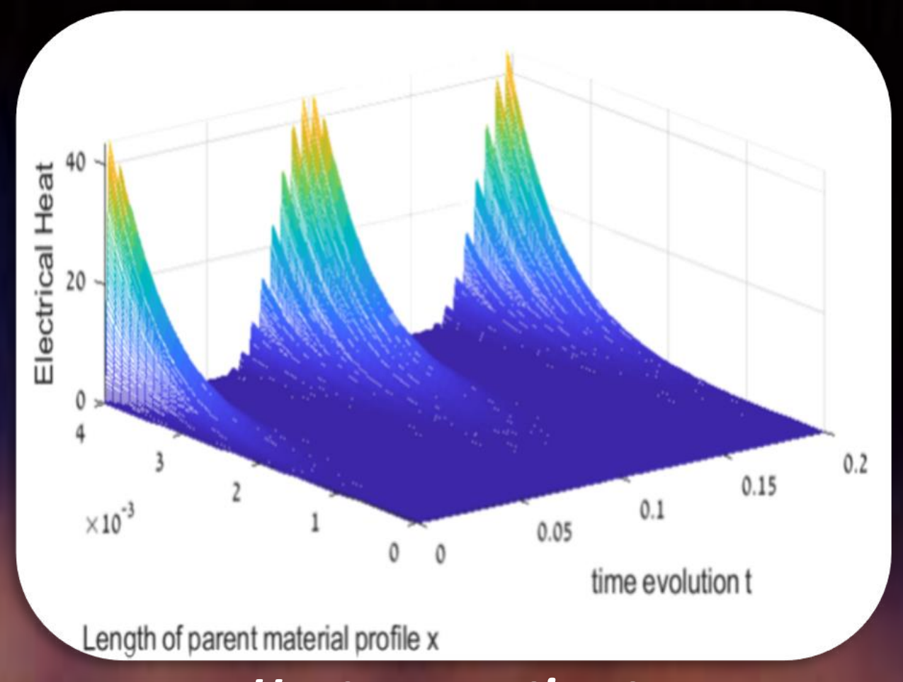
Accuracy of diffusivity recovery

$$LSPM_{Scenario\ 3} = \sqrt{\sum_{i=1}^{\substack{length\\ of\ \alpha}} \sum_{j=1}^{\substack{length\\ of\ L}} \sum_{k=1}^{\substack{length\\ of\ \omega}} \left(\phi_{c_{i,j,k}} - \phi_{m_k}\right)^2} \qquad \phi = \arctan\left[\frac{-B\sin(A)\cosh(A) - (B\cos(A) - \sin(A))\sinh(A)}{(-B\sin(A) - \cos(A))\cosh(A) + B\cos(A)\sinh(A)}\right]$$

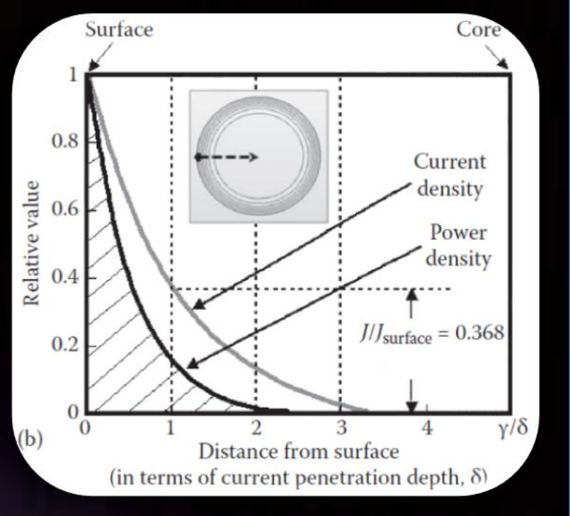

Surface temperature signal vs. gen. signal yields phase



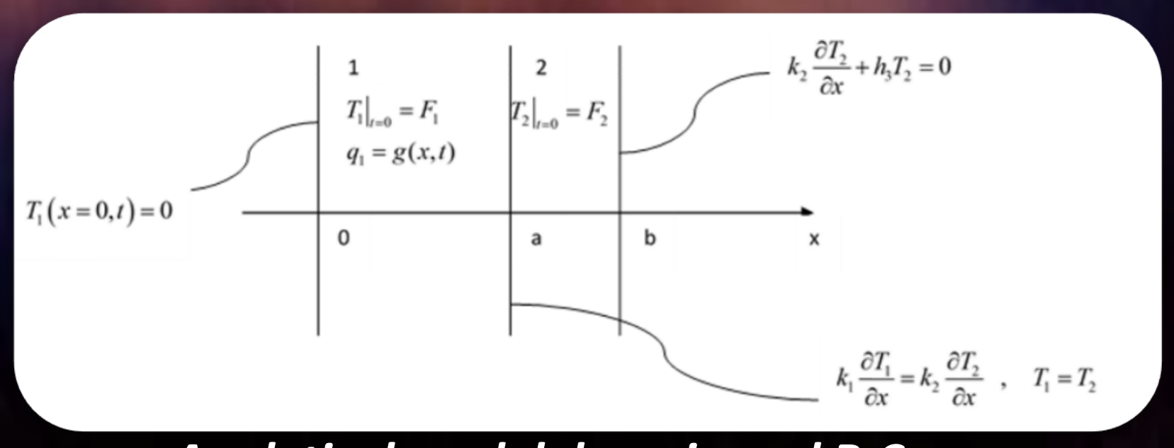
Internal temperature solution



Heat generation term



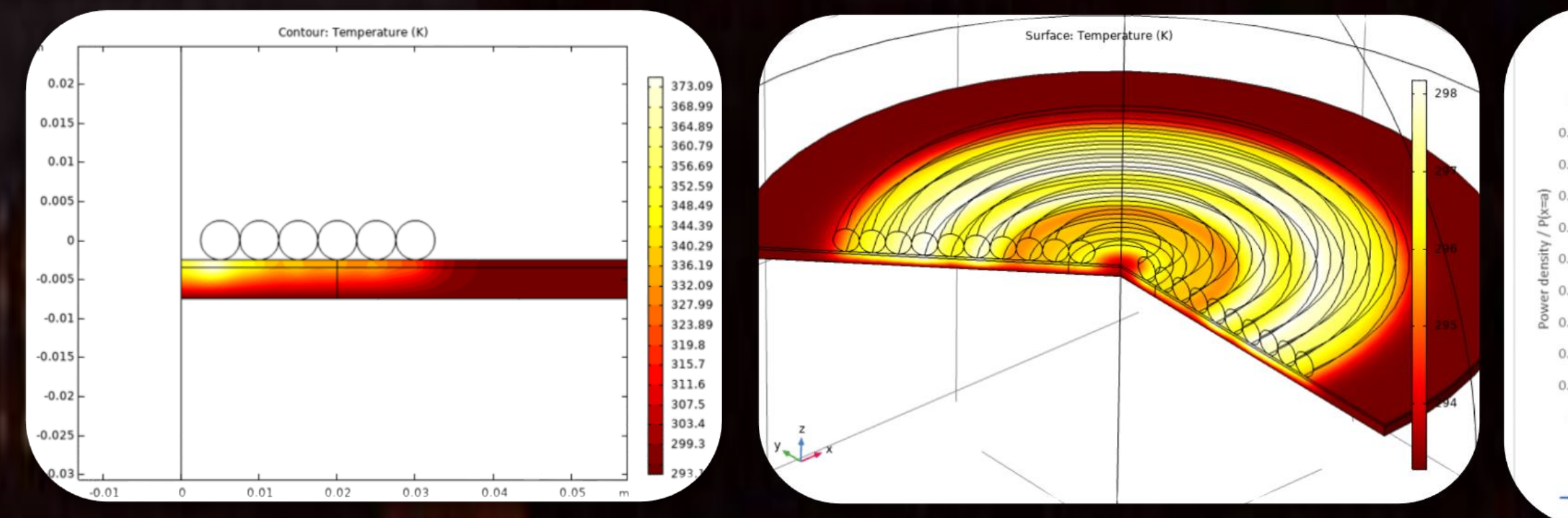
Skin effect theory



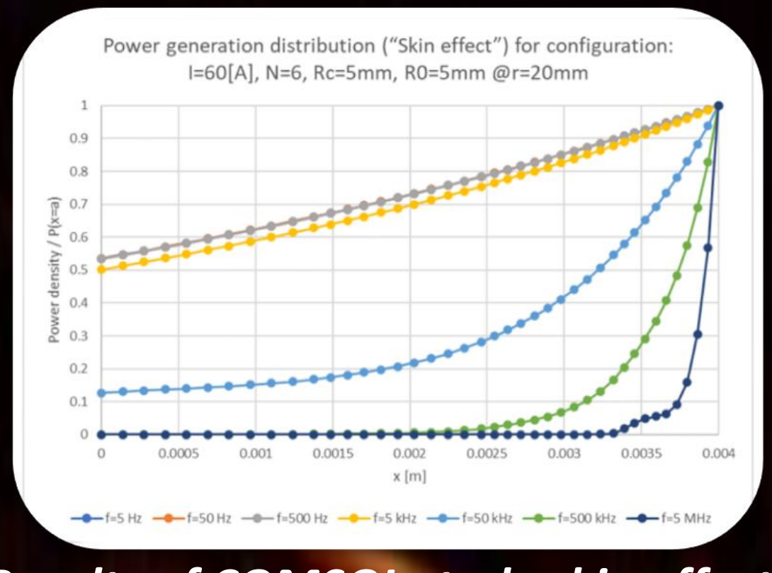
Analytical model domain and B.C.

RECOVERY BY OPTIMIZATION

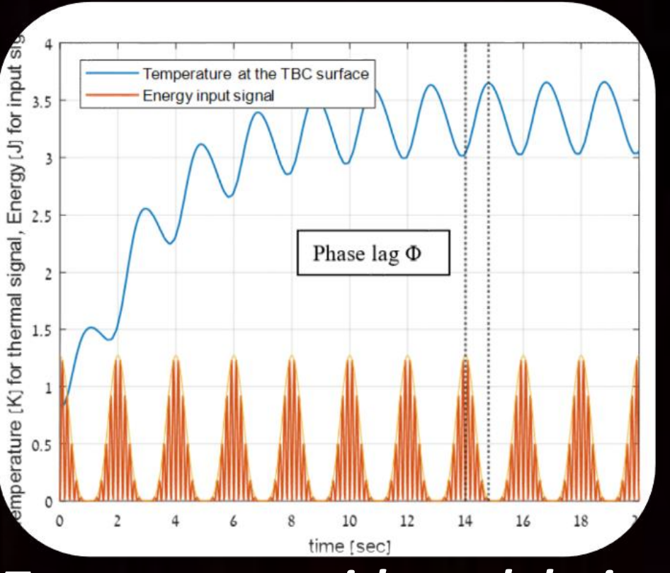
Collected phase data from frequency sweep measurements ϕ(ω) is used to create a minimum error criteria (least square parameter to minimize). Validation by synthetic data of predetermined properties specimens yields recovery accuracy ability of 3.5-5.0%.



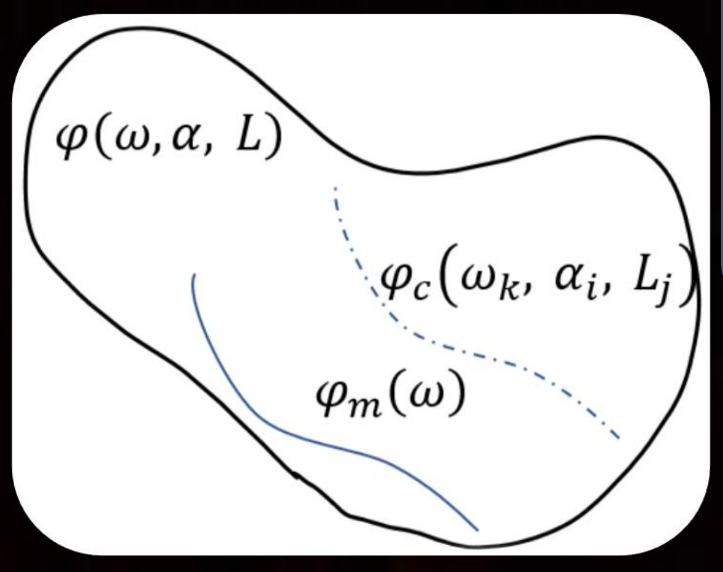
2D induction heating COMSOL study – temperature results



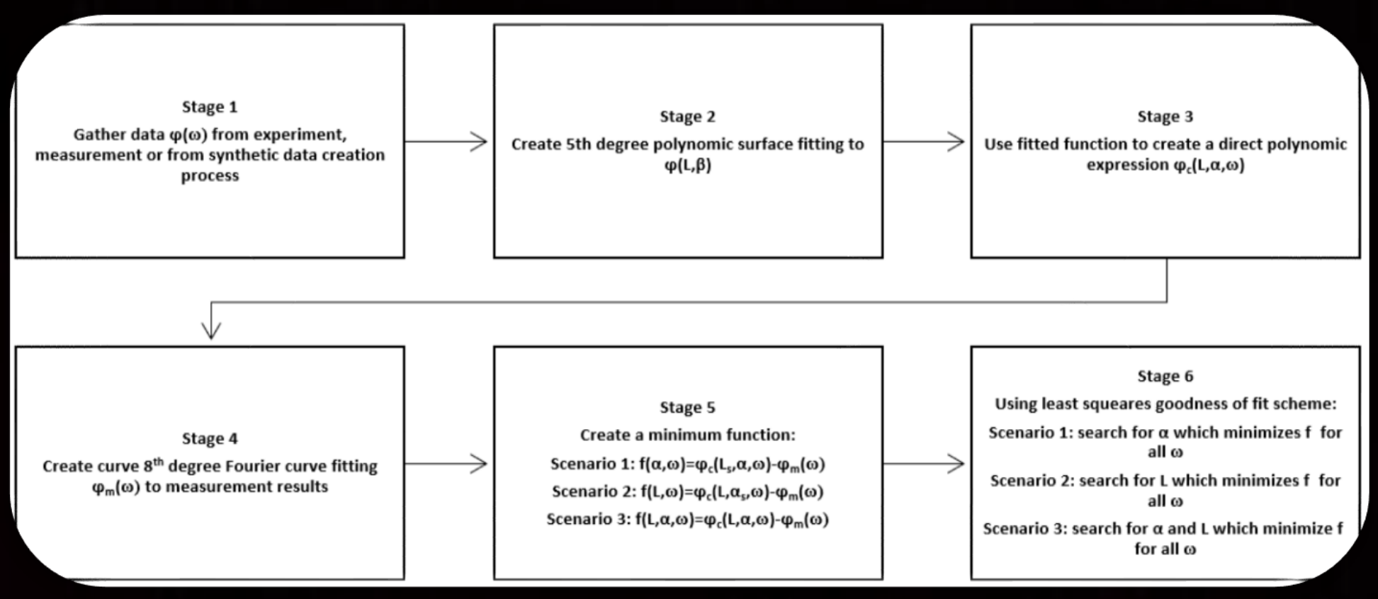
Results of COMSOL study skin effect



Temperature with modulation



Multi-variable phase optimization


Stage 1
Gather data φ(ω) from experiment, measurement or from synthetic data creation process

Stage 2
Create 5th degree polynomic surface fitting to φ(L,β)

Stage 3
Use fitted function to create a direct polynomic expression $\varphi_c(L,\alpha,\omega)$

Stage 4
Create curve 8th degree Fourier curve fitting $\varphi_m(\omega)$ to measurement results

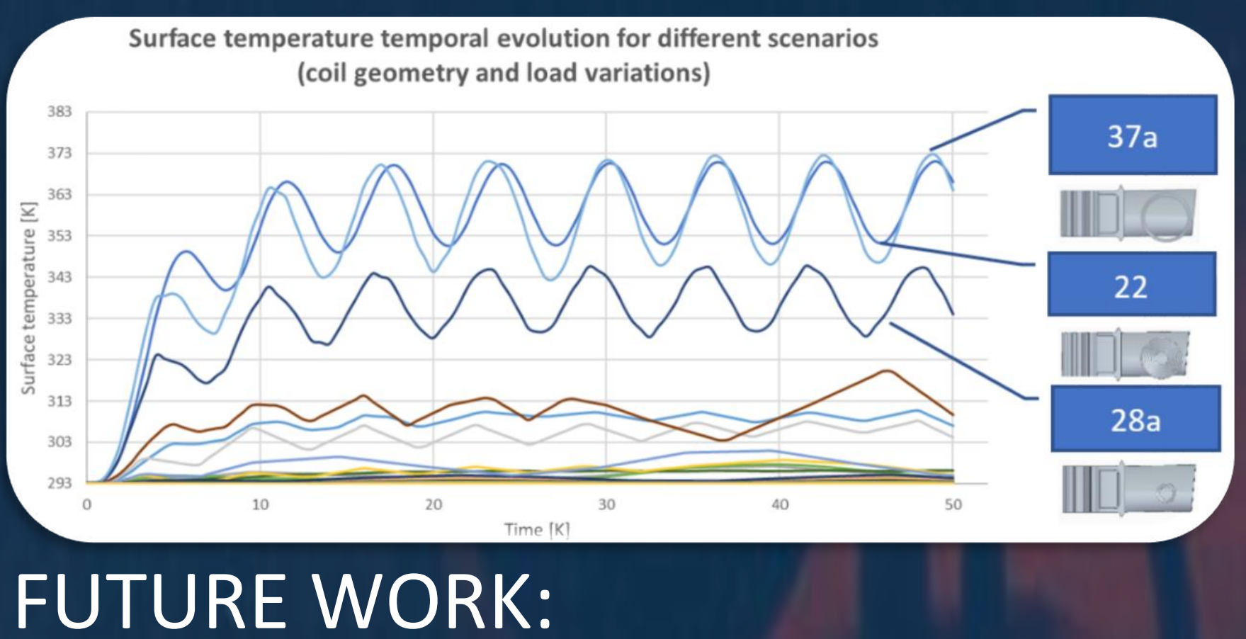
Stage 5
Create a minimum function:
Scenario 1: $f(\alpha,\omega)=\varphi_c(L_s,\alpha,\omega)-\varphi_m(\omega)$
Scenario 2: $f(L,\omega)=\varphi_c(L,\alpha_s,\omega)-\varphi_m(\omega)$
Scenario 3: $f(L,\alpha,\omega)=\varphi_c(L,\alpha,\omega)-\varphi_m(\omega)$

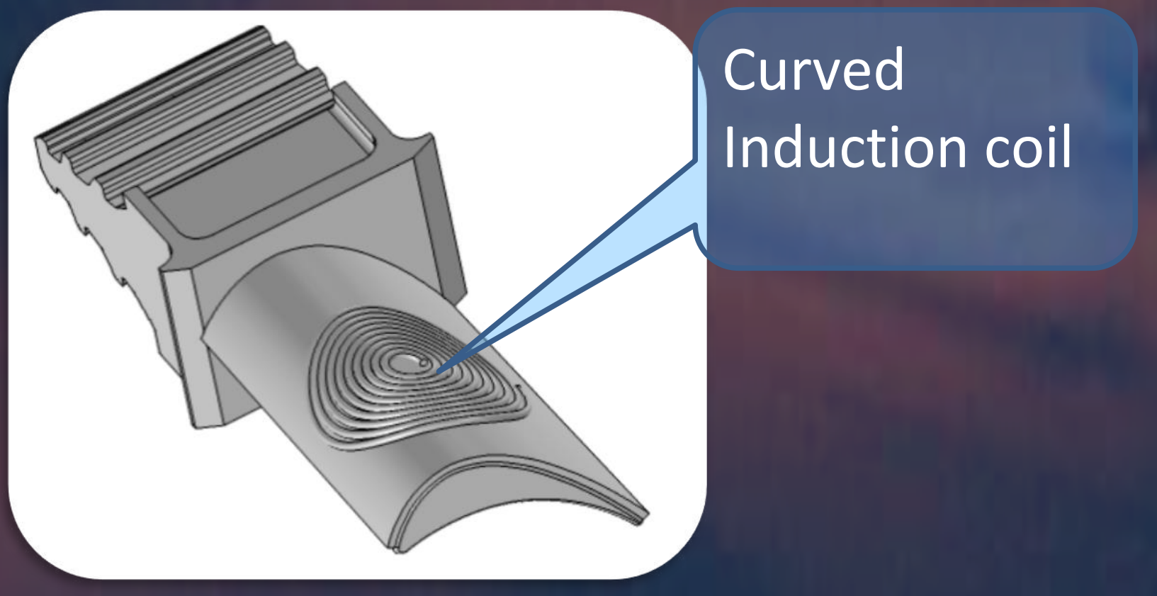
Stage 6
Using least squeares goodness of fit scheme:
Scenario 1: search for α which minimizes f for all ω
Scenario 2: search for L which minimizes f for all ω
Scenario 3: search for α and L which minimize f for all ω

Properties recovery methodology scheme

NUMERICAL VALIDATION

2D COMSOL induction heating frequency-transient study was conducted, validating exact solution and enabling optimal design of coil geometry and required electrical load. 2D Study yields similar temporal behavior for certain number of coil turns. 3D study model was created including a curved coil to enhance induction.





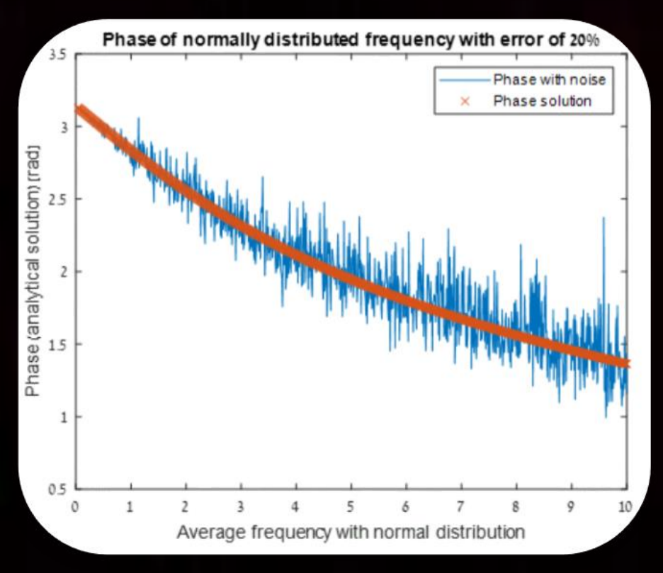
FUTURE WORK:

- Experimental setup based on 3D study geometry and load validation.

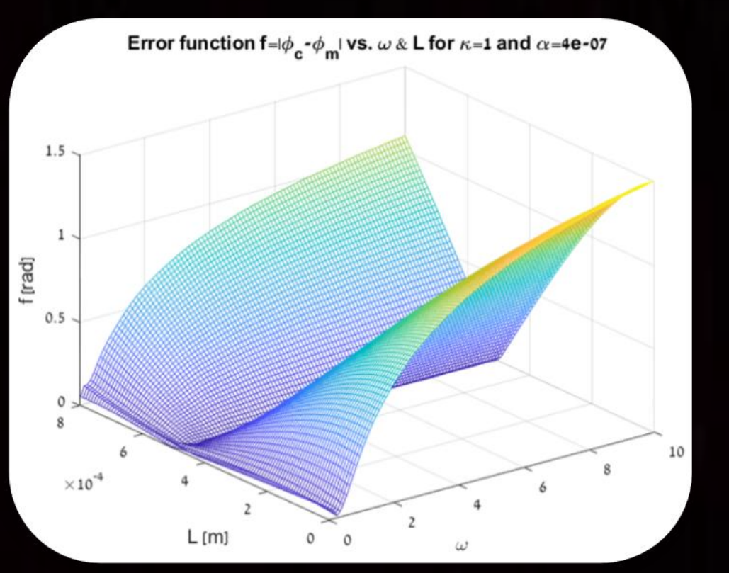
NOISE CONSIDIRATIONS

Noise impact on property recovery was examined by inserting prescribed noise types into synthetic data. Noise was put into frequency before phase calculation. Additionally, noise was put into phase before the fitting process.

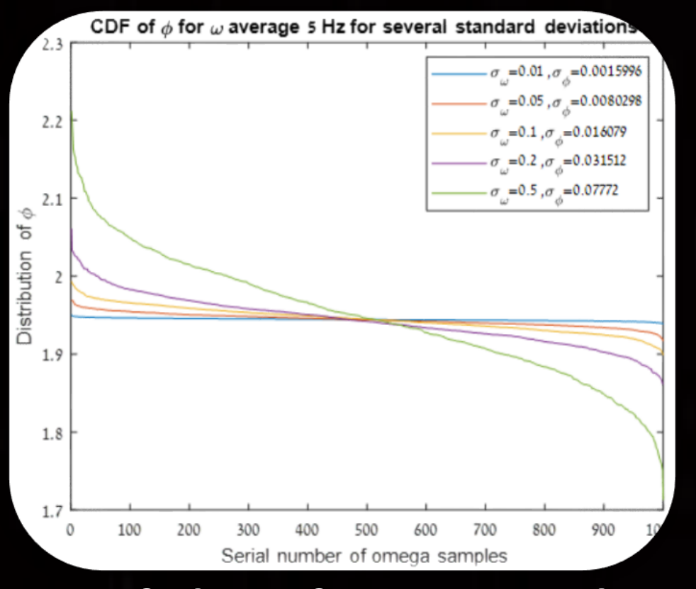
It enabled us to establish bounds, to determine the expected recovered properties bias due to measurement system noise. For example, if commercial temperature pyrometers have up to 2% error, it is estimated that the outcoming error in property prediction will have maximum of around 1.5% error etc.



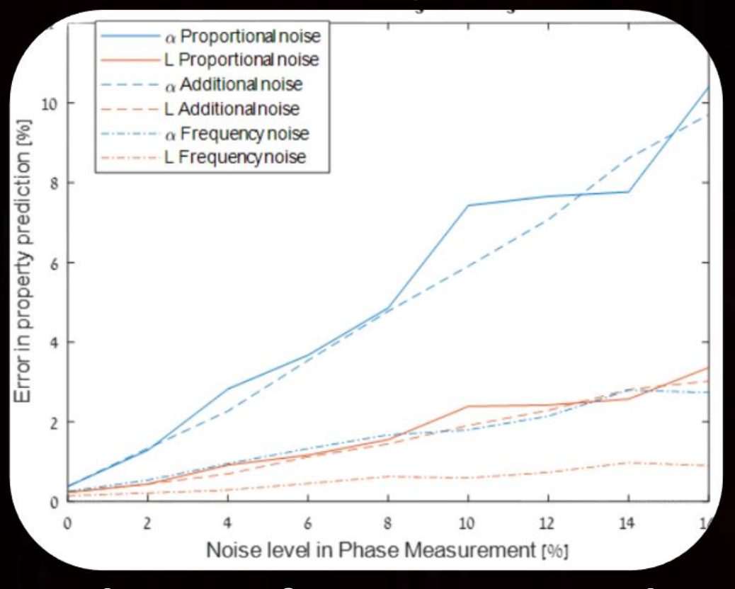
Phase with stochastic noise



LSPM function of thickness recovery



CDF of phase for noise analysis



Prediction of recovery error due to noise

[1] R. E. Taylor, X. Wang, and X. Xu, "Thermophysical properties of thermal barrier coatings," *Surf. Coat. Technol.*, vol. 121, pp. 89–95, 1999, doi: 10.1016/S0257-8972(99)00339-4.
[2] M. N. Özışık, *Boundary value problems of heat conduction*. Scranton, PA: International Textbook Co, 1968.