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Modelling, Simulation and Temperature Effect Analysis of Mutual Induction based High Temperature Level Sensor using COMSOL Multiphysics

Rajalakshmi R.

Subhasis Dutta

Bhabha Atomic Research Center, Mumbai

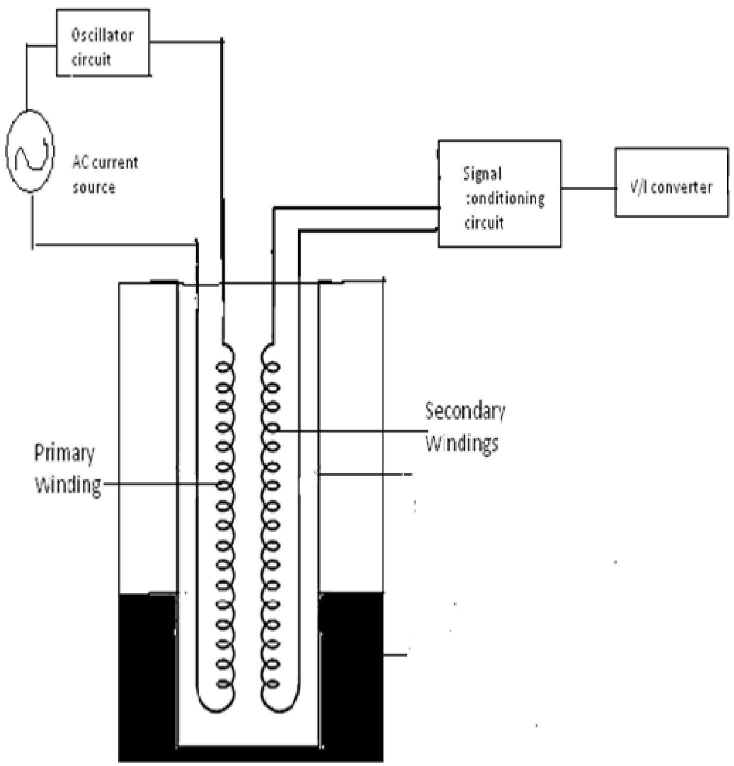
Introduction

- ✓ **Liquid metal (Lead Bismuth Eutectic alloy) is used as coolant in Nuclear reactors.**
- ✓ **A level sensor based on mutual inductance principle has been designed and developed for continuous level measurement at high temperatures of Liquid metal .**

Contents

- Conceptual design and Mathematical model of the Sensor
- Modelling of the sensor geometry in 2D axi-symetric module in COMSOL
- Simulation studies to obtain the sensor characteristics using COMSOL .
- Validation of COMSOL simulation with experimental results.

Sensor's Conceptual design



- The sensor works on the principle of variation of mutual inductance.
- The primary winding is excited with an AC constant current.
- Due to mutual inductance an EMF is induced in the secondary coil.
- As the LBE is conducting eddy current flows it
- Hence the net flux linked with secondary decreases and voltage reduces with LBE level

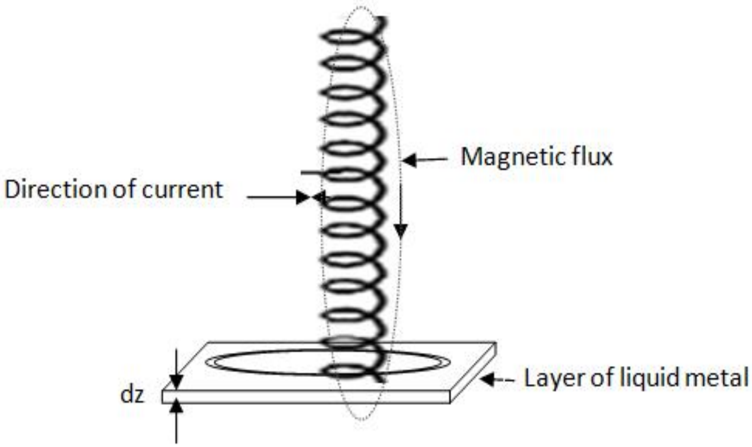
Mathematical Modeling

➢ Consider the coil of primary winding as a solenoid with N number of turns and the current density through it as J

➢ The magnetic flux density and induced emf obtained through Maxwell's equations are

$$\vec{B} = \mu_0 \mu_r \, n i \, \hat{z}$$

$$V = -N \frac{\partial \varphi}{\partial t}$$



➢The field linked with the Liquid metal

$$\vec{B}(r) = \frac{\mu_0 \mu_r i}{2\pi r} \hat{z}$$

➢A layer of liquid metal outside the sensor of thickness dz and a circular ring through the layer of radius r and thickness dr concentric with the cross section of the coil.

Mathematical Modeling contd…

- The conductivity of Lead Bismuth Eutectic Alloy : $\frac{10^8}{(86.334+0.0511\times T)}$
- The emf and eddy current induced in circular elemental section is

$$E_{induced} = \frac{\mu_0 \mu_r r}{2} i_0 \omega \cos \omega t \qquad dI = \frac{E_{induced}}{Resistance\ of\ the\ path}$$

- Considering the elemental circular current carrying path as a ring carrying current. The flux density at a height h in the center of the ring is given by

$$d\vec{B}_Z = \frac{\mu_0 \mu_r\, dI\, r^2}{2(h^2+r^2)^{\frac{3}{2}}} = \frac{\mu_0 \mu_r\, r^2}{2(h^2+r^2)^{\frac{3}{2}}} \times \frac{\frac{\mu_0 \mu_r}{2} i_0 \omega \cos \omega t \;\; dz\; dr}{137.434\times10^{-8}\times 2\pi}$$

- The net flux density along the length of the coil of height H, due to the presence of Liquid metal of level L in the tank is given by

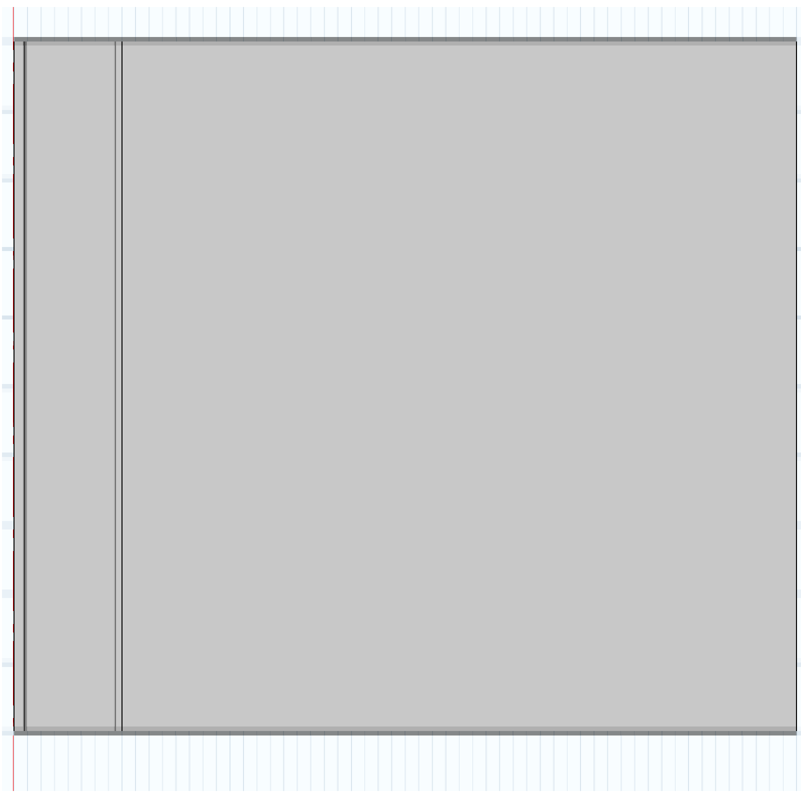
$$\vec{B}_z = -\mu_0 \mu_r \times \frac{\frac{\mu_0 \mu_r}{2} i_0 \omega}{137.434\times10^{-8}\times 16\pi} \times \frac{\cos\left(\tan^{-1}\left(\frac{H}{R_T}-1\right)\right)\times\cos\left(\tan^{-1}\left(\frac{H}{R_E}+1\right)\right)}{\cos\left(\tan^{-1}\left(\frac{H}{R_T}+1\right)\right)\times\cos\left(\tan^{-1}\left(\frac{H}{R_E}-1\right)\right)} \times L \cos \omega t$$

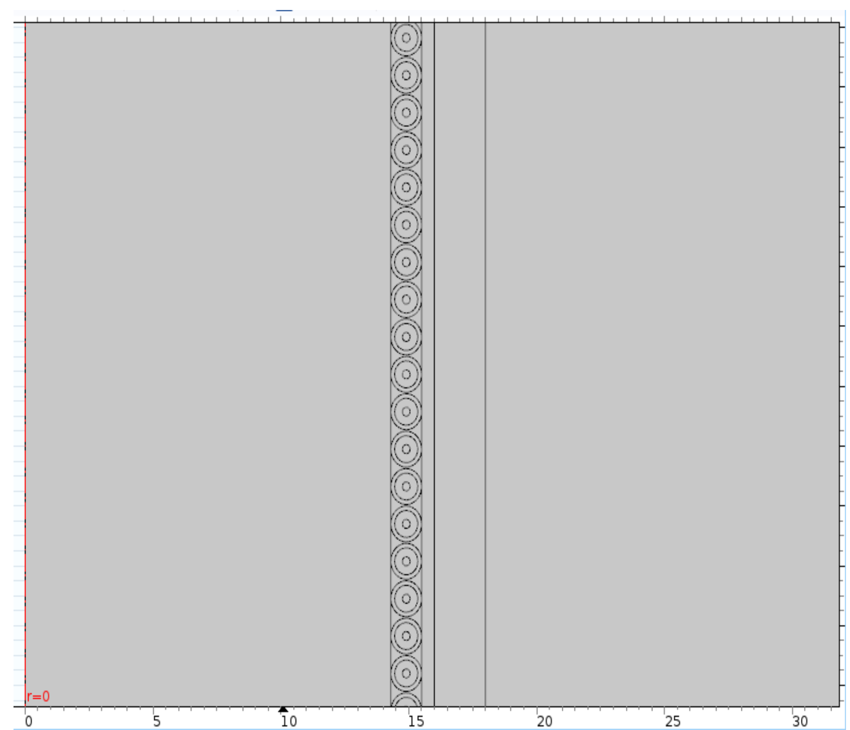
- The voltage induced in the secondary due to this flux : $v_{eddy} = -N \frac{\partial \varphi_z}{\partial t}$

- Net voltage at secondary : $V_0 = |V| - |V_{eddy}|$

Modelling of sensor geometry in COMSOL

The Geometry of the sensor is modeled in 2D axi-symmetric model wizard in COMSOL 5.0 environment is as shown.





Simulation studies using COMSOL Multiphysics

- **AC/DC module**

  1.frequency domain studies

  2.Multiturn coil domain

- **Heat transfer Module**

  1. Stationary domain studies

  2. Temperature coupling between the two modules

Equations and boundary conditions used in COMSOL

❖ **Equations solved in COMSOL**

(a) Heat Transfer Equations

$$\rho C_p \, u \, \nabla T + \nabla . q = Q$$

$$q = - k \, \nabla T$$

(b) Ampere's Law

$$(j\omega\sigma - \omega^2 \epsilon_0 \epsilon_r) A + \nabla \times (\mu_0 \mu_r)^{-1} B - \sigma v \times B = J$$

Magnetic field density: $B = \nabla \times A$

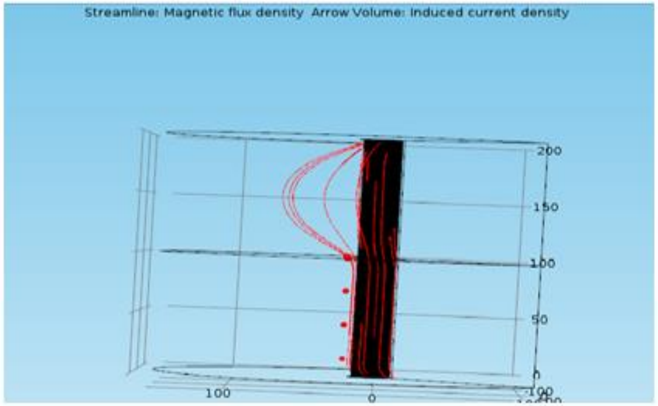
❖ **Boundary Conditions used in COMSOL**

(a) Magnetic Insulation at geometrical boundary : $n \times A = 0$

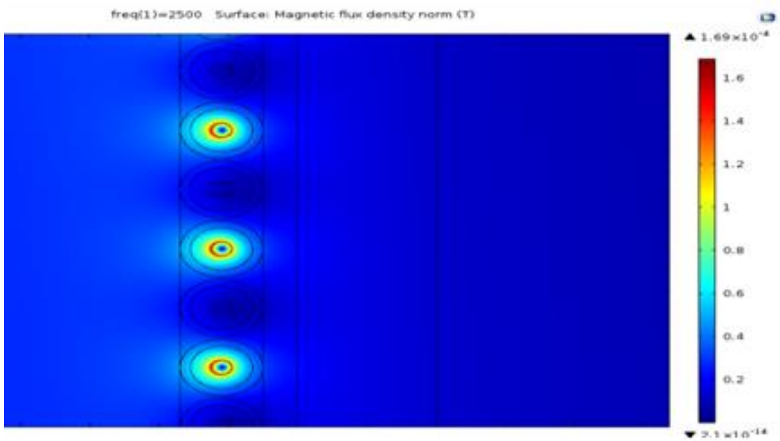
(b) Thermal Insulation at geometrical boundaries : $- n.q = 0$

(c) The surface of the enclosure is at the temperature of Liquid metal and the air at a distance from the tank is at room temperature.

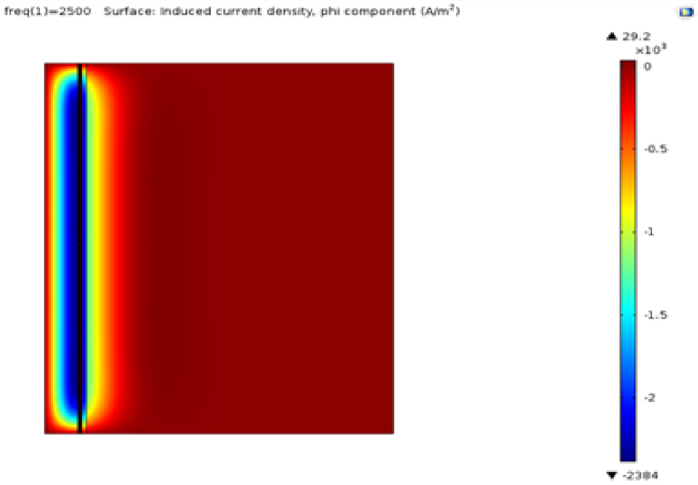
Simulation Results



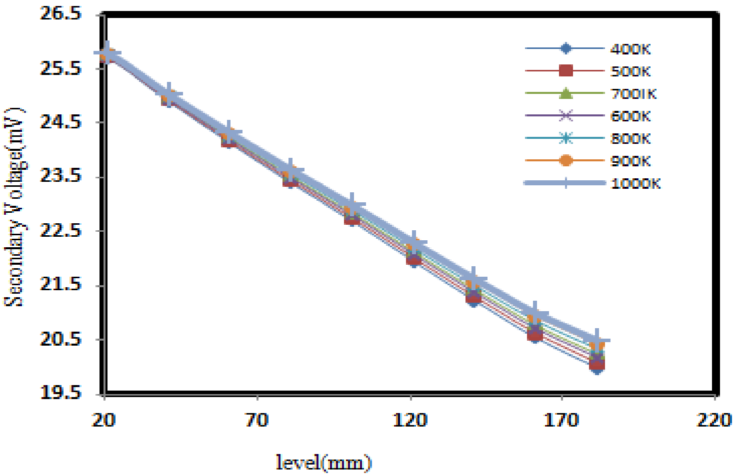
Flux and Eddy current profiles



Variation of Flux density

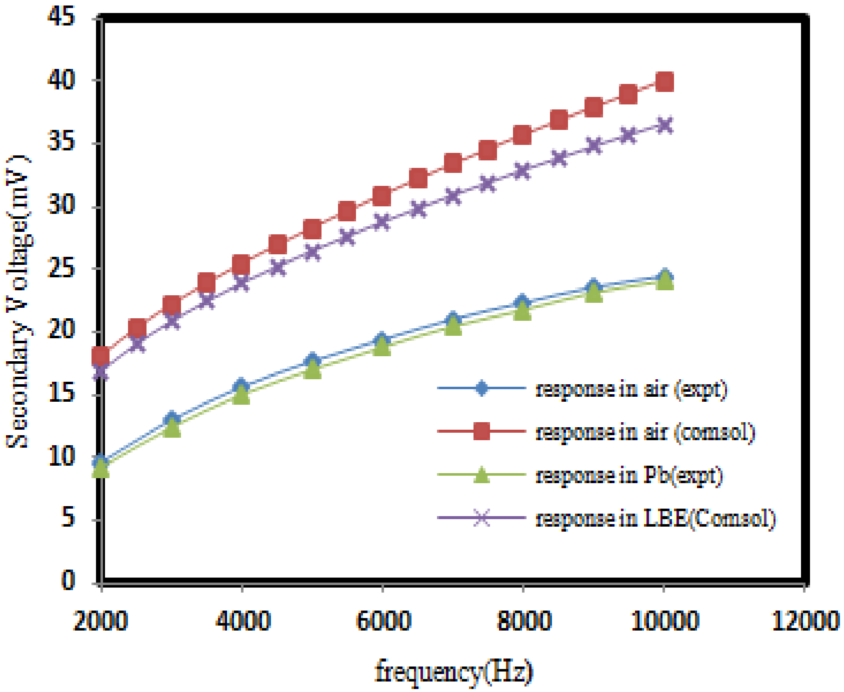


Variation of Induced eddy current

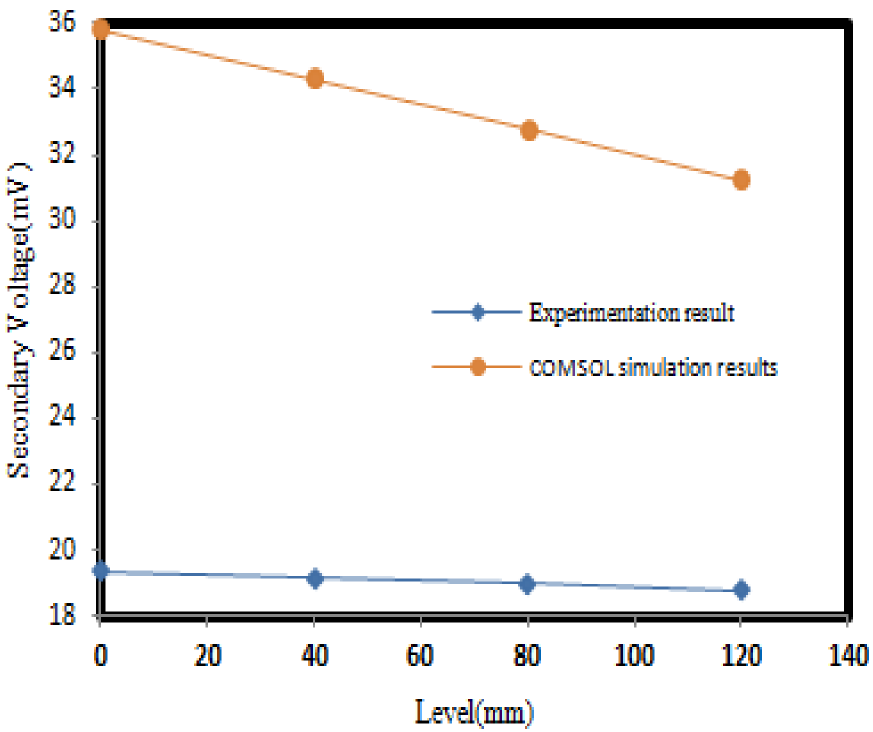


Secondary Voltage vs. Level at different Temperatures

Comparison of Simulation and experimental Results

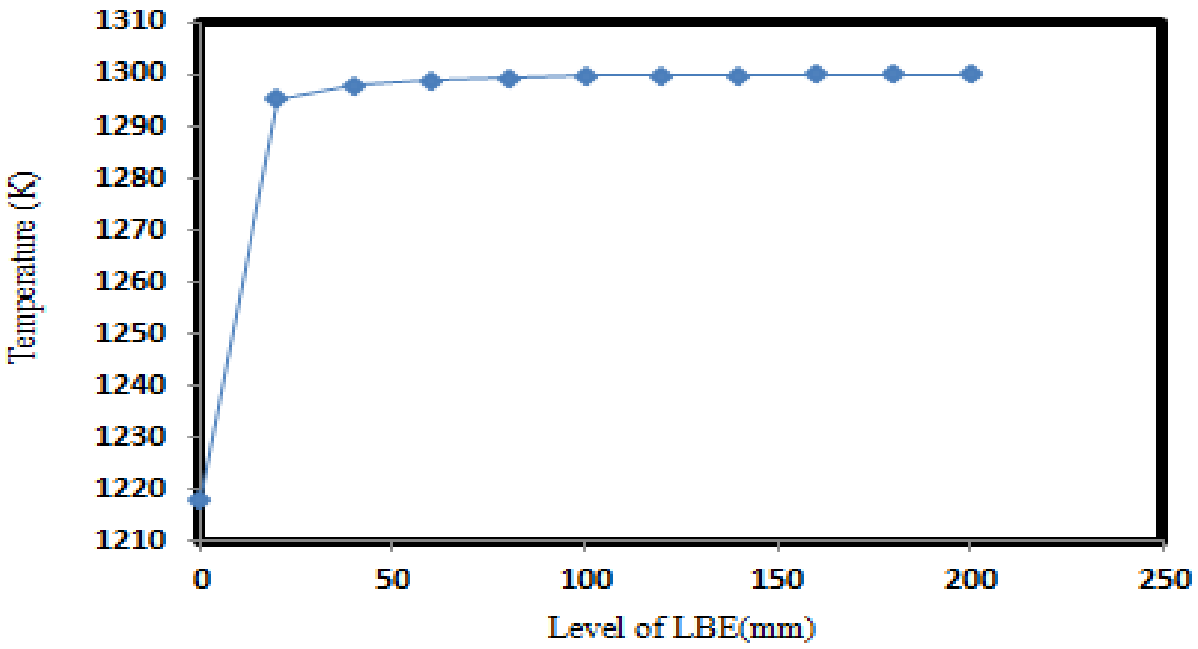


Variation of Sec. Voltage with frequency



COMSOL and experimental Results

Temperature effect Analysis



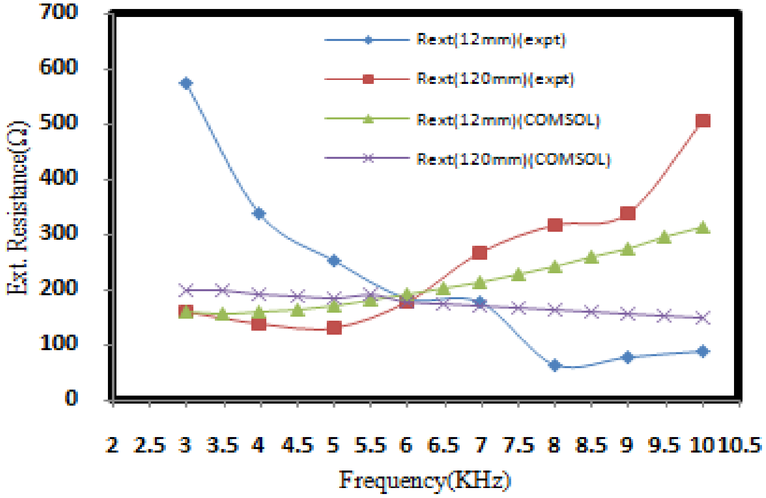
Variation of probe temperature with level

Temperature Compensation Technique

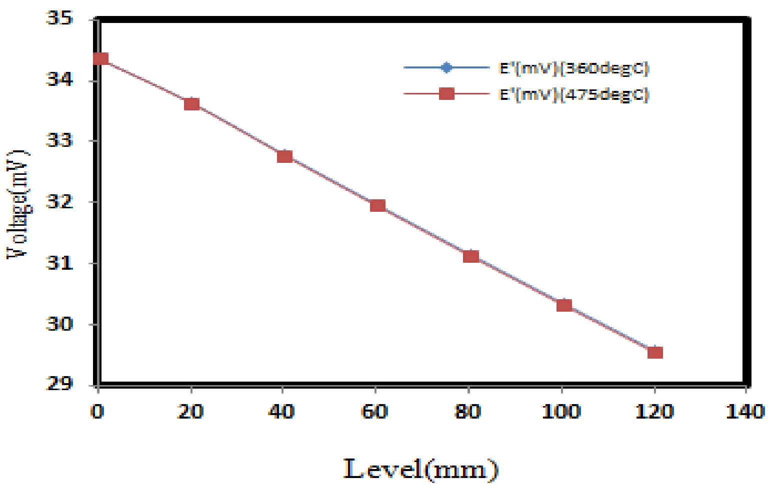
- The resistivity of liquid metal changes with its Temperature, this causes a change in the eddy current induced and thus the Secondary Voltage.
- Compensation with an external Resistance.

$$R_{ext} = \frac{V_0 \times \partial \mathrm{Ri}}{\partial V_0} - R_i$$

Temperature Compensation Technique contd…

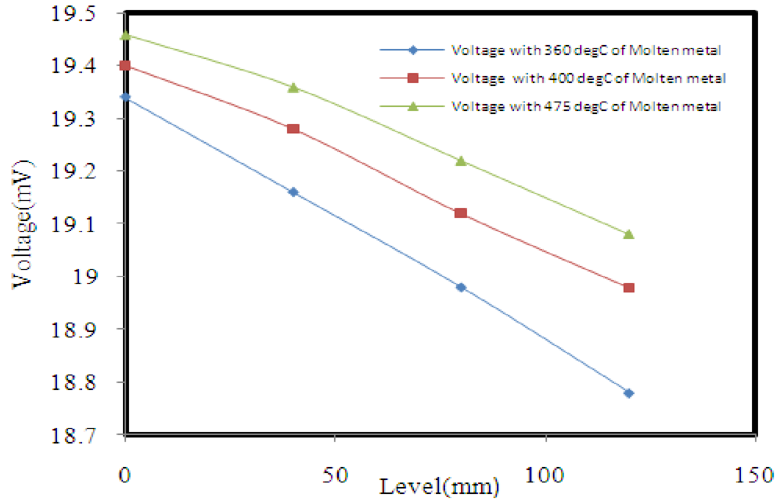


External Resistance vs. Frequency obtained through expt and simulations

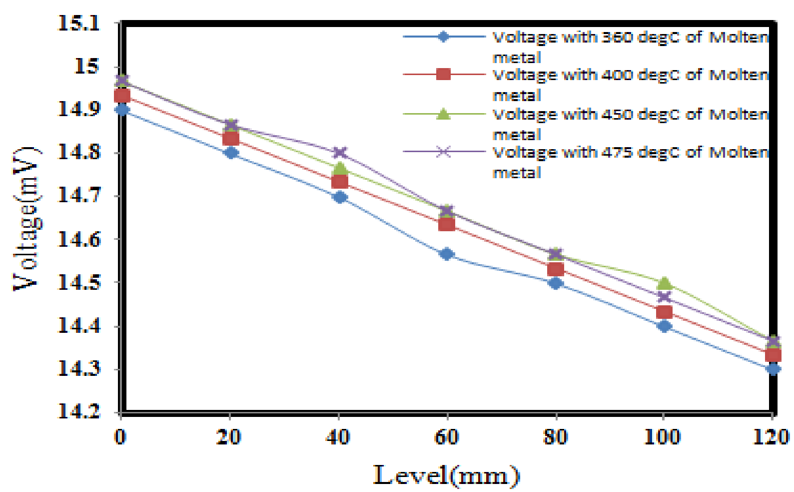


Voltage across external Resistance obtained through COMSOL Simulation

Temperature Compensation Technique contd…



Change in Voltage at Secondary with the Level of LBE



Voltage across ext. Resistance obtained through Experimentation

Discussions

- **A linear decrease in secondary voltage with the level of Lead Bismuth Eutectic alloy were observed through Simulation studies and experimentation.**
- **The span of the sensor for 0 to 120mm of liquid metal level was 0.76 mV, while COMSOL simulations provided a span of 4 mV .**
- **The sensor resolution obtained through experimentation is1.57mm, Sensor resolution obtained through COMSOL simulations is 0.3mm.**

Discussions contd…

- **Temperature compensation through experimentation: The variation was reduced from 1.1% of reading to 0.45% of reading.**

  Temperature compensation through COMSOL simulation: The variation was reduced from 0.21% of reading to 0.09% of reading.

- **There is a 43 % difference on an average between the simulation and experimental results.**

Thank You