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A Multiphysics model for In situ detection of inclusion in liquid steel

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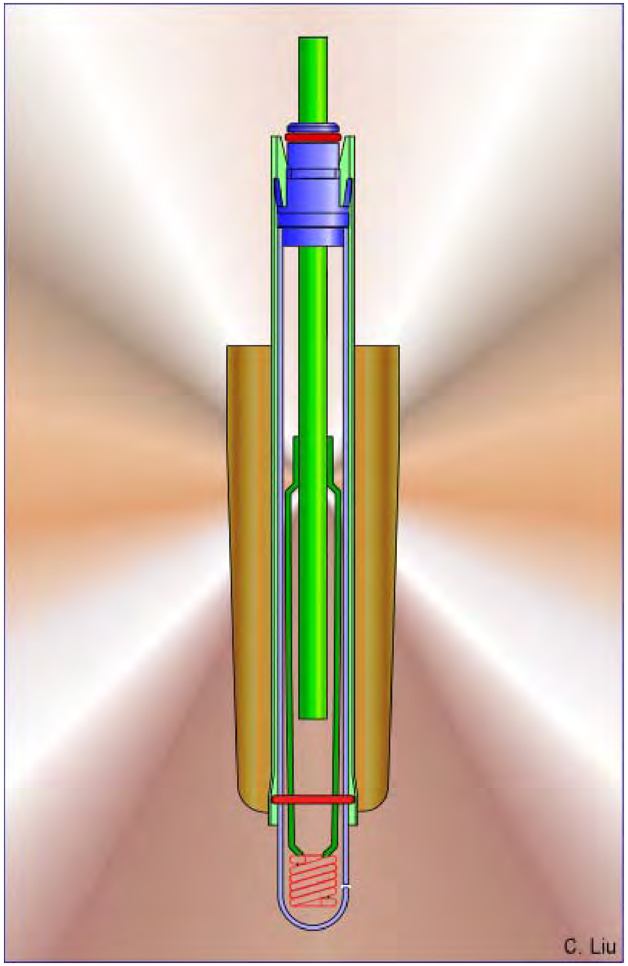
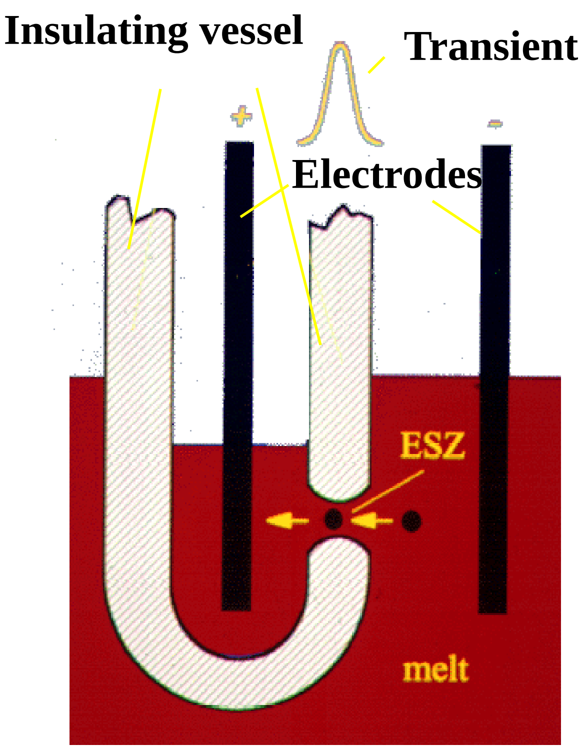
ESZ-PAS® Detects and Measures Inclusions



The technique involves:

- Drawing a sample of liquid steel into an insulating silica tube through a small orifice
- Simultaneously passing an electrical current through the orifice so as to create a small electric sensing zone in the vicinity of the orifice.
- Continuously monitoring the electrical resistance during the steel sampling period, in order to detect the passage of entrained non-metallic inclusions passing through the ESZ into the silica/quartz tube
- Determining the size of each inclusion detected, based on the peak height, current, and electrical resistivity of steel.

ESZ PRINCIPLE OF OPERATION



Maxwell's Equation:

$$\Delta V = \frac{4\rho_e I d^3}{\pi D^4}$$

J.C. Maxwell, A Treatise on electricity and magnetism, 3rd Ed., Clarendon, Oxford. **Vol.1**, pp.429 (1954)

A resistive pulse is generated by the passage of a non-conducting particle through an electric sensing zone (small orifice in an electrically insulating tube)

Theory

Fluid flow:

Continuity

$$\nabla \bullet \mathrm{u} = 0$$

Navier-Stokes

$$\mathrm{u} \bullet \nabla \mathrm{u} = -\frac{\nabla p}{\rho_f} + \nu_f \nabla^2 \mathrm{u} + \frac{1}{\rho_f} \mathrm{F}_e$$

Electromagnetic force (static electric field)

$$\mathbf{F_e} = \mathbf{J} \times \mathbf{B}$$

Self-induction magnetic field (Ampere's law)

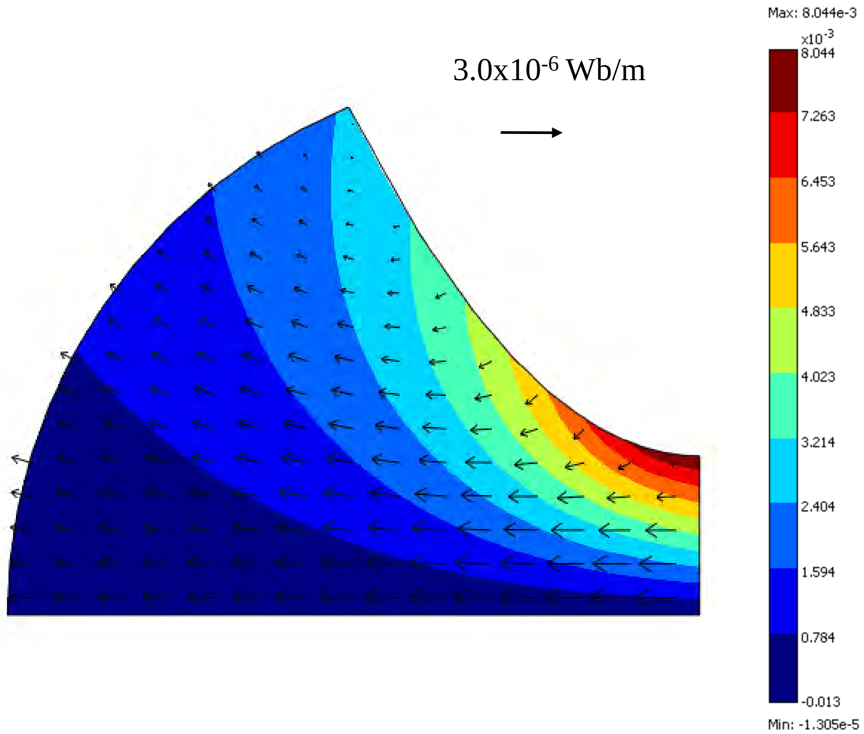
$$\oint_l \mathbf{B} dl = \int_A \mathbf{J} dS = I$$

Predicted Trajectories of Inclusions passing through ESZ

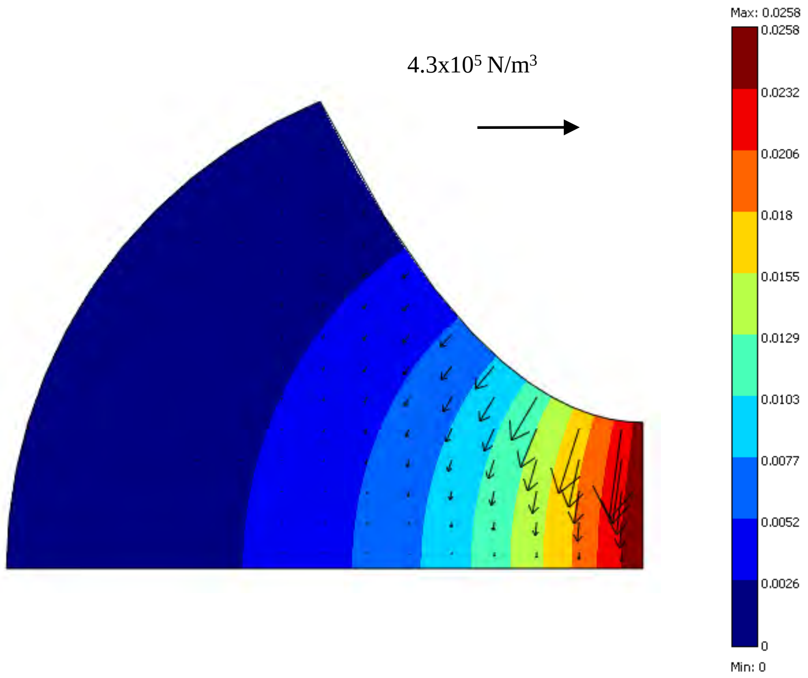
$$\rho_p V_p \frac{du_p}{dt} = \frac{1}{2} C_{Dstd} \pi a^2 \rho_f \left| u - u_p \right| \left(u - u_p \right) + \frac{1}{2} \rho_f V_p \left(\frac{Du}{Dt} - \frac{du_p}{dt} \right) + \rho_f V_p \frac{Du}{Dt}$$
$$+ 6a^2 \sqrt{\pi \mu_f \rho_f} \int_0^t \frac{d\left(u - u_p\right)/d\tau}{\sqrt{t - \tau}} d\tau + V_p \left(\rho_p - \rho_f\right) g - \frac{3(1 - \chi)}{4} V_p F_e$$

(mass×acceleration of particle) = (drag + added mass + fluid acceleration + history + buoyancy + electromagnetic) forces

The electromagnetic force distribution



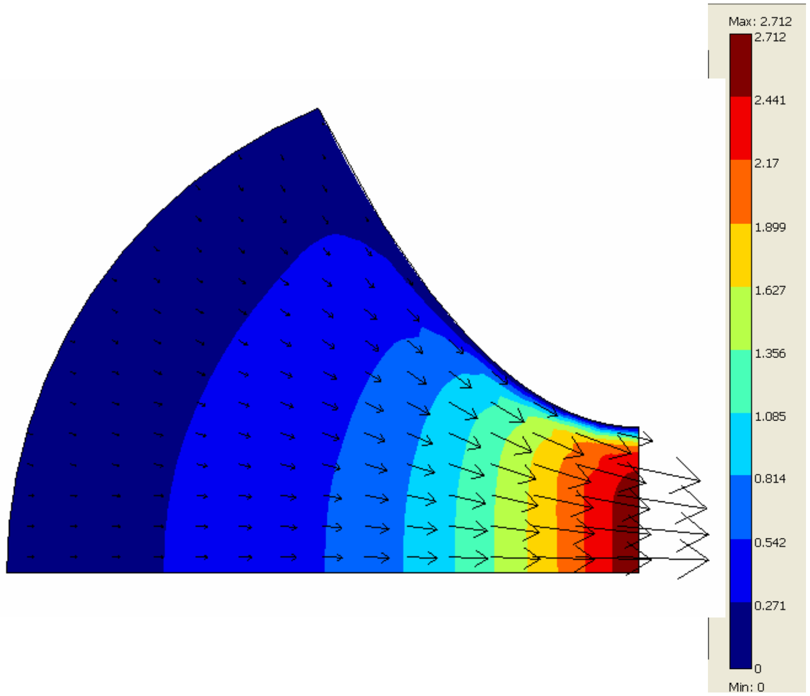
(a) Self-induced magnetic field



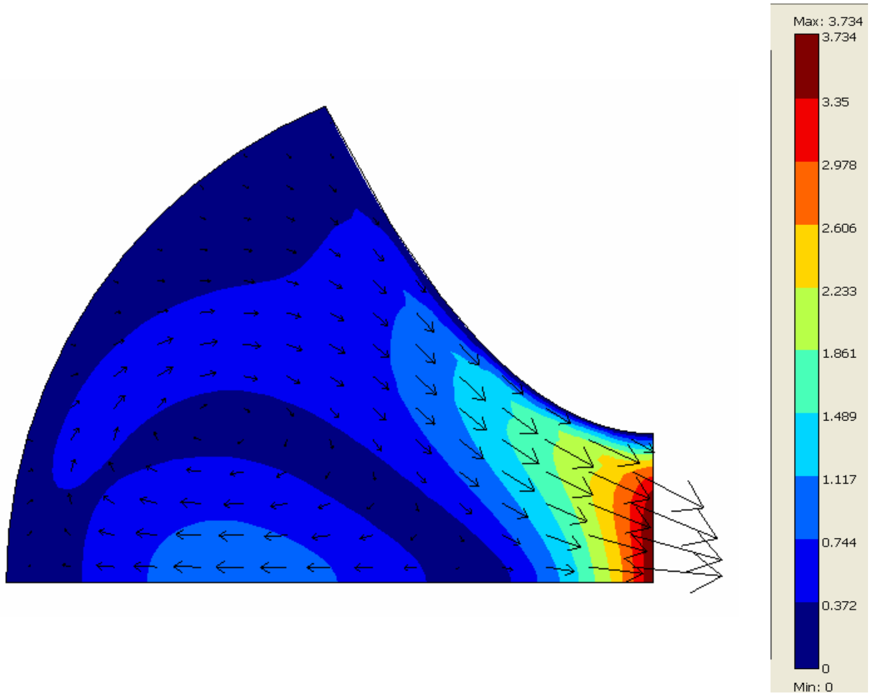
(b) The electromagnetic force distribution.

Conditions: within the ESZ for a DC current *I*=15A, and 500 µm diameter orifice. the magnetic flux density, ***B*** (max. ~8mT).

Fluid field and flow patterns

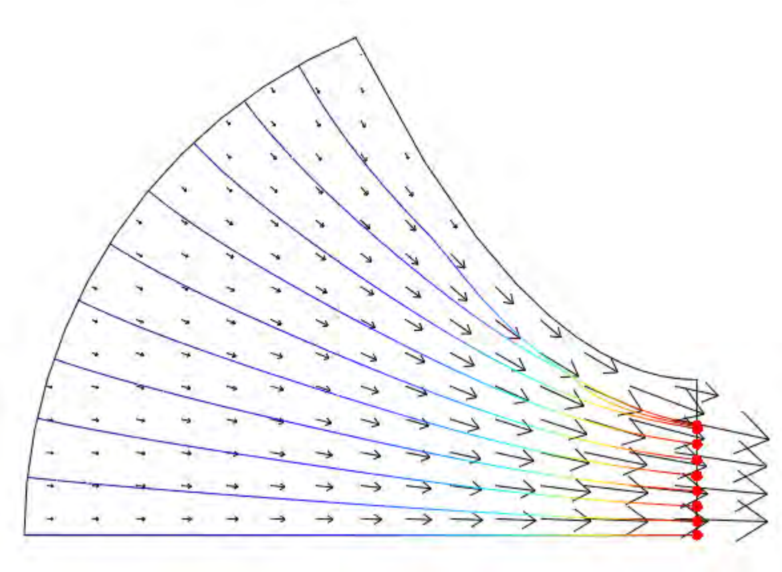


(a) I=15A

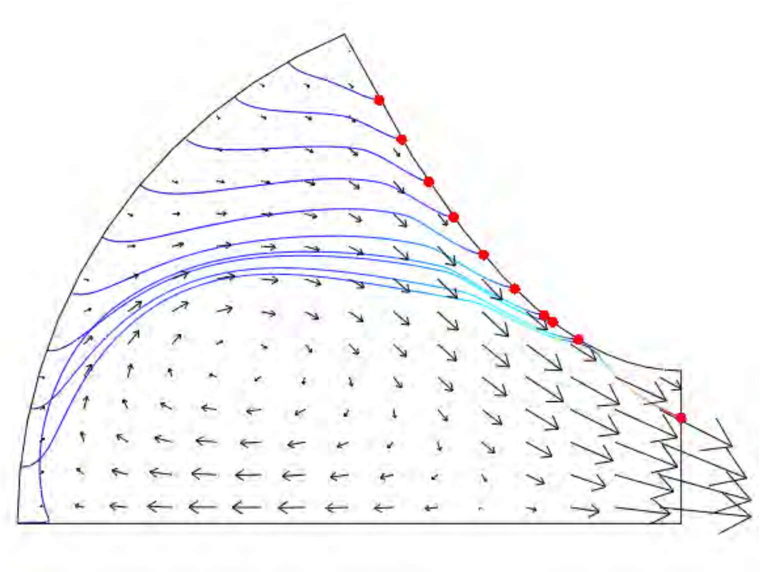


(b) I=300A

Influence of input current on the inclusion motion behaviors



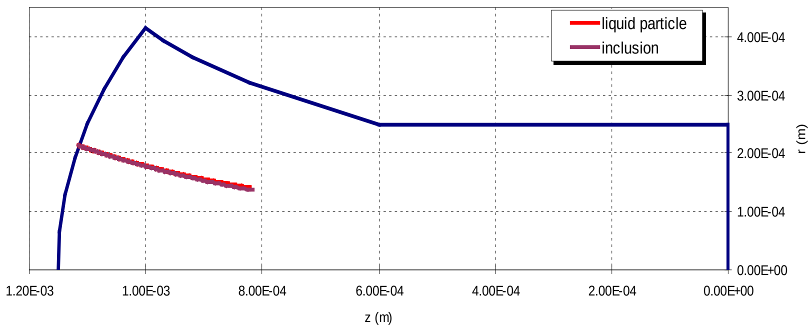
(a) *I*=15A



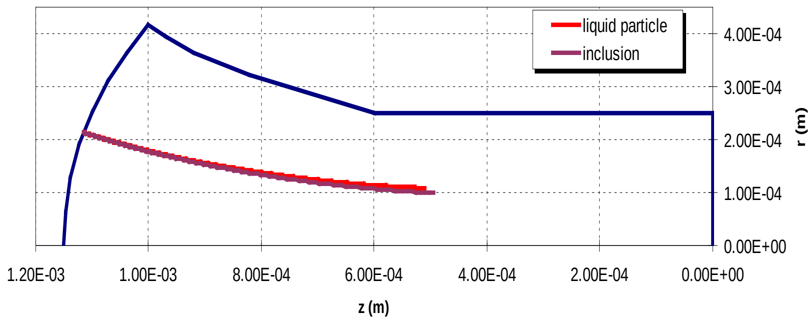
(b) *I*=300A

Predicted trajectories of inclusions (*d*=100μm) and steel flow vectors, when passing DC currents of (a) *I*=15A.and (b) *I*=300A, through liquid steel passing through a 500 micron (throat) diameter ESZ.

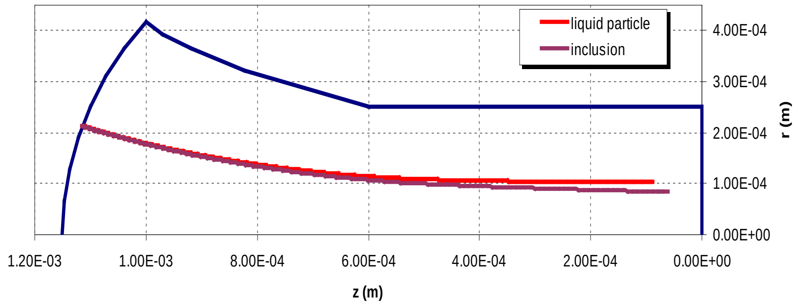
Trajectories comparison between “liquid particle” and inclusion



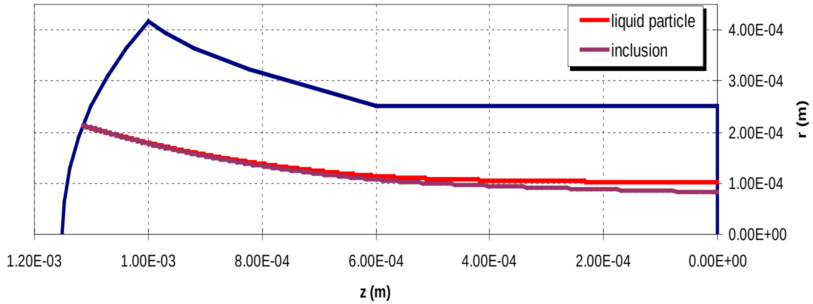
t=1ms



t=1.5ms

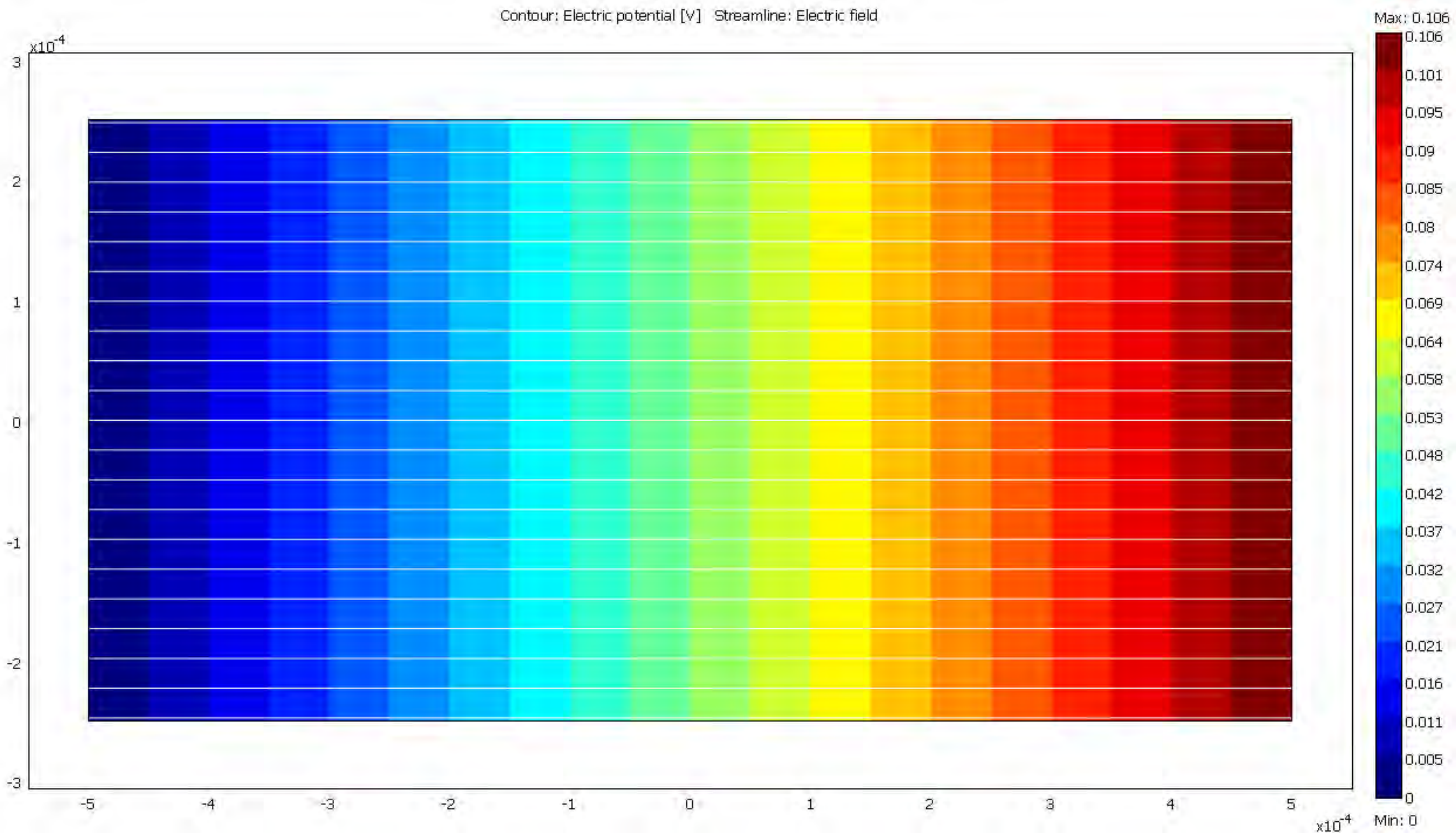


t=2ms

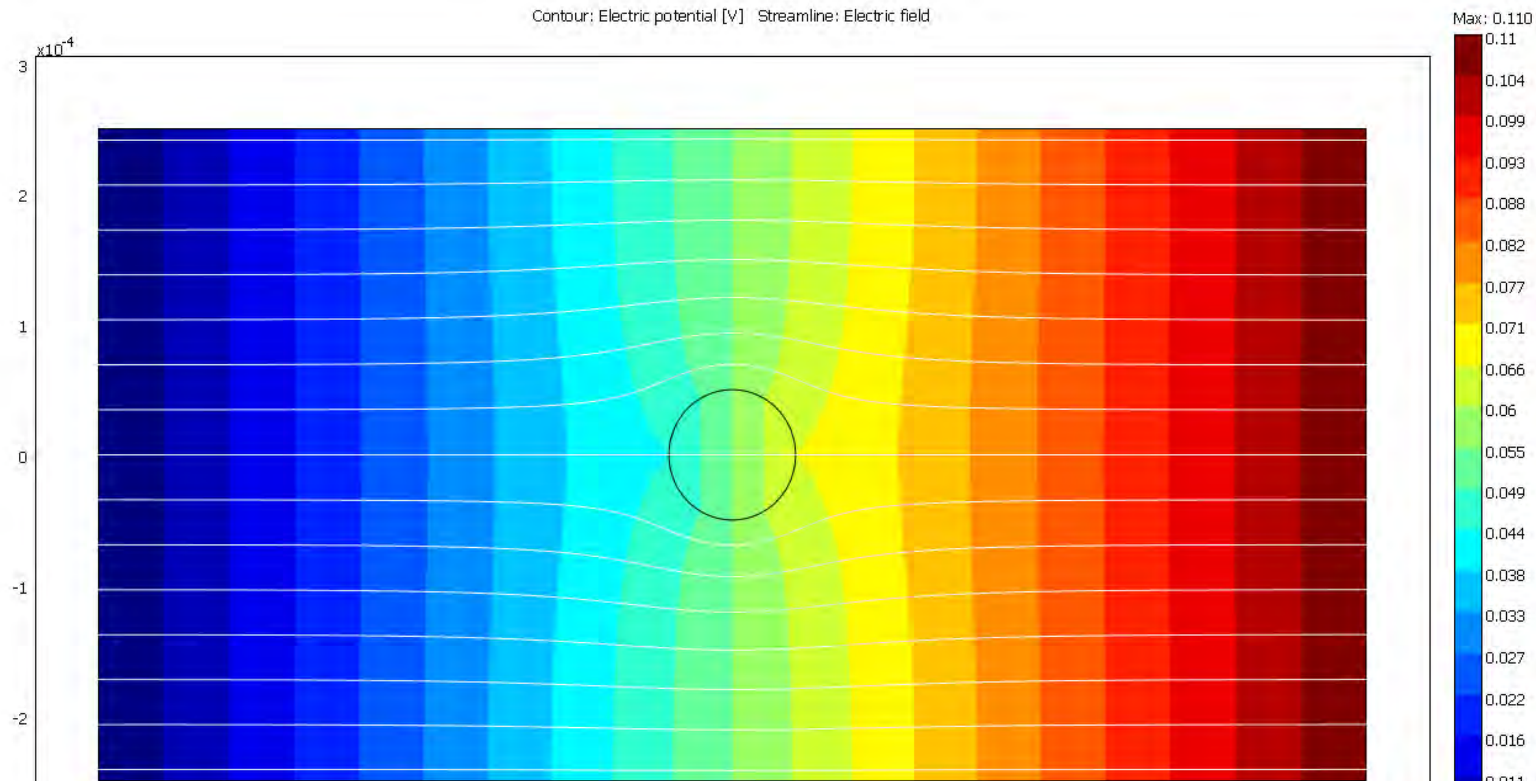


t= “total”

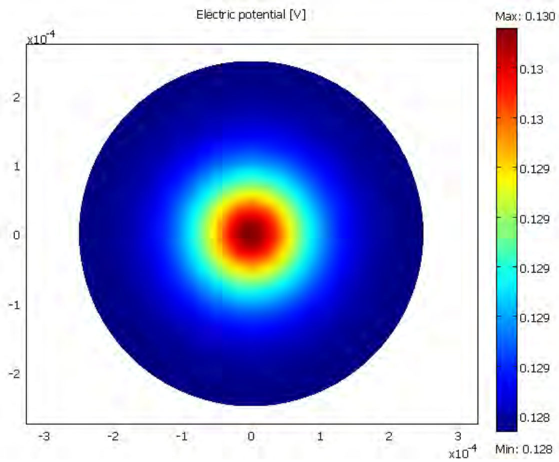
A two-dimensional uniform electric field



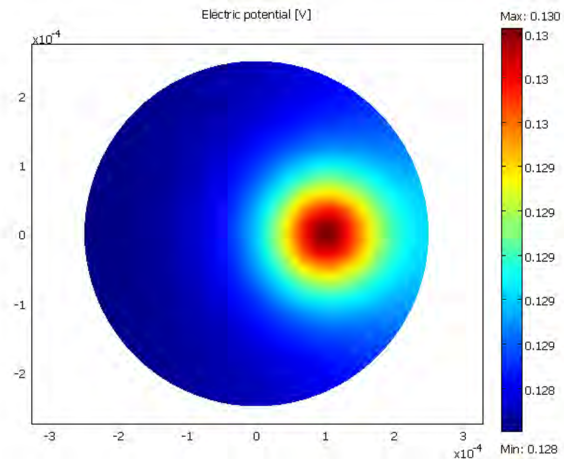
A nonconductive inclusion present in a original uniform electric field



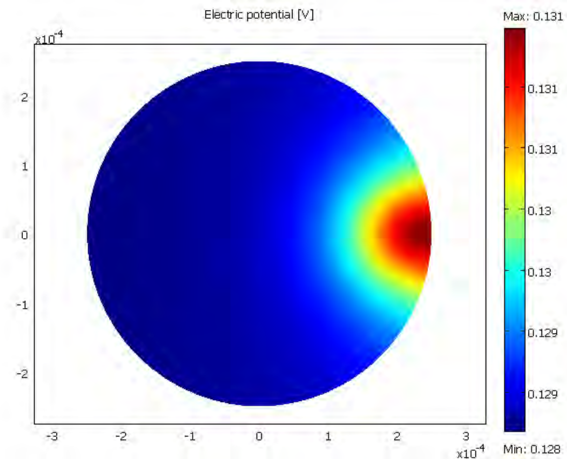
Voltage distribution on the surface of outlet boundaries when an inclusion presents at different positions



(a)



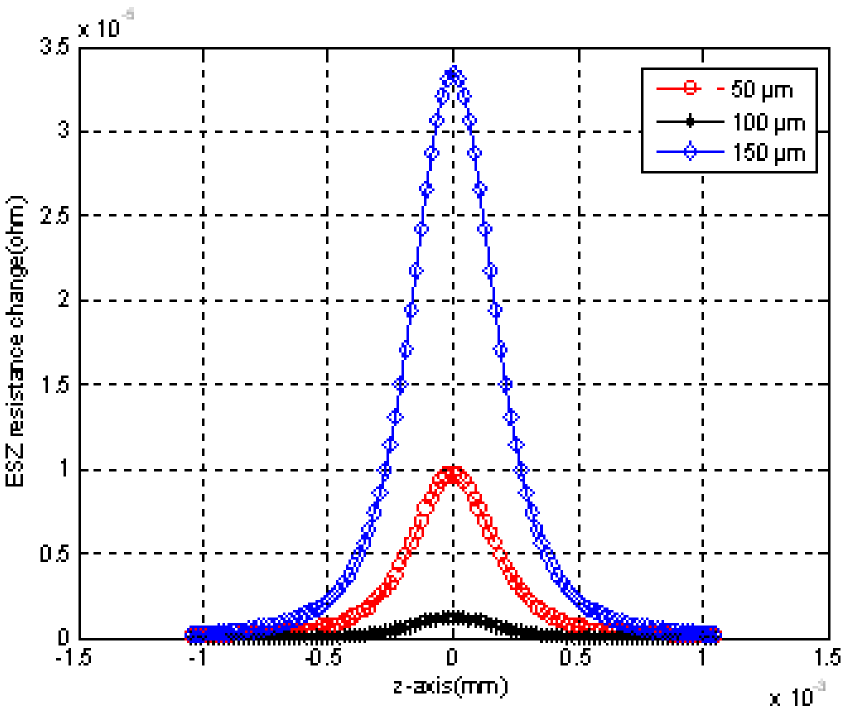
(b)



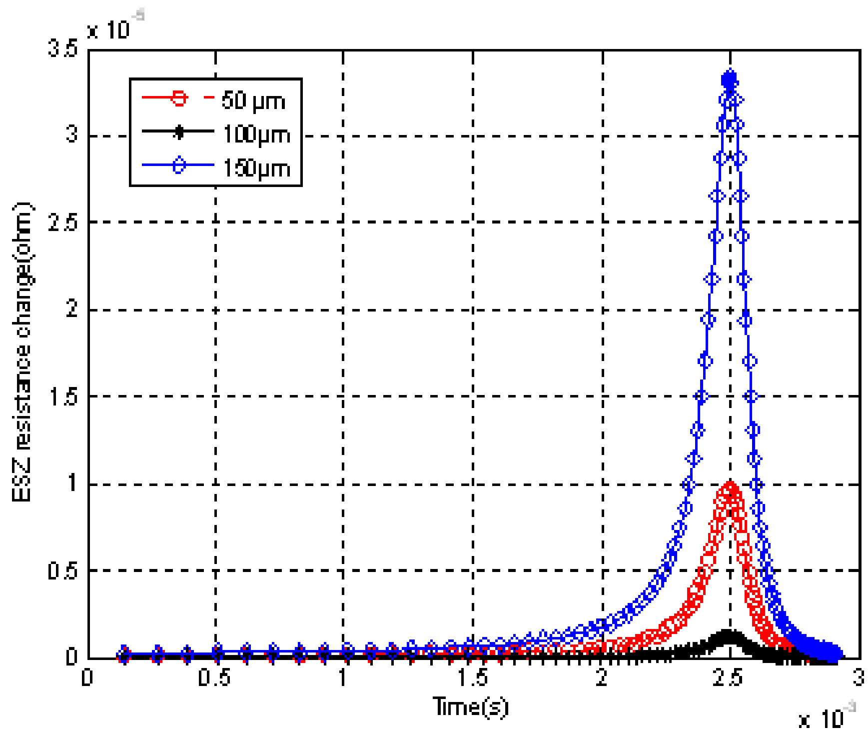
(c)

(a) x=0,y=100um, z=0;
(b) x=100um, y=100um,z=0;
(c) x=200um, y=100um, z=0.

Discrimination of inclusions based on transient electric resistance pulses

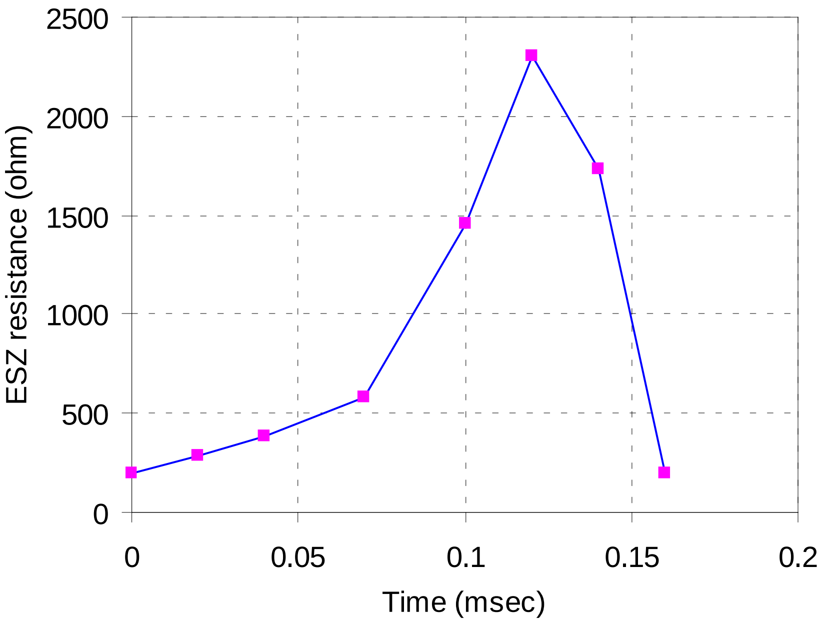


ESZ resistance change with the position of non-conductive particles of various diameters.

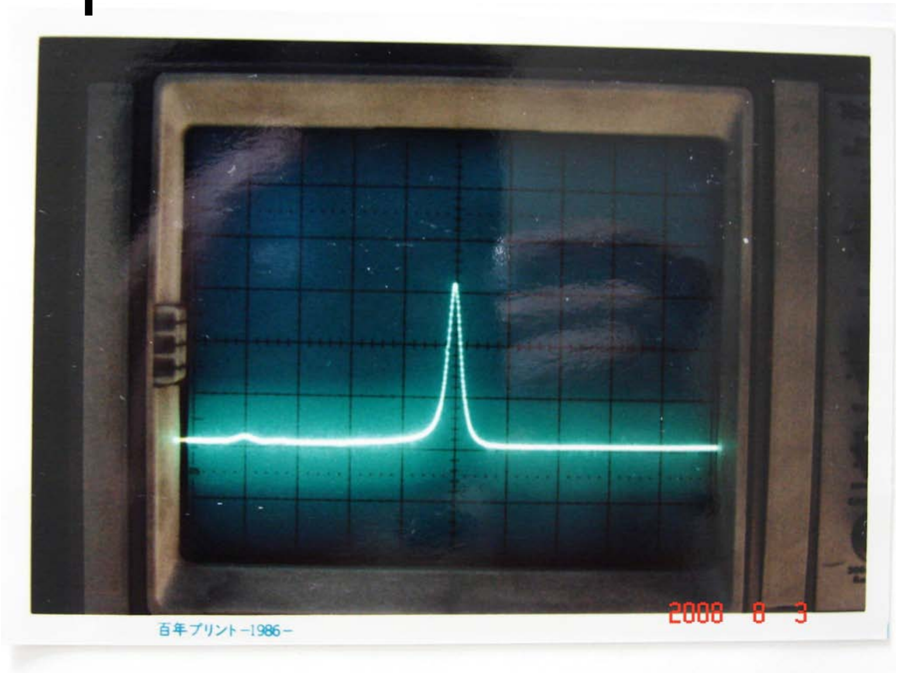


Numerically predicted transient electric pulse vs. residence time of an inclusion (d=100 μm) passing through the ESZ.

Compare with measurement of water-based equivalent experiments



(a)



(b)

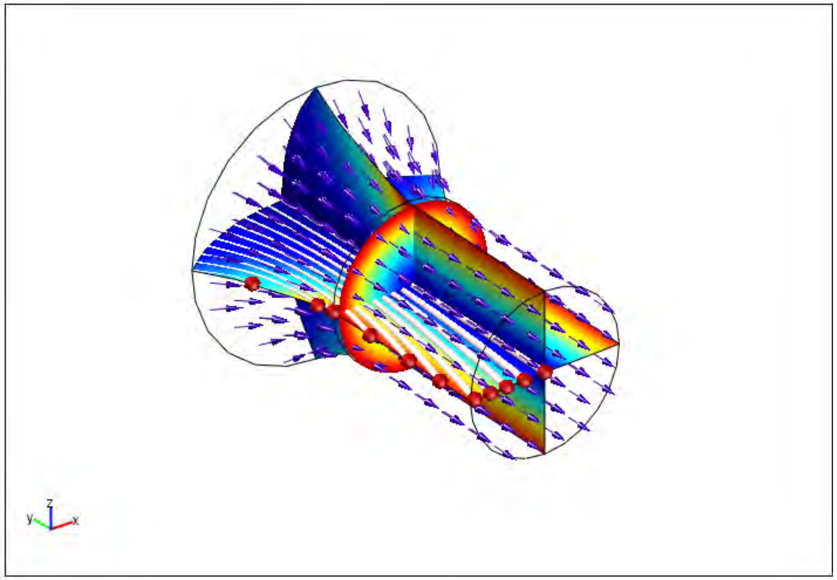
(a) Typical ESZ resistance signal generated by a silica inclusion (d=150 μm) using the APS II unit (250 mmHg pressure drop across the LiMCA probe) [1].

(b) Voltage pulse detected by oscilloscope during passage of a silica particle (diameter d=100μm), through a rounded orifice with throat diameter D=500 μm), aspiration speed 8 m/s [2].

Refs: 1. C. Carozza, Water modelling of particle discrimination using LiMCA technology, *master thesis*, McGill University, pp.57 (1999)

2. S. Tanaka, Modelling inclusion behaviour and slag entrainment in liquid steel processing vessels, Ph.D. *thesis*, McGill University, pp.70 (1986)

Inclusions motion behaviors in liquid steel LiMCA system



RECENT STEELPLANT MEASUREMENTS

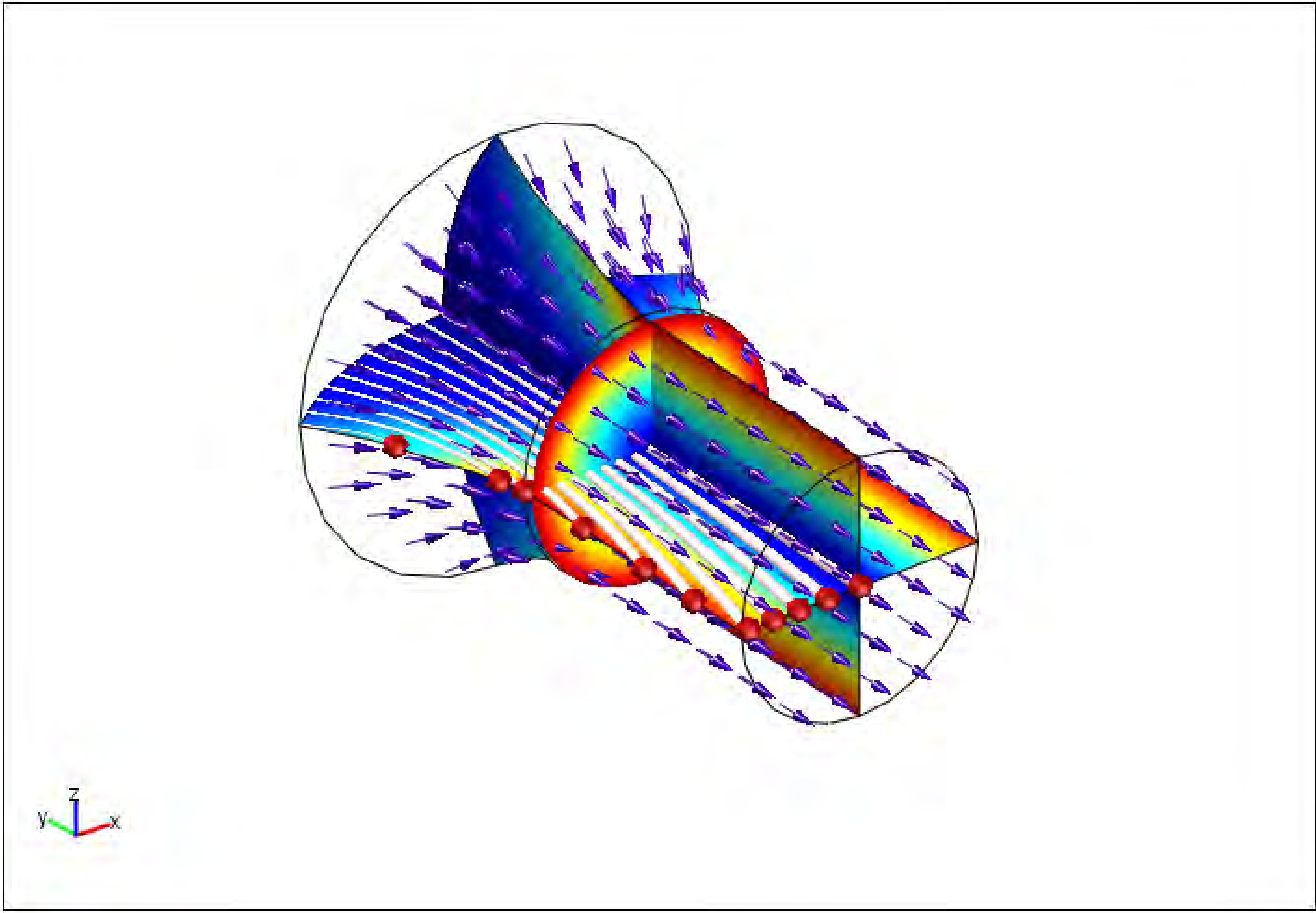
COMSOL numerical investigation

Conclusions

- A mathematical model is proposed using COMSOL to predict the behavior of inclusions in a liquid steel LiMCA system.
- The equation-based solutions provide us information on the influence of the drag, the added mass, inertial effects, and most significantly, electromagnetic forces, on the motions of the inclusions.
- It can predict the fate of inclusions entraining the ESZ, compute transient electric resistances, and provide insights into the experimental resistive pulses records in practice.

Conclusions

- This COMSOL model allows for parametric studies of fluid properties (velocity, viscosity and density), ESZ dimensions (shape, diameter and length), the strength of the electric current and the properties of the inclusion (shape, size, orientation, density and conductivity), or the second phase such as micro-bubbles, or liquid drops.
- Similarly, different kinds of liquid metals can be simulated, such as aluminum, copper, zinc as well as steel.
- The numerical results are further being compared with the LiMCA results from the recently development of light alloy and steel industry.



z
y
x