Bouyancy-induced convective heat transfer in cylindrical transformers filled with mineral oil with nano-suspensions

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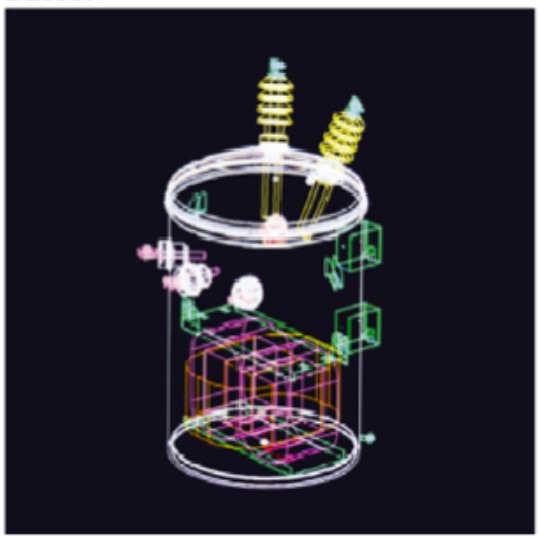
Motivation

- A single degree reduction in transformer winding temperature can increase life span by 10%
- 3.5 billion gallons of oil used as electrical dielectric [EPRI]
- Improvements in thermal properties of the oil can save lots of money

CORE & COIL

DESIGN



We propose to add nanodiamond to transformer oil (NDXO)

Additive considerations

- To put an additive into production, we must consider ...
  - thermal conductivity
  - viscosity
  - dielectric breakdown
  - abrasiveness
  - volatility
  - corrosiveness
  - environmental hazard
  - suspension
  - long-term degradation
  - reactivity
- We are considering increase in thermal performance

Thermal Analyses

- Dimensional analysis

$$\frac{\Delta T_{\text{xo}}}{\Delta T_{\text{ndxo}}} = \frac{\text{Nu}_{\text{ndxo}} k_{\text{ndxo}}}{\text{Nu}_{\text{xo}} k_{\text{xo}}} = \left(\frac{k_{\text{ndxo}}}{k_{\text{xo}}} \right)^{2/3} \left(\frac{\nu_{\text{xo}}}{\nu_{\text{ndxo}}} \right)^{1/3}$$

  ΔT defined in terms of maximum oil temperature to ambient

- Lumped model
- Streamfunction analysis
- 2D axisymmetric CFD analysis (CFDRC)
- 3D cylindrical CFD analysis (Fluent)

NDXO Properties

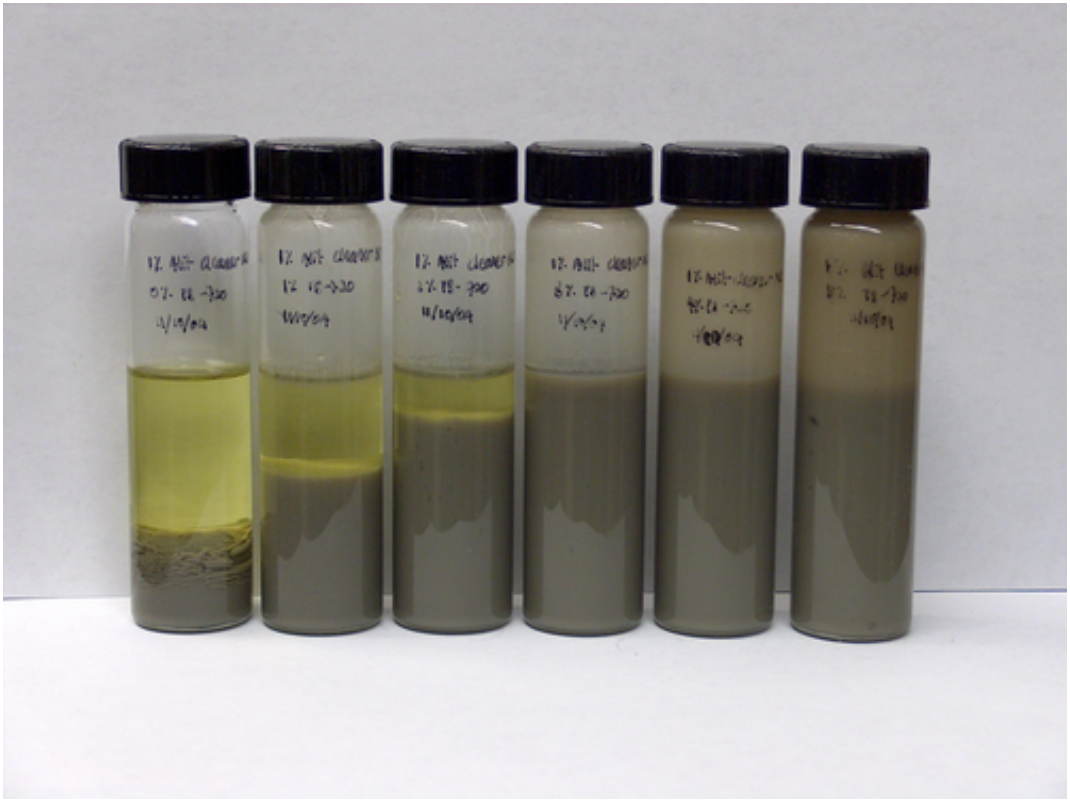
- Constituents
  - No studies on nanodiamond in transformer oil specifically, and conflicting measurements in the literature
  - Does the combination of ethylene glycol (EG) and copper nanoparticles behave similarly? (thermal conductivity is similar, but electrical conductivity is not)
- Suspension: Our nanofluid is suspended using a surfactant; surfactants in Cu/EG dramatically increases thermal conductivity

	Ra	Pr
xo	1.5×10^{10}	590
ndxo	1.0×10^{10}	393

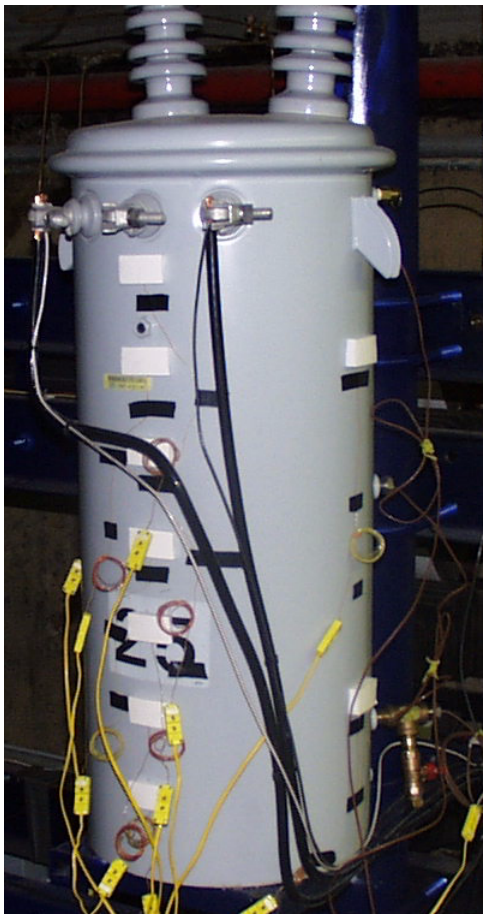
- Values based on 1.5 enhancement of thermal conductivity and zero change in viscosity due to addition of nanoparticles

- Initial indication is that viscosity increases slightly in our case

NDXO Suspension

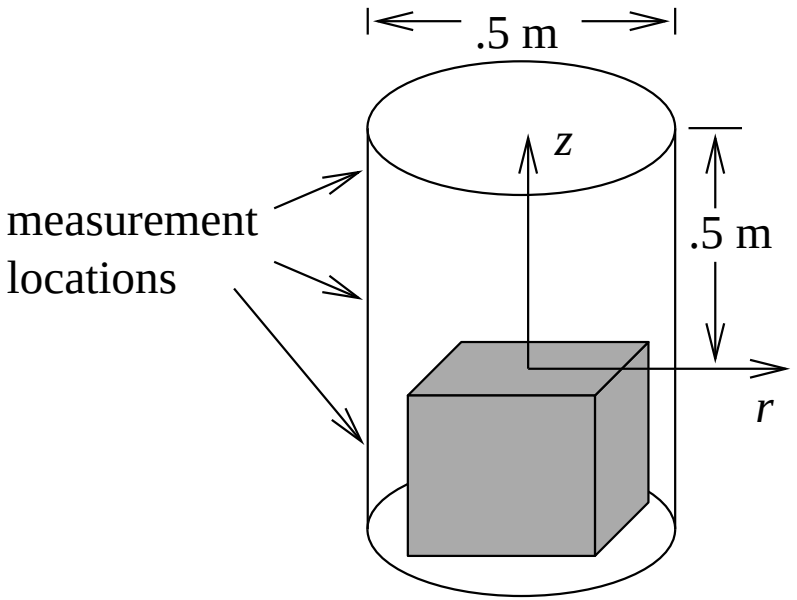


Pole-pig measurements



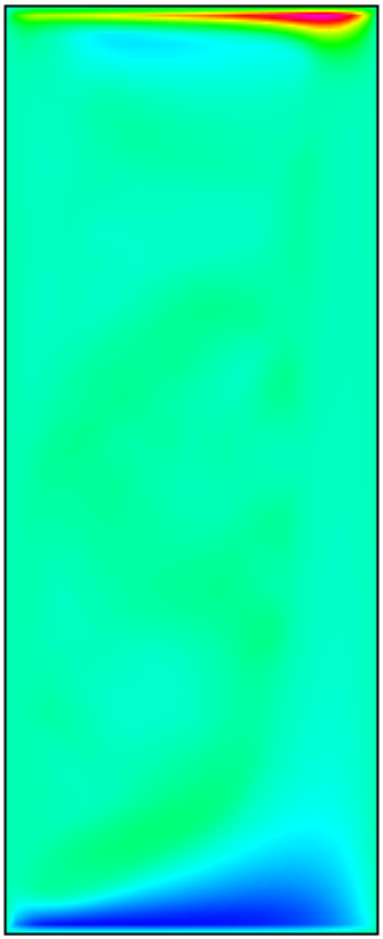
- nine external thermocouples measuring skin temperature
- three internal thermocouples measuring oil temperature near canister wall
- two identical 25kVA transformers (other than the oil) “feeding” off each other
- tests performed at 5kVA, 15kVA
- tests last for several days at each power level
- achieved some “anomalous” readings

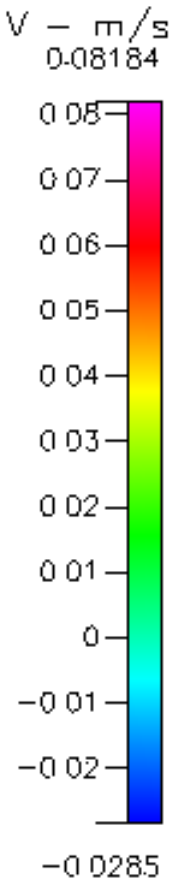
Simulations

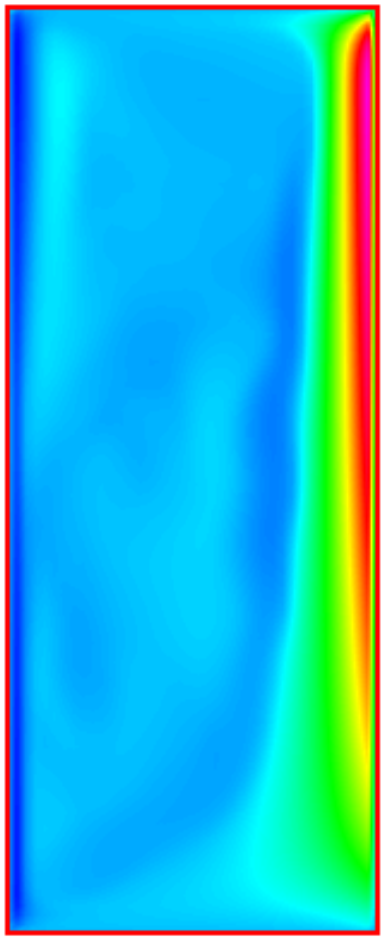


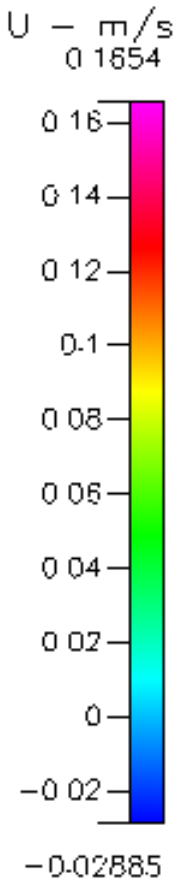
- 2-D axisymmetric?
- steady state?
- laminar?
- domain completely above transformer
- constant properties
- Boussinesq approximation
- boundary conditions
  - bottom: heated, no slip
  - top: insulated, no shear
  - sides: convective, no slip

Velocity (2D)



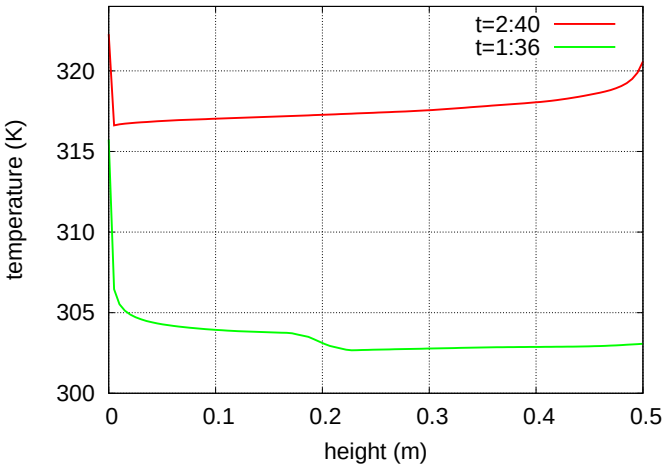

V – m/s
0.08184
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
−0.01
−0.02
−0.0285

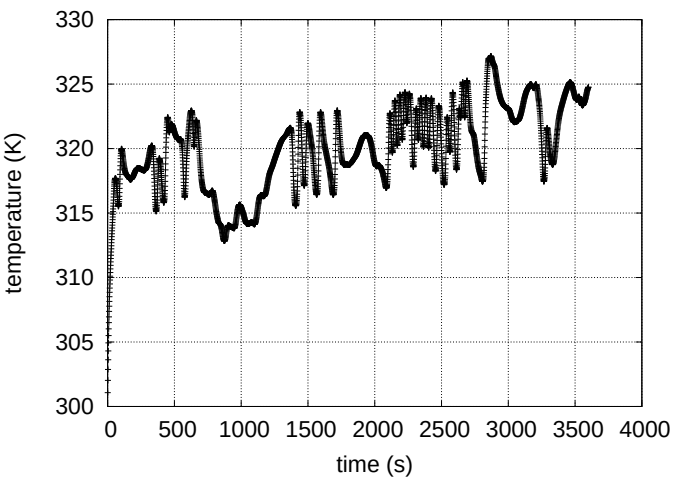



U – m/s
0.1654
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
−0.02
−0.02885

Compare to measurements

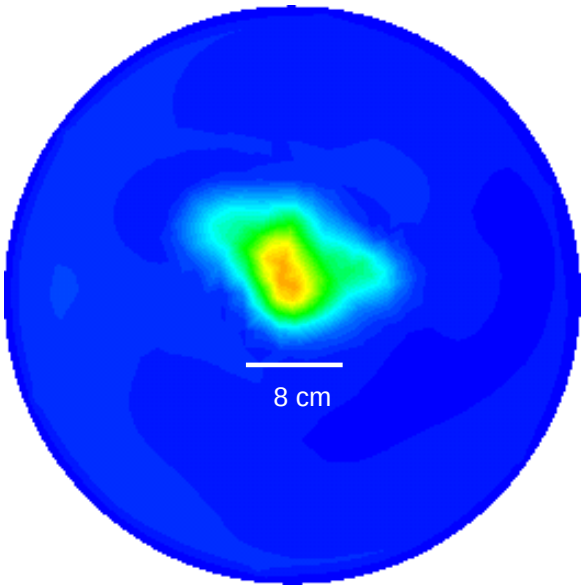
- The measured data indicate the temperature along the vertical surface of the canister is not uniformly changing and that the point of “sudden change” moves in time.

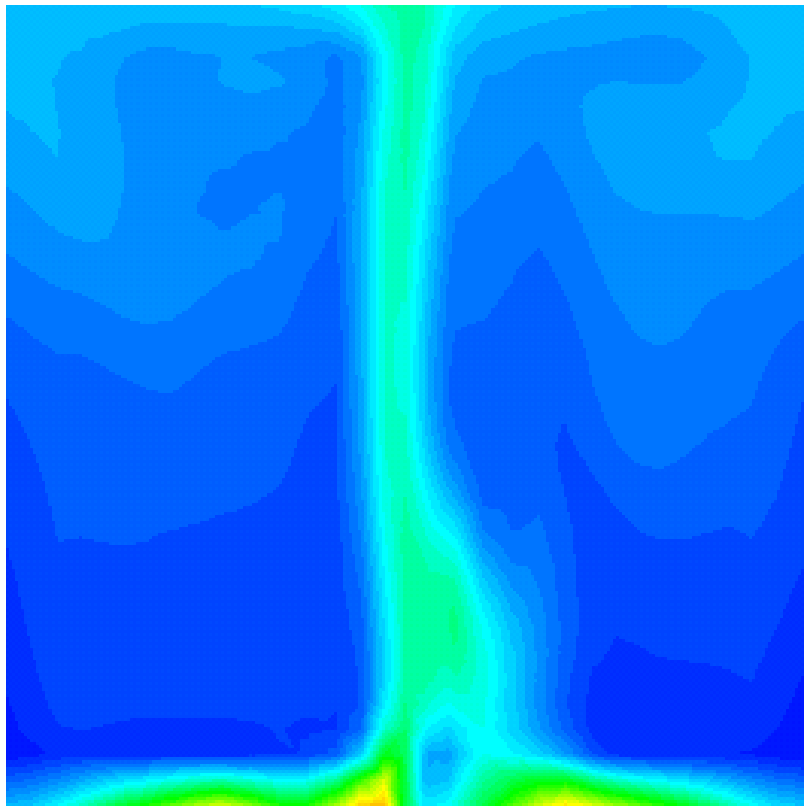




- plumes develop and temperature varies over time

Plume Features





- plume size and velocity correspond to Kaminski, 2003
- unsteady nature corresponds to Busse, 1978

Enhancement

Simulation	Enhancement
dimensional analysis	1.3
2D Streamfunction	2.5
2D axisymmetric	2.0
3D	1.5
Grossman	1.4

- Lumped model provides decent approximations to measured temperature histories
- We would like to find a solution in the literature, but we can't find the following combinations of features in Rayleigh-Bénard flow
  - near unity aspect ratio
  - high Prandtl numbers
  - cylindrical geometry
  - appropriate boundary models

Conclusions

- Preliminary analysis suggests that we can capture heat transfer characteristics using simulation.
- Preliminary property studies suggest that thermal performance can be improved.
- However, we still need ...
  - temperature-dependent properties
  - actual property values
  - to consider alternate convection models
  - consider different thermal boundary conditions
  - parameter sweeps of properties and geometry
  - increase geometrical complexity