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

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2005 International Mechanical Engineering Congress and Exposition
Orlando, FL
November 11, 2005
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

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

\[
\frac{\Delta T_{xo}}{\Delta T_{ndxo}} = \frac{N_{u_{ndxo}} k_{ndxo}}{N_{u_{xo}} k_{xo}} = \left( \frac{k_{ndxo}}{k_{xo}} \right)^{2/3} \left( \frac{\nu_{xo}}{\nu_{ndxo}} \right)^{1/3}
\]

\(\Delta T\) 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

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<tbody>
<tr>
<td>xo</td>
<td>$1.5 \times 10^{10}$</td>
<td>590</td>
</tr>
<tr>
<td>ndxo</td>
<td>$1.0 \times 10^{10}$</td>
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• 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
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

measurement locations

[Diagram showing a cylinder with labeled dimensions and a cube inside, indicating measurement locations]
Velocity (2D)
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

<table>
<thead>
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<th>Simulation</th>
<th>Enhancement</th>
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<tbody>
<tr>
<td>dimensional analysis</td>
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<tr>
<td>2D Streamfunction</td>
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<tr>
<td>3D</td>
<td>1.5</td>
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<tr>
<td>Grossman</td>
<td>1.4</td>
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- 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