MANCHESTER 1824

The University of Manchester

Global Young Member Presentation Showcase
2018 Paris Session
SC A2 – Transformers
PS1/ Thermal characteristics of power transformers

A Generic Solution to the Determination of Winding Hot Spot Temperature

Presenter: Dr. Xiang Zhang
Supervisors: Prof. Zhongdong Wang
Dr. Qiang Liu

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M&I MATERIALS
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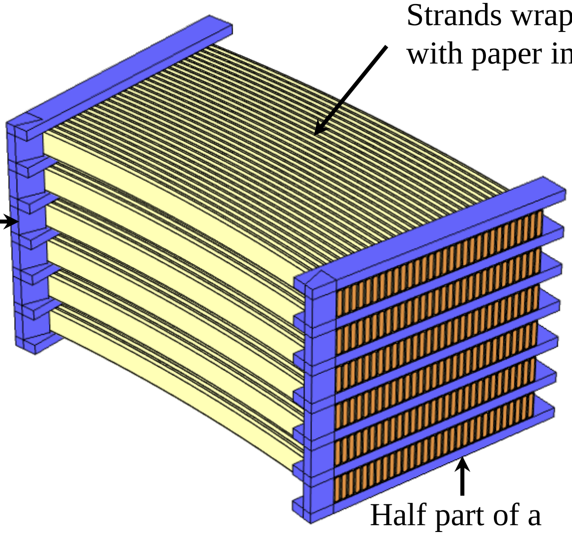
Transformers and Thermal Ageing

Cross-sectional view of 400 kV transformer end insulation*

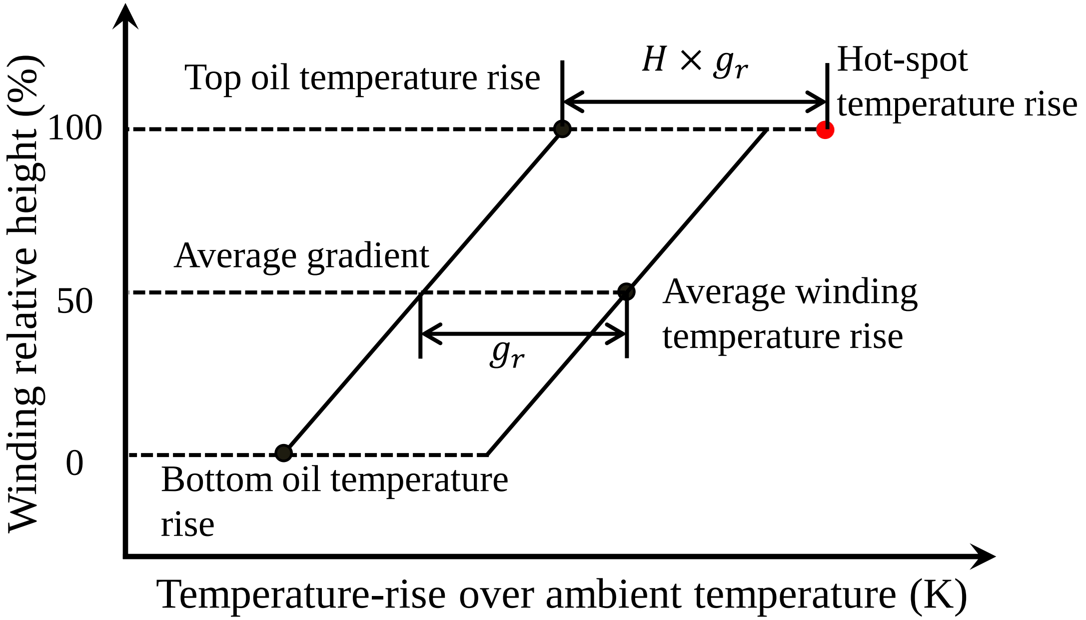
- Transformers in power networks
- Transformer insulation
- Paper thermal ageing rate doubles for every increase of 6-7 °C **



*CIGRE brochure 323 (2007): ageing of cellulose in mineral oil insulated transformers
**IEC 60076-7: 2005 Loading guide for oil-immersed power transformers.

Transformer Thermal Design & Test

- Hotspot temperature determines the thermal ageing rate
- Temperature rise test and thermal diagram*



- ❑ Linearity assumptions
- ❑ Hot-spot factor (*H*)

*IEC 60076-2: 2011 Temperature rise of oil-immersed power transformers

Transformer Thermal Modelling

- Computational fluid dynamics (CFD) models

$$\nabla \cdot (\rho \boldsymbol{u}) = 0$$ Mass conservation

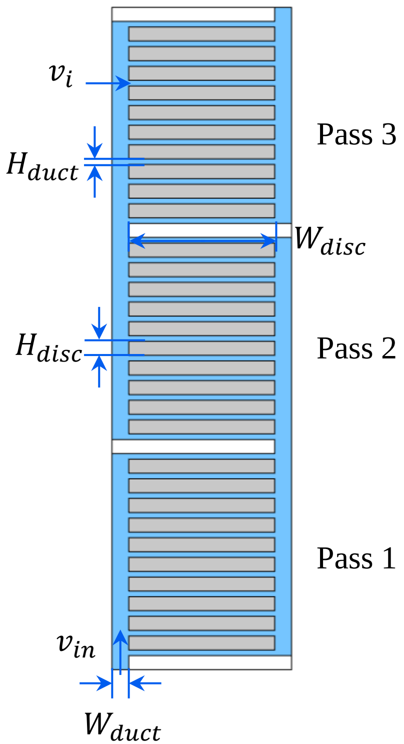
$$\rho \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\nabla p + \nabla \cdot (\mu(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T) - \frac{2\mu}{3}(\nabla \cdot \boldsymbol{u})\boldsymbol{I}) + \rho \boldsymbol{g}$$ Momentum conservation

$$\nabla \cdot (\rho c_p \boldsymbol{u} T) = \nabla \cdot (k \nabla T) + S_E$$ Energy conservation

ρ for density, $\boldsymbol{u}$ for velocity field, μ for dynamic viscosity, p for static pressure, $\boldsymbol{I}$ for identity matrix, $\boldsymbol{g}$ for gravitational acceleration, k for thermal conductivity, c_p for specific heat

- Pump-driven oil directed (OD) cooling modes
- Thermosiphon-driven oil natural (ON) cooling modes

Liquid Flow and Temperature Distribution



2D disc-type winding model for experimental tests

- In pump-driven oil directed (OD) cooling modes

$$v_{in}, \rho, \mu \rightarrow v_i$$

$$v_i, k, c_p \rightarrow T$$

ρ for density, μ for dynamic viscosity, k for thermal conductivity, c_p for specific heat

- Dimensional analysis*
  - Dimensional consideration
  - Functional consideration

$$\frac{v_i}{v_{in}} \cdot \frac{H_{duct}}{W_{duct}} = P_{fi} = f(\mathrm{Re}) \qquad \mathrm{Re} = \frac{\rho \bar{v}_{in}(2W_{duct})}{\mu}$$

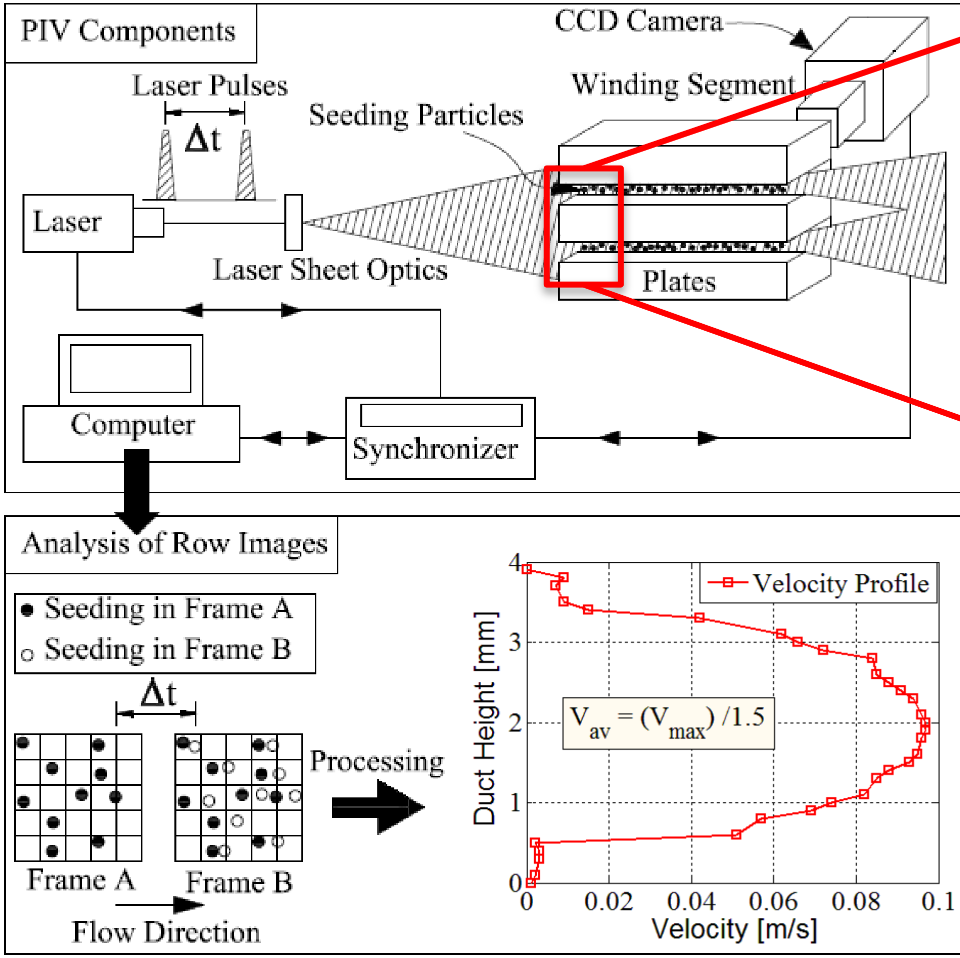
$$\frac{T_{hs} - T_{to}}{T_{aw} - (T_{to} + T_{bo})/2} = H = g(\mathrm{Re}, \mathrm{Pr}) \qquad \mathrm{Pr} = \frac{\mu c_p}{k}$$

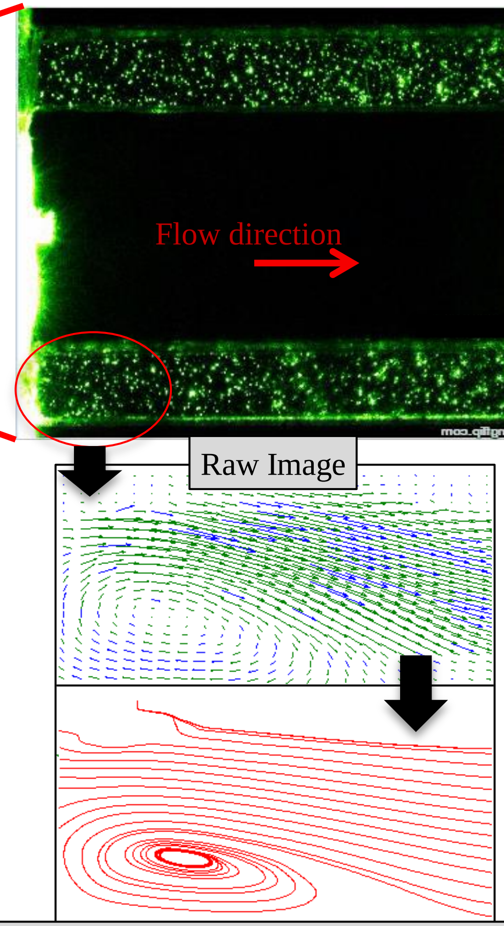
T_{hs} for hotspot temperature, T_{to} for top oil temperature, T_{bo} for bottom oil temperature, T_{aw} for average winding temperature

- CFD parametric sweeps and correlations

*X. Zhang, Z.D. Wang, and Q. Liu, "Prediction of Pressure Drop and Flow Distribution in Disc Type Transformer Windings under an OD Cooling Mode," *IEEE Transactions on Power Delivery*, vol. 32, no. 4, pp. 1655-1664, 2017.

Radial Duct Flow Measurement



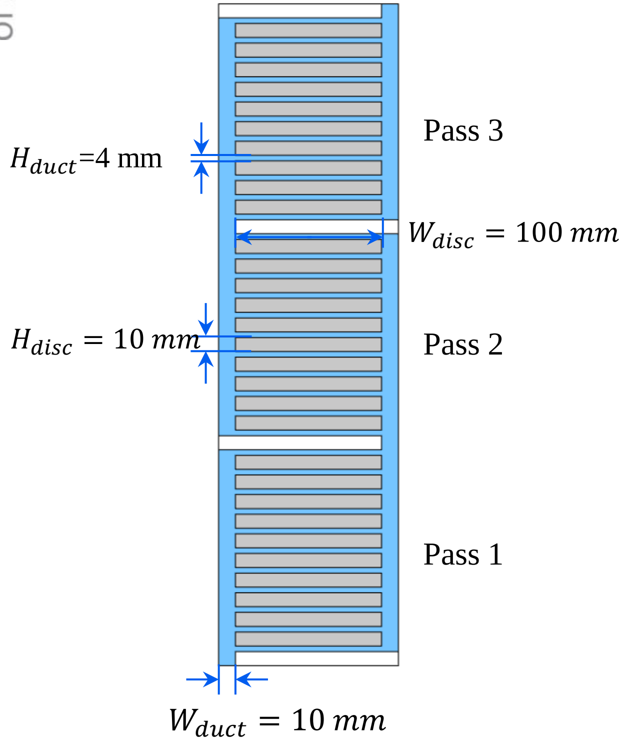


Oil recirculating at Duct Entrance

* Mechanism and typical components of a PIV system with a genuine measured velocity profile in a horizontal cooling duct.

*X. Zhang, M. Daghrah, Z.D. Wang, Q. Liu, P. Jarman, M. Negro, “Experimental Verification of Dimensional Analysis Results on Flow Distribution and Pressure Drop for Disc Type Windings in OD Cooling Modes," *IEEE Transactions on Power Delivery*, In press, accepted on 3rd August, 2017

Experimental Verification of DA for OD

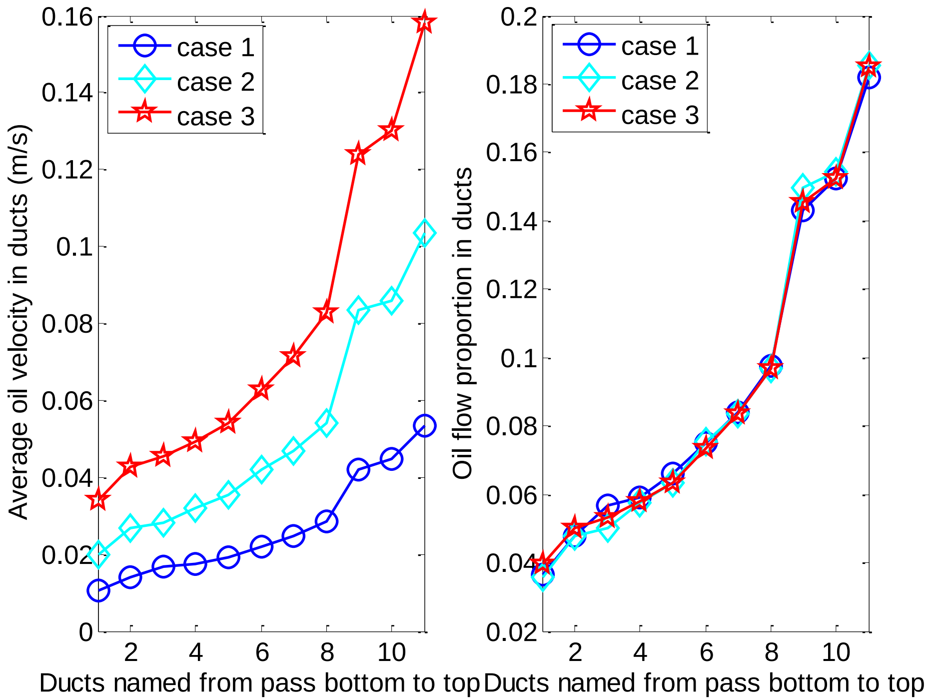


$$\frac{v_i}{v_{in}} \cdot \frac{H_{duct}}{W_{duct}} = P_{fi} = f(\mathrm{Re})$$

$$\mathrm{Re} = \frac{\rho \bar{v}_{in}(2W_{duct})}{\mu}$$

Three cases with similar Re*

	Case 1	Case 2	Case 3
Pass inlet velocity (m/s)	0.1	0.2	0.3
Oil temperature (^oC)	77	48	36
Re	541	536	547



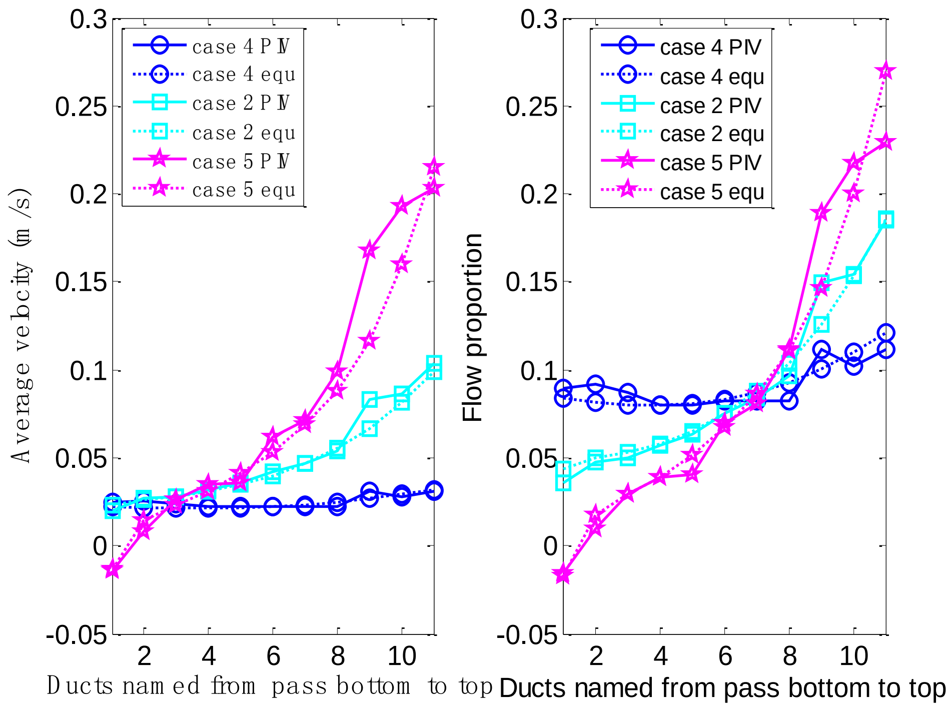
Comparison of flow distribution in pass 3 for the three cases with similar *Re**

* X. Zhang, M. Daghrah, Z.D. Wang, Q. Liu, P. Jarman, M. Negro, "Experimental Verification of Dimensional Analysis Results on Flow Distribution and Pressure Drop for Disc Type Windings in OD Cooling Modes," *IEEE Transactions on Power Delivery*, In press, 2017.

Liquid Flow Distribution for OD

Three cases to cover practical range of Re*

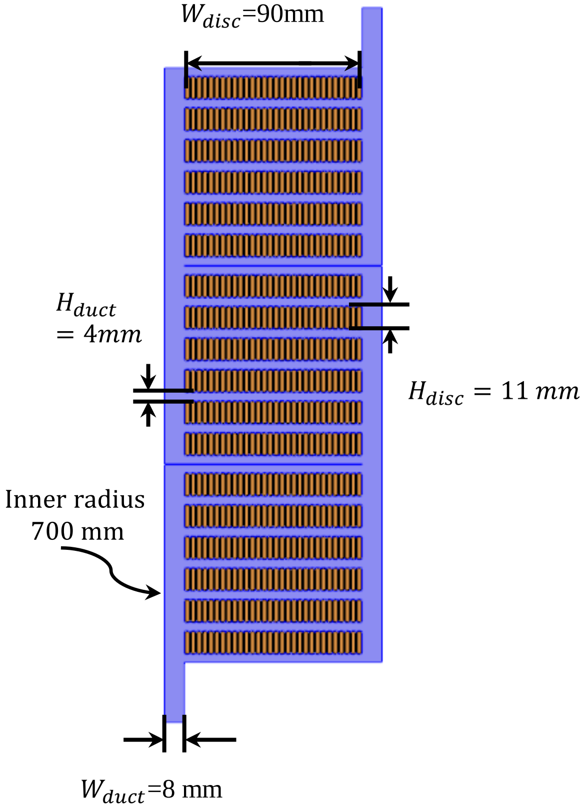
	Case 4	Case 2	Case 5
Pass inlet velocity (m/s)	0.1	0.2	0.3
Oil temperature (°C)	20	48	70
Re	97	536	1402



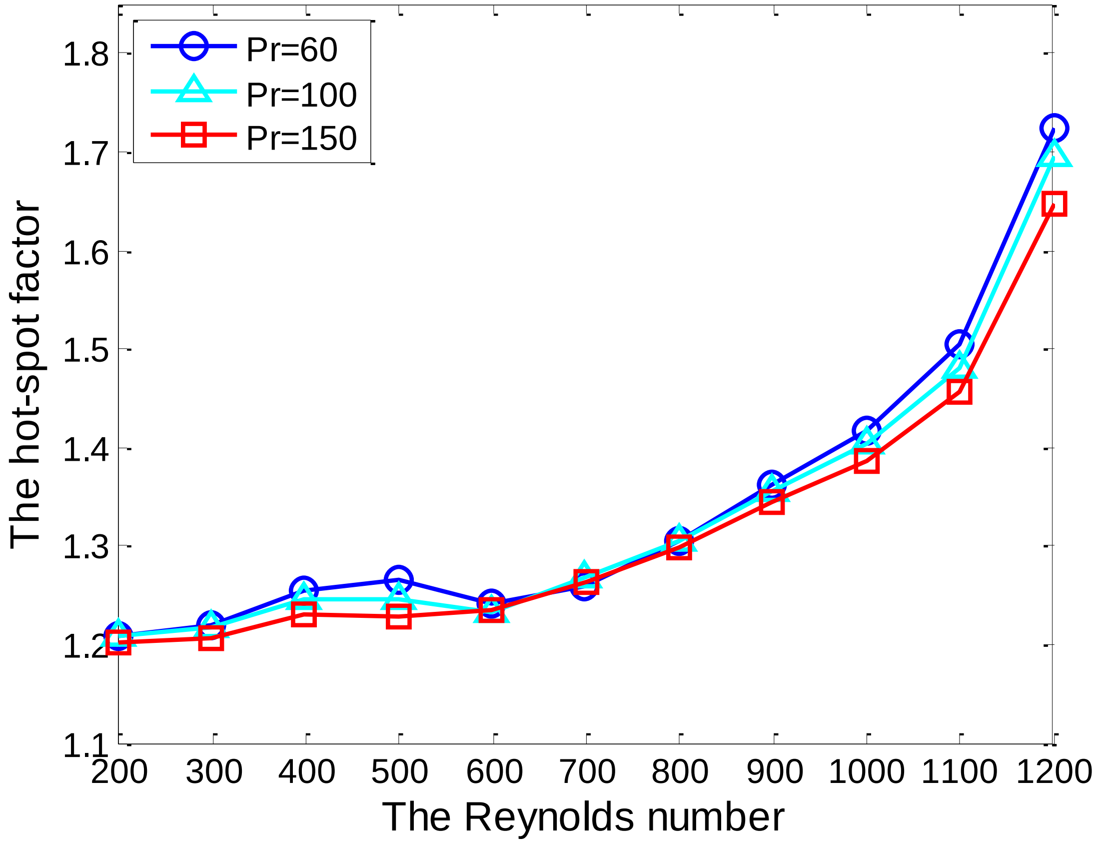
Comparison of flow distribution from PIV measurement and correlation*

* X. Zhang, M. Daghrah, Z.D. Wang, Q. Liu, P. Jarman, M. Negro, “Experimental Verification of Dimensional Analysis Results on Flow Distribution and Pressure Drop for Disc Type Windings in OD Cooling Modes," *IEEE Transactions on Power Delivery*, In press, 2017.

Hotspot Factor for OD Cooling Modes



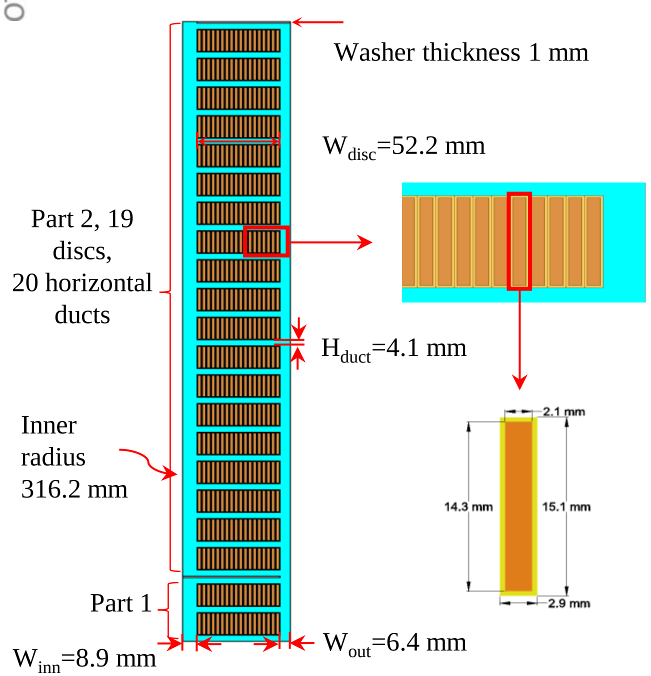
2D axisymmetric winding geometry



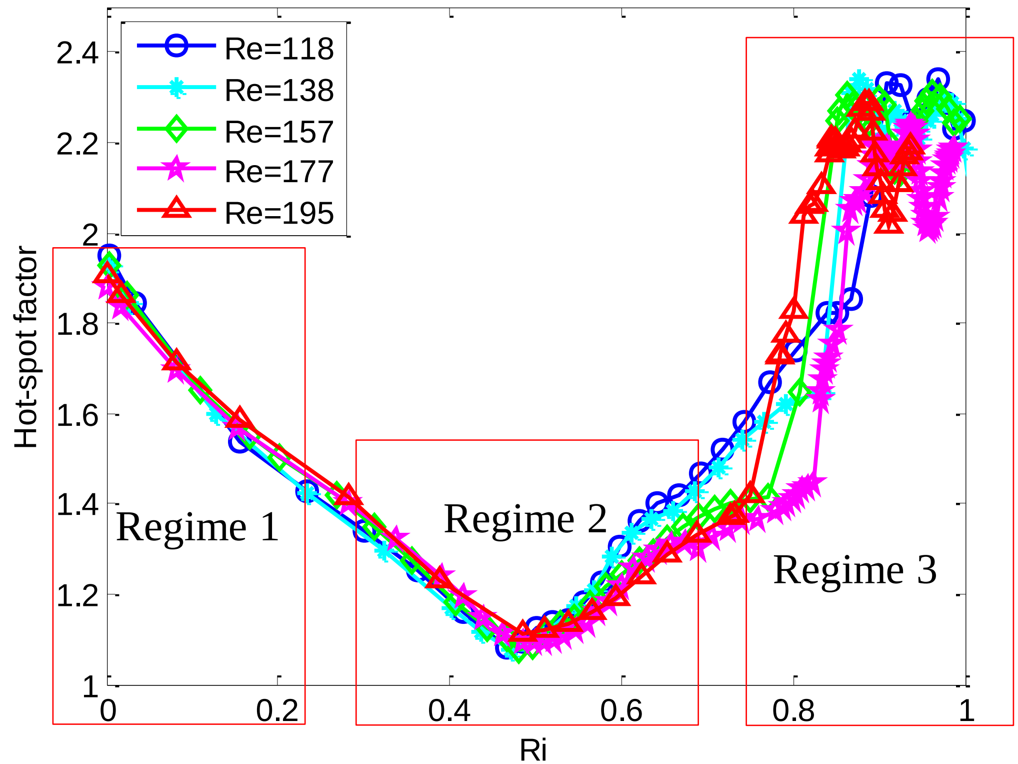
Variation of *H* with *Re* and *Pr*.*

* X. Zhang, Z.D. Wang, and Q. Liu, "Interpretation of Hot Spot Factor for Transformers in OD Cooling Modes," *IEEE Transactions on Power Delivery*, In press, 2017.

Hotspot Factor for ON Cooling Modes



Winding geometry pass 1. Pass 2, 3 and 4 repeat part 2 of pass 1



Variation of *H* with *Ri* and *Re*.*

$$Ri = \frac{Gr}{\mathrm{Re}^2} = \frac{g\beta g_r D_h}{v_{in}^2}$$

Provides a measure of the ratio of buoyancy force to inertial force

g for gravitational acceleration, β for thermal expansion coefficient, g_r for average winding-oil temperature gradient, D_h for hydraulic diameter, v_{in}^2 for winding pass inlet velocity.

* X. Zhang, Z.D. Wang, Q. Liu, P. Jarman, M. Negro "Numerical Investigation of Oil Flow Distribution and Temperature Distribution for ON Transformer Windings," *Applied Thermal Engineering*, vol. 130, pp. 1-9, 2018.

Summary

- Dimensional analyses provide simplicity, insight and universally applicable results.
- For OD cooling modes a high flow rate can be a problem.
- For ON cooling modes a low flow rate is a problem.

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Presented by:
Dr. Xiang Zhang

Postdoctoral Research Associate
Power and Energy Division
School of Electrical & Electronic Engineering
The University of Manchester

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TJ | H2b UK Power Networks WEIDMANN