CFD Analysis of Forced Air Cooling of a High-Speed Electric Motor

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- Professor at Cal Poly Pomona for 15 years
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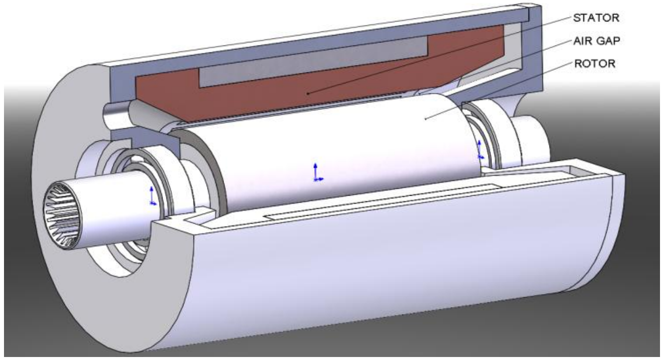
- Senior Spacecraft Thermal Engineer Faculty Part Time Caltech's NASA JPL from 2004 to present
- 20 years of professional industry experience Parsons, NREL, NCAR, Hughes, Boeing, Swales, ATK
- Conversant in STAR-CCM+, ANSYS FLUENT, NX-Flow, COMSOL, OPENFOAM, FLOW-3D, CFD 2000, Thermal Desktop, SINDA/FLUINT, NX Space Systems Thermal, IDEAS TMG software packages
- 20 peer-reviewed journal articles and over 60 conference proceedings in the areas of CFD, Numerical Heat Transfer, Spacecraft Thermal Control, Renewable Energy, Machine Design, Robotics, and Engineering Education
- Assoc. Editor of 15th Intl. Heat Transfer Conf.; Member of Editorial Board for American J. of Engr. Education, Track Organizer for ASME 9th Intl. Conf. on Energy Sustainability; Session Chair for 9th Intl. Boiling & Condensation Heat Transfer Conf.; Reviewer for the following; J. of Clean Energy Technologies, Int. J. of Thermodynamics, Energies, Waste Heat Recovery Strategy & Practice, J. of Applied Fluid Mechanics

Outline

- Problem Motivation
  - This problem is an industrial problem whereby the client wanted to ascertain the effects of frictional drag “windage” losses on the performance of a high-speed motor
- This work is currently in draft as “CFD Investigation of Forced Air Cooling in a High-Speed Electric Motor” by Kevin R. Anderson, James Lin, Chris McNamara and Valerio Magri for submittal to Journal of Electronics Cooling & Thermal Control, Mar. 2015
- CFD Methodology
  - CAD
  - Mesh
  - CFD Model Set-up
- Heat-Transfer Analysis
  - Specified y+ Heat Transfer Coefficient (HTC)
  - Specified y+ Nusselt Number
  - Nusselt number vs. Taylor Correlation for small gap, large Taylor number, large axial Reynolds Number flows
- Fluid-Flow Analysis
  - Torque vs. Speed Correlation of CFD to Experimental Data
  - CFD Windage Force and Power Losses as Compared to Experiments
- Conclusions
- Q&A



Problem Motivation
Why Are We Doing This ?

- High speed high efficiency synchronized electric motors are favored in the automotive industry and turbo machinery industry world wide because of the demands placed on efficiency
- In general, direct coupling the electric motor to the drive shaft will yield simplicity of the mechanical design and deliver high system efficiency
- However, the demand of high rotational speeds and high efficiencies can sometimes present difficulties when the RPM reaches 30,000 RPM to 100,000 RPM
- The drag created in the air gap between the rotor and stator can result significant “windage” losses that impact efficiency and increase motor cooling requirements

Problem Motivation
Why Are We Doing This ?

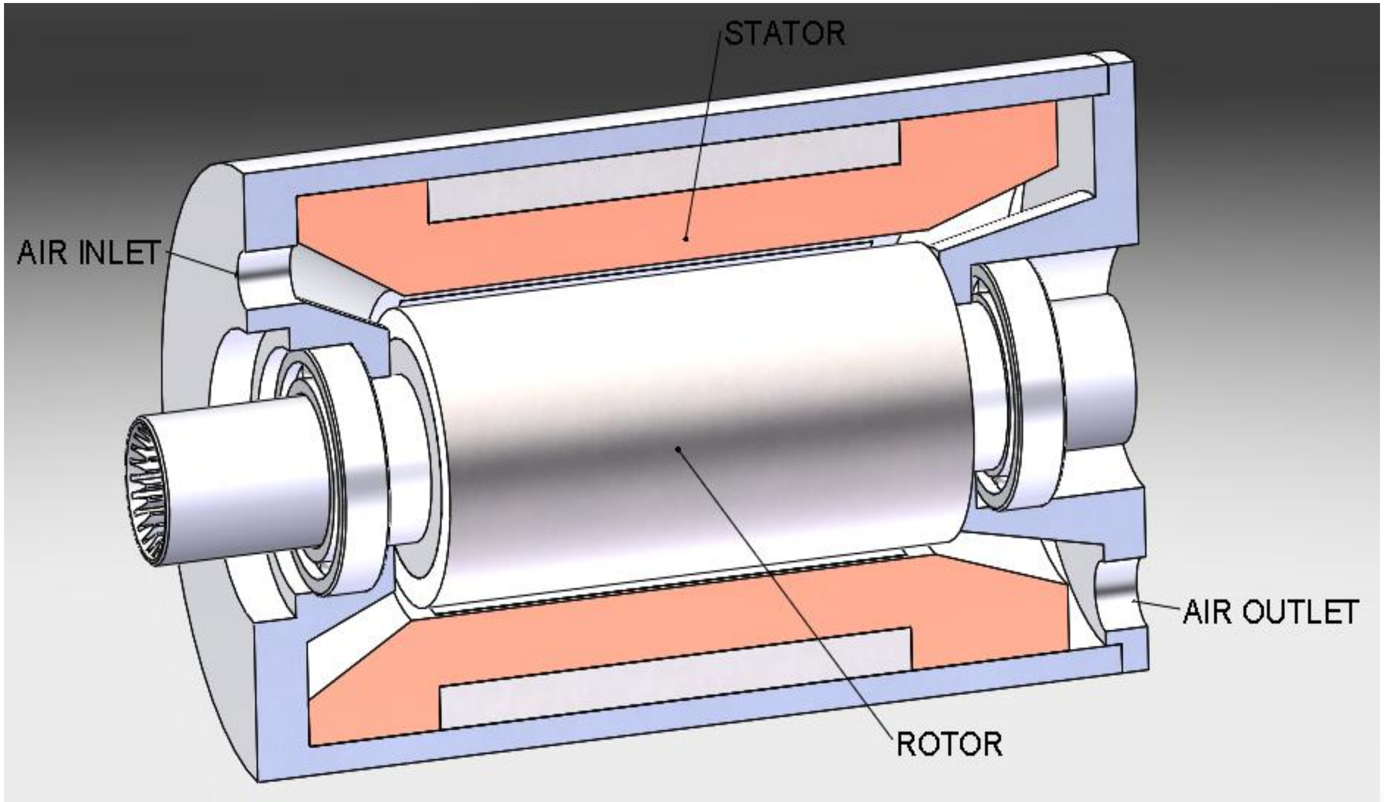
- In some applications involving high power density electric motors forced air cooling is used to cool the rotor
- The high rotational speed combined with cooling air that travels in the axial direction creates very complex fluid dynamic flow profiles with coupled heat transfer and mass transfer
- The relationship between the amount of the cooling air flow, windage generation and maximum temperature the rotor can handle is one of the most important factors in high speed electric motor design
- CFD analysis must be performed to ensure proper cooling with low windage losses in order to achieve high efficiencies

Problem Motivation
Why Are We Doing This ?

- Windage is a force created on an object by friction when there is relative movement between air and the object.
- There are two causes of windage:
  - The object is moving and being slowed by resistance from the air
  - A wind is blowing producing a force on the object
- The term windage can refer to:
  - The effect of the force, for example the deflection of a missile or an aircraft by a cross wind
  - The area and shape of the object that make it susceptible to friction, for example those parts of a boat that are exposed to the wind

Typical Permanent Magnet Air Cooling Path

- Cooling air enters from the drive end of the motor and exits from the non-drive end of the motor as shown below



Typical Permanent Magnet Air Cooling Path

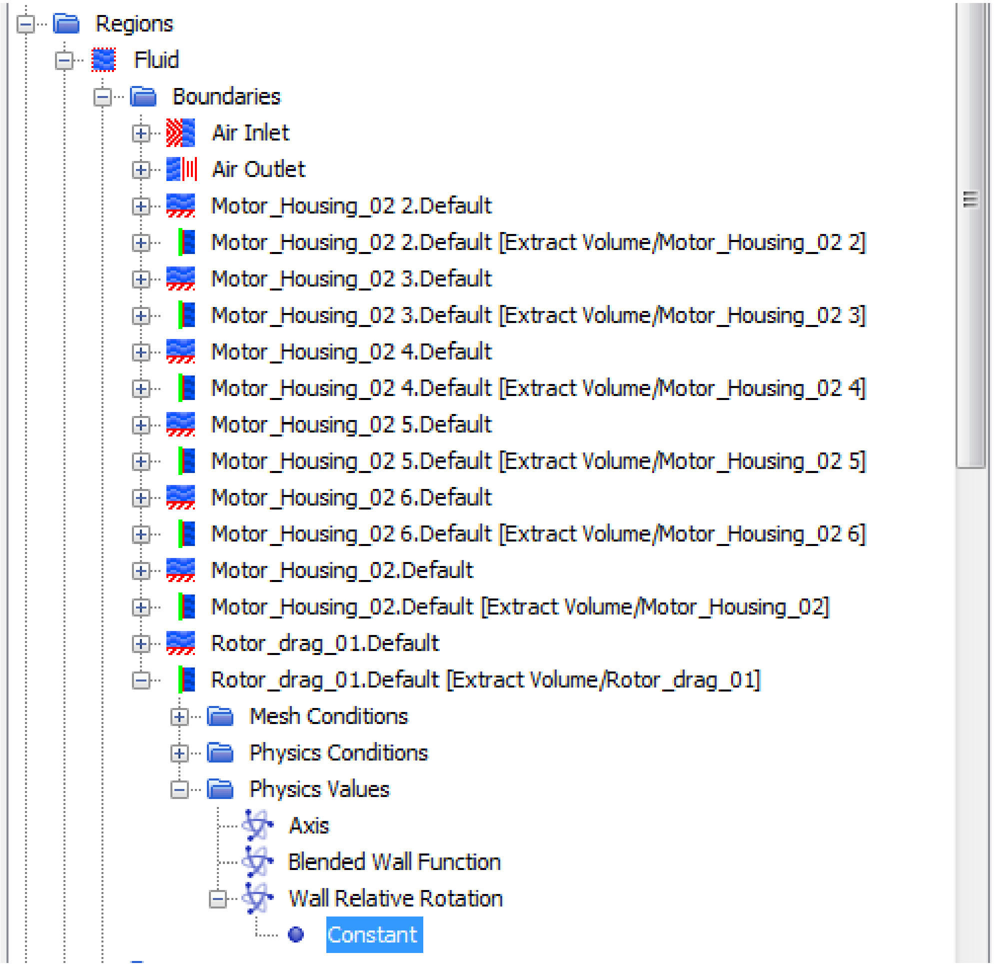
- Cooling air will pass through an air gap between the stator and the rotor where the rotor spinning at 50,000 RPM to 100,000 RPM
- The rotor and have electro-magnetic losses and dissipate heat
- For example, the motor is designed to output 50kW of shaft power in 90,000 RPM while its rotor dissipating 200W and stator dissipating 1000
- The cooling air will generate a windage that may significantly impact the motor efficiency
- On the other hand, the design requirements could place a limit on the maximum temperature of the stator and rotor which could be set at 150°C
- A CFD analysis can help to find appropriate mass flow rate and windage losses while satisfying this maximum temperature requirement

CFD Model Summary

- 3-d unsteady
- Conjugate Heat Transfer
- Incompressible flow (Ma < 0.3)
- Ideal Gas Law for Air
- k-ω SST Turbulent with “all wall” wall-function treatment
- Segregated solver
- SIMPLE Method
- Thin layer embedded mesh, polyhedral mesh, prism layers
    - 765K fluid cells
    - 559K solid cells
- Rotor modeled as rotating region

CFD Model Summary

- Rotating Region Specification in STAR-CCM+

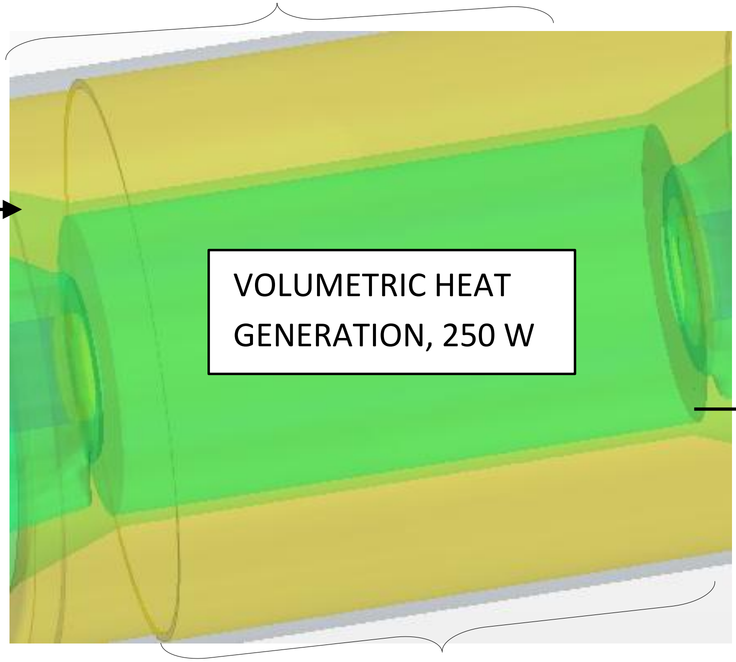


- Regions
  - Fluid
    - Boundaries
      - Air Inlet
      - Air Outlet
      - Motor_Housing_02 2.Default
      - Motor_Housing_02 2.Default [Extract Volume/Motor_Housing_02 2]
      - Motor_Housing_02 3.Default
      - Motor_Housing_02 3.Default [Extract Volume/Motor_Housing_02 3]
      - Motor_Housing_02 4.Default
      - Motor_Housing_02 4.Default [Extract Volume/Motor_Housing_02 4]
      - Motor_Housing_02 5.Default
      - Motor_Housing_02 5.Default [Extract Volume/Motor_Housing_02 5]
      - Motor_Housing_02 6.Default
      - Motor_Housing_02 6.Default [Extract Volume/Motor_Housing_02 6]
      - Motor_Housing_02.Default
      - Motor_Housing_02.Default [Extract Volume/Motor_Housing_02]
      - Rotor_drag_01.Default
      - Rotor_drag_01.Default [Extract Volume/Rotor_drag_01]
        - Mesh Conditions
        - Physics Conditions
        - Physics Values
          - Axis
          - Blended Wall Function
          - Wall Relative Rotation
            - Constant

Simulation Parameters

- Rotor Parameters
  - Rotor Inner Radius = 24.78 mm
  - Rotor Outer Radius = 27.89 mm
  - Annular Gap = 3.11 mm
  - Length = 98.54 mm
  - Rotor rotational speed = 9950 rad/sec
  - Rotor heat dissipation = 250 W
- Inlet Cooling Air Parameters
  - Mass flow rate = 0.011 kg/sec
  - Temperature = 20 °C
  - Viscosity= 1.51E-5 m^2/sec
  - Density = 1.16 kg/m^3
  - Thermal conductivity = 0.0260 W/m-K
  - Specific heat = 1011 J/kg-K

Boundary Conditions



TEMPERATURE, 150 °C

AIR SUPPLY

INLET,

MASS FLOW

RATE AND

TEMPERATURE

PRESCRIBED

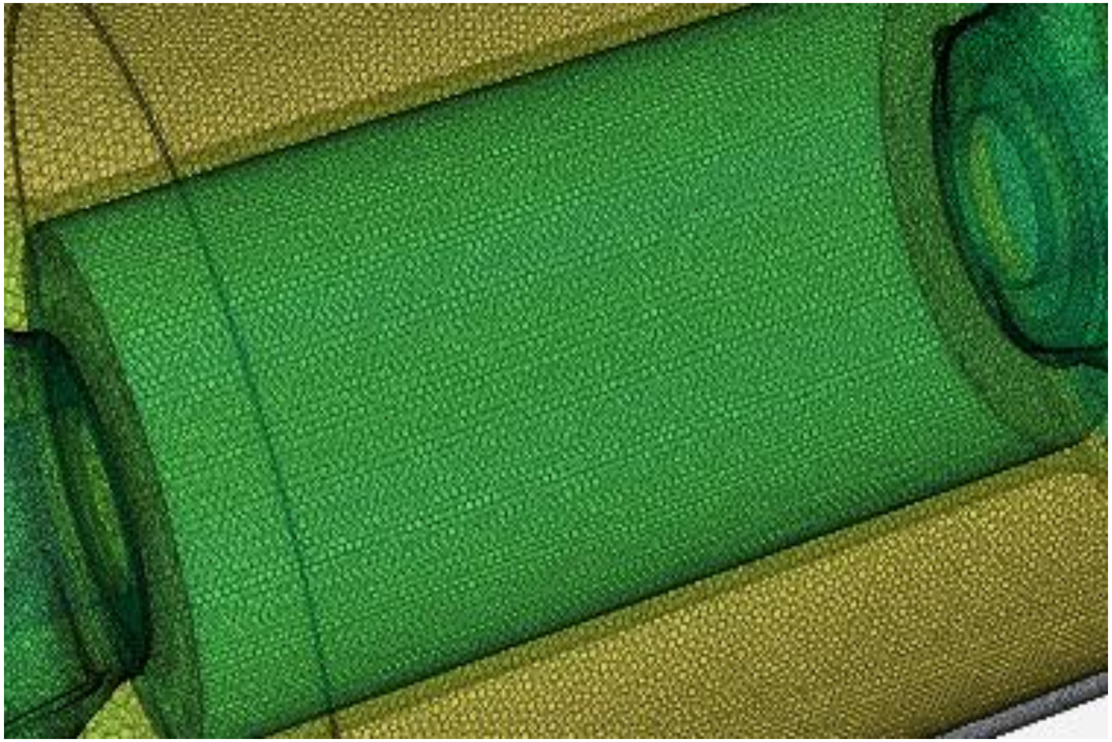
VOLUMETRIC HEAT GENERATION, 250 W

AIR SUPPLY EXIT,

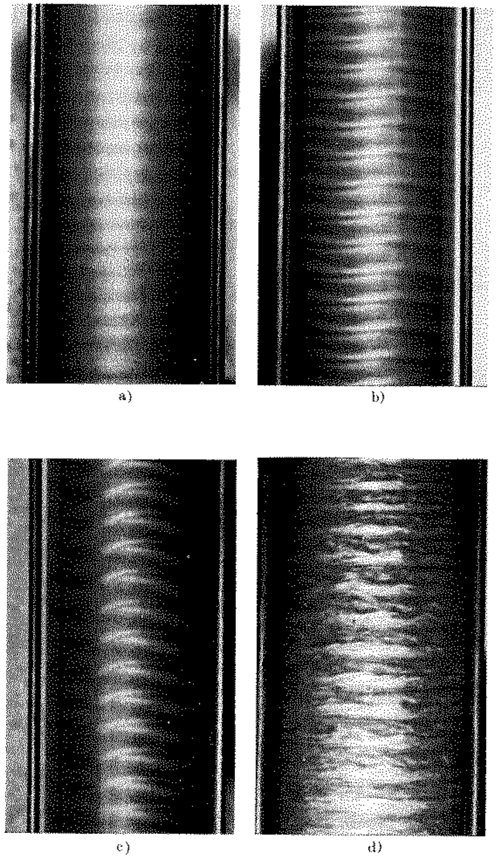
PRESSURE SET AT P=0

TEMPERATURE, 150 °C

Computational Mesh

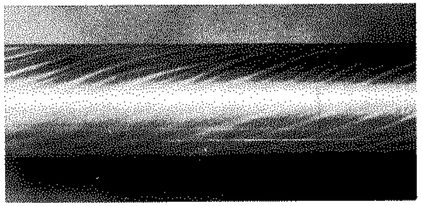


Taylor-Couette Flow History



CF. SCHLICHTING

NO AXIAL FLOW: Taylor vortices for a) Re = 94.5/Ta = 41.3 laminar,onset of vortex formation
b) Re =322/Ta=141 still laminar
c) Re =868/Ta=387 still laminar
d) Re=3960/1715 turbulent



WITH AXIAL FLOW: Unstable flow with vortices in the shape of concentric, rotating cylinders with axial motion. Axial vel. = 37, tangent vel. = 1.58
Axial/Tangent Vel. = 37/1.58 =23.4 CF. SCHLICHTING

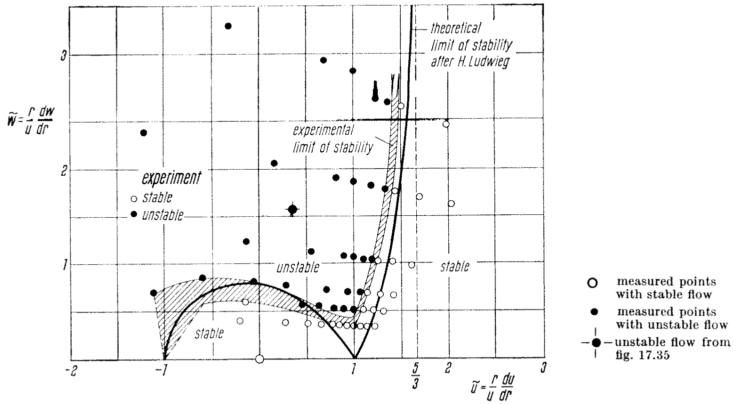
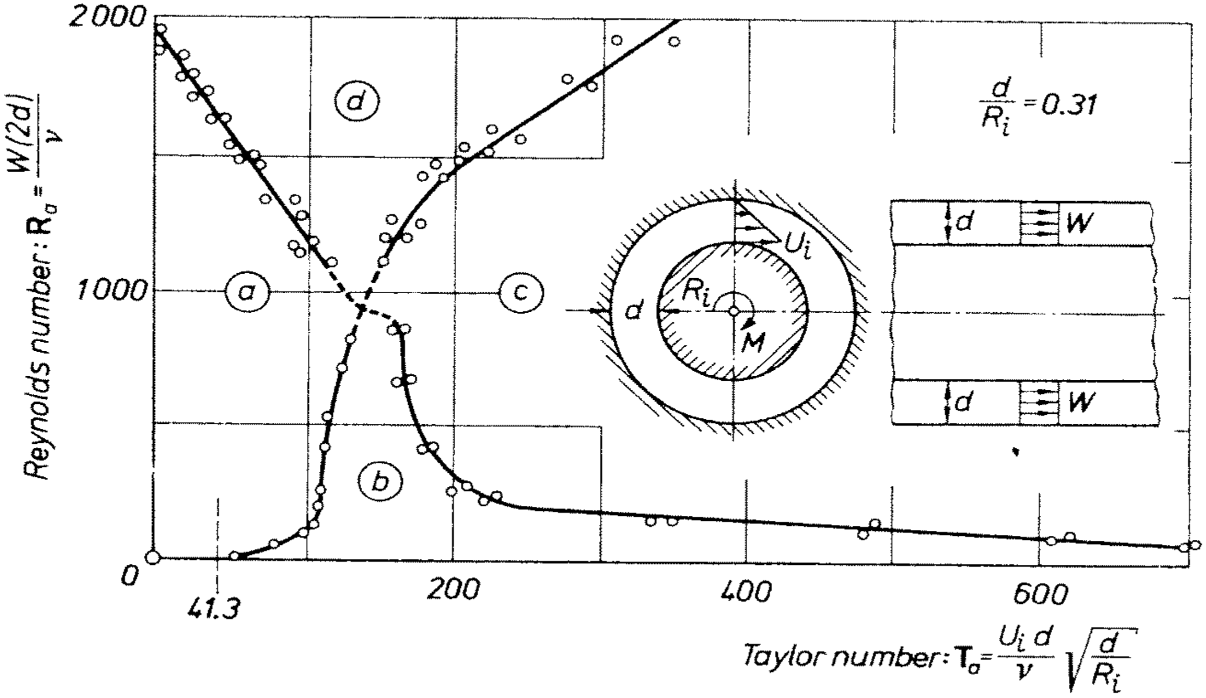


Fig. 17.36. Experimental verification of the stability theory for flow between two concentric, rotating cylinders with axial motion superimposed, after H. Ludwieg [134]
$R = (R_0 - R_i)^2 \omega_i / \nu = 650$
Full curve: limit of stability, according to eqn. (17.23)
Shaded area: experimentally determined limit of stability

CF. SCHLICHTING

CURRENT CFD:
R_o=27.89 mm
R_i=24.78 mm
ω=9950 rad/sec
ν=1.51E-5 m^2/sec
R=$(0.00311)^2$9950/1.51e-5=6373
Vt = 247 m/s, Va = 18.43 m/s,
Axial/Tangent = 18.43/247 = 0.075 (7.5%), thus stable

Re/Ta Flow Regime for Taylor-Couette-Posieuille Flow



ALL CFD FLOWS

CONSIDERED

HEREIN LIE IN

VERY LARGE TAYLOR/REYNOLDS

TURBULENT +VORTICES

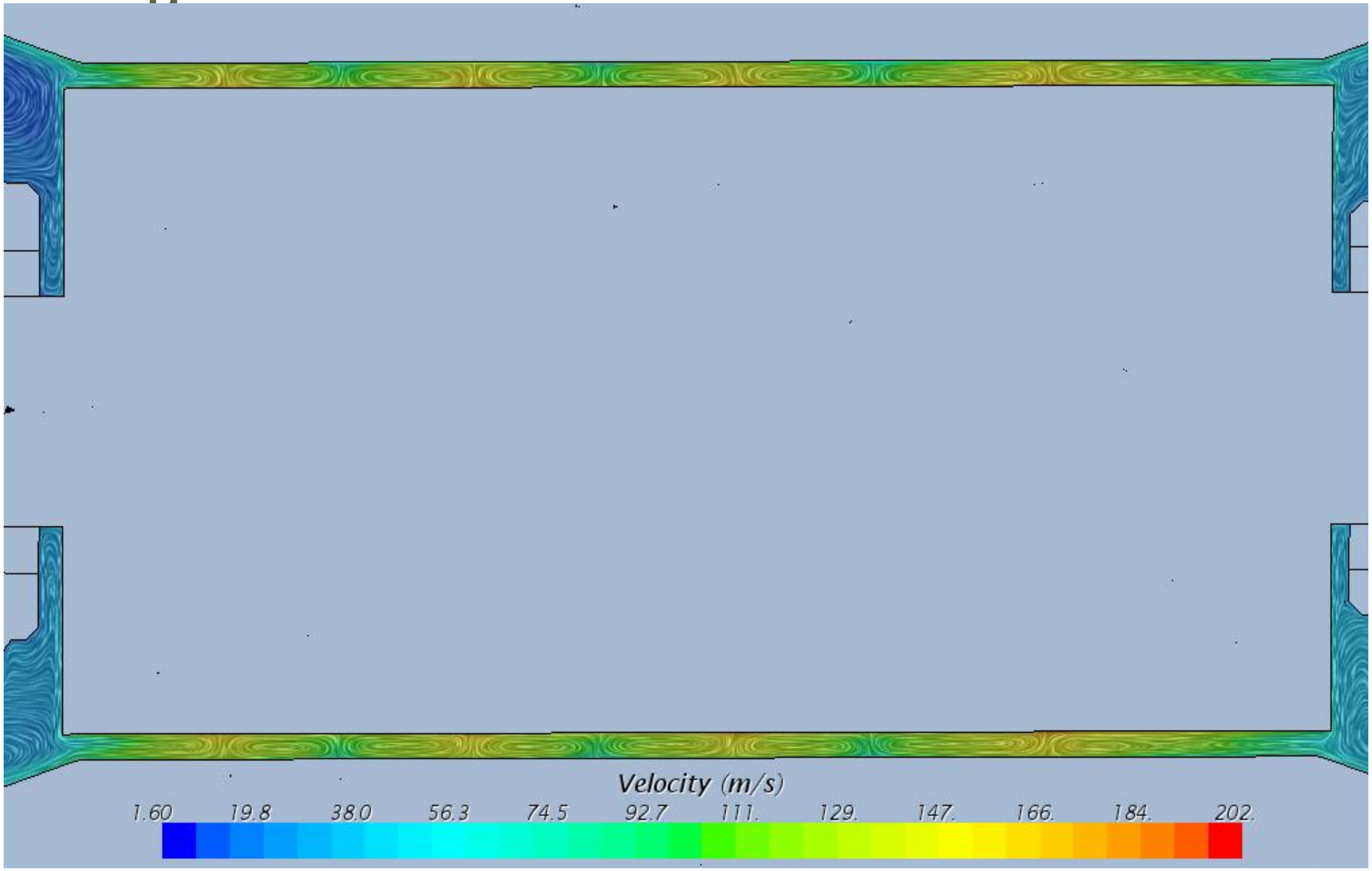
REGION

CF: Schlichting, H. (1935)

Laminar flow, b. laminar flow with Taylor vortices, c. turbulent flow with vortices, d. turbulent flow

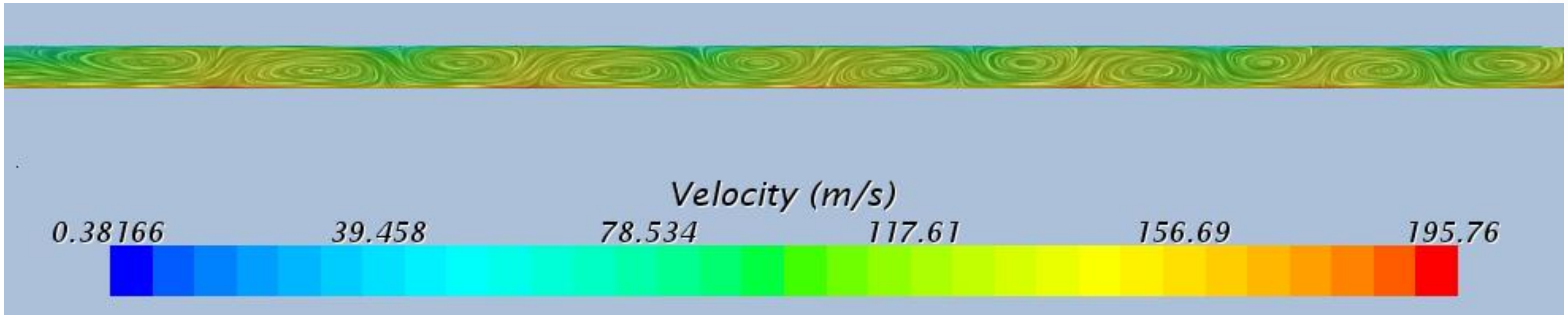
Taylor Cells

$Re_a = 7.59\times10^3$, $Ta = 3.24\times10^8$

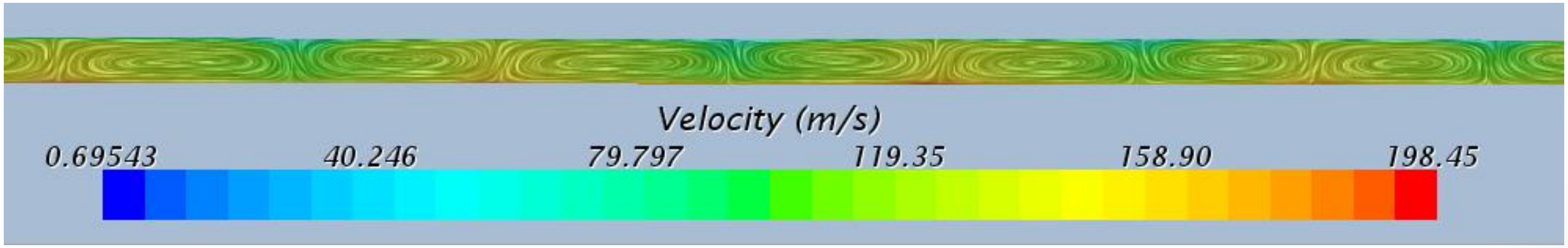


Effect of Inlet Mass Flow on Vortices Structure

No Axial Flow:

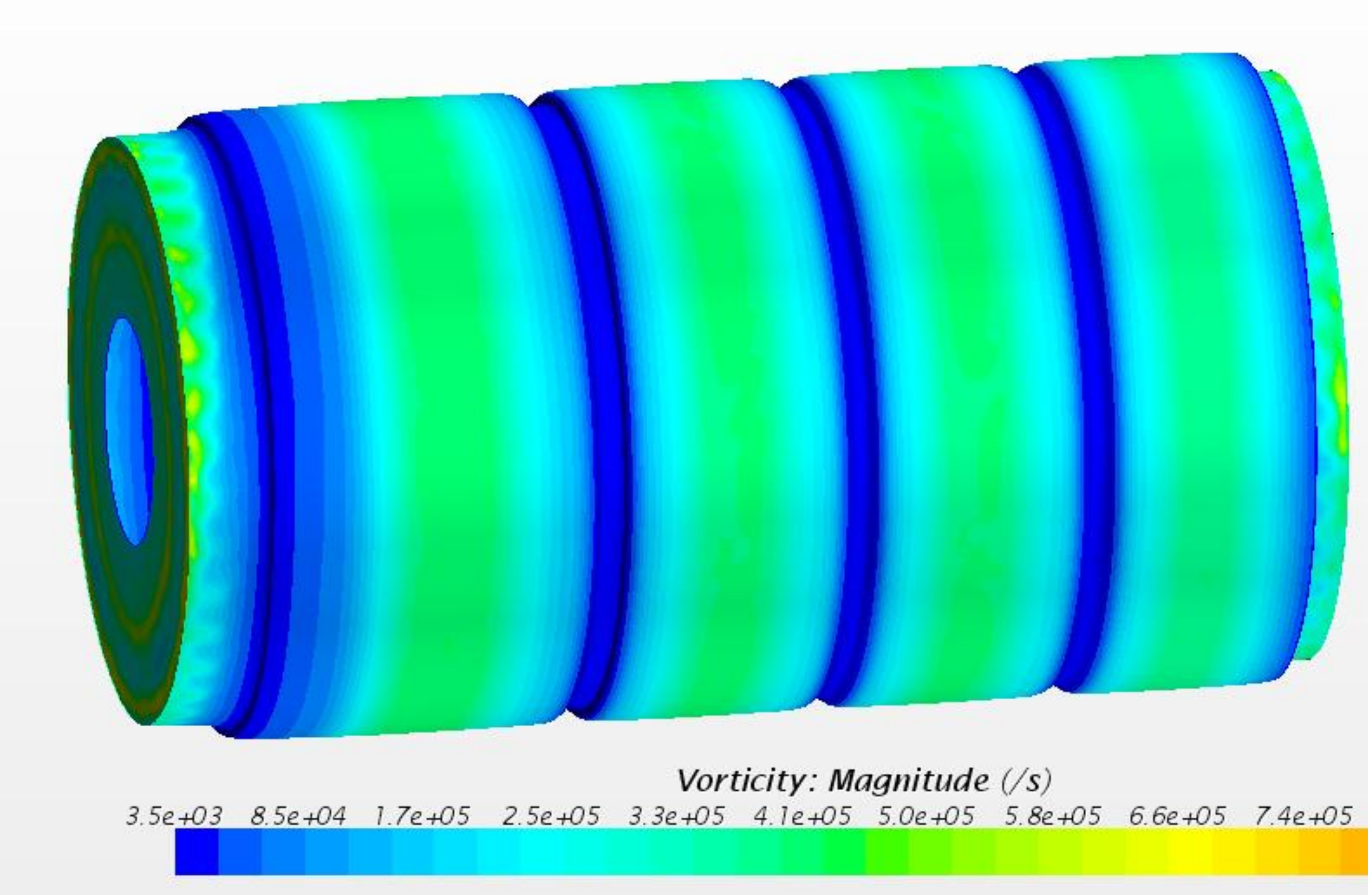


Nominal Axial Flow:

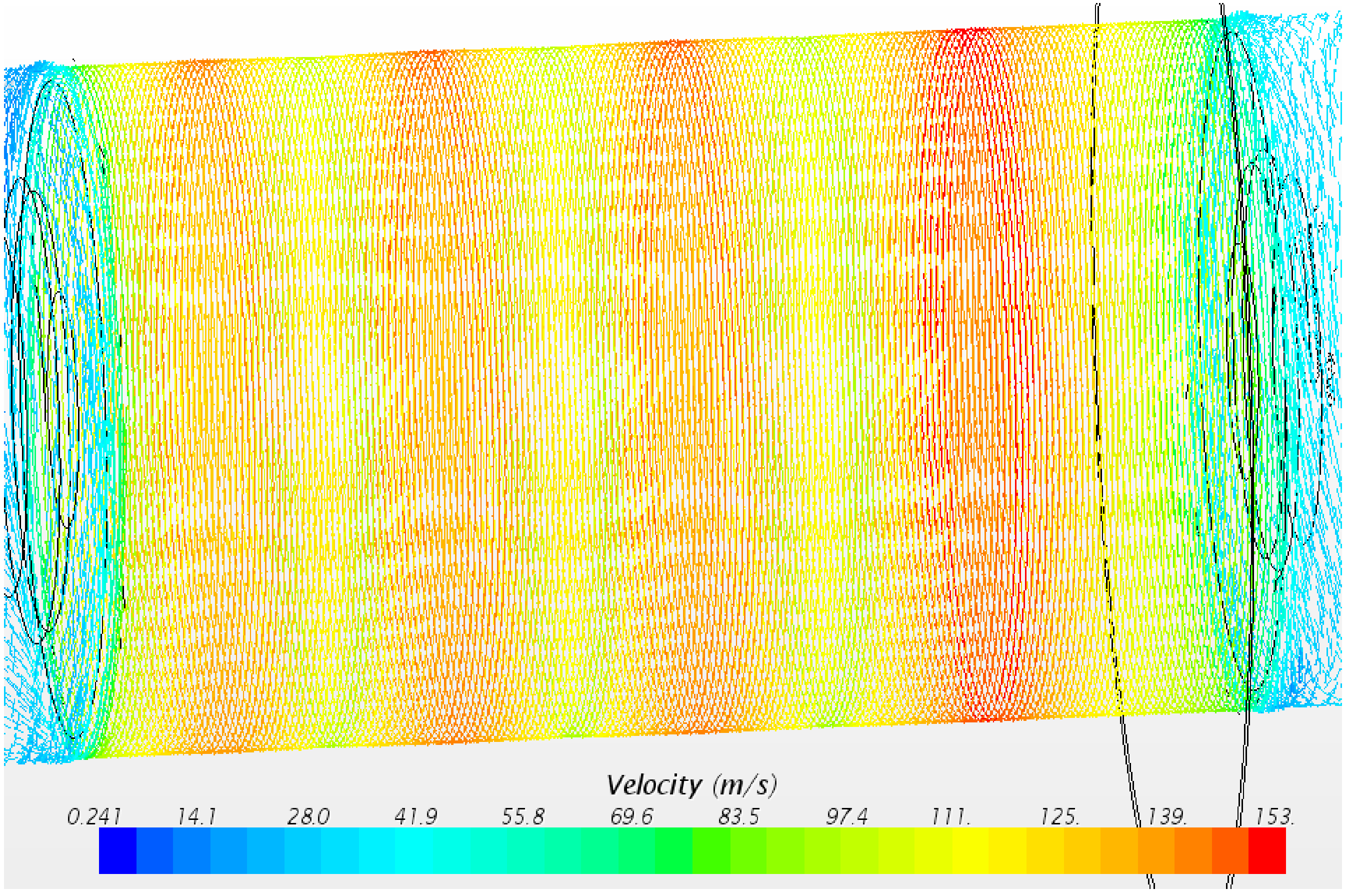


Taylor cells become rectangular versus circular as axial cross-flow rate is increased which is consistent with the published literature

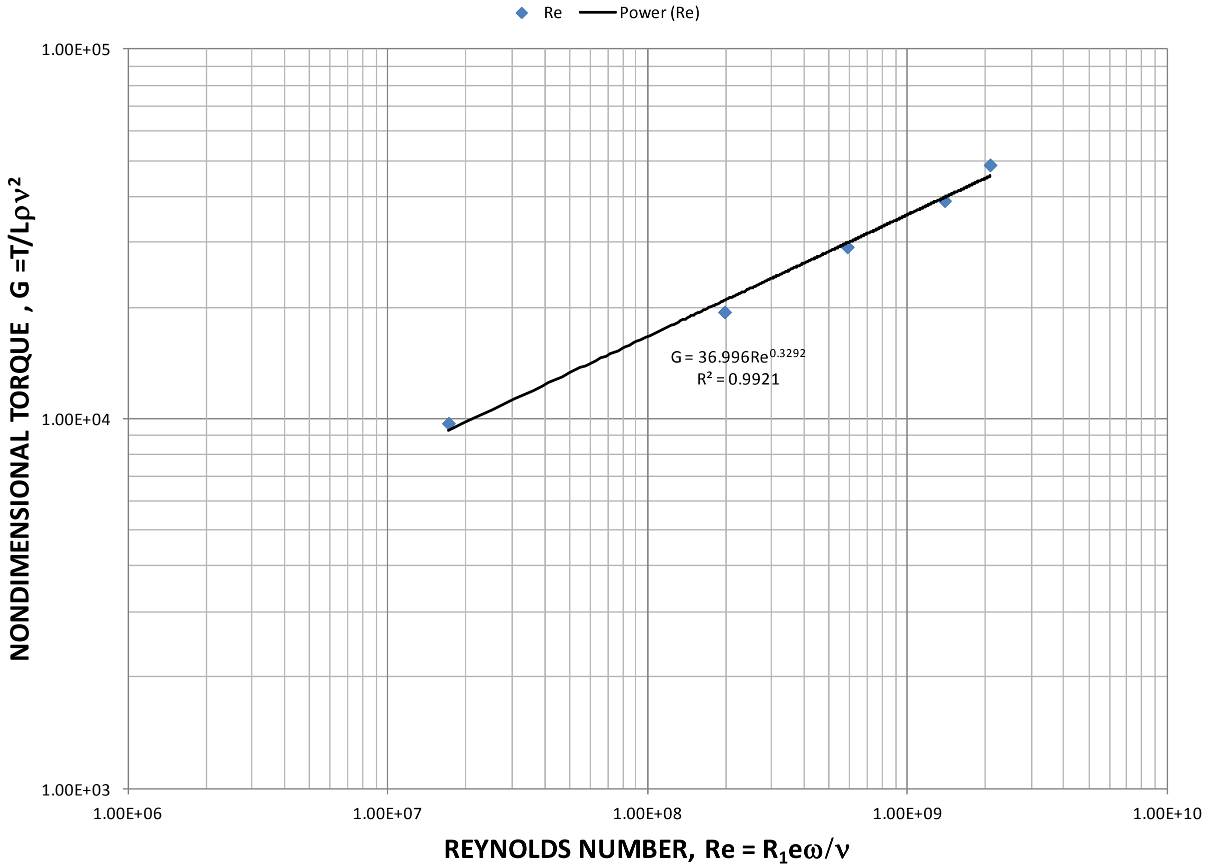
Iso-vorticity contours for $Re_a = 7.59\times10^3$, $Ta = 3.24\times10^8$



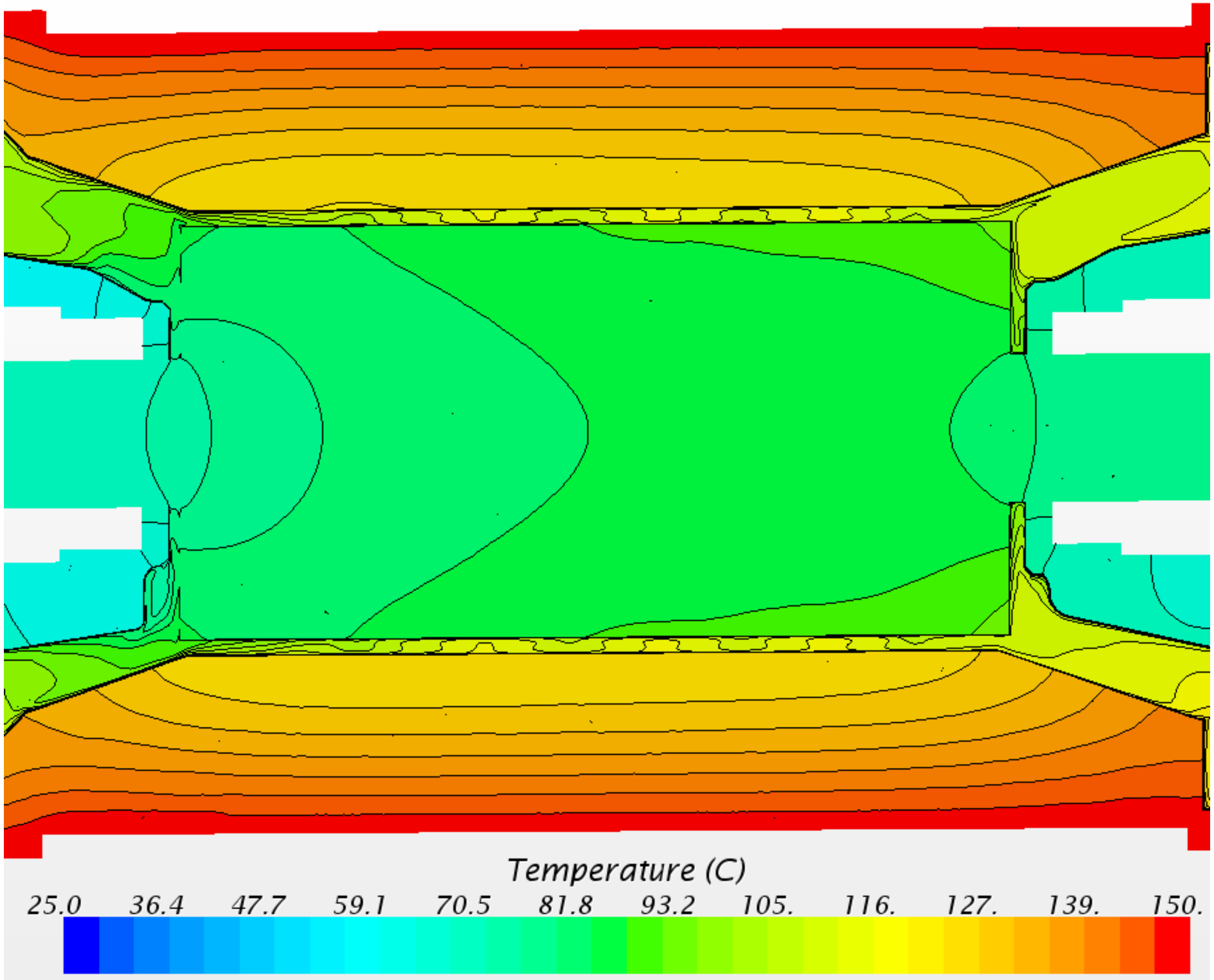
Velocity vectors for $Re_a = 7.59\times10^3$, $Ta = 3.24\times10^8$



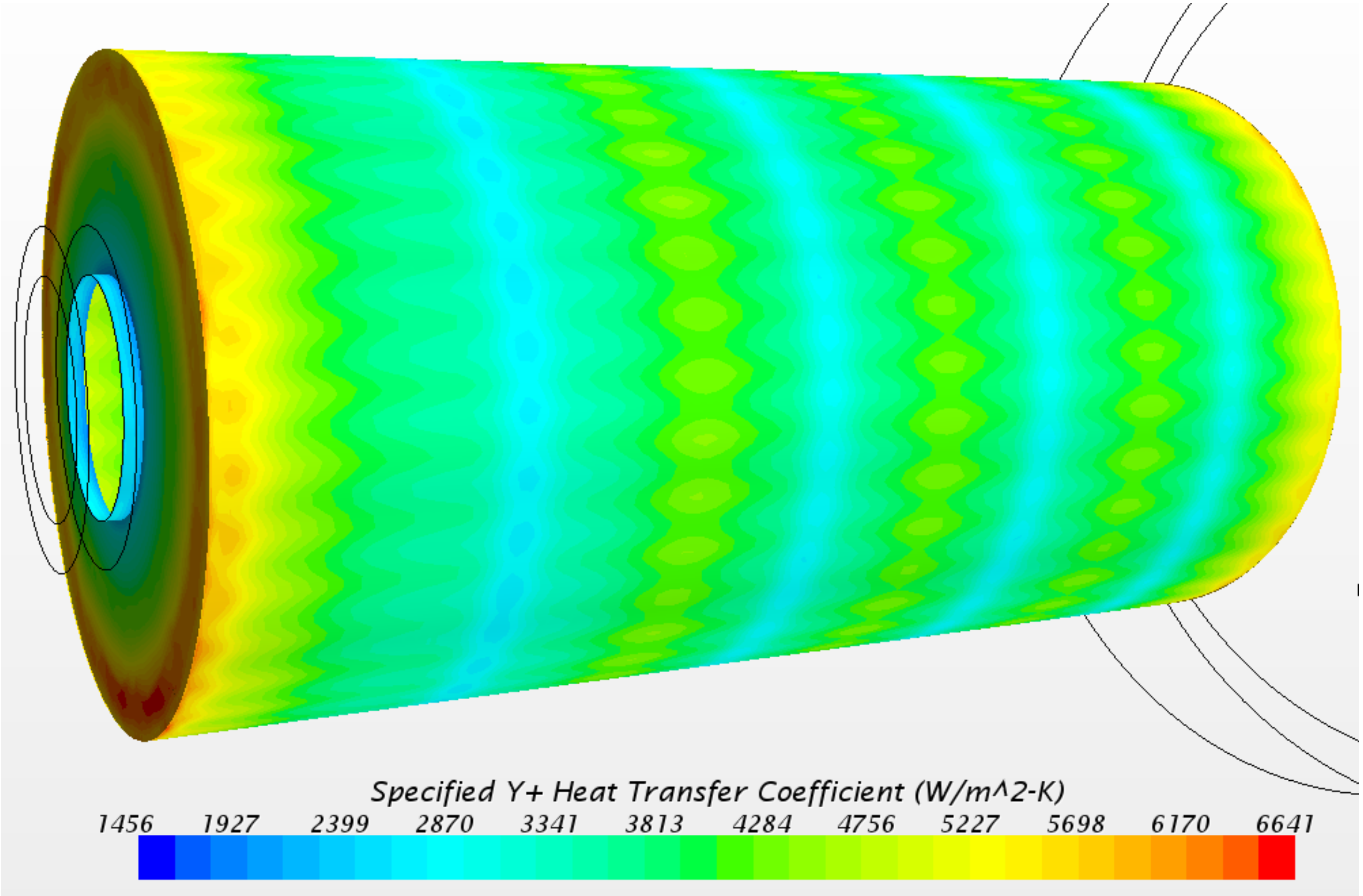
Non-dimensional Torque vs. Reynold's Number



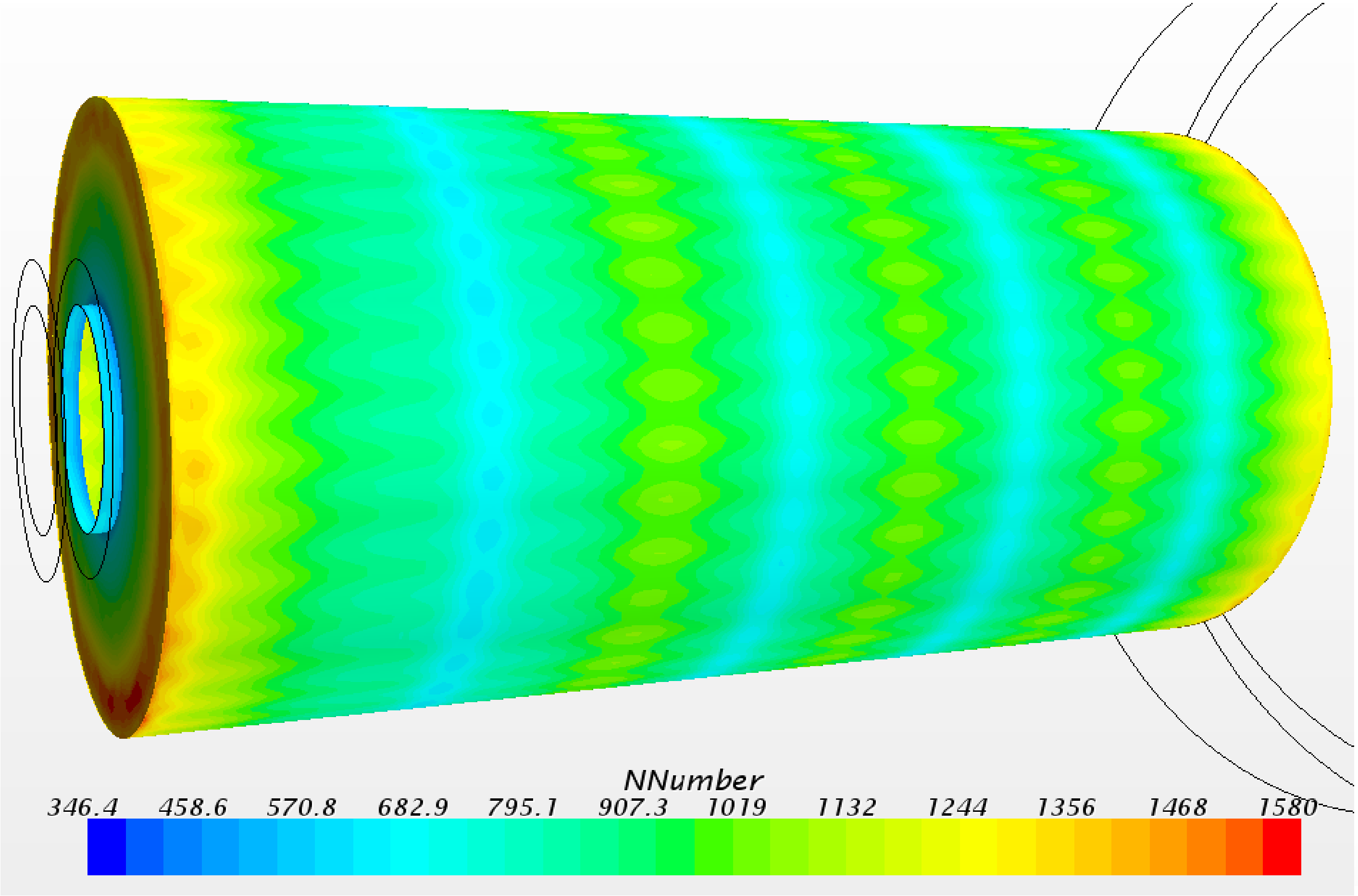
Isotherms for $Re_a = 7.59\times10^3$, $Ta = 3.24\times10^8$



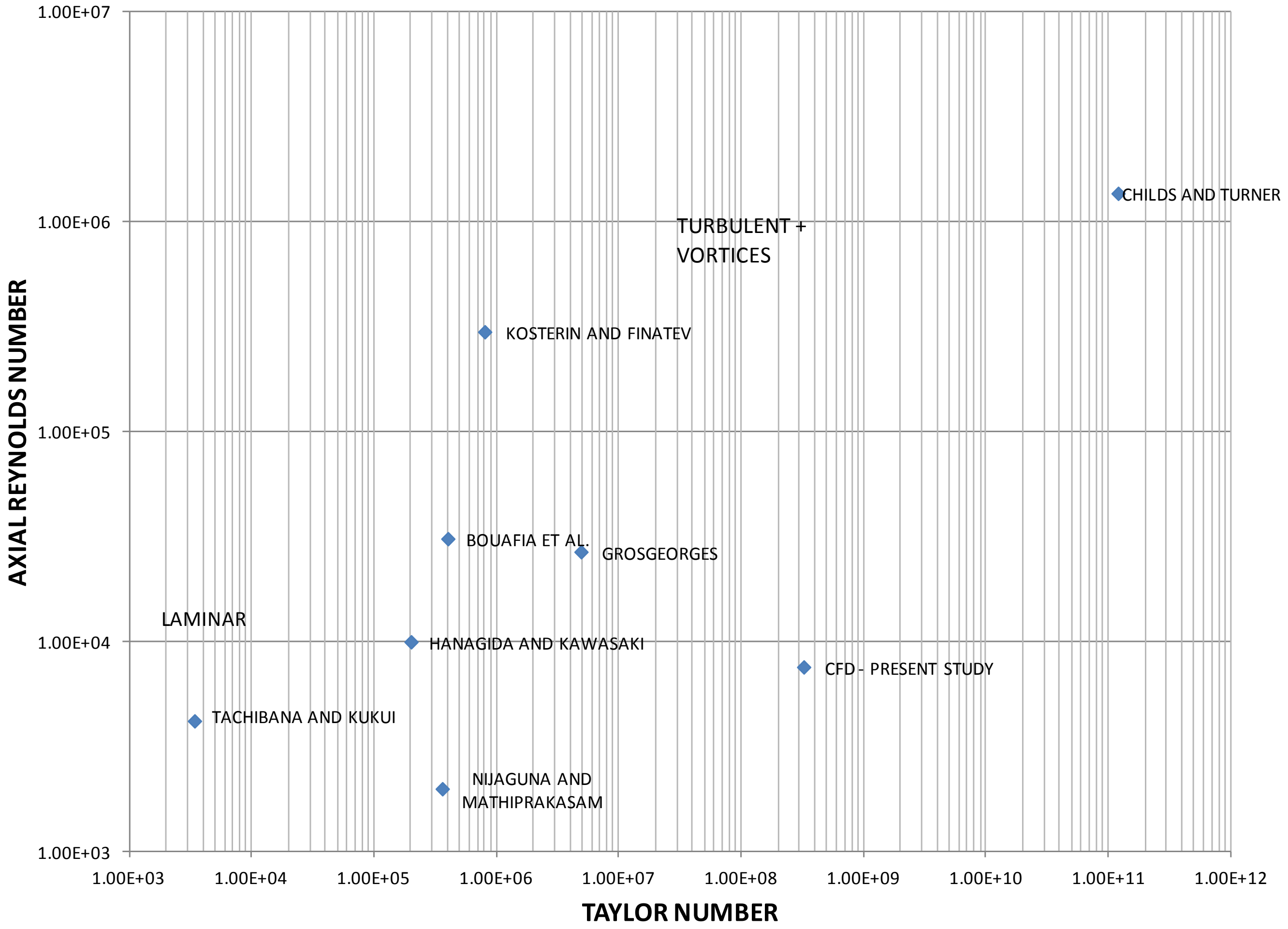
Local User Specified y+ HTC for $Re_a = 7.59\times10^3$, $Ta = 3.24\times10^8$



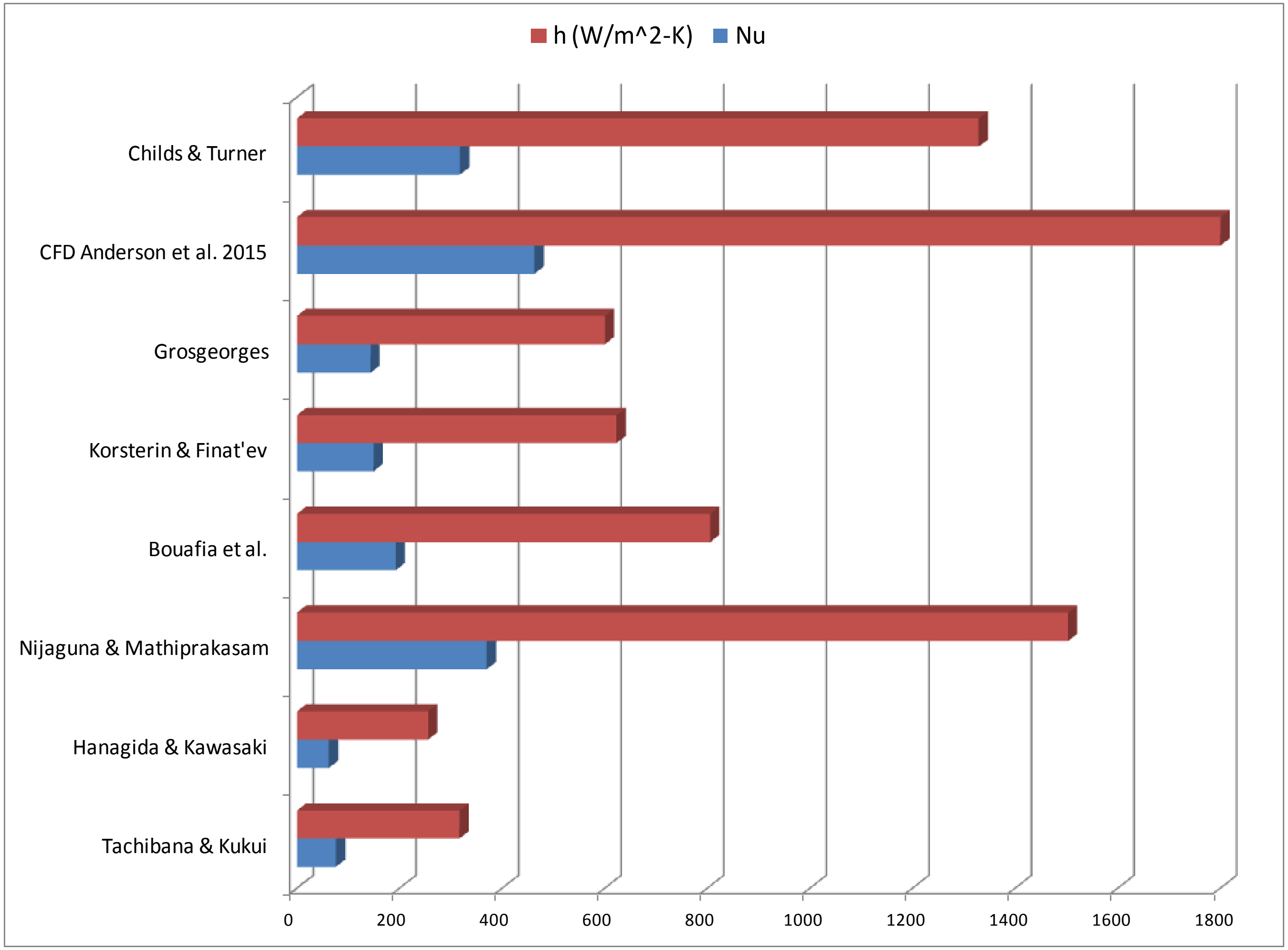
Local Nusselt Number based on User Specified y+ HTC for $Re_a = 7.59\times10^3$, $Ta = 3.24\times10^8$



Re/Ta Flow Regime for Literature & Current Study



HTC/Nu Comparison of Literature & Current Study

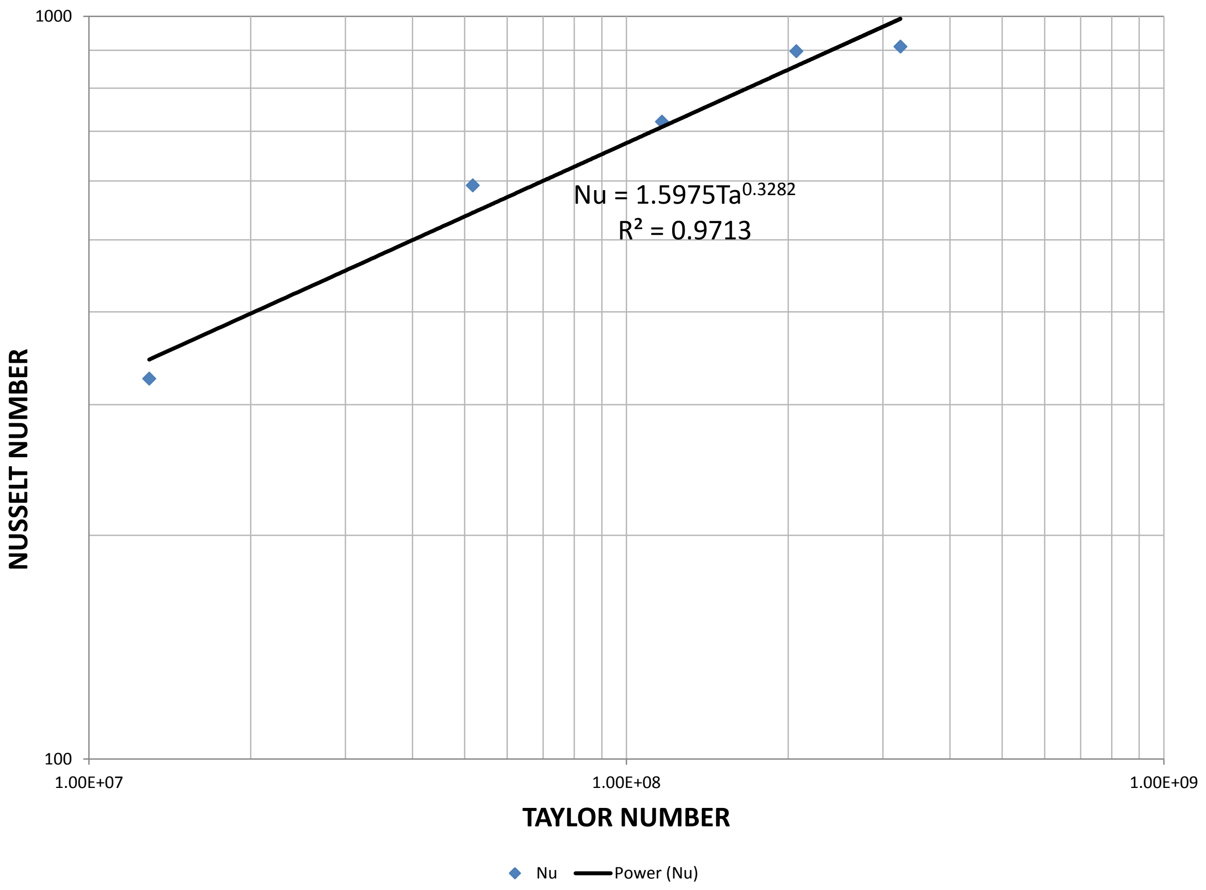


HTC Comparison

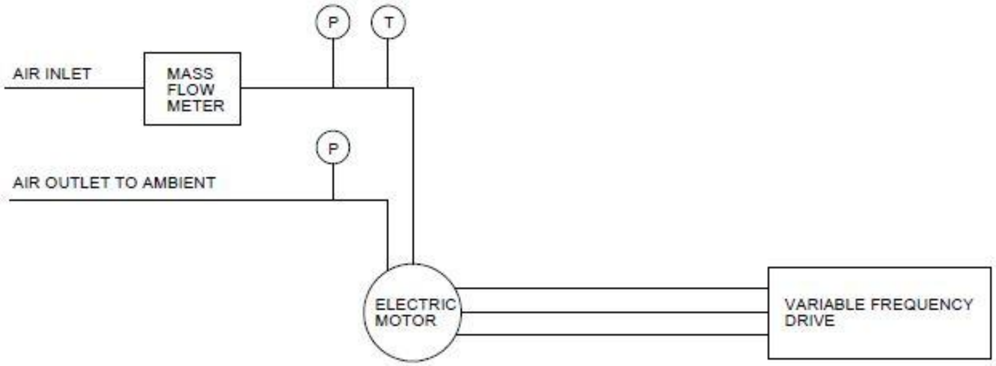
Table 2 Heat transfer correlation comparison

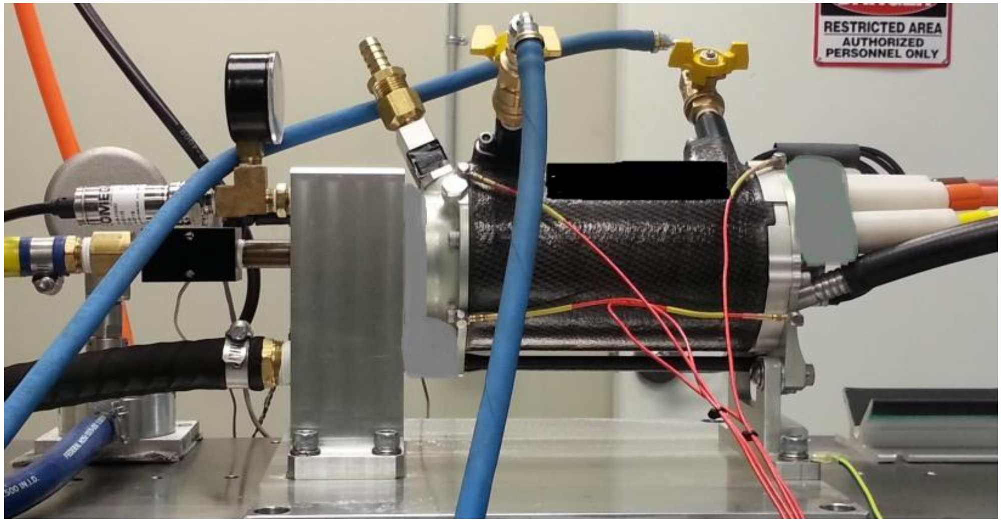
Correlation	Radius ratio $\eta = R_1/R_2$	Cylindrical gap ratio, $\phi = e/R_1$ $e = R_2 - R_1$	Axial ratio, $\Gamma = L/(R_2 - R_1)$	Axial Reynolds Number $Re_a = V_a D_h/\nu$	Taylor Number, $Ta = \omega^3 R_1 e^3/\nu^2$	Nusselt number, *Nu*	Heat Transfer Coeff.,*h* (W/m^2-K)
Tachibana and Kukui (1964)	0.937	0.1700	11.3	4.2×10^3	3.4×10^3	76	317
Hanagida and Kawasaki (1992)	0.990	0.0094	283.0	1.00×10^4	2.0×10^5	62	256
Nijaguna and Mathiprakasam (1982)	0.750	0.1650	195.0	2.00×10^3	3.6×10^5	370	256
Bouafia et al. (1998)	0.956	0.0450	98.4	3.1×10^4	4.0×10^5	193	805
Korsterin and Finat’ev (1963)	0.780	0.0271	77.5	3.0×10^5	8.0×10^5	149	623
Grosgeorge (1983)	0.980	0.0200	200.0	2.69×10^4	4.9×10^6	144	600
Present Study Anderson e al. (2015)	0.888	0.0017	31.7	7.59×10^3	3.24×10^8	463	1800
Childs and Turner (1994)	0.869	0.1500	13.3	1.37×10^6	1.2×10^{11}	318	1329

Nu Number Correlation Proposed by Current Study



Experimental Set-up





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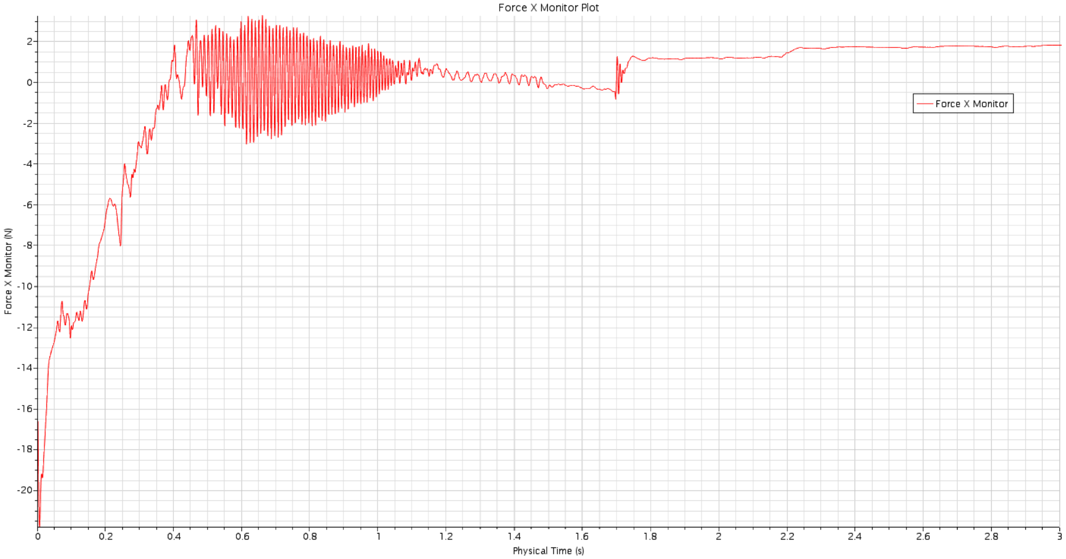
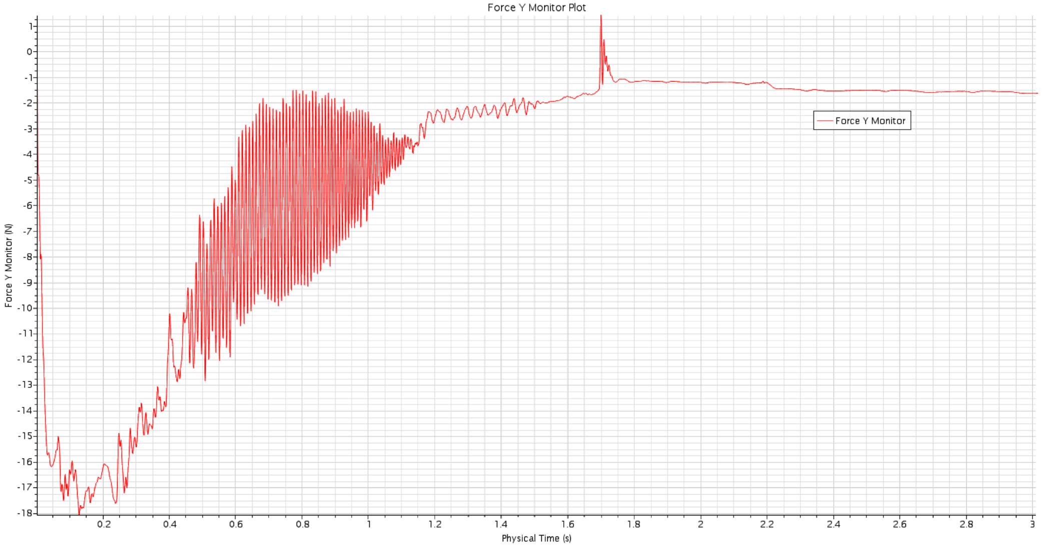
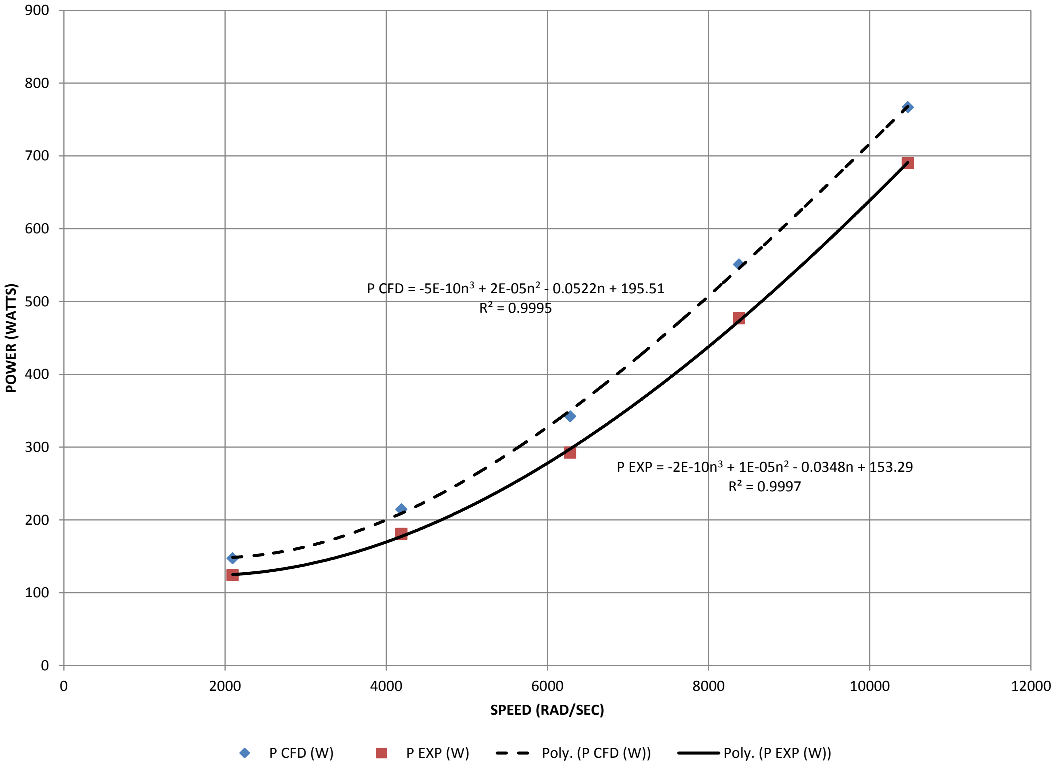
Windage Forces from CFD Model Prediction





Torque vs. Speed Empirical & CFD

Speed RPM	Air inlet Temp. (°C)	Air outlet Temp. (°C)	Air energy outlet (W)	CFD Air outlet Temp. (°C)	CFD air energy outlet (W)	Error (%)
20000	21.8	32.5	124	34.5	147	19
40000	21.5	37.1	181	40.0	215	19
60000	21.5	46.7	292	51.0	342	17
80000	21.5	62.6	477	68.7	551	16
100000	21.9	81.4	690	87.8	767	11



Conclusions

- CFD Model for Air-cooling of a high-speed electronic motor has been presented
- The CFD replicates the expected Taylor-Couette-Poiseuille flow, as expected
- Non-dimensional torque vs. rotational Reynolds number trend agrees with published literature
- HTC and Nu was compared to several published correlations for rotor/stator configuration subject to heat transfer and air-cooling
- Nu vs. Ta number correlation proposed herein extends to the narrow gap, large Taylor number, large axial Reynolds number flows studied herein
- Windage losses from CFD are in agreement with test data, thus CFD can be used to predict efficiency trends in the motor