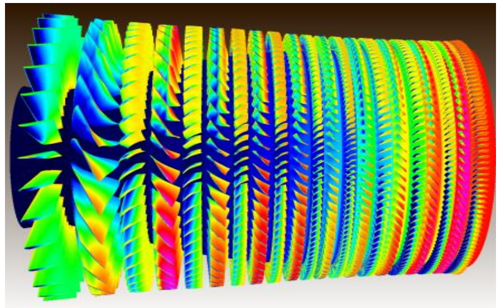
# Bioinspired Heat Exchanger Design for Electric Aircraft

April 28, 2020

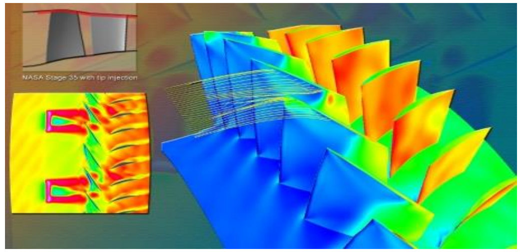
Ezra McNichols
NASA Glenn Research Center
Turbomachinery and Turboelectric Systems

# Turbomachinery and Turbo-Electric Systems Branch Overview

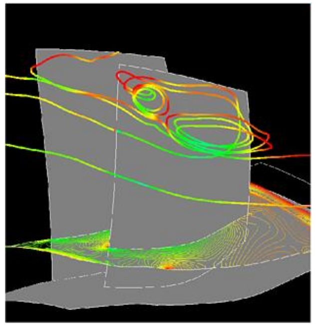
## Numerical Methods:

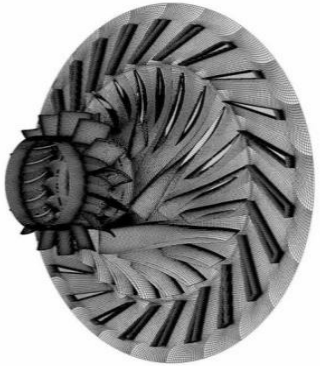


- **Multistage Flow Physics**

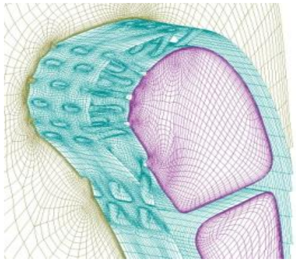


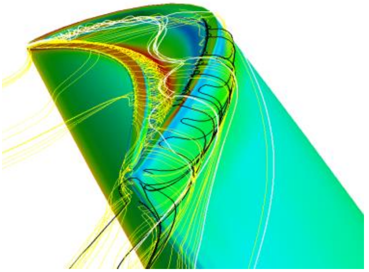

- **Advanced Concept Simulation**

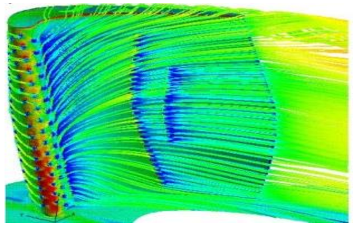




- **Axial & Centrifugal Configurations**







**Turbine Aero / Conjugate Heat Transfer / Film Cooling**

**Turbomachinery Aerodynamics Codes** Analysis and Design of Turbomachinery:

Compressor, Fan, Turbine, and Pump

- Enabling Technologies Being Developed:
  - Reynolds Averaged Navier-Stokes Solver
  - Large Eddy Simulation, Parallel Process
  - Pre- and Post-Processors
  - Flow Transition; Modeling, Blade Losses
  - Film Cooling; Turbine Coolant Passages

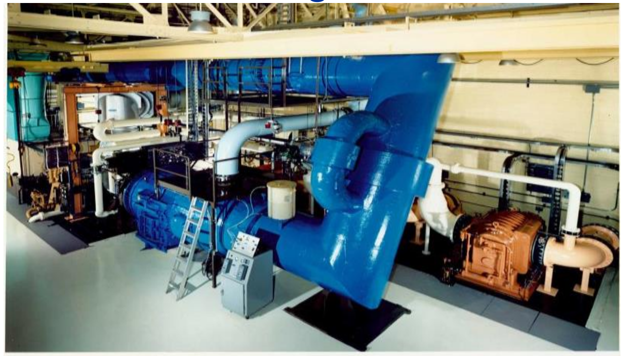
**Advanced Design Concepts:**

- Efficiency Improvement; Reduced Losses
- Compressor Operability; Stall Margin
- Improved Turbine Cooling

**Turbomachinery Testing and Experiments**

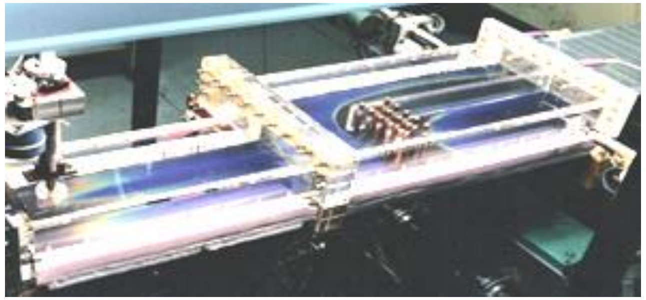
- Multistage Compressor - W7; 15,000 HP
- Low Flow Compressor - CE18; 6,000 HP
- Turbine Test Facility – W6 12,4000 HP
- Single Stage Compressor - W8; 7,000 HP

## Validation Testing



**HP Compressor and Turbine Tests**

**Low Pressure Compressor**



**Laboratory Experiments**

# Biomimicry – Imitation of Life

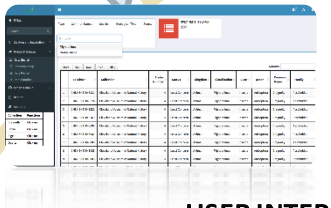
- Life – present and extinct (fossil record)
- Imitation of form, function, culture, environment
- Fossils can be of soft tissue and even surface features can be preserved
  - Quick freezing in permafrost (Siberia)
  - Dehydration (desserts, caves)
  - Encased in tree resin, hardened into amber

# Biomimicry – Rationale

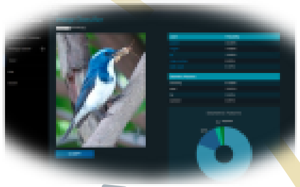
- Life has evolved successful **systems** and technology over 3.8 billion years
- Plenty of free R&D, time-tested
- Life evolves within **earth's operating conditions** - water, energy, gravity, highly nonlinear, dynamic, multifunctional
- Life minimizes energy use to achieve **functionality** (structure, propulsion etc.

# A map of PeTaL architecture

## Problem Statement
- User looking for functional solution
- User browsing for possibilities
- Some combination



## TRANSLATION TOOLS
- Thesaurus
- Pattern/image classification
- NLP

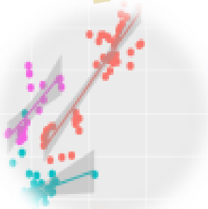


## Computer vision/ML tools
- Clustering
  - Model data
  - Tool clustering
- Composites
- Classification
  - Documents
  - Images
  - Input

## USER INTERFACE
- Website Interface
- Phone app Interface

## Ontology

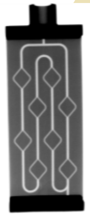
## World Models
- Mapping geolocation to environment
- Mapping geological time, geolocation to species – link to environment
- Climate models
- Atmospheric composition models
- Ocean models…



## VISUALIZATION
- Maps with overlays
- System layout
- Pattern matches
- Plots of data
- Lists of species
- Lists of engineering applications

## Data Gathering and Validation
- Images – 2D and 3D
- Videos
- PDFs
- Csv
- CAD
- Text
- Websites - scraping

## PLATFORM
- Database (MongoDB)
- Language (Python)



Credit: NASA

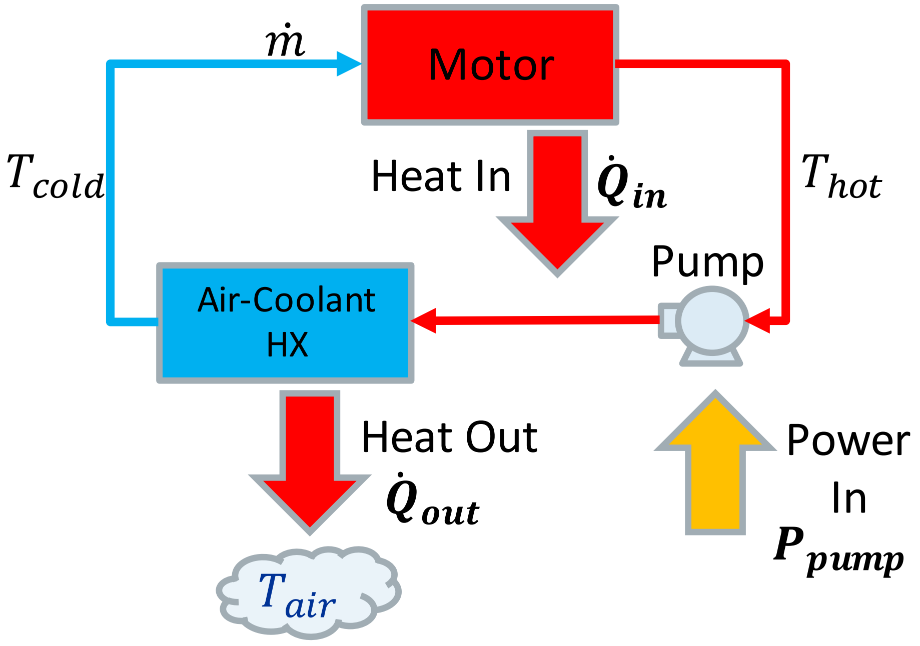
## Technology Synthesis
- Pattern assembly
- Composite sketch
- System analog ID
- Widget options

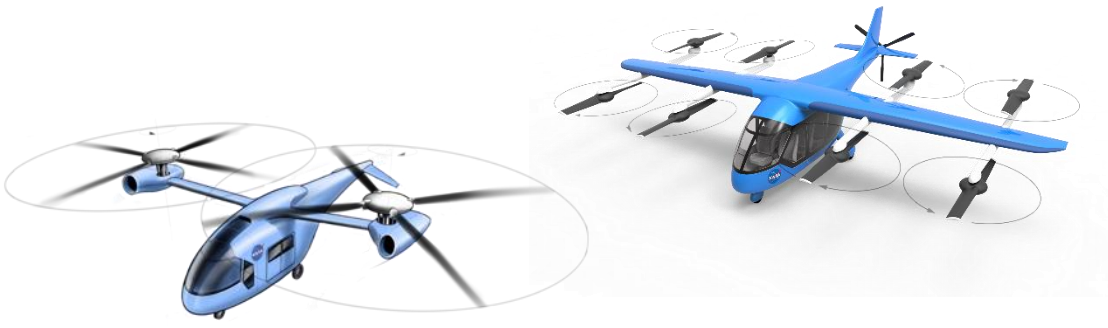


Icons are Creative Commons or from Shyam et al., *Designs* **2019**, *3*(3), 43; https://doi.org/10.3390/designs3030043 - 14 Aug 2019

# RVLT/UAM Thermal Management System Challenges

- **Higher-rated motors require more aggressive cooling approaches** $(\uparrow \dot{Q}_{in})$
  - Require more novel and invasive techniques $(\uparrow complexity)$
- **Large amounts of low-quality heat are generated**
  - Low efficiency components, electronics $(\uparrow \dot{Q}_{in})$
  - Low temperature limits: $60℃ \leq T_{component} \leq 200℃$ $(\downarrow \Delta T_{component})$
- **Potential for heat rejection is reduced at low altitudes (flight altitude at 5-12K)** @$(\downarrow \Delta T_{HX})$
  - Traditional methods would result in large heat exchangers that incur massive drag penalties
- **Component reliability is considerably affected by temperature**
  - Every $10℃$ decrease in component temperature can extend life considerably
  - But this causes the TMS to be more massive and power consuming
- **Aircraft TMS Standards are practically nonexistent**
  - TMS reliability is not easily gauged
  - Design margins not defined (unlike in Space)
  - TMS-specific testing not defined
- **Different vehicle configurations present different and variable challenges**
  - Varying & intense load profile over mission
  - Different flight profiles will determine limits in rejection
  - Physical vehicle constraints may limit components to small spaces, which may lead to greater potential for overheating and higher TMS complexity



Credit: Content Created by Susan Johnson and Hashmatullah Hasseeb (NASA GRC)

# Natural to Engineering Systems with PeTaL

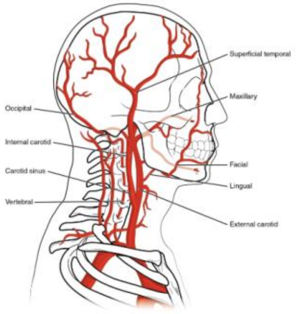
PeTaL starts here

- Large amounts waste heat
- Weight constraints
- Power constraints
- Need high performance heat exchangers that are compact and require minimal power input

Step 1: Problem Statement/analysis

Constraints: things = fluid, solid
Management/distribution of liquids/gases, energy/temperature

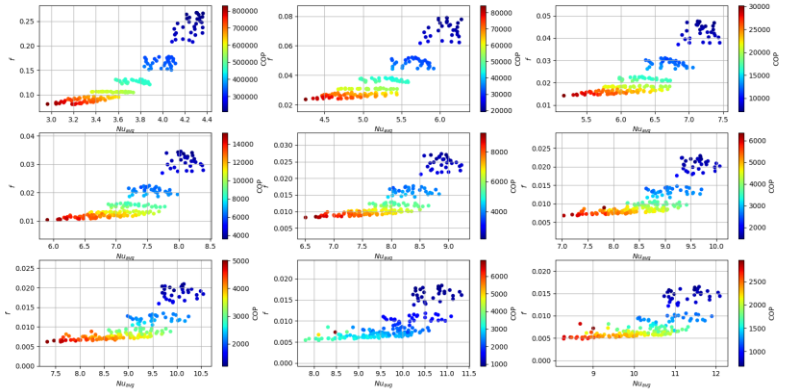
Step 2: Abstraction



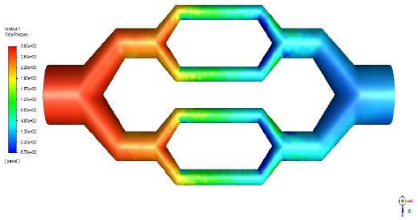



Step 3: Model selection

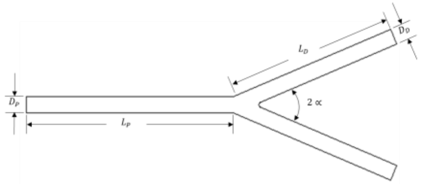
PeTaL ends here



Step 6: Implementation, test, comparison of metrics



Step 5: Transposition to Technology



Step 4: Selection and Abstraction

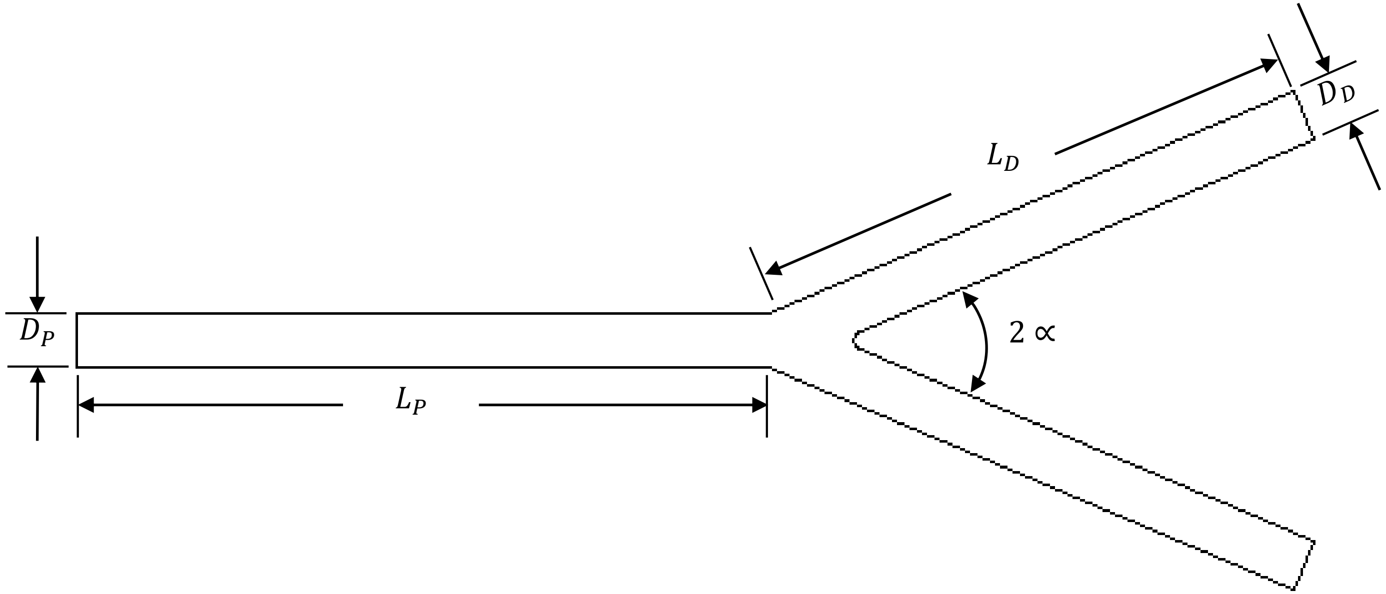
# Fractal Heat Exchangers

- Branching patterns are seen in nature for fluid distribution – do they possess desirable heat transfer characteristics?
- Many studies, both numerical and experimental, have been conducted on these geometries
  - For a detailed review on fractal heat exchangers, please refer to: *Huang, Zhiwei; Hwang, Yunho; Aute, Vikrant; and Radermacher, Reinhard, "Review of Fractal Heat Exchangers" (2016). International Refrigeration and Air Conditioning Conference. Paper 1725. http://docs.lib.purdue.edu/iracc/1725*
- Can achieve higher heat transfer and lower pressure drop compared to traditional designs (compared to serpentine channel and parallel channel)
- Still need correlations between boundary conditions, geometry, and fluid properties for the thermal and hydrodynamic performance of these structures
- We want to develop these correlations and shorten the time for design
- Start simple, with 2D symmetric layouts

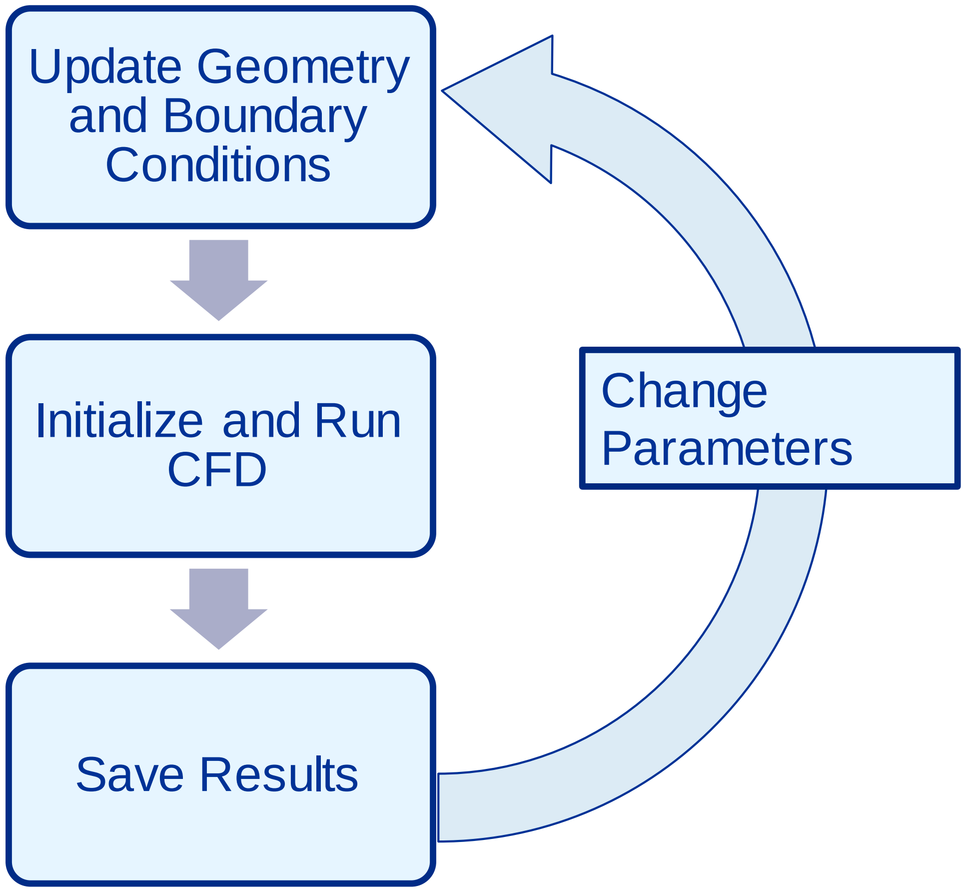
# Step 4: Selection and Abstraction

For simplicity, we did not include fluid property dependence

| Parameter | Range |
|---|---|
| $Re_D$ | 200 - 1800 |
| $D_R = {}^{D_D}/_{D_P}$ | 0.5 - 1 |
| $L_R = {}^{L_D}/_{L_P}$ | 0.5 - 1 |
| α | 0° - 90° |
| $\overline{Nu}$ | |
| $f$ | |

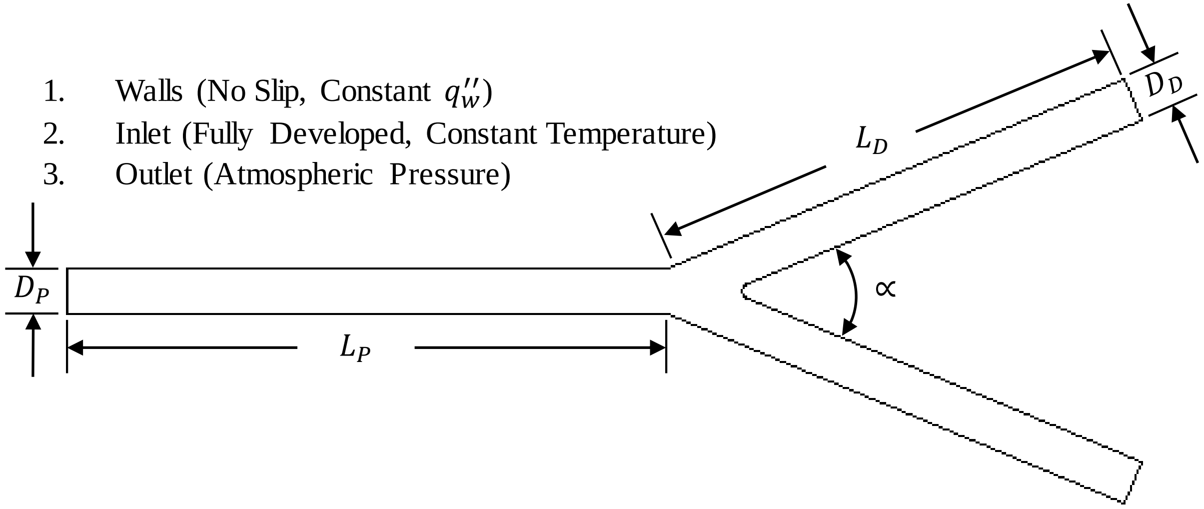


# Step 5: Transposition to Technology (Detailed Analysis)

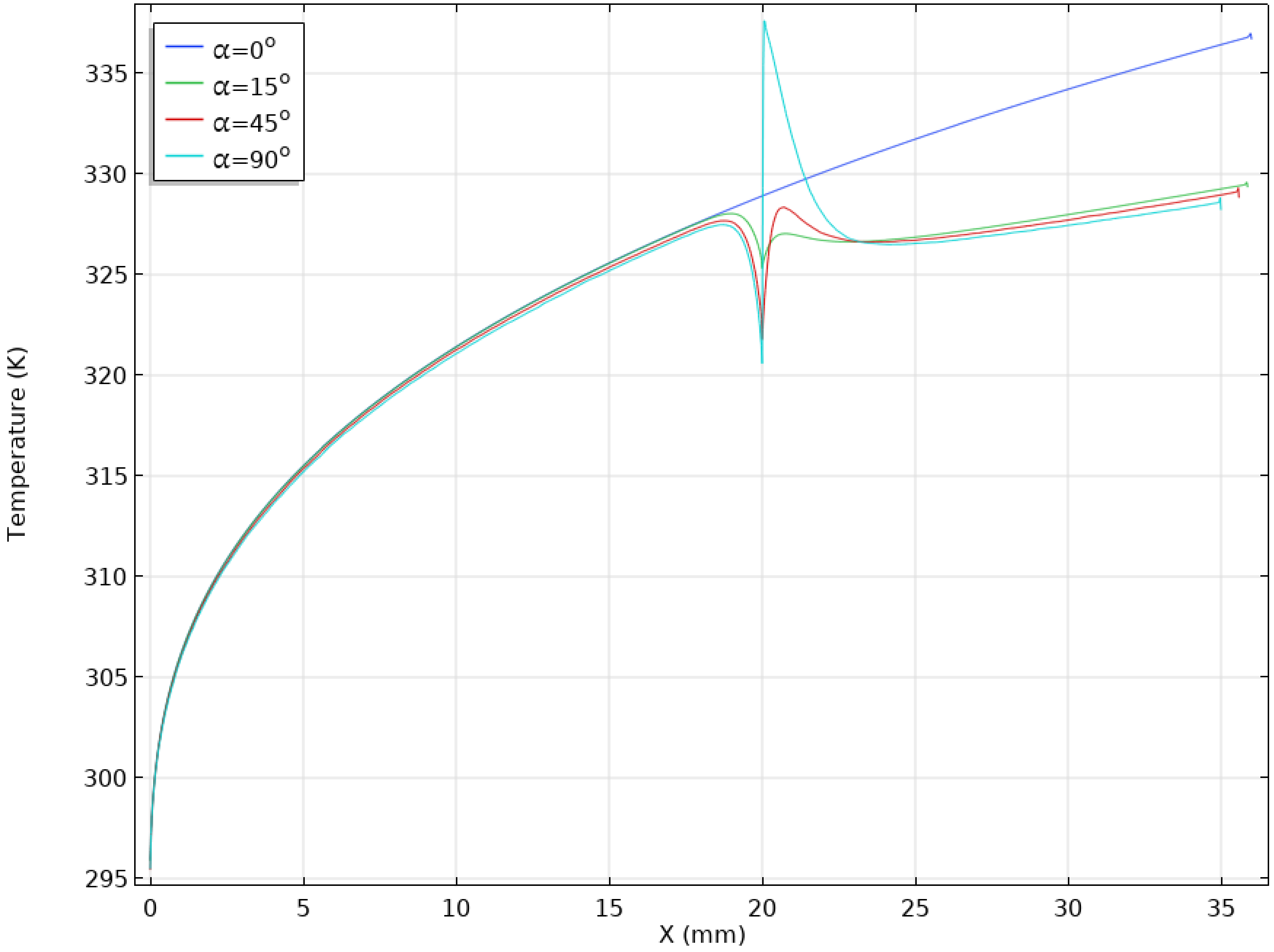



| Parameter | Value |
|---|---|
| $Re_D$ | 200 - 1800 |
| $D_R = {}^{D_D}/_{D_P}$ | 0.5 - 1 |
| $L_R = {}^{L_D}/_{L_P}$ | 0.5 - 1 |
| α | 0° - 90° |

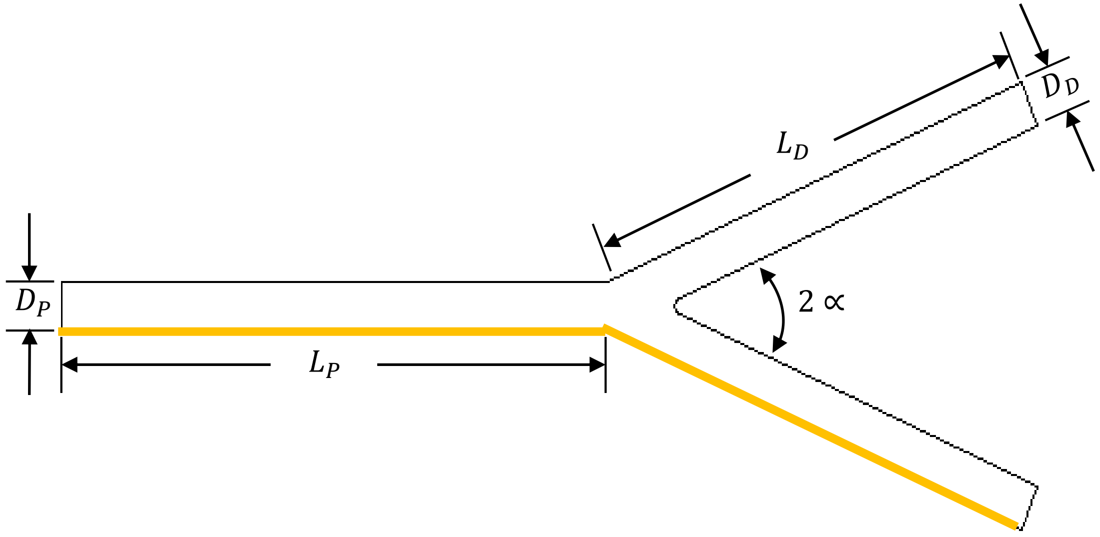
1. Walls (No Slip, Constant $q''_w$)
2. Inlet (Fully Developed, Constant Temperature)
3. Outlet (Atmospheric Pressure)



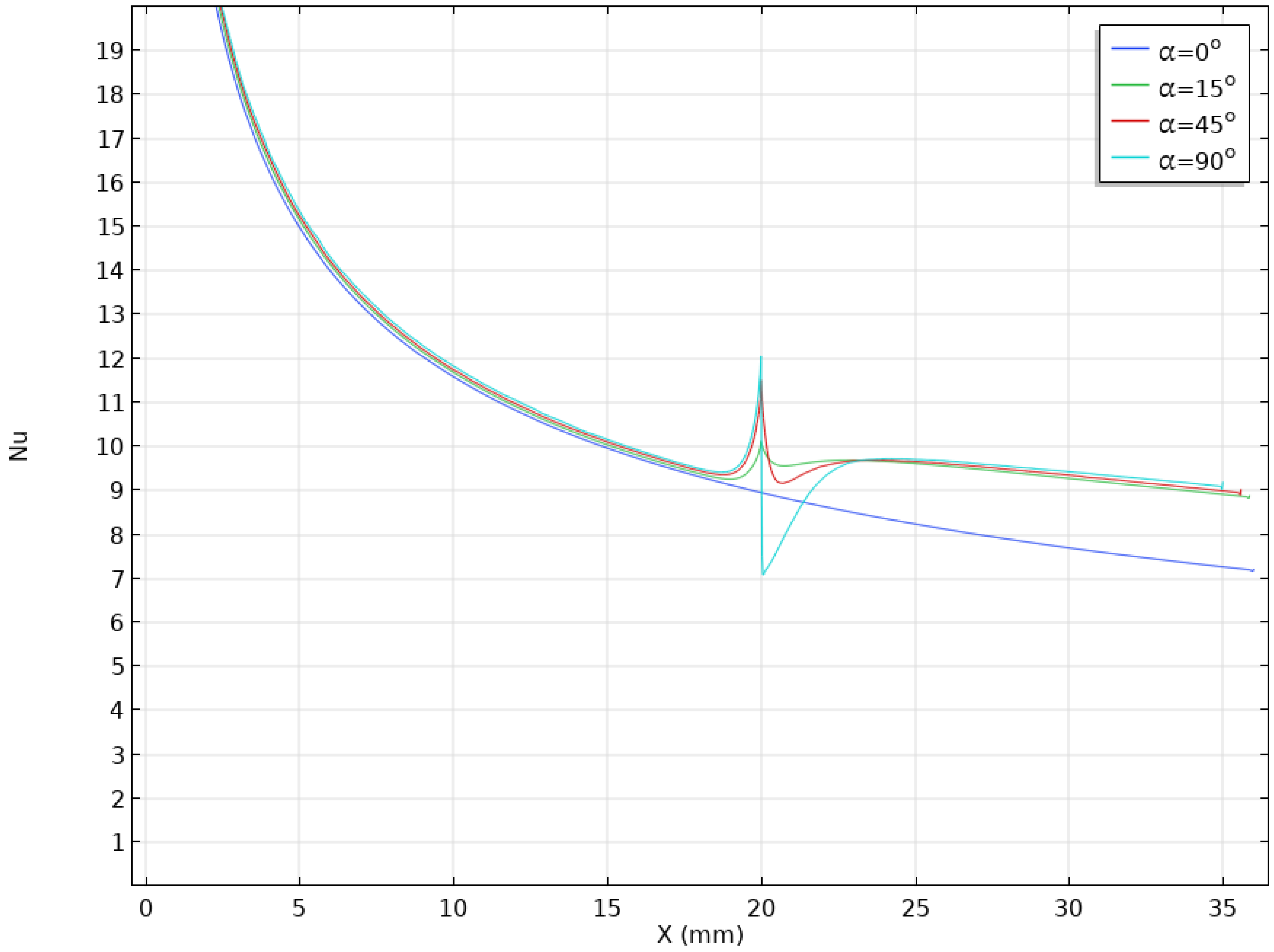
# Effect of Branching Angle – Wall Temperature



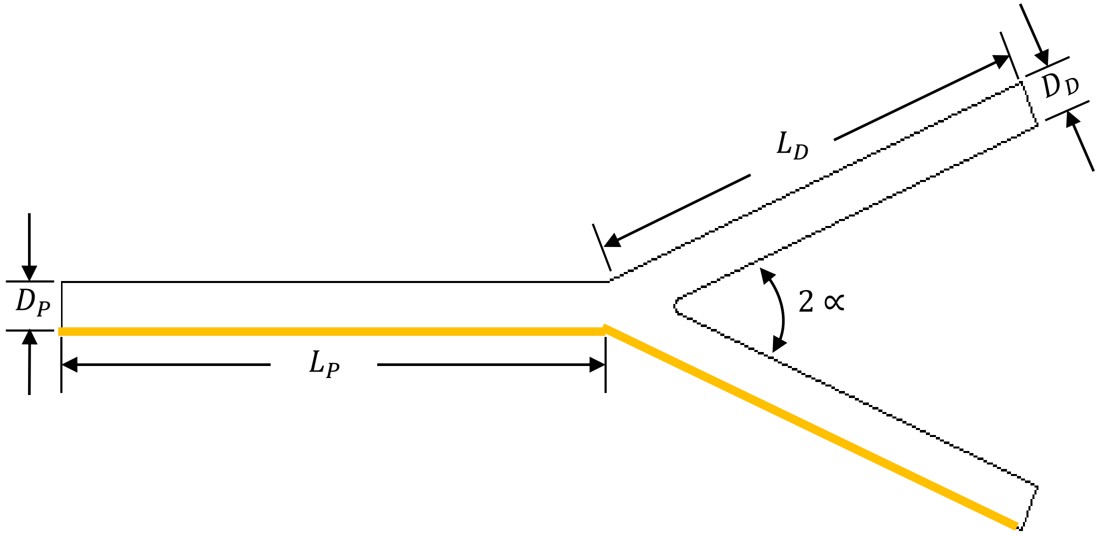

| Parameter | Value |
|---|---|
| $Re_D$ | 1500 |
| $D_R = {}^{D_D}/_{D_P}$ | 0.5 |
| $L_R = {}^{L_D}/_{L_P}$ | 0.8 |
| α | 0° - 90° |



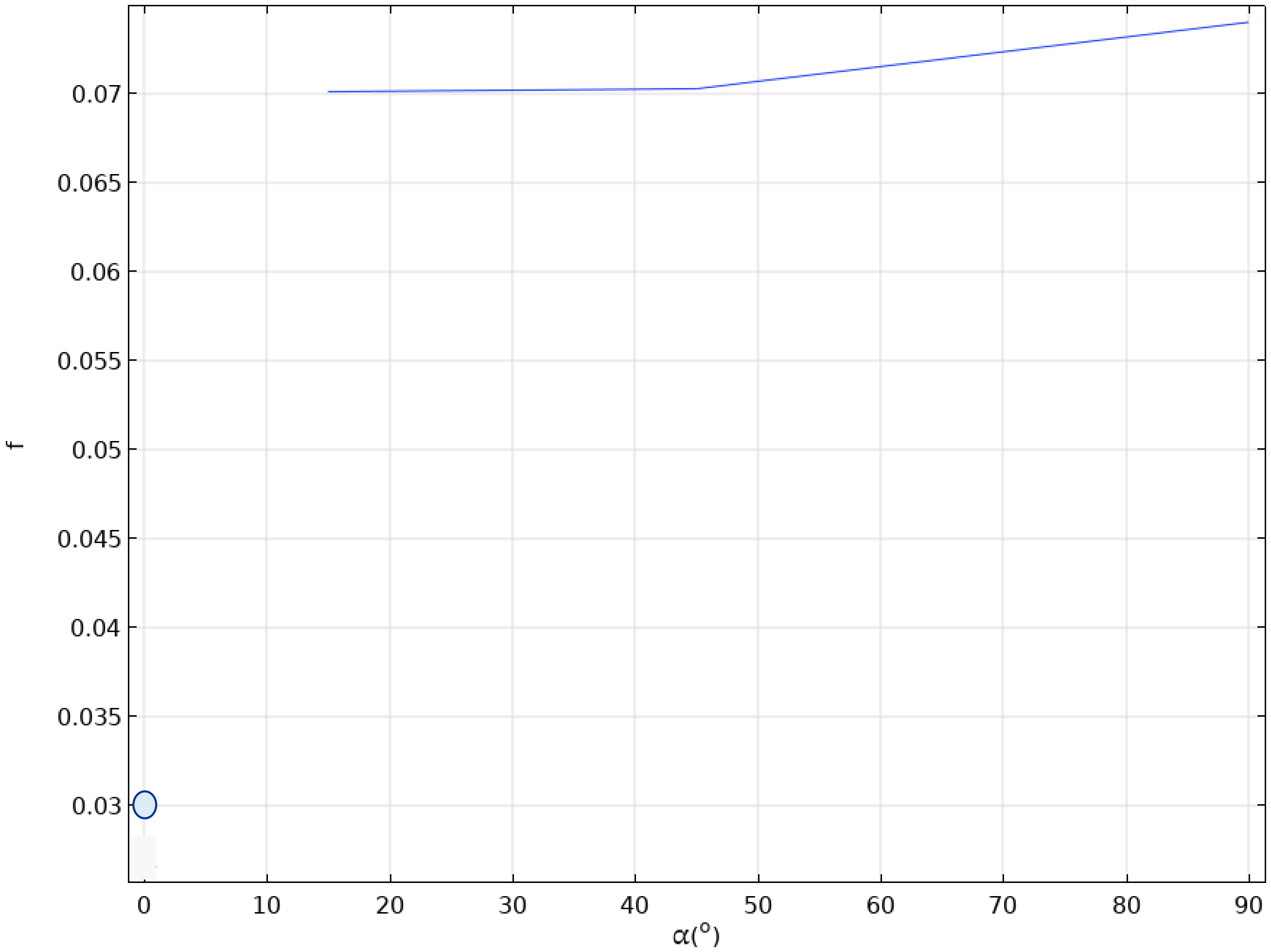
# Effect of Branching Angle – Nusselt Number



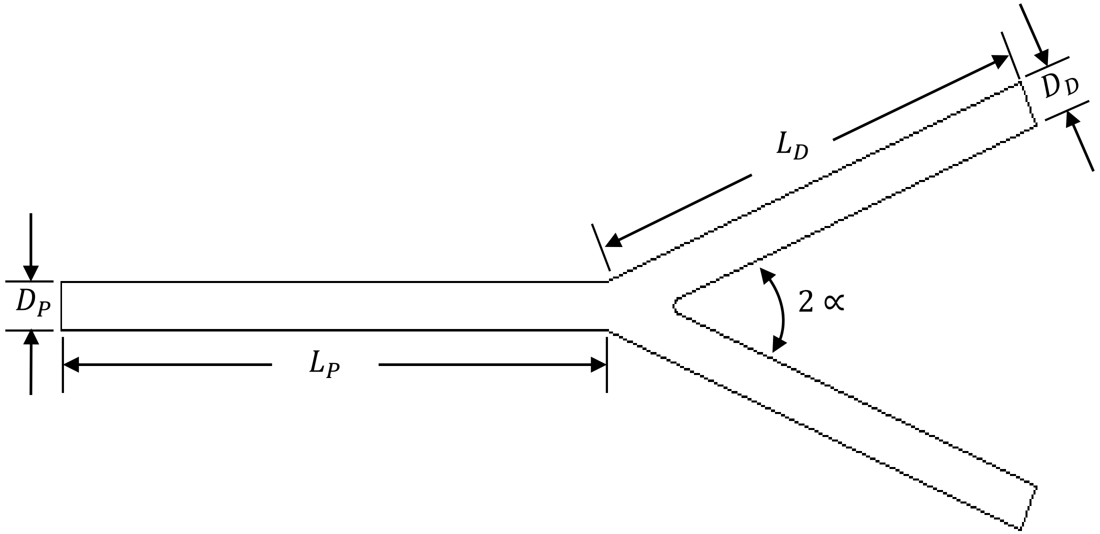

| Parameter | Value |
|---|---|
| $Re_D$ | 1500 |
| $D_R = {}^{D_D}/_{D_P}$ | 0.5 |
| $L_R = {}^{L_D}/_{L_P}$ | 0.8 |
| α | 0° - 90° |



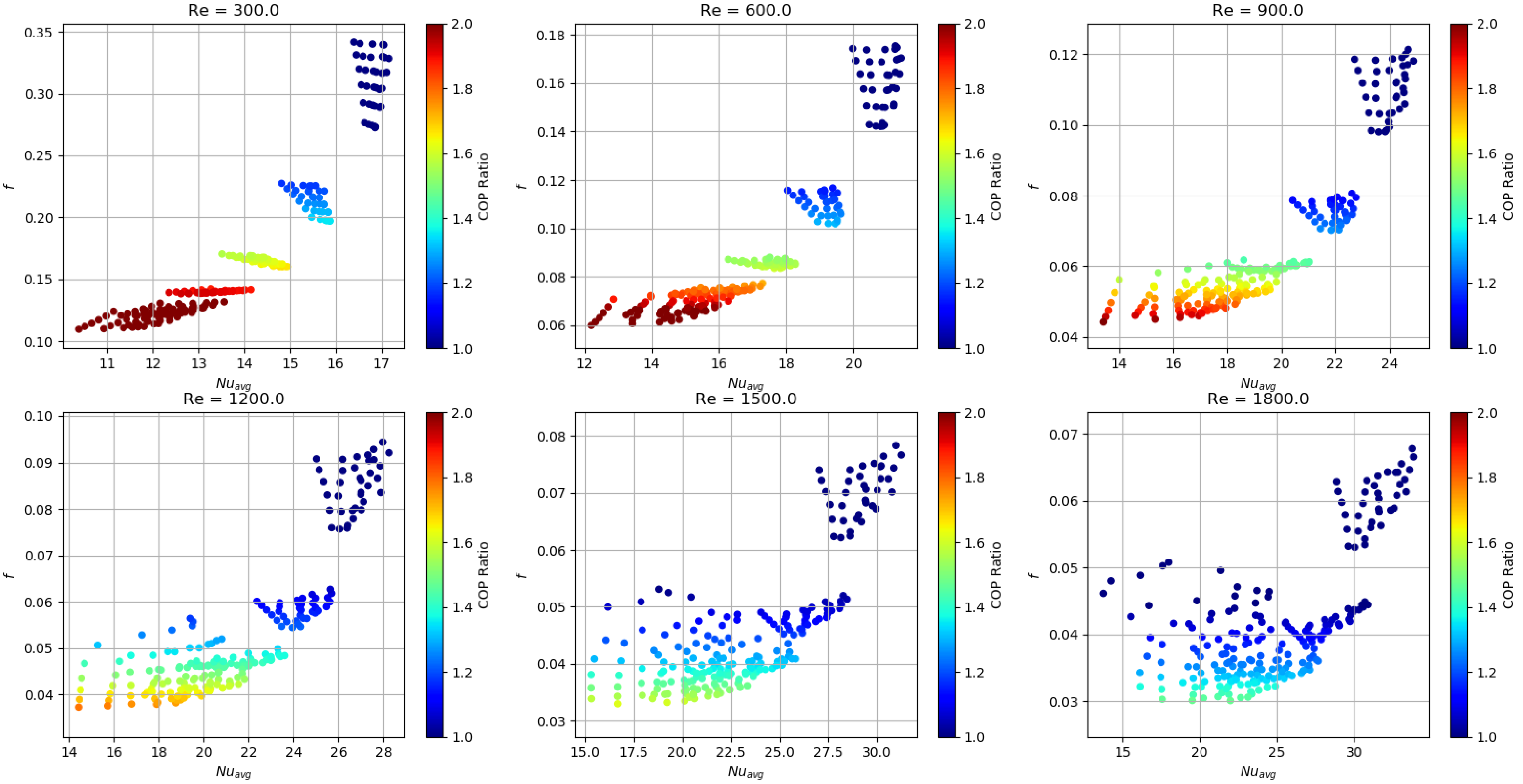
# Effect of Branching Angle – Friction Factor




| Parameter | Value |
| --- | --- |
| $Re_D$ | 1500 |
| $D_R = {D_D}/{D_P}$ | 0.5 |
| $L_R = {L_D}/{L_P}$ | 0.8 |
| α | 0° - 90° |



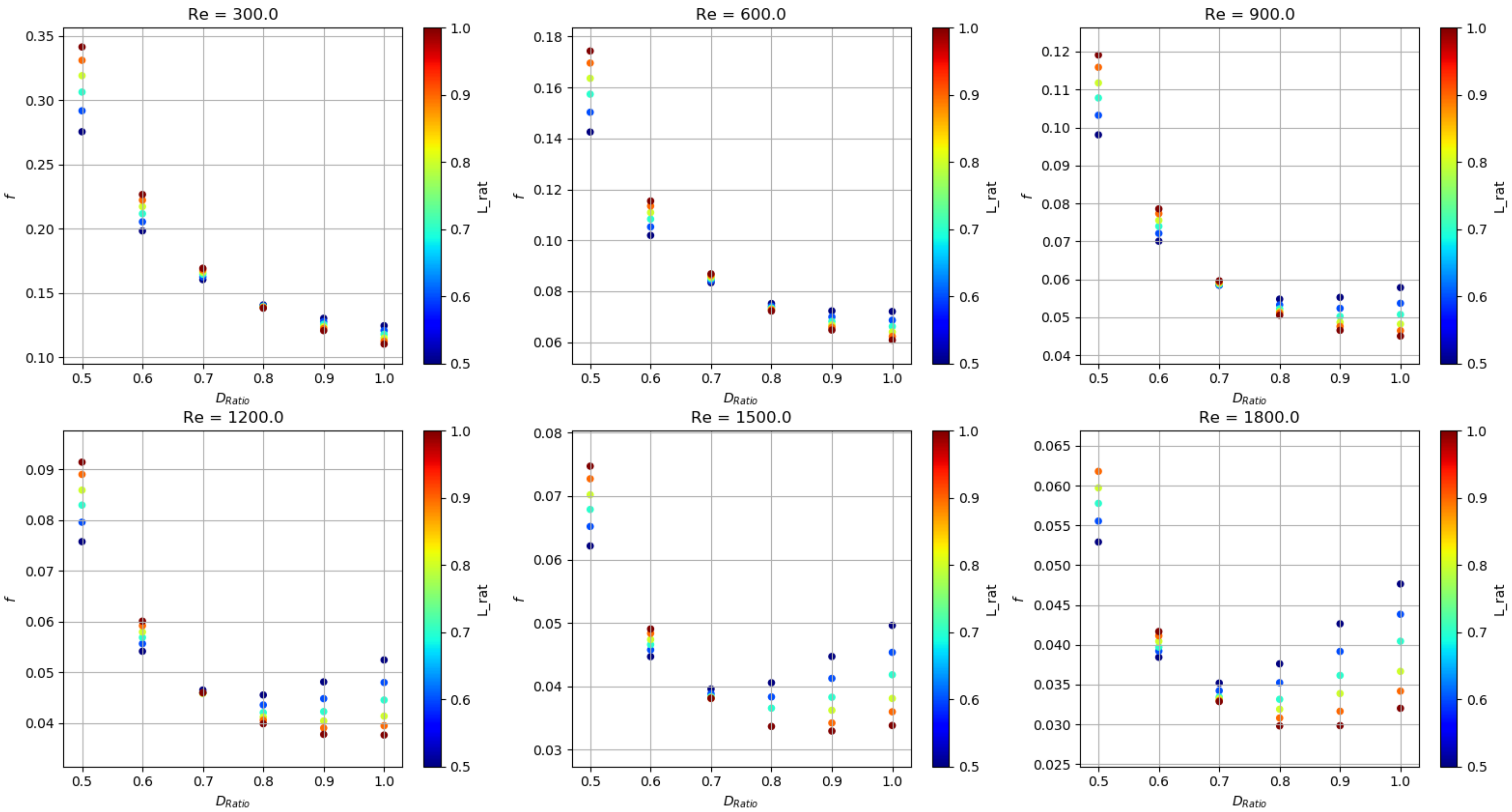
# Step 6: Comparison of Metrics



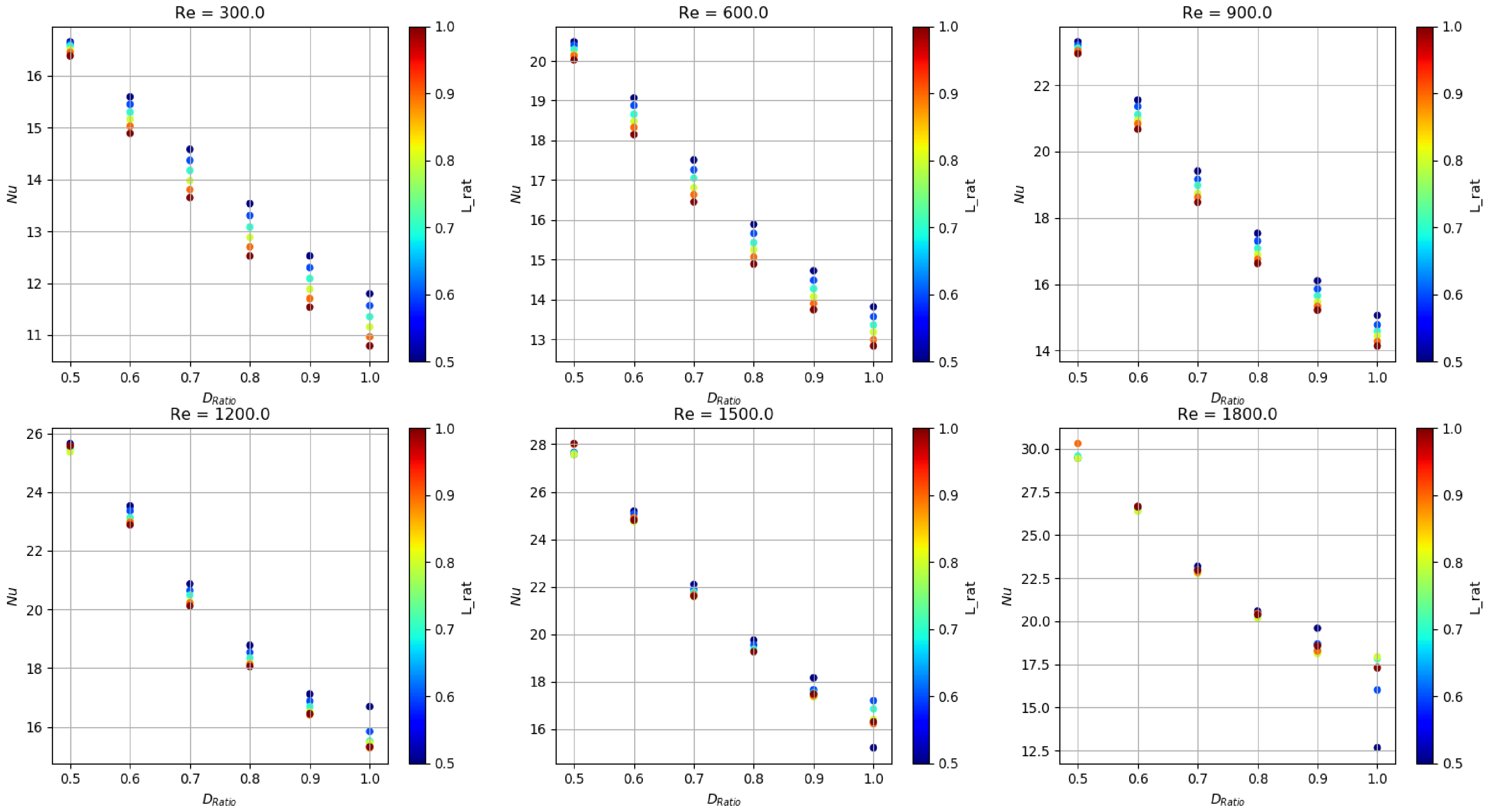
# Step 6: Comparison of Metrics

- Many solutions from CFD, need to know whether they are accurate or not
- Rather than compare exact numbers, focus on trends
- In order to trust the results from simulations, the results must be compared to other published data/trends

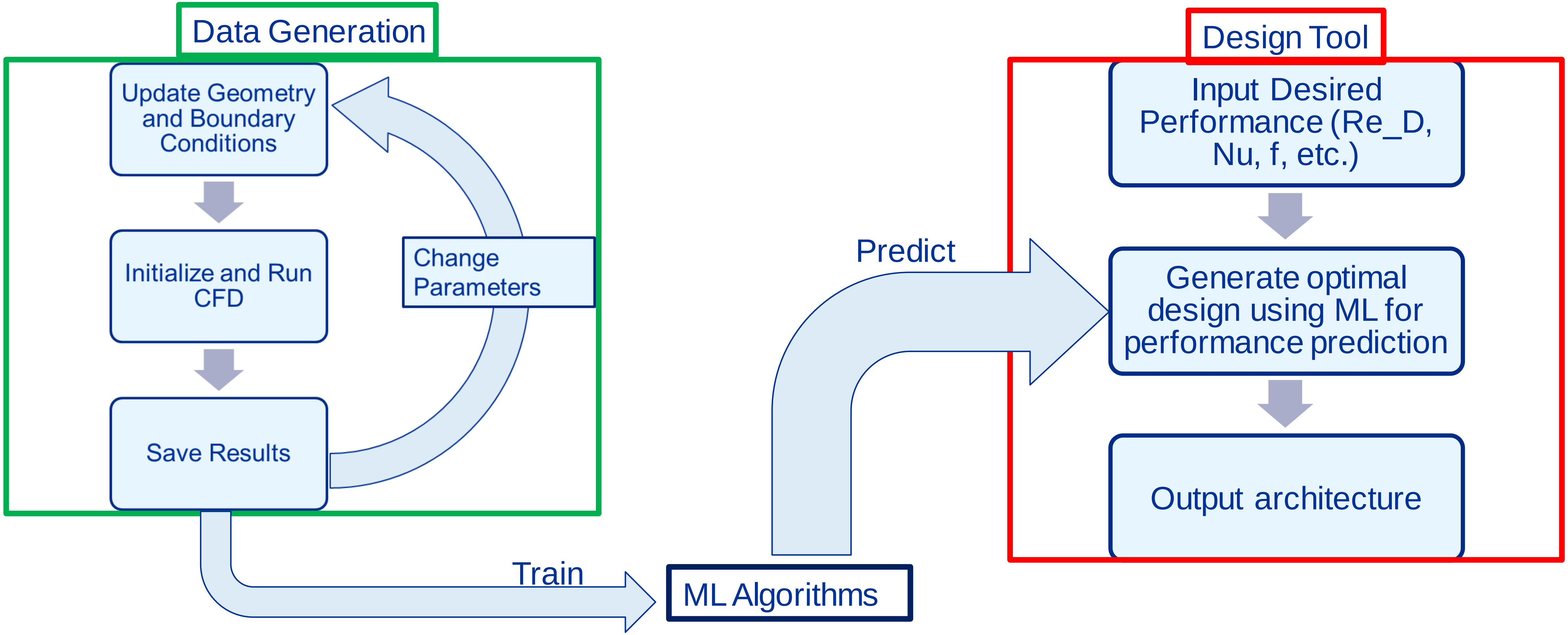
# Step 6: Comparison of Metrics – Friction Factor



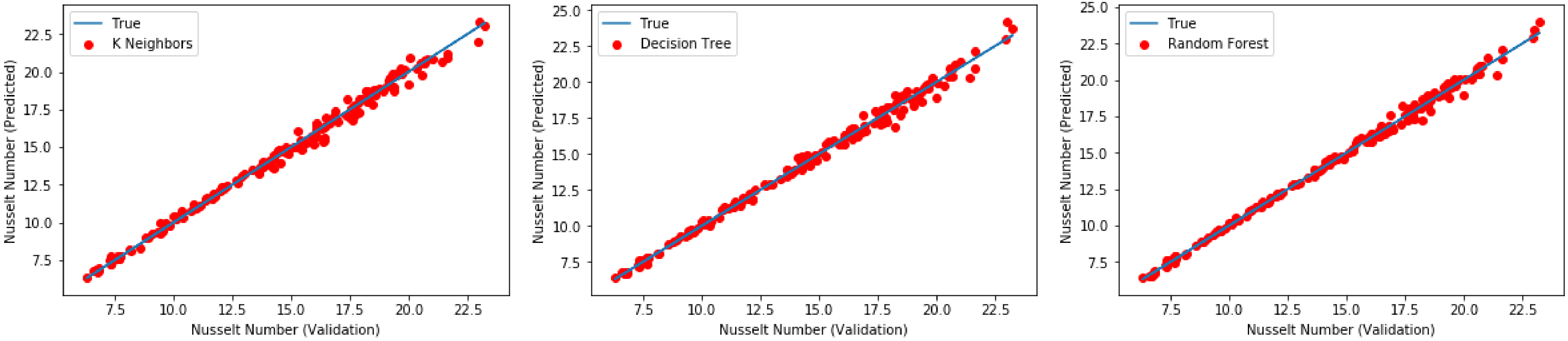
# Step 6: Comparison of Metrics – Nusselt Number



# Machine Learning Models for Performance Predictions



# Machine Learning – Nusselt Number Predictions




- Currently, we are exploring support vector machines and neural networks

# Future and Ongoing Work

- Extend models to 3D and perform a “fluids” sweep with other coolants
- Expand list of parameters: Branching levels, cross sectional shapes, asymmetry, etc.
- Construct the design tool for generating the architecture
- Streamline the machine learning model generation process by adding an “optimization” feature where a sweep of models are assessed

# Questions?