Comparison of Convective Heat Transfer Characteristics of Supercritical Fluid for Circular-Pipes in Horizontal Flow

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Outline

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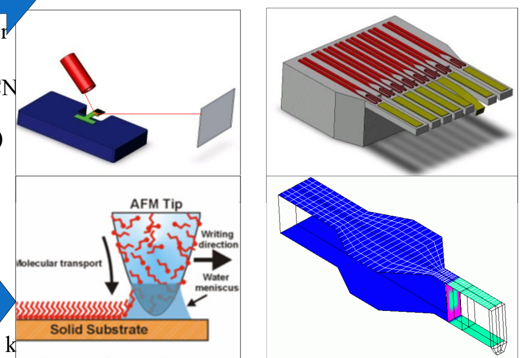
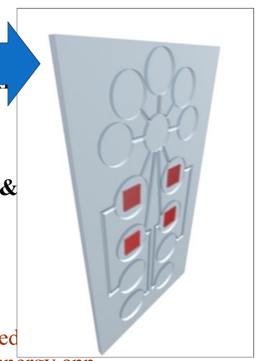
- INTRODUCTION
- MOTIVATION AND GOAL OF STUDY
- METHODOLOGY (INVESTIGATION OF THERMOPHYSICAL PROPERTIES AND PIPE FLOW ANALYSIS)
- RESULTS AND DISCUSSION
- CONCLUSION
- ACKNOWLEDGEMENTS

Multiphase Flows & Heat Transfer Lab.

(Since Jan. 2005, 61 Extra-Mural Funded Projects in 15 years)

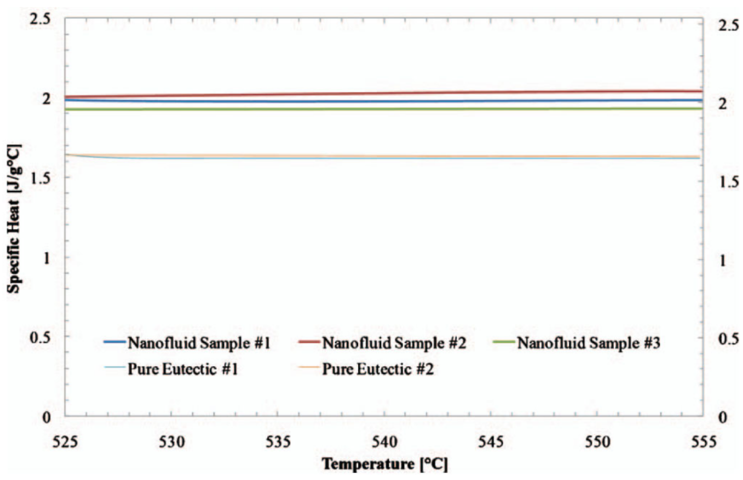
- <u>Nano-Sensors</u> (3 Ph.D., 1 M.S.)
  - **MEMS:**
    - **TEES**: Nano-calorimeter (**EXPLOSIVES SEN**
    - **Nano-MEMS Research/NSF SBIR**: RF-MEMS,RF-Tuner
  - **DPN** (Dip Pen Nanolithography):
    - **DARPA/MTO:** chirality control, low temp. synthesis of CN
    - **ONR STTR/ ADA Tech.: Ultra-Capacitors**
    - **SPAWAR:** low temp. synthesis of Graphene (ONR/ASEE)
    - **TSGC**: Nanolithography+Microfluidics, CFD
    - **GE Research**: Silicon Nanofins
  - **Bio-Microfluidics, Lab-On-Chip:**
    - **AFRL**: Portable water quality monitor
    - **DARPA/MF³**: Micro-Chamber Filling
      - » (1) Vaccine Storage/ Paper microfl
      - » (2) Anthrax Detection using CD
    - **NASA**: Lipid bi-layer sensors for studying protein/peptide k
    - **Energy Institute, Hagler Institute, T3**: Micro/nano-fluidics, thermodynamic properties in shale rocks/ reservoirs, **desalination**
    - **Crisman Institute**: Micro/nano-fluidics, **confined fluid effect** (hydraulic fracturing)
    - **Marathon**: Micro/nano-fluidics, thermodynamic properties in shale rocks/ re
    - **ENMED:** Neural Organoids (organoid-on-Chip/ OoC), LVAD, 4D-MRI, Lun
    - **AFOSR**: Reconfigurable microfluidic device for nano-optics (**META MATERIALS**)

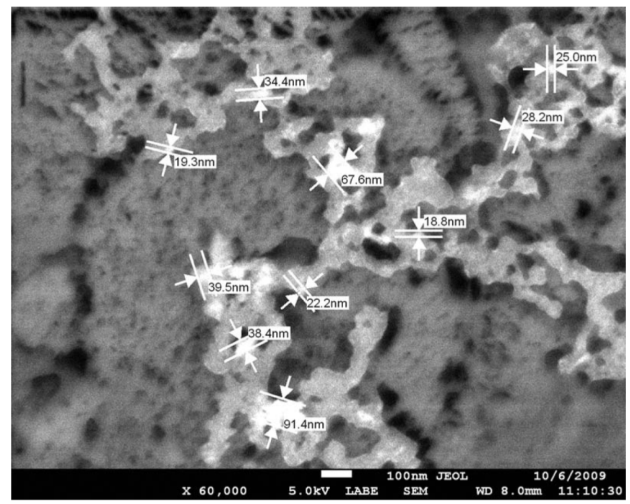




- <u>Thermal Management</u> (3 Ph.D., 1 M.S.)
  - **Nanostructures**
    - **ARPA-E (ARID): Energy-water nexus, Phase Change Materials (PCM): paraffin &**
    - **ONR: Flow Boiling on Carbon Nanotubes**
    - **NSF: Pool Boiling on Silicon Nanofins, Molecular Dynamics**
    - **DOE: Nanofluids for Thermal Energy Storage (SOLAR ENERGY)**
    - **GE-Alstom: Nanofluids for Thermal Energy Storage (SOLAR ENERGY)**
    - **AFOSR/AFRL(ASEE-SFFP): Nano-Fluids**
    - **Qatar National Research Foundation (QNRF):** Nanofluids and Nanofins for enhanced
    - **Photronics Corp./ Trianja Tech. (Si Values Partners/ B G Group):** Nanofluids for energy app.
    - **Irvine Sensors:** Micropump Design for Electronics Cooling (**AFRL SBIR Phase II**)
    - **Aspen Thermal Systems:** Compact condensers (**ONR SBIR Phase I; Phase II**)
  - **Thermo-Chemical Energy Storage (TCES), Thermal Energy Storage (TES)**
    - **AFRL: Chevron Plate Heat Exchangers (PHE) for rapid thermal management**
  - **Biomedical Device (Surgical Sterilizer)**
    - **Lynntech/ ARO SBIR Phase II**: Portable sterilizer for surgical tools using steam.

Molten salt nanofluids



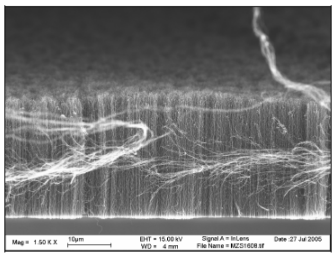
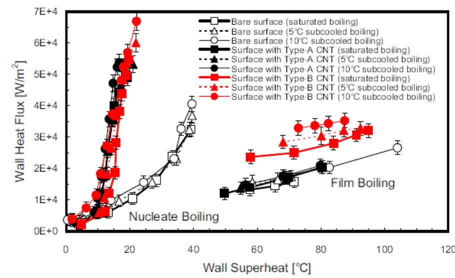
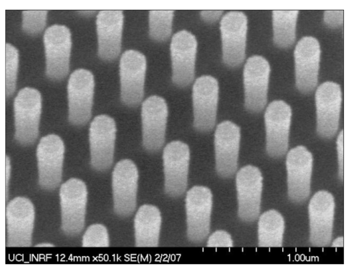
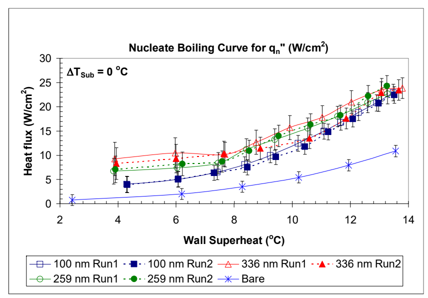


Carbonate salt eutectic + SiO_2

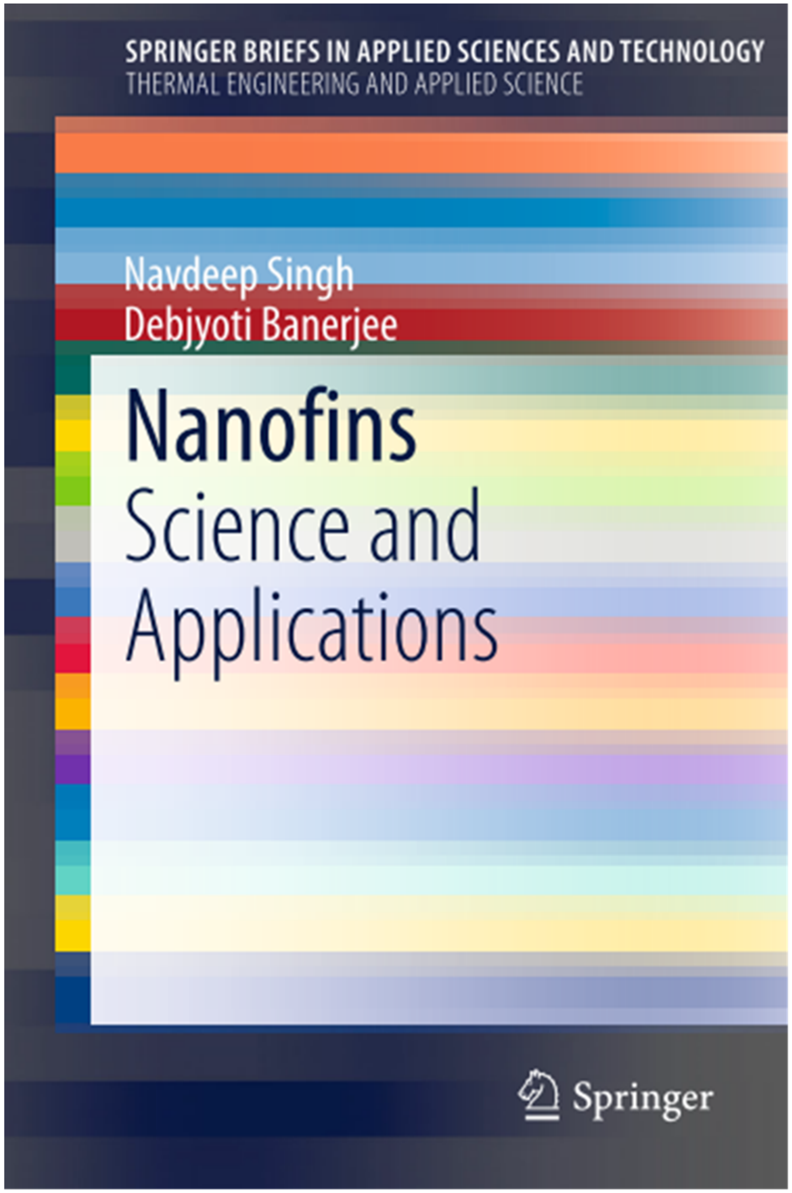
26 % enhancement

Shin and Banerjee, J Heat Trans., 2011

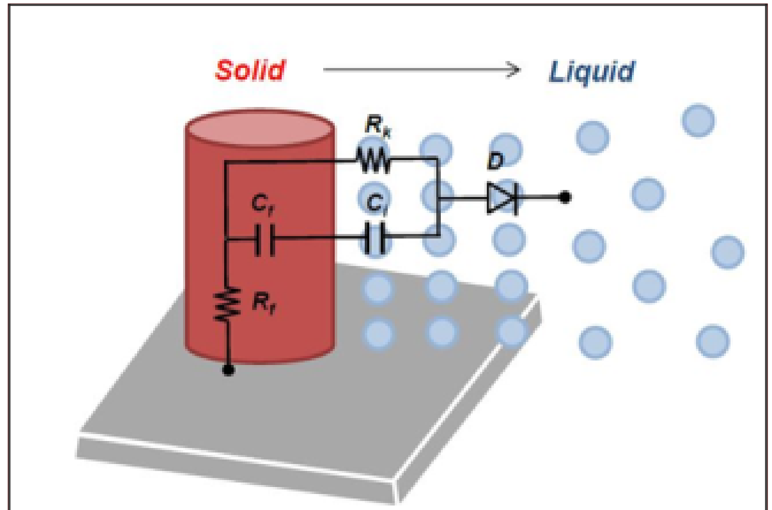
Pool Boiling on Nano-Fins

Nanostructure	*Boiling curve **(large heater)***	*CHF enhancement*
CNT 		~60 % [A]
Silicon 		~120 % [B]

[A] H. Ahn, Heat transfer enhancement in single-phase forced convection with blockages and in two-phase pool boiling with nano-structured surface, Ph. D dissertation, Texas A&M University, 2007
[B] Sriraman, Pool boiling on nano-finned surfaces, Master thesis, Texas A&M University, 2007



"*nano*-Fin Effect" (nFE)



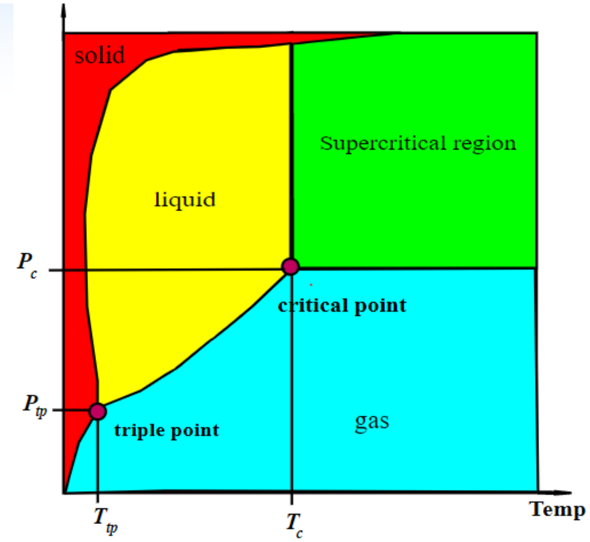
Corrosion reduced by 50~100%

Lee, J., Kuchibhotla, A.*, Banerjee, D., and Berman, D., "Silica Nanoparticles as copper corrosion inhibitors", Materials Research Express, May, 2019.*
https://doi.org/10.1088/2053-1591/ab2270

Introduction

Supercritical fluids exist at temperatures and pressures exceeding the critical point.

They can exist as "liquid-like" or "gas-like" states, and the differentiator between the two states is also known as the "***Widom Line***" / "***Frenken Line***".



P-T Phase diagram

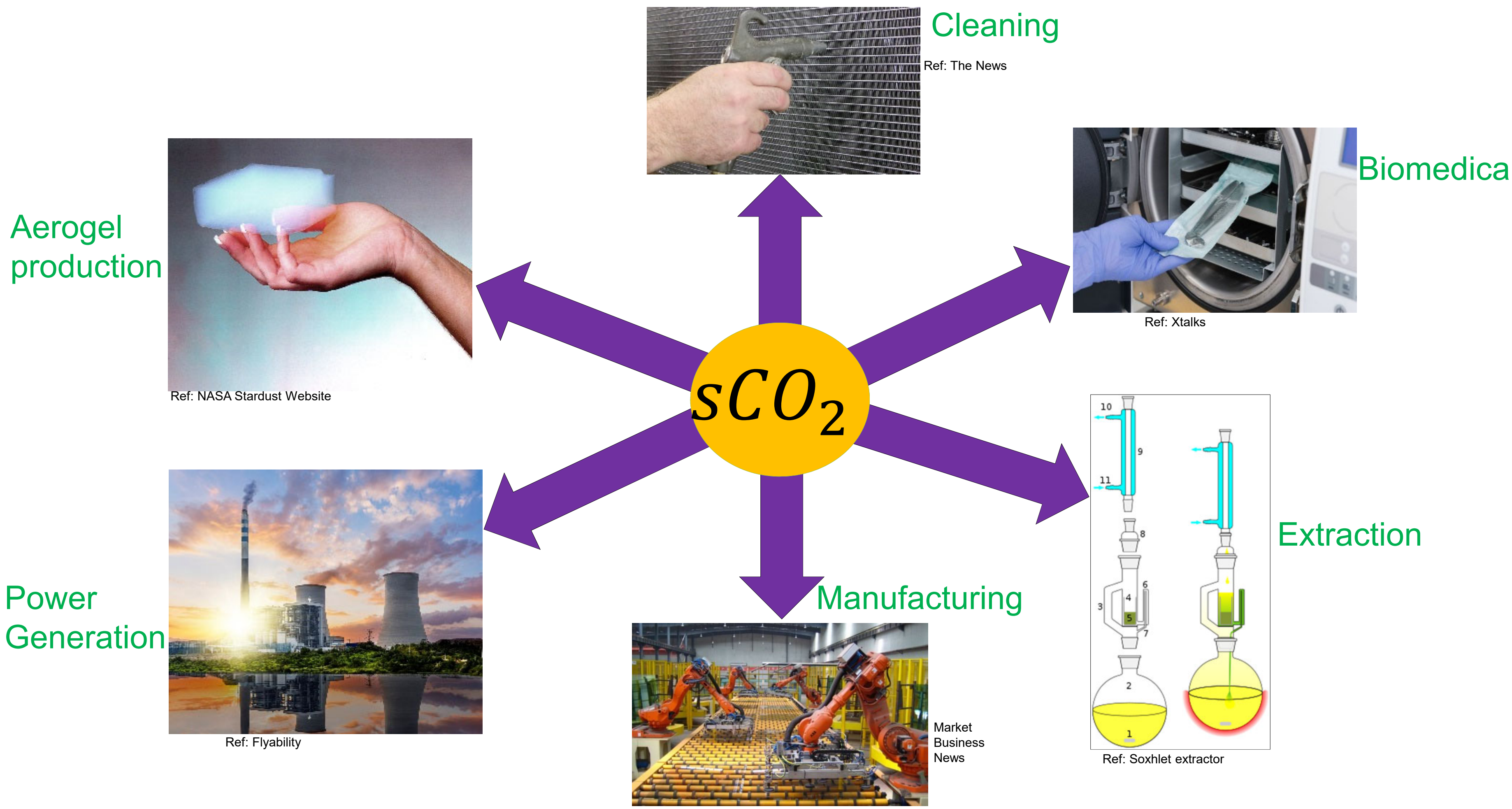
Critical properties of CO_2

Critical pressure	7.38 [MPa]
Critical Temperature	304.1[K]

Fomin, Y. D., Ryzhov, V. N., Tsiok, E. N. & Brazhkin, V. V. Thermodynamic properties of supercritical carbon dioxide: Widom and Frenkel lines. Phys Rev E 91,2015.

https://doi.org/10.1103/PhysRevE.91.022111

Introduction



Motivation and Goal of Study

- Motivation

The motivation of this study was to explore the efficacy of heat exchangers involving forced convective heat transfer of supercritical fluids (tube side) integrated with air cooling (i.e., in free convection).

- Goal

The goal of this study was to determine the forced convective heat transfer characteristics of supercritical carbon dioxide (**s**CO_2) in air-cooled tube heat-exchangers.

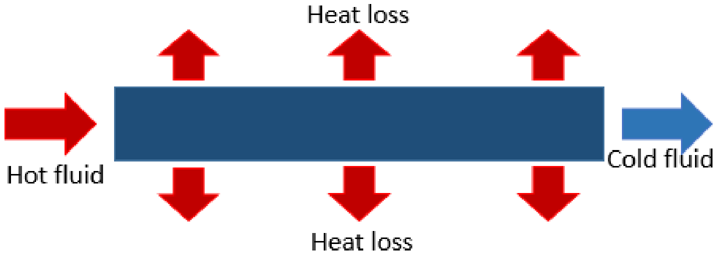
Methodology (Investigation of Thermophysical properties of *s*CO2)

The thermophysical properties of sCO2 was obtained from NIST database for pressure, P=8.12MPa and temperature variation, T=450 – 700[K]. Properties investigated are:

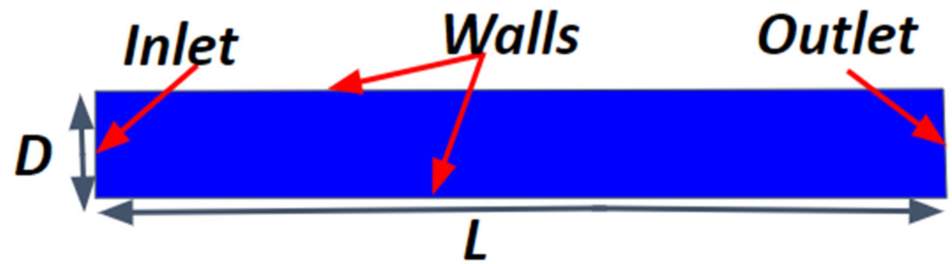
- Specific heat at constant volume, c_v
- Specific heat at constant pressure, c_p
- Density, ρ
- Thermal conductivity, k
- Dynamic viscosity, μ
- Kinematic viscosity, v
- Thermal diffusivity, α
- Prandtl number, Pr

Methodology (Pipe Flow Analysis)

2D Numerical and Analytical investigation of the hydrodynamic and thermal characteristics of sCO_2 flowing in a circular horizontal pipe.



Heat Flow visualization



Boundary conditions

Boundary conditions and fluid properties

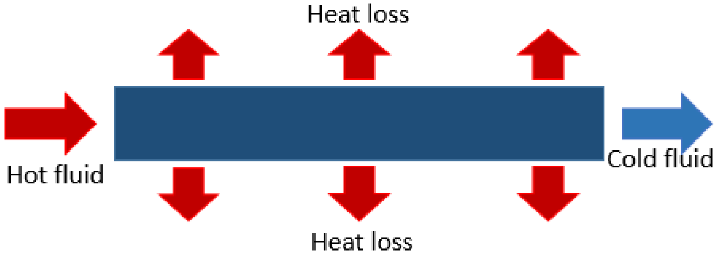
Re	10, 100, 1000, 1500, 5000, 10 000
Reduced Press. ,P_r	1.1
Reduced Temp., T_r	1.64
Inlet Temp., T_{in}	700 [K]
Ambient Temp., T_∞	300 [K]
External convection coefficient, h_o	43.2 [W/m²K]
Density, ρ	90.817 [kg/m³]
Specific heat cap., c_p	1132.2 [J/kgK]
Thermal cond., k	0.036361 [W/mK]
Dynamic visc.,μ	2.5e^{-5} [Pa.s]

Dimensions

Diameter (D)	1, 2, 5 and 10 [mm]
Length (L)	1[m]

Methodology (Pipe Flow Analysis)

2D Numerical and Analytical investigation of the hydrodynamic and thermal characteristics of sCO_2 flowing in a circular horizontal pipe. Numerical simulation performed with ANSYS Fluent 2019R19.1



Heat Flow visualization

Boundary conditions and fluid properties

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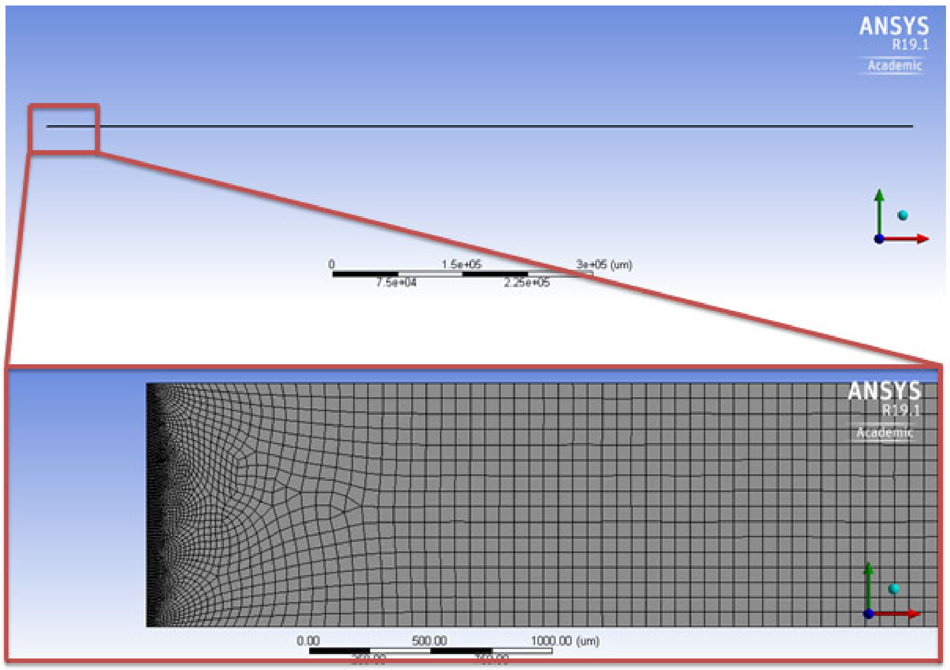
Model and Assumptions

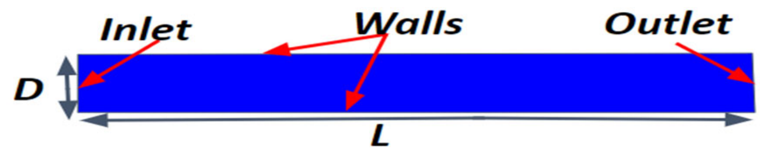
- Pressure based solver
- Steady State
- Constant properties (Incompressible flow)
- Constant ambient condition (synonymous to constant surface temp condition)
- Laminar flow for Re (10, 100, 1000 and 1500);
  Turbulent flow for Re (5000 and 10000) with *k-w* SST (shear stress transport) model
- Energy on

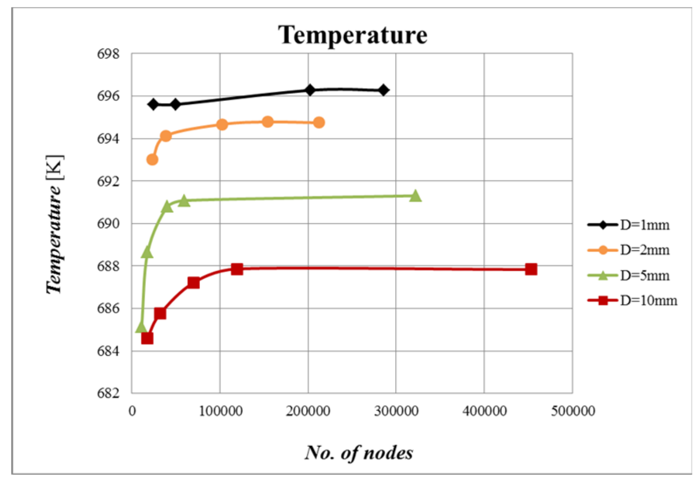
Methodology (Pipe Flow Analysis)

2D Numerical and Analytical investigation of the hydrodynamic and thermal characteristics of sCO_2 flowing in a circular horizontal pipe. Numerical simulation performed with ANSYS Fluent 2019R19.1



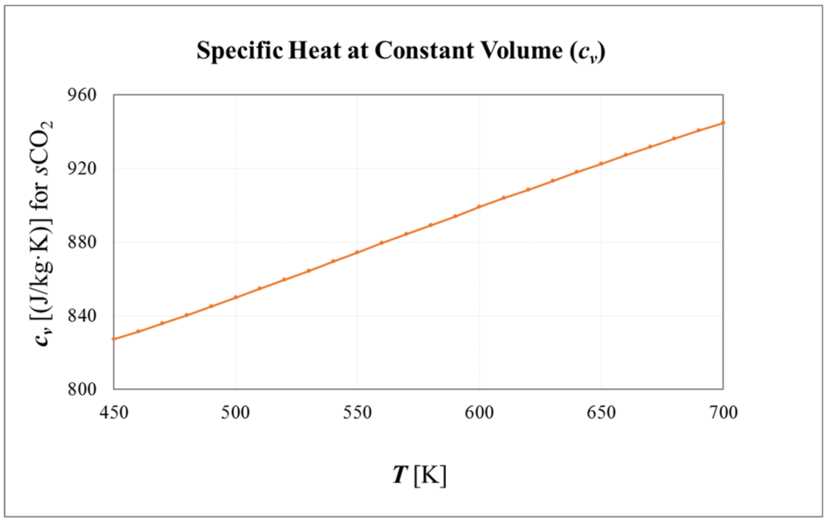
A quadrilateral mesh with refinement at the inlet and outlet sections

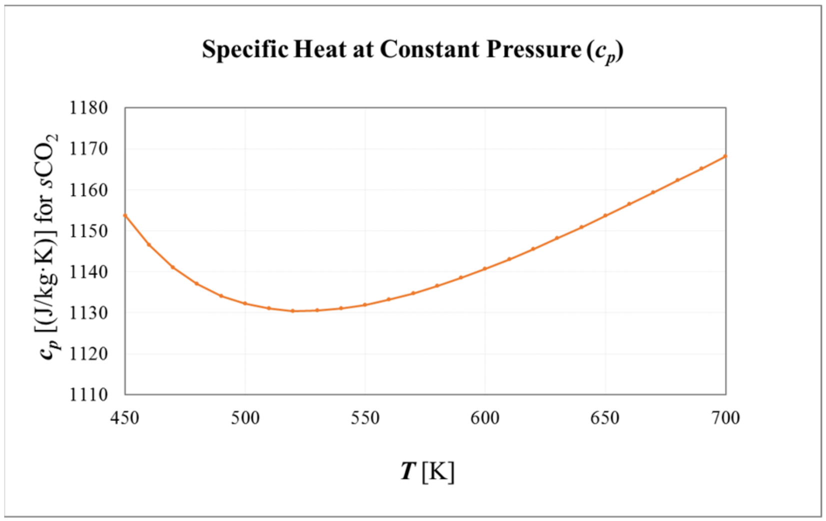




Mesh refinement was performed until there was no significant change to bulk mean temperatures

Results (Investigation of Thermophysical properties of *s*CO2)



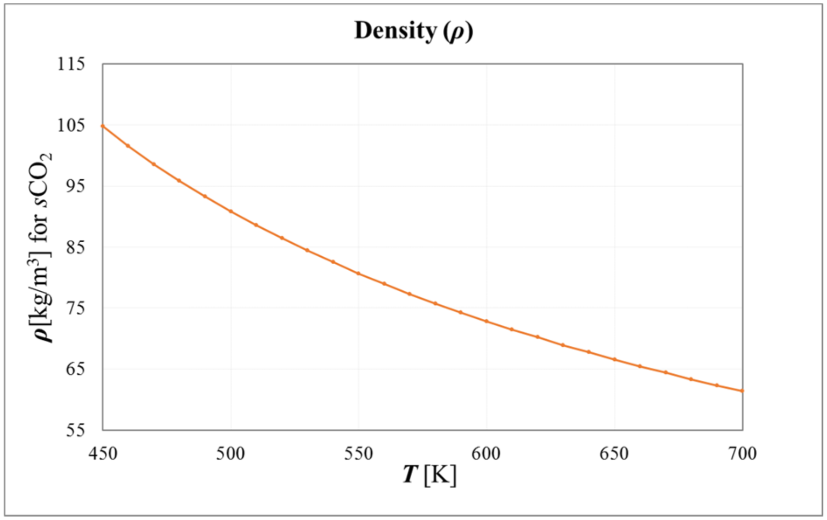


c_v ⬆ as T ⬆ for 450 ≤ T ≤ 700

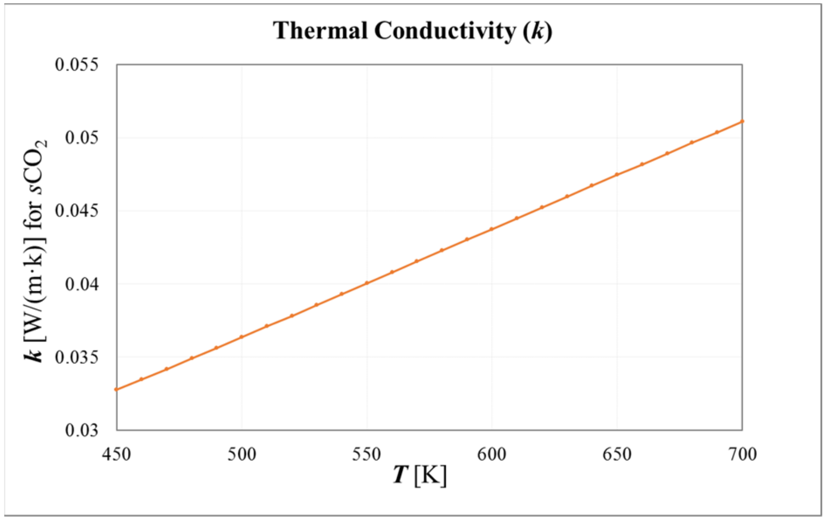
c_p ⬇ as T ⬆ for 450 ≤ T ≤ 520

c_p ⬆ as T ⬆ for 520 ≤ T ≤ 700

Results (Investigation of Thermophysical properties of *s*CO2)

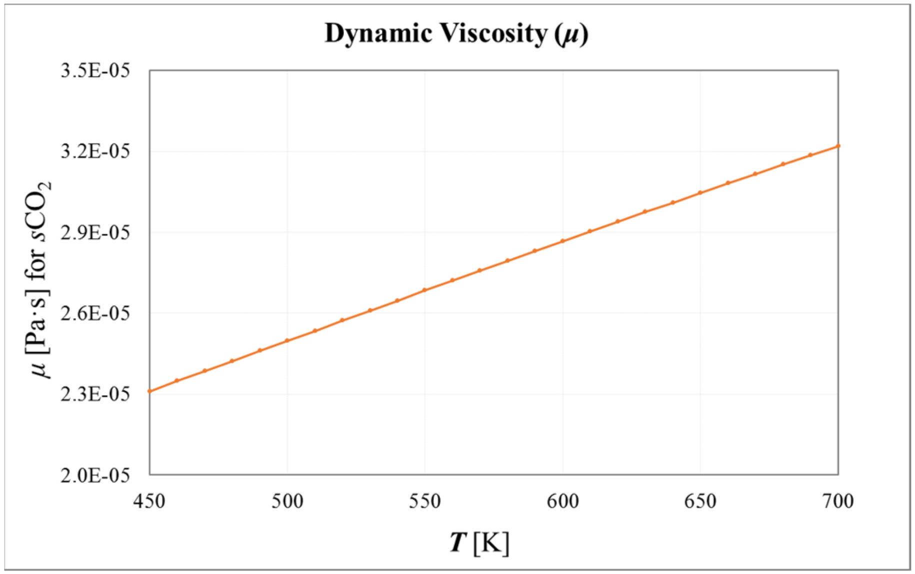


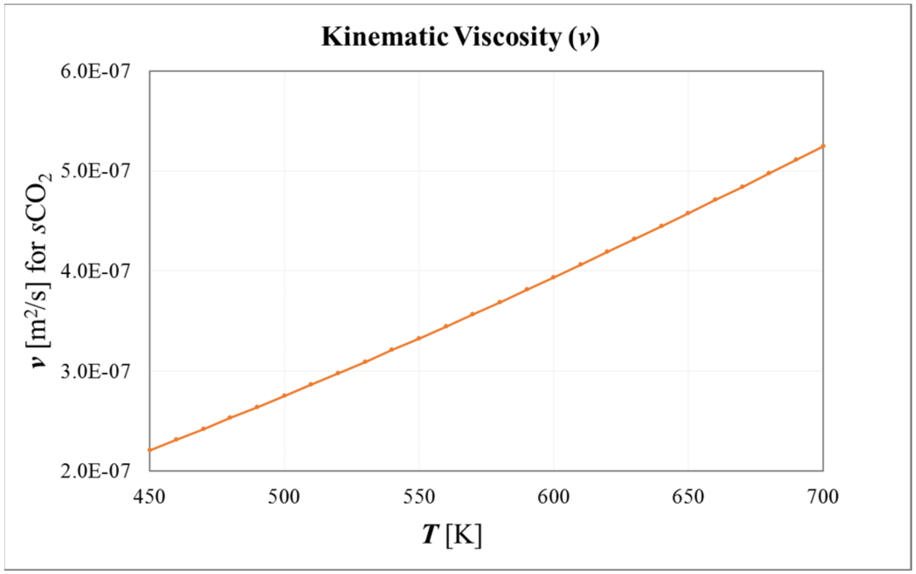
ρ⬇ as T⬆ for 450 ≤ T ≤ 700



k⬆ as T⬆ for 450 ≤ T ≤ 700

Results (Investigation of Thermophysical properties of *s*CO2)

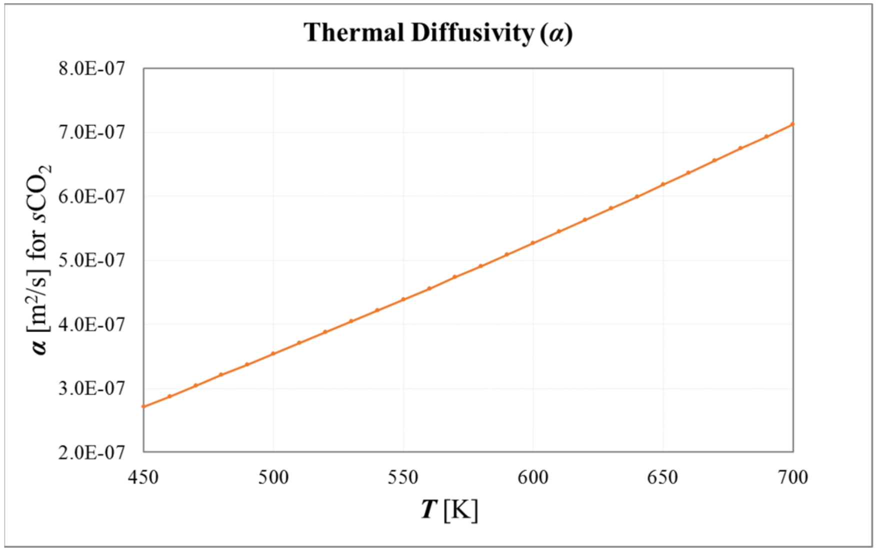


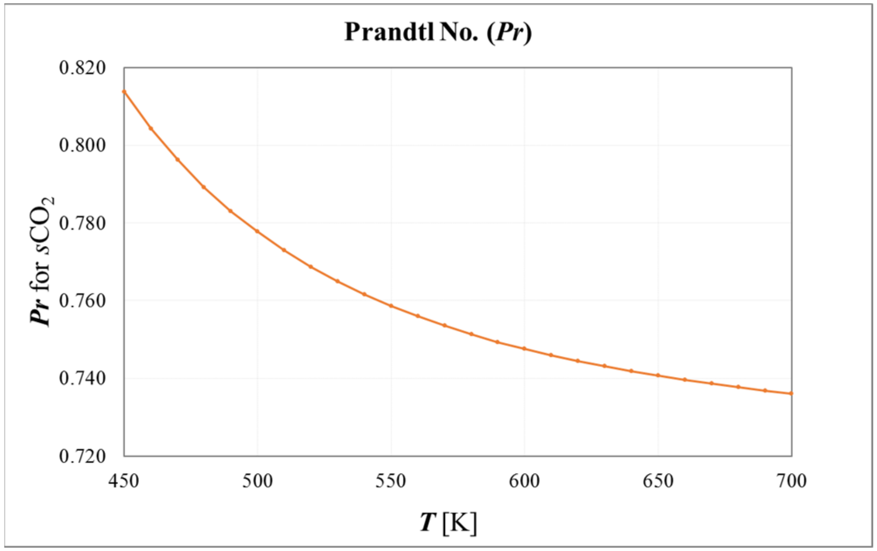


μ⬆ as T⬆ for 450 ≤ T ≤ 700

ν⬆ as T⬆ for 450 ≤ T ≤ 700

Results (Investigation of Thermophysical properties of *s*CO2)

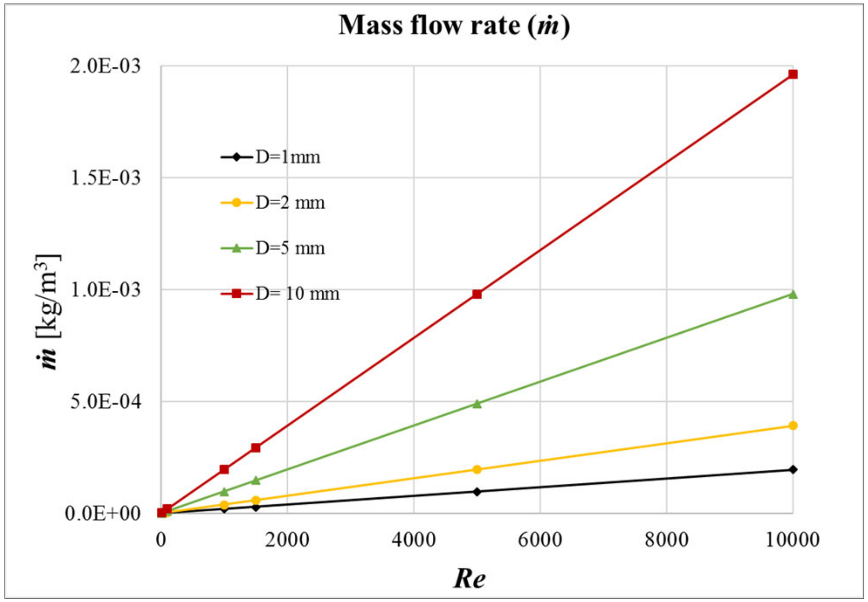


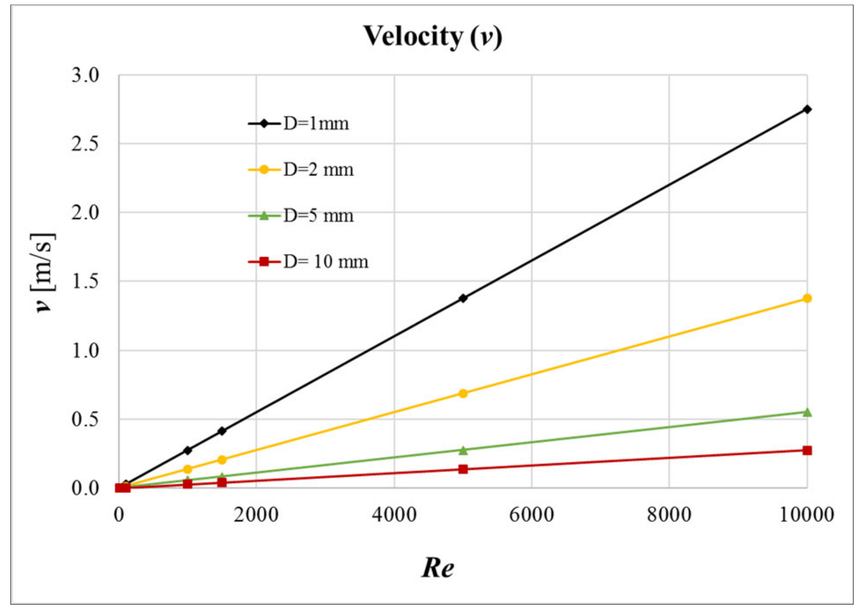


α ⬆ as T ⬆ for 450 ≤ T ≤ 700

Pr ⬇ as T ⬆ for 450 ≤ T ≤ 700

Results (Pipe Flow Analysis)





$\dot{m}$ ⬆ as *Re* ⬆ and *D* ⬆

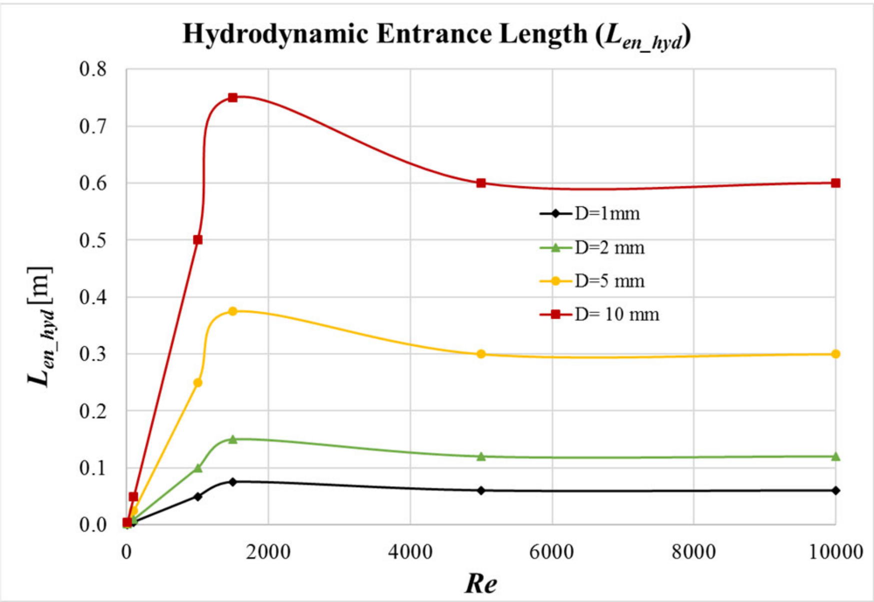
v ⬆ as *Re* ⬆ and *D* ⬇

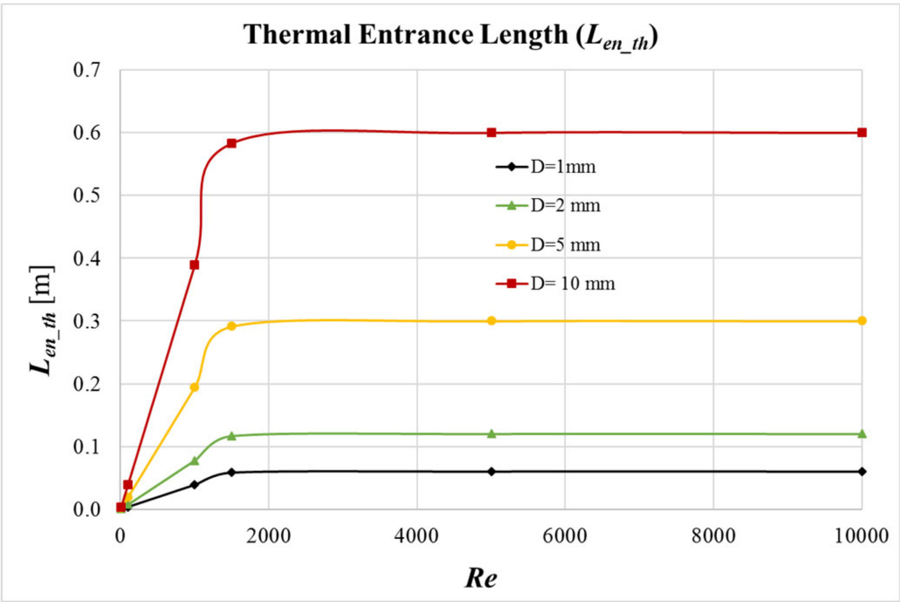
$$\dot{m} = Re\,\pi D \mu/4$$

$$v = \dot{m}/(\rho A)$$

Incompressible flow assumption

Results (Pipe Flow Analysis)



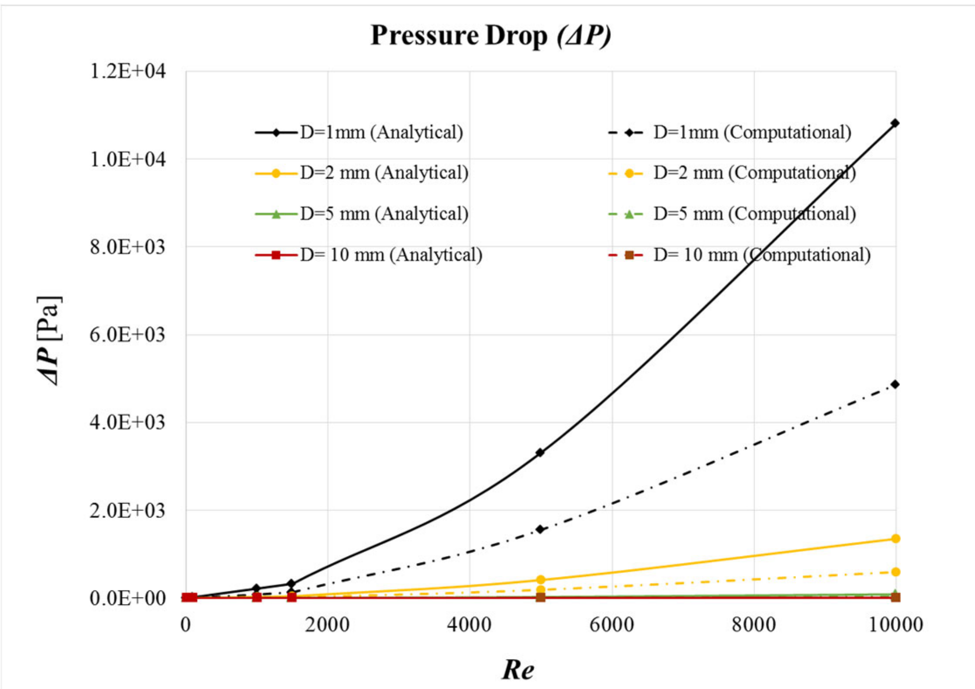


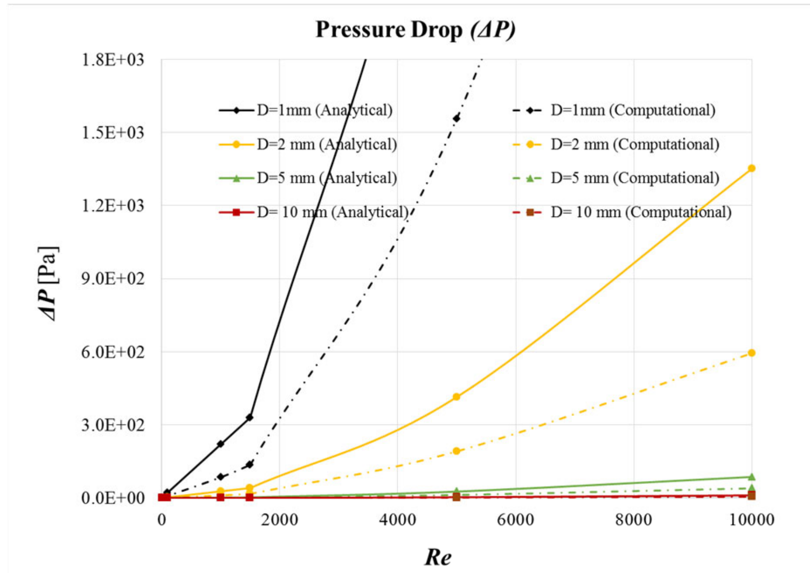
$L_{en\_hyd} = 0.05 Re \cdot D$ (for laminar)
$L_{en\_hyd} = 60D$ (for turbulent flow)

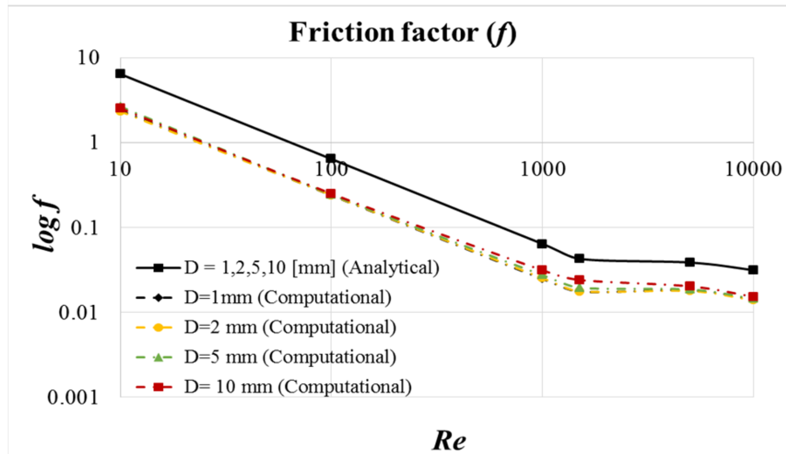
$L_{en\_th} = 0.05 Re \cdot D \cdot Pr$ (for laminar)
$L_{en\_th} = 60D$ (for turbulent)

- In laminar region, $L_{en\_hyd} \propto Re \text{ and } D$; $L_{en\_th} \propto Re, D \text{ and } Pr$
- In turbulent region, L_{en_hyd} and $L_{en\_th} \propto D$
- In laminar region $L_{en\_hyd} > L_{en\_th}, \therefore Pr < 1$

Results (Pipe Flow Analysis)







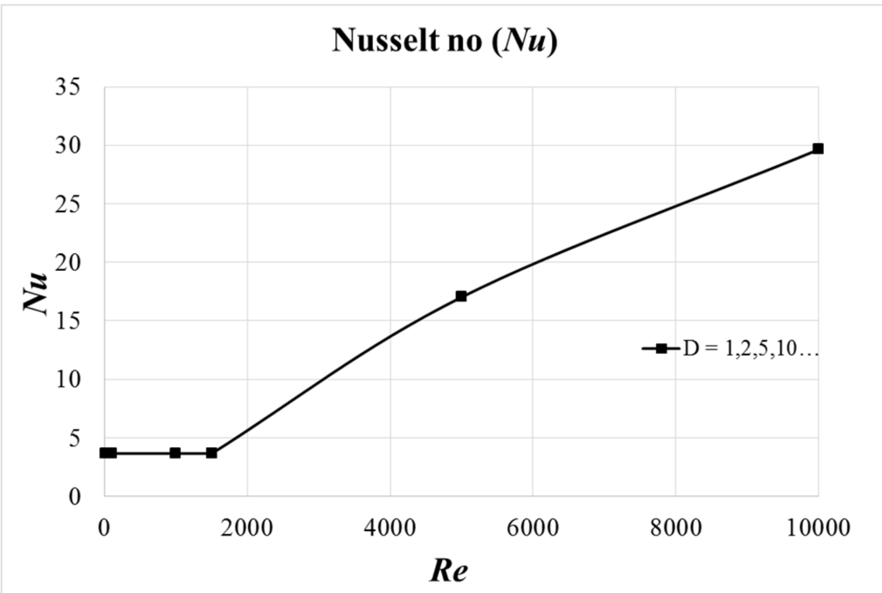
$f = 64 / Re$, $Re < 2000$ (for laminar flow)

$f = (0.79\, In\, (Re) - 1.64)^{-2}$ for $3000 < Re < 5\times10^6$

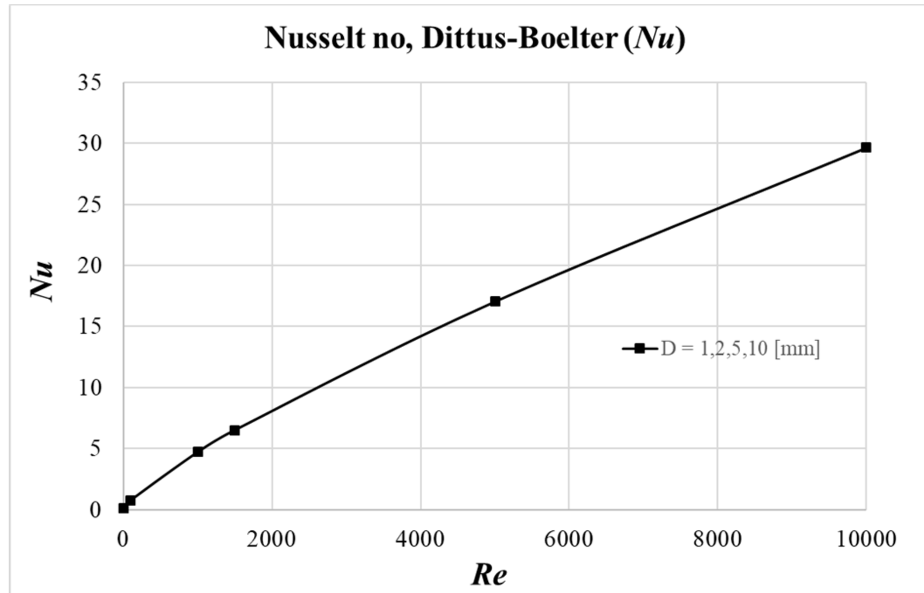
$$\Delta P = f \frac{L}{D} \frac{\rho v^2}{2}$$

- In laminar and turbulent region, $f \alpha \frac{1}{Re}$
- Larger tubes give smaller pressure drop and vice versa.

Results (Pipe Flow Analysis)



Nu = 3.66 used for the laminar regime (fully developed flow)

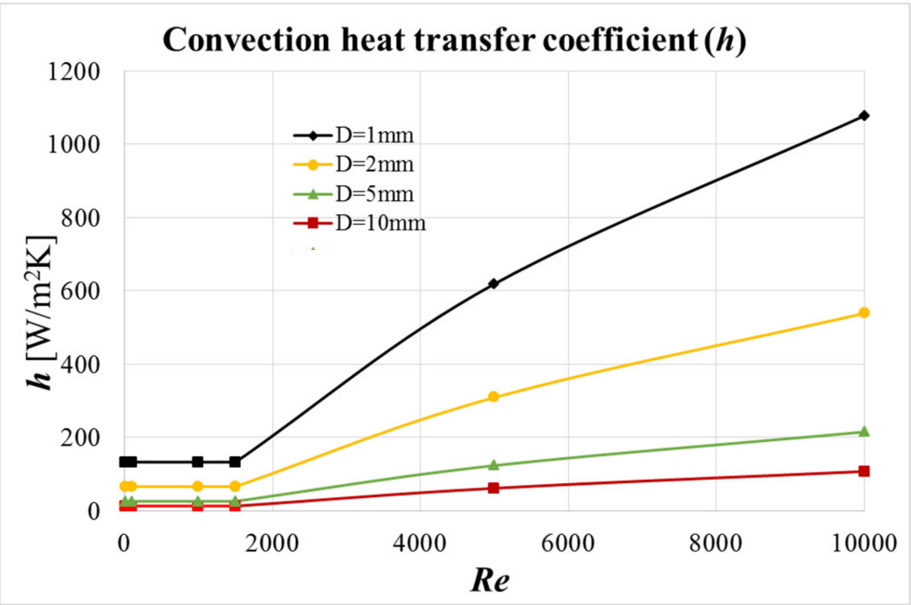


Dittus-Boelter correlation used for laminar and turbulent regime

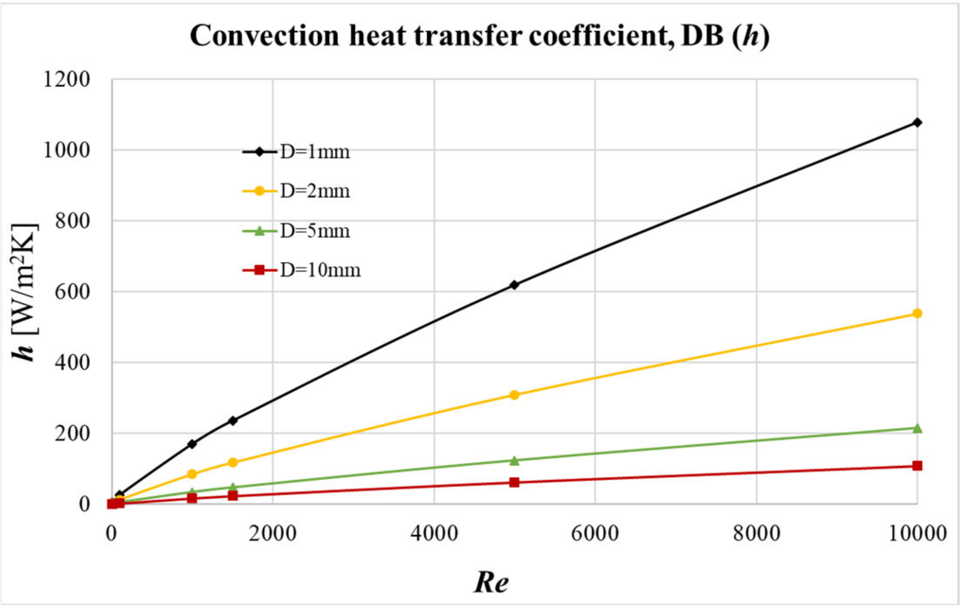
$Nu = 0.023Re^{\frac{4}{5}}Pr^{n}\left(\frac{\mu_b}{\mu_s}\right)^{0.14}$ (n = 0.3 for cooling) Dittus-Boelter

- Dittus-Boelter under-predicts the Nusselt number in the laminar regime.

Results (Pipe Flow Analysis)



$Nu = 3.66$ used for the laminar regime (fully developed flow)

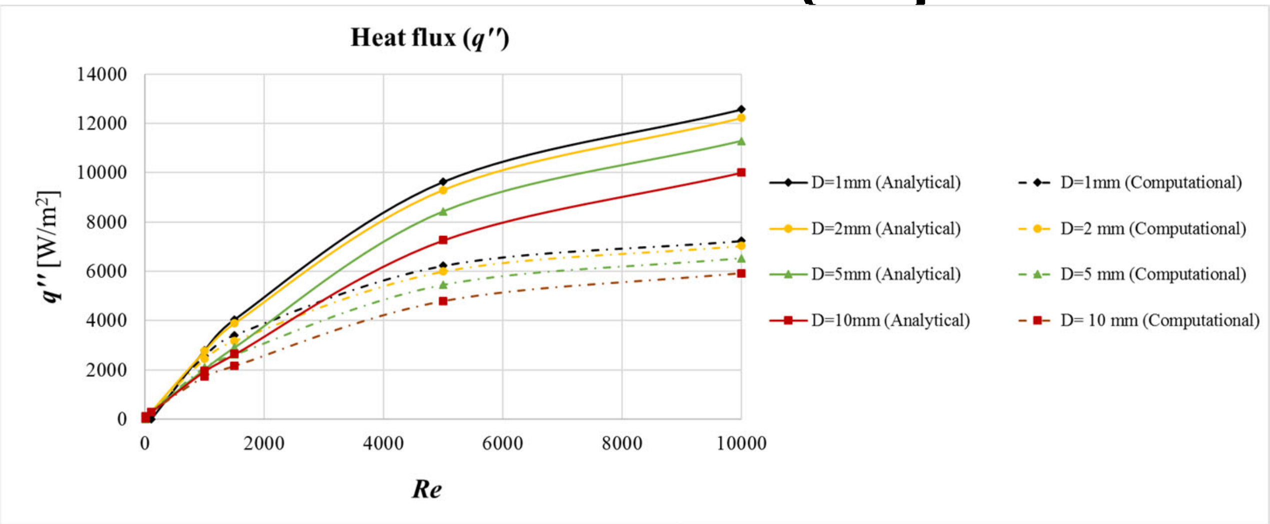


Dittus-Boelter correlation used for laminar and turbulent regime

$$Nu = \frac{hD}{k}; h = \frac{kNu}{D}$$

- The convection heat transfer coefficient, $h \,\alpha\, Re$ (turbulent region)
- $h \,\alpha\, \frac{1}{D}$

Results (Pipe Flow Analysis)



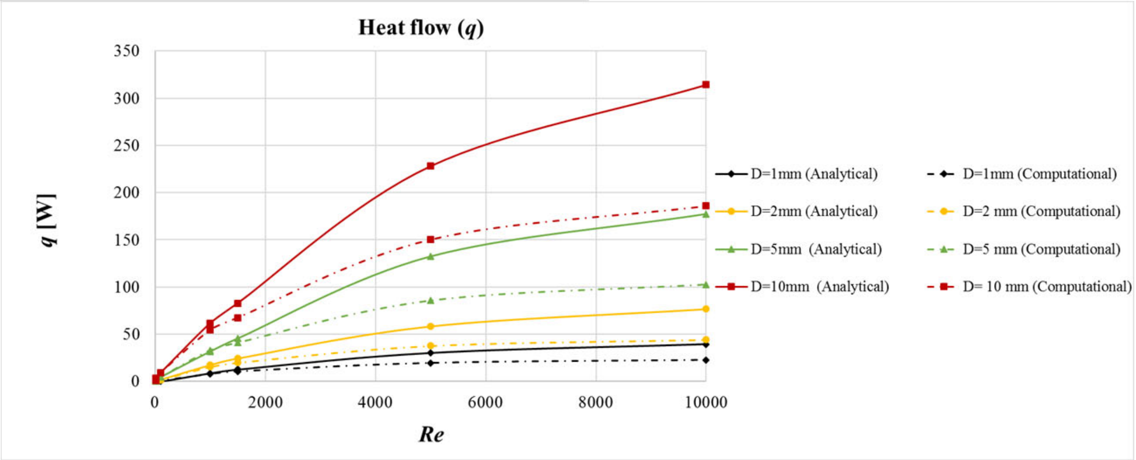
$$q = \bar{U} A_s \Delta T_{lm} = \dot{m} c_p \Delta T$$

$$q'' = q/A_s$$

The heat flow, $q \ \alpha$ D

The heat flux, $q'' \ \alpha \frac{1}{D}$

Analytical estimates exceed numerical estimates of *q* and *q”* by a factor of ~2



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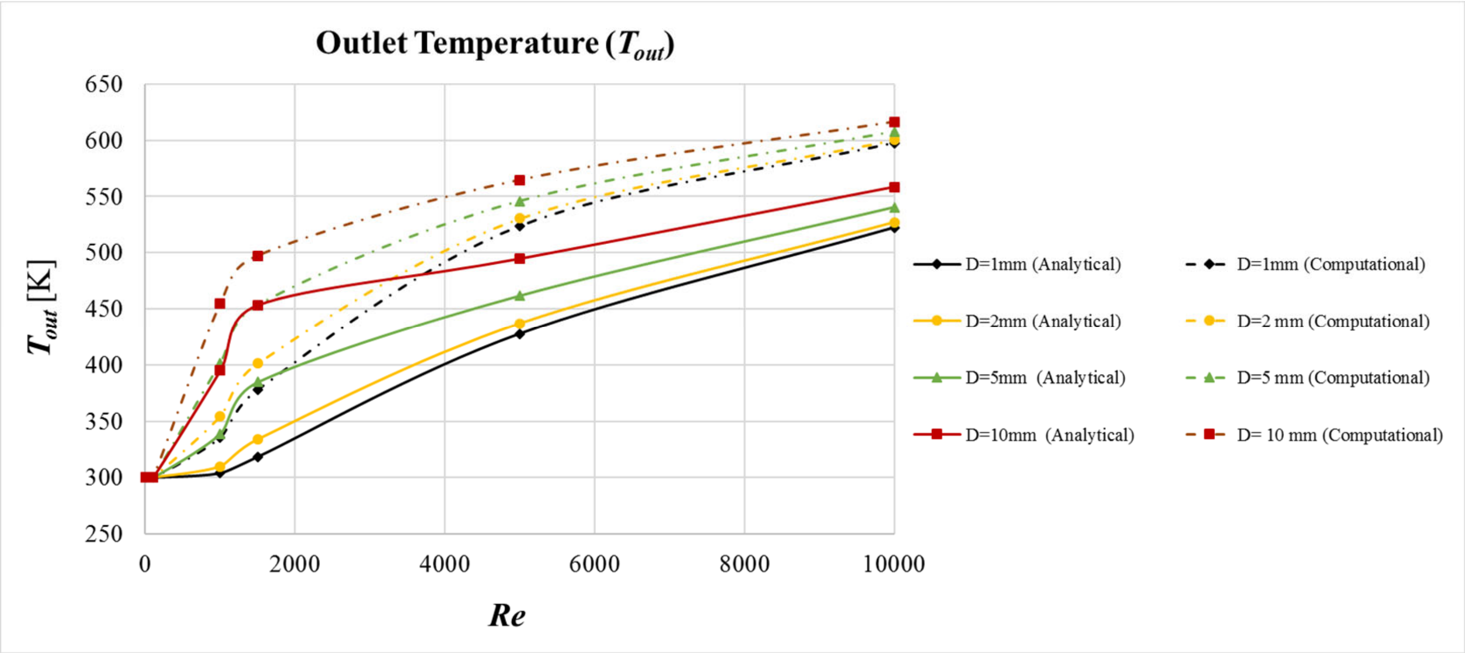
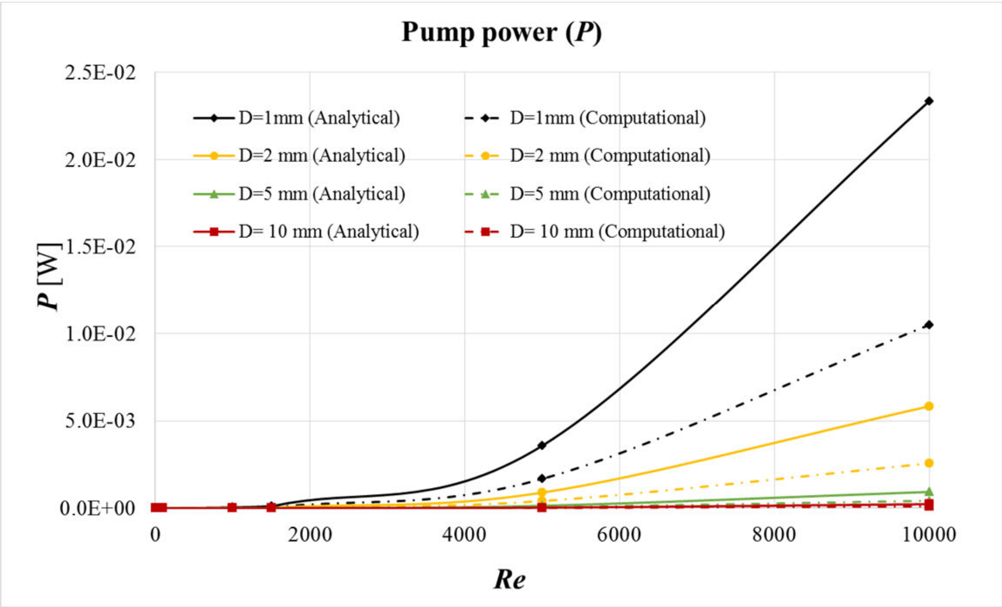


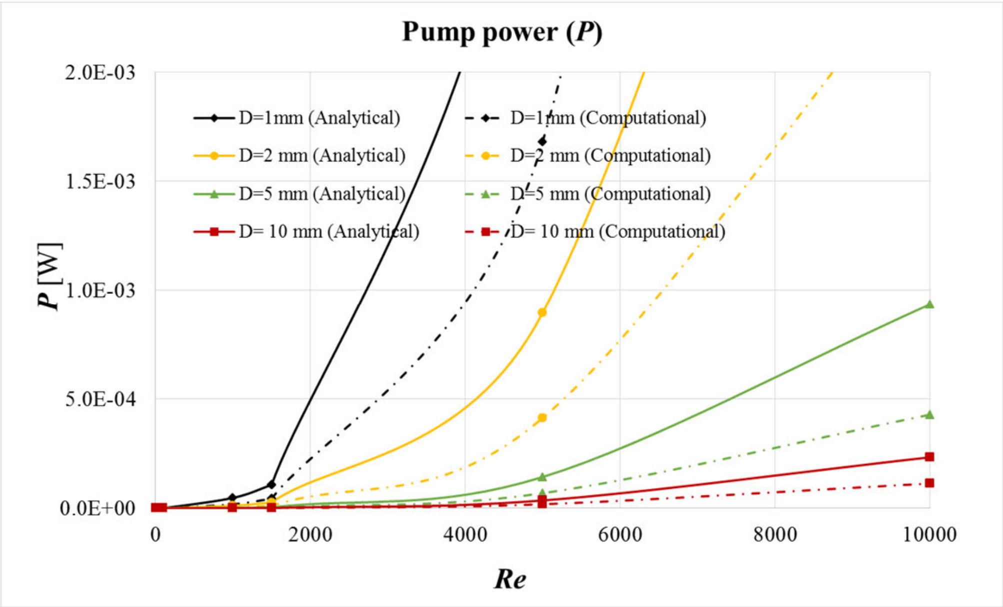
$$\frac{T_\infty - T_{outlet}}{T_\infty - T_{inlet}} = exp\left(\frac{\overline{U}A_s}{\dot{m}c_p}\right)$$

Re ⬆ $= T_{out}$ ⬆

D ⬆ $= T_{out}$ ⬆

Results (Pipe Flow Analysis)





*Pump power, P= QΔP =A*v*ΔP*

- $P\ \alpha$ *volume flow rate Q and pressure drop* ΔP
- $P\ \alpha\ \frac{1}{D}$

$$\Delta P = f\,\frac{L}{D}\frac{\rho v^2}{2}$$

Analytical estimates exceed numerical estimates of power, *P* by a factor of ~2

A=cross sectional area |Q=volume flow rate| ΔP= pressure drop| v = velocity

Conclusion

- The thermophysical properties of sCO2 at P=8.12MPa and T=450-700[K] is consistent with established trends
- Large pressure drop requires greater pumping power. Tradeoffs in cost should be determined between larger and smaller tubes
- Geometric simplification error of 2D assumption resulted in less accurate numerical results

Acknowledgements

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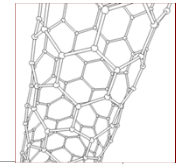
Acknowledgements



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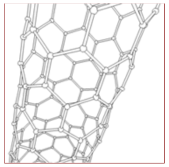

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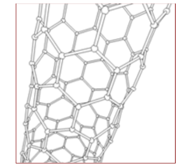

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  - **Ian Papautsky (U. Cincinnati)**
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Industry Partners (DARPA-MF[3] Center)

- **Douglas Scientific**
- **Pioneer Hi-Bred International, Inc.**
- **IDEX Health & Science**
- **SHRINK Nanotechnologies**
- **Microfluidic Innovations**
- **ESI Group**
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- **BIOCOM**

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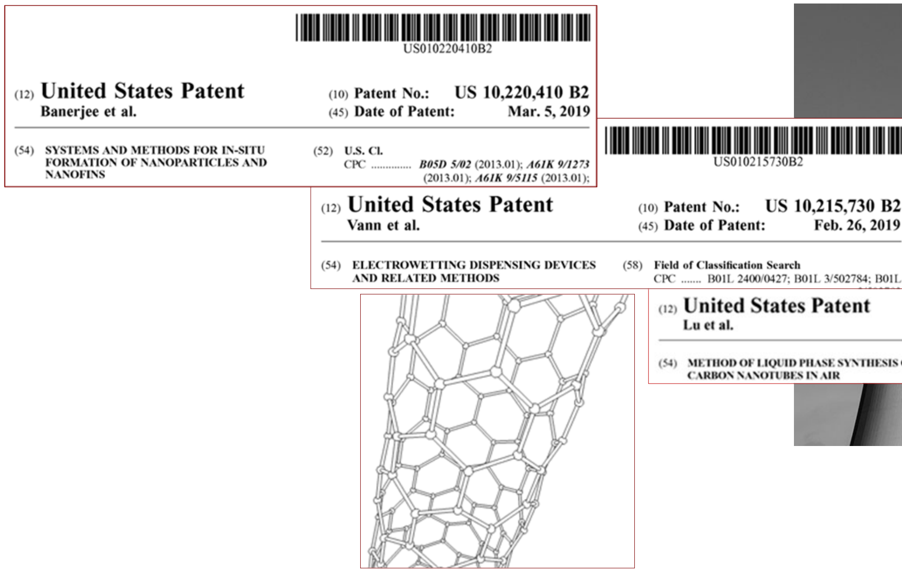
- **Invitrogen**
- **Applied Biosystems (Life Technologies)**
- **Irvine Sensors Corporation**

Contact Information


US010220410B2
(12) United States Patent
Banerjee et al.
(10) Patent No.: US 10,220,410 B2
(45) Date of Patent: Mar. 5, 2019
(54) SYSTEMS AND METHODS FOR IN-SITU FORMATION OF NANOPARTICLES AND NANOFINS
(52) U.S. Cl.
CPC *B05D 5/02* (2013.01); *A61K 9/1273* (2013.01); *A61K 9/5115* (2013.01);

US010215730B2
(12) United States Patent
Vann et al.
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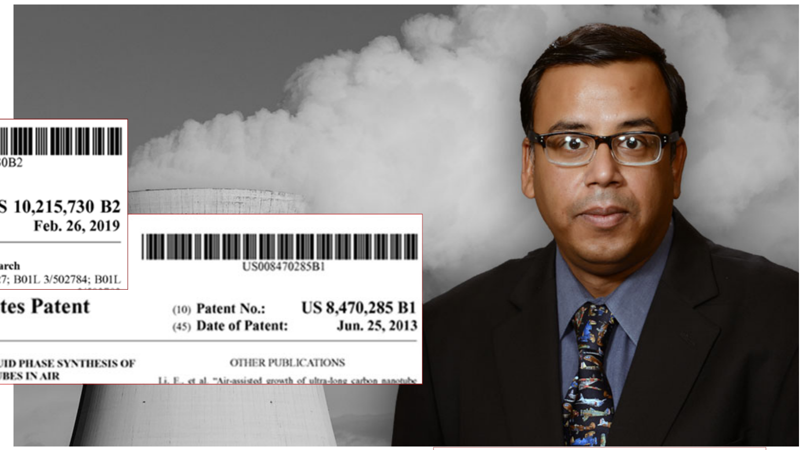
US008470285B1
(12) United States Patent
Lu et al.
(10) Patent No.: US 8,470,285 B1
(45) Date of Patent: Jun. 25, 2013
(54) METHOD OF LIQUID PHASE SYNTHESIS OF CARBON NANOTUBES IN AIR
OTHER PUBLICATIONS



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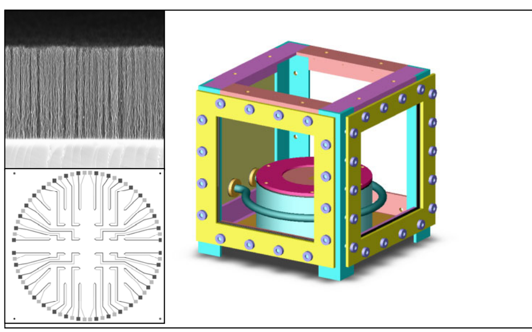
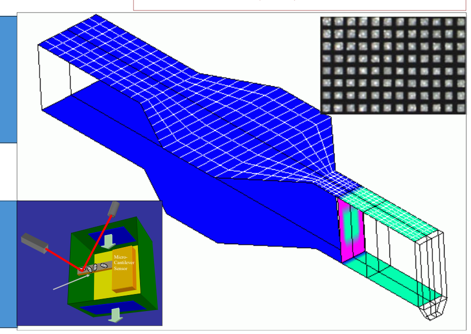


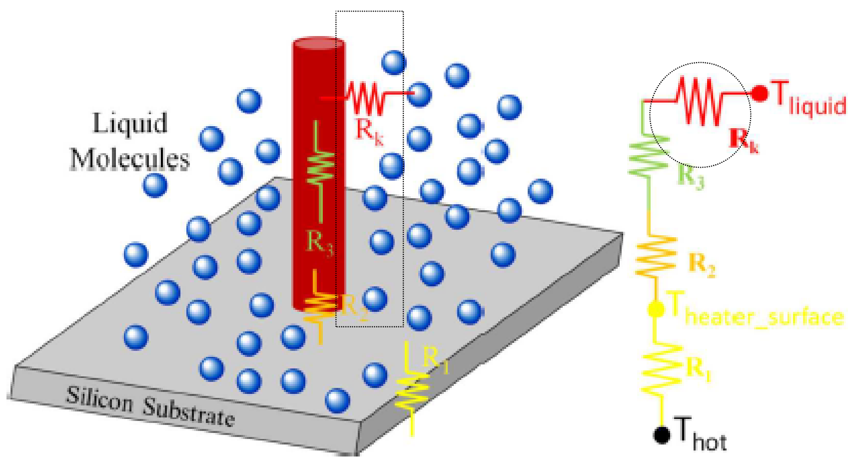
Thermal-Fluids Technologies

Emerging Technologies



Interfacial Thermal Resistance

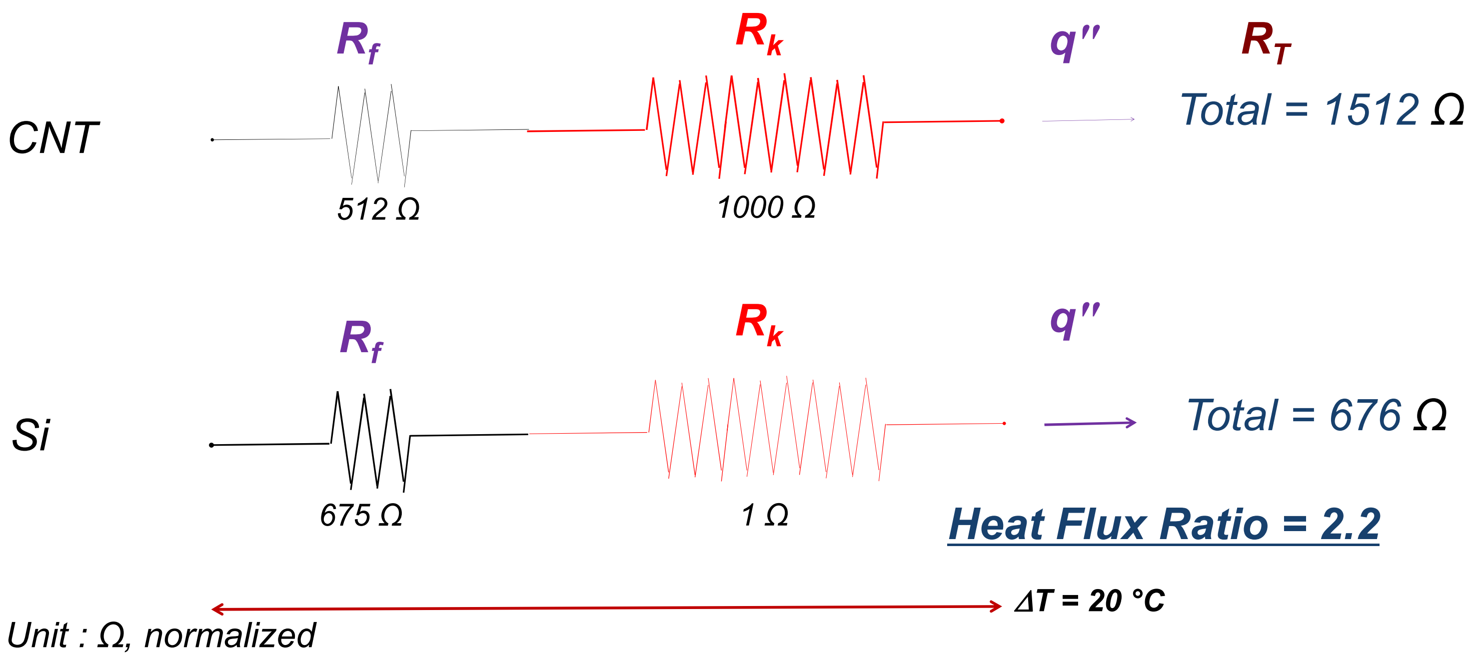
Interfacial thermal resistance :between nanofin and liquids[1)]



1) N. Singh, & D. Banerjee, Nanofins: Science and applications, Springer, 2013

nanoFin Effect (nFE)

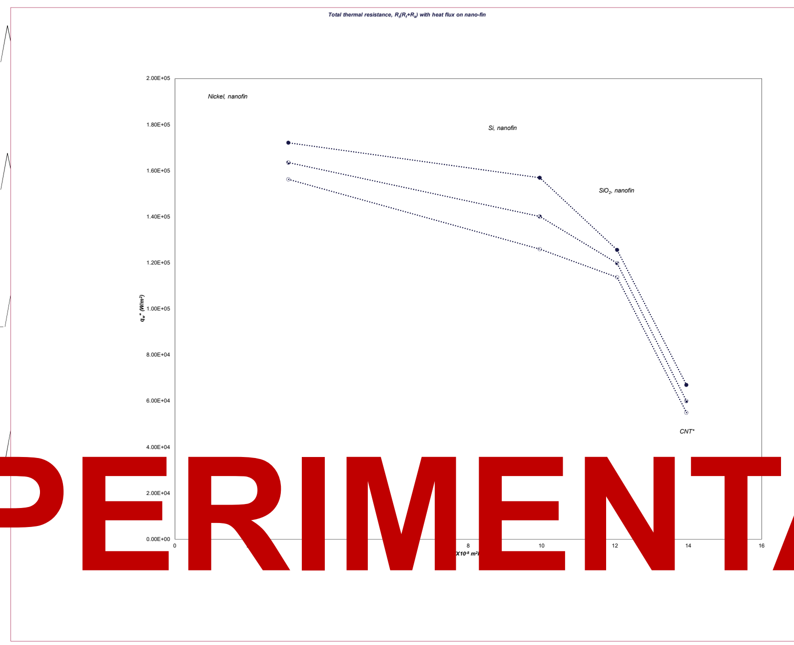
Interfacial thermal resistance (R_k) is critical for heat transfer between solid and liquid.



nanoFin Effect (nFE)

Interfacial thermal resistance (R_k) is critical for heat transfer between solid and liquid.

	R_f Conduction thermal resistance	R_k Interfacial thermal resistance	q''	R_T
CNT				Total = 206 Ω
SiO_2				Total = 179 Ω
Si				Total = 147 Ω
Ni				Total = 46 Ω



Unit : Ω, normalized

EXPERIMENTAL VALIDATION

Mechanisms

- Three Modes:
  - Mode I: Higher specific heat of nano-particles
  - Mode II: Particle-Fluid Interfacial Interactions
  - Mode III: "Semi-Solid" Layering of the Liquid Phase on the nano-particle

$$C_{p,TOTAL} = x \bullet C_{p,particle} + (1-x) \bullet C_{p,fluid}$$

$$C_{p,TOTAL} = x \bullet C_{p,particle} + y \bullet C_{p,compressed-phase} + (1-x-y) \bullet C_{p,fluid}$$

- Shin and Banerjee, *2012,* ASME. J. Heat Tr. (in press)
- Shin and Banerjee, *2011,* Int.. J. Heat & Mass Tr.
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- Shin and Banerjee, *2010, Int. J. of Str. Chg. In Solids*
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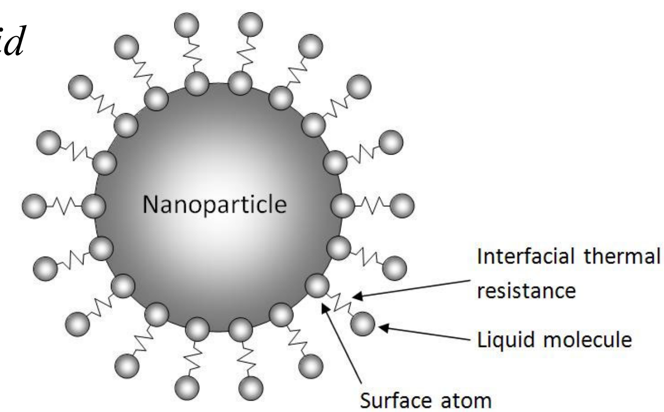
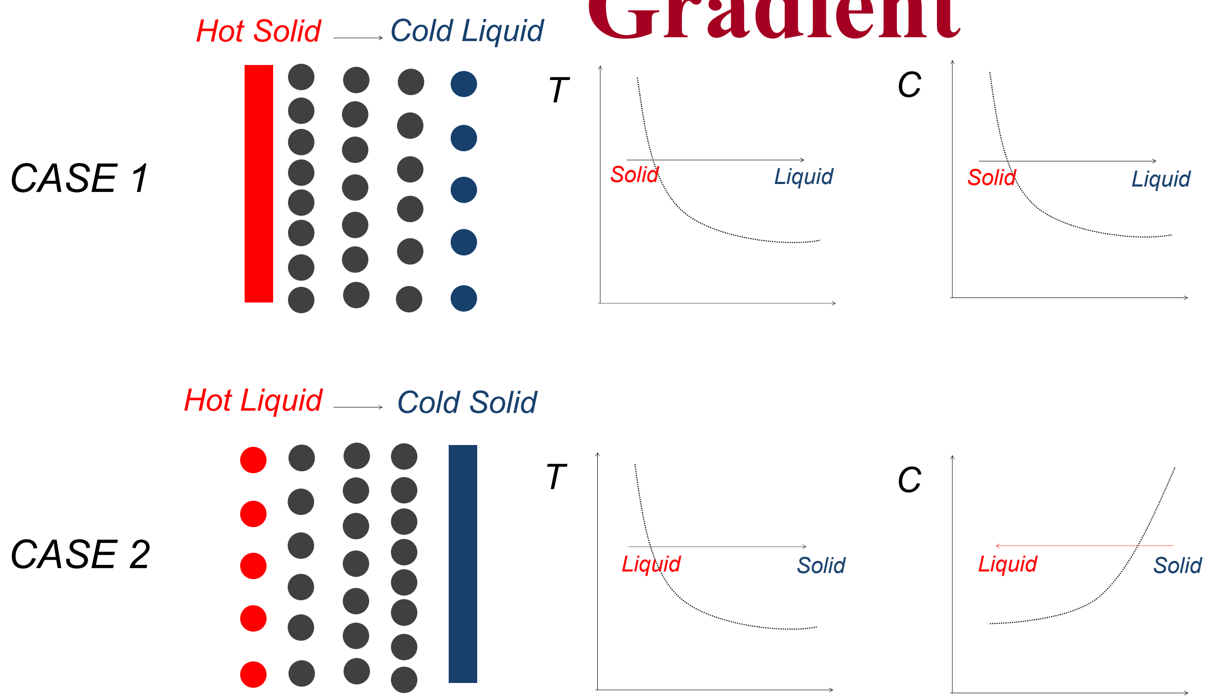


Temperature & Concentration Gradient



Temperature and concentration gradient has same direction at CASE1, but it has opposite direction at CASE2, hence this drive the heat flux bias .

Thermal Diode

1) Heat flux by temperature and concentration gradient

$$q'' = \sum h_i J_i - K\nabla T = \bar{h}J_x - K\nabla T \quad \text{and} \quad J_x = -\rho D\nabla C - \rho D_T C_o(1-C_o)\nabla T \longrightarrow q'' = -\rho D\bar{h}\nabla C - [\rho\bar{h}D_T C_o(1-C_o) + K]\nabla T$$

2) Define dimensionless parameter

$$q_o'' = K\frac{(T_s - T_\infty)}{L_c} \quad Nu = \frac{hL_c}{K} = \frac{(q''/\Delta T)L_c}{K} = \frac{q''}{q_o''} \quad q'' = q_o'' Nu \quad \theta = \frac{T - T_\infty}{T_s - T_\infty} \quad C^* = \frac{C - C_\infty}{C_s - C_\infty} \quad \nabla C = \nabla C^* \frac{(C_s - C_\infty)}{L_c} \quad \nabla T = \nabla\theta\frac{(T_s - T_\infty)}{L_c}$$

3) Dimensionless analysis

$$K\frac{(T_s - T_\infty)}{L_c}Nu = -\rho\bar{h}D\frac{(C_s - C_\infty)}{L_c}\nabla C^* - [\rho\bar{h}D_T C_o(1-C_o) + K]\frac{(Ts - T\infty)}{L_c}\nabla\theta \longrightarrow Nu = -\frac{\rho\bar{h}D}{K}\frac{(C_s - C_\infty)}{(T_s - T_\infty)}\nabla C^* - [\frac{\rho\bar{h}D_T}{K}C_o(1-C_o) + 1]\nabla\theta$$

4) Nu. Number for diode effect

CASE1($Nu._f$): Hot solid → Cold liquid

$$Nu._f = -\frac{\rho\bar{h}D}{K}\frac{(C_s - C_\infty)}{(T_s - T_\infty)}\nabla C^* - [\frac{\rho\bar{h}D_T}{K}C_o(1-C_o) + 1]\nabla\theta$$

Same direction

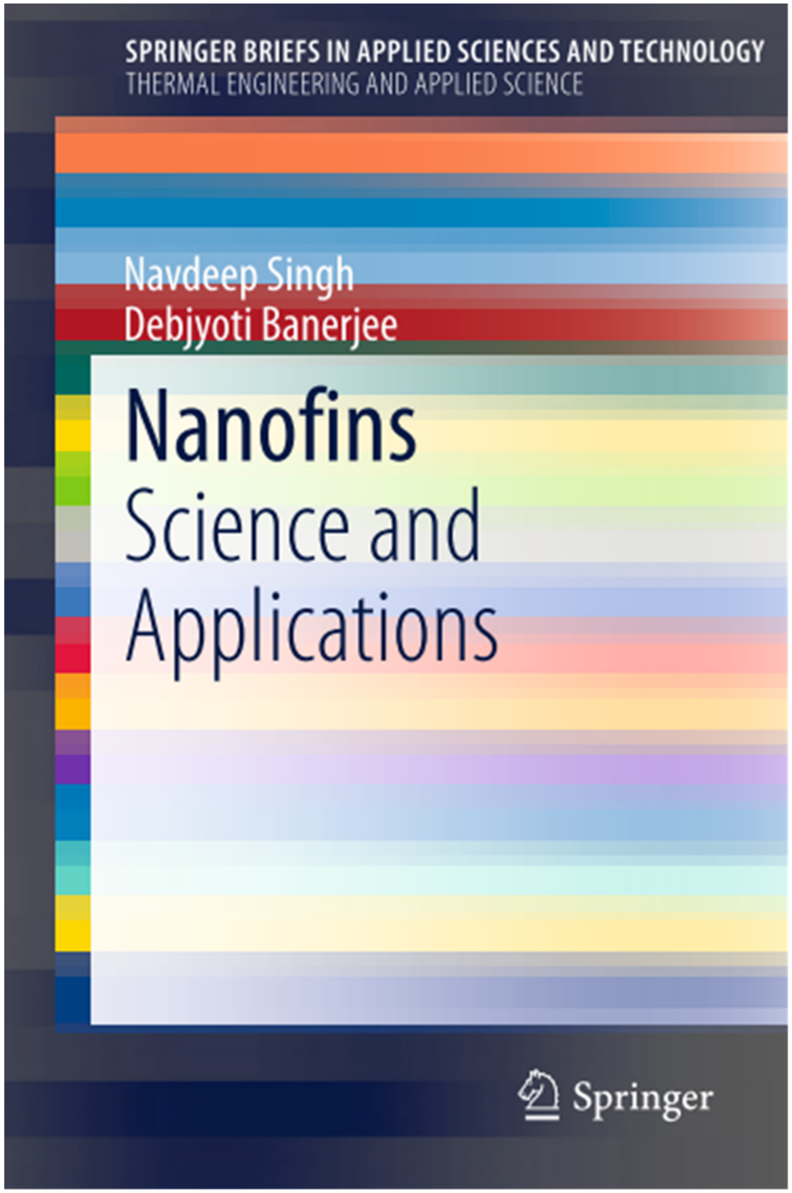
Opposite direction

CASE2($Nu._b$): Hot liquid → Cold solid

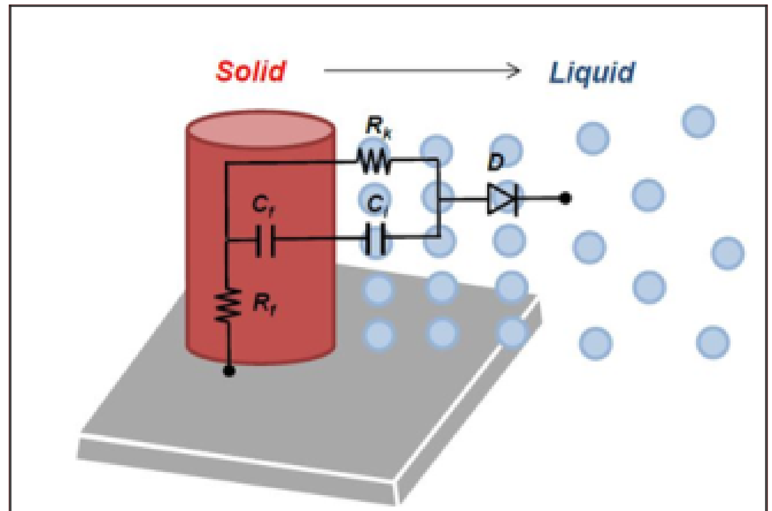
$$Nu._b = \frac{\rho\bar{h}D}{K}\frac{(C_s - C_\infty)}{(T_s - T_\infty)}\nabla C^* - [\frac{\rho\bar{h}D_T}{K}C_o(1-C_o) + 1]\nabla\theta$$

$Nu._D = Nu._f - Nu._b$

$$Nu._D = Nu._f - Nu._b = -2\frac{\rho\bar{h}D}{K}\frac{(C_s - C_\infty)}{(T_s - T_\infty)}\nabla C^*$$



"*nano*Fin Effect"



Corrosion reduced by 50~100%

Work in collaboration with Dr. Diana Berman:
Lee, J., Kuchibhotla, A.*, Banerjee, D., and Berman, D., "Silica Nanoparticles as copper corrosion inhibitors", Materials Research Express, May, 2019.*
https://doi.org/10.1088/2053-1591/ab2270