Impairment of Heat Transfer in the Passive Cooling System due to Mixed Convection

May, 12-13, 2016

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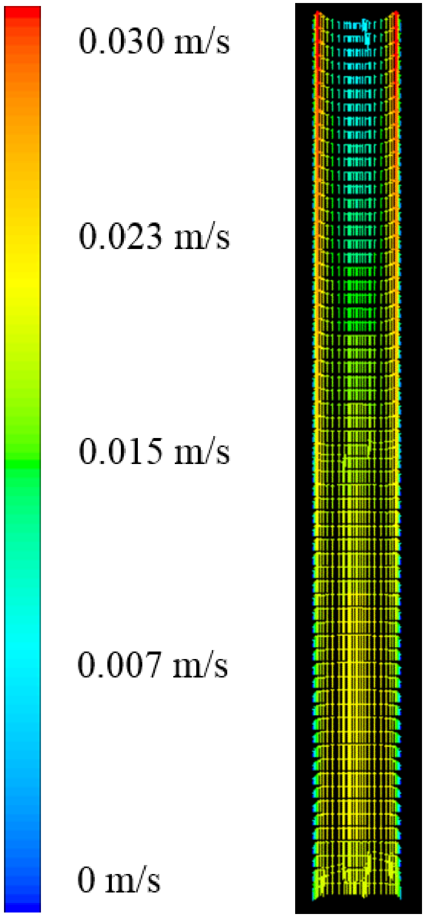
Introduction (1/3)

- Adoption of the Passive Cooling System has been increasing
  - The concept of passive safety is emphasized in design of NPP to accomplish the enhanced safety goal
- The passive cooling system focused on the Natural convection cooling and heat transfer
  - Under accident conditions to remove the residual heat out of the containment
- The Reactor Cavity Cooling System (RCCS) is the passive cooling system
  - Very High Temperature Reactor (VHTR) designed to remove the residual and decay heat

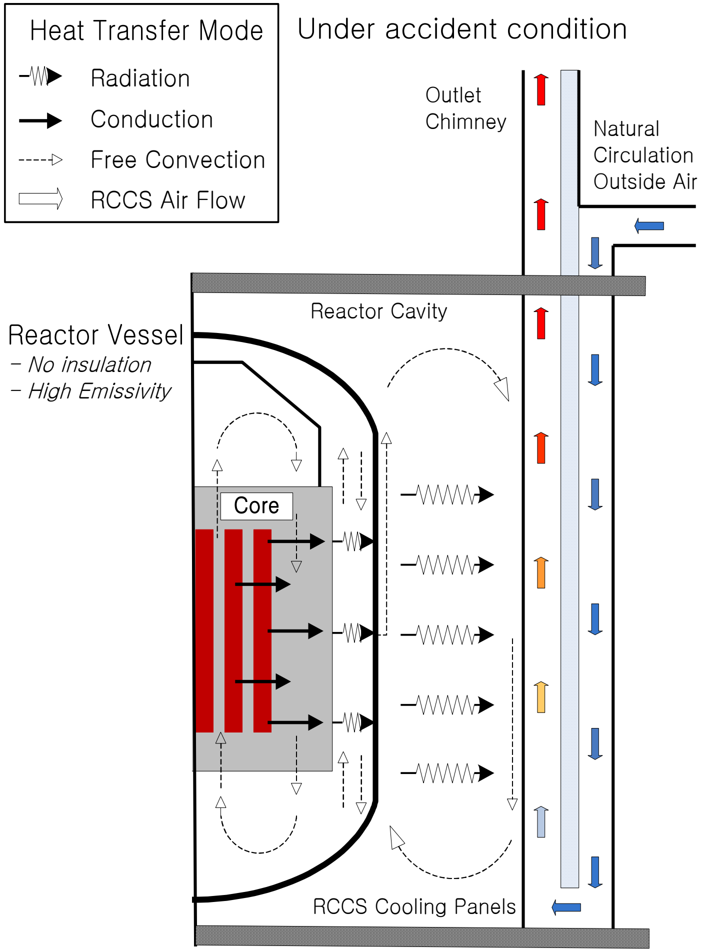
Introduction (2/3)

- When the natural convection occurs in the long enough heated section,
- The flow regime becomes similar to the forced convection
  - Due to the duct flow condition
- This force convective flow together with the local buoyancy effect can form
  - Complex mixed convective flow condition



Introduction (3/3)

- RCCS(Reactor Cavity Cooling System)?
  - The decay heat transfers from the fuels to the graphite by Conduction
  - It transfers to reactor vessel and RCCS cooling panels (Riser tube) by Radiation and Convection
  - The buoyant flows are induced in riser tubes (The fluid temperature ↑, Density↓)
  - Natural circulation of fluid in riser tubes occurs
- This paper discuss
  - Local heat transfer rate in riser tube can be impaired due to the Mixed convective flows



[J.H. Kim et al., KAERI, 2015]

Background (1/4)

- Convective heat transfer is described in one mode which mode is mainly dominated as heat transfer phenomena (Mode : Natural convection, Forced convection)

- Pure forced convection
  - When the flow is generated by external force, effect of natural convection can be neglected in heat transfer

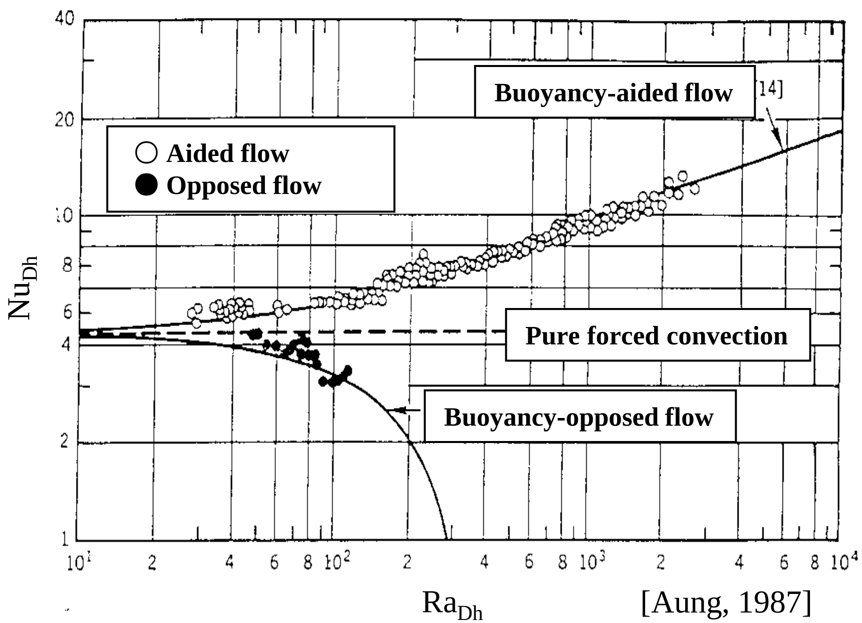
- Mixed convection
  - When the flow is generated by internal and external force, the natural convection should be considered
  - The Mixed Convective flow is influenced both by *Re* and *Gr*
  - The governing parameter B_o should be the combination of both numbers

- B_o, lots of different combinations were used depending on the investigators

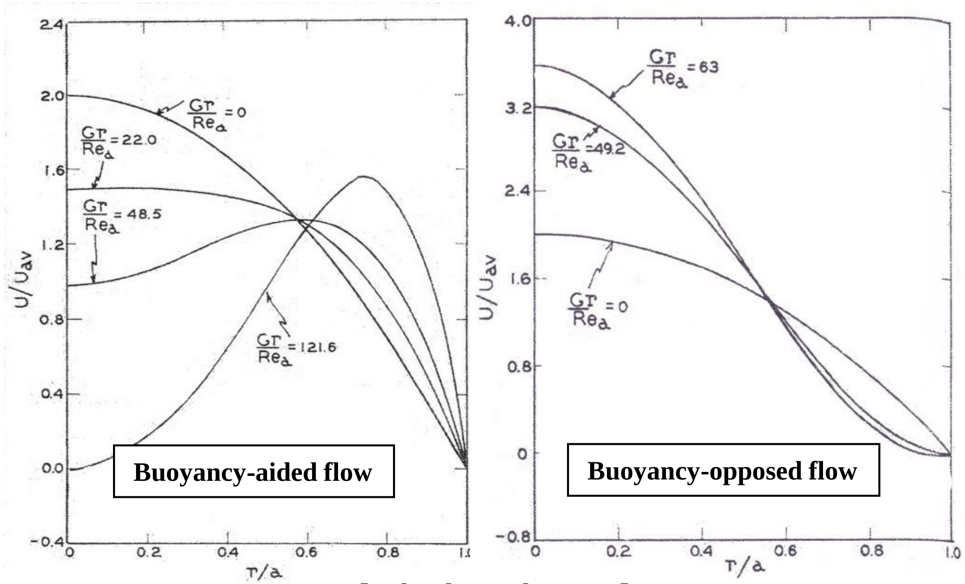
Gr / Re^2	$Gr / Re^{3.636} Pr^{0.818}$	$Gr / Re^{3.425} Pr^{0.8}$	$8 \times 10^4 Gr / Re^{3.425} Pr^{0.8}$
[Easby, 1978]	[Alferov et al., 1973]	[Rouai, 1987]	[Hall and Jackson, 1969]

Background (2/4)

- Heat transfer behavior in Laminar flow



[Aung, 1987]

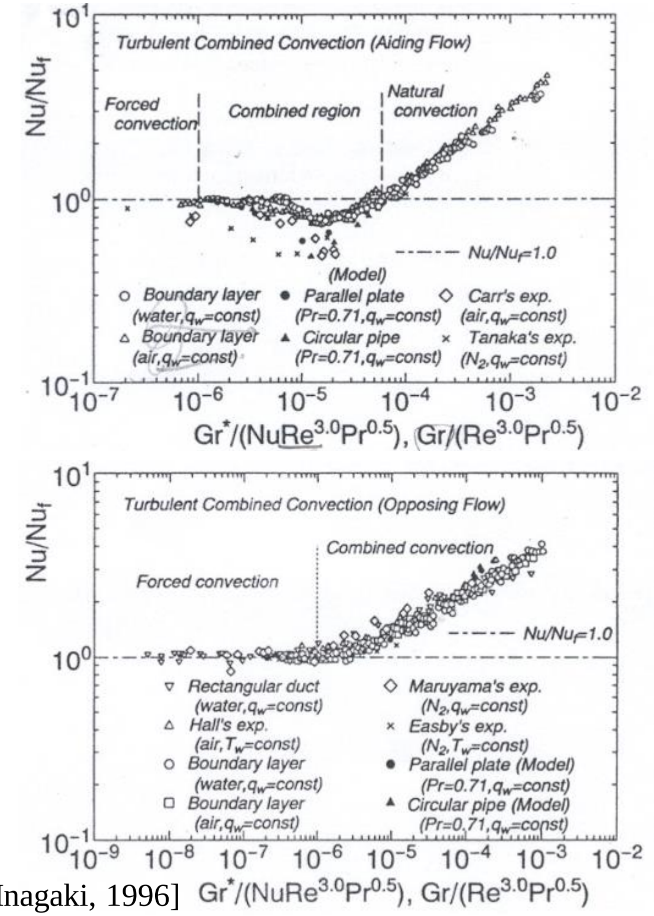


[Scheele et al., 1960]

- Buoyancy-aided flow : Enhanced *Nu* compared to the forced convection
  → Velocity enhances near the heated wall
- Buoyancy-opposed flow : Impaired *Nu* compared to the forced convection
  → Flow velocity reduced

Background (3/4)

- Heat transfer behavior in Turbulent flow

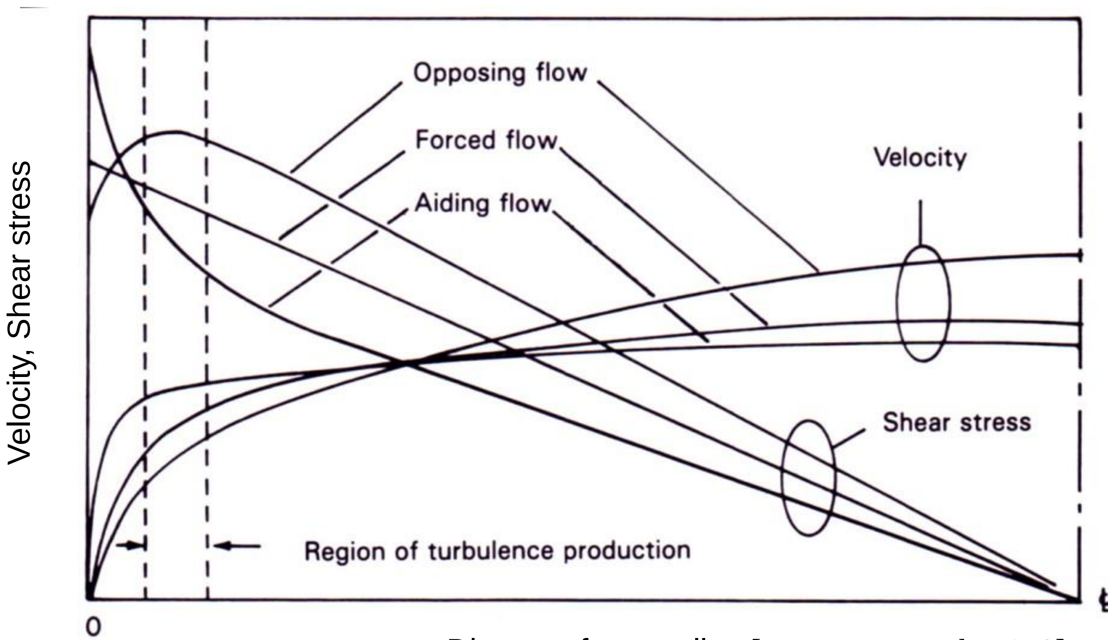


[Inagaki, 1996]

- Buoyancy-aided flow
  - An impairment of the heat transfer rate for small buoyancy
    → Laminarization
    → Same direction of buoyancy impaired turbulence production
  - Then, a gradational enhancement for large buoyancy (over critical *Gr*)
- Buoyancy-opposed flow
  - Enhanced of the heat transfer rate
    → Increased turbulence production

Background (4/4)

- Turbulence production

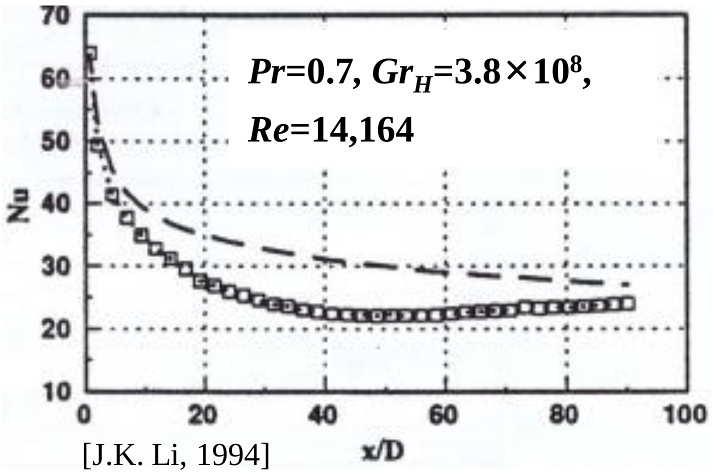


[Joye, Wojnovich, 1978]

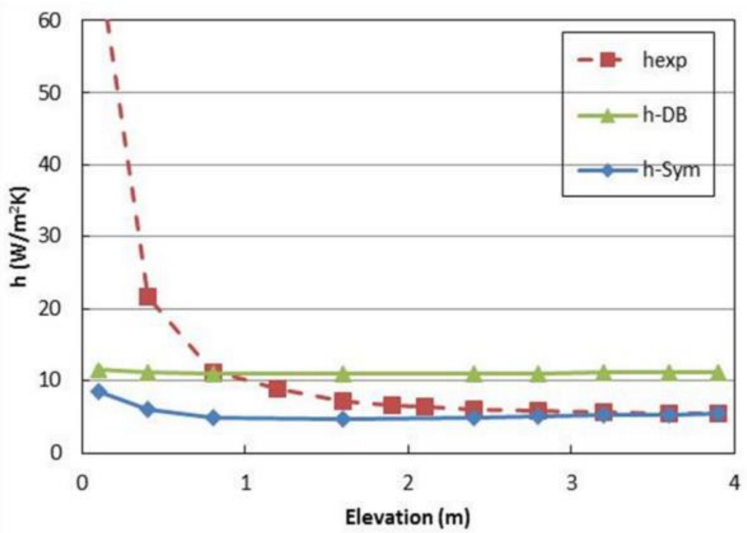
- The region of turbulence production is **Edge of viscous sublayer**
- Proportion of shear stress, velocity gradient

Analysis

- The local *Nu* of the axial position pipe was impaired in certain local *Gr* and *Re* range correspond to the forced convection (Laminarization)
- The local *Nu* is recovered or enhanced
  → This can be associated with the recovery of turbulence production



[J.K. Li, 1994]



– The *Nu* distribution exhibits the non-monotonic behavior

[J.H. Kim et al., KAERI, 2015]

Mass transfer experiments using analogy concept

- Governing equations

Heat transfer	Mass transfer
$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0$	
$\rho\frac{Du}{Dt}=-\frac{\partial P}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+X$	
$\frac{DT}{Dt}=\alpha\nabla^2 T$	$\frac{DC}{Dt}=D_m\nabla^2 C$

- Dimensionless numbers

Heat transfer	Mass transfer
$Nu=\frac{h_h L}{k}$	$Sh=\frac{h_m L}{D_m}$
$Pr=\frac{\nu}{\alpha}$	$Sc=\frac{\nu}{D_m}$
$Ra=\frac{g\beta\Delta T L^3}{\alpha\nu}$	$Ra=\frac{gL^3}{D_m\nu}\frac{\Delta\rho}{\rho}$
$Re=\frac{uD_h}{\nu}$	

- Analogy concept

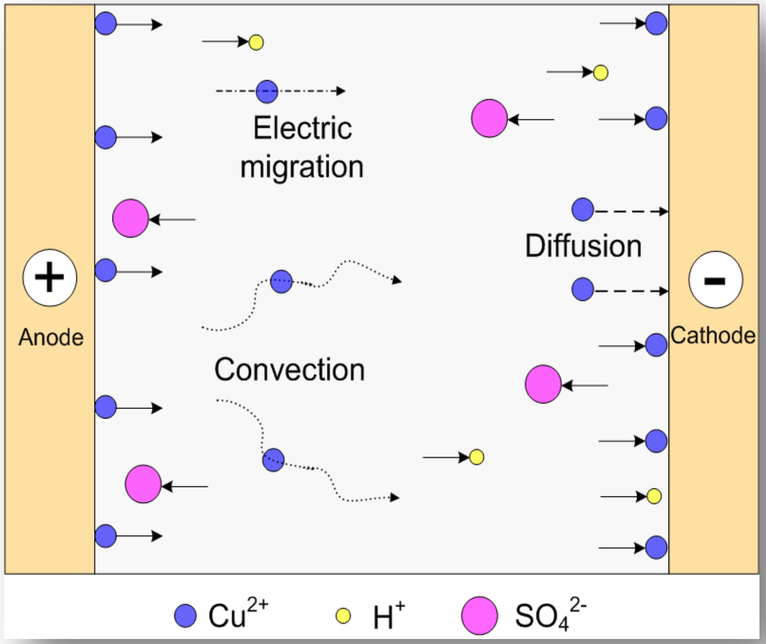
Heat transfer problem = Mass transfer problem

Analogy

Heat transfer solution = Mass transfer solution

Copper Electroplating System

- Measurements were made using limiting electroplating current technique with $CuSO_4$-H_2SO_4



- Total mass transfer rate
  = Electric migration +**Diffusion**+ **Convection**
  $$(N_T = N_{Em} + \boldsymbol{N_D} + \boldsymbol{N_C})$$

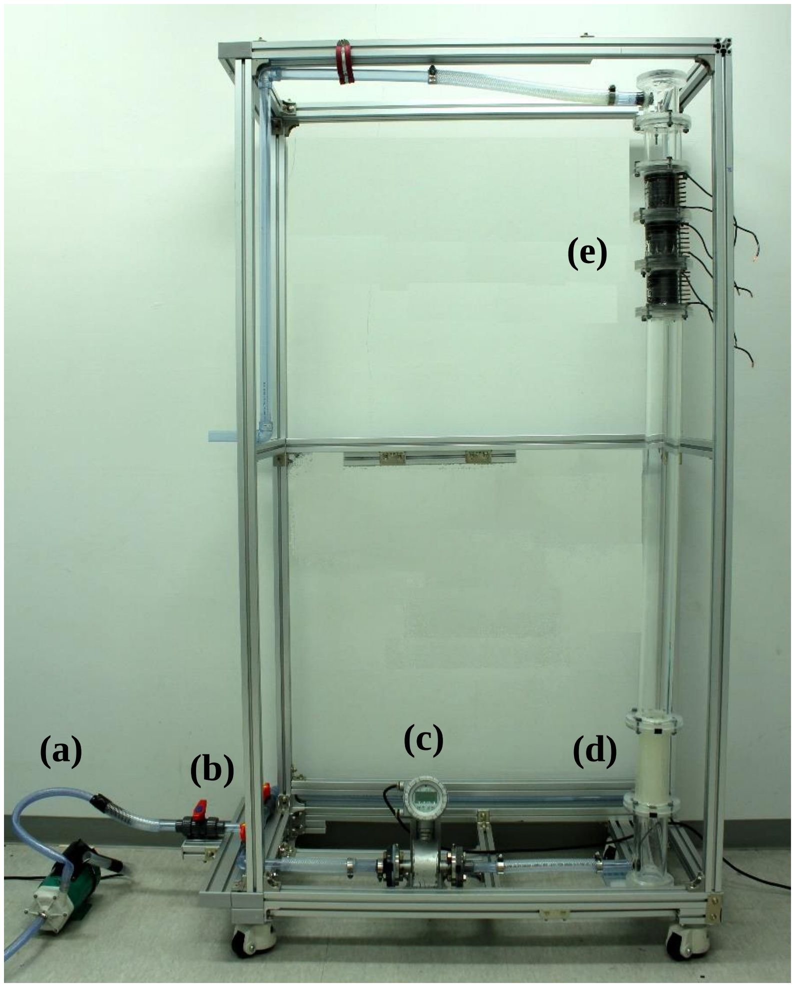
  Not exist in heat transfer, thus minimize it using H_2SO_4

- Mass transfer coefficient

$$h_m = \frac{(1-t_n)I_{lim}}{nF(C_b - C_s)}$$

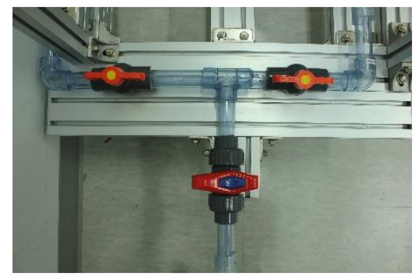
$C_s \approx 0$

Experiments - Apparatus



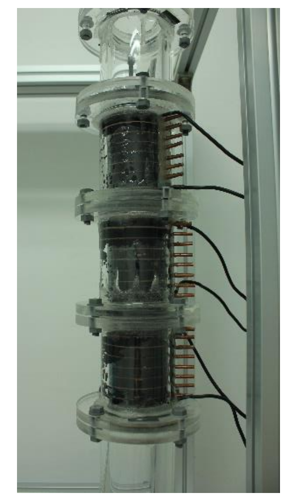
(a) Electric pump

(d) Flow straightener



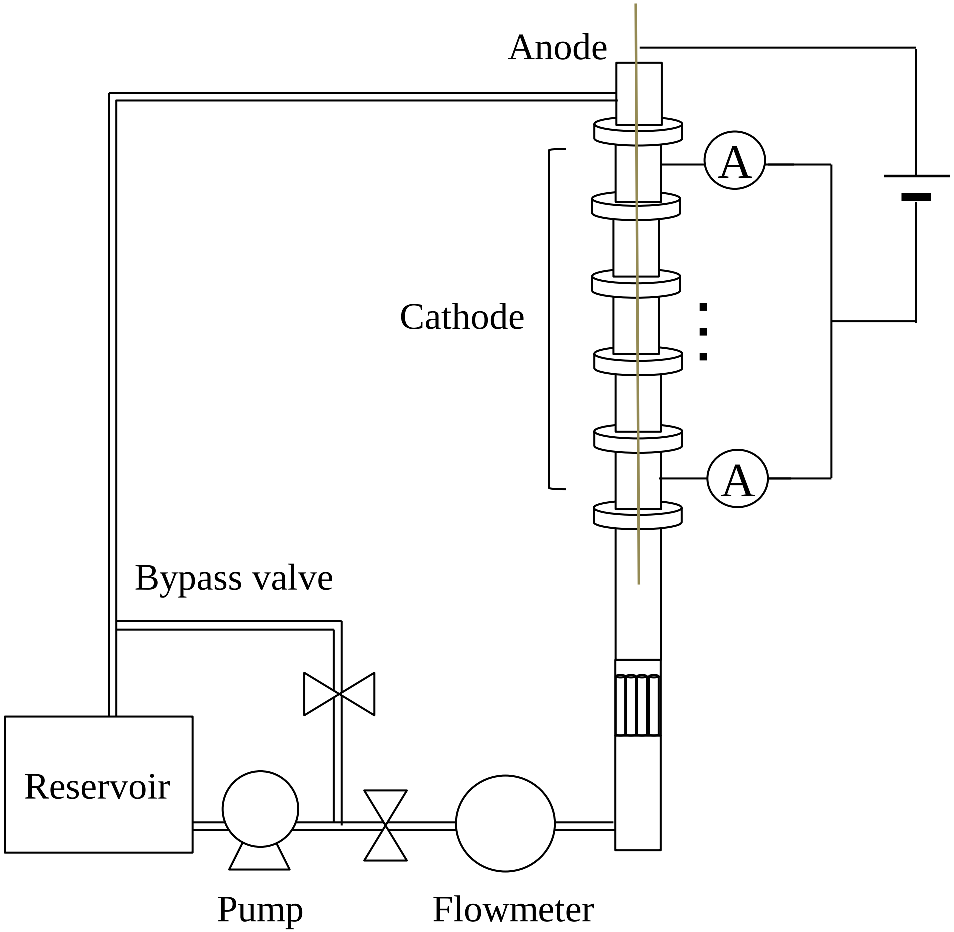
(b) Bypass valve

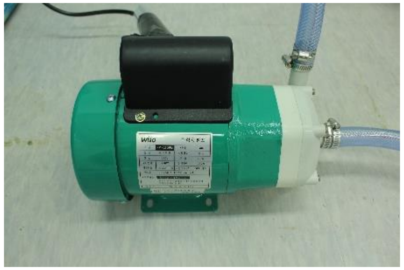
(c) Magnetic flowmeter



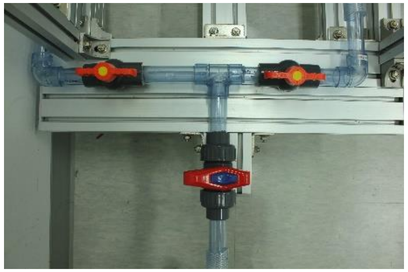
(e) Test section

Experiments - Apparatus





(a) Electric pump



(b) Bypass valve

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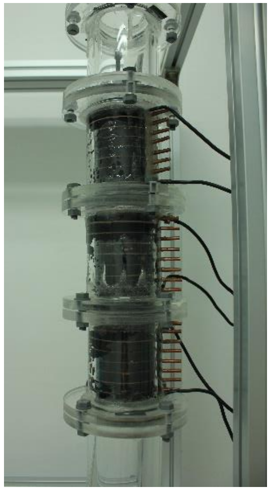
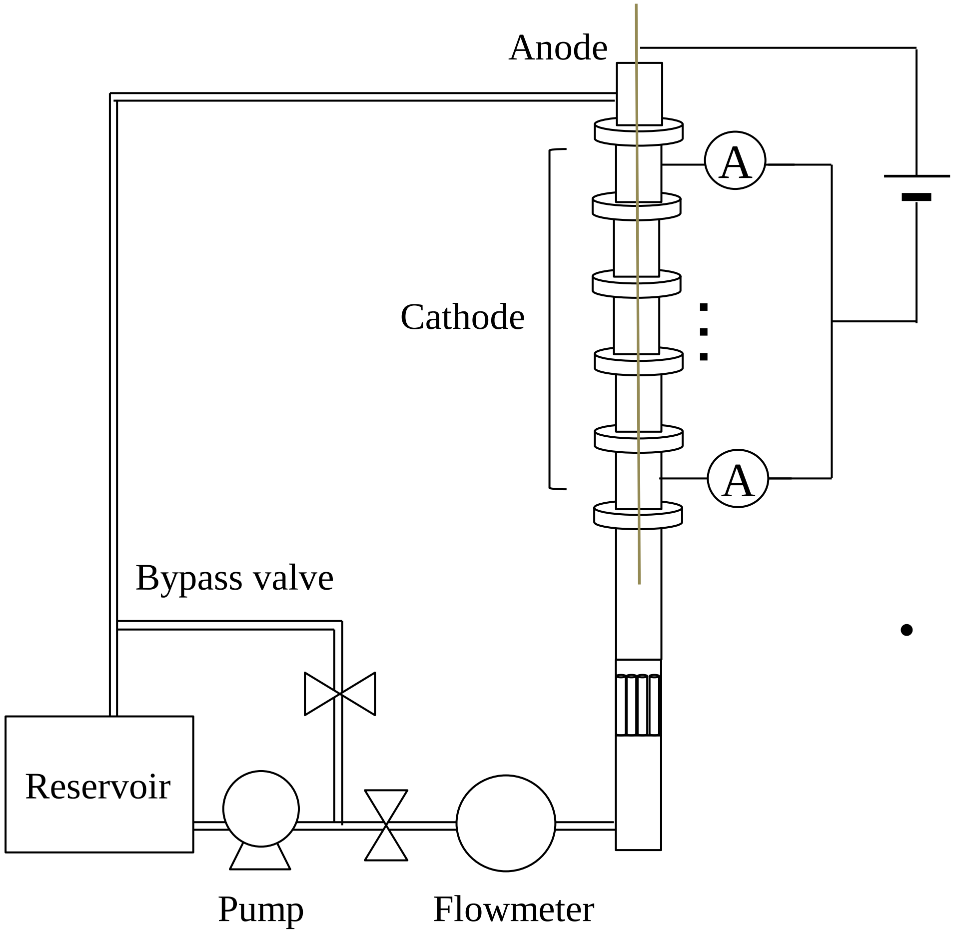
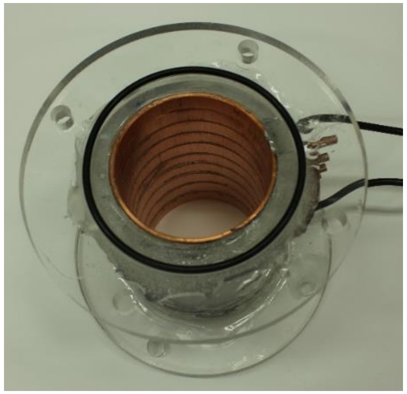


(e) Test section

Experiments - Apparatus





- Adopted piecewise electrodes in order to measure the ***local average Nu***

  – 0.01m × 15 piece (Total length 0.15m)

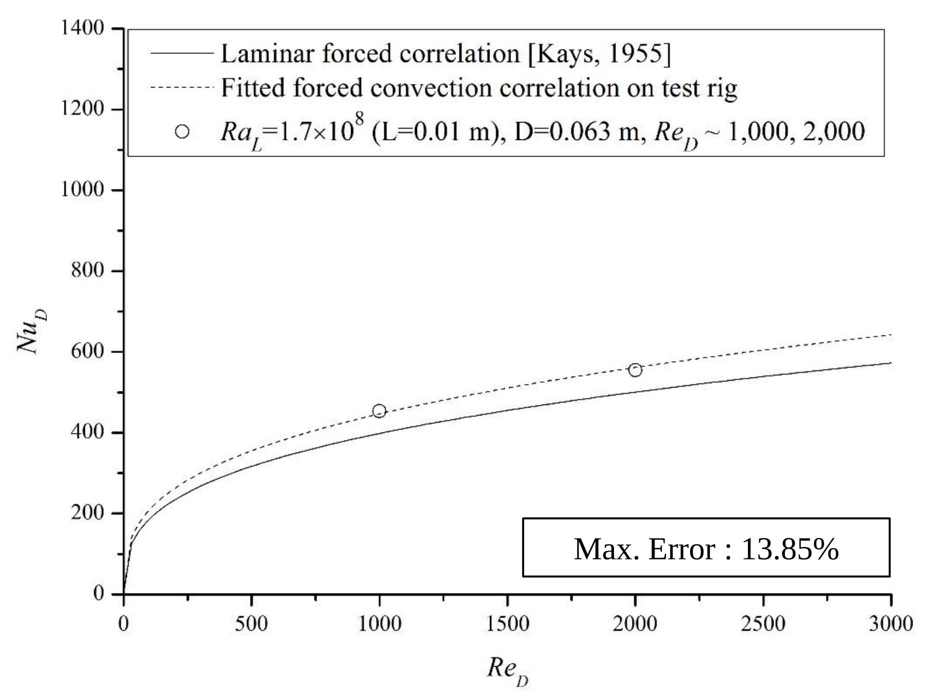
Experiments – Test matrix

	NACEF	Present test facility
Test section type	Rectangular duct	Circular duct
D (m)	0.04 (L=0.24)	0.063
D_h (m)	0.069	0.063
L (m)	4.0	0.15
Velocity (m/s)	1.9	0.11
Re_{Dh}	6,300	
Ra_L	5.7×10^{11}	
Gr_L	8.0×10^{11}	2.7×10^{8}
Pr	0.7	2,094

Pr	D (m)	L (m)	Ra_L	Re_{Dh}
2,094	0.063	0.01	1.7×10^{8}	1,000, 2,000, 6,300, 10,000, 12,800
		0.15	5.7×10^{11}	

Results : Comparison with correlation (1/3)

- Comparison of test results with forced convection correlation (Laminar)
  - Kays (1955) : Laminar forced convection correlation
    (Thermal developing, Hydrodynamic fully developed condition)
  - Fitted forced correlation developed on test rig



- Kays, 1955

$$Nu_D = 3.66 + \frac{0.0668Gz}{1 + 0.04Gz^{2/3}} \quad Pr \geq 5$$

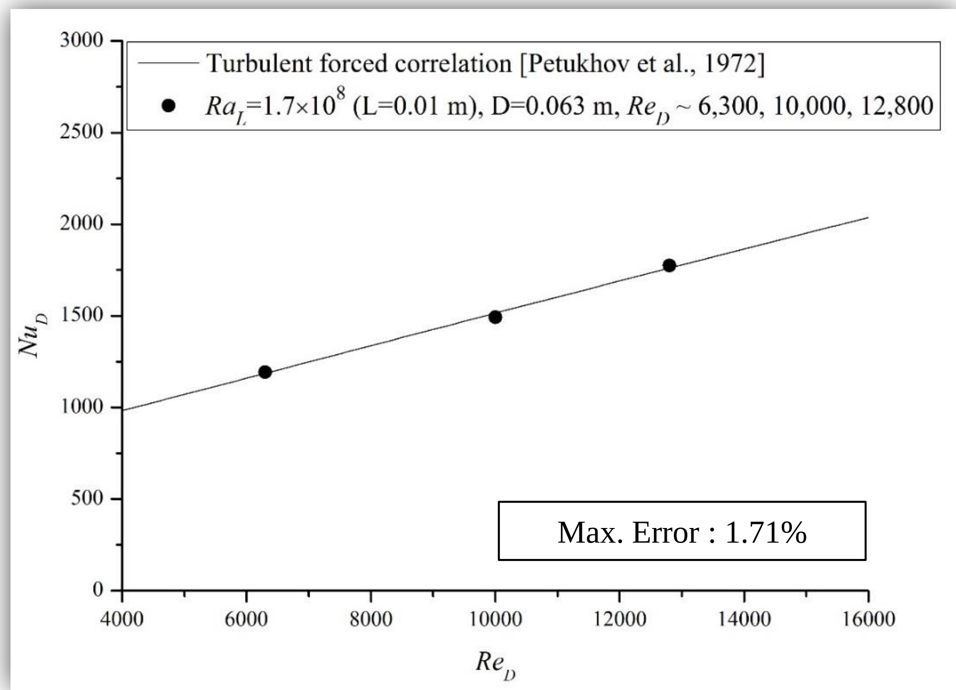
- Fitted correlation

$$Nu_D = 3.66 + \frac{0.075Gz}{1 + 0.04Gz^{2/3}}$$

$$Gz = Re_D Pr(D / L)$$

Results : Comparison with correlation (2/3)

- Comparison of test results with forced convection correlation (Turbulent)
  - Petukhov et al. (1972) : Turbulent forced convection correlation (Thermal developing, Hydrodynamic fully developed condition)



- Petukhov et al., 1972

$$Nu_D = C_{therm.} \times Nu_{fc}$$

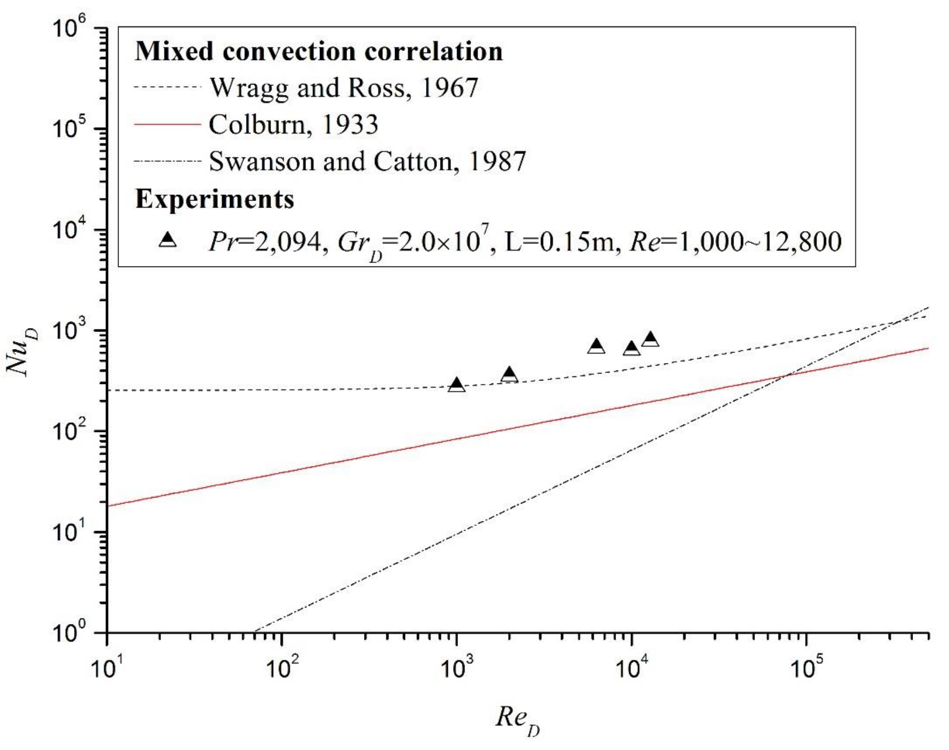
$$Nu_{fc} = \frac{Re \times Pr \times (\frac{f}{8})}{1.07 + (\frac{900}{Re}) - (\frac{0.63}{1 + 10 \times Pr}) + 12.7 \times \sqrt{\frac{f}{8}} \times (Pr^{\frac{2}{3}} - 1)}$$

$$f = \left[1.82 \times log(\frac{Re}{8.0})\right]^{-2}$$

$$C_{therm.} = 1 + 0.48 \times \left(1 + \frac{3600}{Re\sqrt{x/D}}\right) \times \frac{e^{-0.17(x/D)}}{(x/D)^{0.25}}$$

Results : Comparison with correlation (3/3)

- Comparison of test results with mixed convection correlation
  - Similar to Wragg and Ross's correlation



- Wragg and Ross, 1967

$$Sh_D = 1.95\left[Re_D ScD / L + 0.0532 (Gr_D ScD / L)^{0.75} \right]^{0.33}$$

- Colburn, 1933

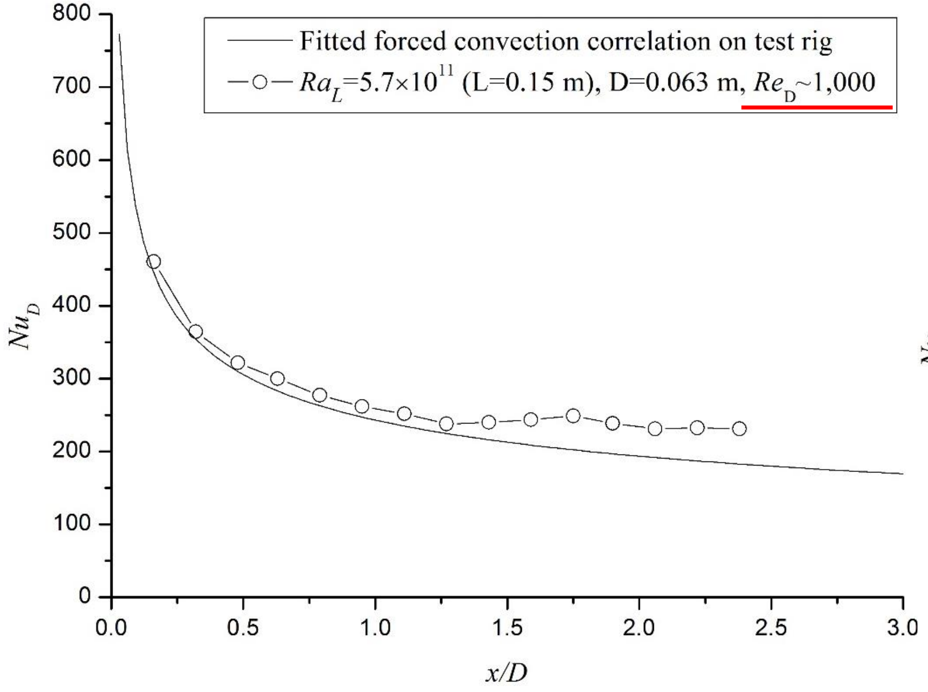
$$Nu_D = 1.65 (Re_D PrD / L)^{1/3} [1 + 0.015 (Gr_D)^{1/3}]$$

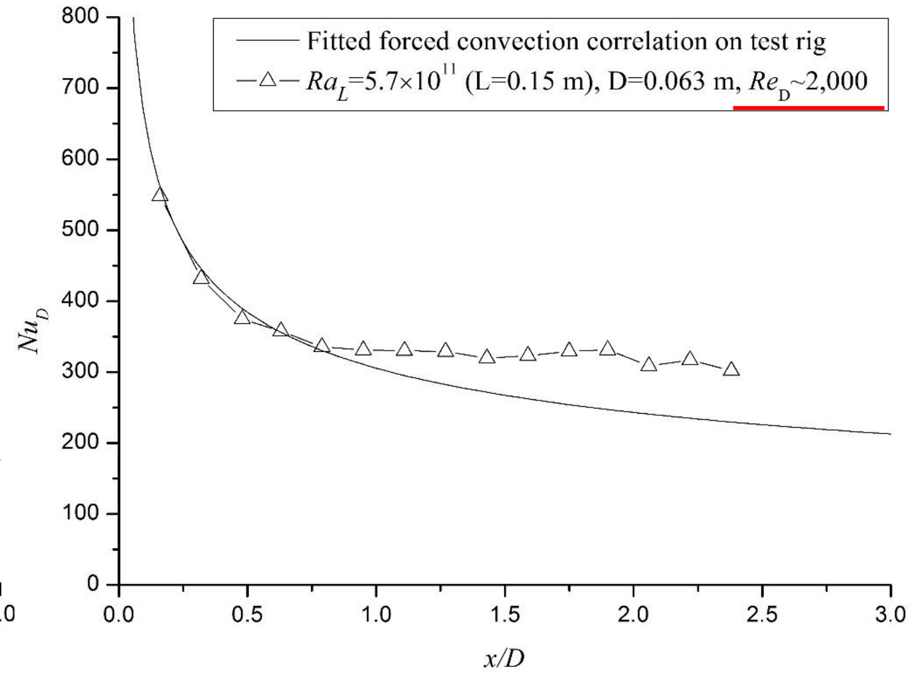
- Swanson and Catton, 1987

$$Nu_D = 0.0115 Re^{0.8} Pr^{0.5} \left[1 + \left\{ 1 - \left(\frac{696}{Re_D^{0.8}} \right) + \left(\frac{8300 Gr_D}{Re_D^{0.26} Pr^{0.5}} \right) \right\}^{0.39} \right]^{-1/3}$$

Results : x/D vs. Nu_D (1/4)

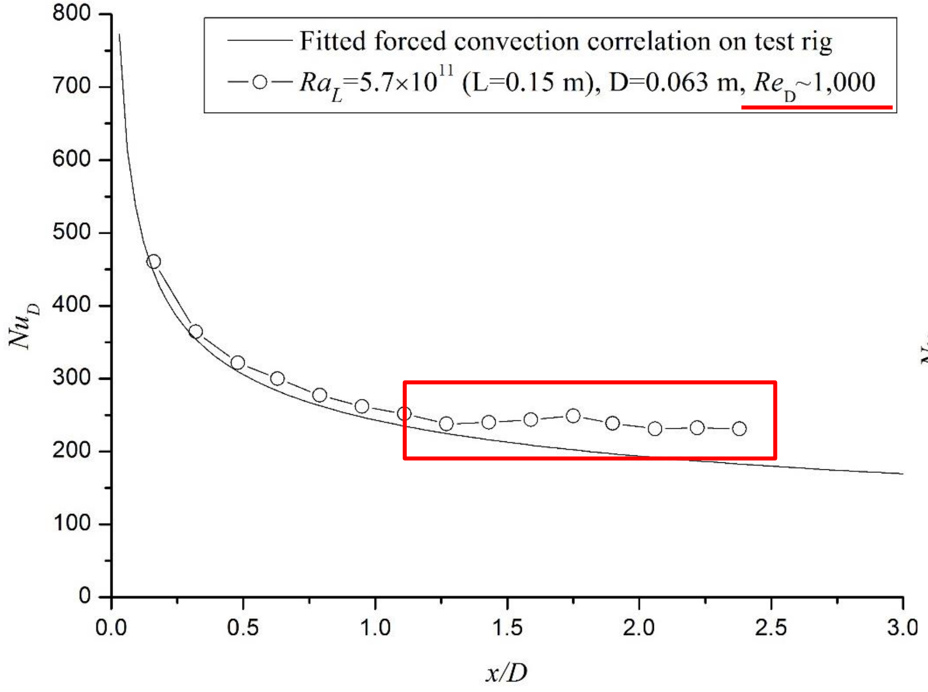
- x/D vs. Nu_D (Laminar flow)

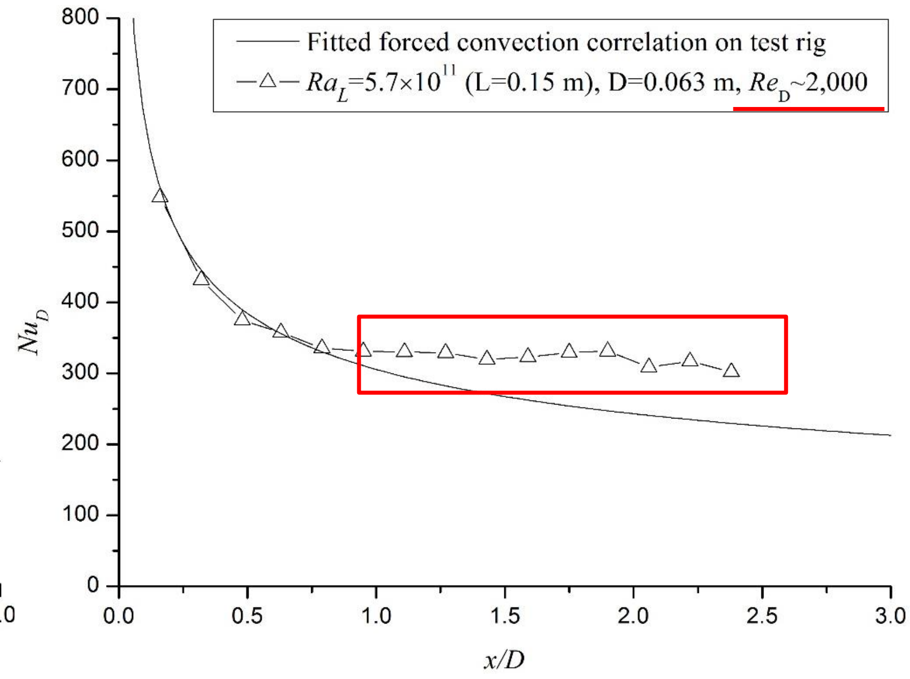




Results : x/D vs. Nu_D (1/4)

- x/D vs. Nu_D (Laminar flow)

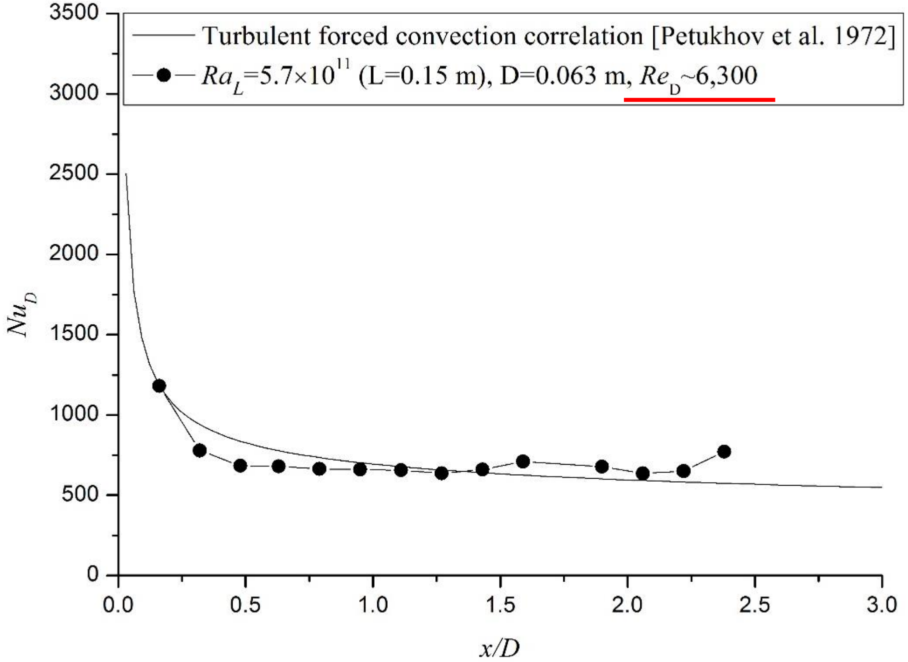


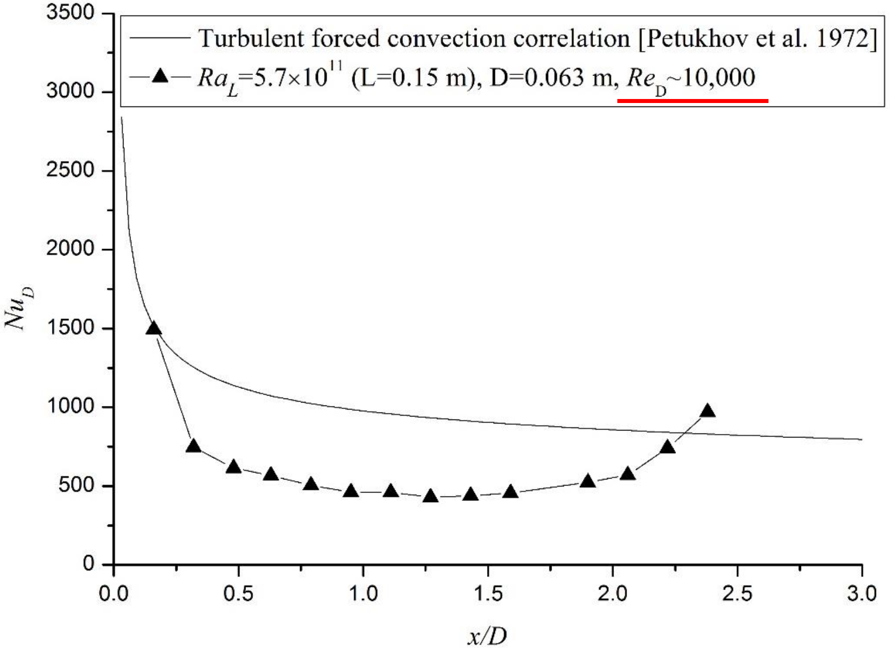


- Increased x/D, Nu_D enhanced → Initial velocity enhanced

Results : x/D vs. Nu_D (2/4)

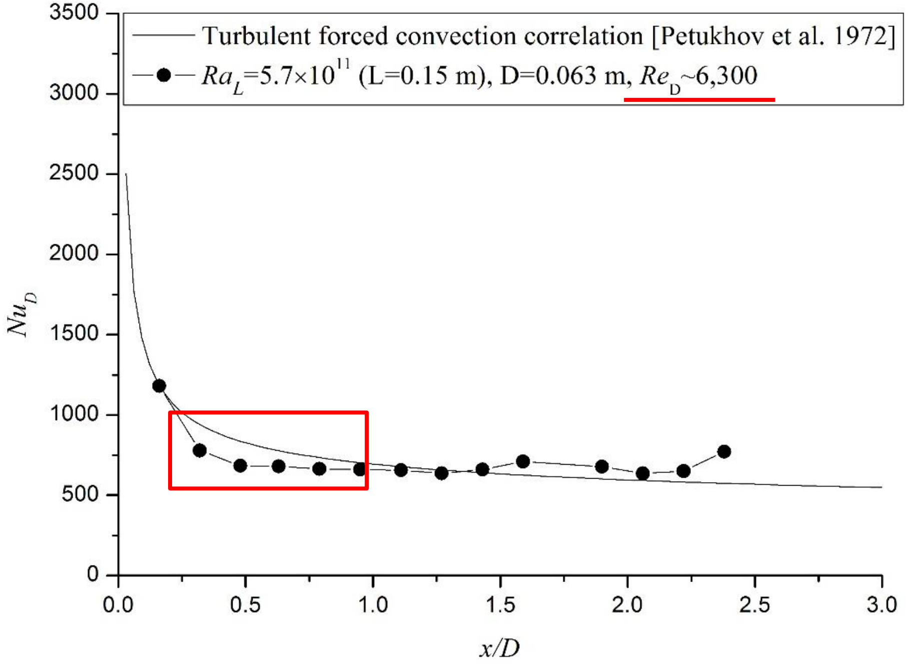
- x/D vs. Nu_D (Turbulent flow)

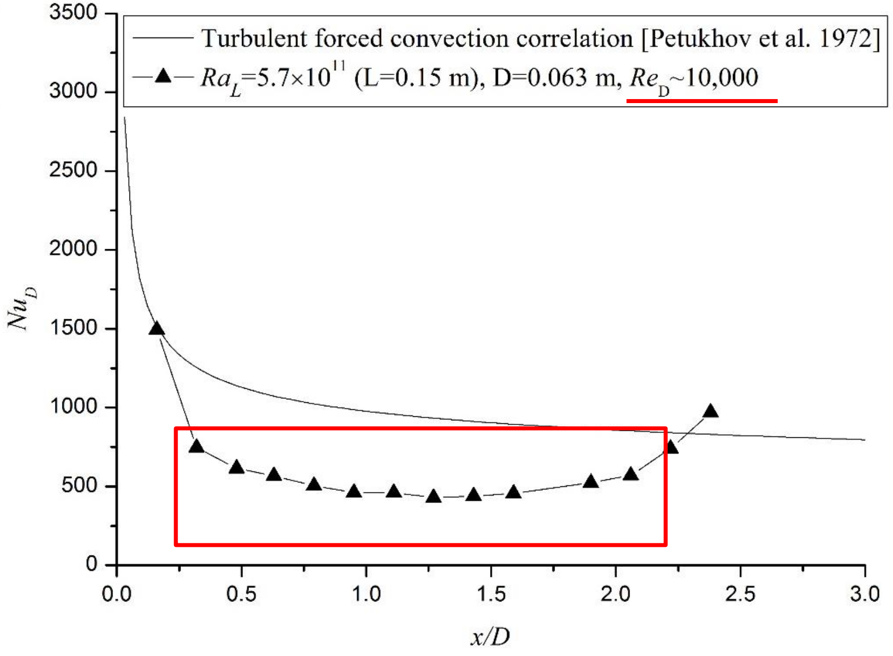




Results : x/D vs. Nu_D (2/4)

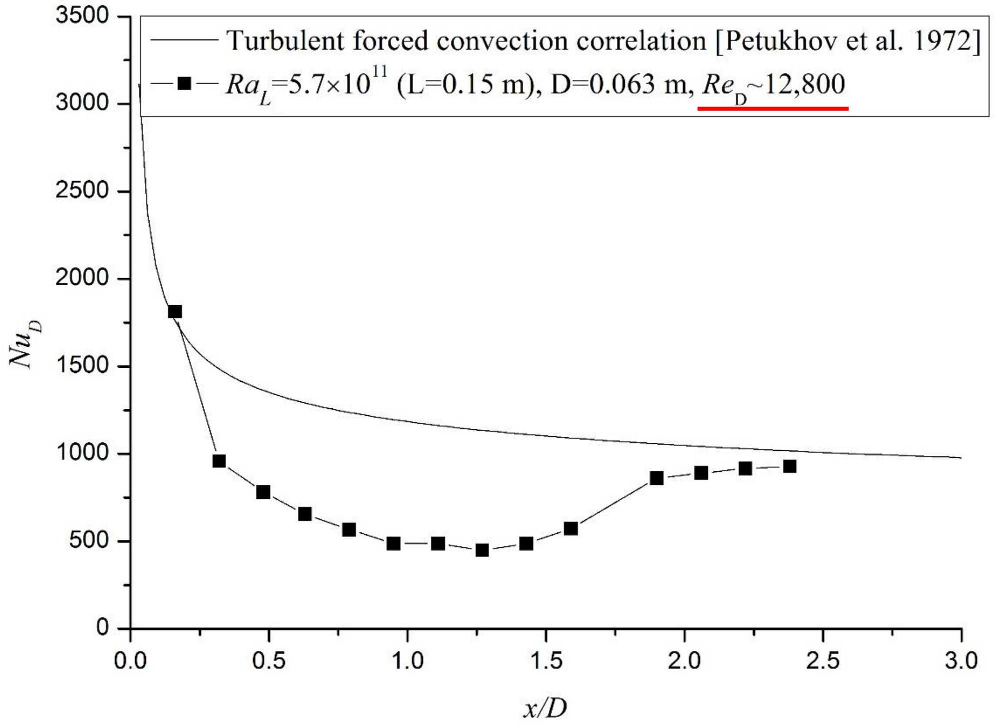
- x/D vs. Nu_D (Turbulent flow)





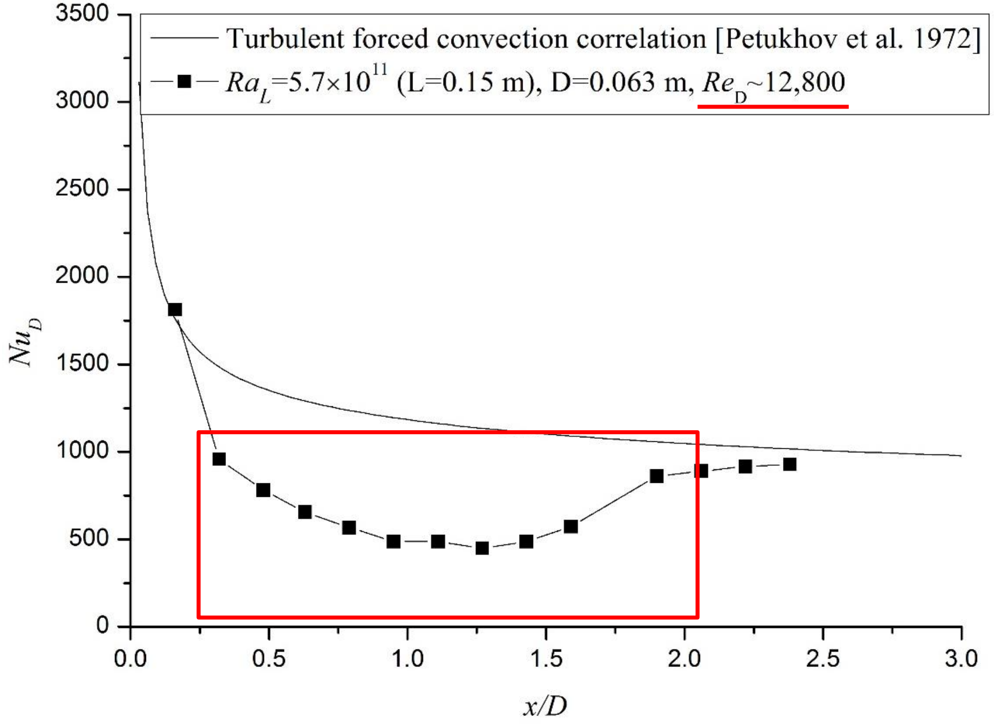
Results : x/D vs. Nu_D (3/4)

- x/D vs. Nu_D (Turbulent flow)



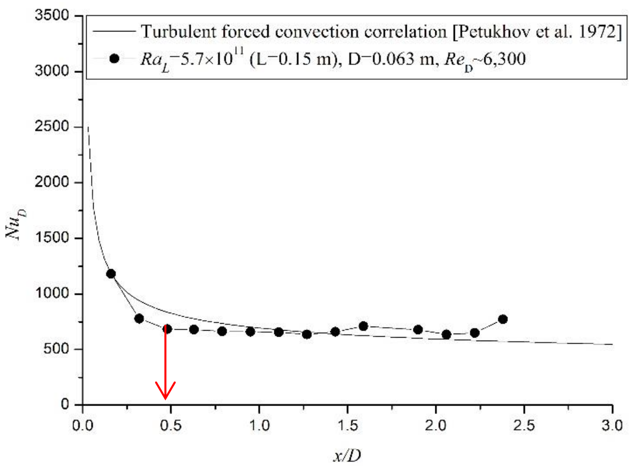
Results : x/D vs. Nu_D (3/4)

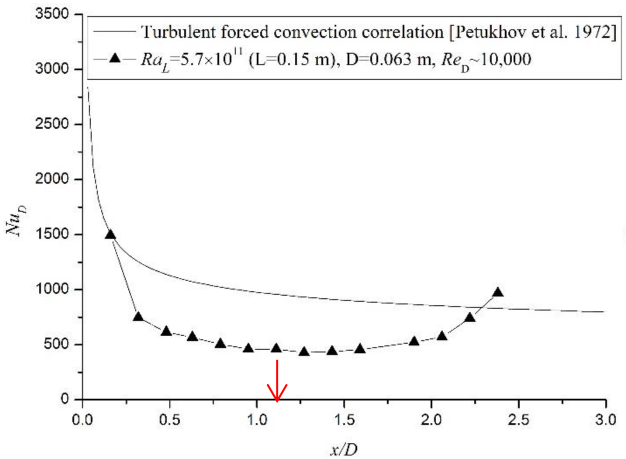
- x/D vs. Nu_D (Turbulent flow)

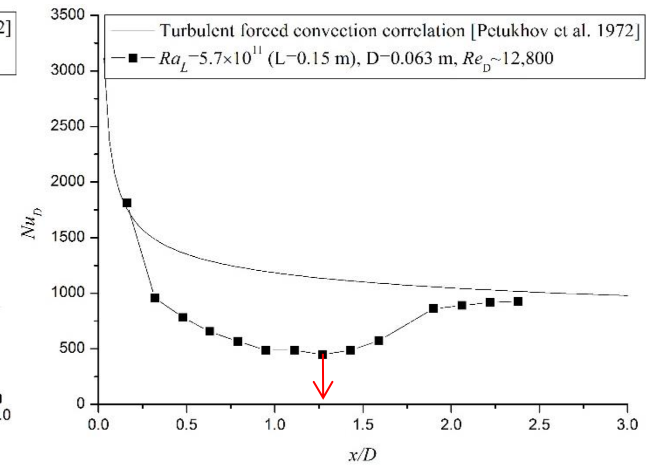


Results : x/D vs. Nu_D (4/4)

- x/D vs. Nu_D (Turbulent flow)







- Increased x/D, Nu_D impaired → Laminarization
- Increased x/D, Nu_D recovered or enhanced → Recovery of turbulence production
- Minimum Nu_D – Re ↑, x/D ↑ (18%, 54%, 56%)

Conclusions

- In the Passive Cooling System devices, RCCS, the buoyant flows are induced
  - *The local average Nu* of natural convective flow can be impaired due to the mixed convective flow

- This study measured the Forced convection and Mixed convection heat transfer in a vertical circular duct by mass transfer experiment using the analogy concept
  - Test range correspond to the Rayleigh number with NACEF
  - Adopting the Piecewise electrodes, Varying Reynolds number

- Comparison of heat transfer rates existing correlation and present data
  - Present data (L=0.01m) agreed with forced convection correlation (Laminar, Turbulent)
  - Present data (L=0.15m) agreed with mixed convection correlation for of Wragg and Ross

Conclusions

- *x/D* vs. *Nu* (Laminar flow)
  - *The local average Nu* : Enhanced compared on the forced convection due to Velocity increased

- *x/D* vs. *Nu* (Turbulent flow)
  - *The local average Nu* : Impaired compared to the forced convection due to Laminarization
  - And then, recovered and enhanced since the turbulence production

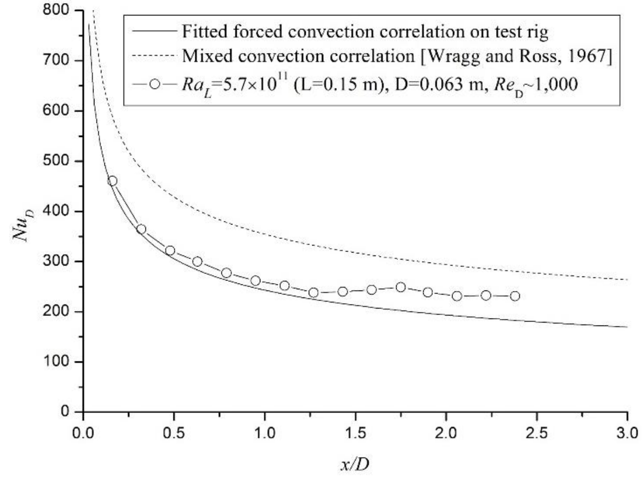
- This study is design of the test facility and experiments test scope for similarity with NACEF

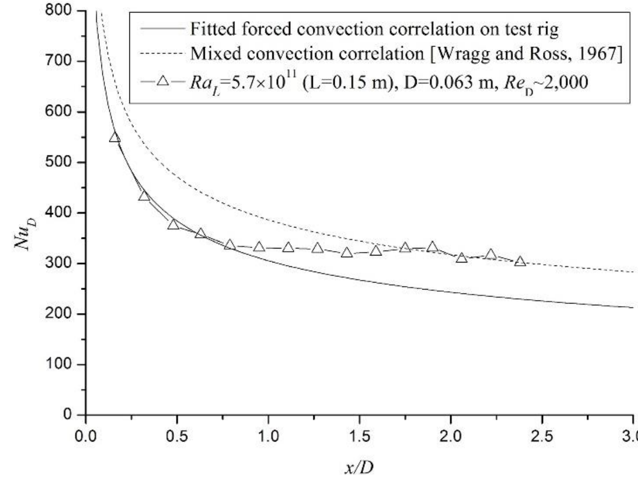
- Extended the test range for Reynolds number, Diameter and Length of test section
  - Characteristic length of *Gr*

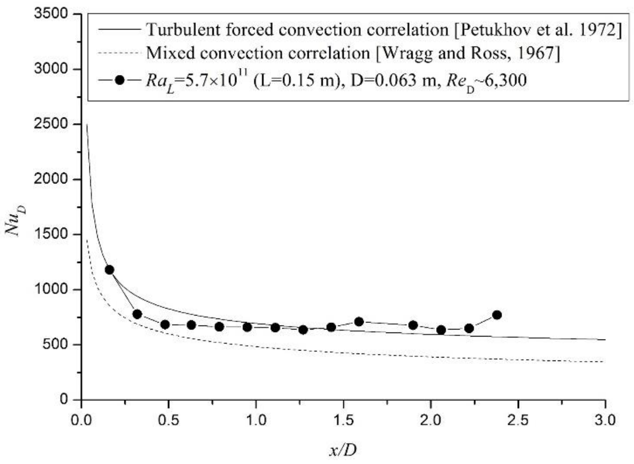
- The phenomenological analysis will be developed in the heat transfer of mixed convection with laminarization and turbulence production

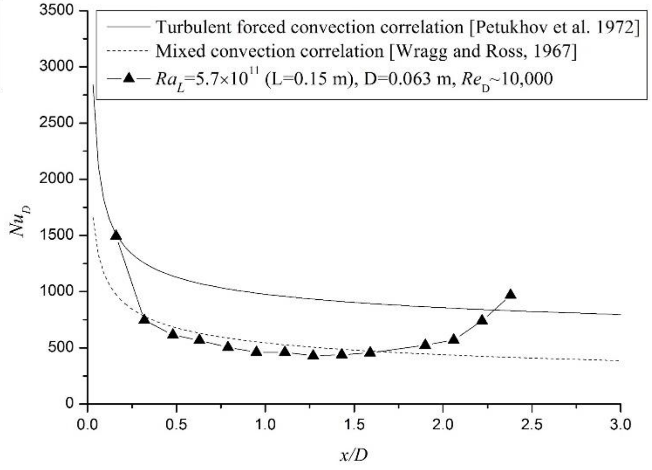
Thank you !

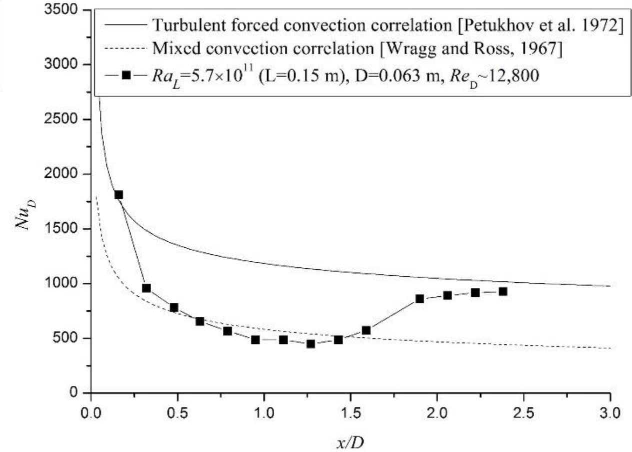
Appendix I


Fitted forced convection correlation on test rig
Mixed convection correlation [Wragg and Ross, 1967]
Ra_L=5.7×10^{11} (L=0.15 m), D=0.063 m, Re_D~1,000
Nu_D
x/D


Fitted forced convection correlation on test rig
Mixed convection correlation [Wragg and Ross, 1967]
Ra_L=5.7×10^{11} (L=0.15 m), D=0.063 m, Re_D~2,000
Nu_D
x/D


Turbulent forced convection correlation [Petukhov et al. 1972]
Mixed convection correlation [Wragg and Ross, 1967]
Ra_L=5.7×10^{11} (L=0.15 m), D=0.063 m, Re_D~6,300
Nu_D
x/D


Turbulent forced convection correlation [Petukhov et al. 1972]
Mixed convection correlation [Wragg and Ross, 1967]
Ra_L=5.7×10^{11} (L=0.15 m), D=0.063 m, Re_D~10,000
Nu_D
x/D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Ra_L=5.7×10^{11} (L=0.15 m), D=0.063 m, Re_D~12,800
Nu_D
x/D