

# Advanced Convective Heat Transfer

Numerical analysis of internal laminar pipe flow

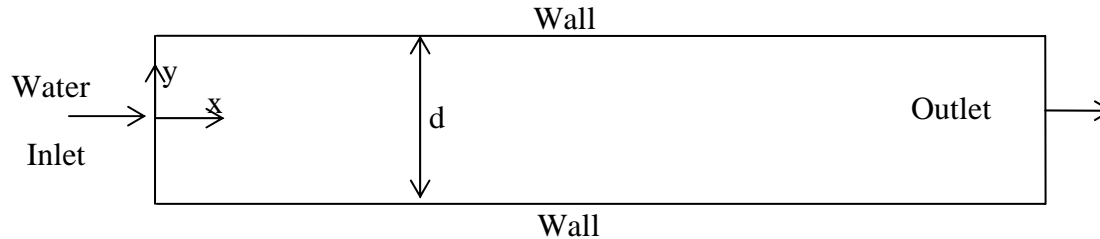
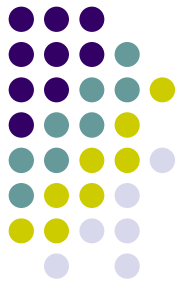
Some CFD Results by Wang Shijun January 2006

# Objectives



1. Understand fundamentals of internal laminar pipe flow- compare analytical results with CFD results
2. Flow and heat transfer characteristics under constant wall temperature and heat flux conditions
3. Introduce numerical solutions of pipe flow using Computational Fluid Dynamics

# Description – Illustrative problem



Cool water enters a tube with either constant wall temperature or heat flux. Water will cool down the hot pipe wall. The pipe is 20 mm in diameter and 1200 mm in length. Unless otherwise stated, water and pipe wall temperatures are set to be 30 C° and 20 C°, respectively. Flow is assumed to be steady, laminar and incompressible with constant properties.

# Governing equations



## Mass conservation equation

$$\frac{\partial u_i}{\partial x_i} = 0$$

## Momentum conservation equations

$$u_i \frac{\partial (u_j)}{\partial x_i} = -\frac{1}{\rho} \frac{\partial p}{\partial x_j} + \nu \frac{\partial}{\partial x_i} \left( \frac{\partial u_j}{\partial x_i} \right)$$

## Energy conservation equation

$$u_i \frac{\partial T}{\partial x_i} = \frac{\nu}{\text{Pr}} \frac{\partial}{\partial x_i} \left( \frac{\partial u_j}{\partial x_i} \right)$$

# Boundary conditions



**Inlet:** Flat velocity and temperature profiles are assumed;  
 $u_{in} = 0.075$  m/s for water at  $Re_{in} = 1500$  and  $T_{in} = 20$  C°

**Outlet:** Fully develop flow is assumed, that is, all variable gradients in the axial direction is zero.

**Wall:** No slip wall and constant wall temperature  $T_w$  or constant wall heat flux  $q_w$  are specified on the pipe wall;

**Working fluid:** water, air, oil. –study effect of fluid Prandtl number

# Numerical Solution



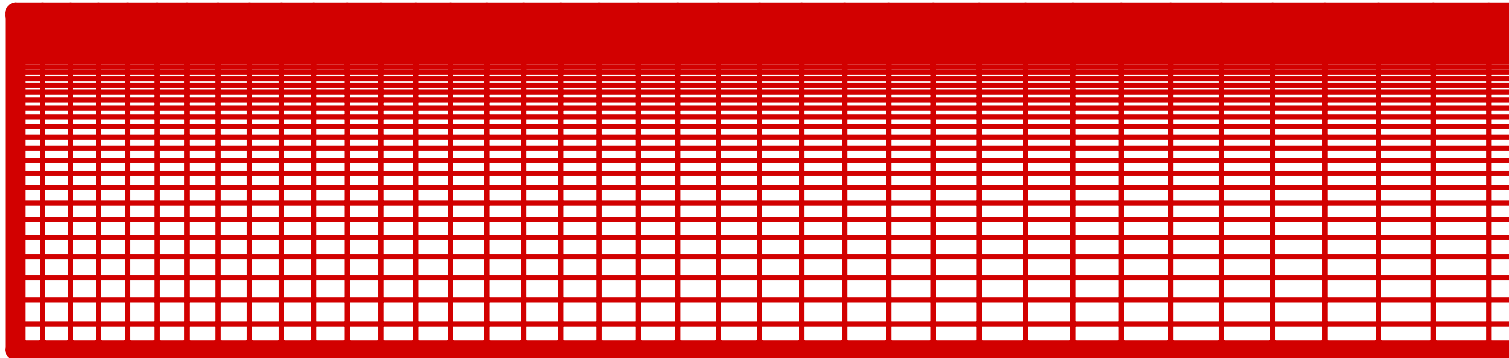
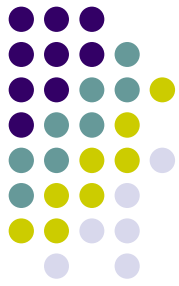
The conservation equations are solved using the control-volume-based software FLUENT 6.2.-details in manual.

The convection terms in equations are discretized using a third order interpolation scheme QUICK

The discretized equations are solved using the SIMPLER algorithm

*The solution is considered converged when the normalized residuals of all dependent variables are less than  $10^{-5}$*

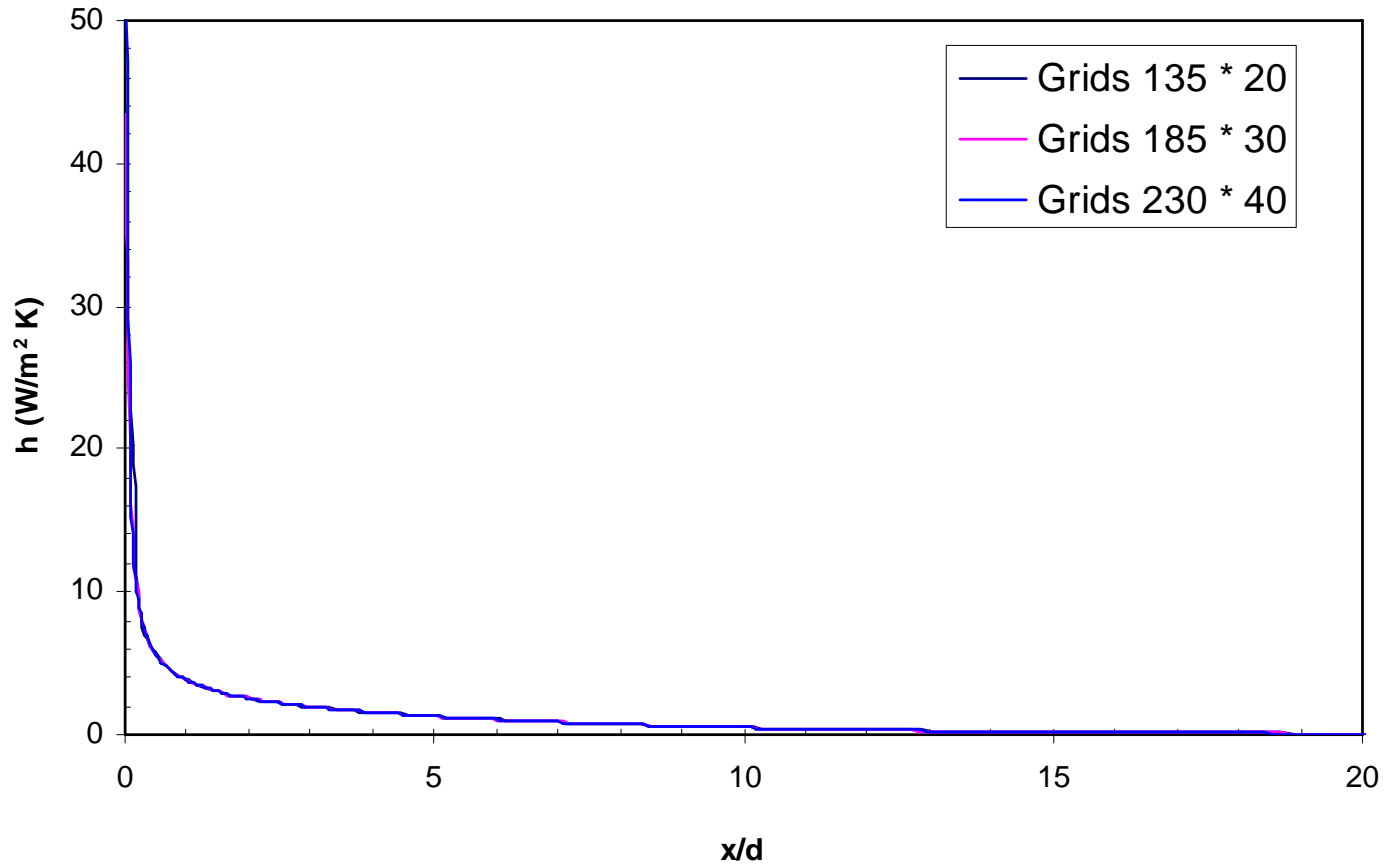
# Grid system



In the r-coordinate, grids cluster near the wall

In the x-coordinate, grids are dense near the inlet and coarser gradually

# Grid-independence test



Effect of grid size on surface heat transfer coefficient,  $Re = 1500$ , Air

Grids of 185 \* 30 in the axial and radial directions provides satisfactory resolution



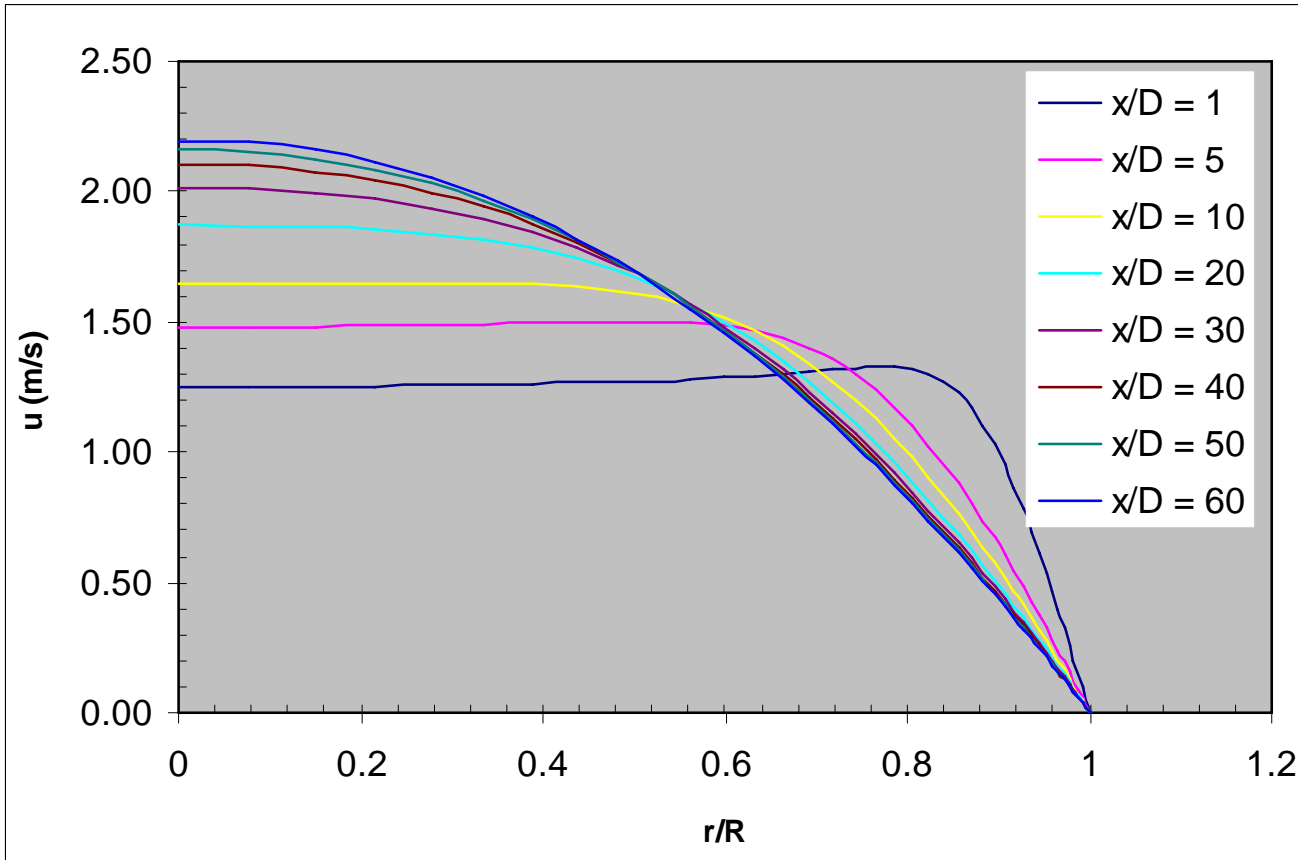
# Fluid properties of air, water and oil

## Comparison of fluid properties of water and oil

$$(T_{air} = T_{water} = 20 \text{ C}^\circ, T_{oil} = 10 \text{ C}^\circ)$$

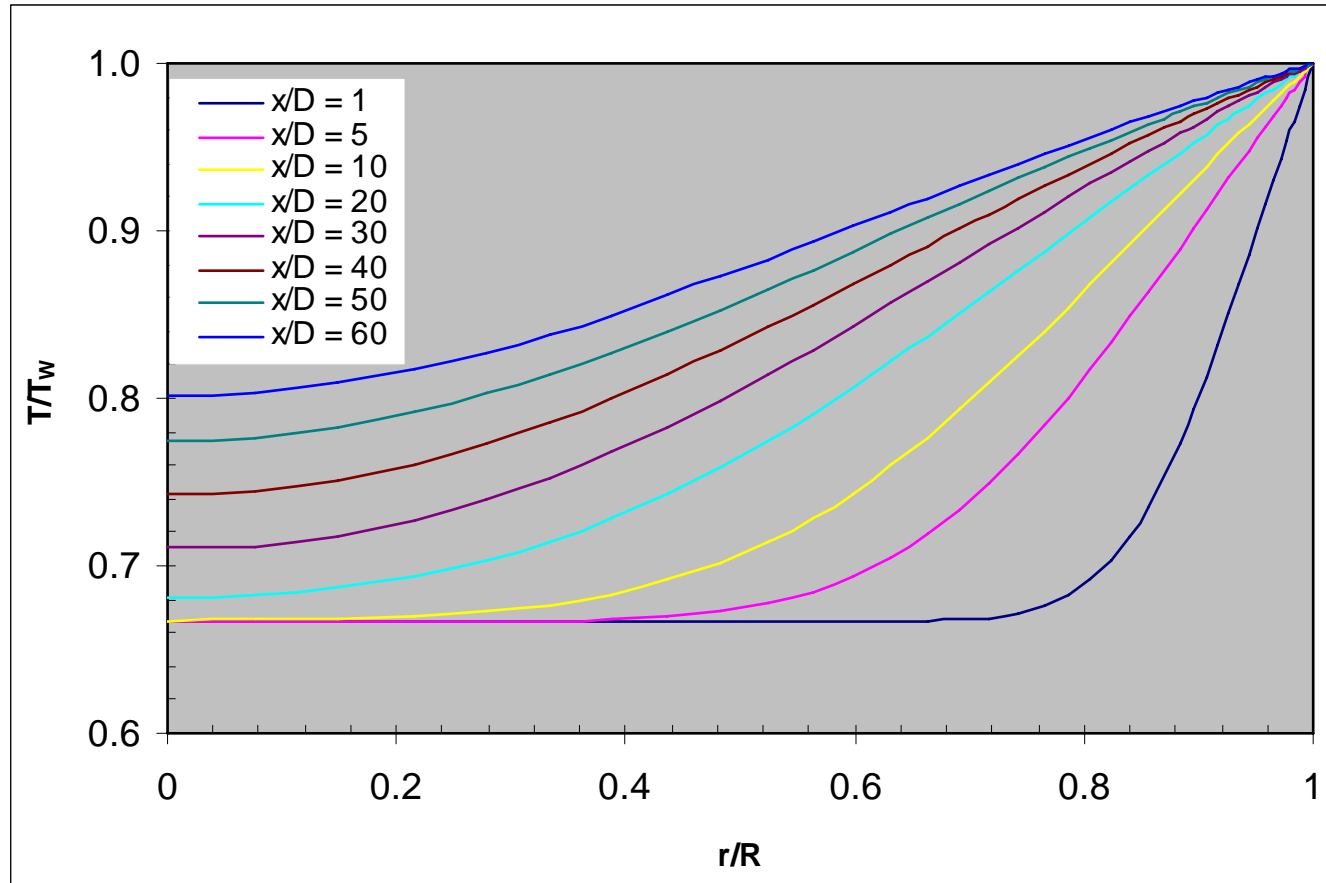
	Density Kg/m <sup>3</sup>	Thermal conductivity (W/m K)	Viscosity (N S/m <sup>2</sup> )	Heat capacity J/kg K	Pr
Air	1.205	0.0259	1.81e-5	1005	0.7
Water	998.2	0.598	0.0001004	4183	7
oil	910	0.14	0.008	19250	1100

# Velocity Profile - Air



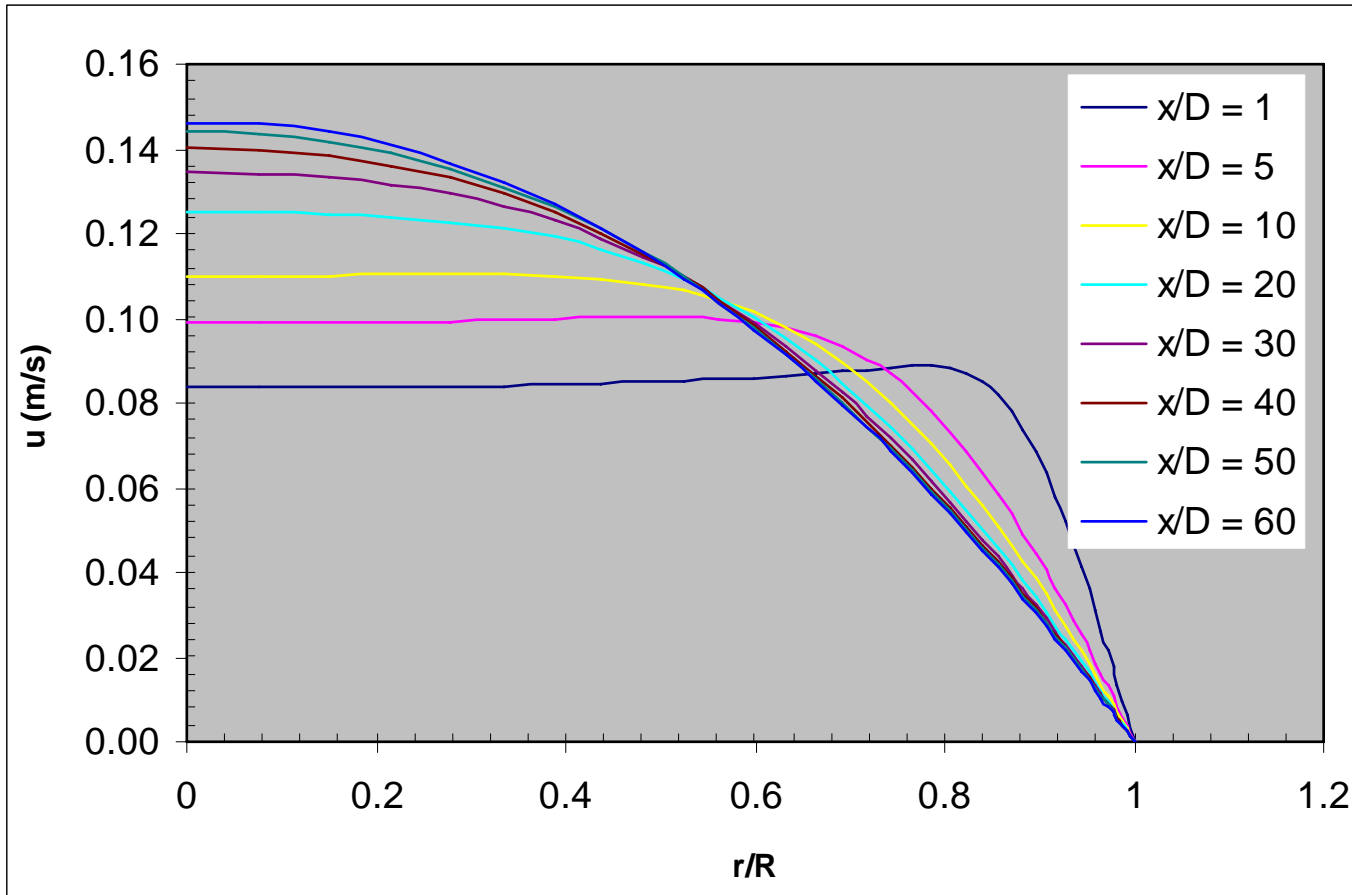
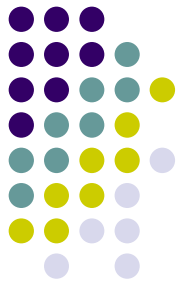
- It is seen that flow is almost fully-developed from  $x/D = 50-60$ . Note that the length needed for fully-developed flow depends on operating conditions

# Temperature Profile - Air



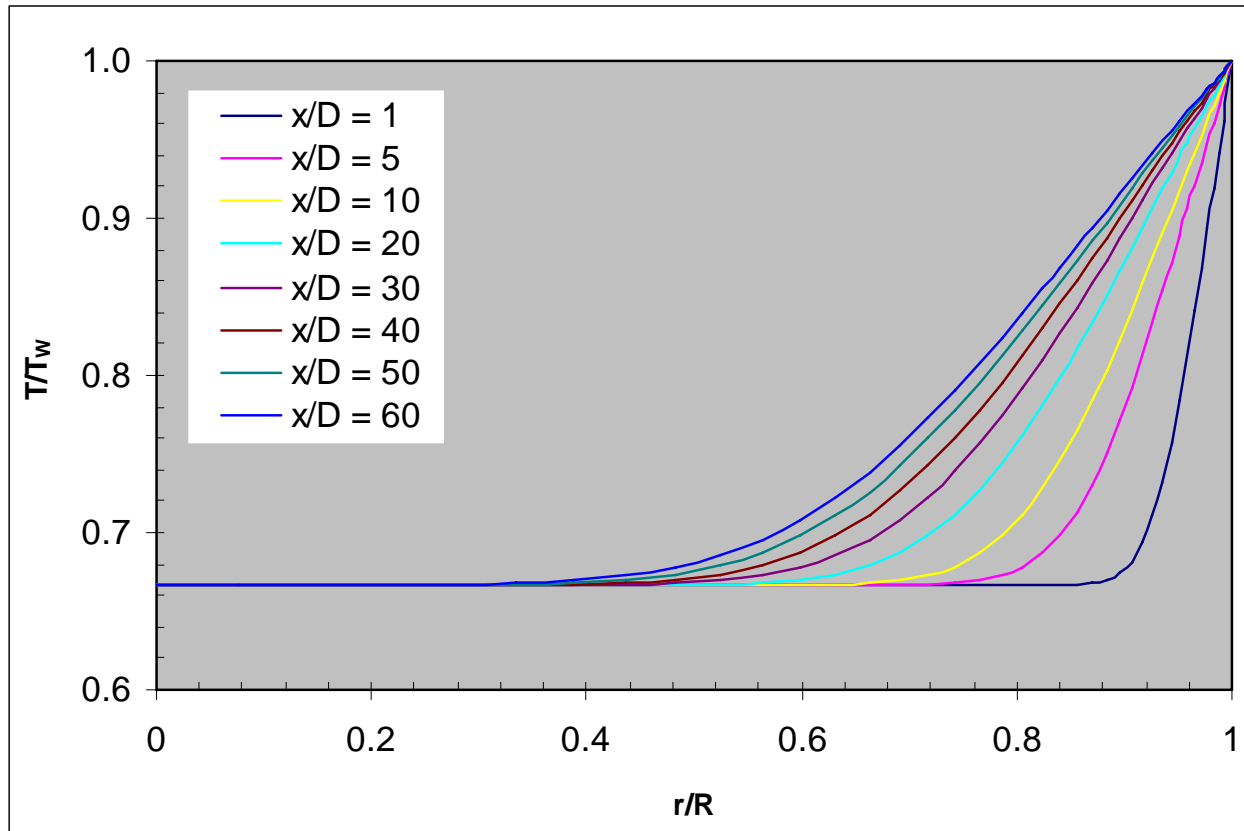
As fluid flows away from the inlet, thermal diffusion decreases due to decrease in temperature difference between the wall and near-wall fluid since near-wall heat transfer is thermal conduction-controlled.

# Velocity Profile - Water



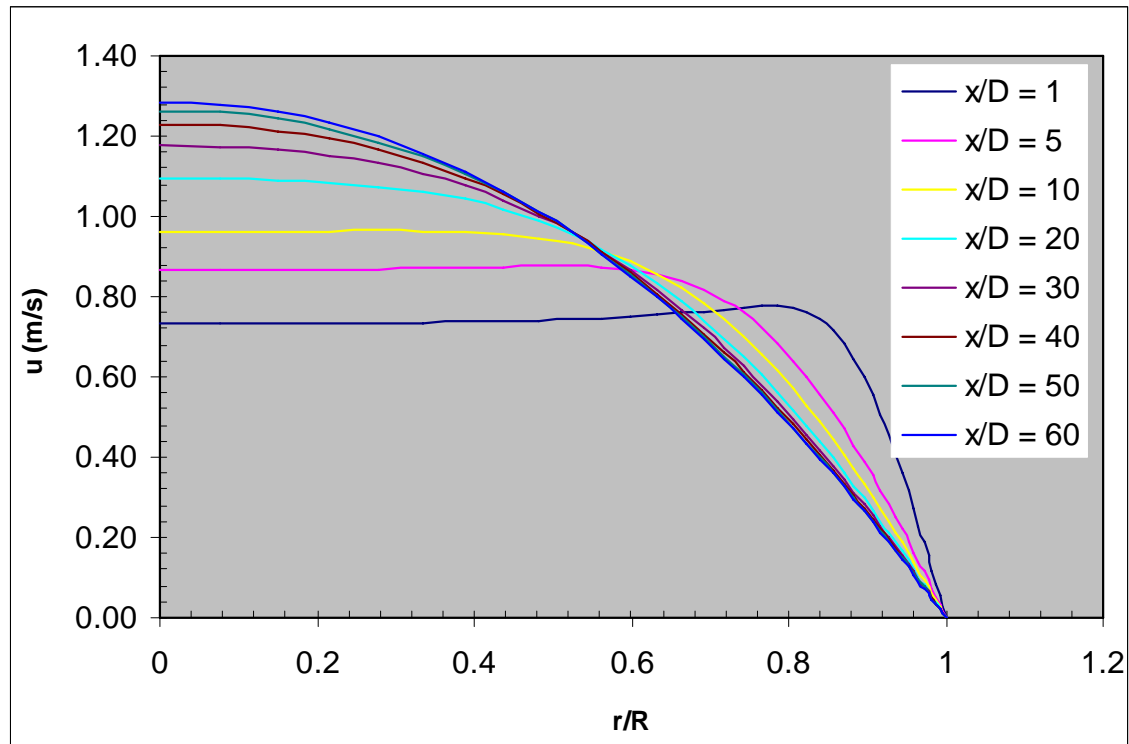
- At the same Reynolds number, water shares the similar evolution characteristics of velocity profile

# Temperature Profile - Water



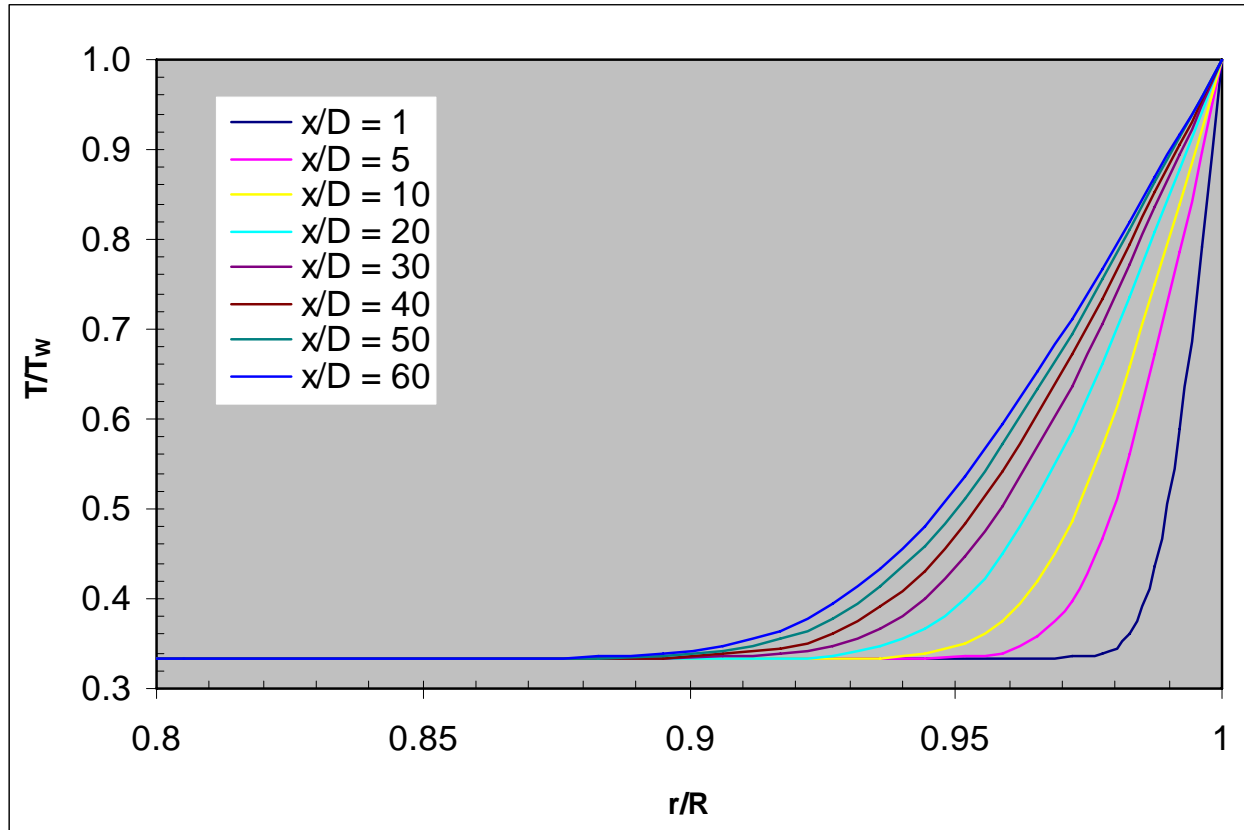
- It is seen that thermal diffusion for water is much slower compared with air, and water has a much better cooling capacity than air due to its high specific heat capacity and  $Pr$  number.

# Velocity Profile - Oil



- Oil shares similar evolution characteristics of velocity profile as air and water

# Temperature Profile - Air



- It is seen that thermal diffusion for oil is the lowest compared to water and air due to its very high specific heat capacity and  $Pr$  number

# Definition of Nusselt number



$$Nu_x = h_x D / k \quad (1)$$

$$h_x = q_w / (T_w - T_{ref}) \quad (2)$$

$$T_m = \frac{\int_A u T dA}{\int_A u dA} \quad (3)$$

Notation:

$D$ : Pipe diameter

$Nu_x$ : Local Nusselt Number

$k$ : Fluid thermal conductivity

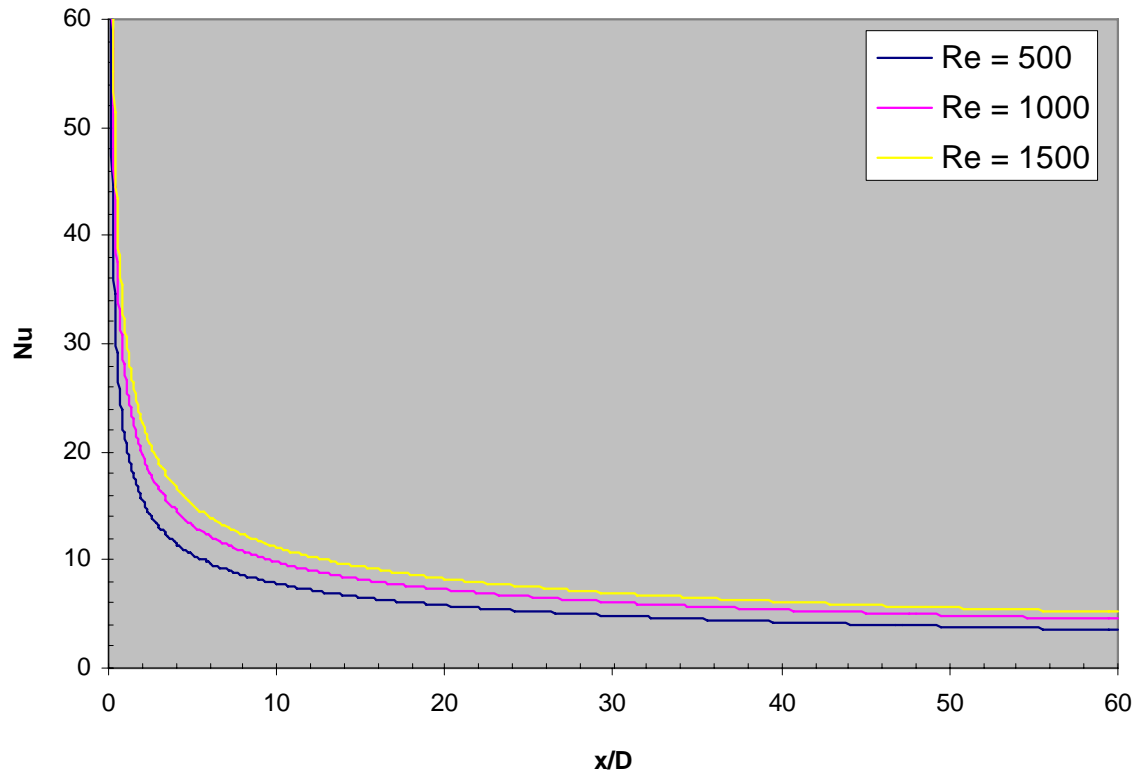
$T_w$ : Wall temperature

$T_m$ : Mean temperature at axial station

$T_{ref}$ : Reference temperature. It is taken as the fluid inlet temperature.

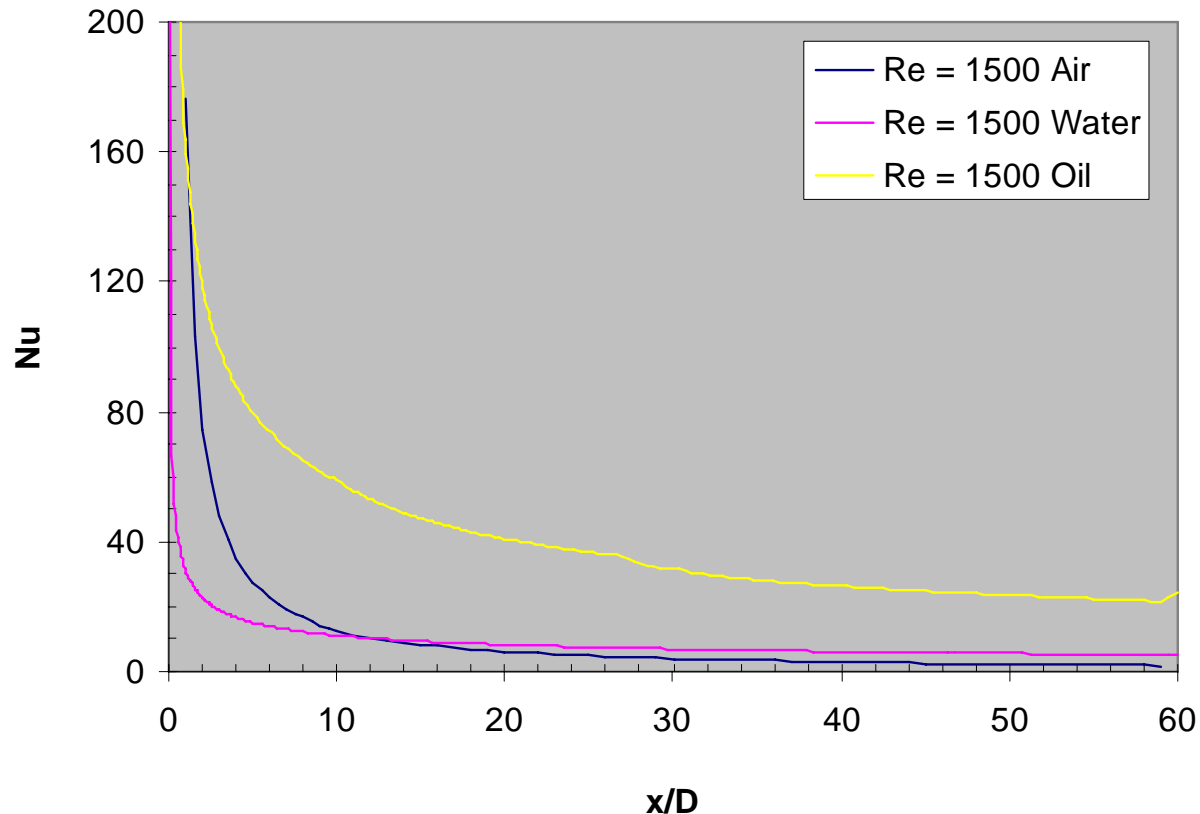
$u$ : Velocity

# Effect of Reynolds number - Water



Increase in Reynolds number leads to better cooling due to increase in velocity and thus convective heat transfer

# Comparison of cooling capacity of air, water and oil



At the same Reynolds number based on the pipe diameter, oil has much higher cooling capacity as compared with air and water; the cooling performance of air is better than water until a critical value of  $x/D$  is reached. This is ascribed to the higher inlet velocity for air, but its small heat capacity make its cooling capacity poorer than water downstream

# Effect of large temperature difference between fluid and wall



The temperature-dependent fluid properties of water are represented by the quadratic expression of  $\mu = a + bT + cT^2$  but viscosity is calculated by a forth-order expression.

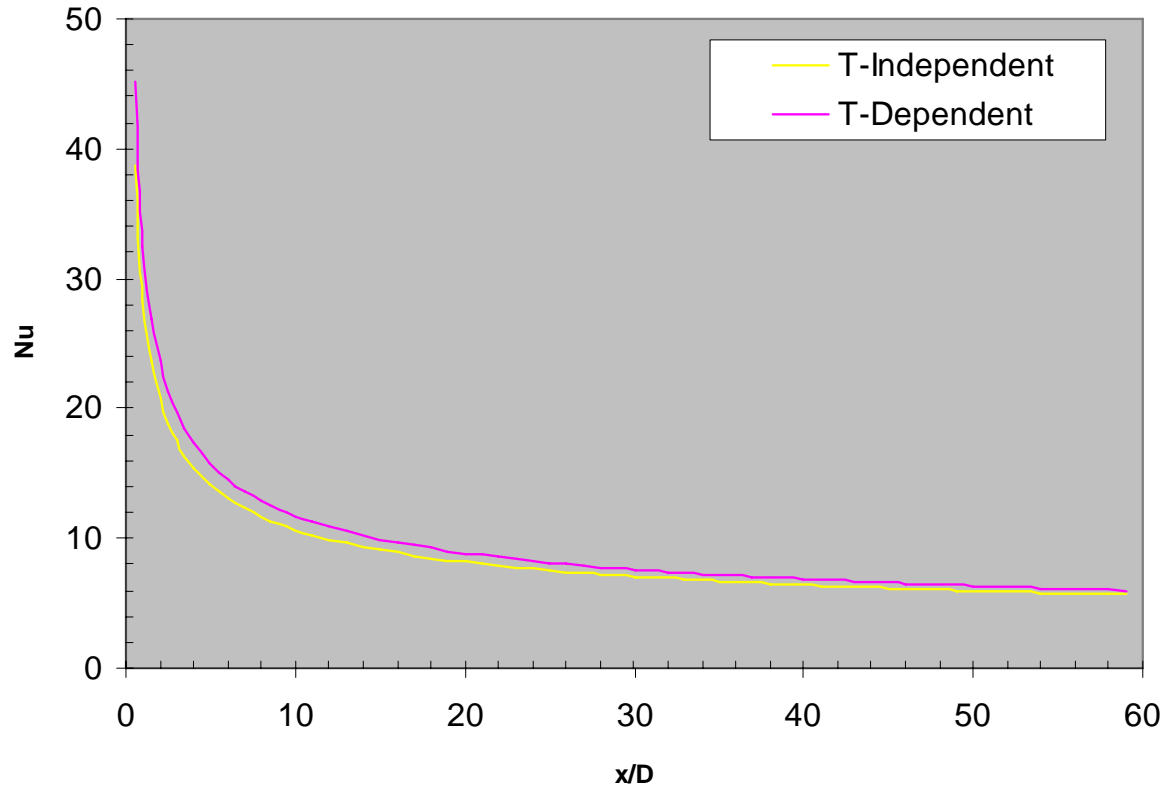
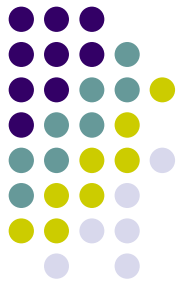
The coefficients of  $a$ ,  $b$ ,  $c$ ,  $d$  for viscosity, and thermal conductivity are given in the following Table.

Property	Unit	$a$	$b$	$c$	$d$	$e$
$\mu$	Kg m <sup>-1</sup> s <sup>-1</sup>	0.12834	-1.2787E-3	4.7947E-6	-7.9896E-9	4.9840E-12
$\rho$	kg m <sup>-3</sup>	862.92	1.2082	-2.5502E-3		
$k$	W m <sup>-1</sup> K <sup>-1</sup>	-0.43207	5.5033E-3	-6.7659E-6		

The heat capacity of water is approximately a constant over the temperature range tested.

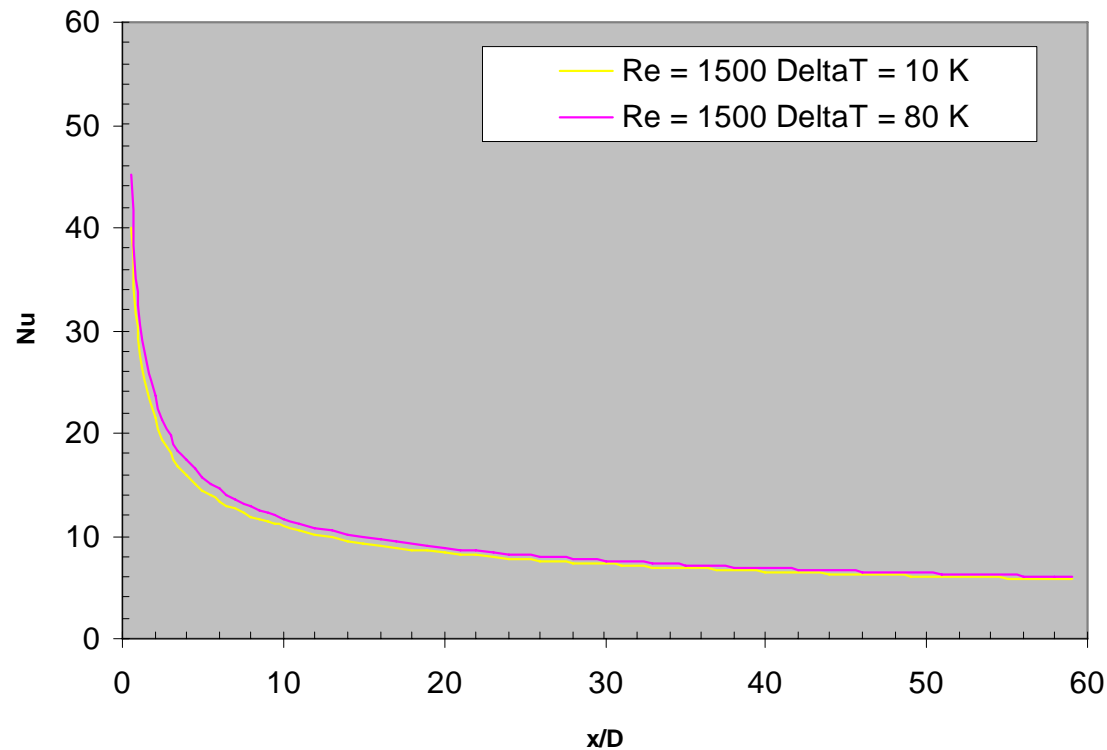
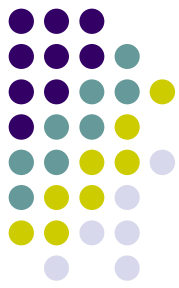
# Effect of fluid properties – Water

$Re = 1500$ ,  $T_W = 30\text{ C}^\circ$   $T_{water} = 20\text{ C}^\circ$

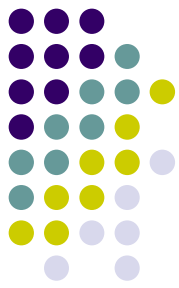


For small temperature difference between working fluid and wall, fluid properties have appreciable effect on heat transfer due to property change with temperature

# Effect of large temperature difference between fluid and wall



- Large wall temperature has minor effect on Nusselt number characteristics



# Air Properties

Due to large temperature changes at constant wall heat flux condition, temperature-dependent thermo-fluid properties of air in the following are used in simulation.

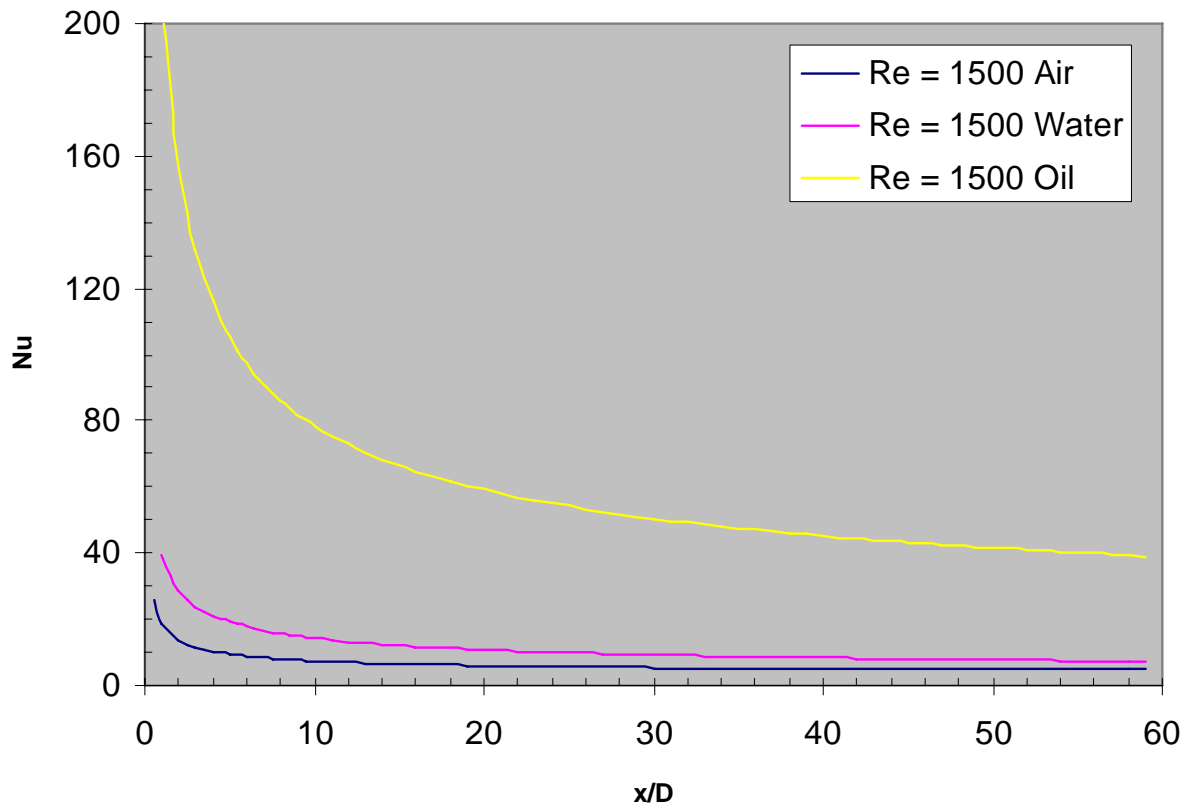
The temperature-dependent fluid properties of air are represented by the quadratic expression of  $\mu = a + bT + cT^2$ , but density is calculated by incompressible ideal gas-law.

The coefficients of  $a$ ,  $b$ ,  $c$  for viscosity, and thermal conductivity are given in the following Table.

Property	Unit	$a$	$b$	$c$
$\mu$	Kg m <sup>-1</sup> s <sup>-1</sup>	0.25641e-5	0.60198E-7	-0.23723E-10
$C_p$	J Kg <sup>-1</sup> K <sup>-1</sup>	1025.6	-0.17317	0.00036146
$k$	W m <sup>-1</sup> K <sup>-1</sup>	0.00038793	0.95425E-4	-0.30699E-7

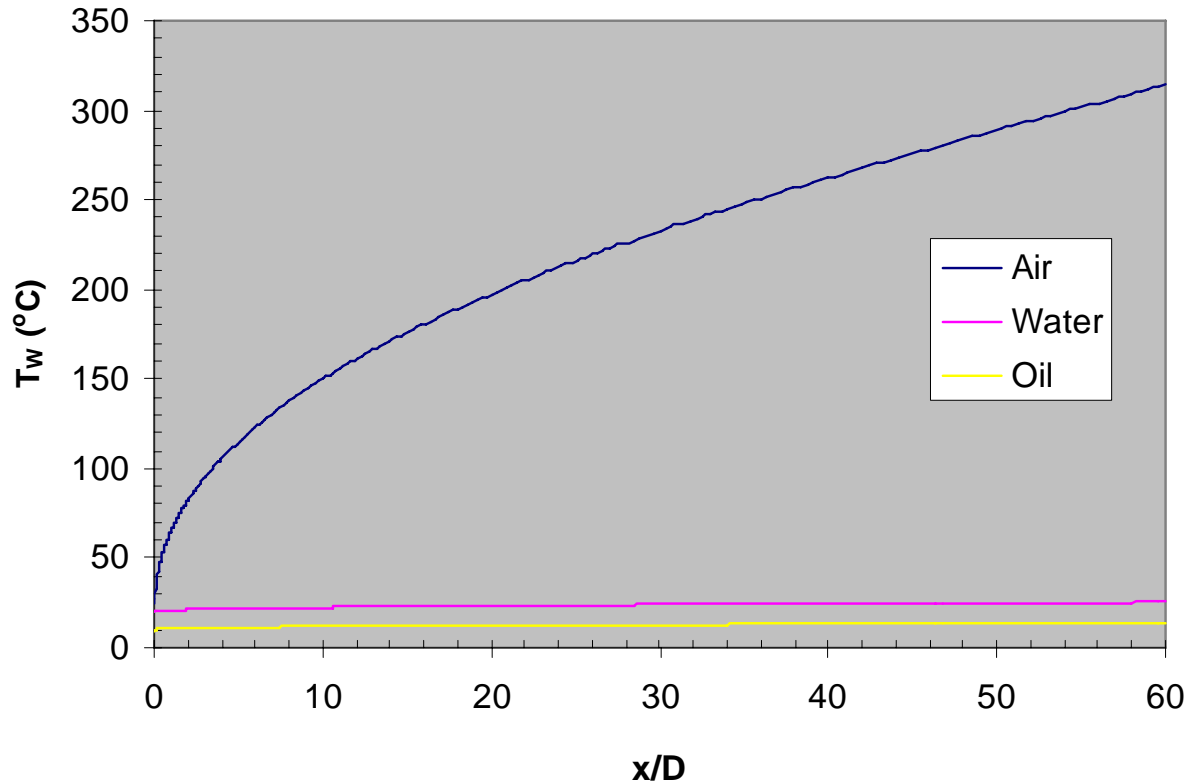
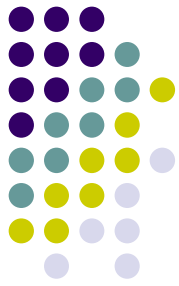
# Const wall flux condition

$q = 1000 \text{ W/m}^2$



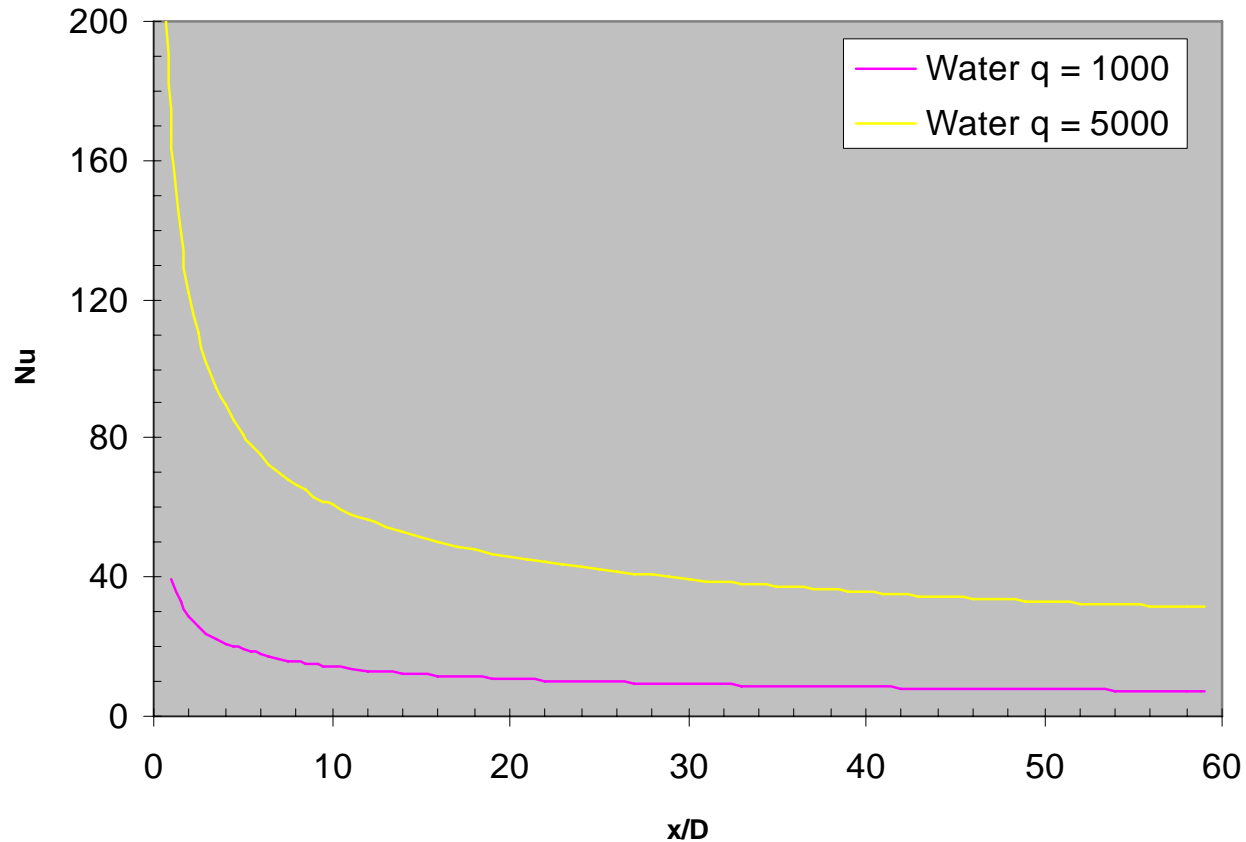
- Again, it is seen that for a given constant wall heat flux oil has the best cooling capacity, followed by water and the last is air.

# Comparison of water temperature for Const wall flux condition $q = 1000 \text{ W/m}^2$



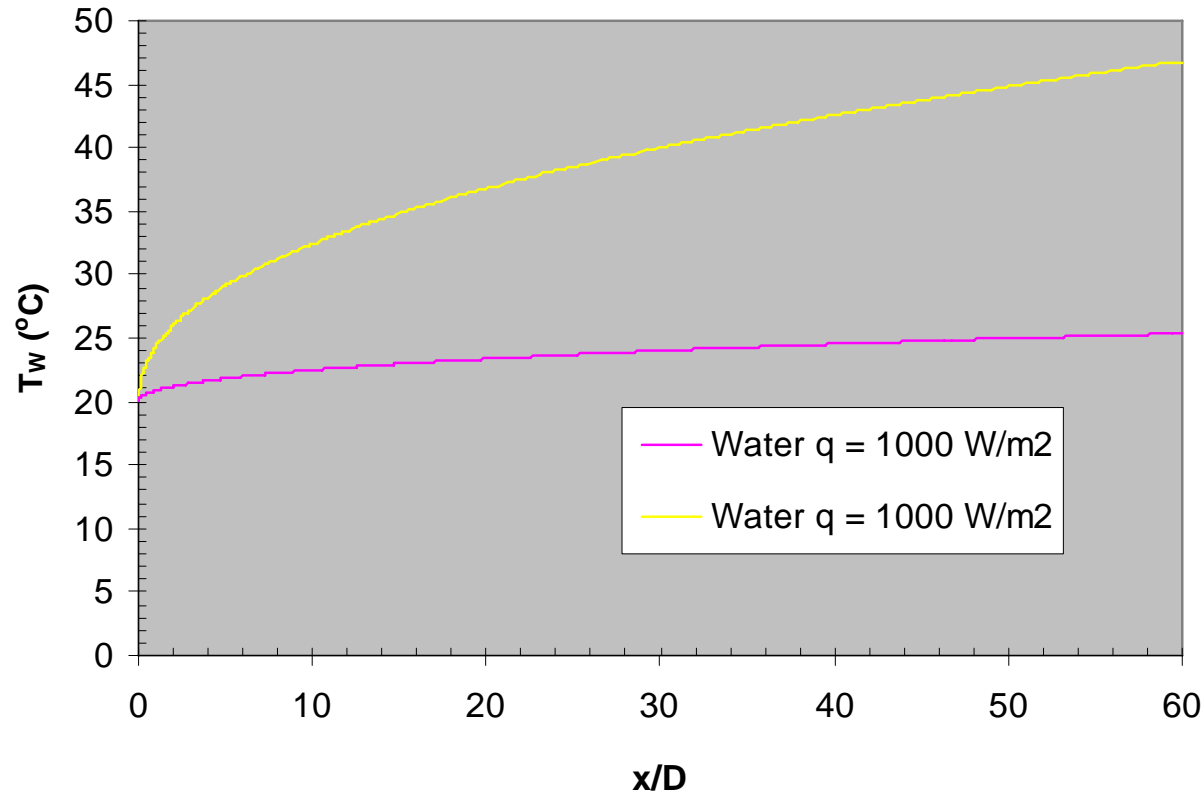
- It is seen that wall temperature increases greatly for air due to its low specific heat capacity and Prandtl number

# Effect of wall heat flux



- At a given Reynolds number, increase in wall heat flux results in increase of values of the local Nussult number

# Comparison of wall temperature



- At a given Reynolds number, increase in wall heat flux results in increase of Nussult number

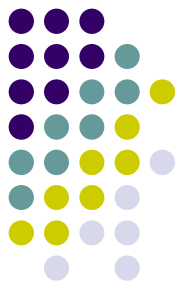


# Conclusions

Flow and heat transfer characteristics of internal laminar pipe flow are numerically studied using a CFD code FLUENT.

Some of specific conclusions are summarized as follows,

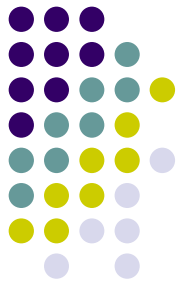
- at a give Reynolds number, flow evolution is similar for air, water and oil. It needs longer exit channel length to be fully-developed, but this length depends on operating conditions
- increase in Reynolds number leads to better cooling performance due to increase in fluid velocity and thus convective heat transfer
- at a give Reynolds number, oil has the best cooling performance, followed by water and air for both constant wall temperature and heat flux conditions



# Conclusions

- As wall heat flux increases, values of the local Nusselt number and the wall temperature increase as well
- CFD results compare perfectly with analytical solutions
- Analytical solutions cannot be found for many practical cases (Try to list some cases!)
- For laminar flows analytical or numerical solutions should be more accurate than experimental one, in general. (WHY?)
- For turbulent flows, however, there is greater uncertainty due to the need to model turbulence itself- which is at best approximate

# References



- [http://e-svu.nus.edu.sg/fluent\\_help/fluent6.2/](http://e-svu.nus.edu.sg/fluent_help/fluent6.2/)
- Introduction to Convective Heat Transfer, Patrick H.O and David N., McGraw-Hill: Singapore