ENGR 292 Fluids and Thermodynamics

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Review of Last Class

- **There are three fundamental forms of heat transfer:**
  - Conduction
  - Convection
  - Radiation (optional)

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Review of Last Class

- **Conduction: heat transfer through non-moving material (solids, confined liquids, gases, etc.)**
- **Convection: heat transfer through moving material (free/moving liquids, gases, etc.)**
- *Some people do not consider convection to be a fundamental mechanism of heat transfer since it is essentially heat conduction in the presence of fluid motion. It can be called as "Conduction with fluid motion".*
- *It is practical to recognize convection as a separate heat transfer mechanism.*

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Review of Last Class

- **Conduction:**

$$\dot{Q} = \frac{kA}{\Delta x}\Delta T$$

k Thermal Conductivity is a property (w/(m℃))

- **Convection:**

$$\dot{Q} = hA\Delta T$$

h (w/(m^2℃)) Convection Heat Transfer Coefficient is NOT a property, which depends on many factors, such as:
  - Surface geometry
  - The nature of fluid motion
  - The property of the fluid
  - The bulk fluid velocity

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Review of Last Class

- **Thermal Resistance R:**

$$\dot{Q} = \frac{\Delta T}{R}$$

- **To calculate the rate of heat transfer $\dot{Q}$:**

$$\dot{Q} = \frac{\Delta T}{R_{total}}$$

$$R_{Total} = \sum R_{Cond} + \sum R_{Conv}$$

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Review of Last Class

- **Thermal Resistance of Conduction and Convection:**

	$R_{Cond.}$	R_{Conv_in}	R_{Conv_out}
Plane Wall	$\frac{L}{kA}$	$\frac{1}{h_1 A}$	$\frac{1}{h_2 A}$
Cylinder	$\frac{\ln(r_2/r_1)}{2\pi Lk}$	$\frac{1}{2\pi r_1 L h_1}$	$\frac{1}{2\pi r_2 L h_2}$
Sphere	$\frac{r_2 - r_1}{4\pi r_1 r_2 k}$	$\frac{1}{4\pi r_1^2 h_1}$	$\frac{1}{4\pi r_2^2 h_2}$

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Review of Last Class

- ***To find conductive heat transfer coefficient k, just to look up its value in the table of properties.***
- ***To find convective heat transfer coefficient h, need a little bit more work.***

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Convection

- ***Convection heat transfer is closely tied with fluid dynamics, and interaction of fluids with solids and other fluids at the boundaries.***

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Convection

- ***Convective heat transfer coefficient h is defined as the rate of heat transfer between a solid surface and a fluid per unit surface area, per unit temperature difference.***

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Convection

- ***Forced Convection***
  - *Fluid was forced to move over a surface or in a tube by external means such as a pump or a fan.*
- ***Natural Convection***
  - *Any fluid motion occurs by natural means such as buoyancy*

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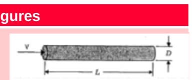
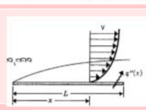
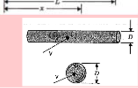
Convection Heat Transfer Correlations (Table C-8)

Forced Convection:

	Cases	Figures
A	Flow in circular tubes	
B	Boundary layer on a flat plate	
C	Single circular cylinder or sphere in cross flow	

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Convection Heat Transfer Correlations (Table C-8)

Natural Convection:

(D) Natural convection from a horizontal cylinder

(E) Natural convection from vertical surfaces

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Convection

- **Four Dimensionless Numbers**
  - *Reynolds Number (Re)*
  - *Nusselt number (Nu)*
  - *Prandtl number (Pr)*
  - *Grashof number (Gr)*

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Procedure for Calculating "h" – Forced Convection

- **Step by Step:**
  1. Determine the geometric parameter L;
  2. Determine the type of the Forced Convection in Table C-8 (A), (B) or (C)

  3. Assume a fluid temperature, T_f(°K) (if it is not given). Look up the thermo-physical properties ($\rho, k, \mu, \upsilon, Pr$) of the fluid used in the convection in Table A-18 (if Pr is not given, use $Pr = \frac{\mu C_p}{k}$)

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Procedure for Calculating "h" – Forced Convection

- **Step by Step:**

  4. Calculate the Reynolds number (Re) or other information to determine the Flow type – Laminar or Turbulent

$$Re = \frac{vL\rho}{\mu} = \frac{vL}{\nu}$$

Please note:

Critical Reynolds Numbers
- Inside a Pipe
  - $Re_{Cr} = 2000$
- Over a Flat Plate
  - $Re_{Cr} = 500,000$

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Procedure for Calculating "h" – Forced Convection

- **Step by Step:**

  5. Calculate Nusselt number (Nu)

$$Nu = CRe_L^m Pr^n$$

Find C, m, n as per flow type and thermal boundary layer condition

  6. Calculate h

$$h = \frac{(Nu)k}{L}$$

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Procedure for Calculating "h" – Natural Convection

- **Step by Step:**
  1. Determine the geometric parameter L;
  2. Determine the type of the Natural Convection in Table C-8 (D) or (E)

  3. Assume a fluid temperature, T_f (°K) (if it is not given). Look up the thermo-physical properties ($\rho, k, \mu, \upsilon, Pr$) of the fluid used in the convection in Table A-18

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Procedure for Calculating "h" – Natural Convection

- **Step by Step:**

  4. Calculate the Grashof number (Gr)

$$Gr = \frac{g\beta(T_{surface} - T_\infty)L^3\rho^2}{\mu^2}$$

$\beta = \frac{1}{T_f}$ for gas only $(K = C + 273.15)$

  5. Calculate Nusselt number (Nu)

$$Nu = C(Gr \times Pr)^n$$

Find C and n as per the value of $(Gr \times Pr)$

  6. Calculate h

$$h = \frac{(Nu)k}{L}$$

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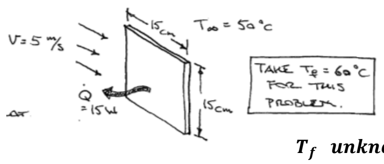
Example

- A vertically orientated 15 cm x 15 cm circuit board uniformly dissipated 15 watts of heat from its component side only. It is cooled by air at 50℃



T_f $unknown$?

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Example

For the 3 situations outlined below find the surface temperature (T_s) of the board.

(a) Forced convection with an air velocity of 5 m/s

(b) Forced convection with an air velocity of 5 m/s and assume a turbulent flow as the components as tabulators

(c) Natural convection

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Example – Situation (a)

- Solution:

(a) Step 1: Determine the geometric parameter L

Geometry: Flat Plate

L = 0.15m

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Example – Situation (a)

- Solution:

(a) Step 2: Determine the type of the Forced Convection in Table C-8 (A), (B) or (C)

(B) Boundary layer on a flat plate

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Example – Situation (a)

- Solution:

(a) Step 3: Assume the Fluid (Air) Temperature $T_f = 60℃$

Look up the thermo-physical properties

Fluid: Air,

$$T_f = 60 + 273.15 = 333.15°K$$

Table A-18 $333.15°K$ is between 330 °K and 340°K

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Example – Situation (a)

- Solution:

(a) Step 3: Look up the thermo-physical properties by the interpolation method.

	330	333.15	340
ρ (kg/m^3)	1.0760	1.0656	1.0430
k $(W/m℃)$	0.0283	0.0285	0.0290
μ (kg/ms)	1.990×10^{-5}	2.0026×10^{-5}	2.03×10^{-5}
$v(m^2/s)$	1.86×10^{-5}	1.8915×10^{-5}	1.96×10^{-5}
Pr	0.708	0.7077	0.707

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Example – Situation (a)

- **Solution:**

(a) Step 3: The thermo-physical properties by the interpolation method at $T_f = 333.15°K$

$$\rho = 1.0656\ kg/m^3;\ k = 0.0285 W/m℃$$
$$\mu = 2.0026 \times 10^{-5} kg/ms;\ v = 1.8915 \times 10^{-5} m^2/s$$
$$Pr = 0.7077$$

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Example – Situation (a)

- **Solution:**

(a) Step 4: Determine the flow type by calculating the Reynolds number (Re) or other information

$$Re = \frac{vL}{\upsilon} = \frac{(5m/s)(0.15m)}{1.8915\times10^{-5} m^2/s} = 39651 \quad < 500{,}000$$

It is a Laminar Flow

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Example – Situation (a)

- **Solution:**

(a)Step 5: Calculate Nusselt Number (Nu)

From Table C-8, Case B.1
Uniform Wall heat flux:

$$Nu = 0.906 Re_L^{1/2} Pr^{1/3}$$
$$= 0.906 \times (39651)^{1/2} \times (0.7077)^{1/3}$$
$$= 160.77$$

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Example – Situation (a)

- **Solution:**

(a) Step 6: Calculate Convective Heat Transfer Coefficient (h)

$$h = Nu\frac{k}{L} = (160.77)\frac{(0.0285)}{(0.15)} = 30.5\ W/m^2℃$$

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Example – Situation (a)

- **Solution:**

(a) Step 7: Calculate the surface temperature

$$\dot{Q} = hA(T_s - T_\infty)$$
$$T_s = T_\infty + \frac{\dot{Q}}{hA}$$
$$= 50 + \frac{15}{(30.5)(0.15 \times 0.15)} = 71.85℃$$

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Example – Situation (a)

- **Solution:**

(a) Step 8: T_f Check

$$T_f = \frac{T_s + T_\infty}{2}$$
$$= \frac{71.85 + 50}{2}$$
$$= 60.93℃$$

Which is very close to our guess: 60℃

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Example – Situation (c)

- **Solution:**

In order to avoid the interpolation process
Let's make another guess of the Fluid (Air) Temperature $T_f = 56.85$℃; *Return back to Step 3:*
(c) Step 3: Look up the thermo-physical properties
Fluid: Air,

$$T_f = 56.85 + 273.15 = 330°K$$

Table A-18 at $330°K$

$$\rho = 1.076\ kg/m^3;\ k = 0.0283W/m℃$$
$$\mu = 1.99 \times 10^{-5} kg/ms;\ \upsilon = 1.86 \times 10^{-5} m^2/s$$
$$Pr = 0.708$$

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Example – Situation (a)

- **Solution:**

(a) Step 4: Determine the flow type by calculating the Reynolds number (Re) or other information

$$Re = \frac{vL}{\upsilon} = \frac{(5m/s)(0.15m)}{1.86\times10^{-5}m^2/s} = 40322.58 < 500{,}000$$

It is a Laminar Flow

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Example – Situation (a)

- **Solution:**

(a)Step 5: Calculate Nusselt Number (Nu)

From Table C-8, Case B.1
Uniform Wall heat flux:

$$Nu = 0.906 Re_L^{1/2} Pr^{1/3}$$
$$= 0.906 \times (40322.58)^{1/2} \times (0.708)^{1/3}$$
$$= 162.15$$

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Example – Situation (a)

- **Solution:**

(a) Step 6: Calculate Convective Heat Transfer Coefficient (h)

$$h = Nu\frac{k}{L} = (162.15)\frac{(0.0283)}{(0.15)} = 30.6\ W/m^2℃$$

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Example – Situation (a)

- **Solution:**

(a) Step 7: Calculate the surface temperature

$$\dot{Q} = hA(T_s - T_\infty)$$
$$T_s = T_\infty + \frac{\dot{Q}}{hA}$$
$$= 50 + \frac{15}{(30.6)(0.15 \times 0.15)} = 71.79℃$$

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Example – Situation (a)

- **Solution:**

(a) Step 8: T_f *Check*

$$T_f = \frac{T_s + T_\infty}{2}$$
$$= \frac{71.79 + 50}{2}$$
$$= 60.89℃$$

Which is not too far from our second guess: 56.85℃; but it is not as good as our first guess 60 ℃

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Example – Situation (c)

- Solution:

Let's make another guess of Temperature of the Fluid (Air), $T_f = 66.85$℃; See what the result will be? Return back to Step 3:

(c) Step 3: Look up the thermo-physical properties

Fluid: Air,

$$T_f = 66.85 + 273.15 = 340°K$$

Table A-18 at $340°K$

$$\rho = 1.043\ kg/m^3;\ k = 0.0290 W/m℃$$

$$\mu = 2.03 \times 10^{-5} kg/ms;\ \upsilon = 1.96 \times 10^{-5} m^2/s$$

$$Pr = 0.707$$

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Example – Situation (a)

- Solution:

(a) Step 4: Determine the flow type by calculating the Reynolds number (Re) or other information

$$Re = \frac{vL}{\upsilon} = \frac{(5m/s)(0.15m)}{1.96\times10^{-5} m^2/s} = 38265.31 < 500{,}000$$

It is a Laminar Flow

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Example – Situation (a)

- Solution:

(a)Step 5: Calculate Nusselt Number (Nu)

From Table C-8, Case B.1

Uniform Wall heat flux:

$$Nu = 0.906 Re_L^{1/2} Pr^{1/3}$$

$$= 0.906 \times (38265.31)^{1/2} \times (0.707)^{1/3}$$

$$= 157.88$$

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Example – Situation (a)

- Solution:

(a) Step 6: Calculate Convective Heat Transfer Coefficient (h)

$$h = Nu\frac{k}{L} = (157.88)\frac{(0.029)}{(0.15)} = 30.52\ W/m^2℃$$

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Example – Situation (a)

- Solution:

(a) Step 7: Calculate the surface temperature

$$\dot{Q} = hA(T_s - T_\infty)$$

$$T_s = T_\infty + \frac{\dot{Q}}{hA}$$

$$= 50 + \frac{15}{(30.52)(0.15 \times 0.15)} = 71.84℃$$

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Example – Situation (a)

- Solution:

(a) Step 8: T_f Check

$$T_f = \frac{T_s + T_\infty}{2}$$

$$= \frac{71.84 + 50}{2}$$

$$= 60.92℃$$

Which is not too far from our third guess: 66.85℃; but it is not as good as our first guess 60 ℃; and our second guess: 56.85℃. The first guess is the best.

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Example – Situation (a)

- **Solution:**

(a) Discussion:

However,

If the dissipated heat is about10 Watts instead 15 Watts, then the second guess will be the best.

If the dissipated heat is about 20 Watts instead of 15 Watts, the third guess will be the best.

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Example – Situation (b)

- **Solution:**

(b) Step 1: Determine the geometric parameter L

Geometry: Flat Plate

L = 0.15m

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Example – Situation (b)

- **Solution:**

(b) Step 2: Determine the type of the Forced Convection in Table C-8 (A), (B) or (C)

(B) Boundary layer on a flat plate

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Example – Situation (b)

- **Solution:**

(b) Step 3: Assume the Fluid (Air) Temperature $T_f = 60℃$

Look up the thermo-physical properties

Fluid: Air,

$$T_f = 60 + 273.15 = 333.15°K$$

Table A-18 $333.15°K$ ***is between 330 °K and 340°K***

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Example – Situation (b)

- **Solution:**

(b) Step 3: Look up the thermo-physical properties by the interpolation method.

	330	333.15	340
$\rho\ (kg/m^3)$	1.0760	1.0656	1.0430
$k\ (W/m℃)$	0.0283	0.0285	0.0290
μ (kg/ms)	1.990×10^{-5}	2.0026×10^{-5}	2.03×10^{-5}
$\upsilon(m^2/s)$	1.86×10^{-5}	1.8915×10^{-5}	1.96×10^{-5}
Pr	0.708	0.7077	0.707

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Example – Situation (b)

- **Solution:**

(b) Step 3: The thermo-physical properties of Air at $T_f = 333.15°K$

$$\rho = 1.0656\ kg/m^3;\ k = 0.0285 W/m℃$$

$$\mu = 2.0026 \times 10^{-5} kg/ms;\ \upsilon = 1.8915 \times 10^{-5} m^2/s$$

$$Pr = 0.7077$$

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Example – Situation (b)

- **Solution:**

(b) Step 4: Determine the flow type by calculating the Reynolds number (Re) or other information

It is a Turbulent Flow because it is assumed a turbulent flow as the components as tabulators

But Reynolds number is still needed to be calculated:

$Re = \frac{vL}{\upsilon} = \frac{(5m/s)(0.15m)}{1.8915\times10^{-5}m^2/s} = 39651$ ***for the next step…***

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Example – Situation (b)

- **Solution:**

(b)Step 5: Calculate Nusselt Number (Nu)

From Table C-8 Case B.2

$Nu = 0.037Re_L^{0.8}Pr^{1/3}$

$= 0.037 \times (39651)^{0.8} \times (0.707)^{1/3}$

$= 157.26$

50

Example – Situation (b)

- **Solution:**

(b) Step 6: Calculate Convective Heat Transfer Coefficient (h)

$$h = Nu\frac{k}{L} = (157.26)\frac{(0.0285)}{(0.15)} = 29.88\ W/m^2℃$$

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Example – Situation (b)

- **Solution:**

(b) Step 7: Calculate the surface temperature

$$\dot{Q} = hA(T_s - T_\infty)$$

$$T_s = T_\infty + \frac{\dot{Q}}{hA}$$

$$= 50 + \frac{15}{(29.88)(0.15 \times 0.15)} = 72.31℃$$

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Example – Situation (b)

- **Solution:**

(b) Step 8: T_f Check

$$T_f = \frac{T_s + T_\infty}{2}$$

$$= \frac{72.31 + 50}{2}$$

$$= 61.16℃$$

Which is very close to our guess: 60℃; but it is not good as the situation (a)

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Example – Situation (c)

- **Solution:**

(c) Step 1: Determine the geometric parameter L

Geometry: Flat Plate

L = 0.15m

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Example – Situation (c)

- **Solution:**

(c) Step 2: Determine the type of the Natural Convection in Table C-8 (D) or (E)

(E) Natural convection from vertical surfaces at Table C-8

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Example – Situation (c)

- **Solution:**

(c) Step 3: Assume the Fluid (Air) Temperature $T_f = 60°C$,

Look up the thermo-physical properties of Fluid: Air,

$$T_f = 60 + 273.15 = 333.15°K$$

Table A-18 $333.15°K$ is between 330 $°K$ and 340$°K$

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Example – Situation (c)

- **Solution:**

(c) Step 3: Look up the thermo-physical properties by the interpolation method.

	330	333.15	340
$\rho\ (kg/m^3)$	1.0760	1.0656	1.0430
$k\ (W/m°C)$	0.0283	0.0285	0.0290
μ (kg/ms)	1.990×10^{-5}	2.0026×10^{-5}	2.03×10^{-5}
$v(m^2/s)$	1.86×10^{-5}	1.8915×10^{-5}	1.96×10^{-5}
Pr	0.708	0.7077	0.707

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Example – Situation (c)

- **Solution:**

(c) Step 3: Thermo-physical properties by air at $T_f = 333.15°K$

$$\rho = 1.0656\ kg/m^3;\ k = 0.0285 W/m°C$$

$$\mu = 2.0026 \times 10^{-5} kg/ms;\ v = 1.8915 \times 10^{-5} m^2/s$$

$$Pr = 0.7077$$

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Example – Situation (c)

- **Solution:**

(c) Step 4: Calculate Grashof number (Gr)

$$Gr = \frac{g\beta(T_s - T_\infty)L^3\rho^2}{\mu^2}$$

$$\beta = \frac{1}{T_f} \quad (for\ gas\ only)$$

$$Gr = \frac{g\frac{T_s - T_\infty}{T_f}L^3\rho^2}{\mu^2}$$

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Example – Situation (c)

- **Solution:**

(c) Step 4: Calculate Grashof number (Gr)

$T_\infty = 50°C$; $T_f = 60°C$ *(assumed);*

$T_f = \frac{T_s + T_\infty}{2} \rightarrow$

$T_s = 2T_f - T_\infty = 70°C$

$T_s - T_\infty = (70 + 273.15)°K - (50 + 273.15)°K = 20°K$

$T_f = 60°C = (60 + 273.15)°K = 333.15°K$

60

Example – Situation (c)

- **Solution:**

(c) Step 4: Calculate Grashof number (Gr)

$$Gr = \frac{g \frac{T_s - T_\infty}{T_f} L^3 \rho^2}{\mu^2}$$

$$= \frac{(9.81)\frac{20}{333.15} 0.15^3 (1.0656)^2}{(2.0026 \times 10^{-5})^2}$$

$$= 5.63 \times 10^6$$

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Example

- **Solution:**

(c) Step 5: Calculate Nusselt Number (Nu)

Calculate $GrPr$

$GrPr = (5.83 \times 10^6)(0.7077) = 3.98 \times 10^6 \in 10^5 - 10^9$

From Table C-8 Case E: $C = 0.555; n = 0.25$

$$Nu = C(GrPr)^n$$
$$= 0.555(3.98 \times 10^6)^{0.25}$$
$$= 24.79$$

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Example – Situation (c)

- **Solution:**

(c) Step 6: Calculate Convective Heat Transfer Coefficient (h)

$$h = Nu\frac{k}{L} = (24.79)\frac{(0.0285)}{(0.15)} = 4.71\ W/m^2 °C$$

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Example – Situation (c)

- **Solution:**

(c) Step 7: Calculate the surface temperature

$$\dot{Q} = hA(T_s - T_\infty)$$

$$T_s = T_\infty + \frac{\dot{Q}}{hA}$$

$$= 50 + \frac{15}{(4.71)(0.15 \times 0.15)} = 191.52 ℃$$

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Example – Situation (c)

- **Solution:**

(c) Step 8: T_f Check

$$T_f = \frac{T_s + T_\infty}{2}$$

$$= \frac{191.52 + 50}{2}$$

$$= 120.76 ℃$$

Which is far from our guess: $60 ℃$

65

Example – Situation (c)

- **Solution:**

Let's make another guess of the Fluid (Air) Temperature $T_f = 100 ℃$; Return back to Step 3:

(c) Step 3: Look up the thermo-physical properties

Fluid: Air,

$$T_f = 100 + 273.15 = 373.15 °K$$

Table A-18 $373.15°K$ ***is between 350 °K and 400 °K***

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Example – Situation (c)

- **Solution:**

(c) Step 3: Look up the thermo-physical properties by the interpolation method.

	350	373.15	400
$\rho\ (kg/m^3)$	1.009	0.951	0.883
$k\ (W/m°C)$	0.0297	0.031	0.0331
μ (kg/ms)	2.08×10^{-5}	2.18×10^{-5}	2.29×10^{-5}
$\upsilon (m^2/s)$	2.06×10^{-5}	2.31×10^{-5}	2.60×10^{-5}
Pr	0.706	0.705	0.703

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Example – Situation (c)

- **Solution:**

(c) Step 4: Calculate Grashof number (Gr)

$T_\infty = 50$℃; $T_f = 100$℃;

$T_f = \frac{T_s + T_\infty}{2} \rightarrow T_s = 2T_f - T_\infty = 150$℃

$$Gr = \frac{g\beta(T_s - T_\infty)L^3\rho^2}{\mu^2}$$

$$T_f = 100℃ = (100 + 273.15)°K$$

$$\beta = \frac{1}{T_f} = \frac{1}{373.15} = 0.0027$$

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Example – Situation (c)

- **Solution:**

(c) Step 4: Determine Grashof number (Gr)

$$Gr = \frac{g\beta(T_s - T_\infty)L^3\rho^2}{\mu^2}$$

$$= \frac{(9.81)(0.0027)(150 - 50)(0.15)^3(0.951)^2}{(2.18 \times 10^{-5})^2}$$

$$= 1.7 \times 10^7$$

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Example – Situation (c)

- **Solution:**

(c) Step 5: Calculate Nusselt Number (Nu)

Calculate $GrPr$

$GrPr = (1.7 \times 10^7)(0.705) = 1.2 \times 10^7 \in 10^5 - 10^9$

From Table C-8 Case E: $C = 0.555; n = 0.25$

$$Nu = C(GrPr)^n$$

$$= 0.555(1.2 \times 10^7)^{0.25}$$

$$= 32.67$$

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Example – Situation (c)

- **Solution:**

(c) Step 6: Calculate Convective Heat Transfer Coefficient (h)

$$h = Nu\frac{k}{L} = (32.67)\frac{(0.031)}{(0.15)} = 6.75\ W/m^2°C$$

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Example – Situation (c)

- **Solution:**

(c) Step 7: Calculate the surface temperature

$$\dot{Q} = hA(T_s - T_\infty)$$

$$T_s = T_\infty + \frac{\dot{Q}}{hA}$$

$$= 50 + \frac{15}{(6.75)(0.15 \times 0.15)} = 148.77℃$$

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Example – Situation (c)

- ***Solution:***

(c) Step 8: T_f Check

$$T_f = \frac{T_s + T_\infty}{2} = \frac{148.77 + 50}{2} = 99.38℃$$

Which is very close to our second guess: $100℃$
If not, keep guessing …an iteration process.

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What is next?

- ***Continue on with Heat Transfer***
  - ***Finned Surface Heat Transfer***

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