ENGR 292 Fluids and Thermodynamics

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Schedule of the Rest of Semester

- ❑ ***Mar. 21 (today) Heat Transfer***
  - ***Assignment 5***
- ❑ ***Mar. 24 Heat Transfer***
- ❑ ***Mar. 28 Heat Transfer***
- ❑ ***Mar.31 Analytical Methods (Optional)***
- ❑ ***Apr.04 Analytical Methods (Optional)***
- ❑ ***Apr.07 Final Review***
- ❑ ***Apr.11 Final Review***
- ❑ ***Apr.14 Holiday***
- ❑ ***Apr.18 Final Exam***

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Assignment

- ❑ ***The Due date of Assignment 3 is extended from Mar.21 to Mar.24.***
- ❑ ***Assignment 4 Due: Mar. 31***
- ❑ ***Assignment 5 Due: Apr.07***

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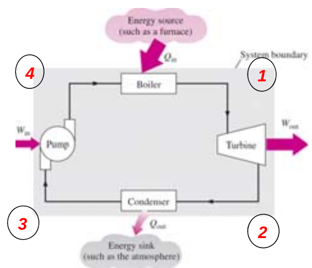
Review of Last Class

- ❑ ***Steam Power Plant – Heat Engine***



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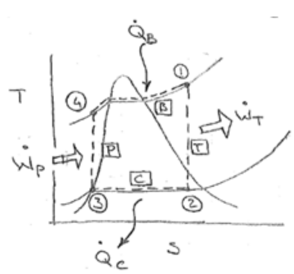
Review of Last Class

- ❑ ***Cycle of Steam Power Plant – Heat Engine***



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Review of Last Class

- ❑ ***Define the Properties (steam tables)***

State	T (℃)	P(MPa)	*v* (m³/kg)	h (kJ/kg)	s (kJ/(kgK))	Condition
1						
2						
3						
4						

- ❑ ***Note: The data given is labeled by ****

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Review of Last Class

- **Energy Analysis**

Energy Analysis	Equations
Net Work	$\dot{W}_{net\ out} = \dot{W}_T - \dot{W}_P$
	$W_{net\ out} = Q_{in} - Q_{out}$
Heat Input	$\dot{Q}_{in} = \dot{Q}_B = \dot{m}_s(h_1 - h_4)$
Thermal Efficiency	$\eta = \frac{\dot{W}_{net\ out}}{\dot{Q}_{in}} = \frac{\dot{W}_T - \dot{W}_P}{\dot{Q}_{in}}$
	$\eta = \frac{W_{net\ out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$

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Review of Last Class

- **Energy Analysis**

Energy Analysis	Equations
Net Power	$P_{net} = \dot{m}\dot{W}_{net\ out}$
Back Work Ratio	$\frac{\dot{W}_P}{\dot{W}_T}$

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Review of Last Class

- **Isentropic Efficiency**

Devices	Isentropic Efficiency
Output device Turbine	$\eta_T = \frac{\dot{W}_{T\_Actual}}{\dot{W}_{T\_Ideal}} = \frac{h_1 - h_2}{h_1 - h_{2s}} < 1$
Input device Pump	$\eta_P = \frac{\dot{W}_{P\_Ideal}}{\dot{W}_{P\_Actual}} = \frac{h_{4s} - h_3}{h_4 - h_3} < 1$

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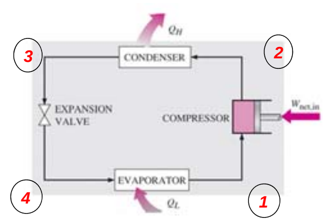
Review of Last Class

- **Refrigerator**



Refrigerator: Cooling effect is desired.

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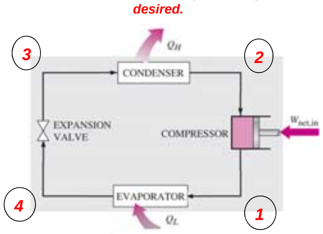
Review of Last Class

- **Heat Pump**

Heat Pump: Heating effect is desired.



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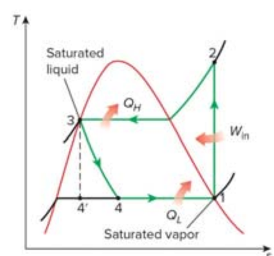
Review of Last Class

- **Cycle of Refrigeration (R) and Heat Pump (HP)**



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Review of Last Class

- **Define the Properties (Refrigerants tables)**

State	T (℃)	P(MPa)	v (m³/kg)	h (kJ/kg)	s (kJ/(kgK))	Condition
1						
2						
3						
4						

- ***Note: The data given is labeled by ****

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Review of Last Class

- **Refrigeration (R) and Heat Pump (HP)**

Energy Analysis	Equations
Compressor	$\dot{W}_c = \dot{m}(h_2 - h_1)$
Expansion Valve	$h_3 = h_4 = h_{f4} + x(h_{g4} - h_{f4})$

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Review of Last Class

- **Refrigeration (R) and Heat Pump (HP)**

Energy Analysis			Equations
Condenser / Evaporator (Rejected)	R	Condenser	$\dot{Q}_{out} = \dot{m}(h_1 - h_4)$
	HP	Evaporator	$\dot{Q}_{in} = \dot{m}(h_2 - h_3)$
Condenser / Evaporator (Desired)	R	Evaporator	$\dot{Q}_{in} = \dot{m}(h_1 - h_4)$
	HP	Condenser	$\dot{Q}_{out} = \dot{m}(h_2 - h_3)$
Coefficients of Performance (COP)	R		$COP_R = \frac{Cooling\ Effect}{Work\ Input} = \frac{\dot{Q}_{in}}{\dot{W}_c} = \frac{h_1 - h_4}{h_2 - h_1}$
	HP		$COP_{HP} = \frac{Heating\ Effect}{Work\ Input} = \frac{\dot{Q}_{out}}{\dot{W}_c} = \frac{h_2 - h_3}{h_2 - h_1}$

Review of Last Class

- **Thermal Efficiency (η) vs. Coefficients of Performance (COP)**

Energy Analysis		Equations
Thermal Efficiency (energy converting)		$\eta = \frac{\dot{W}_{net\ out}}{\dot{Q}_{in}} = \frac{\dot{W}_T - \dot{W}_P}{\dot{Q}_{in}} = \frac{\dot{W}_T - \dot{W}_P}{h_1 - h_4} < 1$
		$\eta = \frac{W_{net\ out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} < 1$
Coefficients of Performance (COP) (energy transferring)	R	$COP_R = \frac{Cooling\ Effect}{Work\ Input} = \frac{\dot{Q}_{in}}{\dot{W}_c} = \frac{h_1 - h_4}{h_2 - h_1}$
	HP	$COP_{HP} = \frac{Heating\ Effect}{Work\ Input} = \frac{\dot{Q}_{out}}{\dot{W}_c} = \frac{h_2 - h_3}{h_2 - h_1}$

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Heat Transfer

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

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Conduction

- **Conduction: heat transfer through non-moving material (solids, confined liquids, gases, etc.)**

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Conduction

- **Fourier's Law of Conduction:**

$$\dot{Q} = -kA\frac{dT}{dx}$$

$\dot{Q}$ = rate of heat transfer (W)
k = the thermal conductivity [W/(m•K)]
A = the surface area perpendicular to direction of heat transfer (m^2)

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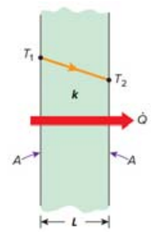
Conduction (Plain Wall)

- **Conduction through a Plain Wall**

$$\dot{Q} = -\frac{kA}{L}(T_2 - T_1)$$
$$= \frac{kA}{L}(T_{hot} - T_{cold})$$

$T_2 = T_{cold}$
$T_1 = T_{hot}$

A = wall surface area normal to heat flow (m^2)
L = wall thickness (m)
T_1 = temperature of one surface of the wall (K)
T_2 = temperature of the other surface of the wall (K)



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Thermal Conductivity (k)

- **Thermal Conductivities (k)**

Material	Thermal Conductivity k W/m °C
Metals:	
Silver (pure)	410
Copper (pure)	385
Aluminum (pure)	202
Nickel (pure)	93
Iron (pure)	73
Carbon Steel, 1% C	43
Lead (pure)	35
Chrome-nickel steel (18% Cr, 8% Ni)	16.3

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Thermal Conductivity (k)

- **Thermal Conductivities (k)**

Material	Thermal Conductivity k W/m °C
Nonmetallic Solids:	
Quartz, parallel to axis	41.6
Magnesite	4.15
Marble	2.08-2.94
Sandstone	1.83
Glass, window	0.78
Maple or Oak	0.17
Sawdust	0.059
Glass wool	0.038

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Thermal Conductivity (k)

- **Thermal Conductivities (k)**

Material	Thermal Conductivity k W/m °C
Liquids:	
Mercury	8.21
Water	0.556
Ammonia	0.054
Lubricating oil, SAE 50	0.147
Freon 12, CCl_2F_2	0.073

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Thermal Conductivity (k)

- **Thermal Conductivities (k)**

Material	Thermal Conductivity k W/m °C
Gases:	
Hydrogen	0.175
Helium	0.141
Air	0.024
Water vapor (saturated)	0.0206
Carbon dioxide	0.0146

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Convection

- Convection: heat transfer through moving material (liquids, gases, etc.)

Convection

- 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.

Convection

- Newton's Law of Cooling:

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

h = the convection heat transfer coefficient of the fluid [W/(m^2•K)]
A = the convection surface area (m^2)
T_w = the wall surface temperature (K)
T_∞ = the bulk fluid temperature (K)

Convection Heat Transfer Coefficient (h)

- Convection Heat Transfer Coefficient (h) is not a property of the fluid.
- It is an experimentally determined parameter whose value depends on the all variables influencing convection such as
  - Surface geometry,
  - The nature of fluid motion
  - The property of the fluid
  - The bulk fluid velocity

Convection Heat Transfer Coefficient (h)

- Convection Heat Transfer Ranges

Convection heat transfer ranges

Process	h(W/m^2.K)
Free convection	
- gases	2-25
- liquids	50-1000
Forced convection	
- gases	25-250
- liquids	50-20,000
Convection with two phase	
- boiling or condensation	2500-100,000

Thermal Resistance

- Thermal Resistance (R)

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

Thermal Resistance

- **Thermal Resistance (R) of Conduction:**

$$\dot{Q}_{Conduction} = -\frac{kA}{L}(T_2 - T_1) = \frac{\Delta T}{\left(\frac{L}{kA}\right)}$$

$$\dot{R}_{Conduction} = \frac{L}{kA}$$

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

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Thermal Resistance

- **Thermal Resistance (R) of Convection:**

$$\dot{Q}_{Convective} = hA(T_w - T_\infty) = \frac{\Delta T}{\left(\frac{1}{hA}\right)}$$

$$\dot{R}_{Convective} = \frac{1}{hA}$$

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

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Heat Transfer

- **Resistances in series are added:**

$$R_{Total} = \sum R$$

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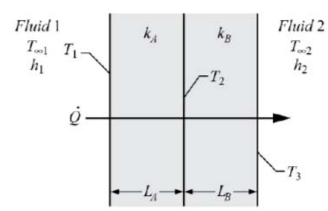
Heat Transfer

- **Composite Plane Wall**



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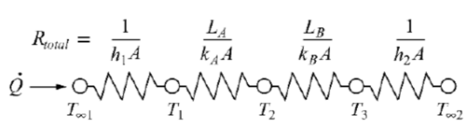
Heat Transfer

- **Composite Plane Wall**



$$R_{total} = \sum R = \frac{1}{h_1 A} + \frac{L_A}{k_A A} + \frac{L_B}{k_B A} + \frac{1}{h_2 A}$$

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

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Example 1

Heat Loss through a Single-Pane Window

Consider a 0.8-m-high and 1.5-m-wide glass window with a thickness of 8 mm and a thermal conductivity of $k = 0.78$ W/m · °C. Determine the steady rate of heat transfer through this glass window and the temperature of its inner surface for a day during which the room is maintained at 20°C while the temperature of the outdoors is −10°C. Take the heat transfer coefficients on the inner and outer surfaces of the window to be $h_1 = 10$ W/m^2 · °C and $h_2 = 40$ W/m^2 · °C, which includes the effects of radiation.

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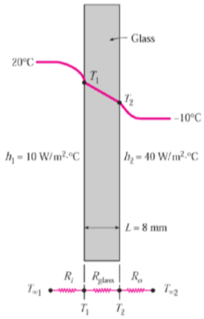
Example 1



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Example 1

Noting that the area of the window is $A = 0.8 \text{ m} \times 1.5 \text{ m} = 1.2 \text{ m}^2$, the individual resistances are evaluated from their definitions to be

$$R_i = R_{\text{conv},1} = \frac{1}{h_1 A} = \frac{1}{(10 \text{ W/m}^2 \cdot {}^\circ\text{C})(1.2 \text{ m}^2)} = 0.08333^\circ\text{C/W}$$

$$R_{\text{glass}} = \frac{L}{kA} = \frac{0.008 \text{ m}}{(0.78 \text{ W/m} \cdot {}^\circ\text{C})(1.2 \text{ m}^2)} = 0.00855^\circ\text{C/W}$$

$$R_o = R_{\text{conv},2} = \frac{1}{h_2 A} = \frac{1}{(40 \text{ W/m}^2 \cdot {}^\circ\text{C})(1.2 \text{ m}^2)} = 0.02083^\circ\text{C/W}$$

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Example 1

Noting that all three resistances are in series, the total resistance is

$$R_{\text{total}} = R_{\text{conv},1} + R_{\text{glass}} + R_{\text{conv},2} = 0.08333 + 0.00855 + 0.02083 = 0.1127^\circ\text{C/W}$$

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Example 1

Then the steady rate of heat transfer through the window becomes

$$\dot{Q} = \frac{T_{\infty 1} - T_{\infty 2}}{R_{\text{total}}} = \frac{[20 - (-10)]^\circ\text{C}}{0.1127^\circ\text{C/W}} = \mathbf{266 \text{ W}}$$

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Example 1

Knowing the rate of heat transfer, the inner surface temperature of the window glass can be determined from

$$\dot{Q} = \frac{T_{\infty 1} - T_1}{R_{\text{conv},1}} \longrightarrow T_1 = T_{\infty 1} - \dot{Q}R_{\text{conv},1} = 20^\circ\text{C} - (266 \text{ W})(0.08333^\circ\text{C/W}) = \mathbf{-2.2^\circ C}$$

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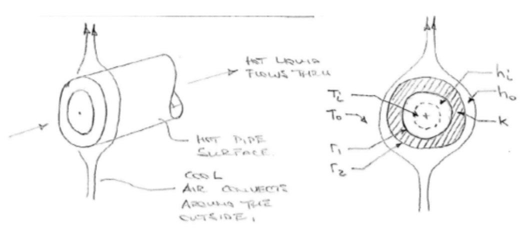
Cylindrical/Spherical Shapes



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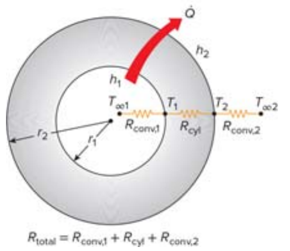
Cylindrical/Spherical Shapes



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Conduction of Cylindrical Pipe

- ***Conduction of Cylindrical Pipe (with Length:** L**, inside radius** r_1 **and outside radius :** r_2**)***

$$R_{Conduction,cyl} = \frac{ln(r_2/r_1)}{2\pi Lk}$$

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Convection of Cylindrical Pipe

- ***Convection of Cylindrical Pipe (with Length:** L**, inside radius** r_1 **and outside radius:** r_2**)***

$$R_{Convection,cyl,inside} = \frac{1}{2\pi\, r_1 L h_1}$$

$$R_{Convection,cyl,outside} = \frac{1}{2\pi\, r_2 L h_2}$$

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Conduction of Spherical Shell

- ***Conduction of Spherical Shell (inside radius** r_1 **and outside radius :** r_2**)***

$$R_{Conduction,sph} = \frac{r_2 - r_1}{4\pi r_1 r_2 k}$$

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Convection of Spherical Shell

- ***Convection of Spherical Shell (inside radius** r_1 **and outside radius :** r_2**)***

$$R_{Convection,sph,inside} = \frac{1}{4\pi r_1^2 h_1}$$

$$R_{Convection,sph,outside} = \frac{1}{4\pi r_2^2 h_2}$$

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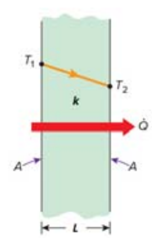
General Equation of Heat Transfer

- ***General Equation of Heat Transfer***

$$\dot{Q} = -UA\,(T_2 - T_1)$$

U = 'The' heat transfer coefficient, W/m²·K



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Thermal Resistance 'R' vs. Heat Transfer Coefficient 'U'

- ***Thermal Resistance 'R' vs. Heat Transfer Coefficient 'U'***

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

General Equation of Heat Transfer

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

Therefore:

$$U = \frac{1}{AR}$$

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Summary

- ***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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Summary

- ***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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Summary

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

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What is next?

- ***Continue on with Heat Transfer***
  - ***Convective Heat Transfer - Finding 'h' – Examples***
  - ***Finned Surface Heat Transfer – Examples***

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