

# **Thermodynamics (ME2121)**

## **Review Lecture**

### **Nov. 9, 2005**

# **PART 1**

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# Outline

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- Summary of what was covered in Part 1 of ME2121
- Some example problems – particularly on Entropy
- Some guidelines for study

# Summary of Chapter 2

- **Basic concepts – become familiar with**
- **Pure substance and its Phase-change process**  
Compressed and saturated liquid, mixture, saturated and superheated vapor), Property diagrams for Phase-change process (T-v, P-v, P-h, etc.), Enthalpy ( $h = u + Pv$ ), Quality, etc.
- **The use of various property tables**  
Ideal-gas specific heats of various common gas (Table A-2 P825), Saturated water and steam table (Table A-4, P830), Superheated water (Table A-6, P834), Compressed liquid water (Table A-7, P838), etc.



# Summary of Chapter 2

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- The ideal-gas equation of state- remember

$$Pv = RT \quad PV = mRT \quad PV = nR_u T$$

R is called the gas constant,  $R_u$  is the universal gas constant

- Specific heats-rememembr

$$du = C_v dT$$

$$dh = C_p dT$$

$$C_p = C_v + R$$

Specific heat ratio,  $k = C_p/C_v$

KNOW System vs Control Volume; Closed vs Open systems



# Summary of Chapters 3&4

- \* Moving Boundary Work  $W_b = \int_1^2 P dV$
- \* Mass Balance Principle  $m_{in} - m_{out} = \Delta m_{system}$
- \* Total energy of a non-flowing fluid (P147)  $\theta = u + ke + pe = u + \frac{V^2}{2} + gz$
- \* Total energy of a flowing fluid (P147)  $\theta = h + ke + pe = h + \frac{V^2}{2} + gz$
- \* The general form of conservation of energy principle (P167)  $E_{in} - E_{out} = \Delta E_{system}$
- \* The conservation of energy principle during a process not-involving mass flow (P169)  
 $E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) = \Delta E_{sys} = E_{final} - E_{initial}$
- \* The conservation of energy principle during a process involving mass flow (P169)

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{mass,in} - E_{mass,out}) = \Delta E_{sys} = E_{final} - E_{initial}$$



# Summary of Chapters 3&4

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- \* The conservation of energy principle for steady flow systems (P181-184)

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system} = 0 \quad (\text{in rate form})$$

- \* Applications of the conservation of energy principle (P184-197)

Nozzles and Diffusers, Compressor, Steam Turbine, Throttling Valves, Mixing Chambers, Heat exchangers (Please visit the website of Prof Mujumdar <http://serve.me.nus.edu.sg/arun/> or IVLE to download the file for further information)

- \* Concepts of steady (P14, P181), uniform flow process (P198), quasi-equilibrium state (P13)
- \* Energy balance for uniform flow process (P198)

$$(\dot{Q}_{in} + \dot{W}_{in} + \sum m_i \theta_i) - (\dot{Q}_{out} + \dot{W}_{out} + \sum m_e \theta_e) = \Delta \dot{E}_{system}$$

$$\Delta E_{system} = (E_{final} - E_{initial})_{system} = (m_2 u_2 - m_1 u_1)_{system}$$



# Summary of Chapters 5&6

- \* The second law of Thermodynamics (P253, P262) Prof. C. Yap

**Kelvin-Planck Statement** : It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work.

**Clausius Statement**: It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

- \* Principles of heat engines, Refrigerators and heat pumps (P257-260)

Heat engine: 
$$\eta_{th} = \frac{W_{net.out}}{Q_{in}}$$

Refrigerator: 
$$COP_R = \frac{Q_L}{W_{net.in}} = \frac{Q_L}{Q_H - Q_L} = \frac{T_L}{T_H - T_L}$$

Heat pump: 
$$COP_{HP} = \frac{Q_H}{W_{net.in}} = \frac{Q_H}{Q_H - Q_L} = \frac{T_H}{T_H - T_L}$$



# Summary of Chapters 5&6

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- \* Reversible and irreversible processes (P265-269)

Reversible process is a process that can be reversed without leaving any trace on the surroundings (Ideal condition)

Typical irreversibilities -causes:

Friction

Unrestrained expansion of a gas

Heat transfer through a finite difference

Mixing

Chemical reactions, etc.

- \* The Carnot cycle and its principles

Reversible isothermal expansion

Reversible adiabatic expansion (Isentropic)

Reversible isothermal compression

Reversible adiabatic expansion (Isentropic)

# Summary of Chapters 5&6

\* **Definition of Entropy**  $dS = \left( \frac{\delta Q}{T} \right)_{\text{int,rev}}$  a measure of molecular disorder or randomness of a system and it can be created but cannot be destroyed.

• **Increase of entropy principle:** The entropy of an isolated system during a process always increases or, in the limiting case of a reversible process, remains constant  $S_{gen} \geq 0$

•\* **property diagrams involving entropy (h-s, t-s) (p314), The Tds relations (p320)**

$$Tds = du + Pdv \text{ (Gibb's equation)}$$

$$Tds = dh - vdP$$

\* **Entropy change of liquids and solids (small temperature change)**

$$ds = \frac{du}{T} = \frac{C_{av} dT}{T} \Rightarrow s_2 - s_1 = C_{av} \ln \frac{T_2}{T_1}$$

\* **The entropy change of ideal gases (small temperature change)**

$$ds = \frac{du}{T} + \frac{Pdv}{T} = C_v \frac{dT}{T} + R \frac{dv}{v} \Rightarrow s_2 - s_1 = C_{v,av} \ln \frac{T_2}{T_1} + R \ln \frac{v_2}{v_1}$$

$$ds = \frac{dh}{T} + \frac{vdv}{T} P = C_p \frac{dT}{T} + R \frac{dP}{P} \Rightarrow s_2 - s_1 = C_{p,av} \ln \frac{T_2}{T_1} - R \ln \frac{P_2}{P_1}$$

# Summary of Chapters 5&6

- \* Reversible steady-flow work (for information)

$$w_{rev,in} = \int v dp + \Delta ke + \Delta pe$$

$v$  should be smaller for work-consuming devices---pumps, compressors, etc.

$v$  should be greater for work-producing devices---steam turbines, etc.

- \* Isentropic processes (internally irreversible, adiabatic, const  $C_p$  and  $C_v$ ) (p313)

Isentropic process  $Pv^k = const$

Polytropic process  $Pv^n = const$

Isothermal process  $Pv = const$

No conservation of entropy principle/equation!

- \* Entropy balance (P347)
- The entropy change of a system during a process is equal to the net entropy transfer through the system and the entropy generated within the system.

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = \Delta \dot{S}_{system} = S_2 - S_1$$

Net entropy transfer  
by heat and mass

Entropy  
Generation

Change  
in entropy



# Summary of Chapters 5&6

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\*Entropy transfer by Heat transfer

$$S_{heat} = \frac{Q}{T} (T = const)$$

$$S_{heat} = \int_1^2 \frac{Q}{T} \cong \sum \frac{Q_k}{T_k}$$

\*Entropy transfer by Mass flow

$$S_{mass} = ms$$

$$S_{mass} = \int_{\Delta t} \dot{S}_{mass} dt$$

$$\dot{S}_{mass} \int_A s \rho V dA$$

\* **Entropy change for a closed system and its surroundings**

$$S_{gen} = \sum \Delta S = \Delta S_{sys} + \Delta S_{sur}$$

Since any closed system and its surroundings can be treated as an adiabatic system in which the entropy generation equals the entropy change of the adiabatic system



# Summary of Chapters 5&6

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\* Entropy balance for a closed system

$$\sum \frac{Q_k}{T_k} + S_{gen} = \Delta S_{sys}$$

\* Entropy balance for a control volume

$$\sum \frac{Q_k}{T_k} + \sum m_i s_i - \sum m_e s_e + S_{gen} = \Delta S_{sys}$$

$$\Delta S_{sys} = S_{final} - S_{initial} = S_2 - S_1$$

\* Entropy change for a general **steady** flow process

$$\dot{S}_{gen} = \sum \dot{m}_e s_e - \sum \dot{m}_i s_i - \sum \frac{\dot{Q}_k}{T_k} \quad (\text{since } \Delta \dot{S}_{sys} = 0)$$

Typical processes operated steadily in such devices as turbines, compressors, nozzles, diffusers, heat exchangers, pipes, ducts, etc.



# Availability of Power Point Slides

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- For detailed Notes visit following URL. It includes extended PPT files in pdf format for academic users only. They contain more information than what could be done in time available for lectures.
- Numerous useful websites are listed; they are only for your use if you wish to read /study further a specific topic. Not required for examination. Visit:  
<http://serve.me.nus.edu.sg/arun>
- Look under Teaching Resources-Thermodynamics
- Notes also being referred to by overseas faculty members and students. Hence they appear on both IVLE (within NUS) and the internet as well.

**Apologies for any typos that may have slipped and remained undetected at this first round!**

# Problem 5

## Problem C5 (Problem 6-122)

An ordinary egg can be approximated as a 5.5 cm diameter sphere. The egg is initially at a uniform temperature of 8 °C and is dropped into boiling water at 97 °C. Taking the properties of the egg to be  $\rho = 1020 \text{ kg/m}^3$  and  $C_p = 3.32 \text{ kJ/(kg } ^\circ\text{C)}$ , determine how much heat is transferred to the egg by the time the average temperature of the egg rises to 70°C and the amount of entropy generation associated with this heat transfer process.

### Solution:

### Assumptions Comment on each assumption-why needed?

1. The egg is spherical in shape with a radius of 5.5cm.
2. The thermal properties of the egg are constant.
3. Energy absorption or release associated with any chemical and/or phase changes within the egg is negligible.
4. There are no changes in kinetic and potential energies.

### Properties

The density and specific heat of the egg are given to be

$$\rho = 1020 \text{ kg/m}^3 \quad \text{and} \quad c_p = 3.32 \text{ kJ/kg} \cdot ^\circ\text{C}$$

Boiling  
Water

Egg  
8°C

A diagram showing an oval representing an egg. The text 'Egg 8°C' is written inside the oval. To the left of the oval, the text 'Boiling Water' is written.

# Problem 5

## Problem C5 (Problem 6-122)

An ordinary egg can be approximated as a 5.5 cm diameter sphere. The egg is initially at a uniform temperature of 8 °C and is dropped into boiling water at 97 °C. Taking the properties of the egg to be  $\rho = 1020 \text{ kg/m}^3$  and  $C_p = 3.32 \text{ kJ/(kg } ^\circ\text{C)}$ , determine how much heat is transferred to the egg by the time the average temperature of the egg rises to 70°C and the amount of entropy generation associated with this heat transfer process.

### Analysis

We take the egg as the system. This is a closed system since no mass enters or leaves the egg. The energy balance for this closed system can be expressed as

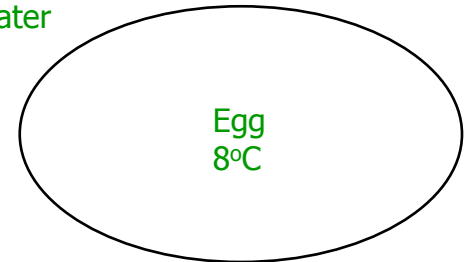
$$\text{Energy balance: } \dot{E}_{in} - \dot{E}_{out} = \Delta E_{system}$$

Net energy transfer  
By heat, work, and mass

Change in internal, kinetic,  
Potential, etc. energies

$$Q_{in} = \Delta U_{egg} = m(u_2 - u_1) = mC_v(T_2 - T_1)$$

Boiling  
Water



Then the mass of the egg and the amount of heat transfer become

$$m = \rho V = \rho \frac{\pi D^3}{6} = (1020 \text{ kg/m}^3) \frac{\pi (0.055 \text{ m})^3}{6} = 0.0889 \text{ kg}$$

$$Q_{in} = \Delta U_{egg} = m(u_2 - u_1) = mC_p(T_2 - T_1) = (0.0889 \text{ kg})(3.32 \text{ kJ/kg} \cdot ^\circ\text{C})(70 - 8)^\circ\text{C}$$

# Problem 5

## Problem C5 (Problem 6-122)

An ordinary egg can be approximated as a 5.5 cm diameter sphere. The egg is initially at a uniform temperature of 8 °C and is dropped into boiling water at 97°C. Taking the properties of the egg to be  $\rho = 1020 \text{ kg/m}^3$  and  $C_p = 3.32 \text{ kJ/(kg } ^\circ\text{C)}$ , determine how much heat is transferred to the egg by the time the average temperature of the egg rises to 70°C and the amount of entropy generation associated with this heat transfer process.

### Solution:

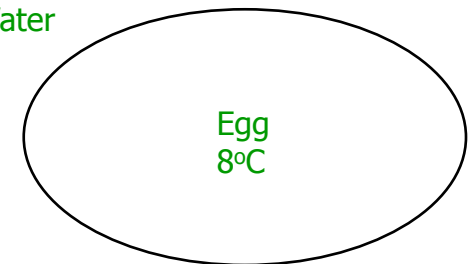
We again take a single egg as the system. The entropy generated during this process can be determined by applying an entropy balance on an extended system that includes the egg and its immediate surroundings so that the boundary temperature of the extended system is at 97 °C at all times:

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = \Delta \dot{S}_{system}$$

Net entropy transfer by heat and mass    Entropy Generation    Change in entropy

$$\frac{Q_{in}}{T_b} + S_{gen} = \Delta S_{system} \rightarrow S_{gen} = -\frac{Q_{in}}{T_b} + \Delta S_{system}$$

Boiling  
Water



where

$$\Delta S_{system} = m(s_2 - s_1) = mC_{av} \ln \frac{T_2}{T_1} = (0.0889 \text{ kg})(3.32 \text{ kJ/kg} \cdot \text{K}) \ln \frac{70 + 273}{8 + 273} = 0.0588 \text{ kJ/K}$$

# Problem 5

## Problem C5 (Problem 6-122)

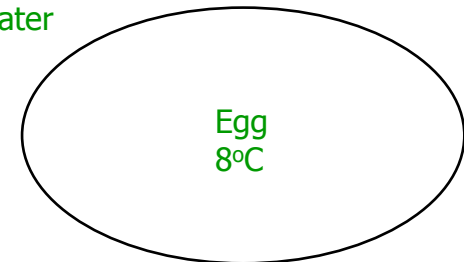
An ordinary egg can be approximated as a 5.5 cm diameter sphere. The egg is initially at a uniform temperature of 8 °C and is dropped into boiling water at 97 °C. Taking the properties of the egg to be  $\rho = 1020 \text{ kg/m}^3$  and  $C_p = 3.32 \text{ kJ/(kg } ^\circ\text{C)}$ , determine how much heat is transferred to the egg by the time the average temperature of the egg rises to 70°C and the amount of entropy generation associated with this heat transfer process. Assume constant specific heat.

### Solution:

Substituting,

$$S_{gen} = -\frac{Q_{in}}{T_b} + \Delta S_{system} = -\frac{18.3kJ}{370K} + 0.0588kJ/K = 0.00961kJ/K \quad (\text{per egg})$$

Boiling  
Water



# Problem 6

## Problem C6 (Problem 6-133)

A  $0.4\text{m}^3$  rigid tank is filled with saturated liquid water at  $200\text{ }^\circ\text{C}$ . A valve at the bottom of the tank is now opened, and one-half of the total mass is withdrawn from the tank in liquid form. Heat is transferred to water from a source at  $250\text{ }^\circ\text{C}$  so that the temperature in the tank remains constant. Determine (a) the amount of heat transfer and (b) the total entropy generation for this process.

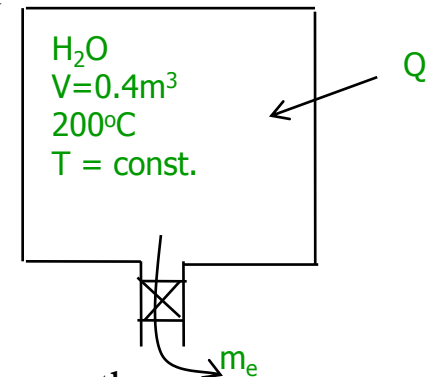
### Solution:

### Assumptions

1. This is an unsteady process since the conditions within the device are changing during the process, but it can be analyzed as uniform-flow process since the state of fluid leaving the device remains constant.
2. Kinetic and potential energies are negligible.
3. There are no work interactions involved.
4. The direction of heat transfer is to the tank (will be verified).
5. No water evaporates during discharging.

### Analysis

(a) We take the tank as the system, which is a control volume since mass crosses the boundary. Noting that the microscopic energies of flowing and nonflowing fluids are represented by enthalpy  $h$  and internal energy  $u$ , respectively, the mass and energy balances for this uniform-flow system can be expressed as



# Problem 6

## Problem C6 (Problem 6-133)

A 0.4m<sup>3</sup> rigid tank is filled with saturated liquid water at 200 °C. A valve at the bottom of the tank is now opened, and one-half of the total mass is withdrawn from the tank in liquid form. Heat is transferred to water from a source at 250 °C so that the temperature in the tank remains constant. Determine (a) the amount of heat transfer and (b) the total entropy generation for this process.

### Solution:

$$\text{Mass balance: } m_{in} - m_{out} = \Delta m_{system} \rightarrow m_e = m_1 - m_2$$

$$\text{Energy balance: } \dot{E}_{in} - \dot{E}_{out} = \dot{\Delta E}_{system}$$

Net energy transfer  
By heat, work, and mass

Change in internal, kinetic,  
Potential, etc. energies

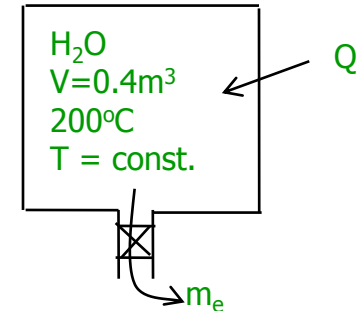
$$Q_{in} = m_e h_e + m_2 u_2 - m_1 u_1 \quad (\text{Since } W \cong ke \cong pe \cong 0)$$

### Properties

The properties of water are (Tables A-4 through A-6)

$$T_1 = 200^\circ C \left. \begin{array}{l} \\ sat.liquid \end{array} \right\} \Rightarrow \begin{cases} v_1 = v_f @ 200^\circ C = 0.001157 m^3 / kg \\ u_2 = u_f @ 200^\circ C = 850.65 kJ / kg \\ s_1 = s_f @ 200^\circ C = 2.3309 kJ / kg \cdot K \end{cases}$$

$$T_e = 200^\circ C \left. \begin{array}{l} \\ sat.liquid \end{array} \right\} \Rightarrow \begin{cases} h_e = h_f @ 200^\circ C = 852.45 kJ / kg \\ s_e = s_f @ 200^\circ C = 2.3309 kJ / kg \cdot K \end{cases}$$



# Problem 6

## Problem C6 (Problem 6-133)

A  $0.4\text{m}^3$  rigid tank is filled with saturated liquid water at  $200\text{ }^\circ\text{C}$ . A valve at the bottom of the tank is now opened, and one-half of the total mass is withdrawn from the tank in liquid form. Heat is transferred to water from a source at  $250\text{ }^\circ\text{C}$  so that the temperature in the tank remains constant. Determine (a) the amount of heat transfer and (b) the total entropy generation for this process.

### Solution:

The initial and the final masses in the tank are

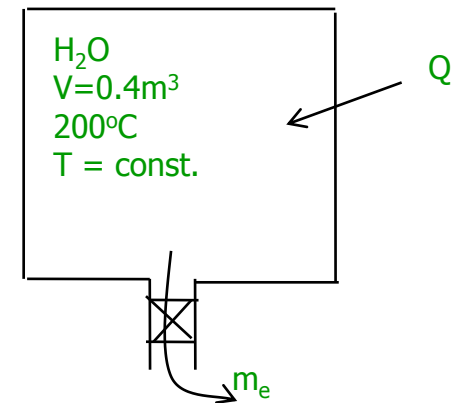
$$m_1 = \frac{V}{v_1} = \frac{0.4\text{m}^3}{0.001157\text{m}^3/\text{kg}} = 345.72\text{kg}$$

$$m_2 = \frac{1}{2}m_1 = \frac{1}{2}(345.72\text{kg}) = 172.86\text{kg} = m_e$$

Now we determine the final internal energy and entropy,

$$v_2 = \frac{V}{m_2} = \frac{0.4\text{m}^3}{172.86\text{kg}} = 0.002314\text{m}^3/\text{kg}$$

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{0.002314 - 0.001157}{0.12736 - 0.001157} = 0.00917$$





# Problem 6

## Problem C6 (Problem 6-133)

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### Solution:

$$\left. \begin{array}{l} T_2 = 200^\circ\text{C} \\ x_2 = 0.00917 \end{array} \right\} \Rightarrow \begin{cases} u_2 = u_f + x_2 u_{fg} = 850.65 + (0.00917)(1744.7) = 866.65\text{kJ/kg} \\ s_2 = s_f + x_2 s_{fg} = 2.3309 + (0.00917)(1.1014) = 2.3685\text{kJ/kg}\cdot\text{K} \end{cases}$$

The heat transfer during this process is determined by substituting these values into the energy balance equation,

$$\begin{aligned} Q_{in} &= m_e h_e + m_2 u_2 - m_1 u_1 \\ &= (172.86\text{kg})(852.4\text{kJ/kg}) + (172.96\text{kJ/kg})(866.65\text{kJ/kg}) - (345.72\text{kg})(850.65\text{kJ/kg}) \\ &= 3077\text{kJ} \end{aligned}$$

(b) The total entropy generation is determined by considering a combined system that includes the tank and the heat source. Noting that no heat crosses the boundaries of this combined system and no mass enters, the entropy balance for it can be expressed as

# Problem 6

## Problem C6 (Problem 6-133)

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### Solution:

$$\sum_{in} \bar{s} - \sum_{out} \bar{s} + S_{gen} = \Delta S_{system}$$

Net entropy transfer  
by heat and mass

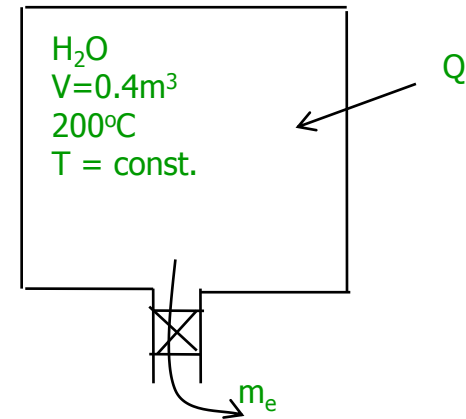
Entropy  
Generation

Change  
in entropy

$$-m_e s_e + S_{gen} = \Delta S_{tank} + \Delta S_{source}$$

Therefore, the total entropy generated during the process is

$$\begin{aligned} S_{gen} &= m_e s_e + \Delta S_{tank} + \Delta S_{source} = m_e s_e + (m_2 s_2 - m_1 s_1) - \frac{Q_{source}}{T_{source}} \\ &= (172.86\text{kg})(2.3309\text{kJ/kg}\cdot\text{K}) + (172.86\text{kg})(2.3685\text{kJ/kg}\cdot\text{K}) \\ &\quad - (345.72\text{kg})(2.3309\text{kJ/kg}\cdot\text{K}) - \frac{3077\text{kJ}}{523\text{K}} \\ &= 0.616\text{kJ/K} \end{aligned}$$





# A word about the final exam

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- Prepare yourself well-no need to worry!
- **Closed book.** Remember very basic equations and procedures for simple derivations
- Two problems consisting of conceptual questions and numerical problems. (**PART 1**)
- Be concise, complete and precise! State all key assumptions. Write your answers neatly in easy to read steps- and in proper order.



# THE END

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- Study by reading textbook, going over Notes (supplied and your own), tutorial problems/solutions and Example problems from textbook
- While PPT Notes supplied are very detailed; only with a little additional effort on your part, you can customize them for your own use. They are purposely keyed to textbook to facilitate learning and **reduce** entropy! They are not designed to supplant textbook or need for you to draft own Notes!
- ***Try to learn to retain*** the basic concepts as they will be needed in later years too!
- Best wishes!