# ENGR 292 Fluids and Thermodynamics

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## Review of Last Class

- ***T-v diagram***
- ***P-v diagram***
- ***Steam Table***

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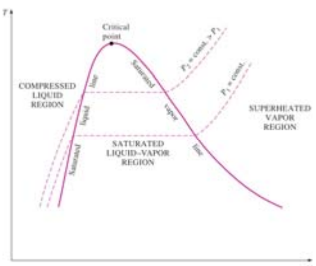
## Review of Last Class

- ***T-v diagram***

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## Review of Last Class

- ***Compressed (Subcooled) Liquid***
  - ***Higher pressure ($P > P_{sat}$ at a given T)***
  - ***Lower temperature ($T < T_{sat}$ at a given P)***
  - ***Lower specific volume ($v < v_f$ at a given P or T)***
  - ***Lower internal energy($u < u_f$ at a given P or T)***
  - ***Lower enthalpies ($h < h_f$ at a given P or T)***

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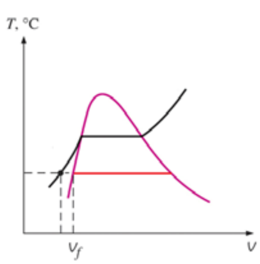
## Review of Last Class

- ***Compressed (Subcooled) Liquid***

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## Review of Last Class

- ***Superheated Vapor***
  - ***Lower pressure ($P < P_{sat}$ at a given T)***
  - ***Higher temperature ($T > T_{sat}$ at a given P)***
  - ***Higher specific volume ($v > v_g$ at a given P or T)***
  - ***Higher internal energy($u > u_g$ at a given P or T)***
  - ***Higher enthalpies ($h > h_g$ at a given P or T)***

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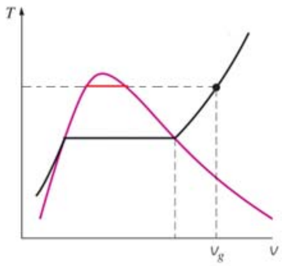
## Review of Last Class

- **Superheated Vapor**





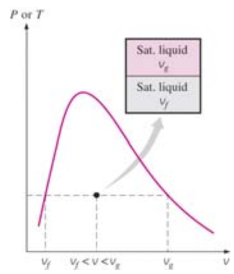

## Review of Last Class

- **Saturated Liquid-Vapor Mixture**
  - *Saturated pressure ($P = P_{sat}$at a given T)*
  - *Saturated temperature ($T = T_{sat}$at a given P)*
  - *Quality* $0 < x < 1$
  - *Specific volume ($v_f < v < v_g$)*
  - *Internal energy ($u_f < u < u_g$)*
  - *Higher enthalpies ($h_f < h < h_g$)*



## Review of Last Class

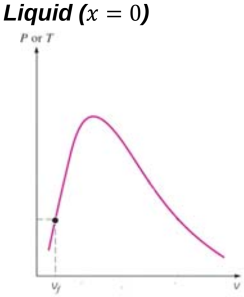
- **Saturated Liquid-Vapor Mixture ($0 < x < 1$)**






## Review of Last Class

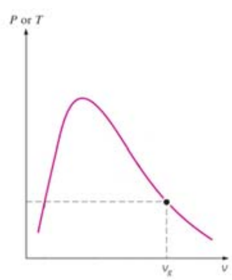
- **Saturated Liquid ($x = 0$)**






## Review of Last Class

- **Saturated Vapor ($x = 1$)**






## Review of Last Class

- **Enthalpy – A Combination Property**

*Total Enthalpy*

$$H = U + PV$$

*Specific Enthalpy (per unit mass):*

$$h = u + Pv$$

## Total Energy of a Flowing Fluid

- ***The total energy of a flowing fluid on a unit-mass basis (denoted by $\theta$, methalpy)***

$$\theta = \boxed{Pv + u} + ke + pe$$
$$= \boxed{Pv + u} + \frac{v^2}{2} + gz$$
$$= h + \frac{v^2}{2} + gz \ (kJ/kg)$$

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## Energy Transferred by Heat

- ***Amount of Heat transferred is denoted by*** $Q\ (kJ)$
- ***Heat transfer per unit mass is denoted by*** $q = \frac{Q}{m}\ (kJ/kg)$
- ***Rate of Heat Transfer (the amount of heat transferred per unit time) is denoted by*** $\dot{Q}\ (kJ/s)\ or\ (kW)$

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## Energy Transferred by Work

- ***The work done during a process is denoted by*** $W\ (kJ)$
- ***Work done per unit mass is denoted by***

$$w = \frac{W}{m}\ (kJ/kg)$$

- ***The work done per unit time is denoted by*** $\dot{W}\ (kJ/s)\ or\ (kW)$

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## Energy Transported by Mass

- ***Amount of Energy Transport:***

$$E_{mass} = m\theta = m\left(h + \frac{v^2}{2} + gz\right)\ (kJ)$$

- ***Rate of Energy Transport:***

$$\dot{E}_{mass} = \dot{m}\theta = \dot{m}\left(h + \frac{v^2}{2} + gz\right)\ (kW)$$

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## Energy Transported by Mass

- ***If the kinetic and potential energies of a fluid stream are negligible, then***
  - ***Amount of Energy Transport:***

$$E_{mass} = mh\ \ (kJ)$$

  - ***Rate of Energy Transport:***

$$\dot{E}_{mass} = \dot{m}h\ \ (kW)$$

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## The First Law of Thermodynamics

- ***The first law of thermodynamics is simply a statement of the conservation of energy principle.***

- ***The general energy balance:***

$$E_{in} - E_{out} = \Delta E_{system}$$

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## The First Law of Thermodynamics

- **The general energy balance:**

$$E_{in} - E_{out} = \Delta E_{system}$$

$$E_{in} - E_{out} = (Q_{in} - Q_{out}) + (W_{in} - W_{out}) + (E_{massin} - E_{massout}) = \Delta E_{system}$$

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## Some Steady-Flow Engineering Devices

***A large number of engineering devices such as***

- ***Nozzle***
- ***Turbine***
- ***Compressor***
- ***Heat Exchanger***
- ***Valve***

***Operates for long periods of time under same conditions, and they classified as steady flow devices.***

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## Steady Flow Systems

- ***Energy balance for steady-flow systems***
- ***The general energy balance:***

$$E_{in} - E_{out} = \Delta E_{system}$$

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## Some Steady-Flow Engineering Devices

- ***All the devices have steady mass flow through them***

$$\frac{dm_{cv}}{dt} = 0$$

- ***And there is no change in stored energy***

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## Some Steady-Flow Engineering Devices

***Therefore***

$$\frac{\dot{Q}_{cv}}{\dot{m}} - \frac{\dot{W}_{cv}}{\dot{m}} + (h_i - h_e) + \frac{v_i^2 - v_e^2}{2} + g(z_i - z_e) = 0$$

***Where: cv = control volume***

***i = inlet***

***e = exit***

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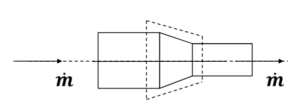
## Nozzle




$$\frac{\dot{Q}_{cv}}{\dot{m}} - \frac{\dot{W}_{cv}}{\dot{m}} + (h_i - h_e) + \frac{v_i^2 - v_e^2}{2} + g(z_i - z_e) = 0$$

$$(h_i - h_e) + \frac{v_i^2 - v_e^2}{2} = 0$$

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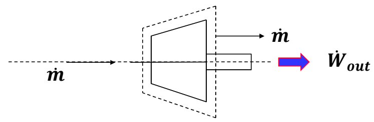
## Turbine



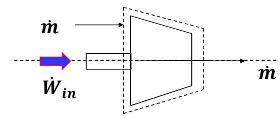

$$\frac{\dot{Q}_{cv}}{\dot{m}} - \frac{\dot{W}_{cv}}{\dot{m}} + (h_i - h_e) + \frac{v_i^2 - v_e^2}{2} + g(z_i - z_e) = 0$$

$$-\frac{\dot{W}_{cv}}{\dot{m}} + (h_i - h_e) = 0$$

$$\dot{W}_{out} = \dot{W}_{cv}$$



## Compressor (Pump)




$$\frac{\dot{Q}_{cv}}{\dot{m}} - \frac{\dot{W}_{cv}}{\dot{m}} + (h_i - h_e) + \frac{v_i^2 - v_e^2}{2} + g(z_i - z_e) = 0$$

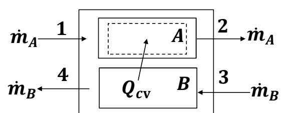
$$-\frac{\dot{W}_{cv}}{\dot{m}} + (h_i - h_e) = 0$$

$$\dot{W}_{in} = -\dot{W}_{cv}$$



## Heat Exchanger (Boiler)

- For System A or B, one at a time;



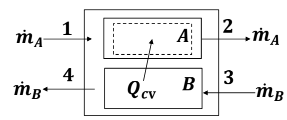

$$\frac{\dot{Q}_{cv}}{\dot{m}} - \frac{\dot{W}_{cv}}{\dot{m}} + (h_i - h_e) + \frac{v_i^2 - v_e^2}{2} + g(z_i - z_e) = 0$$

$$\frac{\dot{Q}_{cv}}{\dot{m}} + (h_i - h_e) = 0$$



## Heat Exchanger (Boiler)

- For System A or B



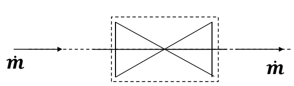

$$\dot{Q}_{Ain} = -\dot{Q}_{Bout} = \dot{Q}_{cv}$$

$$\dot{m}_A(h_1 - h_2) = -\dot{m}_B(h_3 - h_4) = \dot{Q}_{cv}$$

$$\frac{\dot{m}_A}{\dot{m}_B} = \frac{h_1 - h_2}{h_4 - h_3}$$



## Valve




$$\frac{\dot{Q}_{cv}}{\dot{m}} - \frac{\dot{W}_{cv}}{\dot{m}} + (h_i - h_e) + \frac{v_i^2 - v_e^2}{2} + g(z_i - z_e) = 0$$

$$(h_i - h_e) = 0$$

$$\therefore h_i = h_e$$



## Entropy

- *Entropy – Another Combination Property*

*Total Entropy $S$*

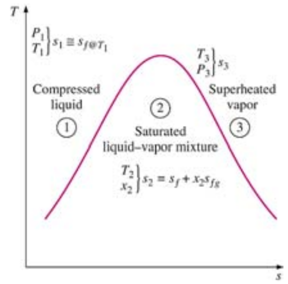
$$dS = \frac{\delta Q}{T} \quad (kJ/K)$$

*Specific Entropy (per unit mass):*

$$ds = \frac{\delta Q}{Tm} \; (kJ/(kg \cdot K))$$

## Control Volume Energy Analysis

- T-s diagram






## The Second Law of Thermodynamics

- ***It is known that a process must satisfy the first law to occur.***
- ***However, satisfying the first law alone does not ensure that the process will actually take place.***



## The Second Law of Thermodynamics

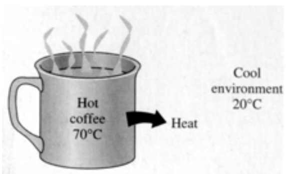



**FIGURE 1–3**
Heat flows in the direction of decreasing temperature.



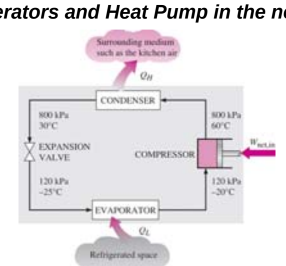
## The Second Law of Thermodynamics

- ***Clausius statement of the second law:***
  - ***It is impossible for any system to operate in such a way that the sole result would be an energy transfer by heat from a cooler to hotter body***
  - ***The Clausius statement does not rule out the possibility of transferring energy by heat from a cooler body to a hotter body***
  - ***The Clausius statement implies that it is impossible to construct a refrigeration cycle that operates without an input of work***



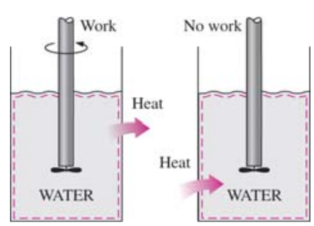
## The Second Law of Thermodynamics

- ***Clausius statement of the second law:***
  - ***Refrigerators and Heat Pump in the next class***






## The Second Law of Thermodynamics



## The Second Law of Thermodynamics

- **Kelvin-Planck statement of the second law:**
  - *It is impossible for any system to operate in a thermodynamic cycle and deliver a net amount of energy by work to its surroundings while receiving energy by heat transfer from a single thermal reservoir.*

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## Heat Engines

- ***That work can be converted to heat directly and completely, but converting heat to work requires the use of some special devices. These devices are called heat engines.***

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## Heat Engines

- ***Heat engines differ considerable from one another, but all can be characterized by the following:***
  - *They receive heat from a high-temperature source*
  - *They convert part of this heat to work*
  - *They reject the remaining waste heat to a low-temperature sink*
  - *They operate on a cycle.*

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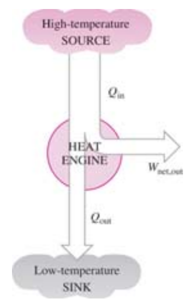
## Heat Engines

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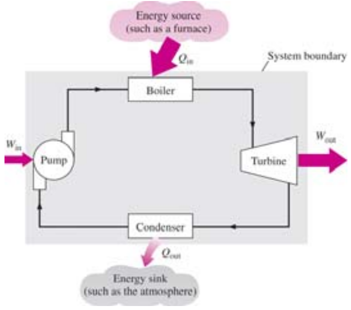
## Schematic of a Steam Power Plant

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## Steam Power Plant

- ***The various quantities shown on above figure are as follows:***
  - $Q_{in}$ *= amount of heat supplied to steam in boiler from a high-temperature source*
  - $Q_{out}$ *= amount of heat rejected from steam in condenser to low temperature sink*
  - $W_{out}$ *= amount of work delivered by steam as it expands in turbine*
  - $W_{in}$ *= amount of work required to compress water to boiler pressure*

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## Steam Power Plant

- **The net work output:**

$$W_{net\ out} = W_{out} - W_{in}$$

$$W_{net\ out} = Q_{in} - Q_{out}$$

- **Thermal Efficiency:**

$$Thermal\ efficiency = \frac{Net\ Work\ Output}{Total\ Heat\ Input}$$

$$\eta = \frac{W_{net\ out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

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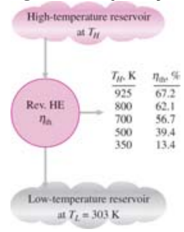
## The Quality of Energy

- **The Quality of Energy**
  - ***More of the high-temperature thermal energy can be converted to work. Therefore, the higher the temperature, the higher the quality of the energy***

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## Vapor Power Plant

**4.76** Figure P4.76 shows a simple vapor power plant operating at steady state with water circulating through the components. Relevant data at key locations are given on the figure. The mass flow rate of the water is 130 kg/s. Kinetic and potential energy effects are negligible. Determine

**(a)** the heat transfer rate to the steam passing through the steam generator, in kW.
**(b)** the *net* power developed for adiabatic operation of the turbine and pump, in kW.
**(c)** the mass flow rate of the cooling water passing through the condenser, in kg/s, if the cooling water experiences a temperature rise of 15°C and a negligible pressure drop.

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## Vapor Power Plant

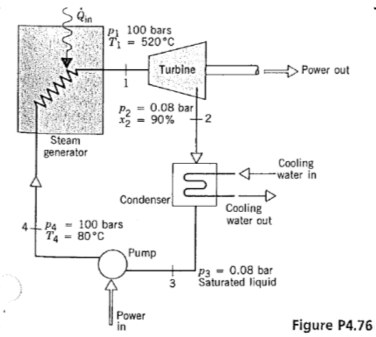


Figure P4.76

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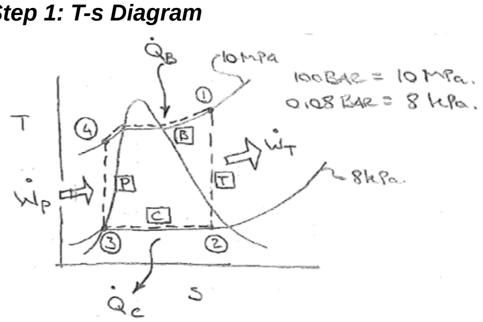
## Rankine Cycle

- ***Step 1: T-s Diagram***

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## Rankine Cycle

- **Step 2 Define the Properties**

| State | T (°C) | P(Pa) | h (kJ/kg) | Phase |
|---|---|---|---|---|
| 1 | 520* | 10 M* | ? | Superheated Vapor* |
| 2 | ? | 8 K* | ? | x = 0.9 * |
| 3 | ? | 8 K* | ? | Saturated Liquid* |
| 4 | 80* | 10 M* | ? | Compressed Liquid* |

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

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## Rankine Cycle

### Step 2 Define the Properties

- State (1)
- It is in the superheated vapor region, and the temperature and pressure are given: $T = 520℃$; $P = 10Mpa$;
- h value can be determined from the superheated vapor table (Table A-6) by interpolation method.

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## Rankine Cycle

- A partial list of Table A-6

TABLE A–6

Superheated water (*Continued*)

| *T* °C | *v* m³/kg | *u* kJ/kg | *h* kJ/kg | *s* kJ/kg·K | *v* m³/kg | *u* kJ/kg | *h* kJ/kg | *s* kJ/kg·K |
|---|---|---|---|---|---|---|---|---|
| | *P* = 9.0 MPa (303.35°C) | | | | *P* = 10.0 MPa (311.00°C) | | | |
| Sat. | 0.020489 | 2558.5 | 2742.9 | 5.6791 | 0.018028 | 2545.2 | 2725.5 | 5.6159 |
| 325 | 0.023284 | 2647.6 | 2857.1 | 5.8738 | 0.019877 | 2611.6 | 2810.3 | 5.7596 |
| 350 | 0.025816 | 2725.0 | 2957.3 | 6.0380 | 0.022440 | 2699.6 | 2924.0 | 5.9460 |
| 400 | 0.029960 | 2849.2 | 3118.8 | 6.2876 | 0.026436 | 2833.1 | 3097.5 | 6.2141 |
| 450 | 0.033524 | 2956.3 | 3258.0 | 6.4872 | 0.029782 | 2944.5 | 3242.4 | 6.4219 |
| 500 | 0.036793 | 3056.3 | 3387.4 | 6.6603 | 0.032811 | 3047.0 | 3375.1 | 6.5995 |
| 550 | 0.039885 | 3153.0 | 3512.0 | 6.8164 | 0.035655 | 3145.4 | 3502.0 | 6.7585 |
| 600 | 0.042861 | 3248.4 | 3634.1 | 6.9605 | 0.038378 | 3242.0 | 3625.8 | 6.9045 |
| 650 | 0.045755 | 3343.4 | 3755.2 | 7.0954 | 0.041018 | 3338.0 | 3748.1 | 7.0408 |
| 700 | 0.048589 | 3438.8 | 3876.1 | 7.2229 | 0.043597 | 3434.0 | 3870.0 | 7.1693 |
| 800 | 0.054132 | 3632.0 | 4119.2 | 7.4606 | 0.048629 | 3628.2 | 4114.5 | 7.4085 |
| 900 | 0.059562 | 3829.6 | 4365.7 | 7.6802 | 0.053547 | 3826.5 | 4362.0 | 7.6290 |
| 1000 | 0.064919 | 4032.4 | 4616.7 | 7.8855 | 0.058391 | 4029.9 | 4613.8 | 7.8349 |
| 1100 | 0.070224 | 4240.7 | 4872.7 | 8.0791 | 0.063183 | 4238.5 | 4870.3 | 8.0289 |
| 1200 | 0.075492 | 4454.2 | 5133.6 | 8.2625 | 0.067938 | 4452.4 | 5131.7 | 8.2126 |
| 1300 | 0.080733 | 4672.9 | 5399.5 | 8.4371 | 0.072667 | 4671.3 | 5398.0 | 8.3874 |

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## Rankine Cycle

### Step 2 Define the Properties

- State (1) Cont'd
- From Table A-6

$T_1 = 500℃$; $h_1 = 3375.1 kJ/kg$;

$T_2 = 550℃$; $h_1 = 3502.0\ kJ/kg$;

Therefore

$T = 520℃$;

$$h = h_1 + (T - T_1)\frac{h_2 - h_1}{T_2 - T_1}$$

$$= 3375.1 + (520 - 500)(\frac{3502.0 - 3375.1}{550 - 500})$$

$$= 3425.86\ kJ/kg$$

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## Rankine Cycle

### Step 2 Define the Properties

| State | T (℃) | P(Pa) | h (kJ/kg) | Phase |
|---|---|---|---|---|
| 1 | 520* | 10 M* | 3425.86 | Superheated Vapor* |
| 2 | ? | 8 K* | ? | x = 0.9 * |
| 3 | ? | 8 K* | ? | Saturated Liquid* |
| 4 | 80* | 10 M* | ? | Compressed Liquid* |

- Note: The data given is labeled by *

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## Rankine Cycle

### Step 2 Define the Properties

- State (2)
- The quality x given to be $x = 0.9$, which implies that 90 percent of the mass is in the vapor phase and the remaining 10 percent is in the liquid phase. Therefore, we have saturated liquid-vapor mixture at a pressure 8 kPa.
- Then the temperature must be the saturation temperature at the given pressure by interpolation (Table A-5)

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## Rankine Cycle

- A partial list of Table A-5

TABLE A–5

Saturated water—Pressure table

| | | Specific volume, m³/kg | | Internal energy, kJ/kg | | | Enthalpy, kJ/kg | | | Entropy, kJ/kg·K | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Press., $P$ kPa | Sat. temp., $T_{sat}$ °C | Sat. liquid, $v_f$ | Sat. vapor, $v_g$ | Sat. liquid, $u_f$ | Evap., $u_{fg}$ | Sat. vapor, $u_g$ | Sat. liquid, $h_f$ | Evap., $h_{fg}$ | Sat. vapor, $h_g$ | Sat. liquid, $s_f$ | Evap., $s_{fg}$ | Sat. vapor, $s_g$ |
| 1.0 | 6.97 | 0.001000 | 129.19 | 29.302 | 2355.2 | 2384.5 | 29.303 | 2484.4 | 2513.7 | 0.1059 | 8.8690 | 8.9749 |
| 1.5 | 13.02 | 0.001001 | 87.964 | 54.686 | 2338.1 | 2392.8 | 54.688 | 2470.1 | 2524.7 | 0.1956 | 8.6314 | 8.8270 |
| 2.0 | 17.50 | 0.001001 | 66.990 | 73.431 | 2325.5 | 2398.9 | 73.433 | 2459.5 | 2532.9 | 0.2606 | 8.4621 | 8.7227 |
| 2.5 | 21.08 | 0.001002 | 54.242 | 88.422 | 2315.4 | 2403.8 | 88.424 | 2451.0 | 2539.4 | 0.3118 | 8.3302 | 8.6421 |
| 3.0 | 24.08 | 0.001003 | 45.654 | 100.98 | 2306.9 | 2407.9 | 100.98 | 2443.9 | 2544.8 | 0.3543 | 8.2222 | 8.5765 |
| 4.0 | 28.96 | 0.001004 | 34.791 | 121.39 | 2293.1 | 2414.5 | 121.39 | 2432.3 | 2553.7 | 0.4224 | 8.0510 | 8.4734 |
| 5.0 | 32.87 | 0.001005 | 28.185 | 137.75 | 2282.1 | 2419.8 | 137.75 | 2423.0 | 2560.7 | 0.4762 | 7.9176 | 8.3938 |
| 7.5 | 40.29 | 0.001008 | 19.233 | 168.74 | 2261.1 | 2429.8 | 168.75 | 2405.3 | 2574.0 | 0.5763 | 7.6738 | 8.2501 |
| 10 | 45.81 | 0.001010 | 14.670 | 191.79 | 2245.4 | 2437.2 | 191.81 | 2392.1 | 2583.9 | 0.6492 | 7.4996 | 8.1488 |
| 15 | 53.97 | 0.001014 | 10.020 | 225.93 | 2222.1 | 2448.0 | 225.94 | 2372.3 | 2598.3 | 0.7549 | 7.2522 | 8.0071 |

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## Rankine Cycle

- **Step 2 Define the Properties**
  - ***State (2) Cont'd***
  - ***From Table A-5***

$P_1 = 7.5\ kPa;\ T_{sat1} = 40.29℃;$

$P_2 = 10\ kPa;\ T_{sat2} = 45.81℃;$

***Therefore***

*If* $P = 8\ kPa;$

$$T_{sat@8\ kPa} = T_{sat1} + (P - P_1)\frac{T_{sat2} - T_{sat1}}{P_2 - P_1}$$
$$= 40.29 + (8 - 7.5)(\frac{45.81 - 40.29}{10 - 7.5})$$
$$= 41.39℃;$$

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## Rankine Cycle

- **Step 2 Define the Properties**
  - ***State (2) Cont'd***

$P_1 = 7.5\ kPa;\ h_{f1} = 168.75 kJ/kg;$

$P_2 = 10\ kPa;\ h_{f2} = 191.81 kJ/kg;$

***Therefore***

*If* $P = 8\ kPa;$

$$h_{f@8kPa} = h_{f1} + (P - P_1)\frac{h_{f2} - h_{f1}}{P_2 - P_1}$$
$$= 168.75 + (8 - 7.5)(\frac{191.81 - 168.75}{10 - 7.5})$$
$$= 173.36\ kJ/kg;$$

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## Rankine Cycle

- **Step 2 Define the Properties**
  - ***State (2) Cont'd***

$P_1 = 7.5\ kPa;\ h_{g1} = 2574.0\ kJ/kg;$

$P_2 = 10\ kPa;\ h_{g2} = 2583.9 kJ/kg;$

***Therefore***

*If* $P = 8\ kPa;$

$$h_{g@8kPa} = h_{g1} + (P - P_1)\frac{h_{g2} - h_{g1}}{P_2 - P_1}$$
$$= 2574.0 + (8 - 7.5)(\frac{2583.9 - 2574.0}{10 - 7.5})$$
$$= 2575.8\ kJ/kg;$$

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## Rankine Cycle

- **Step 2 Define the Properties**
  - ***State (2) Cont'd***
  - ***Then the average enthalpy of the mixture is***

$$h_{@8kPa} = h_{f@8kPa} + x h_{fg@8kPa}$$
$$= h_{f@8kPa} + x(h_{g@8kPa} - h_{f@8kPa})$$
$$= 173.36\ kJ/kg + (0.9)(2575.8\ kJ/kg - 173.36\ kJ/kg)$$
$$= 2335.56\ kJ/kg$$

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## Rankine Cycle

- **Step 2 Define the Properties**

| State | T (℃) | P(Pa) | h (kJ/kg) | Phase |
|---|---|---|---|---|
| 1 | 520* | 10 M* | 3425.86 | Superheated Vapor* |
| 2 | 41.39 | 8 K* | 2335.56 | x = 0.9 * |
| 3 | ? | 8 K* | ? | Saturated Liquid* |
| 4 | 80* | 10 M* | ? | Compressed Liquid* |

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

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## Rankine Cycle

- **Step 2 Define the Properties**
  - ***State (3)***
  - ***We have saturated liquid at specified pressure of 8 kPa. Then the temperature must be the saturation temperature at the given pressure, and the enthalpy must have the saturated liquid value:***

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## Rankine Cycle

### Step 2 Define the Properties

- State (3) Cont'd
- From Table A-5

$P_1 = 7.5\ kPa;\ T_{sat1} = 40.29℃;$

$P_2 = 10\ kPa;\ T_{sat2} = 45.81℃;$

**Therefore**

If $P = 8\ kPa;$

$$T_{sat@8\ kPa} = T_{sat1} + (P - P_1)\frac{T_{sat2} - T_{sat1}}{P_2 - P_1}$$
$$= 40.29 + (8 - 7.5)(\frac{45.81 - 40.29}{10 - 7.5})$$
$$= 41.39℃;$$

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## Rankine Cycle

### Step 2 Define the Properties

- State (3) Cont'd

$P_1 = 7.5\ kPa;\ h_{f1} = 168.75 kJ/kg;$

$P_2 = 10\ kPa;\ h_{f2} = 191.81 kJ/kg;$

**Therefore**

If $P = 8\ kPa;$

$$h_{f@8kPa} = h_{f1} + (P - P_1)\frac{h_{f2} - h_{f1}}{P_2 - P_1}$$
$$= 168.75 + (8 - 7.5)(\frac{191.81 - 168.75}{10 - 7.5})$$
$$= 173.36\ kJ/kg;$$

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## Rankine Cycle

- A partial list of Table A-5

TABLE A–5
Saturated water—Pressure table

| Press., P kPa | Sat. temp., $T_{sat}$ °C | Specific volume, m³/kg: Sat. liquid, $v_f$ | Sat. vapor, $v_g$ | Internal energy, kJ/kg: Sat. liquid, $u_f$ | Evap., $u_{fg}$ | Sat. vapor, $u_g$ | Enthalpy, kJ/kg: Sat. liquid, $h_f$ | Evap., $h_{fg}$ | Sat. vapor, $h_g$ | Entropy, kJ/kg·K: Sat. liquid, $s_f$ | Evap., $s_{fg}$ | Sat. vapor, $s_g$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.0 | 6.97 | 0.001000 | 129.19 | 29.302 | 2355.2 | 2384.5 | 29.303 | 2484.4 | 2513.7 | 0.1059 | 8.8690 | 8.9749 |
| 1.5 | 13.02 | 0.001001 | 87.964 | 54.686 | 2338.1 | 2392.8 | 54.688 | 2470.1 | 2524.7 | 0.1956 | 8.6314 | 8.8270 |
| 2.0 | 17.50 | 0.001001 | 66.990 | 73.431 | 2325.5 | 2398.9 | 73.433 | 2459.5 | 2532.9 | 0.2606 | 8.4621 | 8.7227 |
| 2.5 | 21.08 | 0.001002 | 54.242 | 88.422 | 2315.4 | 2403.8 | 88.424 | 2451.0 | 2539.4 | 0.3118 | 8.3302 | 8.6421 |
| 3.0 | 24.08 | 0.001003 | 45.654 | 100.98 | 2306.9 | 2407.9 | 100.98 | 2443.9 | 2544.8 | 0.3543 | 8.2222 | 8.5765 |
| 4.0 | 28.96 | 0.001004 | 34.791 | 121.39 | 2293.1 | 2414.5 | 121.39 | 2432.3 | 2553.7 | 0.4224 | 8.0510 | 8.4734 |
| 5.0 | 32.87 | 0.001005 | 28.185 | 137.75 | 2282.1 | 2419.8 | 137.75 | 2423.0 | 2560.7 | 0.4762 | 7.9176 | 8.3938 |
| 7.5 | 40.29 | 0.001008 | 19.233 | 168.74 | 2261.1 | 2429.8 | 168.75 | 2405.3 | 2574.0 | 0.5763 | 7.6738 | 8.2501 |
| 10 | 45.81 | 0.001010 | 14.670 | 191.79 | 2245.4 | 2437.2 | 191.81 | 2392.1 | 2583.9 | 0.6492 | 7.4996 | 8.1488 |
| 15 | 53.97 | 0.001014 | 10.020 | 225.93 | 2222.1 | 2448.0 | 225.94 | 2372.3 | 2598.3 | 0.7549 | 7.2522 | 8.0071 |

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## Rankine Cycle

### Step 2 Define the Properties

| State | T (℃) | P(Pa) | h (kJ/kg) | Phase |
|---|---|---|---|---|
| 1 | 520* | 10 M* | 3425.86 | Superheated Vapor* |
| 2 | 41.39 | 8 K* | 2335.56 | x = 0.9 * |
| 3 | 41.39 | 8 K* | 173.36 | Saturated Liquid* |
| 4 | 80* | 10 M* | ? | Compressed Liquid* |

- Note: The data given is labeled by *

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## Rankine Cycle

### Step 2 Define the Properties

- State (4)
- We have a compressed liquid

$P = 10\ Mpa;\ T = 80℃;$

**From Table A-7, we can get the enthalpy:**

$$h_{@10Mpa\&80℃} = 342.94\ kJ/kg;$$

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## Rankine Cycle

- A partial list of Table A-7

TABLE A–7
Compressed liquid water

| T °C | P = 5 MPa (263.94°C): v m³/kg | u kJ/kg | h kJ/kg | s kJ/kg·K | P = 10 MPa (311.00°C): v m³/kg | u kJ/kg | h kJ/kg | s kJ/kg·K | P = 15 MPa (342.16°C): v m³/kg | u kJ/kg | h kJ/kg | s kJ/kg·K |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sat. | 0.0012862 | 1148.1 | 1154.5 | 2.9207 | 0.0014522 | 1393.3 | 1407.9 | 3.3603 | 0.0016572 | 1585.5 | 1610.3 | 3.6848 |
| 0 | 0.0009977 | 0.04 | 5.03 | 0.0001 | 0.0009952 | 0.12 | 10.07 | 0.0003 | 0.0009928 | 0.18 | 15.07 | 0.0004 |
| 20 | 0.0009996 | 83.61 | 88.61 | 0.2954 | 0.0009973 | 83.31 | 93.28 | 0.2943 | 0.0009951 | 83.01 | 97.93 | 0.2932 |
| 40 | 0.0010057 | 166.92 | 171.95 | 0.5705 | 0.0010035 | 166.33 | 176.37 | 0.5685 | 0.0010013 | 165.75 | 180.77 | 0.5666 |
| 60 | 0.0010149 | 250.29 | 255.36 | 0.8287 | 0.0010127 | 249.43 | 259.55 | 0.8260 | 0.0010105 | 248.58 | 263.74 | 0.8234 |
| 80 | 0.0010267 | 333.82 | 338.96 | 1.0723 | 0.0010244 | 332.69 | 342.94 | 1.0691 | 0.0010221 | 331.59 | 346.92 | 1.0659 |
| 100 | 0.0010410 | 417.65 | 422.85 | 1.3034 | 0.0010385 | 416.23 | 426.62 | 1.2996 | 0.0010361 | 414.85 | 430.39 | 1.2958 |
| 120 | 0.0010576 | 501.91 | 507.19 | 1.5236 | 0.0010549 | 500.18 | 510.73 | 1.5191 | 0.0010522 | 498.50 | 514.28 | 1.5148 |
| 140 | 0.0010769 | 586.80 | 592.18 | 1.7344 | 0.0010738 | 584.72 | 595.45 | 1.7293 | 0.0010708 | 582.69 | 598.75 | 1.7243 |
| 160 | 0.0010988 | 672.55 | 678.04 | 1.9374 | 0.0010954 | 670.06 | 681.01 | 1.9316 | 0.0010920 | 667.63 | 684.01 | 1.9259 |
| 180 | 0.0011240 | 759.47 | 765.09 | 2.1338 | 0.0011200 | 756.48 | 767.68 | 2.1271 | 0.0011160 | 753.58 | 770.32 | 2.1206 |
| 200 | 0.0011531 | 847.92 | 853.68 | 2.3251 | 0.0011482 | 844.32 | 855.80 | 2.3174 | 0.0011435 | 840.84 | 858.00 | 2.3100 |
| 220 | 0.0011868 | 938.39 | 944.32 | 2.5127 | 0.0011809 | 934.01 | 945.82 | 2.5037 | 0.0011752 | 929.81 | 947.43 | 2.4951 |
| 240 | 0.0012268 | 1031.6 | 1037.7 | 2.6983 | 0.0012192 | 1026.2 | 1038.3 | 2.6876 | 0.0012121 | 1021.0 | 1039.2 | 2.6774 |
| 260 | 0.0012755 | 1128.5 | 1134.9 | 2.8841 | 0.0012653 | 1121.6 | 1134.3 | 2.8710 | 0.0012560 | 1115.1 | 1134.0 | 2.8586 |
| 280 | | | | | 0.0013226 | 1221.8 | 1235.0 | 3.0565 | 0.0013096 | 1213.4 | 1233.0 | 3.0410 |
| 300 | | | | | 0.0013980 | 1329.4 | 1343.3 | 3.2488 | 0.0013783 | 1317.6 | 1338.3 | 3.2279 |
| 320 | | | | | | | | | 0.0014733 | 1431.9 | 1454.0 | 3.4263 |
| 340 | | | | | | | | | 0.0016311 | 1567.9 | 1592.4 | 3.6555 |

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## Rankine Cycle

### ❑ Step 2 Define the Properties

| State | T (℃) | P(Pa) | h (kJ/kg) | Phase |
|---|---|---|---|---|
| 1 | 520* | 10 M* | 3425.86 | Superheated Vapor* |
| 2 | 41.39 | 8 K* | 2335.56 | x = 0.9 * |
| 3 | 41.39 | 8 K* | 173.36 | Saturated Liquid* |
| 4 | 80* | 10 M* | 342.94 | Compressed Liquid* |

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

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## Rankine Cycle

### ❑ Step 3 Energy Analysis

***(a)The heat transfer rate to the steam passing through the steam generator (Boiler)***

***The mass flow rate of the water is given:***

$$\dot{m}_s = 130kg/s$$
$$\dot{Q}_B = \dot{m}_s(h_1 - h_4)$$
$$= (130\text{kg/s})(3425.86kJ/kg - 342.94kJ/\text{kg})$$
$$= (130\text{kg/s})(3425.86\text{kJ/kg} - 342.94\text{kJ/kg})$$
$$= 400779.6\ kJ/s$$
$$= 400779.6\ kW$$

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## Rankine Cycle

### ❑ Step 3 Energy Analysis

***(b) The net power developed for adiabatic operation of the turbine and pump in kW.***

***The mass flow rate of the water is given:*** $\dot{m}_s = 130kg/s$

$$\dot{W}_{net\ out} = \dot{W}_T - \dot{W}_P$$
$$= \dot{m}_s[(h_1 - h_2)(h_4 - h_3)\ ]$$
$$= (130)[(3436 - 2336.8)(342.8 - 173.4)\ ]$$
$$= 120874\ kJ/s$$
$$= 120874\ kW$$

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## Rankine Cycle

### ❑ Step 3 Energy Analysis

***(c) To determine the mass flow rate of the cooling water ($\dot{m}_c$)passing through the condenser in kg/s. if the cooling water experiences a temperature rise of 15 ℃, and a negligible pressure drop.***

$$\dot{Q}_C = \dot{m}_s(h_2 - h_3)$$
$$\dot{Q} = \dot{m}C_p\Delta T$$

***So:***

$$\dot{m}_c = \frac{\dot{Q}_C}{C_p\Delta T} = \frac{\dot{m}_s(h_2 - h_3)}{C_p\Delta T}$$

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## Rankine Cycle

### ❑ Step 3 Energy Analysis

***(c) cont'd:***

***$C_p$is the specific heat of the water, which can be found in Table A-15.***

$$C_p = \frac{4182J}{kgc} = \frac{4.182kJ}{kgc}$$

***So:***

$$\dot{m}_c = \frac{\dot{Q}_C}{C_p\Delta T} = \frac{\dot{m}_s(h_2 - h_3)}{C_p\Delta T} = \frac{(130)(2336.8 - 173.4)}{(4.182)(15)} = 4483.4kg/s$$

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## Rankine Cycle

❑ ***A partial list of Table A-15***

TABLE A–15

Properties of saturated water

| Temp. $T$, °C | Saturation Pressure $P_{sat}$, kPa | Density $\rho$, kg/m³ Liquid | Vapor | Enthalpy of Vaporization $h_{fg}$, kJ/kg | Specific Heat $c_p$, J/kg · K Liquid | Vapor | Thermal Conductivity k, W/m · k Liquid | Vapor | Dynamic Viscosity $\mu$, kg/m · s Liquid | Vapor | Prandtl Number Pr Liquid | Vapor | Volume Expansion Coefficient $\beta$, 1/K Liquid |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.01 | 0.6113 | 999.8 | 0.0048 | 2501 | 4217 | 1854 | 0.561 | 0.0171 | $1.792 \times 10^{-3}$ | $0.922 \times 10^{-5}$ | 13.5 | 1.00 | $-0.068 \times 10^{-3}$ |
| 5 | 0.8721 | 999.9 | 0.0068 | 2490 | 4205 | 1857 | 0.571 | 0.0173 | $1.519 \times 10^{-3}$ | $0.934 \times 10^{-5}$ | 11.2 | 1.00 | $0.015 \times 10^{-3}$ |
| 10 | 1.2276 | 999.7 | 0.0094 | 2478 | 4194 | 1862 | 0.580 | 0.0176 | $1.307 \times 10^{-3}$ | $0.946 \times 10^{-5}$ | 9.45 | 1.00 | $0.733 \times 10^{-3}$ |
| 15 | 1.7051 | 999.1 | 0.0128 | 2466 | 4185 | 1863 | 0.589 | 0.0179 | $1.138 \times 10^{-3}$ | $0.959 \times 10^{-5}$ | 8.09 | 1.00 | $0.138 \times 10^{-3}$ |
| 20 | 2.339 | 998.0 | 0.0173 | 2454 | 4182 | 1867 | 0.598 | 0.0182 | $1.002 \times 10^{-3}$ | $0.973 \times 10^{-5}$ | 7.01 | 1.00 | $0.195 \times 10^{-3}$ |
| 25 | 3.169 | 997.0 | 0.0231 | 2442 | 4180 | 1870 | 0.607 | 0.0186 | $0.891 \times 10^{-3}$ | $0.987 \times 10^{-5}$ | 6.14 | 1.00 | $0.247 \times 10^{-3}$ |
| 30 | 4.246 | 996.0 | 0.0304 | 2431 | 4178 | 1875 | 0.615 | 0.0189 | $0.798 \times 10^{-3}$ | $1.001 \times 10^{-5}$ | 5.42 | 1.00 | $0.294 \times 10^{-3}$ |
| 35 | 5.628 | 994.0 | 0.0397 | 2419 | 4178 | 1880 | 0.623 | 0.0192 | $0.720 \times 10^{-3}$ | $1.016 \times 10^{-5}$ | 4.83 | 1.00 | $0.337 \times 10^{-3}$ |
| 40 | 7.384 | 992.1 | 0.0512 | 2407 | 4179 | 1885 | 0.631 | 0.0196 | $0.653 \times 10^{-3}$ | $1.031 \times 10^{-5}$ | 4.32 | 1.00 | $0.377 \times 10^{-3}$ |

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## What is next?

- ***Assignment 3 will be posted soon***
- ***Continue on with Thermodynamics***

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