

Chapter 2 - Properties of a Pure Substance

Lecture 4 Sections 2.4, 2.6-2.7

MEMS 0051 Introduction to Thermodynamics

Mechanical Engineering and Materials Science Department
University of Pittsburgh



Student Learning Objectives

At the end of the lecture, students should be able to:

- ▶ Understand how to use the thermodynamics tables
- ▶ Be able to identify the compressed/subcooled and saturated liquid regions and superheated vapor region on a T - v diagram, as well as in the steam tables
- ▶ Be able to interpolate between two published values

Learning Objectives

2.4 Table of
Thermodynamic
Properties

2.6 The Liquid and
Solid States

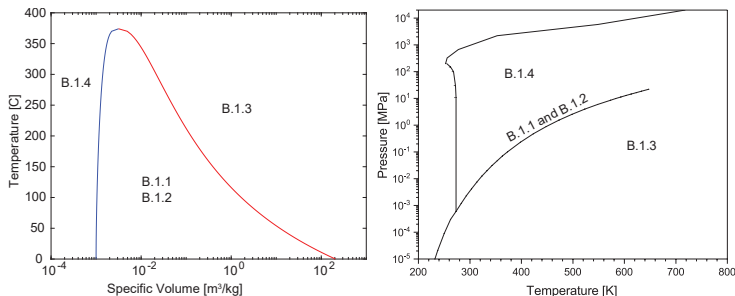
2.7 The
Superheated Vapor
States

Summary



Thermodynamic Tables

- ▶ A **steam table** has tabulated values of properties based upon temperature and pressure, reflecting the liquid and vapor phases
- ▶ A helpful graph, shown below, shows which table to use if you have a subcooled, compressed or saturated liquid or saturated or superheated vapor



Saturated Water

- ▶ The saturated water temperature-entry table, B.1.1, starts on page 776

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TABLE B.1
Thermodynamic Properties of Water

TABLE B.1.1
Saturated Water

Temp. (°C)	Press. (kPa)	Specific Volume, m ³ /kg			Internal Energy, kJ/kg		
		Sat. Liquid v_f	Evap. v_{fg}	Sat. Vapor v_g	Sat. Liquid u_f	Evap. u_{fg}	Sat. Vapor u_g
0.01	0.6113	0.001000	206.131	206.132	0	2375.33	2375.33
5	0.8721	0.001000	147.117	147.118	20.97	2361.27	2382.24
10	1.2276	0.001000	106.376	106.377	41.99	2347.16	2389.15

Image taken from Borgnakke & Sonntag, 8e

- ▶ The **saturated liquid** values of ν , u , etc. are denoted by a subscript f
- ▶ The **saturated vapor** values of ν , u , etc. are denoted by a subscript g
- ▶ The difference between g and f is the subscript fg



Saturated Water

- The saturated water, pressure-entry table, B.1.2, starts on page 780

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TABLE B.1.2
Saturated Water Pressure Entry

Press. (kPa)	Temp. (°C)	Specific Volume, m ³ /kg			Internal Energy, kJ/kg		
		Sat. Liquid v_f	Evap. u_{fg}	Sat. Vapor v_g	Sat. Liquid u_f	Evap. u_{fg}	Sat. Vapor u_g
0.6113	0.01	0.001000	206.131	206.132	0	2375.3	2375.3
1	6.98	0.001000	129.20702	129.20802	29.29	2355.69	2384.98
1.5	13.03	0.001001	87.97913	87.98013	54.70	2338.63	2393.32
2	17.50	0.001001	67.00285	67.00385	73.47	2326.02	2399.48
2.5	21.08	0.001002	54.25285	54.25385	88.47	2315.93	2404.40
3	24.08	0.001003	45.66402	45.66502	101.03	2307.48	2408.51

Image taken from Borgnakke & Sonntag, 8e

- Note: you should consult both tables if the substance is given as saturated

Learning Objectives

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Example #1

- Determine the saturated vapor specific volume v_g of water existing at 225 [kPa] and 124.00 °C.



Compressed Liquid

- ▶ It is noted a **compressed liquid** refers both to the **compressed liquid** state and the **subcooled liquid** state
- ▶ What you notice is that the specific volume is strongly dependent on temperature and weakly dependent on pressure, such that if you are looking for ν at an elevated pressure and know the temperature, you can use the saturated water temperature-entry table using T :

$$\nu \approx \nu(T) = \nu_f$$

- ▶ This is because water is an incompressible substance:

$$\nu \not\approx \nu(P)$$



Compressed Liquid

- The compressed liquid water table, B.1.4, starts on page 790

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TABLE B.1.4
Compressed Liquid Water

Temp. (°C)	v (m ³ /kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kg-K)	v (m ³ /kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kg-K)
	500 kPa (151.86°C)				2000 kPa (212.42°C)			
Sat.	0.001093	639.66	640.21	1.8606	0.001177	906.42	908.77	2.4473
0.01	0.000999	0.01	0.51	0.0000	0.000999	0.03	2.03	0.0001
20	0.001002	83.91	84.41	0.2965	0.001001	83.82	85.82	.2962
40	0.001008	167.47	167.98	0.5722	0.001007	167.29	169.30	.5716
60	0.001017	251.00	251.51	0.8308	0.001016	250.73	252.77	.8300
80	0.001029	334.73	335.24	1.0749	0.001028	334.38	336.44	1.0739

Image taken from Borgnakke & Sonntag, 8e

- Note the sub-pressure entry tables
- Note there are no saturated states, i.e. f or g

Learning Objectives

2.4 Table of Thermodynamic Properties

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Example #2

- ▶ Determine the specific volume v of water existing at 10,000 [kPa] and 60 °C using the compressed liquid water table B.1.4.
- ▶ How does this compare to the value of $v_f(60\text{ °C})$ published on the saturated water temperature-entry table B.1.1.?



Superheated Vapor

- ▶ A **superheated vapor** state is when T is greater than T_{sat} for a given P_{sat}
- ▶ Alternatively, a superheated vapor occurs when P is less than P_{sat} for a given T_{sat}
- ▶ The superheated vapor water table, B.1.3, starts on page 784

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TABLE B.1.3
Superheated Vapor Water

Temp. (°C)	v (m ³ /kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kg-K)	v (m ³ /kg)	u (kJ/kg)	h (kJ/kg)	s (kJ/kg-K)
	$P = 10 \text{ kPa (45.81°C)}$				$P = 50 \text{ kPa (81.33°C)}$			
Sat.	14.67355	2437.89	2584.63	8.1501	3.24034	2483.85	2645.87	7.5939
50	14.86920	2443.87	2592.56	8.1749	—	—	—	—
100	17.19561	2515.50	2687.46	8.4479	3.41833	2511.61	2682.52	7.6947
150	19.51251	2587.86	2782.99	8.6881	3.88937	2585.61	2780.08	7.9400
200	21.82507	2661.27	2879.52	8.9037	4.35595	2659.85	2877.64	8.1579
250	24.13559	2735.95	2977.31	9.1002	4.82045	2734.97	2975.99	8.3555

Image taken from Borgnakke & Sonntag, 8e



Example #3

- ▶ Suppose you are looking for the specific volume of water at $400\text{ }^{\circ}\text{C}$ and a pressure of $22,089\text{ [kPa]}$. Is this possible?



- A helpful interpretation of the T - v diagram in terms of T_{sat} and P_{sat} helps direct which table you should consult:

T	P	State	Table
$T=T_{\text{sat}}$	$P=P_{\text{sat}}$	Saturated Water	B.1.1-B.1.2
$T<T_{\text{sat}}$	$P=P_{\text{sat}}$	Subcooled Liquid	B.1.4, B.1.1
$T=T_{\text{sat}}$	$P>P_{\text{sat}}$	Compressed Liquid	B.1.4, B.1.1
$T>T_{\text{sat}}$	$P=P_{\text{sat}}$	Superheated Vapor	B.1.3
$T=T_{\text{sat}}$	$P<P_{\text{sat}}$		

- **IF THE VALUE IS NOT ON THE TABLE, YOU ARE DOING SOMETHING WRONG** - these tables are the backbone of all thermodynamics cycles - if they were wrong, modern civilization would not exist

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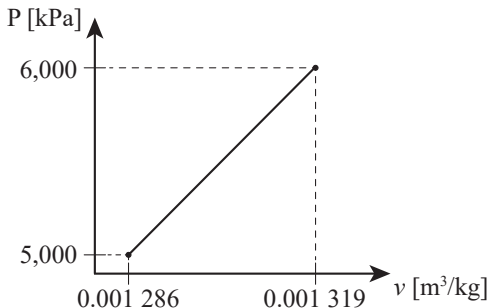
Linear Interpolation

- ▶ What happens when we are interested in a value between published values?
- ▶ **Linear interpolation** assumes the slope between two known points is linear, and therefore any point on that line in reference to a published value will create a line of the same slope of the two published values



Linear Interpolation

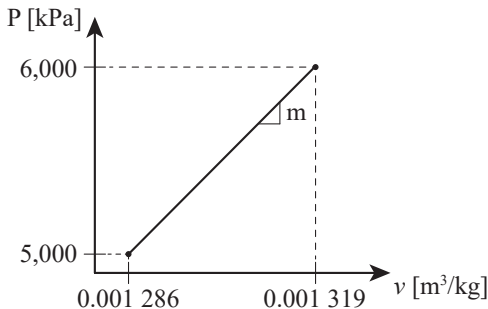
- ▶ Let us consider a representative example. Say we want to determine the saturated liquid specific volume at a pressure of 5,328 [kPa].
- ▶ We see this pressure is bounded between 5,000 and 6,000 [kPa], which have corresponding ν_f of 0.001 286 and 0.001 319 [m³/kg], respectively



Linear Interpolation

- The slope m is the rise per run:

$$m = \frac{(6,000 - 5,000) \text{ [kPa]}}{(0.001\,319 - 0.001\,286) \text{ [m}^3\text{/kg]}}$$



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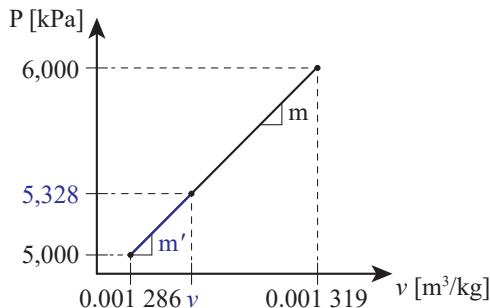
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Linear Interpolation

- To find the specific volume at a pressure of 5,328 [kPa], we will plot the pressure value on the line existing between 5,000 and 6,000 [kPa], recognizing m' is equal to m



$$m' = \frac{(5,328 - 5,000) \text{ [kPa]}}{(\nu - 0.001\,286) \text{ [m}^3\text{/kg]}}$$

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Linear Interpolation

- ▶ Setting the RHS of the expression of m and m' equal:

$$\frac{(6,000 - 5,000) [\text{kPa}]}{(0.001\,319 - 0.001\,286) [\text{m}^3/\text{kg}]} = \frac{(5,328 - 5,000) [\text{kPa}]}{(\nu - 0.001\,286) [\text{m}^3/\text{kg}]}$$

- ▶ Or in terms of ratios of rises and runs:

$$\underbrace{\frac{(5,328 - 5,000) [\text{kPa}]}{(6,000 - 5,000) [\text{kPa}]}}_{0.328 []} = \frac{(\nu - 0.001\,286) [\text{m}^3/\text{kg}]}{(0.001\,319 - 0.001\,286) [\text{m}^3/\text{kg}]}$$

- ▶ Therefore:

$$\begin{aligned}\nu &= 0.328(0.001\,319 - 0.001\,286) [\text{m}^3/\text{kg}] + 0.001\,286 [\text{m}^3/\text{kg}] \\ &= 0.001\,297 [\text{m}^3/\text{kg}]\end{aligned}$$

- ▶ Check you answer is between the upper and lower bounds of the value on the x-axis



Example #4

- Find $\nu_g(T=32.5\text{ }^{\circ}\text{C})$ from the saturated water table.



Example #5

- Find $\nu(T=400\text{ }^{\circ}\text{C}, P=350\text{ [kPa]})$ from the superheated vapor water table.



Student Learning Objectives

At the end of the lecture, students should be able to:

- ▶ Understand how to use the thermodynamics tables
 - ▶ The thermodynamics tables are structured such that if you have two independent properties (temperature and pressure), you can pull pertinent values, such as specific volume, from the tables.
- ▶ Be able to identify the compressed/subcooled and saturated liquid regions and superheated vapor region on a T - v diagram, as well as in the steam tables
 - ▶ Tables B.1.1 and B.1.2 are used for saturated water, B.1.3 for superheated vapor, and B.1.4 for compressed/subcooled liquids.

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Summary

- ▶ Be able to interpolate between two published values
 - ▶ Given two published points, we can construct an equation describing the slope. If we have an intermediate value, i.e. between the two published points, we will assume the slope created by the intermediate point and either of the published points is equal to the slope of the two published points.



Suggested Problems

- ▶ Our text does not have problems focusing purely on interpolation.

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