Concepts of Thermodynamics
Prof. Suman Chakraborty
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture – 04
Introduction to Property Tables

Today, we will see that how to deal with the properties of pure substances for identifying various thermodynamic states. What we have discussed earlier to summarize that we can say that properties are signatures of states right. So, if you have a thermodynamic state, the thermodynamic state is designated by a combination of thermodynamic properties. If it is a simple compressible pure substance, it requires two independent intensive thermodynamic properties to specify the state of the system.

So, condition of a system designated by its properties is called as the state of the system. So, when we say that it means that if we can identify two in independent intensive thermodynamic properties, we will be in a position to identify the state; that means, all other properties whatever are relevant can be obtained from that. How do you obtain those properties? So, this is a very important concept to realize that in school level most of you have done some kind of thermodynamics where the properties where dictated by the ideal gas type of relationships.

For example, for an ideal gas you can write p v equal to nRT. So, when you write that, what you are essentially describing is an equation of state where pressure, volume and temperature are related with each other. So that means, if you specify pressure and volume the third property which is temperature is automatically defined by that equation. In many practical scenarios the substance is not an ideal gas. When it is not an ideal gas you cannot use may be in certain cases for non-ideal substances such equations of states are available, some are empirical, some are not.

But, in general such a simple equation of state which is typically like the ideal gas equation of state, will not work for a substance which is more practical than an ideal gas. So, if it is like that then how do you determine the properties that is an important question. And, that is an important situation very challenging situation that most of the students face in working out problems in thermodynamics where the properties are not the properties of ideal gases.

So, what would you do? So, for such a scenario we either have an equation of state which is more complex than the ideal gas equation of state which defines the relationship between properties. That means, if you give two independent intensive properties as input the third property will come as an output from that equation may be a complex equation. But, where pressure is a function of temperature and density in some way or the other or temperature is a function of pressure and density in some way or the other.

So, these things are there. However, it is very convenient if all these data points for a particular substance are summarized or tabulated in the form of thermodynamic property tables. And, today we will try to work out examples where we will illustrate how to use the thermodynamic tables. I would like to emphasize here is that thermodynamics education has gone through a shift of paradigm, traditionally and even when I was myself an undergraduate student we use to follow the property tables very judiciously to identify the state points.

However, over the past few years there has been an emerging trend of using computerized data tables. That means, if you give the properties or give two independent properties as input the third property which is a function of those two properties; we will come out automatically as a part of the software instead of having to look into the table. So, that kind of paradigm has come up recently; it does not change the concepts in thermodynamics, but it changes the approach in which you may possibly solve a problem. So, in this course what we have design is that we will consider both these approaches.

So, one the traditional approach where, looking into the table is important and I will tell you that there is a benefit of the traditional approach. The benefit of the traditional approach is that you can visualize very nicely that what is the physical state of the system; is it two phase system, is it superheated system, is it a sub cooled system. These things you can nicely visualize from the tabular information. The computerized system the advantages that despite the fact that it does not give you an easy visualization until and unless you plot using the computer generated data; you can work out problems relatively quickly and elegantly without making the toil of looking into the property tables in the hard form.

So, there are advantages and disadvantages. I will not get into the debate of which one is a better method and which one is not so convenient. These both these approaches have their own merits and possibly some demerits also. And, I will straight away start helping you out to see that to understand that how the property tables look and how the property tables can be used to solve problems.

(Refer Slide Time: 07:15)

STEAM TABLES

So, if you look into the property tables there are property tables of various substances and many of the substances are actually face changing substances. That means, given a heat transfer to the system we will see later on what is heat and all, but we can qualitatively understand that by transferring heat you are energizing the molecules of the system. And, then the molecules from the liquid phase for example, can go to the vapor phase or from solid phase can go to the liquid phase. So, this kind of phase changing substances their properties can be nicely tabulated in the form of a structure table.

Why we are interested in such substances because, water one of the most common engineering fluids is of substance of that type. So, properties of water are described or enumerated in the form of tables known as steam tables. So, I would like to explain you first that how the steam tables look and how to look into the properties through steam tables. So, before getting into the steam tables and how do they look? I would like to give you conceptual description of what we are talking about.
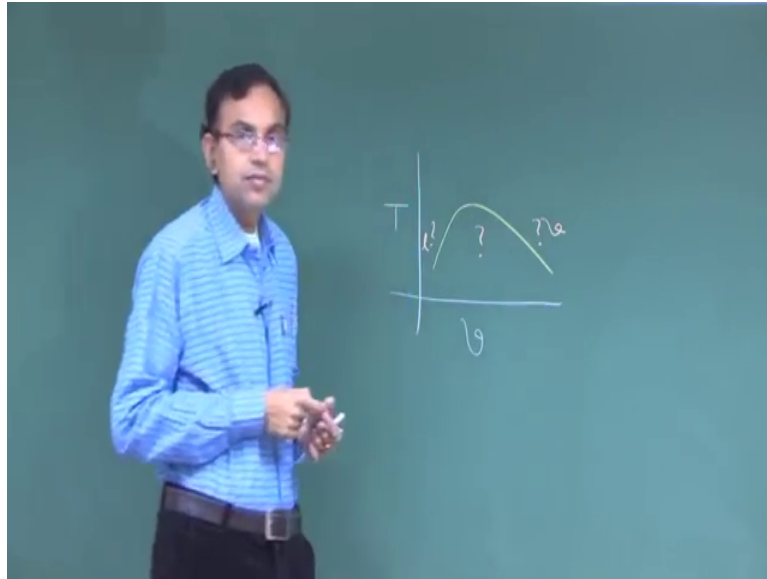
So, let us say that we are interested to plot one state point in a p v diagram or a T v diagram whatever. So, when we are interested to so, let us say for example, this is T this is v temperature specific volume diagram. So, for a substance like water you have a diagram like this; dome shaped region below which you have the change of phase as you heat it from liquid to vapor. So, this is let me write it in symbols. So, on this side it is liquid, on this side it is vapor, and in between there is a liquid to vapor transition as you heat the material or heat the fluid. When you have your data point or a state point for which the temperature and pressure is beyond this that is called a supercritical fluid and that does not pass through this phase change process.

So, the first question that given a data given a set of properties where does the state point lie. Does it lie here? Does it lie here or does it lie here? This is the first question that you might be interested to answer before solving a problem. This is state this is like you know step 0 of understanding thermodynamics. We have not yet started looking into thermodynamics, but this is the absolutely essential for solving problems in thermodynamics. So, which where is the state point lie, how do you understand that?

(Refer Slide Time: 11:22)

So, to understand that we can refer to specific problem: and then we can try to solve the problem and through that problem we will learn how to use the table. So, for that I will refer to this example problem. So, the problem is described in the slide and we will of course, share these slides with you as a part of supplementary material of this course. But, you can note this problem down so that it helps you to you know do a pen and paper solution of this problem.

So, let me go through the problem statement first. Water vapor initially at 3 MPa 300 degree centigrade which is state 1 is contained within a piston cylinder assembly. The water is cooled at constant volume until its temperature reaches state 2 which is 200 degree centigrade. And, the water is compressed isothermally to a state when the pressure is 2.5 MPa. Locate state 1, 2 and 3 on T v and p v diagram. Determine the specific volumes at state 1, 2 and 3 and quality at state 2. This problem I will do in a very different way. So, I will give you the idea of how to identify the state points.

You have to generate the data from the table and this will be your first homework problem for this particular course. So, let us so whenever there is a problem in thermodynamics. See thermodynamics is many times a very challenging subject to students, because the problem solution is not very structured. Every problem has a different way of looking into it, but we can try to structure this to the extent possible; so,

that it helps you out. So, first is water vapor initially at so, let me look into the properties. So, water vapor initially at 3 MPa 300 degree centigrade so, state 1.

(Refer Slide Time: 13:44)
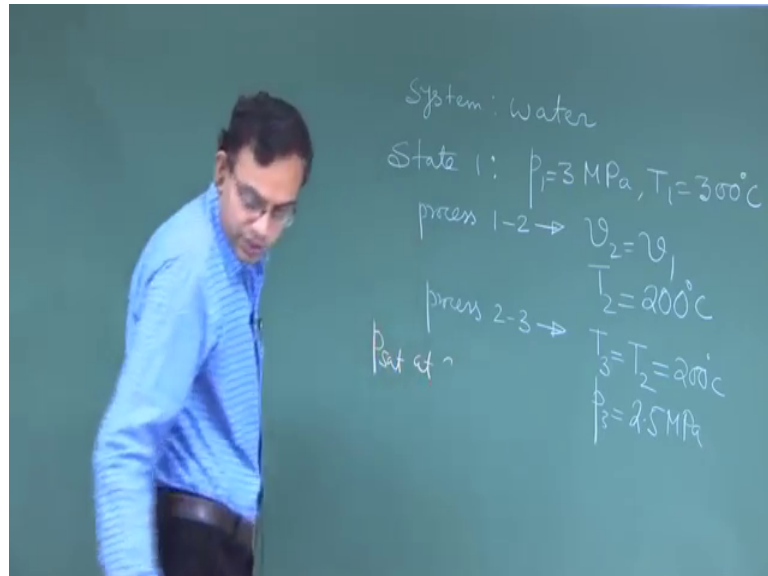
So, the system thermodynamic system is water state 1 3 MPa and 300 degree centigrade. So, p 1 is 3 mega Pascal T 1 is 300 degree centigrade ok; then the process from 1 to 2, what is the kind of process? It is given, it is cooled in a constant volume process. The process is such that v 2 equal to v 1 see it is a control mass system where the mass is constant.

So, if the total volume is constant and mass is constant; that means, specific volume is also constant. We will discuss later on that why specific volume is considered to be such an important property instead of its inverse which is density in thermodynamics. Why we use specific volume so, commonly instead of using density of course, density is just inverse of the specific volume so, we could use the density also. But specific volume why it is so, convenient to use specific volume as a property and density not so, much convenient while working out problems in thermodynamics; we will discuss about that.

So, the process 1 to 2 v 2 is equal to v 1 and then this is the other information remember that we require two independent properties because; water is a simple compressible pure substance. So, we require two independent properties for specifying its state. So, what is T 2? T 2 is given as 200 degree centigrade. It is cooled from 300 to 200 degree centigrade. Then from state 2 to state 3, what it does? The water is compressed

isothermally to a state 3. So, process 2 to 3 T 3 is equal to T 2 and which is 200 degree centigrade and p 3 is equal to 2.5 mega Pascal.

What you have to do for this problem is simply identify the state points on a p v and T v diagram and maybe the processes and determine the specific volume at 1, 2 and 3 and quality at state 2 ok. So, let us try to look into this problem. I will do the initial problems very slowly; so, that you can understand that how to solve these problems by looking into the property tables; state 1 3 or 3 MPa T 300 degree centigrade. Now, can you tell whether this is liquid water, liquid plus vapor or superheated vapor; how can you tell this. So, let us look into the steam table.

So, just look into the table which is given in the slide. So, the first portion of the table is saturated water vapor table ok. So, in the saturated water vapor table let us look into the data of 3 mega Pascal, 3 mega Pascal is 3000 kilo Pascal. So, if you look here you will see that the first column is like pressure, second column is temperature. See in the two phase region if you defined the value of pressure the temperature is also defined automatically.

Because the saturation pressure and saturation temperature they are unique functions of each other. So, when you have saturation pressure as 300 3000 kilo Pascal, its corresponding saturation temperature is 233.9 degree centigrade, you look it from the table. So, when you have this as 233.9 degree centigrade what is your given temperature. So, let us write this p saturation at sorry T saturation at p 1, what is that. It is 233.9 degree centigrade ok.

(Refer Slide Time: 19:20)
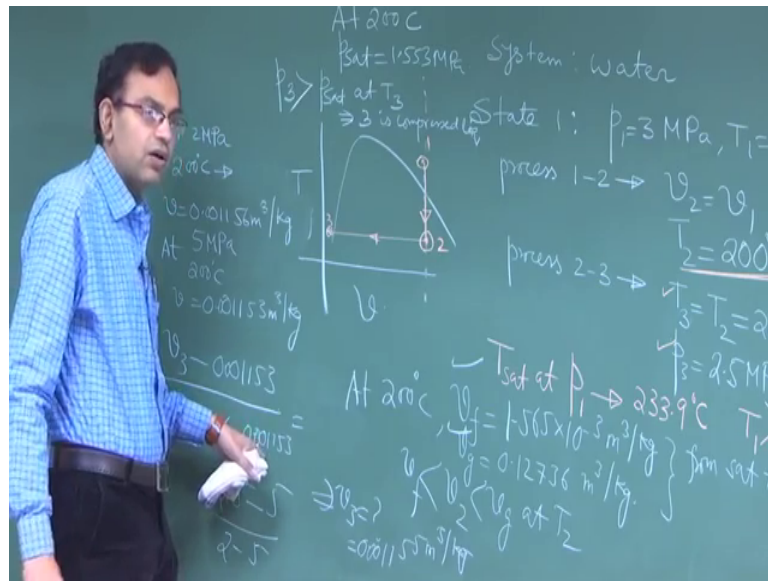
Your T 1 is greater than this; that means, it has crossed the saturation temperature limit. This implies that it is in the superheated vapor region. So, when it is in the superheated vapor region, this table which is the saturated water vapor table you can see here this saturated water vapor table will not work anymore. You have to consider the superheated table, but even if it is a superheated data point your first check is from the saturated water table to figure out whether it is actually superheated or not. So, once you get that data what do you do is, you find out you look into the superheated vapor table.

(Refer Slide Time: 20:29)

(Refer Slide Time: 19:20)

Steam table data

Temp. (°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)
	3000 kPa (233.90°C)		Superheated water vapor		4000 kPa (250.40°C)			
Sat.	0.06668	2604.10	2804.14	6.1869	0.04978	2602.27	2801.38	6.0700
250	0.07058	2644.00	2855.75	6.2871	—	—	—	—
300	0.08114	2750.05	2993.48	6.5389	0.05884	2725.33	2960.68	6.3614
350	0.09053	2843.66	3115.25	6.7427	0.06645	2826.65	3092.43	6.5820

Saturated water vapor

Temp. (°C)	Press. (kPa)	Specific Volume, m³/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
195	1397.8	0.001149	0.13990	0.14105	828.36	1764.43	2592.79
200	1553.8	0.001156	0.12620	0.12736	850.64	1744.66	2595.29
205	1723.0	0.001164	0.11405	0.11521	873.02	1724.49	2597.52

Temp. (°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)
	2000 kPa (212.42°C)		Compressed liquid water		5000 kPa (263.99°C)			
160	0.001101	674.14	676.34	1.9410	0.001099	672.61	678.10	1.9374
180	0.001127	761.46	763.71	2.1382	0.001124	759.62	765.24	2.1341
200	0.001156	850.30	852.61	2.3301	0.001153	848.08	853.85	2.3254

So, in the superheated vapor table if you have the pressure as 3 MPa which is here or 3000 kilo Pascal at 300 degree centigrade, you get what is the specific volume. Some other properties are there internal energy, enthalpy entropy. Whenever we will require these properties we will discuss, but for this problem it is the specific volume that is required. So state 1, so, we can simply write that from superheated table from superheated water table you have the specific volume at state 1 is 0. 08114 0.0811 say let us stop here meter cube per kg.

So, I will draw one of the diagram say T v diagram. So, state 1 is someone here this is what you can visualize. From state 1 to state 2 you have v 2 is equal to v 1 which is this one and T 2 is 200 degree centigrade. So, the question is, is it still in the superheated or it has come to saturated. What is the on which line the point state point 2 will lie, if you draw a vertical line. Somewhere on this it will lie if because, it is cooled it will be down. But, the question is down where beyond this line or below this line. So, for that again you have to look into the table at 200 degree centigrade. So, let us try to look into that, the saturated table so, 200 degree centigrade so.

(Refer Slide Time: 23:19)

Steam Table – Saturated Water [1]

Temp. (°C)	Press. (kPa)	Specific Volume, m³/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
15	1.705	0.001001	77.924	77.925	62.98	2333.06	2396.04
20	2.339	0.001002	57.7887	57.7897	83.94	2318.98	2402.91
25	3.169	0.001003	43.3583	43.3593	104.86	2304.90	2409.76
30	4.246	0.001004	32.8922	32.8932	125.77	2290.81	2416.58
35	5.628	0.001006	25.2148	25.2158	146.65	2276.71	2423.36
40	7.384	0.001008	19.5219	19.5229	167.53	2262.57	2430.11
45	9.593	0.001010	15.2571	15.2581	188.41	2248.40	2436.81
50	12.350	0.001012	12.0308	12.0318	209.30	2234.17	2443.47
55	15.758	0.001015	9.56734	9.56835	230.19	2219.89	2450.08
60	19.941	0.001017	7.60969	7.67071	251.09	2205.54	2456.63
65	25.03	0.001020	6.19554	6.19656	272.00	2191.12	2463.12
70	31.19	0.001023	5.04114	5.04217	292.93	2176.62	2469.55
75	38.58	0.001026	4.13021	4.13123	313.87	2162.03	2475.91
80	47.39	0.001029	3.40612	3.40715	334.84	2147.36	2482.19
85	57.83	0.001032	2.82654	2.82757	355.82	2132.58	2488.40
90	70.14	0.001036	2.35953	2.36056	376.82	2117.70	2494.52
95	84.55	0.001040	1.98082	1.98186	397.86	2102.70	2500.56
100	101.3	0.001044	1.67185	1.67290	418.91	2087.58	2506.50

[1] BORGNAKKE, C., SONNTAG, R. E., SOM, Fundamental of Thermodynamics, Seventh Edition, Wiley Publication.

So, 200 degree centigrade I do not have the data point with me here in this table. It is up to 100 degree centigrade it is given because this is just way of giving you an idea how to do that. So, at 100 degree centigrade for example, you have v f and v g. If it is in the two

phase region at 100 degree centigrade this is v f where, I have pointed the pointer and this is what is v g. So, if your v is between v f and v g then it is in the two phase region.

(Refer Slide Time: 24:04)

Steam Table – Saturated Water (Pressure Table)[2]

Press. (kPa)	Temp. (°C)	Specific Volume, m³/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
0.6113	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
4	28.96	0.001004	34.79915	34.80015	121.44	2293.73	2415.17
5	32.88	0.001005	28.19150	28.19251	137.79	2282.70	2420.49
7.5	40.29	0.001008	19.23674	19.23775	168.76	2261.74	2430.50
10	45.81	0.001010	14.67254	14.67355	191.79	2246.10	2437.89
15	53.97	0.001014	10.02117	10.02218	225.90	2222.83	2448.73
20	60.06	0.001017	7.64835	7.64937	251.35	2205.36	2456.71
25	64.97	0.001020	6.20322	6.20424	271.88	2191.21	2463.08
30	69.10	0.001022	5.22816	5.22918	289.18	2179.22	2468.40
40	75.87	0.001026	3.99243	3.99345	317.51	2159.49	2477.00
50	81.33	0.001030	3.23931	3.24034	340.42	2143.43	2483.85
75	91.77	0.001037	2.21607	2.21711	394.29	2112.39	2496.67
100	99.62	0.001043	1.69296	1.69400	417.33	2088.72	2506.06

[2] BORGNAKKE, C., SONNTAG, R. E., SOM, Fundamental of Thermodynamics, Seventh Edition, Wiley Publication.

Similarly, at 200 degree centigrade you will have some v f and some v g.

(Refer Slide Time: 24:07)

Steam Table – Superheated Water Vapor[3]

[3] BORGNAKKE, C., SONNTAG, R. E., SOM, Fundamental of Thermodynamics, Seventh Edition, Wiley Publication.

So, at 200 degree centigrade so this table will be continued up to even higher temperatures; so, at 200 degree centigrade you have to look what is v f and what is vg. So, at 200 degree centigrade you have so, I have the data with me, I can tell you at 200

degree centigrade this you can verify from the table saturated table v f is 1.56 into 10 to the power 1.565 into 10 to the power minus 3 meter cube per kg and v g is 0.12736.

This is from saturated table ok. Now, you tell your v is between v f and v g right. So, your v is 0.8 11 which is in between these two values. So, v 2 is between v f and v g at T 2; if that be the case then the state point 2 will lie somewhere here in the two phase region. So, what is the specific volume at state 2? It is same as v 1. What is the quality at state 2? So, v 2 is x v g 2 plus 1 minus, this formula has been derived earlier in one of the classes.

So, I will not get into the details here, but you see the point that I want to raise is that it is for this reason that we use specific volume not density. See the specific volume of the mixture is a weighted average of the specific volumes of the liquid and vapor phases, not the weighted average of the density right. So, by using law of mixture it is very easy to calculate the properties of mixtures. So, here x 2 is what mass of vapor at state 2 by total mass. So, you have v g 2 and v f 2 this two and v 2. So, from here you can calculate what is x 2 ok. So, once you have calculated x 2.

So, you can check this should be between 0 and 1; that means, you have you are there in the two phase region. In the process 2 to 3 you have T 3 is equal to T 2 and p 3 is 2.5 MPa. So now, again you have to see at 200 degree centigrade or at 2.5 MPa whatever you look into the saturated table. So, let us let us see that at 2.5 MPa what is the saturation temperature; so, 2.5 MPa. So, let us look into the saturation temperature at 2.5 MPa. So, even in the superheated vapor tables the saturation temperature is indicated.

Steam Table – Compressed Liquid Water[4]

[4] BORGNAKKE, C., SONNTAG, R. E., SOM, Fundamental of Thermodynamics, Seventh Edition, Wiley Publication.

So, 2.5 MPa is what? 2.5 MPa just look into the superheated water vapor table; so 2.5 MPa or 200 degree centigrade; let us say 200 degree centigrade. So, 200 degree centigrade I do not have the data at 200 degree centigrade. But, if you look into the 200 degree centigrade you will have the saturation temperature at 200 degree centigrade. If you will look into the property table I do not have that part of the table, but I have the data at 200 degree centigrade the saturation pressure is 1.553 MPa.

That part of the table I do not have at this moment, but this is your homework. So, I have deliberately left that part of the table out. So, I have only kept up to 100 degree centigrade which you see here, you will have an extension of this up to higher temperatures. So, at 100 degree centigrade the saturation pressure is 101.3 kilo Pascal. Similarly, from the saturation table at 200 degree centigrade you will get the saturation pressure as 1.553 mega Pascal. Now, this p 3 is greater than that; that means it is in a compressed liquid state. So, p 3 is greater than p sat at T 3, this means it is 3 in compressed liquid.

So, compress liquid in other case in other words is also called as sub cooled liquid. What does it mean? It means that at 2.5 mega Pascal whatever is the saturation temperature, this temperature is less than that saturation temperature. So, from that angle from the temperature angle you can call it sub cooled, from the pressure angle you can call it

compressed liquid all the same. So, at the state point 3 it will be in the fully liquid state and from 2 to 3, it will be something like this isothermal process.

So, 1 to 2 like this and 2 to 3 like this. So, how to identify state 3? 200 degree centigrade and p 3 as 2.5 MPa which table you should look for now. So, we have looked into the saturated water table and the superheated water vapor table; there is a third table which is called as compressed liquid water table. So, at 2.5 mega Pascal you see that you have a table at 2 mega Pascal and 5 mega Pascal. So, 2.5 you my you may have to interpolate, at 2 mega Pascal at 200 degree centigrade you have a specific volume.

So, I am using this part of the board at 2 mega Pascal 200 degree centigrade the specific volume is 0.001156 ok. Let us write it in 1 line 0.01156 and at 5 MPa see the table does not contain 2.5 MPa at 5 MPa 200 degree centigrade it is 0.001153 ok. So, the question is at 2.5 MPa what is that? So, let us say that at 2.5 MPa it is v 3. So, v 3 minus 0.01153 by 0.01156 minus 0.01153 we are doing an interpretation.

It is v 3 is p 3 which is the corresponding pressure is p 3 equal to 2.5 minus the corresponding pressure is 5 divided by 2 minus 5 right; y minus y 1 by y 2 minus y 1 is equal to x minus x 1 by x 2 minus x 1. We are interpolating the pressure versus volume data with y as volume and x as pressure. So, this will tell you what is v 3. The answer to this is 0.01155 meter cube per kg. See it is not always necessary to go through this laborious process, when it is state 3 and the temperature is around this 200 like that. So, water at 200 degree centigrade liquid water, what will be its density. It will not be far from 1000 kg per meter cube right.

So, 1 by specific volume will be 1 by 1000 and it will be close to that. So, at least 0.01 sorry this is 0.00 0.00115 not 01. So 0, this is 0.00 all another 0 is there I have missed this ok. So, 0.001153 0; these are all another 0 will be there. So, this mistake you can common you can very easily detect because, water density it normally is 1000. So, 1 by 1000 is 0.001. So, another 0 will be there so, you see that only in the third, fourth, fifth decimal the values are changing.

So, for all practical purposes if you even do not look into the table, but just figure out that it is a compress liquid, then you can easily say that compress liquid means it is almost like the density of water under normal temperature. I mean with from normal temperature to 200 degree centigrade the density of water will not vary that much, if it is

liquid water ok. So, this problem I have spent a lot of time, but I have try to make sure that by looking into the tables how can you identify these state points.

And, I hope this was useful. From the next lecture onwards we will start looking into some more specific problems on properties of pure substances.

Thank you.