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ANALYSIS OF THERMODYNAMIC PROCESSES OF WATER VAPOUR

Guidelines for practical and laboratory workshop
on the course «Power facilities»

for students majoring in
141 «Electric Power, Electrical Engineering and Electromechanics»

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INTRODUCTION

Steam power constitutes an important power source for industrial society. Water vapour is one of the real gases, it is widely used in heat and power engineering. The steam used to drive turbogenerators furnishes most of the world’s electric power. Steam is also widely employed in such industrial processes as the manufacture of steel, aluminum, copper, and nickel; the production of chemicals; and the refining of petroleum.

Steam is useful in power generation because of the unusual properties of water. Water has a high boiling point and a high latent heat of vaporization compared with other liquids; that is, it takes considerable heat to turn liquid water into steam, which is available when the steam is condensed.

The main advantages of vapour as a heat medium are as follows:

- vapour is formed from water, which is relatively easily available in nature;
- vapour can absorb and transfer a significant amount of heat at a relatively low temperature compared to other liquids or gases;
- vapour pressure and temperature can be adjusted in a wide range depending on the needs;
- steam can be supplied to the places of use using only its internal energy;
- steam losses are simply detected and quite simply replenished;
- water vapour is environmentally friendly, does not pose a hazard to health and the environment, is not fire hazardous and does not cause pollution.

Therefore, the study of vapour properties is of great practical importance.

1 MAIN DEFINITIONS

Phase transitions (or ***phase changes***) are the physical processes of transition between the basic states of matter: solid, liquid and gas.

Water vapour is a transparent gas formed when water changes from a liquid to a gaseous state.

Vaporization is a phase transition from the liquid phase to vapour. There exist two types of vaporization, so water vapour can be produced from the evaporation or boiling of liquid water.

Evaporation is a surface phenomenon and only occurs on the phase boundary between the liquid and the gaseous phase. The surface molecules gain energy from surroundings and overcome the attractions of other molecules and get vapourized. Evaporation only occurs when the partial pressure of the vapour of a substance is less than the equilibrium vapour pressure that is gaseous phase is not saturated with the evapourating substance.

Boiling describes the bulk phenomenon of the rapid vaporization of a liquid at its boiling point. The entire bulk of liquid and all the molecules including the interior and the surface gain energy to change to vapour state. The temperature at which boiling occurs is the ***boiling temperature***, or ***boiling point***. The boiling point varies with the pressure of the environment. For example, the boiling point of pure water is 100 °C at standard atmospheric pressure. Even though heat is supplied to boiling water, there is no increase in its temperature. Once water starts boiling, all the heat supplied to it is used up in breaking the bonds between the liquid molecules and so the liquid boils at a constant temperature.

The ***heat of vaporization*** is defined as the quantity of heat required at a specified temperature to convert unit mass of boiling liquid into vapour. The heat of vaporization is a latent heat. Latent comes from the Latin *latere*, which means to lie hidden or concealed. Latent heat is the additional heat required to change the state of a substance, for example, from liquid to gas at its boiling point, after the temperature of the substance has reached this point. Note that a latent heat is associated with no change in temperature, but a change of state. The heat of vaporization is a function of the pressure at which that transformation takes place.

Condensation is the change of the physical state of matter from the gas phase into the liquid phase, and is the reverse of vaporization. When condensation occurs, heat is released. The ***heat of condensation*** is equal to the heat of vaporization with the opposite sign.

Phase diagram (fig.1) gives the relationship between the phase in equilibrium in a system as a function of temperature, pressure and compositions.

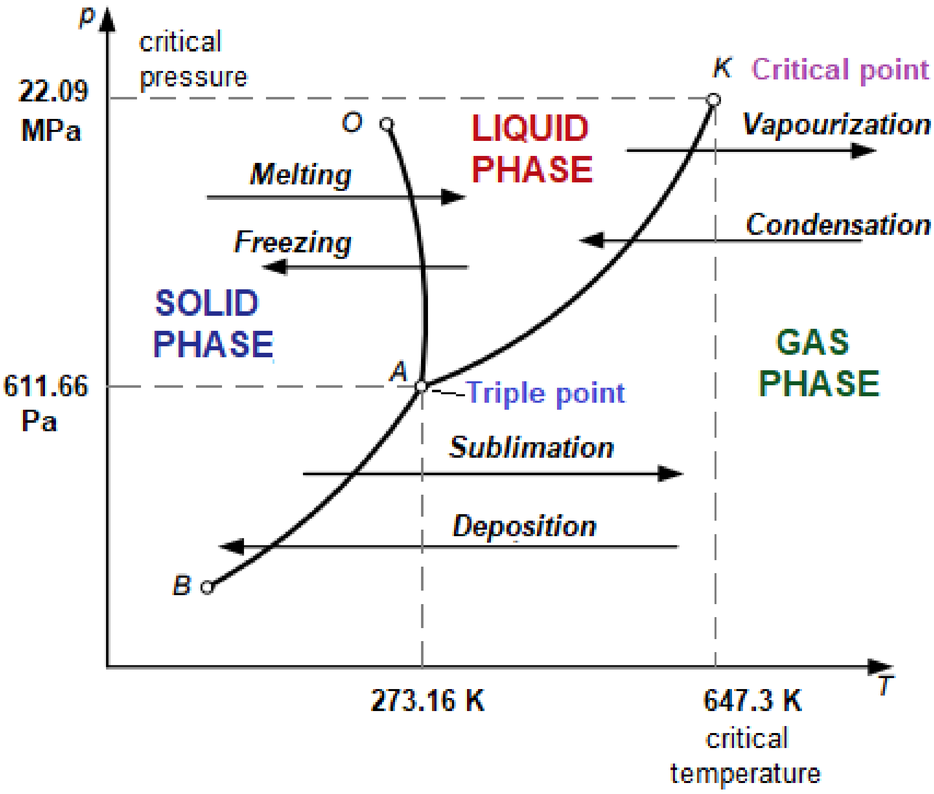


Figure 1 – Phase diagram for water:
BA – sublimation curve; *AO* – melting curve; *AK* – vapourization curve; *A* – triple point; *K* – critical point

A curve on the phase diagram represents the boundary between two phases of the substance. Along any curve, two phases can coexist in equilibrium.

Phase diagram of water consists of three curves: sublimation curve, vaporization curve and melting curve meeting each other at a point called ***triple point***. The triple point of a substance is the unique combination of temperature and pressure at which solid phase, liquid phase, and gaseous phase can all coexist in thermodynamic equilibrium. The triple point of water corresponds to a pressure of 611.66 Pascals and temperature (0.01 °C) 273.16 K.

The vaporization line ends at the ***critical point*** because there is no distinct change from the liquid phase to the vapour phase above the critical point. At the critical point the saturated liquid and saturated vapour states are identical. The heat of vaporization becomes zero at the point. Above the critical point, there is no constant-temperature vaporization process, so the liquid and vapour phases are indistinguishable, and the substance is called a supercritical fluid.

The temperature, pressure, and specific volume at the critical point are called the ***critical temperature***, ***critical pressure***, and ***critical volume***. For water, these parameters are the following:

- pressure P_{cr} = 22.09 MPa,
- temperature T_{cr} = 374.14 °C (or 647.3 K),
- specific volume v_{cr} = 0.003155 m^3/kg.

The ***vaporization curve*** indicates that the boiling point of water increases with increase in pressure.

If a substance exists as liquid at the saturation (boiling) temperature and pressure it is called ***saturated liquid***.

If the temperature is of the liquid is lower than saturation temperature at the existing pressure it is called ***sub-cooled liquid*** or ***compressed liquid***.

When the liquid and gaseous phases of water exist simultaneously at a given temperature and pressure ***saturated steam*** occurs. In simpler terms, saturated steam is the steam in equilibrium with the heated water. When a liquid evaporates into a limited space, the opposite phenomenon (that is vapour condensation) also occurs. Some molecules moving in the vapour space collide the liquid surface and return to it back. At a certain moment, when the number of molecules escaping from the liquid becomes equal to the number of molecules returning to it back, dynamic equilibrium will occur in the system. In this equilibrium, the maximum possible number of molecules will be in the vapour space that is this vapour will have the maximum density.

Saturated steam can be ***wet*** or ***dry***.

Wet steam occurs when saturated steam and condensate water molecules are mixed. As can be seen from the phase diagram of water (see fig. 1), in the two-phase regions (e.g. on the border of vapour/liquid phases), specifying temperature alone will set the pressure and specifying pressure will set the temperature. But these parameters will not define the volume and enthalpy because we will need to know the relative proportion of the two phases present.

The mass fraction of the vapour in a two-phase liquid-vapour region is called the ***vapour quality*** (or ***dryness fraction***), ***x***, and it is given by following formula:

$$x = \frac{m_{vapor}}{m_{liquid} + m_{vapor}},$$

where *m* – mass.

The value of the quality ranges from zero to unity. If $x < 1$ then the steam is wet, when $x = 1$ the steam is dry. Although defined as a ratio, the quality is frequently given as a percentage.

Example of wet steam: turbine exhaust in a condenser.

Dry steam is characterized by the vapour quality, which is equal to unity. When the vapour quality is equal to 0, it is referred to as the saturated liquid state (single-phase). At constant pressure, an addition of energy (heat) does not change the temperature of the mixture, but the vapour quality and specific volume changes. In the case of dry steam (100 % quality), it contains 100 % of the ***latent heat*** available at that pressure. Saturated liquid water, which has no latent heat and therefore 0 % quality, will therefore only contain ***sensible heat***.

Example: steam exiting steam generator is "almost" 100 % saturated.

From this point of view the ***heat of vaporization*** is defined as the amount of heat needed to turn 1 kg of a saturated liquid into a saturated vapour, without a rise in the temperature of the liquid.

Superheated vapour or superheated steam is a vapour at a temperature higher than its boiling point at the absolute pressure where the temperature is measured. ***Degrees of superheat*** is the difference in temperature between a superheated vapour and saturated vapour at the same pressure.

The pressure and temperature of superheated vapour are independent properties, since the temperature may increase while the pressure remains constant.

Actually, the substances we call gases are highly superheated vapours. Vapour is a substance in the gas phase at a temperature lower than its critical temperature, which means that the vapour can be condensed to a liquid by increasing the pressure on it without reducing the temperature. While gases cannot be liquified by increasing the pressure.

A study of the properties of water and steam is necessary to understand the steam processes.

The ***state*** of a steam as a working fluid refers to the physical properties it possesses at a particular pressure, temperature and volume. If each of these are known with respect to a substance, the state of the substance is known.

The main energy properties of a working fluid are enthalpy and entropy.

Enthalpy represents the total energy content of steam. It expresses the internal energy and flow work, or the total potential energy and kinetic energy contained within a substance. The advantage of enthalpy is that we can express in one term all of the energy in a substance which is due to its pressure and temperature. Enthalpy values are used to represent the energy level of steam entering a turbine, a value useful for determining turbine efficiency. By superheating steam, we can add enthalpy to steam without raising the pressure of the steam. For example, steam at 16 MPa and 350°C can do more work in a turbine than steam that is 16 MPa and 210°C.

Entropy represents the unavailability of energy. The second law of thermodynamics states that when heat is transferred from high temperature to low temperature regions, some of the heat will be rejected and not converted into mechanical work. Entropy is a measure of how much heat must be rejected to a lower temperature receiver at a given pressure and temperature. A complex explanation of the mathematical significance of the definition of entropy is unnecessary. It is a term which attempts to describe the universe's tendency to evenly distribute all mass and energy throughout space. Processes which produce entropy are possible and those which destroy entropy are impossible to take place spontaneously.

A ***thermodynamic process*** is any process which changes the state of the working fluid. These processes can be classified by the nature of the state change that takes place. Common types of thermodynamic processes include the following:

An ***adiabatic process*** is a state change where there is no transfer of heat to or from the system during the process. Because heat transfer is relatively slow, any rapidly performed process can approach being adiabatic. Compression and expansion of working fluids are frequently achieved adiabatically with pumps and turbines.

An ***isothermal process*** is a state change in which no temperature change occurs. Note that boiling and condensation occurs without causing a change in temperature of the working fluid.

An ***isobaric process*** is a state change in which the pressure of the working fluid is constant throughout the change. An isobaric state change occurs in any heat exchanger of steam or gas power plant, for example in the boiler superheater, as the heat of the exiting steam is increased without increasing its associated pressure.

2 TABLES OF THERMODYNAMIC PROPERTIES

Experimentally, accurately determined, values of useful thermodynamic properties like temperature *t*, pressure *P*, specific volume *v*, specific internal energy *u*, specific enthalpy *h* and specific entropy *s* are tabulated in tables that are called as Steam tables. These values form the basis for many calculations concerned with steam engineering. These tables are to be used because ***vapours do not obey general gas laws***. The values given in the tables are for one kg of dry and saturated steam but these values can also be employed for wet steam calculations.

Since the properties like internal energy, enthalpy and entropy of a system cannot be directly measured; they are related to change in the energy of the system. Hence one can determine Δu, Δh, Δs, but not the absolute values of these properties. Therefore, it is necessary to choose a reference state to which these properties are arbitrarily assigned some numerical values.

For water, the ***triple point*** (t = 0.01 ^{o}C and P = 0.6113 kPa) is selected as the reference state, where the ***internal energy*** and ***entropy*** of saturated liquid are ***assigned a zero value***.

In the saturated steam tables, the properties of saturated liquid that is in equilibrium with saturated vapour are presented. During phase transition, the pressure and temperature are not independent of each other. If the temperature is specified, the pressure at which both phases coexist in equilibrium is equal to the saturation pressure. Hence, it is possible to choose either temperature or pressure as the independent variable, to specify the state of two-phase system. Depending on whether the temperature or pressure is used as the independent variable, the tables are called temperature or pressure tables. In both the tables, the values of specific volume (v_f), enthalpy (h_f), and entropy (s_f) of water in saturated liquid state and values of specific volume (v_g), enthalpy (h_g), and entropy (s_g) of steam in saturated vapour state are directly noted down. The two phases-liquid and vapour can coexist in a state of equilibrium only up to the critical point. Therefore, the listing of the thermodynamic properties of steam in the saturated steam tables ends at the critical point (374.15 ^{o}C and 212.2 bar).

If the steam exists in only one phase (***superheated steam***), it is necessary to specify ***two independent variables***, pressure and temperature, for the complete specification of the state. In the superheated steam tables, the properties *v*, *u*, *h*, and *s* are tabulated from the saturation temperature to some temperature for a given pressure.

The thermodynamic properties of a ***liquid and vapour mixture*** are calculated by the parameters of saturated liquid and saturated vapour under the same pressure and the quality ***x***:

$$v_x = (1 - x)v_f + x \cdot v_g \,,$$

$$u_x = (1 - x)u_f + x\, u_g \,,$$

$$h_x = (1 - x)h_f + x\, h_g = h_f + x\, h_{fg} \,,$$

$$s_x = (1 - x)s_f + x\, s_g \,,$$

where h_{fg} – latent heat of vaporization, $h_{fg} = h_g - h_f$, index f stands for liquid (fluid), index g stands for vapour (gas).

In order to determine the properties of steam at some pressure (or temperatures) between those given in tables, we interpolate assuming the **linear relation between these values**. The method is very simple and at the same time accurate. The strategy for linear interpolation is to use a straight line to connect the given data points (fig. 2).

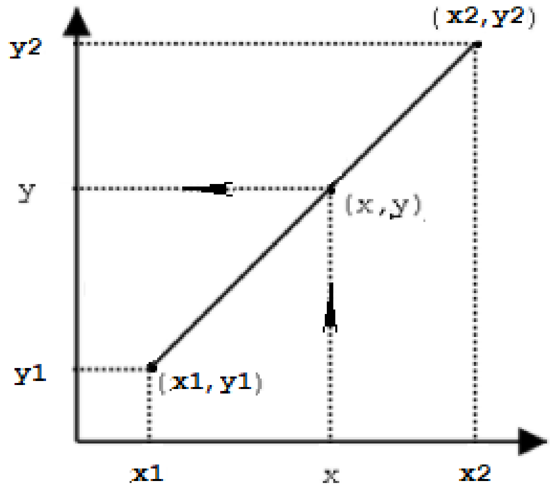


Figure 2 – Linear interpolation scheme

The simplest interpolation formula is given below

$$y = y_1 + \frac{(x - x_1)}{(x_2 - x_1)}(y_2 - y_1),$$

where x_1 and y_1 are the first coordinates; x_2 and y_2 are the second coordinates; x is the point to perform the interpolation; y is the interpolated value.

Let's use the method of linear interpolation to find, say, enthalpy for saturated water at 10.2 bar pressure. Table 1 contains the required initial data.

Table 1 – Table for properties of saturated liquid and saturated steam (fragment)

Pressure bar	Sat. temp. °C	Volume m^3 /kg		Enthalpy kJ/kg			Entropy kJ/kg K		
		V_f	V_g	H_f	H_{fg}	H_g	S_f	S_{fg}	S_g
10.0	179.88	0.0011274	0.19429	762.61	2013.6	2776.2	2.1382	4.4443	6.5828
10.5	182.02	0.0011303	0.18545	772.03	2005.9	2778.0	2.1588	4.4071	6.5659

Here we have $x_1 = p_1 = 10$ bar, $y_1 = h_1 = 762.61$ kJ/kg,

$x_2 = p_2 = 10.5$ bar, $y_2 = h_2 = 772.03$ kJ/kg,

$x = p = 10.2$ bar.

$$h = h_1 + \frac{(p - p_1)}{(p_2 - p_1)}(h_2 - h_1) = 762.61 + \frac{(10.2 - 10)}{(10.5 - 10)}(772.03 - 762.61) =$$

$$= 766.378 \text{ kJ/kg}.$$

3 STATE DIAGRAMS FOR WATER AND WATER VAPOUR

The states of water and steam and vaporization process can be visualized using so-called thermodynamic (or state) diagrams. The main feature of thermodynamic diagrams is the equivalence between the area or segment length in the diagram and energy.

Main thermodynamic diagrams for water and water vapour include: absolute pressure – specific volume (*p*–*v*) diagram, absolute temperature – specific entropy (*T*–*s*) diagram and specific enthalpy – specific entropy (*h*–*s* or Mollier) diagram.

T–*s* diagram helps to visualize the heat transfer during a process. For reversible (ideal) processes, the **area under the *T*–*s* curve** of a process **is** the **heat transferred** to or from the system during that process. While the **area under the *p*–*v* curve** of a process **is** the **work** of this process.

The generation of water vapour has experienced three stages.

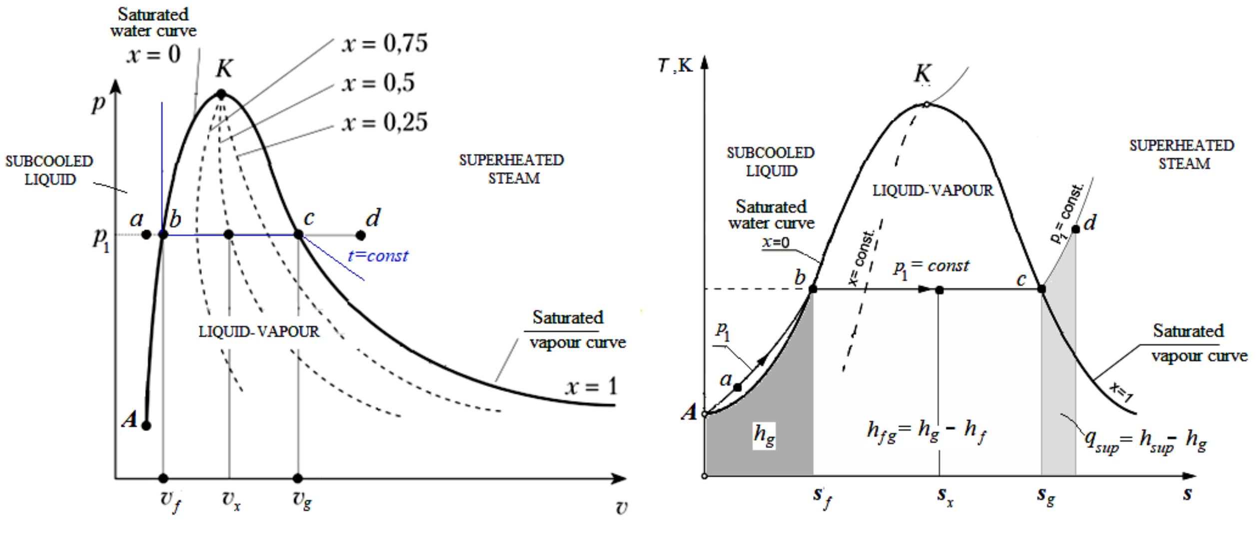
The **first stage** is the **pre-heat stage**: sub-cooled liquid to saturated liquid

($t < t_s$). A sub-cooled liquid is also called a compressed liquid. It is unsaturated water. At this stage, the temperature is lower than the saturation temperature of the corresponding pressure. Until the saturated water state is reached, the saturation temperature is reached.

The **second** is the **vaporization stage**: saturated liquid to saturated vapour ($t = t_s$). In this stage the temperature of the working medium is always saturated temperature and remains unchanged if the pressure is held constant. During the entire phase-change process, the liquid and vapour phases coexistence in equilibrium, which is called saturated liquid-vapour mixture.

The **third** is the **superheat stage**: saturated vapour to superheated vapour ($t > t_s$). At this stage, further transfer of heat results in an increase in temperature. The temperature is higher than the saturation temperature corresponding to the pressure.

The *p*–*v* diagram and *T*–*s* diagram of the phase change process of water at a constant pressure can be drawn, as shown in Fig. 3 .



a ***b***

Figure 3 – Phase change process for water:
a – *p*–*v* diagram; *b* – *T*–*s* diagram

In the fig.3, *a*–*b* is the pre-heat stage, *b*–*c* is the vaporization stage, *c*–*d* is the superheat stage.

The locus of all the saturated water states gives the saturated water curve and the locus of all the saturated vapour states gives the saturated vapour states gives the saturated vapour states gives the saturated vapour curve. A saturated liquid or vapour would lie on their appropriate lines, and is exactly where a liquid would saturate or vaporize at an existing pressure.

The saturation vapour curve is the curve separating the two-phase state and the superheated vapour state. The saturated liquid curve is the curve separating the subcooled liquid state and the two-phase state.

The point ***K*** represents the critical point. The difference between v_g and v_f reduces as the pressure is increased, and at the critical point $v_g = v_f$.

The point ***A*** represents the triple point where the enthalpy and the entropy is considered to be equal to zero value.

The region bounded by the saturated liquid curve and saturated vapour curve is called ***vaporization dome***. Everything "under the dome" considered a wet vapour (liquid vapour mixture). ***Inside the vapour dome the constant pressure lines are also lines of constant temperature***.

The area under the line *b–c* on the *T–s* diagram represents the ***heat of vaporization***. It is obvious from the *T–s* diagram that heat of vaporization decreases as the temperature rises and becomes zero at the critical point.

The area under the line *c–d* represents the ***heat of superheating*** q_{sup}.

Mollier *h–s* diagram (named after Richard Mollier, 1863-1935) was a logical extension of the *T–s* diagram, retaining the advantages of *T–s* diagrams but introducing several new advantages. A typical *h–s* Mollier diagram for water is shown in Fig. 4.

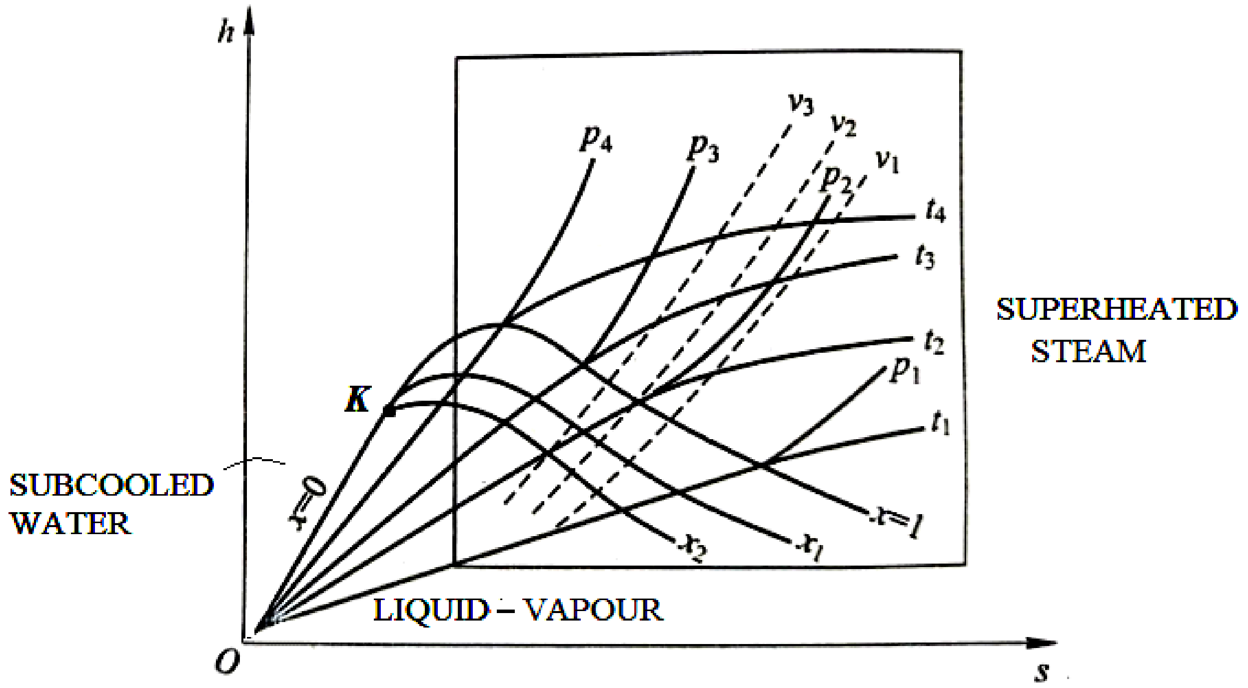


Figure 4 – *h–s* Mollier diagram for water

This diagram has a series of **constant temperature lines**, **constant pressure lines**, **constant quality lines**, and **constant volume lines**. Constant pressure lines are plotted on the diagram through both the wet steam area and the superheat area. Constant pressure lines are straight lines in the wet region and curved in the superheat area. Lines of constant dryness fraction are plotted in the wet steam area, and lines of constant temperature in the superheat area.

The Mollier diagram is used only when quality is greater than 50% and for superheated steam. For any state, at least two properties should be known to determine the other unknown properties of steam at that state. In such truncated diagram property of liquid cannot be read.

Power generation are most conveniently represented on *h–s* diagrams because ***work can be calculated*** directly from ***vertical distances*** as opposed to areas on *T–s* and *p–v* diagrams.

4 THERMODYNAMICS PROCESSES FOR WATER VAPOUR

For various thermodynamics processes, vapour cannot be treated in the same way as a gas because vapour does not follow laws relating to gases. Therefore, the analysis of various processes for vapour is required. However, the following basic energy equations derived from First and Second Laws for the vapour are the same as those deduced for a perfect gas.

$$\delta q = du + \delta w, \qquad \delta q = dh - v \cdot dp, \qquad \delta q = T \cdot ds, \qquad \delta w = p \cdot dv.$$

Once a vapour becomes superheated the various processes of heating and expansion of gases may be applied to vapour as vapour in superheated state will approximately follow the laws of gases except well below its critical temperature.

Assume that steam undergoes a process from its initial state to final state. Let the initial condition of steam be in the wet region as point *1* at pressure p_1 having dryness fraction x_1 and the final condition in the superheat region as point *2* at pressure p_2 ($p_2 = p_1$) and super heating temperature $t_{sup,2}$.

Representation of main processes on *p–v*, *T–s* and *h–s* diagrams is shown in Fig. 5–8.

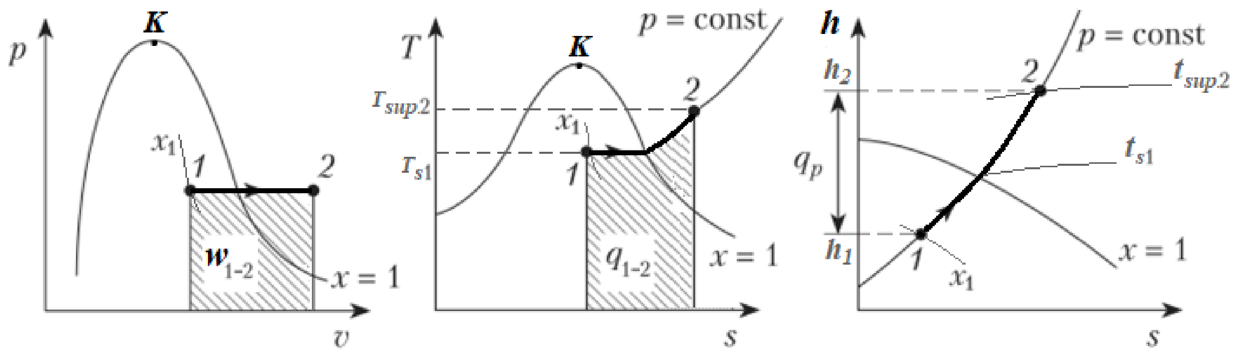


Figure 5 – Constant pressure heating process of vapour

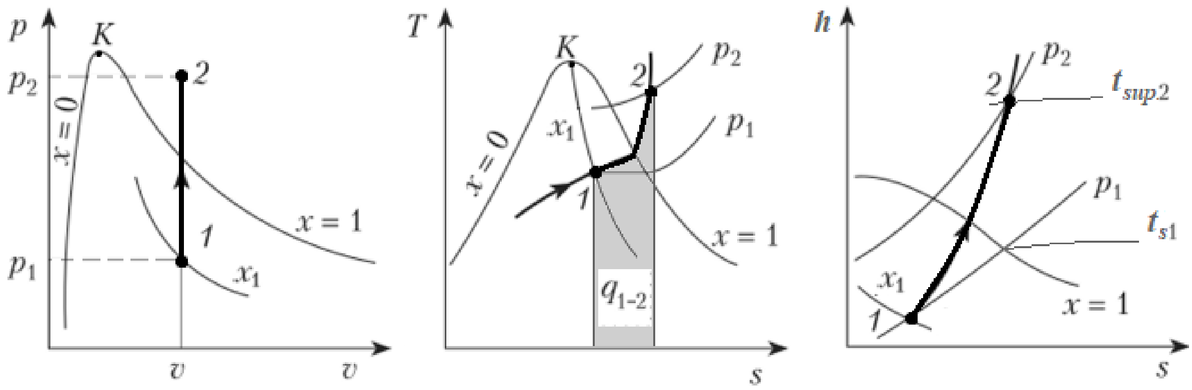


Figure 6 – Constant volume heating process of vapour

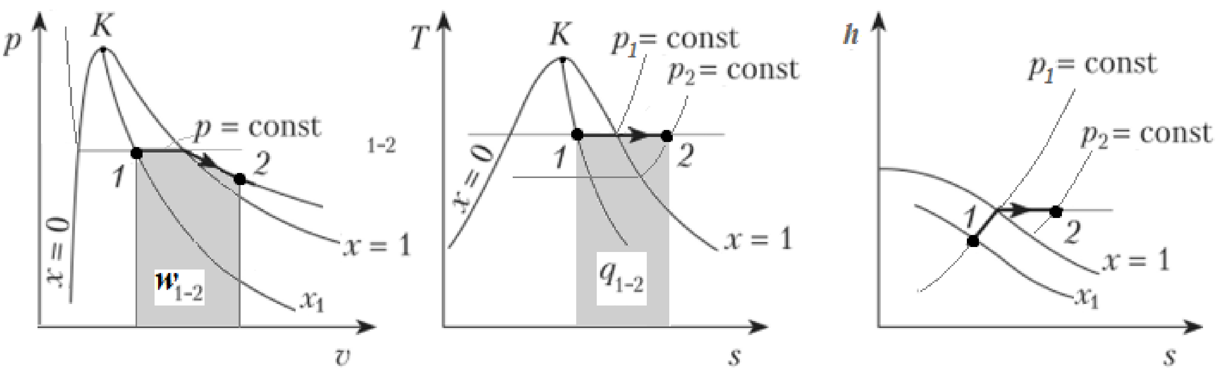


Figure 7 – Isothermal expansion process of vapour

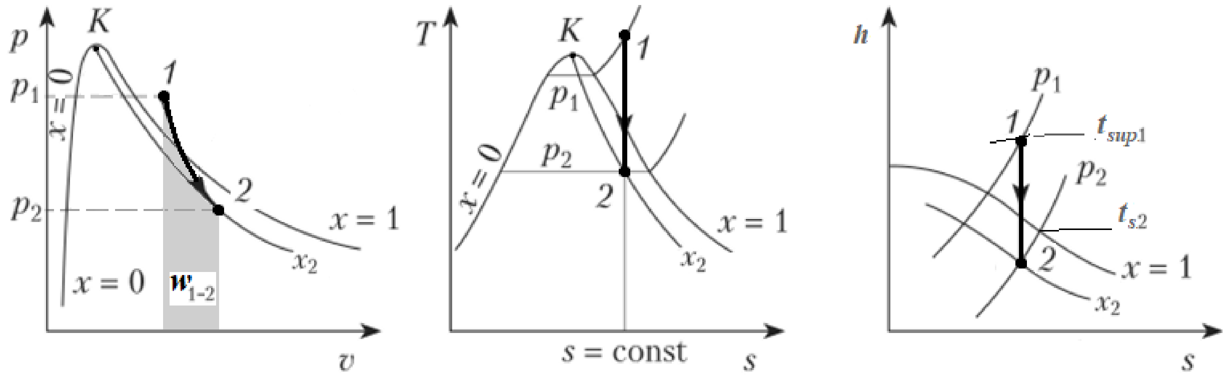


Figure 8 – Adiabatic expansion process of steam (the initial condition of steam is in the superheat region as point *1* at pressure p_1 and super heating temperature t_{sup1} and the final condition in the wet region as point *2* at pressure p_2 and dryness fraction x_2.)

Formulas for determining the energy characteristics of thermodynamic processes are given in table 2.

Table 2 – Energy characteristics of thermodynamic processes

Thermodynamic process	Process characteristics		
	Internal energy change	Specific work	Specific heat
Isobaric process (p = const)	$\Delta u = u_2 - u_1 =$ $= (h_2 - p_2v_2) - (h_1 - p_1v_1) =$ $= (h_2 - h_1) - (p_2v_2 - p_1v_1) =$ $= (h_2 - h_1) - p\,(v_2 - v_1)$	$w = \int_1^2 p\,dv =$ $= p\int_1^2 dv =$ $= p(v_2 - v_1)$	$q = w + \Delta u =$ $= p(v_2 - v_1) +$ $+ (h_2 - h_1) -$ $- p\,(v_2 - v_1) =$ $= h_2 - h_1$
Isochoric process (v = const)	$\Delta u = u_2 - u_1 =$ $= (h_2 - p_2v_2) - (h_1 - p_1v_1) =$ $= (h_2 - h_1) - v\,(p_2 - p_1)$	$w = \int_1^2 p\,dv = 0$	$q = \Delta u$
Isothermal process (t = const)	$\Delta u = u_2 - u_1 =$ $= (h_2 - h_1) - (p_2v_2 - p_1v_1) =$ $= (h_2 - p_2v_2) - (h_1 - p_1v_1)$	$w = q - \Delta u$	$q = \int_1^2 T\,ds =$ $= \int_1^2 T\,ds =$ $= T\,(s_2 - s_1)$
Adiabatic (isentropic) process (s = const, q = 0)	$\Delta u = u_2 - u_1 =$ $= (h_2 - h_1) - (p_2v_2 - p_1v_1) =$ $= (h_2 - p_2v_2) - (h_1 - p_1v_1)$	$w = -\Delta u$	$q = 0$

5 INDIVIDUAL WORK

Vapour processes on *P–v*, *T–s* and *h–s* state diagrams

1. Point 1 is characterized by two parameters (table 3). Find the other parameters for this state (full set of parameters is: temperature *t*, pressure *p*, specific volume *v* , specific enthalpy *h*, specific entropy *s*).
2. Plot these processes on *P–v*, *T–s* and *h–s* diagrams every time starting from Point 1 (respect the scale and the correct location of points relative to the saturated vapour line (x = 1)).
3. For the final state of vapour for these processes the one parameter is given (as shown in table 3). Find the other parameters for the final state of vapour for these processes (full set of parameters is: temperature *t*, pressure *p*, specific volume *v* , specific enthalpy *h*, specific entropy *s*).
4. Find changes in internal energy Δu, heat *q* and work *w* for 1 kg of vapour for each of the processes.
5. For any of the calculated points, check the parameters found from the diagram using the water tables.

Table 3 – Initial data

Variant	Point 1		Point 2*v* for isochoric process	Point 2*p* for isobaric process	Point 2*t* for isothermal process	Point 2*s* for adiabatic process
1	$P_1 = 6$	$t_1 = 175$	$P_{2v} = 10$	$x_{2p} = 0.95$	$P_{2t} = 3$	$P_{2s} = 1$
2	$P_1 = 16$	$x_1 = 0.96$	$P_{2v} = 13$	$t_{2p} = 250$	$s_{2t} = 6.7$	$\mathrm{P}_{2s} = 3$
3	$P_1 = 10$	$t_1 = 300$	$t_{2v} = 350^oC$	$h_{2p} = 3300$	$h_{2t} = 3000$	$P_{2s} = 1$
4	$P_1 = 22$	$t_1 = 250$	$s_{2v} = 6.7$	$i_{2p} = 2600$	$P_{2t} = 10$	$P_{2s} = 5$
5	$P_1 = 8$	$x_1 = 0.95$	$P_2 = 7$	$h_2 = 3000$	$s_{2t} = 7.1$	$t_{2s} = 350$
6	$P_1 = 29$	$t_1 = 400$	$h_{2v}= 2800$	$h_{2p} = 3000$	$P_{2t} = 5$	$t_{2s} = 200$
7	$P_1 = 20$	$t_1 = 340$	$s_{2v} = 6.7$	$s_{2p} = 7.5$	$P_{2t} = 4$	$t_{2s} = 140$
8	$P_1 = 10$	$t_1 = 260$	$t_{2v}= 300$	$s_{2p} = 7.5$	$P_{2t} = 2$	$t_{2s} = 100$
9	$P_1 = 60$	$x_1 = 0.9$	$t_{2v} = 280$	$t_{2p} = 320$	$P_{2t} = 0.9$	$x_{2s} = 0.8$
10	$P_1 = 4$	$x_1 = 0.8$	$x_{2v} = 1$	$t_{2p} = 160$	$s_{2t} = 8$	$h_{2s} = 2600$

Notes. *In the table pressure* ***P*** *is given in bar, temperature* ***t*** *– in ^{o}C, specific entropy* ***s*** *– in kJ/(kg·K), specific enthalpy* ***h*** *– in kJ/kg, dryness fraction* ***x*** *is dimensionless.*

Example for individual work

Initial given data are presented in the table 4.

Table 4 – Initial data for the problem

Point1		Point 2*v* for isochoric process	Point 2*p* for isobaric process	Point 2*t* for isothermal process	Point 2*s* for adiabatic process
$P_1 = 8$ bar	$x_1 = 0.96$	$t_{2v} = 270$°C	$s_{2p} = 7.2$ kJ/(kg K)	$h_{2t} = 2500$ kJ/kg	$h_{2s} = 2100$ kJ/kg

Let's find the parameters for each steam state.

Point 1 is located at an intersection of 8 bar pressure line and 0.96 dryness fraction line in wet vapour region (fig. 9).

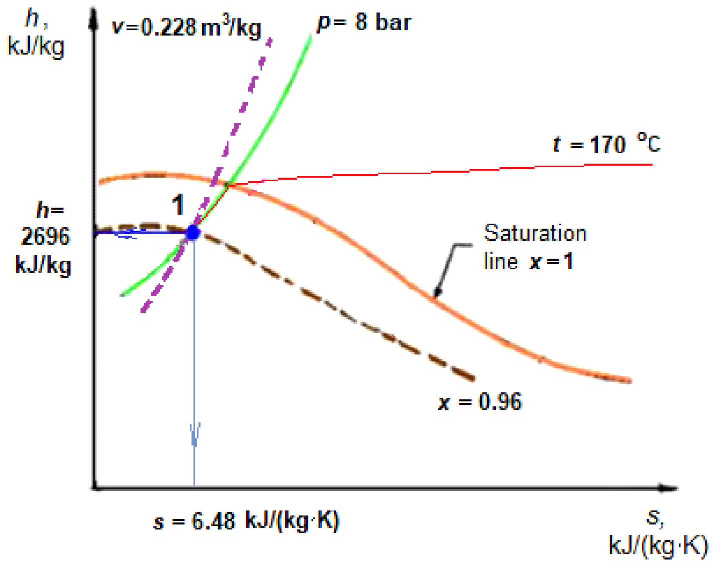


Figure 9 – Point 1 finding scheme

The value of parameters from Mollier diagram corresponding to point 1:

- specific enthalpy h_1 = 2696 kJ/kg,
- specific volume v_1 = 0.228 m^3/kg,
- specific entropy s_1 = 6.48 kJ/(kg·K),
- temperature t_1 = 170 °C.

Point 2*v*. Process 1–2*v* is given to be an isochore. For this process volume remains constant: $v_1 = v_{2v}$ = 0. 228 m^3/kg.

Now two properties are known for point 2*v*. Thus, the point is located at an intersection of 270 °C temperature line (the temperature is given) and 0.228 m^3/kg specific volume line (fig. 10). The steam is superheated at the point.

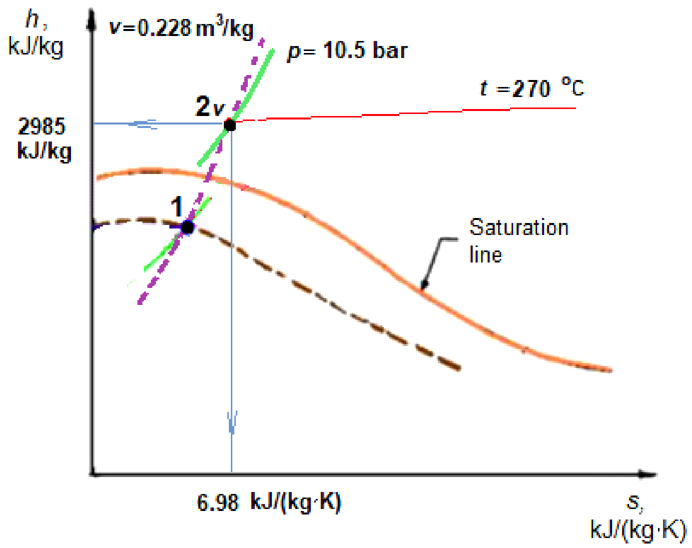


Figure 10 – Point 2*v* finding scheme

By using *h*–*s* diagram we have

- specific enthalpy h_{2v} = 2985 kJ/kg,
- specific entropy s_{2v} = 6,98 kJ/(kg·K),
- pressure p_{2v} = 10.5 bar.

Point 2*p*. Process 1–2*p* is given to be an isobar, so $p_1 = p_{2p}$ = 8 bar. For the point specific entropy is also given. Thus, the point is located at an intersection of 8 bar pressure line and 7.2 m^3/kg specific volume line (fig. 11). The steam is superheated at the point.

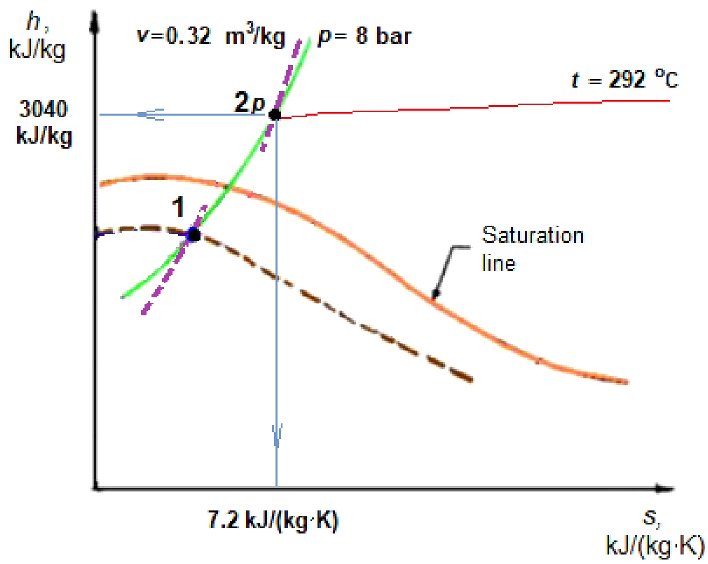


Figure 11 – Point 2*p* finding scheme

By using *h*–*s* diagram we have

- specific enthalpy h_{2p} = 3040 kJ/kg,

- specific volume v_{2p} = 0.32 m^3/kg,
- temperature t_{2p}= 292 ^{o}C.

Point 2*t*. Process 1–2*t* is given to be an isotherm, so $t_1 = t_{2t}$ = 170 ^{o}C. For the point specific enthalpy is also given. Thus, the point is located at an intersection of 170 ^{o}C temperature line and 2500 kJ/kg specific enthalpy line (fig. 12). The vapour is wet at the point.

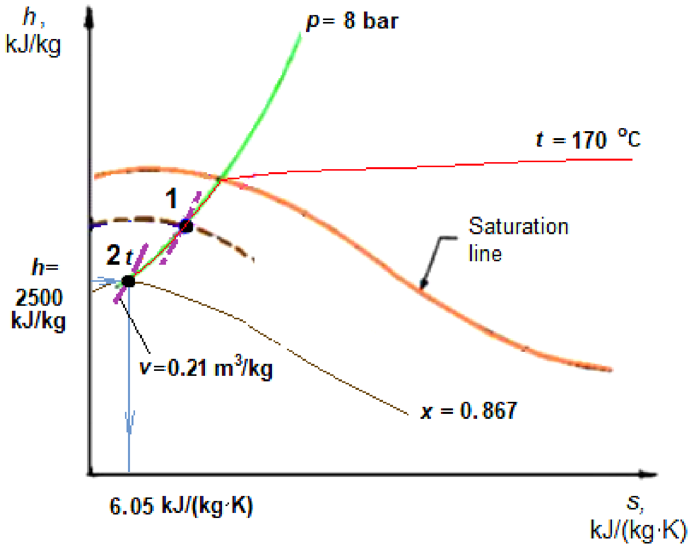


Figure 12 – Point 2*t* finding scheme

By using *h*–*s* diagram we have

- specific entropy s_{2t} = 3040 kJ/kg,
- specific volume s_{2t} = 0.32 m^3/kg,
- pressure p_{2t} = 8 bar,
- dryness fraction x = 0.867.

Point 2*s*. Process 1–2*s* is given to be an isentrope, so $s_1 = s_{2s}$ = 6.48 kJ/(kg·K). For the point specific enthalpy is also given. Thus, the point is located at an intersection of 6.48 kJ/(kg·K) specific entropy line and 2100 kJ/kg specific enthalpy line (fig. 13). The vapour is wet at the point.

By using *h*–*s* diagram we have

- temperature t_{2s} = 57 ^{o}C,
- specific volume v_{2s} = 0.32 m^3/kg,
- pressure p_{2s} = 0.155 bar,
- dryness fraction x = 0.79.

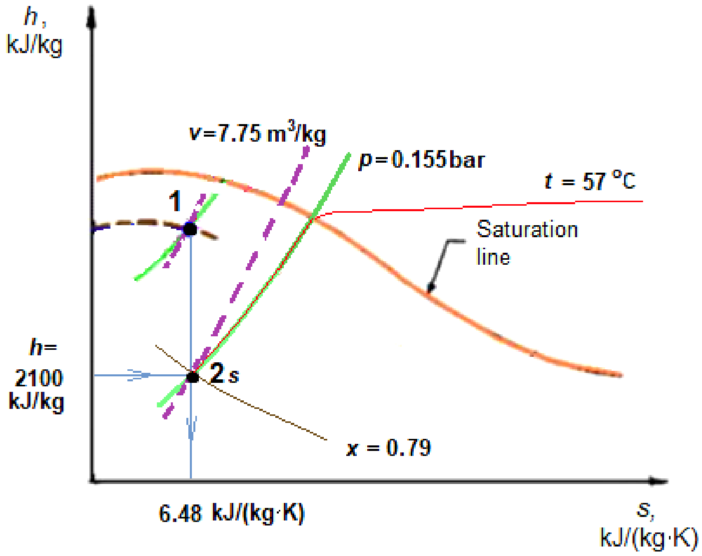


Figure 13 – Point 2*s* finding scheme

All the parameters for considering points are conveniently placed in the table 5. The initial parameters are indicated in bold letters.

Table 5 – Parameter table

	P, bar	*t*, °C	*v*, m^3/kg	*h*, kJ/kg	*s*, kJ/(kg °C)	*x*
Point *1*	**8**	170	0.228	2696	6.48	**0.96**
Point *2v*	10.5	**270**	0.228	2985	6.98	–
Point *2p*	8	292	0.32	3040	**7.2**	–
Point *2t*	8	170	0.21	**2500**	6.05	0.867
Point 2*s*	0.155	57	7.75	**2100**	6.48	0.79

Processes analysis

The process characteristics can be defined using formulae in table 2.

Point 1 – Point 2*v* (isochoric process)

Work of the process

$$w = 0 \text{ kJ/kg}.$$

Heat and internal energy change for the process

$$q = \Delta u = (h_{2v} - p_{2v} \cdot v_{2v}) - (h_1 - p_1 \cdot v_1) =$$
$$= (2985 - 10{,}5 \cdot 10^2 \cdot 0.228) - (2696 - 8 \cdot 10^2 \cdot 0.228) = 232 \text{ kJ/kg}.$$

Point 1–Point 2*p* (isobaric process)

$$w = p_1(v_{2p} - v_1) = 8{\cdot}10^2\,(0.32 - 0.228\,) = 73.6 \text{ kJ/kg.}$$

$$q = h_{2p} - h_1 = 3040 - 2696 = 344 \text{ kJ/kg.}$$

$$\Delta u = (h_{2p} - p_{2p}{\cdot}v_{2p}) - (h_1 - p_1{\cdot}v_1) =$$
$$= (3040 - 8{\cdot}10^2{\cdot}0.32) - (2696 - 8{\cdot}10^2{\cdot}0.228) = 270.4 \text{ kJ/kg.}$$

Point 1–Point 2*t* (isothermal process)

$$q = T_1(s_{2t} - s_1\,) = (170{+}273)(6.05 - 6.48) = -190.5 \text{ kJ/kg.}$$

$$\Delta u = (h_{2t} - p_{2t}{\cdot}v_{2t}) - (h_1 - p_1{\cdot}v_1) = (\,2500 - 8{\cdot}10^2{\cdot}0.21) - (2696 - 8{\cdot}10^2{\cdot}0.228) =$$
$$= -181.6 \text{ kJ/kg.}$$

$$w = q - \Delta u = -8.89 \text{ kJ/kg.}$$

Point 1–Point 2*s* (adiabatic process)

$$q = 0 \text{ kJ/kg.}$$

$$\Delta u = (h_{2s} - p_{2s}{\cdot}v_{2s}) - (h_1 - p_1{\cdot}v_1) =$$
$$= (2100 - 0.155\,{\cdot}10^2{\cdot}7.75) - (\,2696 - 8{\cdot}10^2{\cdot}0.228{\cdot}) = -533.7 \text{ kJ/kg.}$$

$$w = -\Delta u = 533.7 \text{ kJ/kg.}$$

For all the processes make sure the first law of thermodynamics must be respected: q = Δu + w.

All processes are presented together in state diagrams (fig. 14–16).

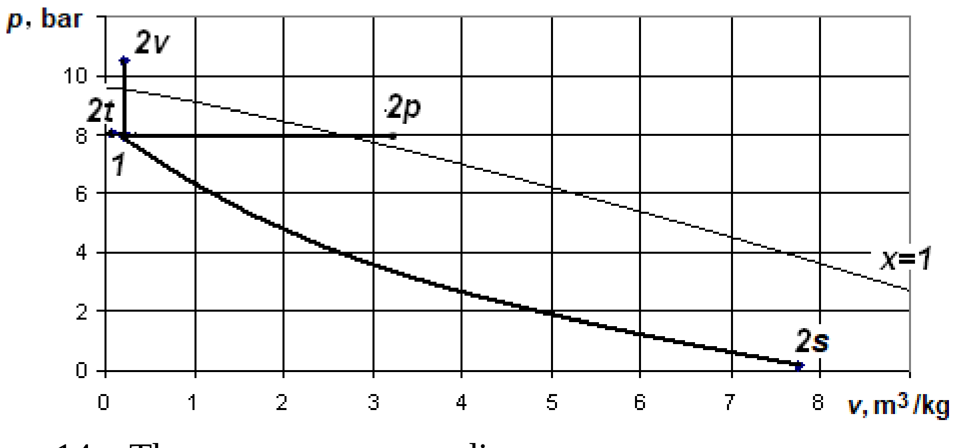


Figure 14 – The processes on p–v diagram

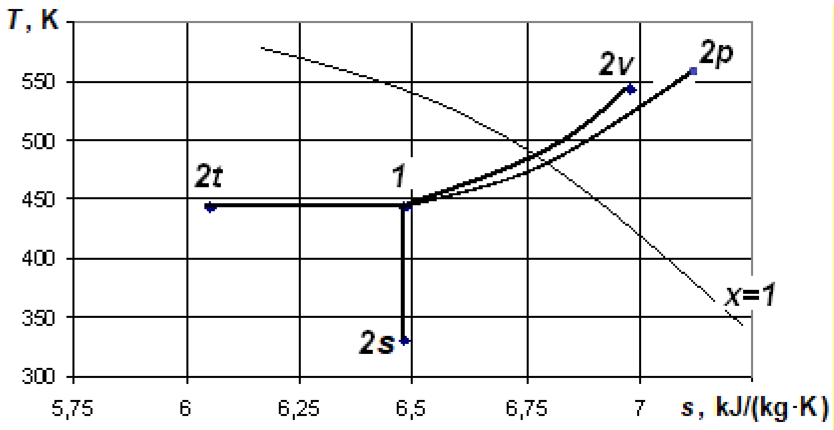


Figure 15 – The processes on *T*–*s* diagram

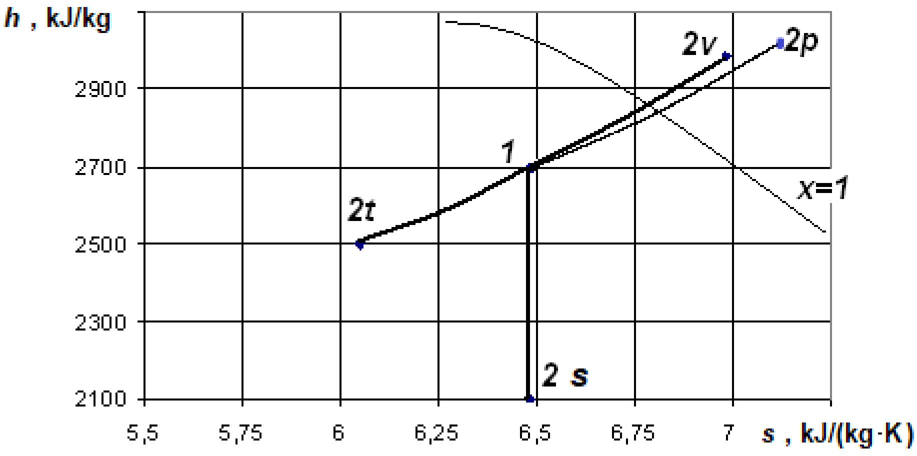


Figure 14 – The processes on *h*–*s* diagram

Check the parameters for **point 1** using the water tables.

We have $p_1 = 8$ bar and $x_1 = 0.96$ as given parameters. As the vapour is wet let's use the table A.2. To convert units of pressure, table B.1 can be used.

$p_1 = 8$ bar = 800 kPa,

$t_1 = 170.4066\ ^oC$,

$v_f \cdot 10^3 = 1.1148\ \text{kg/m}^3 \rightarrow v_f = 1.1148 \cdot 10^{-3}\ \text{kg/m}^3$;

$v_g = 0.24035\ \text{kg/m}^3$;

$h_f = 720.87$ kJ/kg;

$h_g = 2768.3$ kJ/kg;

$s_f = 2.04566$ kJ/(kg·K);

$s_g = 6.6616$ kJ/(kg·K).

$$v_{x1} = (1 - x)v_f + x \cdot v_g = (1 - 0.96)\ 1.1148 \cdot 10^{-3} + 0.96 \cdot 0.24035 = 0{,}2308\ \text{kg/m}^3,$$

$$h_{x1} = (1 - x)h_f + x\, h_g = h_f + x\, h_{fg} = (1 - 0.96)\ 720.87 + 0.96 \cdot 2768.3 = 2686{,}4\ \text{kJ/kg},$$

$$s_{x1} = (1 - x)s_f + x\, s_g = (1 - 0.96)\ 2.04566 + 0.96 \cdot 6.6616 = 6{,}47\ \text{kJ/(kg·K)}.$$

Previously from the *h*-*s* diagram we have:

$t_1 = 170\ ^oC$,

$v_1 = 0.228\ m^3/kg$,

$h_1 = 2696$ kJ/kg,

$s_1 = 6.48$ kJ/(kg·K).

So the parameters can be accepted as found with sufficient accuracy.

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3. Michael J. Moran, Howard N. Shapiro. Fundamentals of Engineering Thermodynamics. – Wiley, 2014. – 1062 p.

APPENDIXES

Appendix A. Property Tables for Water

Tables A.1 and A.2 present data for saturated liquid and saturated vapour. Table A-1 is presented information at regular intervals of temperature while Table A-2 is presented at regular intervals of pressure. Table A-3 presents data for superheated vapour over a matrix of temperatures and pressures. Table A-4 presents data for compressed liquid over a matrix of temperatures and pressures. These tables were generated using EES with the substance Steam_IAPWS which implements the high accuracy thermodynamic properties of water described in *1995 Formulation for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use*, issued by the International Associated for the Properties of Water and Steam (IAPWS).

Table A.1 – Properties of saturated water and saturated vapour (temperature based)

Temp. T (°C)	Pressure P (kPa)	Specific volume (m^3/kg)		Specific internal energy (kJ/kg)		Specific enthalpy (kJ/kg)		Specific entropy (kJ/kg-K)		T (°C)
		$10^3\, v_f$	v_g	u_f	u_g	h_f	h_g	s_f	s_g	
0.01	0.6117	1.0002	206.00	0	2374.9	0.000	2500.9	0	9.1556	0.01
2	0.7060	1.0001	179.78	8.3911	2377.7	8.3918	2504.6	0.03061	9.1027	2
4	0.8135	1.0001	157.14	16.812	2380.4	16.813	2508.2	0.06110	9.0506	4
6	0.9353	1.0001	137.65	25.224	2383.2	25.225	2511.9	0.09134	8.9994	6
8	1.0729	1.0002	120.85	33.626	2385.9	33.627	2515.6	0.12133	8.9492	8
10	1.2281	1.0003	106.32	42.020	2388.7	42.022	2519.2	0.15109	8.8999	10
12	1.4028	1.0006	93.732	50.408	2391.4	50.410	2522.9	0.18061	8.8514	12
14	1.5989	1.0008	82.804	58.791	2394.1	58.793	2526.5	0.20990	8.8038	14
16	1.8187	1.0011	73.295	67.169	2396.9	67.170	2530.2	0.23898	8.7571	16
18	2.0646	1.0015	65.005	75.542	2399.6	75.544	2533.8	0.26784	8.7112	18
20	2.3392	1.0018	57.762	83.913	2402.3	83.915	2537.4	0.29649	8.6661	20
22	2.6452	1.0023	51.422	92.280	2405.1	92.283	2541.1	0.32493	8.6217	22
24	2.9857	1.0028	45.861	100.65	2407.8	100.65	2544.7	0.35318	8.5782	24
26	3.3638	1.0033	40.975	109.01	2410.5	109.01	2548.3	0.38123	8.5354	26
28	3.7830	1.0038	36.673	117.37	2413.2	117.37	2551.9	0.40909	8.4933	28
30	4.2469	1.0044	32.879	125.73	2415.9	125.74	2555.6	0.43676	8.4520	30
32	4.7596	1.0050	29.527	134.09	2418.6	134.10	2559.2	0.46425	8.4114	32
34	5.3251	1.0057	26.560	142.45	2421.3	142.46	2562.8	0.49155	8.3714	34
36	5.9480	1.0064	23.929	150.81	2424.0	150.82	2566.4	0.51868	8.3322	36
38	6.6330	1.0071	21.593	159.17	2426.7	159.18	2569.9	0.54563	8.2935	38
40	7.3851	1.0079	19.515	167.53	2429.4	167.53	2573.5	0.57241	8.2556	40
42	8.2098	1.0087	17.663	175.89	2432.1	175.90	2577.1	0.59902	8.2182	42
44	9.1127	1.0095	16.010	184.25	2434.8	184.26	2580.7	0.62546	8.1815	44
46	10.100	1.0104	14.534	192.61	2437.4	192.62	2584.2	0.65174	8.1454	46
48	11.178	1.0112	13.212	200.97	2440.1	200.98	2587.8	0.67786	8.1098	48
50	12.352	1.0122	12.026	209.33	2442.7	209.34	2591.3	0.70382	8.0748	50
55	15.763	1.0146	9.5639	230.24	2449.3	230.26	2600.1	0.76803	7.9898	55
60	19.947	1.0171	7.6670	251.16	2455.9	251.18	2608.8	0.83130	7.9082	60
65	25.043	1.0199	6.1935	272.09	2462.4	272.12	2617.5	0.89366	7.8296	65
70	31.202	1.0228	5.0396	293.04	2468.9	293.07	2626.1	0.95514	7.7540	70
75	38.597	1.0258	4.1291	313.99	2475.3	314.03	2634.6	1.01578	7.6812	75
80	47.416	1.0291	3.4053	334.97	2481.6	335.02	2643.0	1.07559	7.6111	80
85	57.868	1.0324	2.8260	355.96	2487.8	356.02	2651.4	1.13461	7.5435	85
90	70.183	1.0360	2.3593	376.97	2494.0	377.04	2659.6	1.19288	7.4782	90
95	84.609	1.0396	1.9808	398.00	2500.1	398.09	2667.6	1.25040	7.4151	95
100	101.42	1.0435	1.6720	419.06	2506.0	419.17	2675.6	1.30722	7.3542	100

Appendix A (continued)

Table A.1 (continued) – Properties of saturated water and saturated vapour (temperature based)

Temp. T (°C)	Pressure P (kPa)	Specific volume (m^3/kg)		Specific internal energy (kJ/kg)		Specific enthalpy (kJ/kg)		Specific entropy (kJ-kg-K)		T (°C)
		10^3 v_f	v_g	u_f	u_g	h_f	h_g	s_f	s_g	
105	120.90	1.0474	1.4186	440.15	2511.9	440.28	2683.4	1.3634	7.2952	105
110	143.38	1.0516	1.2094	461.27	2517.7	461.42	2691.1	1.4188	7.2382	110
115	169.18	1.0559	1.0360	482.42	2523.3	482.59	2698.6	1.4737	7.1829	115
120	198.67	1.0603	0.89136	503.60	2528.9	503.81	2706.0	1.5279	7.1292	120
125	232.23	1.0649	0.77012	524.83	2534.3	525.07	2713.1	1.5816	7.0771	125
130	270.28	1.0697	0.66808	546.10	2539.5	546.38	2720.1	1.6346	7.0265	130
135	313.22	1.0746	0.58179	567.41	2544.7	567.75	2726.9	1.6872	6.9773	135
140	361.53	1.0798	0.50850	588.77	2549.6	589.16	2733.5	1.7392	6.9294	140
145	415.68	1.0850	0.44600	610.19	2554.4	610.64	2739.8	1.7908	6.8827	145
150	476.16	1.0905	0.39248	631.66	2559.1	632.18	2745.9	1.8418	6.8371	150
160	618.23	1.1020	0.30680	674.79	2567.8	675.47	2757.5	1.9426	6.7492	160
170	792.18	1.1143	0.24260	718.20	2575.7	719.08	2767.9	2.0417	6.6650	170
180	1002.8	1.1274	0.19385	761.92	2582.8	763.05	2777.2	2.1392	6.5841	180
190	1255.2	1.1414	0.15636	806.00	2589.0	807.43	2785.3	2.2355	6.5059	190
200	1554.9	1.1565	0.12721	850.46	2594.2	852.26	2792.0	2.3305	6.4302	200
210	1907.7	1.1727	0.10429	895.38	2598.3	897.61	2797.3	2.4245	6.3563	210
220	2319.6	1.1901	0.086094	940.79	2601.3	943.55	2801.0	2.5176	6.2840	220
230	2797.1	1.2089	0.071505	986.76	2602.9	990.14	2802.9	2.6100	6.2128	230
240	3347.0	1.2294	0.059707	1033.4	2603.1	1037.5	2803.0	2.7018	6.1424	240
250	3976.2	1.2516	0.050085	1080.7	2601.8	1085.7	2801.0	2.7933	6.0721	250
260	4692.3	1.2759	0.042175	1128.9	2598.7	1134.8	2796.6	2.8847	6.0017	260
270	5503.0	1.3028	0.035622	1178.0	2593.7	1185.1	2789.7	2.9762	5.9305	270
280	6416.6	1.3326	0.030153	1228.2	2586.4	1236.7	2779.9	3.0681	5.8579	280
290	7441.8	1.3660	0.025554	1279.7	2576.5	1289.8	2766.7	3.1608	5.7834	290
300	8587.9	1.4038	0.021659	1332.7	2563.6	1344.8	2749.6	3.2548	5.7059	300
310	9865.0	1.4475	0.018333	1387.7	2547.1	1402.0	2727.9	3.3506	5.6243	310
320	11284.3	1.4987	0.015470	1445.1	2526.0	1462.0	2700.6	3.4491	5.5372	320
330	12858.1	1.5604	0.012979	1505.7	2499.2	1525.8	2666.0	3.5516	5.4422	330
340	14600.7	1.6377	0.010783	1570.7	2464.5	1594.6	2622.0	3.6602	5.3358	340
350	16529.3	1.7407	0.008806	1642.4	2418.3	1671.2	2563.9	3.7788	5.2114	350
360	18666.0	1.8950	0.006950	1726.2	2351.9	1761.5	2481.6	3.9165	5.0537	360
370	21043.8	2.2172	0.004953	1844.5	2230.1	1891.2	2334.3	4.1119	4.8009	370
373.95	22064.0	3.1056	0.003106	2015.7	2015.7	2084.3	2084.3	4.4070	4.4070	373.95

Appendix A (continued)

Table A.2 – Properties of saturated water and saturated vapour (pressure based)

Pressure *P* (kPa)	Temp. *T* (°C)	Specific volume (m^3/kg)		Specific internal energy (kJ/kg)		Specific enthalpy (kJ/kg)		Specific entropy (kJ/kg-K)		*P* (kPa)
		$10^3\ v_f$	v_g	u_f	u_g	h_f	h_g	s_f	s_g	
1	6.9705	1.0001	129.19	29.302	2384.5	29.303	2513.7	0.10593	8.9749	1
1.5	13.0205	1.0007	87.964	54.686	2392.8	54.688	2524.7	0.19558	8.8270	1.5
2	17.4957	1.0014	66.990	73.431	2398.9	73.433	2532.9	0.26058	8.7227	2
2.5	21.0777	1.0021	54.242	88.422	2403.8	88.424	2539.4	0.31184	8.6421	2.5
3	24.0796	1.0028	45.654	100.98	2407.9	100.98	2544.8	0.35430	8.5765	3
4	28.9607	1.0041	34.791	121.39	2414.5	121.39	2553.7	0.42240	8.4734	4
5	32.8743	1.0053	28.185	137.75	2419.8	137.75	2560.7	0.47620	8.3938	5
6	36.1587	1.0065	23.733	151.47	2424.2	151.48	2566.6	0.52082	8.3291	6
7	38.9992	1.0075	20.524	163.34	2428.1	163.35	2571.7	0.55903	8.2745	7
8	41.5082	1.0085	18.099	173.83	2431.4	173.84	2576.2	0.59249	8.2273	8
10	45.8056	1.0103	14.670	191.80	2437.2	191.81	2583.9	0.64919	8.1488	10
12	49.4178	1.0119	12.358	206.90	2442.0	206.91	2590.3	0.69628	8.0850	12
14	52.5458	1.0134	10.691	219.98	2446.1	219.99	2595.8	0.73663	8.0311	14
16	55.3120	1.0147	9.4307	231.55	2449.8	231.57	2600.7	0.77201	7.9847	16
18	57.7971	1.0160	8.4432	241.95	2453.0	241.96	2605.0	0.80354	7.9438	18
20	60.0569	1.0172	7.6481	251.40	2456.0	251.42	2608.9	0.83202	7.9073	20
25	64.9618	1.0199	6.2034	271.93	2462.4	271.96	2617.5	0.89319	7.8302	25
30	69.0942	1.0222	5.2287	289.24	2467.7	289.27	2624.6	0.94407	7.7675	30
40	75.8560	1.0264	3.9933	317.58	2476.3	317.63	2636.1	1.02607	7.6691	40
50	81.3163	1.0299	3.2403	340.49	2483.2	340.54	2645.2	1.09120	7.5931	50
60	85.9255	1.0331	2.7320	359.85	2489.0	359.91	2652.9	1.14545	7.5312	60
70	89.9314	1.0359	2.3650	376.68	2493.9	376.75	2659.4	1.19208	7.4791	70
80	93.4853	1.0385	2.0873	391.63	2498.2	391.71	2665.2	1.23305	7.4340	80
100	99.6059	1.0432	1.6941	417.40	2505.6	417.51	2675.0	1.30277	7.3589	100
101.325	99.9743	1.0434	1.6734	418.95	2506.00	419.06	2675.56	1.30693	7.35451	101.325
120	104.7837	1.0473	1.4285	439.24	2511.7	439.36	2683.1	1.36094	7.2978	120
140	109.2919	1.0510	1.2367	458.27	2516.9	458.42	2690.0	1.41101	7.2461	140
160	113.2977	1.0544	1.0915	475.21	2521.4	475.38	2696.1	1.45507	7.2015	160
180	116.9117	1.0576	0.97759	490.51	2525.5	490.70	2701.4	1.49448	7.1621	180
200	120.2106	1.0605	0.88578	504.50	2529.1	504.71	2706.3	1.53018	7.1270	200
250	127.4120	1.0672	0.71873	535.08	2536.8	535.35	2716.5	1.60724	7.0525	250
300	133.5230	1.0732	0.60582	561.11	2543.2	561.43	2724.9	1.67173	6.9917	300
350	138.8577	1.0786	0.52422	583.89	2548.5	584.26	2732.0	1.72738	6.9402	350
400	143.6089	1.0836	0.46242	604.22	2553.1	604.66	2738.1	1.77646	6.8955	400
500	151.8315	1.0925	0.37483	639.54	2560.7	640.09	2748.1	1.86039	6.8207	500
600	158.8268	1.1006	0.31560	669.72	2566.8	670.38	2756.2	1.93083	6.7593	600
700	164.9464	1.1080	0.27278	696.23	2571.8	697.00	2762.8	1.99178	6.7071	700
800	170.4066	1.1148	0.24035	719.97	2576.0	720.87	2768.3	2.04566	6.6616	800
900	175.3505	1.1212	0.21489	741.55	2579.6	742.56	2773.0	2.09405	6.6213	900

Appendix A (continued)

Table A.2 (continued) – Properties of saturated water and saturated vapour (pressure based)

Pressure P (kPa)	Temp. T (°C)	Specific volume (m^3/kg)		Specific internal energy (kJ/kg)		Specific enthalpy (kJ/kg)		Specific entropy (kJ/kg-K)		P (kPa)
		$10^3\, v_f$	v_g	u_f	u_g	h_f	h_g	s_f	s_g	
1000	179.88	1.1272	0.19437	761.39	2582.8	762.51	2777.1	2.1381	6.5850	1000
1100	184.06	1.1330	0.17745	779.78	2585.5	781.03	2780.7	2.1785	6.5520	1100
1200	187.96	1.1385	0.16326	796.96	2587.8	798.33	2783.8	2.2159	6.5217	1200
1300	191.60	1.1438	0.15119	813.10	2589.9	814.59	2786.5	2.2508	6.4936	1300
1400	195.04	1.1489	0.14078	828.35	2591.8	829.96	2788.9	2.2835	6.4675	1400
1500	198.29	1.1539	0.13171	842.82	2593.4	844.55	2791.0	2.3143	6.4430	1500
1600	201.37	1.1587	0.12374	856.59	2594.8	858.44	2792.8	2.3435	6.4200	1600
1700	204.31	1.1633	0.11668	869.75	2596.1	871.72	2794.5	2.3711	6.3982	1700
1800	207.11	1.1679	0.11037	882.35	2597.3	884.46	2795.9	2.3975	6.3775	1800
1900	209.80	1.1724	0.10471	894.46	2598.3	896.69	2797.2	2.4226	6.3578	1900
2000	212.38	1.1767	0.099587	906.12	2599.1	908.47	2798.3	2.4467	6.3390	2000
2200	217.25	1.1852	0.090701	928.24	2600.6	930.85	2800.1	2.4921	6.3038	2200
2400	221.79	1.1934	0.083247	948.97	2601.7	951.83	2801.4	2.5342	6.2712	2400
2600	226.05	1.2013	0.076901	968.51	2602.4	971.63	2802.4	2.5735	6.2409	2600
2800	230.06	1.2091	0.071432	987.02	2602.9	990.41	2802.9	2.6105	6.2124	2800
3000	233.85	1.2166	0.066667	1004.6	2603.2	1008.3	2803.2	2.6454	6.1856	3000
3250	238.33	1.2258	0.061508	1025.6	2603.2	1029.5	2803.1	2.6866	6.1541	3250
3500	242.56	1.2349	0.057061	1045.4	2603.0	1049.7	2802.7	2.7253	6.1244	3500
3750	246.55	1.2437	0.053186	1064.3	2602.5	1069.0	2801.9	2.7618	6.0963	3750
4000	250.35	1.2524	0.049779	1082.4	2601.7	1087.4	2800.8	2.7966	6.0696	4000
4500	257.44	1.2695	0.044061	1116.4	2599.7	1122.1	2798.0	2.8613	6.0198	4500
5000	263.94	1.2862	0.039448	1148.1	2597.0	1154.5	2794.2	2.9207	5.9737	5000
6000	275.59	1.3190	0.032449	1205.8	2589.9	1213.8	2784.6	3.0275	5.8902	6000
7000	285.83	1.3515	0.027378	1258.0	2581.0	1267.5	2772.6	3.1220	5.8148	7000
8000	295.01	1.3843	0.023525	1306.0	2570.5	1317.1	2758.7	3.2077	5.7450	8000
9000	303.35	1.4177	0.020489	1350.9	2558.5	1363.7	2742.9	3.2866	5.6791	9000
10,000	311.00	1.4522	0.018028	1393.3	2545.2	1407.9	2725.5	3.3603	5.6159	10,000
11,000	318.08	1.4881	0.015988	1433.9	2530.4	1450.2	2706.3	3.4299	5.5544	11,000
12,000	324.68	1.5260	0.014264	1473.0	2514.3	1491.3	2685.4	3.4964	5.4939	12,000
13,000	330.85	1.5663	0.012781	1511.1	2496.6	1531.4	2662.7	3.5606	5.4336	13,000
14,000	336.67	1.6097	0.011487	1548.4	2477.1	1571.0	2637.9	3.6232	5.3728	14,000
15,000	342.16	1.6572	0.010341	1585.5	2455.7	1610.3	2610.8	3.6848	5.3108	15,000
16,000	347.36	1.7100	0.009312	1622.6	2432.0	1649.9	2581.0	3.7461	5.2466	16,000
18,000	356.99	1.8402	0.007504	1699.1	2375.0	1732.2	2510.0	3.8720	5.1064	18,000
20,000	365.75	2.0378	0.005862	1785.8	2294.8	1826.6	2412.1	4.0146	4.9310	20,000
22,000	373.71	2.7031	0.003644	1951.7	2092.4	2011.1	2172.6	4.2942	4.5439	22,000
22,064	373.95	3.1056	0.003106	2015.7	2015.7	2084.3	2084.3	4.4067	4.4072	22,064

Appendix A (continued)

Table A.3 – Properties of superheated vapour (pressure from 10 kPa to 400 kPa)

P (kPa)		Temperature, *T* (°C)									
		50	100	150	200	300	400	500	600	800	1000
10	*v* (m^3/kg)	14.867	17.196	19.513	21.826	26.446	31.063	35.68	40.296	49.527	58.758
	u (kJ/kg)	2443.3	2515.5	2587.9	2661.4	2812.3	2969.3	3132.9	3303.3	3665.4	4055.3
	h (kJ/kg)	2592.0	2687.5	2783.0	2879.6	3076.7	3280.0	3489.7	3706.3	4160.6	4642.8
	s (kJ/kg-K)	8.1741	8.4489	8.6893	8.9049	9.2827	9.6094	9.8998	10.163	10.631	11.043
20	*v* (m^3/kg)		8.5855	9.7486	10.907	13.220	15.530	17.839	20.147	24.763	29.379
	u (kJ/kg)		2514.5	2587.4	2661.0	2812.1	2969.2	3132.8	3303.3	3665.3	4055.2
	h (kJ/kg)		2686.2	2782.3	2879.2	3076.5	3279.8	3489.6	3706.2	4160.6	4642.8
	s (kJ/kg-K)		8.1263	8.3681	8.5843	8.9625	9.2893	9.5798	9.8432	10.311	10.723
40	*v* (m^3/kg)		4.2799	4.8662	5.448	6.6067	7.7628	8.9179	10.073	12.381	14.689
	u (kJ/kg)		2512.5	2586.3	2660.3	2811.7	2969.0	3132.7	3303.2	3665.3	4055.2
	h (kJ/kg)		2683.7	2780.9	2878.2	3076.0	3279.5	3489.4	3706.1	4160.5	4642.7
	s (kJ/kg-K)		7.8011	8.0456	8.2629	8.642.0	8.9691	9.2597	9.5231	9.9913	10.403
60	*v* (m^3/kg)		2.8445	3.2387	3.6283	4.4023	5.1739	5.9444	6.7144	8.2538	9.7927
	u (kJ/kg)		2510.5	2585.2	2659.6	2811.4	2968.8	3132.5	3303.0	3665.2	4055.1
	h (kJ/kg)		2681.1	2779.5	2877.3	3075.5	3279.2	3489.2	3705.9	4160.4	4642.7
	s (kJ/kg-K)		7.6084	7.8559	8.0743	8.4542	8.7816	9.0723	9.3359	9.8041	10.216
80	*v* (m^3/kg)		2.1267	2.4250	2.7184	3.3002	3.8794	4.4576	5.0353	6.1901	7.3444
	u (kJ/kg)		2508.4	2584.1	2658.9	2811.0	2968.5	3132.4	3302.9	3665.1	4055.1
	h (kJ/kg)		2678.5	2778.1	2876.4	3075.0	3278.9	3489.0	3705.7	4160.3	4642.6
	s (kJ/kg-K)		7.4699	7.7204	7.9401	8.3208	8.6485	8.9394	9.2030	9.6712	10.083
100	*v* (m^3/kg)		1.6959	1.9367	2.1724	2.6389	3.1027	3.5655	4.0279	4.9519	5.8755
	u (kJ/kg)		2506.2	2582.9	2658.2	2810.7	2968.3	3132.2	3302.8	3665.0	4055.0
	h (kJ/kg)		2675.8	2776.6	2875.5	3074.5	3278.6	3488.7	3705.6	4160.2	4642.6
	s (kJ/kg-K)		7.3611	7.6148	7.8356	8.2172	8.5452	8.8362	9.0999	9.5682	9.9800
200	*v* (m^3/kg)			0.9599	1.0805	1.3162	1.5493	1.7814	2.0130	2.4755	2.9375
	u (kJ/kg)			2577.1	2654.6	2808.8	2967.2	3131.4	3302.2	3664.7	4054.8
	h (kJ/kg)			2769.1	2870.7	3072.1	3277.0	3487.7	3704.8	4159.8	4642.3
	s (kJ/kg-K)			7.2810	7.5081	7.8941	8.2236	8.5153	8.7793	9.2479	9.6599
300	*v* (m^3/kg)			0.6340	0.7164	0.8753	1.0315	1.1867	1.3414	1.6500	1.9582
	u (kJ/kg)			2571.0	2651.0	2807.0	2966.0	3130.6	3301.6	3664.3	4054.5
	h (kJ/kg)			2761.2	2865.9	3069.6	3275.5	3486.6	3704.0	4159.3	4642.0
	s (kJ/kg-K)			7.0792	7.3132	7.7037	8.0347	8.3271	8.5915	9.0605	9.4726
400	*v* (m^3/kg)			0.4709	0.5343	0.6549	0.7726	0.8894	1.0056	1.2373	1.4686
	u (kJ/kg)			2564.4	2647.2	2805.1	2964.9	3129.8	3301.0	3663.9	4054.3
	h (kJ/kg)			2752.8	2860.9	3067.1	3273.9	3485.5	3703.3	4158.9	4641.7
	s (kJ/kg-K)			6.9306	7.1723	7.5677	7.9003	8.1933	8.4580	8.9274	9.3396
P (kPa)		50	100	150	200	300	400	500	600	800	1000
		Temperature, *T* (°C)									

Appendix A (continued)

Table A.3 (continued) – Properties of superheated vapour (pressure from 500 kPa to 1.6 MPa)

P		Temperature, T (°C)									
(kPa)		200	250	300	400	500	600	700	800	900	1000
500	v (m^3/kg)	0.4250	0.4744	0.5226	0.6173	0.7109	0.8041	0.897	0.9897	1.0823	1.1748
	u (kJ/kg)	2643.3	2723.8	2803.3	2963.7	3129.0	3300.4	3478.6	3663.6	3855.4	4054.0
	h (kJ/kg)	2855.8	2961.0	3064.6	3272.4	3484.5	3702.5	3927.0	4158.4	4396.6	4641.4
	s (kJ/kg-K)	7.0610	7.2725	7.4614	7.7956	8.0893	8.3544	8.5978	8.8240	9.0362	9.2364
600	v (m^3/kg)	0.3521	0.3939	0.4344	0.5137	0.5920	0.6698	0.7472	0.8246	0.9018	0.9789
	u (kJ/kg)	2639.4	2721.2	2801.4	2962.5	3128.2	3299.8	3478.1	3663.2	3855.1	4053.8
	h (kJ/kg)	2850.6	2957.6	3062.0	3270.8	3483.4	3701.7	3926.4	4157.9	4396.2	4641.1
	s (kJ/kg-K)	6.9683	7.1833	7.3740	7.7097	8.0041	8.2695	8.5132	8.7395	8.9518	9.1521
700	v (m^3/kg)	0.3000	0.3364	0.3714	0.4398	0.5070	0.5738	0.6403	0.7066	0.7729	0.8390
	u (kJ/kg)	2635.3	2718.6	2799.5	2961.4	3127.4	3299.3	3477.6	3662.8	3854.8	4053.5
	h (kJ/kg)	2845.3	2954.0	3059.5	3269.2	3482.3	3700.9	3925.9	4157.5	4395.9	4640.8
	s (kJ/kg-K)	6.8884	7.1070	7.2995	7.6368	7.9319	8.1977	8.4415	8.6681	8.8804	9.0807
800	v (m^3/kg)	0.2609	0.2932	0.3242	0.3843	0.4433	0.5019	0.5601	0.6182	0.6762	0.7341
	u (kJ/kg)	2631.1	2715.9	2797.5	2960.2	3126.6	3298.7	3477.2	3662.5	3854.5	4053.3
	h (kJ/kg)	2839.8	2950.4	3056.9	3267.7	3481.3	3700.1	3925.3	4157.0	4395.5	4640.5
	s (kJ/kg-K)	6.8177	7.0402	7.2345	7.5735	7.8692	8.1354	8.3794	8.6061	8.8185	9.0189
900	v (m^3/kg)	0.2304	0.2596	0.2874	0.3411	0.3938	0.4459	0.4977	0.5494	0.6010	0.6525
	u (kJ/kg)	2626.7	2713.2	2795.6	2959.1	3125.8	3298.1	3476.7	3662.1	3854.2	4053.0
	h (kJ/kg)	2834.1	2946.8	3054.3	3266.1	3480.2	3699.4	3924.7	4156.6	4395.1	4640.3
	s (kJ/kg-K)	6.7539	6.9805	7.1767	7.5173	7.8138	8.0804	8.3246	8.5514	8.7639	8.9644
1000	v (m^3/kg)	0.2060	0.2327	0.2580	0.3066	0.3541	0.4011	0.4478	0.4944	0.5408	0.5872
	u (kJ/kg)	2622.3	2710.4	2793.7	2957.9	3125.0	3297.5	3476.3	3661.7	3853.9	4052.7
	h (kJ/kg)	2828.3	2943.1	3051.6	3264.5	3479.1	3698.6	3924.1	4156.1	4394.8	4640.0
	s (kJ/kg-K)	6.6956	6.9265	7.1246	7.4670	7.7642	8.0311	8.2755	8.5024	8.7150	8.9155
1200	v (m^3/kg)	0.1693	0.1924	0.2139	0.2548	0.2946	0.3339	0.3730	0.4118	0.4506	0.4893
	u (kJ/kg)	2612.9	2704.7	2789.7	2955.5	3123.4	3296.3	3475.3	3661.0	3853.3	4052.2
	h (kJ/kg)	2816.1	2935.6	3046.3	3261.3	3477.0	3697.0	3922.9	4155.2	4394.0	4639.4
	s (kJ/kg-K)	6.5909	6.8313	7.0335	7.3793	7.6779	7.9456	8.1904	8.4176	8.6303	8.8310
1400	v (m^3/kg)	0.1430	0.1636	0.1823	0.2178	0.2522	0.2860	0.3195	0.3529	0.3861	0.4193
	u (kJ/kg)	2602.7	2698.9	2785.7	2953.1	3121.8	3295.1	3474.4	3660.3	3852.7	4051.7
	h (kJ/kg)	2803.0	2927.9	3040.9	3258.1	3474.8	3695.5	3921.7	4154.3	4393.3	4638.8
	s (kJ/kg-K)	6.4975	6.7488	6.9553	7.3046	7.6047	7.8730	8.1183	8.3458	8.5587	8.7595
1600	v (m^3/kg)		0.1419	0.1587	0.1901	0.2203	0.2500	0.2794	0.3087	0.3378	0.3669
	u (kJ/kg)		2692.9	2781.6	2950.8	3120.1	3293.9	3473.5	3659.5	3852.1	4051.2
	h (kJ/kg)		2919.9	3035.4	3254.9	3472.6	3693.9	3920.5	4153.4	4392.6	4638.2
	s (kJ/kg-K)		6.6753	6.8864	7.2394	7.5410	7.8101	8.0558	8.2834	8.4965	8.6974
P		200	250	300	400	500	600	700	800	900	1000
(kPa)		Temperature, T (°C)									

Appendix A (continued)

Table A.3 (continued) – Properties of superheated vapour (pressure from 1.8 MPa to 9 MPa)

P		Temperature, *T* (°C)									
(kPa)		250	300	350	400	500	600	700	800	900	1000
1800	*v* (m^3/kg)	0.1250	0.1402	0.1546	0.1685	0.1955	0.2220	0.2482	0.2743	0.3002	0.3261
	u (kJ/kg)	2686.7	2777.4	2863.6	2948.3	3118.5	3292.7	3472.6	3658.8	3851.5	4050.7
	h (kJ/kg)	2911.7	3029.9	3141.9	3251.6	3470.4	3692.3	3919.4	4152.4	4391.9	4637.6
	s (kJ/kg-K)	6.6088	6.8246	7.0120	7.1814	7.4845	7.7543	8.0005	8.2284	8.4417	8.6427
2000	*v* (m^3/kg)	0.1115	0.1255	0.1386	0.1512	0.1757	0.1996	0.2233	0.2467	0.2701	0.2934
	u (kJ/kg)	2680.3	2773.2	2860.5	2945.9	3116.9	3291.5	3471.7	3658.0	3850.9	4050.2
	h (kJ/kg)	2903.3	3024.2	3137.7	3248.4	3468.3	3690.7	3918.2	4151.5	4391.1	4637.1
	s (kJ/kg-K)	6.5475	6.7684	6.9583	7.1292	7.4337	7.7043	7.9509	8.1791	8.3925	8.5936
3000	*v* (m^3/kg)	0.07063	0.08118	0.09056	0.09938	0.1162	0.1325	0.1484	0.1642	0.1799	0.1955
	u (kJ/kg)	2644.7	2750.8	2844.4	2933.6	3108.6	3285.5	3467.0	3654.3	3847.9	4047.7
	h (kJ/kg)	2856.5	2994.3	3116.1	3231.7	3457.2	3682.8	3912.2	4146.9	4387.5	4634.2
	s (kJ/kg-K)	6.2893	6.5412	6.7450	6.9235	7.2359	7.5103	7.759	7.9885	8.2028	8.4045
4000	*v* (m^3/kg)		0.05887	0.06647	0.07343	0.08644	0.09886	0.1110	0.1229	0.1348	0.1465
	u (kJ/kg)		2726.2	2827.4	2920.8	3100.3	3279.4	3462.4	3650.6	3844.8	4045.1
	h (kJ/kg)		2961.7	3093.3	3214.5	3446	3674.9	3906.3	4142.3	4383.9	4631.2
	s (kJ/kg-K)		6.3639	6.5843	6.7714	7.0922	7.3706	7.6214	7.8523	8.0675	8.2698
5000	*v* (m^3/kg)		0.04535	0.05197	0.05784	0.06858	0.07870	0.08852	0.09816	0.1077	0.1172
	u (kJ/kg)		2699.0	2809.5	2907.5	3091.8	3273.3	3457.7	3646.9	3841.8	4042.6
	h (kJ/kg)		2925.7	3069.3	3196.7	3434.7	3666.9	3900.3	4137.7	4380.2	4628.3
	s (kJ/kg-K)		6.2111	6.4516	6.6483	6.9781	7.2605	7.5136	7.7458	7.9619	8.1648
6000	*v* (m^3/kg)		0.03619	0.04225	0.04742	0.05667	0.06527	0.07355	0.08165	0.08964	0.09756
	u (kJ/kg)		2668.4	2790.4	2893.7	3083.1	3267.2	3453.0	3643.2	3838.8	4040.1
	h (kJ/kg)		2885.6	3043.9	3178.3	3423.1	3658.8	3894.3	4133.1	4376.6	4625.4
	s (kJ/kg-K)		6.0703	6.3357	6.5432	6.8826	7.1693	7.4247	7.6582	7.8751	8.0786
7000	*v* (m^3/kg)		0.02949	0.03526	0.03996	0.04816	0.05567	0.06285	0.06986	0.07675	0.08357
	u (kJ/kg)		2633.5	2770.1	2879.5	3074.3	3261.0	3448.3	3639.5	3835.7	4037.5
	h (kJ/kg)		2839.9	3016.9	3159.2	3411.4	3650.6	3888.3	4128.5	4373.0	4622.5
	s (kJ/kg-K)		5.9337	6.2305	6.4502	6.8000	7.0910	7.3487	7.5836	7.8014	8.0055
8000	*v* (m^3/kg)		0.02428	0.02997	0.03434	0.04177	0.04846	0.05483	0.06101	0.06708	0.07308
	u (kJ/kg)		2592.3	2748.3	2864.6	3065.4	3254.7	3443.6	3635.7	3832.7	4035.0
	h (kJ/kg)		2786.5	2988.1	3139.4	3399.5	3642.4	3882.2	4123.8	4369.3	4619.6
	s (kJ/kg-K)		5.7937	6.1321	6.3658	6.7266	7.0221	7.2822	7.5185	7.7372	7.9419
9000	*v* (m^3/kg)			0.02582	0.02996	0.03679	0.04286	0.04859	0.05413	0.05956	0.06492
	u (kJ/kg)			2725.0	2849.2	3056.3	3248.4	3438.8	3632.0	3829.6	4032.4
	h (kJ/kg)			2957.3	3118.8	3387.4	3634.1	3876.1	4119.2	4365.7	4616.7
	s (kJ/kg-K)			6.038	6.2876	6.6603	6.9605	7.2229	7.4606	7.6802	7.8855
P		250	300	350	400	500	600	700	800	900	1000
(kPa)		Temperature, *T* (°C)									

Appendix A (continued)

Table A.3 (continued) – Properties of superheated vapour (pressure from 10 MPa to 26 MPa)

P (kPa)		Temperature, *T* (°C)									
		350	400	500	600	700	800	900	1000	1100	1200
10,000	*v* (m^3/kg)	0.02244	0.02644	0.03281	0.03838	0.04360	0.04863	0.05355	0.05839	0.06318	0.06794
	u (kJ/kg)	2699.6	2833.1	3047.0	3242.0	3434.0	3628.2	3826.5	4029.9	4238.5	4452.4
	h (kJ/kg)	2924.0	3097.5	3375.1	3625.8	3870.0	4114.5	4362.0	4613.8	4870.3	5131.7
	s (kJ/kg-K)	5.946	6.2141	6.5995	6.9045	7.1693	7.4085	7.6290	7.8349	8.0289	8.2126
12,000	*v* (m^3/kg)	0.01722	0.02111	0.02683	0.03165	0.03611	0.04037	0.04452	0.0486	0.05262	0.05661
	u (kJ/kg)	2641.4	2798.7	3028.1	3229.1	3424.4	3620.7	3820.4	4024.8	4234.2	4448.7
	h (kJ/kg)	2848.1	3052.0	3350.0	3608.9	3857.7	4105.1	4354.7	4608.0	4865.6	5128.0
	s (kJ/kg-K)	5.7609	6.0764	6.4903	6.8054	7.0753	7.3173	7.5396	7.7468	7.9416	8.126
14,000	*v* (m^3/kg)	0.01323	0.01724	0.02254	0.02684	0.03076	0.03448	0.03808	0.04161	0.04508	0.04852
	u (kJ/kg)	2567.8	2761.0	3008.4	3216.0	3414.7	3613.1	3814.3	4019.7	4229.9	4444.9
	h (kJ/kg)	2753.1	3002.3	3324.1	3591.8	3845.4	4095.8	4347.4	4602.1	4861.0	5124.2
	s (kJ/kg-K)	5.5598	5.9460	6.3932	6.7191	6.9941	7.2391	7.4632	7.6716	7.8673	8.0523
16,000	*v* (m^3/kg)	0.009766	0.01428	0.01932	0.02324	0.02675	0.03006	0.03325	0.03636	0.03942	0.04245
	u (kJ/kg)	2460.7	2719.1	2988.1	3202.6	3404.9	3605.4	3808.1	4014.6	4225.5	4441.2
	h (kJ/kg)	2617.0	2947.6	3297.3	3574.4	3832.9	4086.4	4340.1	4596.3	4856.3	5120.4
	s (kJ/kg-K)	5.3045	5.8180	6.3046	6.6421	6.9224	7.1704	7.3964	7.6060	7.8025	7.9882
18,000	*v* (m^3/kg)		0.01192	0.01681	0.02043	0.02363	0.02662	0.02949	0.03228	0.03502	0.03773
	u (kJ/kg)		2671.9	2967.1	3189.1	3395.1	3597.8	3801.9	4009.4	4221.2	4437.5
	h (kJ/kg)		2886.4	3269.7	3556.8	3820.4	4076.9	4332.7	4590.5	4851.6	5116.6
	s (kJ/kg-K)		5.6883	6.2223	6.5721	6.8579	7.1089	7.3368	7.5476	7.7451	7.9313
20,000	*v* (m^3/kg)		0.009950	0.01479	0.01819	0.02113	0.02387	0.02648	0.02902	0.03150	0.03396
	u (kJ/kg)		2617.9	2945.3	3175.3	3385.1	3590.1	3795.7	4004.3	4216.9	4433.8
	h (kJ/kg)		2816.9	3241.2	3539.0	3807.8	4067.5	4325.4	4584.7	4847.0	5112.9
	s (kJ/kg-K)		5.5526	6.1446	6.5075	6.7991	7.0531	7.2829	7.4950	7.6933	7.8802
22,000	*v* (m^3/kg)		0.008256	0.01314	0.01635	0.01909	0.02162	0.02403	0.02635	0.02863	0.03086
	u (kJ/kg)		2554.2	2922.7	3161.4	3375.1	3582.4	3789.5	3999.2	4212.5	4430.1
	h (kJ/kg)		2735.8	3211.8	3521.0	3795.1	4058.0	4318.1	4578.9	4842.3	5109.1
	s (kJ/kg-K)		5.4051	6.0705	6.4474	6.7448	7.0020	7.2337	7.4470	7.6462	7.8337
24,000	*v* (m^3/kg)		0.006732	0.01175	0.01481	0.01739	0.01975	0.02198	0.02413	0.02623	0.02829
	u (kJ/kg)		2475.9	2899.4	3147.2	3365.0	3574.6	3783.3	3994.0	4208.2	4426.4
	h (kJ/kg)		2637.5	3181.4	3502.7	3782.4	4048.5	4310.7	4573.1	4837.7	5105.4
	s (kJ/kg-K)		5.2369	5.9991	6.3908	6.6943	6.9546	7.1883	7.4029	7.6029	7.7911
26,000	*v* (m^3/kg)		0.005285	0.01058	0.01352	0.01595	0.01816	0.02024	0.02225	0.02420	0.02611
	u (kJ/kg)		2373	2875.1	3132.8	3354.8	3566.8	3777.1	3988.9	4203.9	4422.7
	h (kJ/kg)		2510.4	3150.2	3484.3	3769.6	4039	4303.4	4567.3	4833.1	5101.6
	s (kJ/kg-K)		5.0302	5.9298	6.3373	6.6469	6.9105	7.1461	7.362	7.5629	7.7517
P (kPa)		350	400	500	600	700	800	900	1000	1100	1200
		Temperature, *T* (°C)									

Appendix A (continued)

Table A.4 – Properties of compressed liquid

P (MPa)		Temperature, *T* (°C)									
		0	20	40	60	80	100	120	140	160	180
5	10^3 *v* (m^3/kg)	0.9977	0.9996	1.0057	1.0149	1.0267	1.0410	1.0576	1.0769	1.0988	1.1240
	u (kJ/kg)	0.0441	83.609	166.92	250.29	333.82	417.65	501.91	586.80	672.55	759.47
	h (kJ/kg)	5.030	88.610	171.95	255.36	338.96	422.85	507.19	592.18	678.04	765.09
	s (kJ/kg-K)	0.00014	0.29543	0.57046	0.82865	1.0723	1.3034	1.5236	1.7344	1.9374	2.1338
10	10^3 *v* (m^3/kg)	0.9952	0.9973	1.0035	1.0127	1.0244	1.0385	1.0549	1.0738	1.0954	1.1200
	u (kJ/kg)	0.1171	83.308	166.33	249.43	332.69	416.23	500.18	584.72	670.06	756.48
	h (kJ/kg)	10.069	93.281	176.37	259.55	342.94	426.62	510.73	595.45	681.01	767.68
	s (kJ/kg-K)	0.00034	0.29435	0.56852	0.82602	1.0691	1.2996	1.5191	1.7293	1.9316	2.1272
20	10^3 *v* (m^3/kg)	0.9904	0.9929	0.9992	1.0084	1.0199	1.0337	1.0496	1.0679	1.0886	1.1122
	u (kJ/kg)	0.2257	82.708	165.17	247.75	330.50	413.50	496.85	580.71	665.28	750.78
	h (kJ/kg)	20.033	102.57	185.16	267.92	350.90	434.17	517.84	602.07	687.05	773.02
	s (kJ/kg-K)	0.00047	0.29208	0.56461	0.8208	1.0627	1.2920	1.5105	1.7194	1.9203	2.1143
40	10^3 *v* (m^3/kg)	0.9811	0.9845	0.9911	1.0001	1.0113	1.0245	1.0397	1.0569	1.0762	1.0980
	u (kJ/kg)	0.3078	81.520	162.96	244.58	326.37	408.36	490.61	573.26	656.43	740.32
	h (kJ/kg)	39.553	120.90	202.60	284.59	366.82	449.34	532.20	615.53	699.48	784.24
	s (kJ/kg-K)	-0.00024	0.28716	0.55676	0.81054	1.0503	1.2775	1.4938	1.7006	1.8990	2.0903
60	10^3 *v* (m^3/kg)	0.9725	0.9765	0.9833	0.9923	1.0032	1.0159	1.0304	1.0467	1.0649	1.0852
	u (kJ/kg)	0.2357	80.345	160.86	241.62	322.54	403.61	484.88	566.44	648.40	730.90
	h (kJ/kg)	58.584	138.94	219.87	301.16	382.73	464.56	546.70	629.24	712.30	796.01
	s (kJ/kg-K)	-0.00208	0.2818	0.54885	0.80049	1.0383	1.2637	1.4781	1.6829	1.8792	2.0681
80	10^3 *v* (m^3/kg)	0.9643	0.9690	0.9760	0.9849	0.9956	1.0078	1.0217	1.0372	1.0545	1.0735
	u (kJ/kg)	0.03710	79.182	158.88	238.85	318.96	399.20	479.57	560.16	641.05	722.35
	h (kJ/kg)	77.184	156.70	236.96	317.64	398.61	479.83	561.31	643.14	725.41	808.23
	s (kJ/kg-K)	-0.00489	0.27604	0.54087	0.79062	1.0266	1.2503	1.4631	1.6661	1.8605	2.0474
100	10^3 *v* (m^3/kg)	0.9567	0.9619	0.9691	0.9779	0.9883	1.0002	1.0136	1.0284	1.0448	1.0628
	u (kJ/kg)	-0.2637	78.031	156.99	236.24	315.62	395.09	474.65	554.36	634.29	714.52
	h (kJ/kg)	95.40	174.22	253.90	334.03	414.46	495.11	576.01	657.20	738.77	820.80
	s (kJ/kg-K)	-0.00851	0.26992	0.53284	0.7809	1.0153	1.2375	1.4487	1.6501	1.8429	2.0280
P (MPa)		0	20	40	60	80	100	150	200	250	300
		Temperature, *T* (°C)									

Appendix B. Pressure units

Table B.1 – Pressure unites conversion table

	atm	ata (kg/cm^2)	Torr (mm Hg)	in Hg (32°F)	mm water (4℃)	in water (60°F)	bar	MPa	kPa	PSI (lb/in)
atm	1	1.033	760	29.92	10332.56	406.79	1.013	0.1013	101.32	14.69
ata (kg/cm^2)	0.968	1	735.56	28.96	10000.03	393.71	0.981	0.0981	98.07	14.22
Torr (mm Hg)	$1.316x10^{-3}$	$1.36\ x10^{-3}$	1	0.03937	13.60	0.535	$1.333x10^{-3}$	$1.333x10^{-4}$	0.1333	0.0194
in Hg (32°F)	0.03342	0.0345	25.4	1	345.40	13.60	0.03386	$3.387x10^{-3}$	3.387	0.491
mm water (4℃)	$9.67x10^{-5}$	$9.99x10^{-5}$	0.0736	$2.895x10^{-3}$	1	$2.904x10^{-3}$	$9.81x10^{-5}$	$9.81x10^{-6}$	$9.81x10^{-3}$	$1.422x10^{-3}$
in water (60°F)	$2.456x10^{-3}$	$2.54x10^{-3}$	1.866	0.0736	25.4	1	$2.49x10^{-3}$	$2.49x10^{-4}$	0.249	0.03613
bar	0.9872	1.02	750.06	29.53	10197.44	401.47	1	0.1	100	14.50
MPa	9.872	10.20	7500	295.3	101974.42	4018.60	10	1	1000	145
kPa	$9.87x10^{-3}$	0.01	7.50	0.2953	101.97	4.018	0.01	0.001	1	0.145
PSI (lb/in)	0.068	0.070	51.71	2.036	703.09	27.71	0.0689	$6.893x10^{-3}$	6.893	1

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