ENG 3165 LECTURE 10

THERMODYNAMICS COMPONENT

Steam and Two Phase Systems

Introduction

- ❑In this lecture advances water as a thermodynamic working fluid.
- ❑As a working fluid, water is sometimes in liquid phase and some times in vapor phase.
- ❑The various phase transformations and states of water are discussed

GENERAL INTRODUCTION

- Matter can take the forms, solid, liquid, vapour or gas
- Each change from one form to another is called a change of phase, and is accomplished by either the addition or extraction of heat.
- A change of volume accompanies a change of phase. Generally, the change of volume which accompanies a change from solid to liquid is not very great. On the other hand, the change of volume during the change from liquid to vapour or gaseous phase can be very large.
- the ability of a fluid to readily expand or contract is the requisite feature for successful operation of a thermodynamic engine. Thus both vapours and gases can be used in thermodynamic engines. The technique used for vapours, however, is different from that used with gases.

GENERAL INTRODUCTION

- A vapour results from a change of phase of a liquid due to a transfer of heat, The bulk of the liquid is, in general, very much smaller than the bulk of the vapour formed.
- A liquid that can easily be obtained and handled can be used as the generator of the vaporous working substance for use in an engine.
- Water is such a liquid. It is in abundant supply, can be easily handled and turned into its vaporous phase called steam.

THE FORMATION OF STEAM

- It will be assumed that the water and ultimately the steam are in a suitable container called a boiler.
- Now steam is usually formed at constant pressure and hence our focus will be on this constant pressure formation of steam.
- If a mass of water is heated then, its temperature increases. There will also be a small increase in volume.
- Further heating produces further temperature rise but and soon bubbles are formed on and near the heating surface, they rise a little through the water and collapse. These are steam bubbles being formed. These steam bubbles rise as a result of their lower density.

THE FORMATION OF STEAM

- The temperature still continues to rise with the transfer of heat and, with the increase, the bubble activity increases.
- Finally, the water mass is at such a temperature that the steam bubbles are able to completely rise through the water and the steam escapes from the water surface. The water mass is in an extremely turbulent state now, and this turbulent state of steam formation is called **boiling**
- At the onset of boiling, the temperature ceased to rise, remaining at what is commonly called the **boiling point**.
- While boiling continues, the temperature will remain constant independent of the quantity of heat transferred to the water. In fact, it appears that, so long as there is water present, then it is impossible to increase the temperature beyond the boiling point. This is called **saturation temperature.**

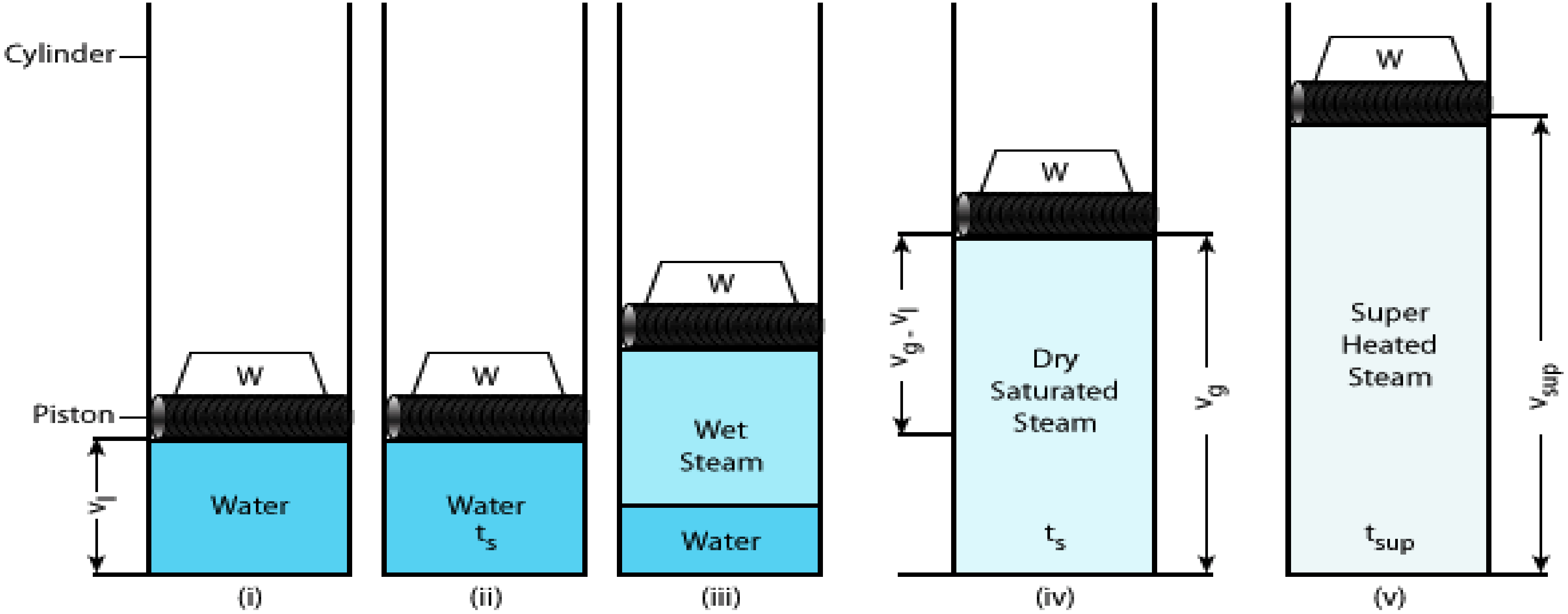
THE FORMATION OF STEAM

- As the steam breaks away from the water surface it will carry with it small droplets of water. The larger droplets will gravitate back to the water surface, but the smaller ones will continue on their way with the steam. Steam with these small droplets of water in suspension is called **wet steam.**
- it is the water droplets in suspension which makes wet steam visible. Steam is a transparent vapour but the inclusion of water droplets in suspension gives it the white cloudy appearance.

THE FORMATION OF STEAM

- Further transfer of heat to the wet steam will convert the suspended water droplets into steam and finally a state will be reached when all the water has been turned into steam. The steam is then called **dry saturated steam**. The steam has now lost its visible characteristic, having now become completely transparent and, also, this condition marks the end of the constant temperature intermediate phase.
- Further transfer of heat to the now dry saturated steam produces a temperature rise and the steam now becomes what is known as **superheated steam**. This is the last phase in the transformation of water into steam.

THE FORMATION OF STEAM



t_s = Boiling point

t_{sup} = Temperature of superheated steam

v_l = Volume of water

v_g = Volume of dry & saturated steam

v_{sup} = Volume of superheated steam

STAGES IN THE PRODUCTION OF STEAM

- **Stage 1:** This is the warming phase in which the temperature of the water increases up to saturation temperature. The energy required to produce this temperature rise is called the **liquid enthalpy**.
- **Stage 2**: This takes place at constant temperature (saturation temperature) and is the stage during which the transformation from water into steam takes place. It is punctuated by being all water at saturation temperature at the beginning and all dry saturated steam at saturation temperature at the end. Between these two extremes, the steam formed will always be wet steam. The energy required to produce the total change from all water into all steam is called the **enthalpy of evaporation**

STAGES IN THE PRODUCTION OF STEAM

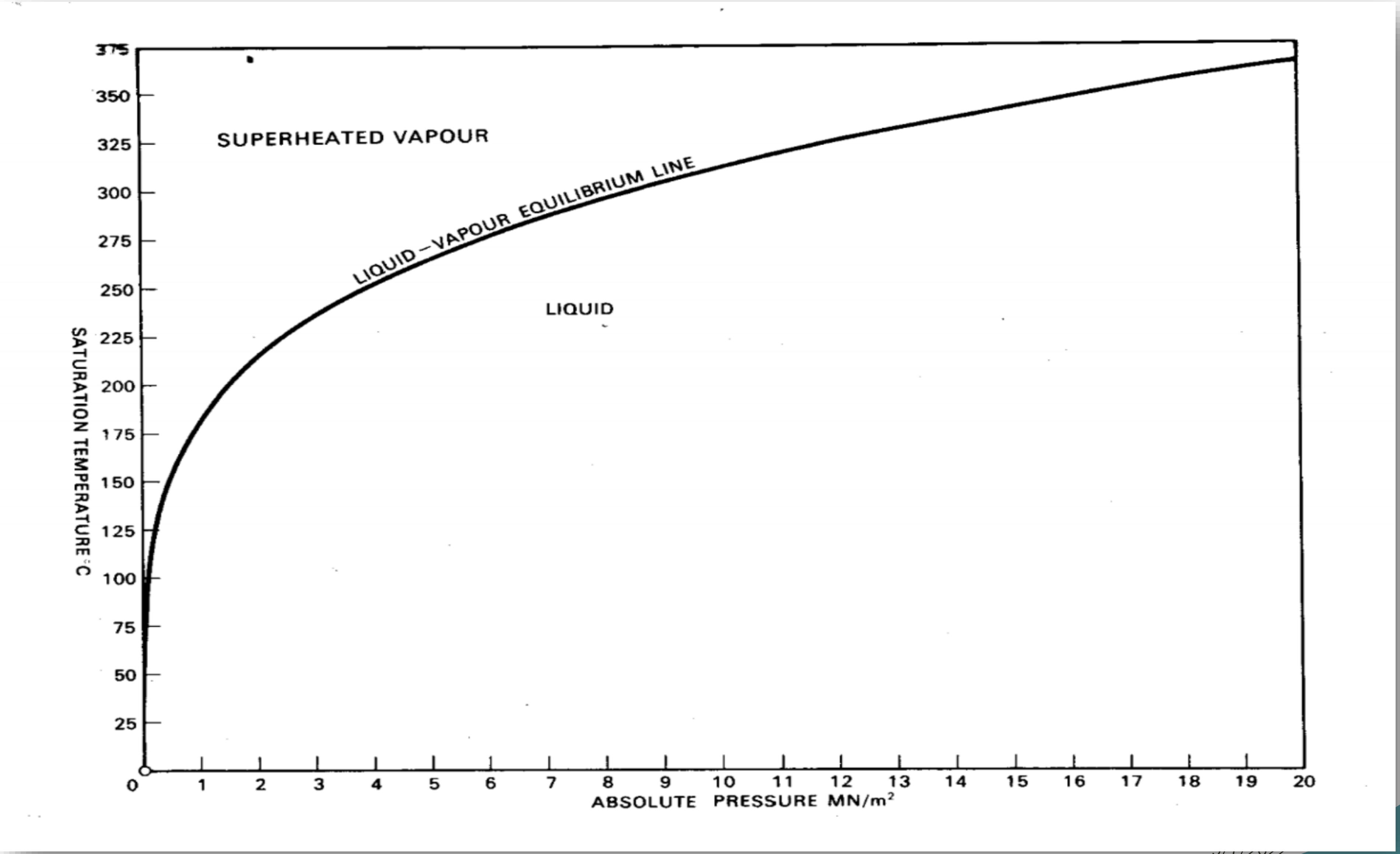
- **Stage 3**: This phase begins when all dry saturated steam has been formed at saturation temperature. Further transfer of heat produces superheated steam which is accompanied by a rise in temperature. The amount of energy added in the superheat phase is called the **superheat enthalpy**.

- The phenomenon of temperature change only occurs in a single phase, be it solid, liquid or vapour, and happens with all substances. If a two-phase mixture exists (solid-liquid or liquid-vapour) then the temperature remains constant until a complete change from one phase to another has been completed.

SATURATION TEMPERATURE AND PRESSURE

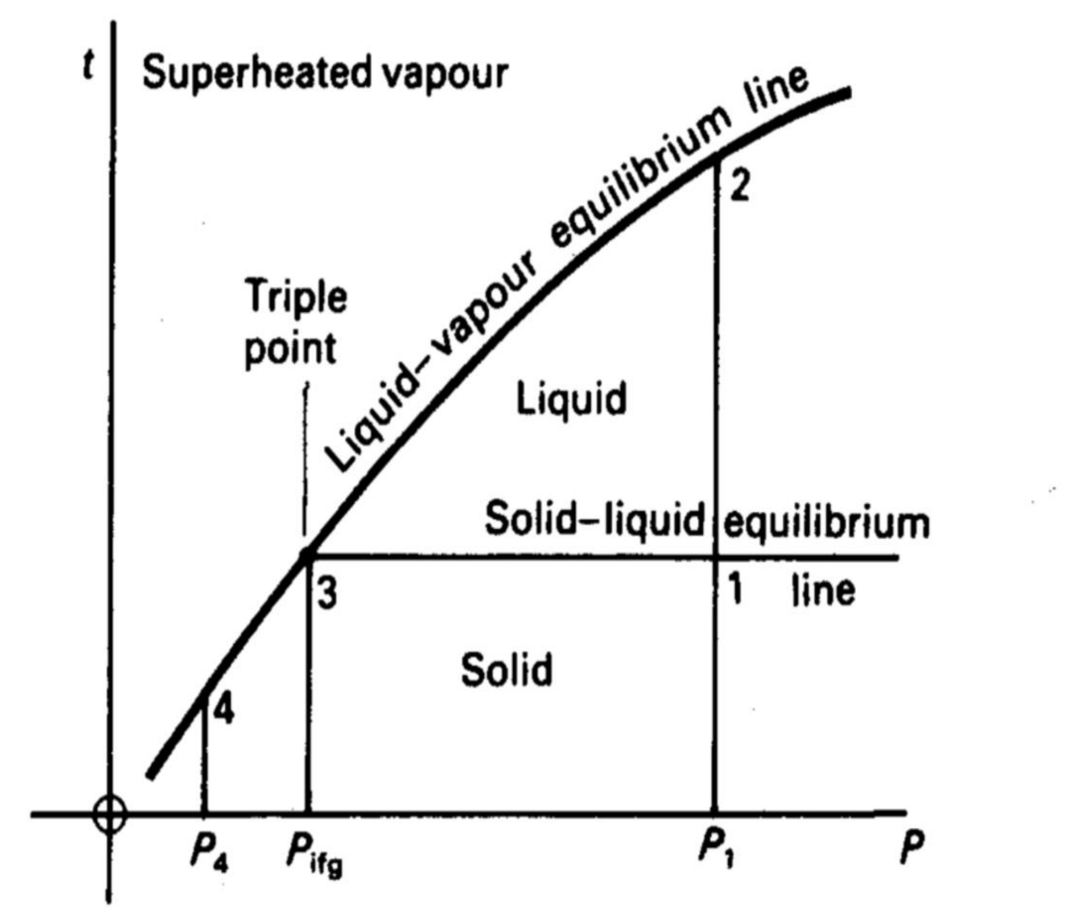
- Steam is usually produced at **constant pressure**.
- Boiling will occur at saturation temperature and it is found that saturation temperature depends upon the pressure exerted at the surface of the water, or, in other words it depends upon the pressure at which the steam is being formed.
- It will then be noted that boiling point of water at 100°C is only the case for atmospheric pressure, 760 mmHg.
- Actually, if this pressure is increased then the boiling point or saturation temperature, as it is called, increases. Conversely, if the pressure decreases then so also does the saturation temperature.

LIQUID-VAPOUR EQUILIBRIUM LINE



THE TRIPLE POINT

- If an enlarged plot at the lower temperature and pressure end of the liquid-vapour equilibrium line is made the graph will have the appearance as shown.
- A further line has been introduced, this being the line dividing the solid and liquid and is the solid-liquid equilibrium line. The two lines join at point 3, **the-triple point.**
- The solid-liquid equilibrium line has been shown having a horizontal nature indicating that there is little change in the solid-liquid (melting) point as a result of change in pressure



ENTHALPY AND THE FORMATION OF STEAM AT CONSTANT PRESSURE

- Consider unit mass of a substance and let heat energy *Q* be transferred at constant pressure *P* thus changing the state of the substance from specific internal energy u_1, and specific volume v_1 to specific internal energy u_2, and specific volume v_2 . By the non-flow energy equation:

$$\boldsymbol{Q = \Delta u + W} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

For this case,

$$\boldsymbol{Q = (u_2 - u_1) + P(v_2 - v_1)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$\boldsymbol{Q = (u_2 + Pv_2) - (u_1 + Pv_1)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

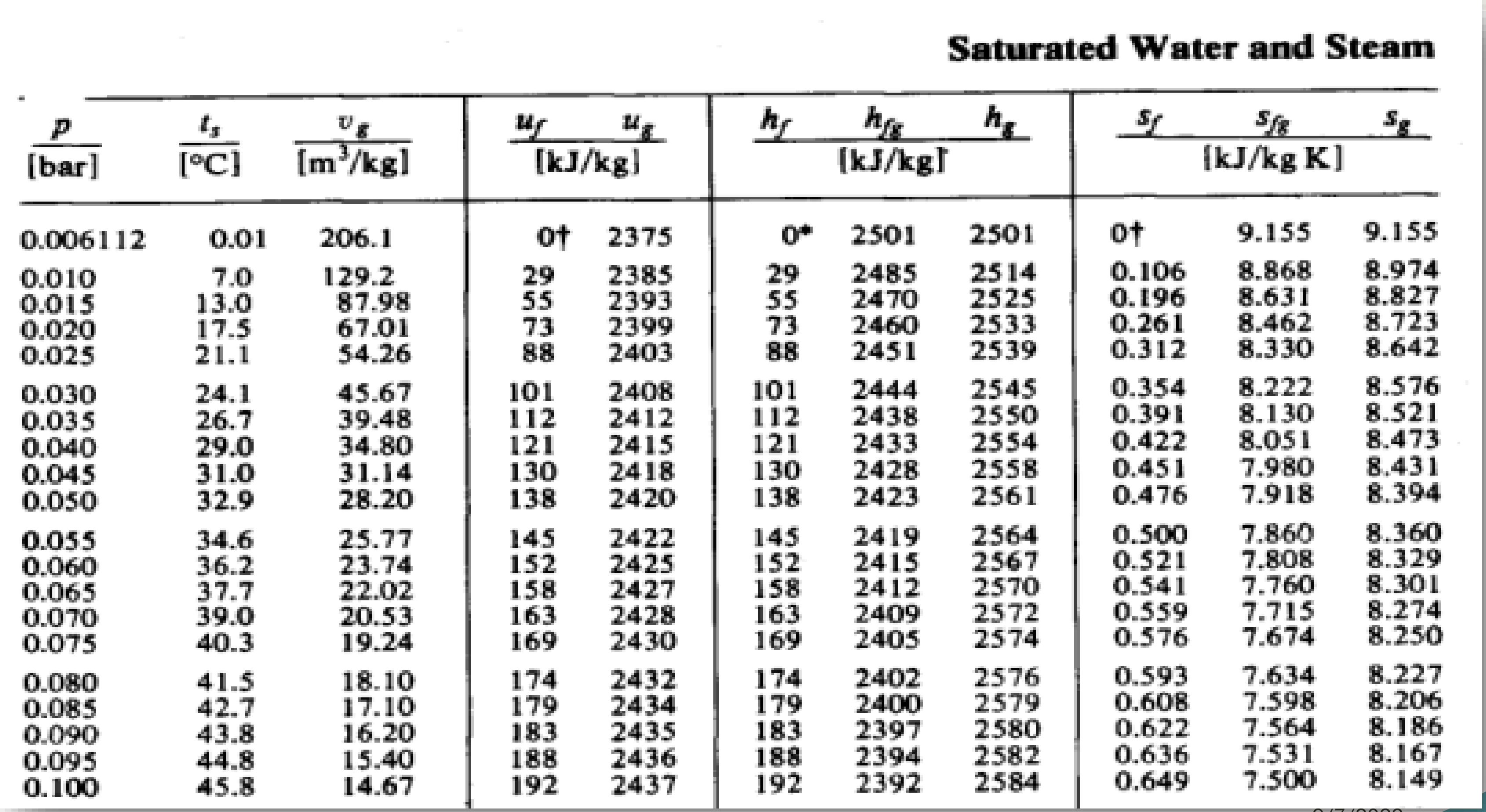
Or

$$\boldsymbol{Q = h_2 - h_1 = change\ of\ specific\ \ enthalpy} \qquad\qquad (4)$$

- Steam is almost invariably formed at constant pressure and thus it follows from the above discussion that heat energy transferred during the formation of steam (or some other vapour), at constant pressure, appears as a change of enthalpy in the steam

ENTHALPY TABLES

- Enthalpy values as they occur in the formation of steam and other vapours at constant pressure are commonly set out in tabular form.
- Most tables are made out for the formation of unit mass (1 kg) of steam or vapour



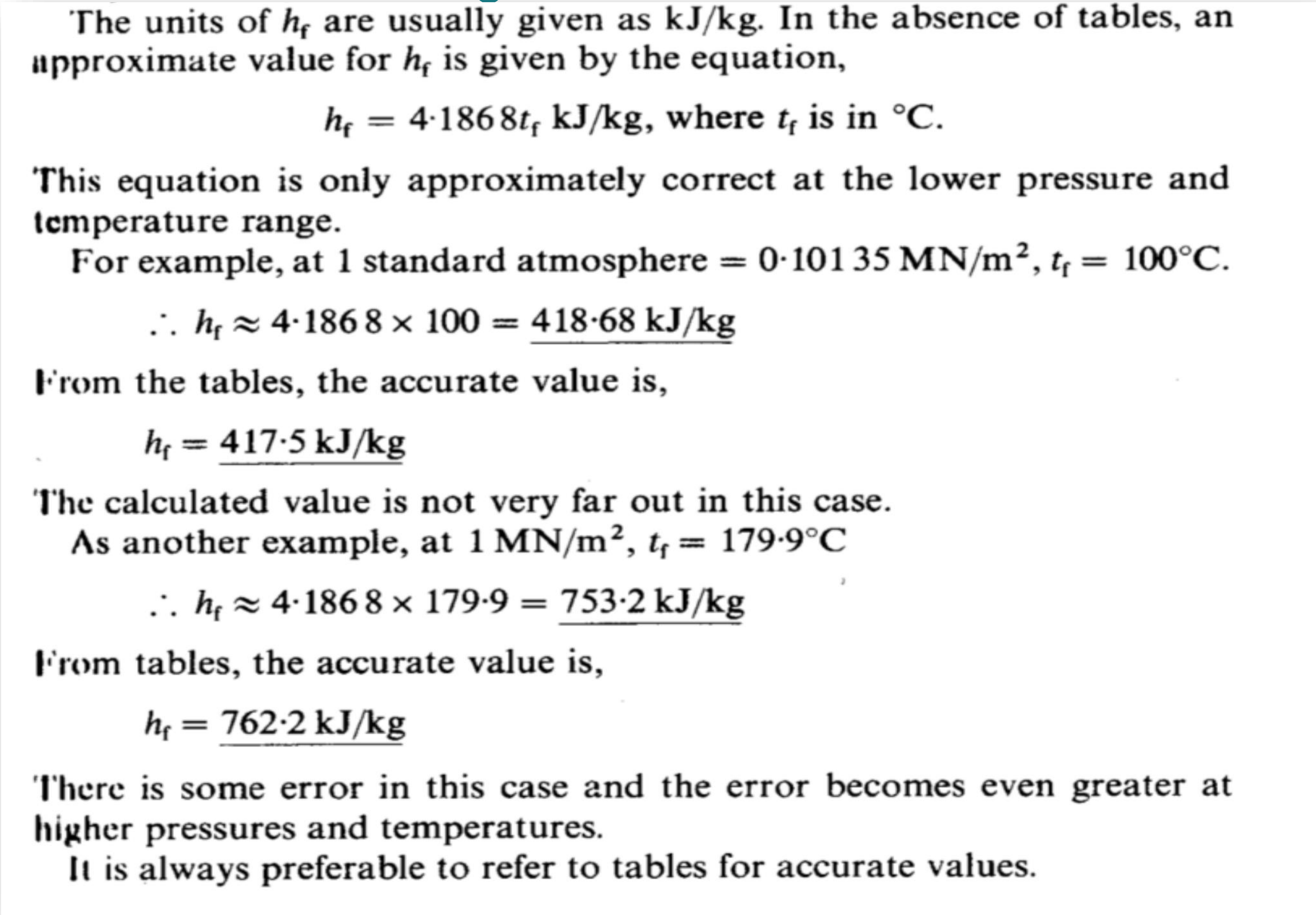
Saturated Water and Steam

p	t_s	v_g	u_f	u_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
[bar]	[°C]	[m^3/kg]	[kJ/kg]		[kJ/kg]			[kJ/kg K]		
0.006112	0.01	206.1	0†	2375	0*	2501	2501	0†	9.155	9.155
0.010	7.0	129.2	29	2385	29	2485	2514	0.106	8.868	8.974
0.015	13.0	87.98	55	2393	55	2470	2525	0.196	8.631	8.827
0.020	17.5	67.01	73	2399	73	2460	2533	0.261	8.462	8.723
0.025	21.1	54.26	88	2403	88	2451	2539	0.312	8.330	8.642
0.030	24.1	45.67	101	2408	101	2444	2545	0.354	8.222	8.576
0.035	26.7	39.48	112	2412	112	2438	2550	0.391	8.130	8.521
0.040	29.0	34.80	121	2415	121	2433	2554	0.422	8.051	8.473
0.045	31.0	31.14	130	2418	130	2428	2558	0.451	7.980	8.431
0.050	32.9	28.20	138	2420	138	2423	2561	0.476	7.918	8.394
0.055	34.6	25.77	145	2422	145	2419	2564	0.500	7.860	8.360
0.060	36.2	23.74	152	2425	152	2415	2567	0.521	7.808	8.329
0.065	37.7	22.02	158	2427	158	2412	2570	0.541	7.760	8.301
0.070	39.0	20.53	163	2428	163	2409	2572	0.559	7.715	8.274
0.075	40.3	19.24	169	2430	169	2405	2574	0.576	7.674	8.250
0.080	41.5	18.10	174	2432	174	2402	2576	0.593	7.634	8.227
0.085	42.7	17.10	179	2434	179	2400	2579	0.608	7.598	8.206
0.090	43.8	16.20	183	2435	183	2397	2580	0.622	7.564	8.186
0.095	44.8	15.40	188	2436	188	2394	2582	0.636	7.531	8.167
0.100	45.8	14.67	192	2437	192	2392	2584	0.649	7.500	8.149

LIQUID ENTHALPY

- The first phase in the production of steam is that of warming the water up to saturation temperature, $\boldsymbol{t_f}$. The energy added to the water in this phase is called liquid enthalpy.
- For unit mass of steam, specific liquid enthalpy is written $\boldsymbol{h_f}$. The accurate value of h_f at any given saturation temperature corresponding to a particular pressure is given in steam tables'

LIQUID ENTHALPY



The units of h_f are usually given as kJ/kg. In the absence of tables, an approximate value for h_f is given by the equation,

$$h_f = 4{\cdot}1868 t_f \text{ kJ/kg, where } t_f \text{ is in °C.}$$

This equation is only approximately correct at the lower pressure and temperature range.

For example, at 1 standard atmosphere $= 0{\cdot}10135 \text{ MN/m}^2$, $t_f = 100°\text{C}$.

$$\therefore\ h_f \approx 4{\cdot}1868 \times 100 = \underline{418{\cdot}68 \text{ kJ/kg}}$$

From the tables, the accurate value is,

$$h_f = \underline{417{\cdot}5 \text{ kJ/kg}}$$

The calculated value is not very far out in this case.

As another example, at 1 MN/m^2, $t_f = 179{\cdot}9°\text{C}$

$$\therefore\ h_f \approx 4{\cdot}1868 \times 179{\cdot}9 = \underline{753{\cdot}2 \text{ kJ/kg}}$$

From tables, the accurate value is,

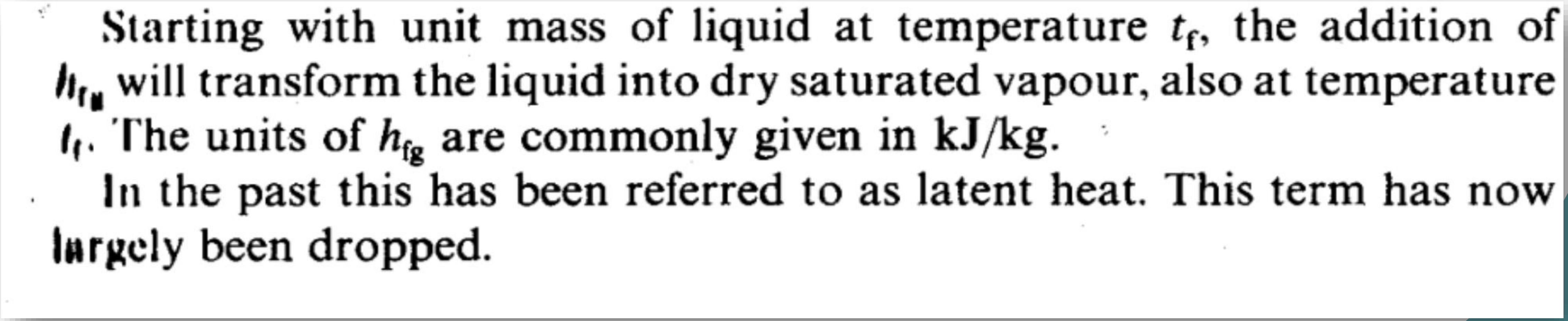
$$h_f = \underline{762{\cdot}2 \text{ kJ/kg}}$$

There is some error in this case and the error becomes even greater at higher pressures and temperatures.

It is always preferable to refer to tables for accurate values.

ENTHALPY OF EVAPORATION

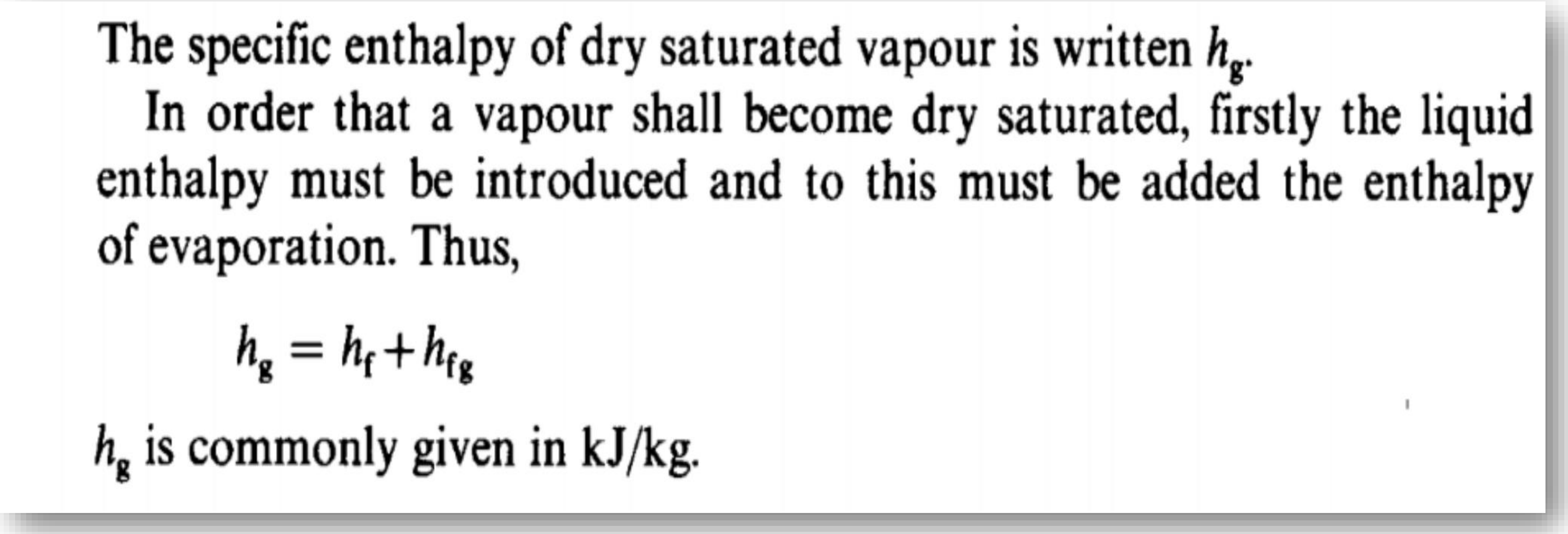
- The specific enthalpy of evaporation is written as $\boldsymbol{h_{fg}}$ and it can be looked up in tables. The evaporation of a liquid into vapour takes place at constant saturation temperature, as already stated. Thus h_{fg}, is added at constant saturation temperature t_f.



Starting with unit mass of liquid at temperature t_f, the addition of h_{fg} will transform the liquid into dry saturated vapour, also at temperature t_f. The units of h_{fg} are commonly given in kJ/kg.

In the past this has been referred to as latent heat. This term has now largely been dropped.

ENTHALPY OF DRY SATURATED VAPOUR

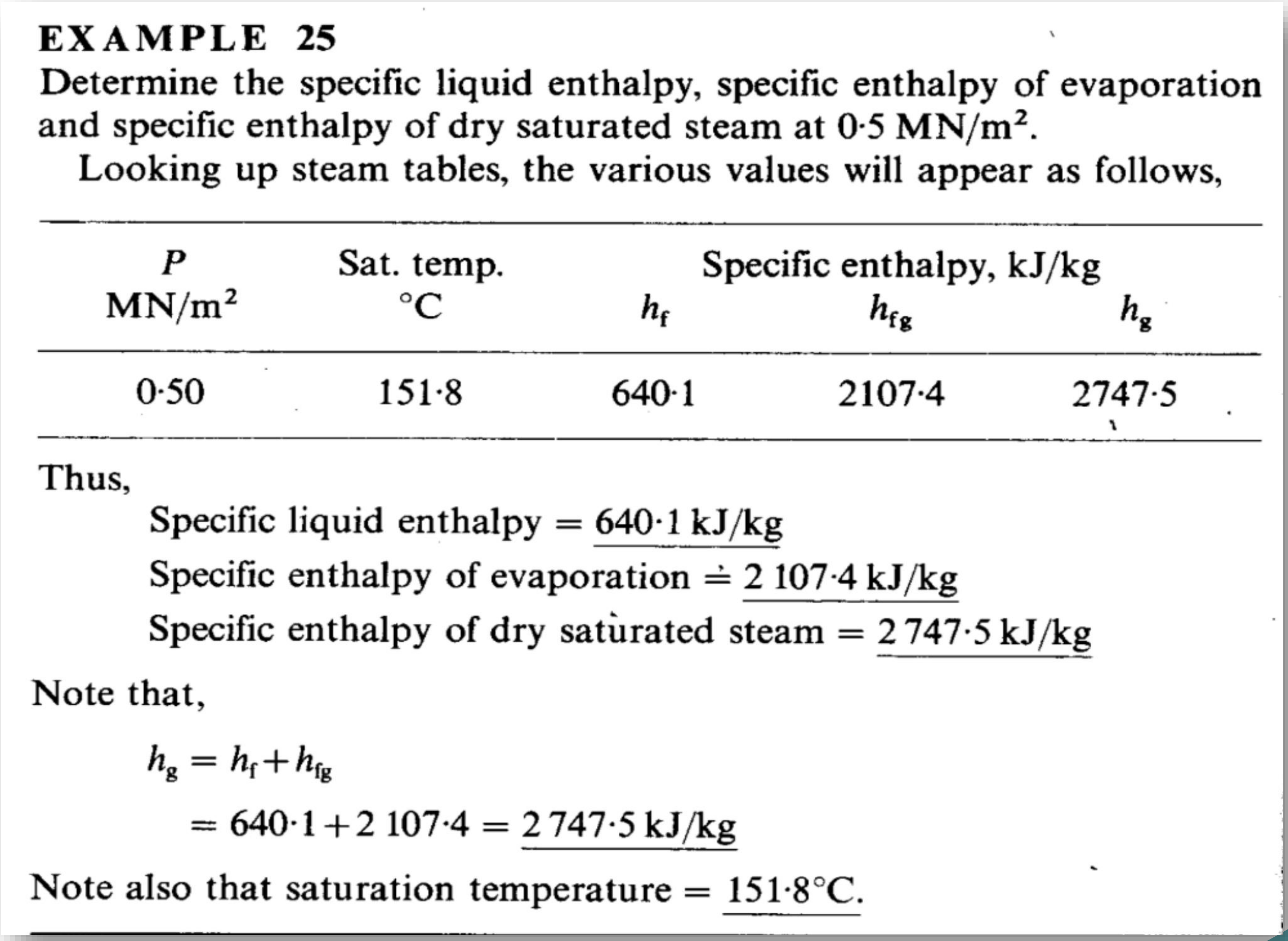


The specific enthalpy of dry saturated vapour is written h_g.

In order that a vapour shall become dry saturated, firstly the liquid enthalpy must be introduced and to this must be added the enthalpy of evaporation. Thus,

$$h_g = h_f + h_{fg}$$

h_g is commonly given in kJ/kg.



EXAMPLE 25

Determine the specific liquid enthalpy, specific enthalpy of evaporation and specific enthalpy of dry saturated steam at 0·5 MN/m².

Looking up steam tables, the various values will appear as follows,

P MN/m²	Sat. temp. °C	Specific enthalpy, kJ/kg h_f	h_{fg}	h_g
0·50	151·8	640·1	2107·4	2747·5

Thus,

Specific liquid enthalpy = 640·1 kJ/kg

Specific enthalpy of evaporation = 2 107·4 kJ/kg

Specific enthalpy of dry saturated steam = 2 747·5 kJ/kg

Note that,

$$h_g = h_f + h_{fg}$$

$$= 640{\cdot}1 + 2\,107{\cdot}4 = \underline{2\,747{\cdot}5\ \text{kJ/kg}}$$

Note also that saturation temperature = 151·8°C.

ENTHALPY OF SUPERHEATED VAPOUR

- From the dry saturated condition, a vapour receives superheat and its temperature rises above saturation temperature t_f
- It has now entered the superheat phase
- The difference between the superheat vapour temperature t and the saturation temperature t_f is called the $degree\ of\ superheat$. Thus,

$$\boldsymbol{Degree\ of\ Superheat = (t - t_f)K} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

- The enthalpy added during the superheat phase is called the Superheat Enthalpy

ENTHALPY OF SUPERHEATED VAPOUR

- The **total enthalpy of superheated vapour** will be the sum of the enthalpy of dry saturated vapour and the superheat enthalpy,

$$\boldsymbol{h = h_g + superheat\ enthalpy}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

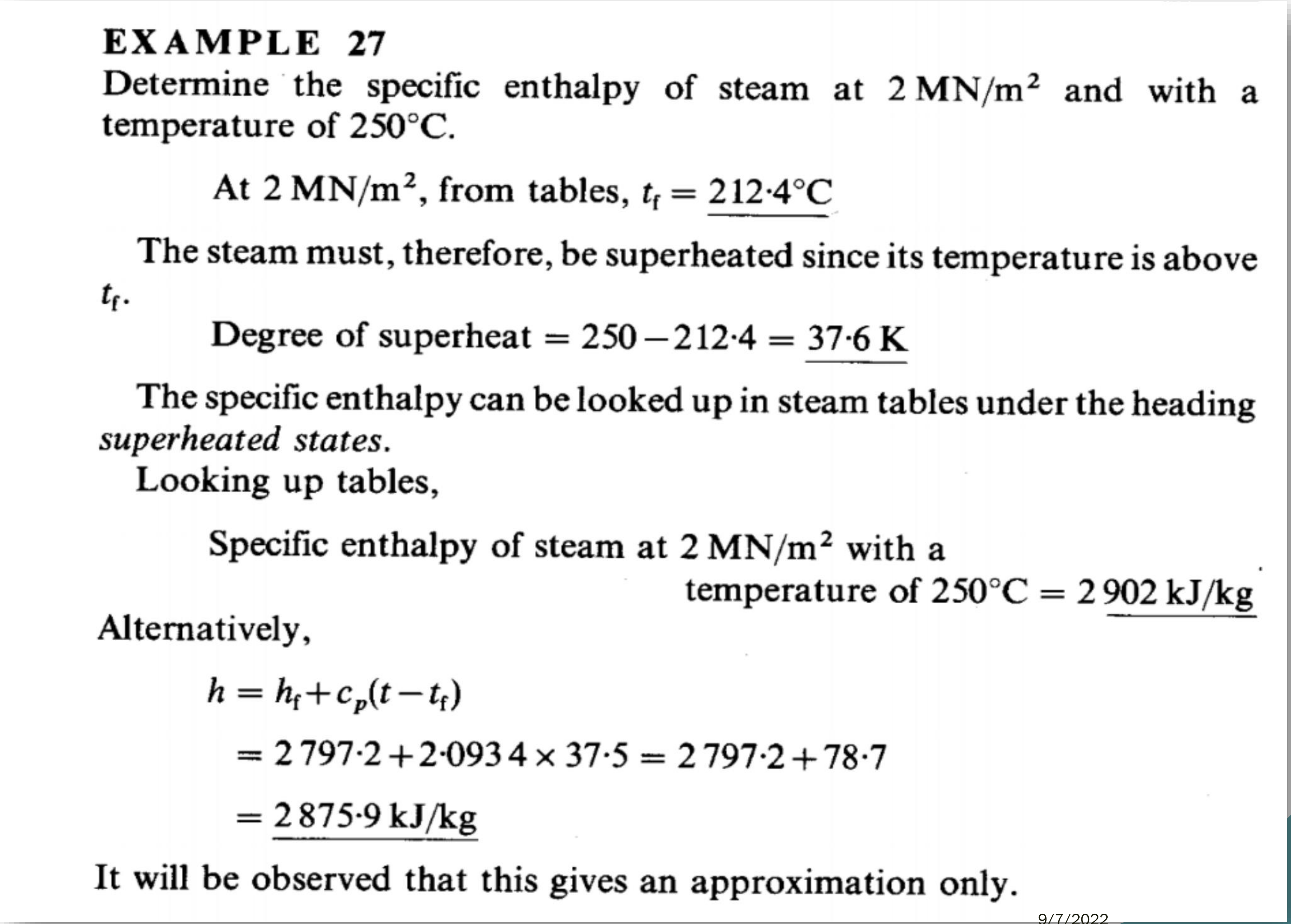
- An approximation of the value of superheat enbthalpy can be found with the following:

$$\boldsymbol{Specific\ Superheat\ Enthalpy = c_p(t - t_f)}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where c_p=specific heat of superheated vapour at constant temperature

$$\therefore \boldsymbol{h = h_g + c_p(t - t_f)}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

- **An average value of c_p for superheated steam is 2.0934 k/kg K. Accurate values of h are given in tables, equation (4) being used as an approximation only**



EXAMPLE 27

Determine the specific enthalpy of steam at 2 MN/m^2 and with a temperature of 250°C.

$$\text{At } 2\ \text{MN/m}^2\text{, from tables, } t_f = \underline{212{\cdot}4°\text{C}}$$

The steam must, therefore, be superheated since its temperature is above t_f.

$$\text{Degree of superheat} = 250 - 212{\cdot}4 = \underline{37{\cdot}6\ \text{K}}$$

The specific enthalpy can be looked up in steam tables under the heading *superheated states.*

Looking up tables,

$$\text{Specific enthalpy of steam at } 2\ \text{MN/m}^2 \text{ with a temperature of } 250°\text{C} = \underline{2\,902\ \text{kJ/kg}}$$

Alternatively,

$$h = h_f + c_p(t - t_f)$$

$$= 2\,797{\cdot}2 + 2{\cdot}093\,4 \times 37{\cdot}5 = 2\,797{\cdot}2 + 78{\cdot}7$$

$$= \underline{2\,875{\cdot}9\ \text{kJ/kg}}$$

It will be observed that this gives an approximation only.

WET VAPOUR AND DRYNESS FRACTION

- As already stated, the vapour produced at saturation temperature in the transformation stage will contain liquid droplets in suspension for so long as there is liquid present. It should be noted that vapour, as such, is dry.
- The vapour is made wet by liquid droplets in suspension.
- Any mass of wet vapour will be made up of some dry saturated vapour together with liquid droplets in suspension. The degree of wetness should be known .
- The ratio,

$$\frac{\boldsymbol{Mass\ of\ dry\ saturated\ vapour}}{\boldsymbol{Mass\ of\ wet\ vapour\ containing\ the\ dry\ saturated\ vapour}}$$

is called the **dryness fraction**, designated by the letter *x*.

WET VAPOUR AND DRYNESS FRACTION

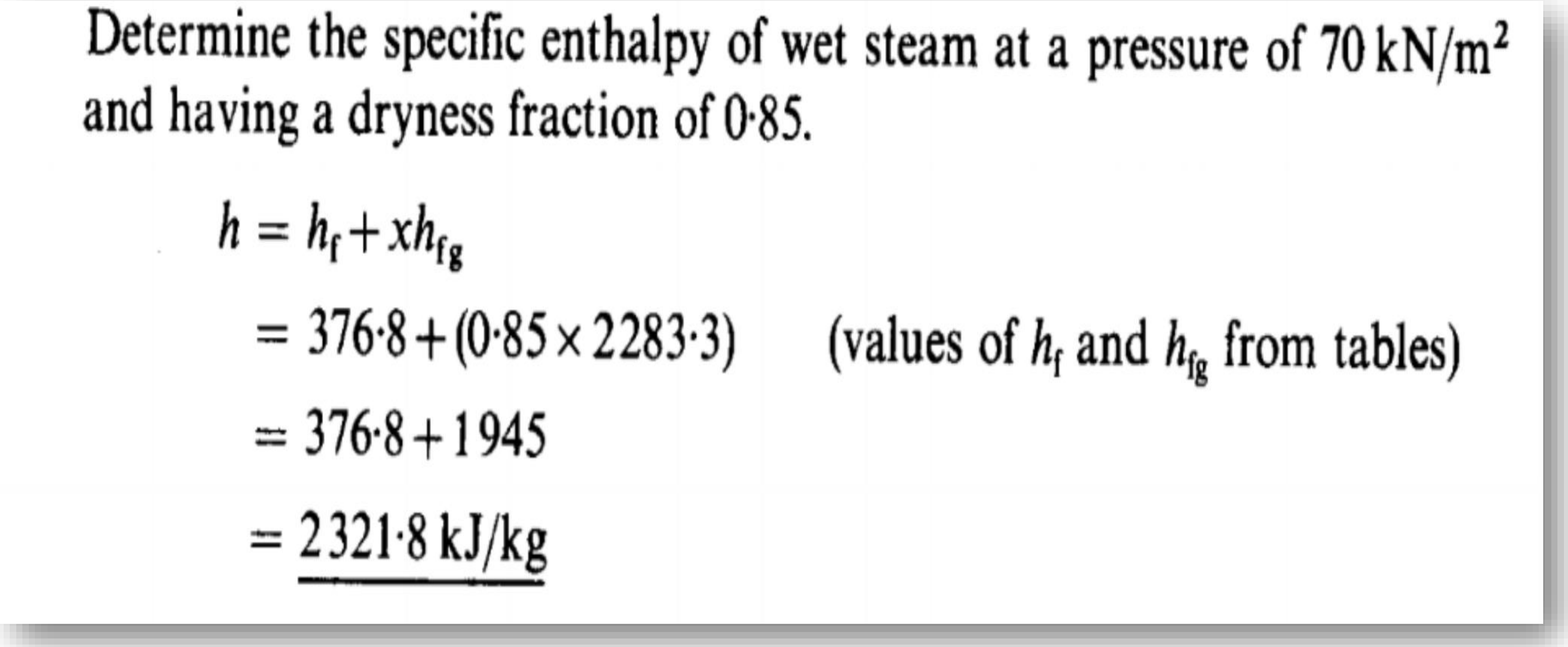
- Consider, then, 1kg of wet vapour of dryness fraction *x*. The 1kg will be made up of x kg of dry saturated vapour at saturation temperature t_f together with $(1-x)$kg of liquid droplets in suspension, also at saturation temperature t_f .
- Evidently, then, only *x* kg have received the enthalpy of evaporation.

$$\therefore \boldsymbol{specific\ enthalpy\ of\ evaporation\ of\ wet\ vapour = xh_{fg}}$$

And

$$\boldsymbol{h = h_f + xh_{fg}}$$

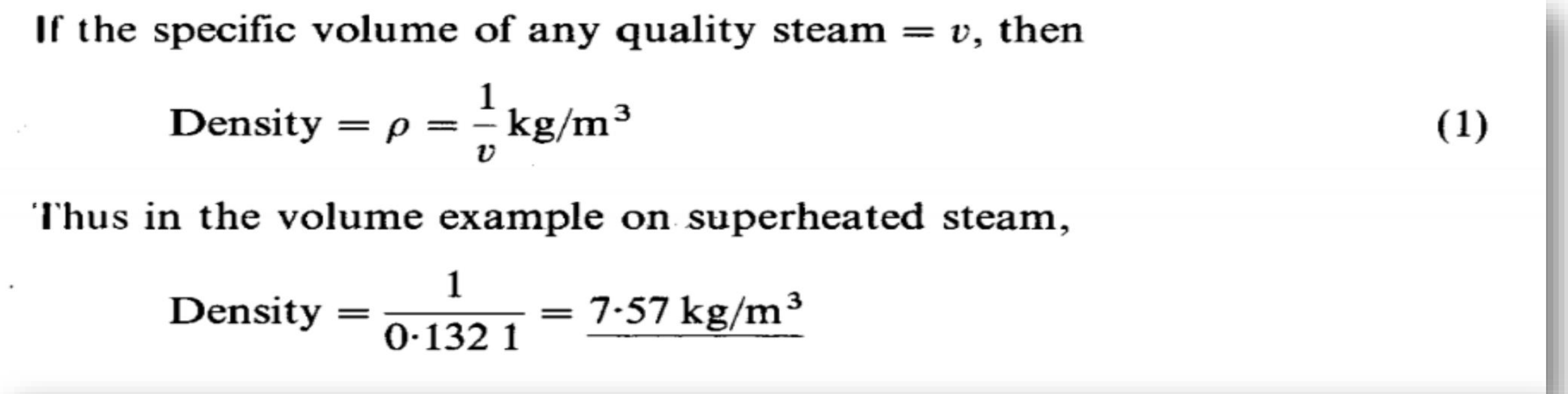
Example



Determine the specific enthalpy of wet steam at a pressure of $70\,\mathrm{kN/m^2}$ and having a dryness fraction of 0·85.

$$
\begin{aligned}
h &= h_f + x h_{fg} \\
&= 376{\cdot}8 + (0{\cdot}85 \times 2283{\cdot}3) \qquad \text{(values of } h_f \text{ and } h_{fg} \text{ from tables)} \\
&= 376{\cdot}8 + 1945 \\
&= \underline{2321{\cdot}8\ \mathrm{kJ/kg}}
\end{aligned}
$$

DENSITY OF STEAM

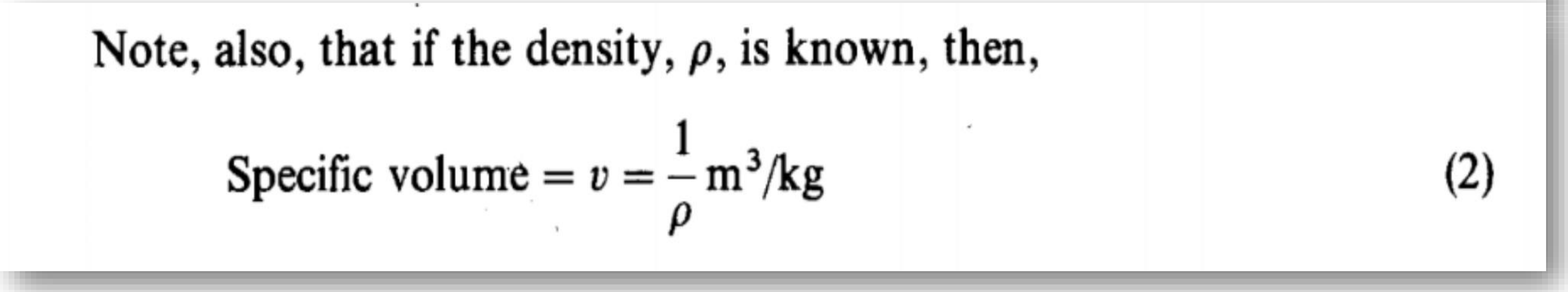


If the specific volume of any quality steam $= v$, then

$$\text{Density} = \rho = \frac{1}{v}\,\text{kg/m}^3 \qquad (1)$$

Thus in the volume example on superheated steam,

$$\text{Density} = \frac{1}{0{\cdot}132\,1} = \underline{7{\cdot}57\,\text{kg/m}^3}$$

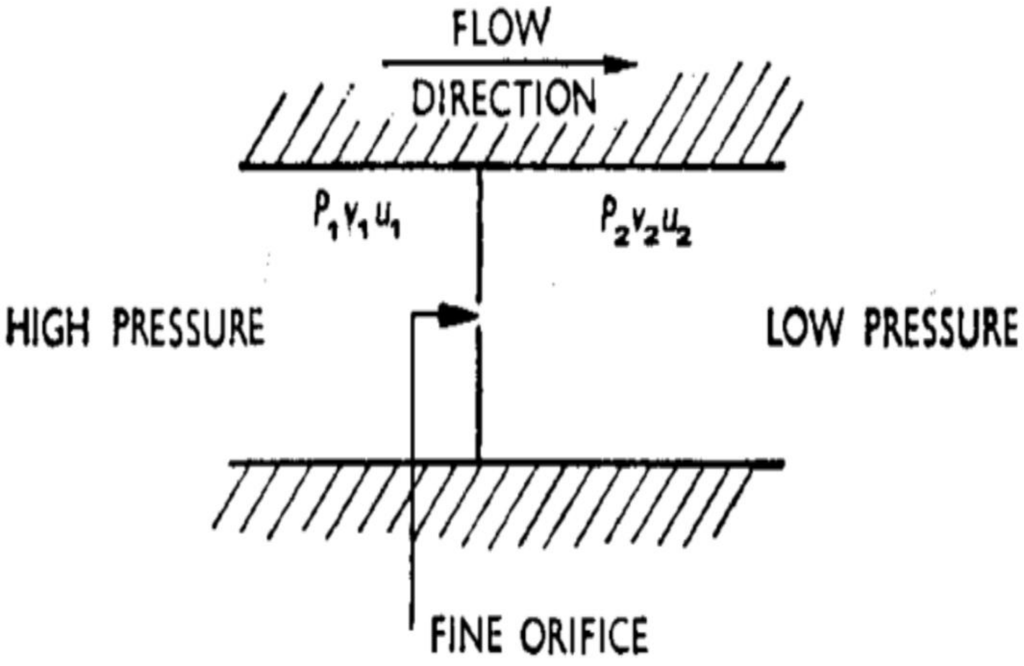


Note, also, that if the density, ρ, is known, then,

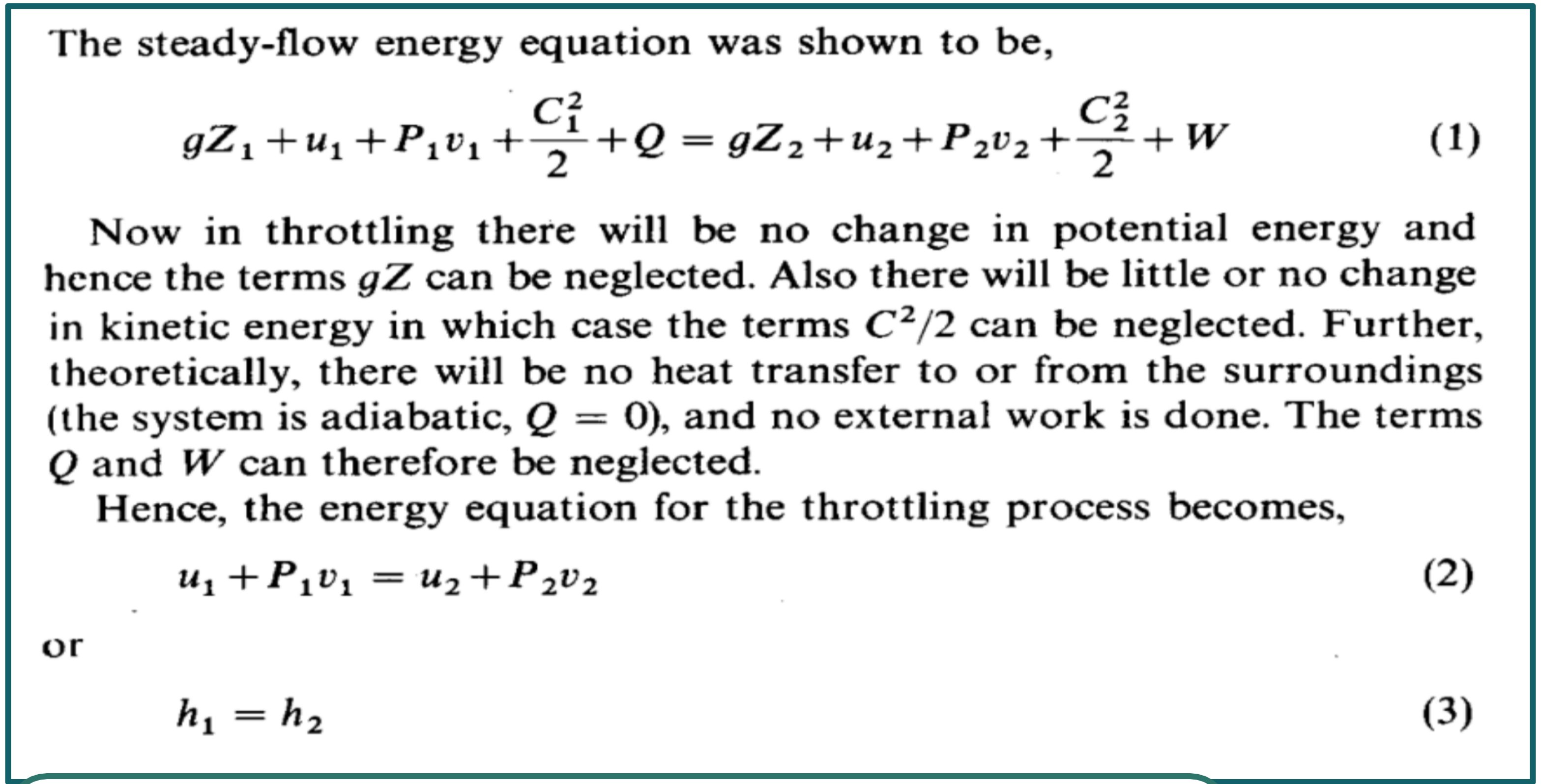
$$\text{Specific volume} = v = \frac{1}{\rho}\,\text{m}^3/\text{kg} \qquad (2)$$

THROTTLING

- If a gas or steam (or any other vapour) is passed through a fine orifice, as shown, then it is said to have been throttled.
- The gas or steam will pass from the high pressure to the low pressure side and hence throttling is a flow condition when applied to the steady-flow energy equation.



THROTTLING



The steady-flow energy equation was shown to be,

$$gZ_1 + u_1 + P_1v_1 + \frac{C_1^2}{2} + Q = gZ_2 + u_2 + P_2v_2 + \frac{C_2^2}{2} + W \qquad (1)$$

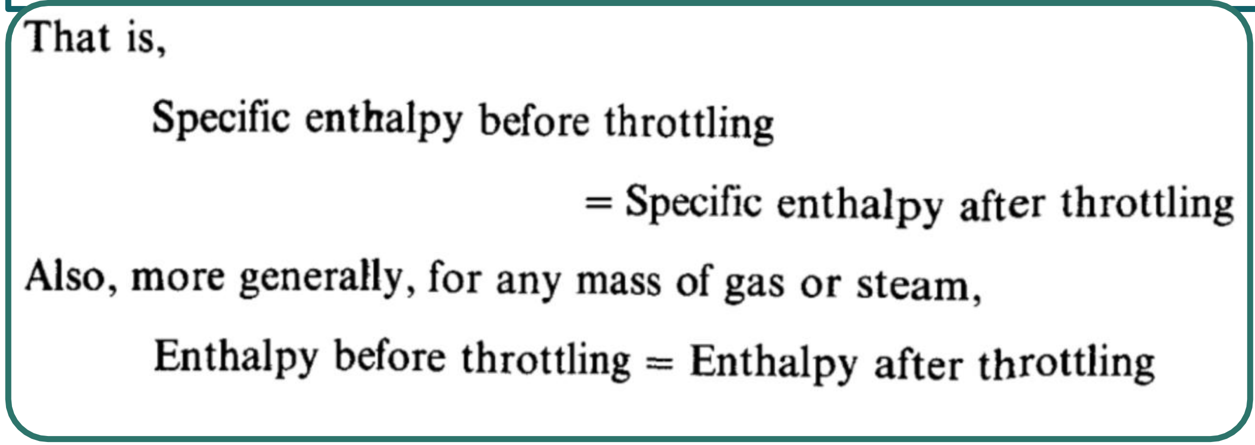
Now in throttling there will be no change in potential energy and hence the terms gZ can be neglected. Also there will be little or no change in kinetic energy in which case the terms $C^2/2$ can be neglected. Further, theoretically, there will be no heat transfer to or from the surroundings (the system is adiabatic, $Q = 0$), and no external work is done. The terms Q and W can therefore be neglected.

Hence, the energy equation for the throttling process becomes,

$$u_1 + P_1v_1 = u_2 + P_2v_2 \qquad (2)$$

or

$$h_1 = h_2 \qquad (3)$$



That is,

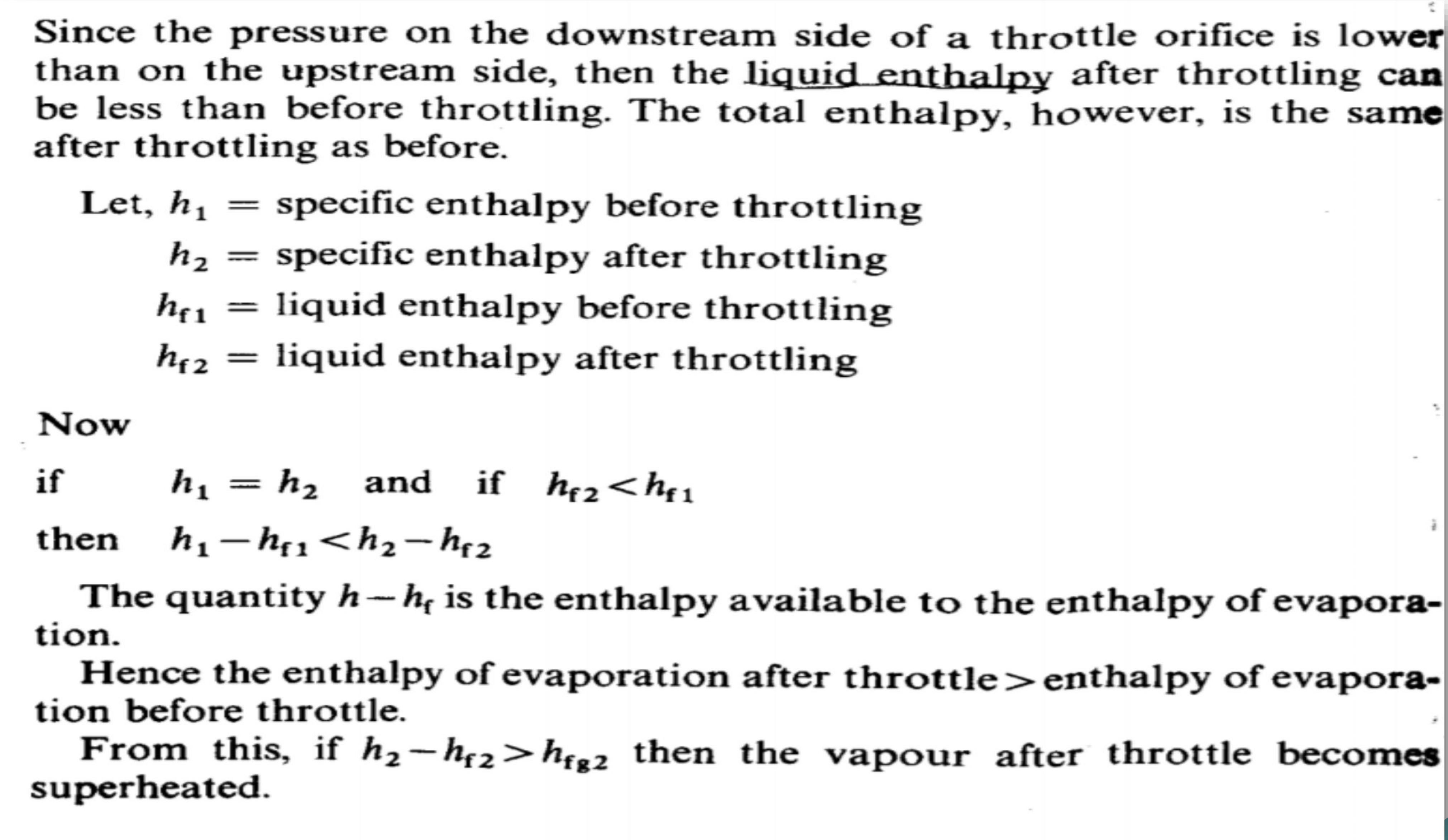
Specific enthalpy before throttling

= Specific enthalpy after throttling

Also, more generally, for any mass of gas or steam,

Enthalpy before throttling = Enthalpy after throttling

THE EFFECT OF THROTTLING ON A VAPOUR



Since the pressure on the downstream side of a throttle orifice is lower than on the upstream side, then the liquid enthalpy after throttling can be less than before throttling. The total enthalpy, however, is the same after throttling as before.

Let, h_1 = specific enthalpy before throttling
h_2 = specific enthalpy after throttling
h_{f1} = liquid enthalpy before throttling
h_{f2} = liquid enthalpy after throttling

Now

if $h_1 = h_2$ and if $h_{f2} < h_{f1}$

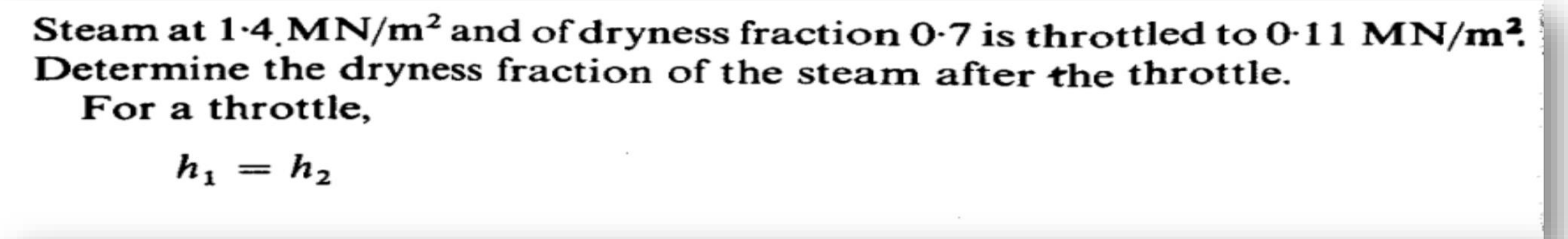
then $h_1 - h_{f1} < h_2 - h_{f2}$

The quantity $h - h_f$ is the enthalpy available to the enthalpy of evaporation.

Hence the enthalpy of evaporation after throttle > enthalpy of evaporation before throttle.

From this, if $h_2 - h_{f2} > h_{fg2}$ then the vapour after throttle becomes superheated.

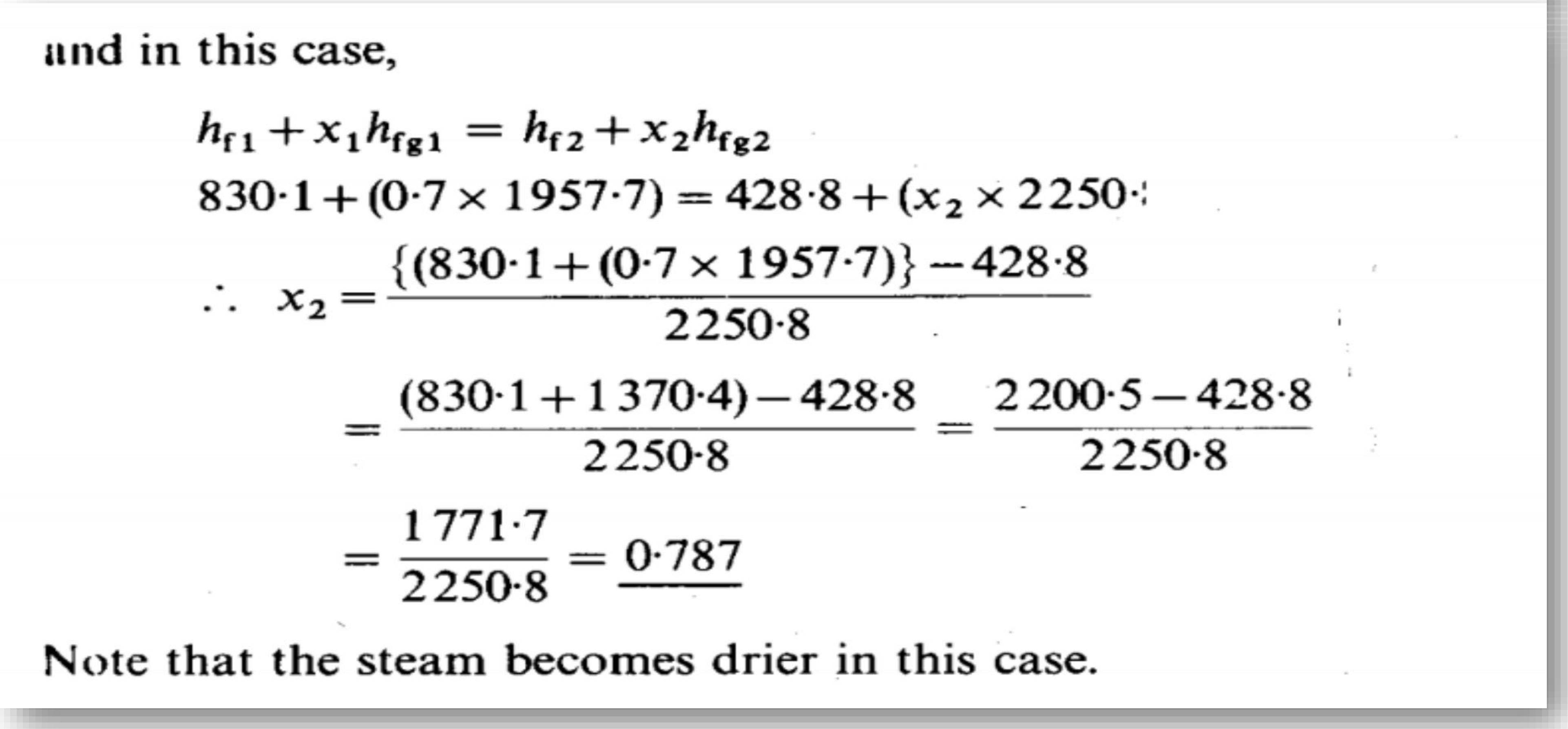
Example



Steam at 1·4 MN/m^2 and of dryness fraction 0·7 is throttled to 0·11 MN/m^2. Determine the dryness fraction of the steam after the throttle.

For a throttle,

$$h_1 = h_2$$



and in this case,

$$h_{f1} + x_1 h_{fg1} = h_{f2} + x_2 h_{fg2}$$

$$830{\cdot}1 + (0{\cdot}7 \times 1957{\cdot}7) = 428{\cdot}8 + (x_2 \times 2250{\cdot}$$

$$\therefore \quad x_2 = \frac{\{(830{\cdot}1 + (0{\cdot}7 \times 1957{\cdot}7)\} - 428{\cdot}8}{2250{\cdot}8}$$

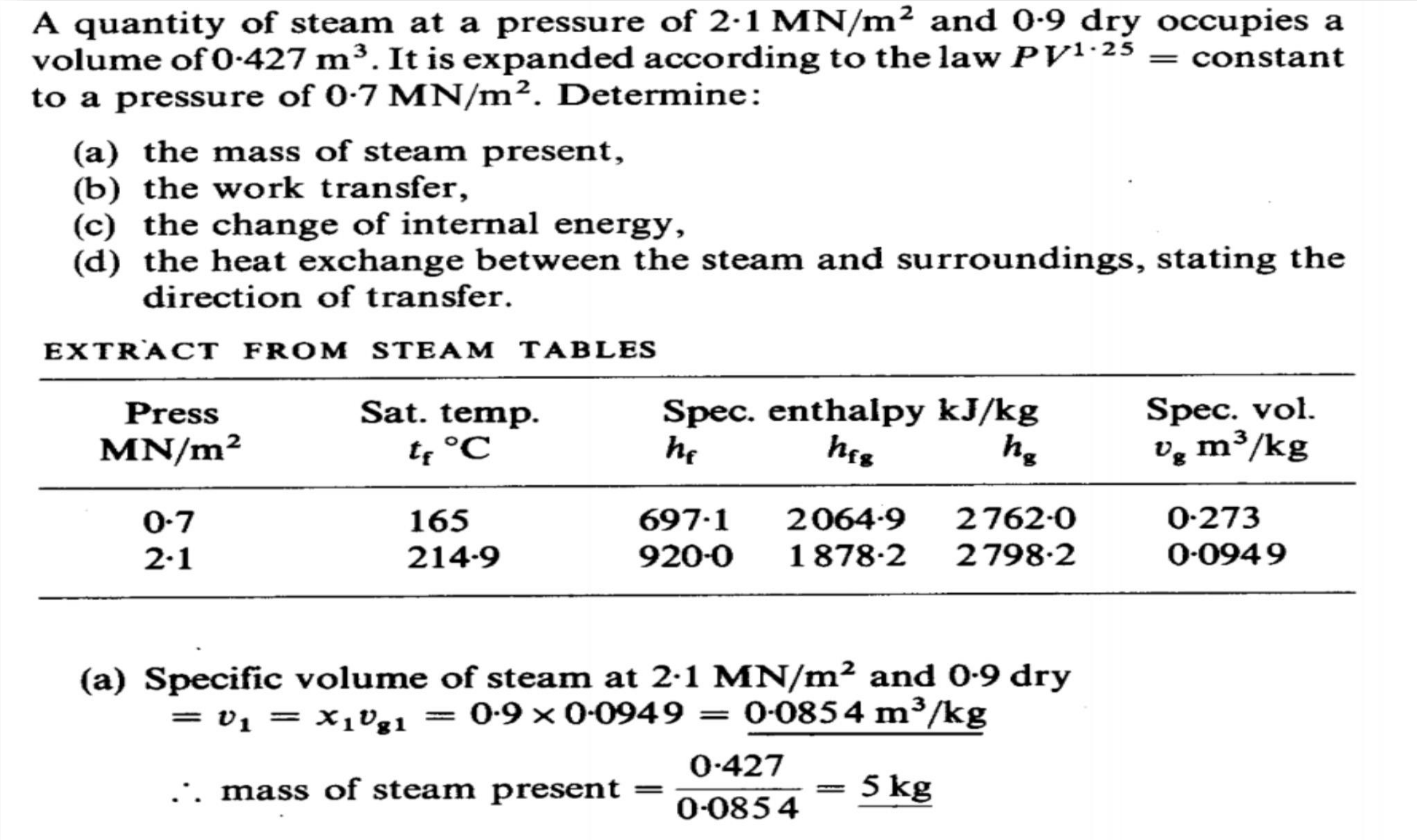
$$= \frac{(830{\cdot}1 + 1370{\cdot}4) - 428{\cdot}8}{2250{\cdot}8} = \frac{2200{\cdot}5 - 428{\cdot}8}{2250{\cdot}8}$$

$$= \frac{1771{\cdot}7}{2250{\cdot}8} = \underline{0{\cdot}787}$$

Note that the steam becomes drier in this case.

VARIOUS NON-FLOW PROCESSES WITH STEAM

EXAMPLE: THE POLYTROPIC PROCESS $PV^n = C$



A quantity of steam at a pressure of 2·1 MN/m² and 0·9 dry occupies a volume of 0·427 m³. It is expanded according to the law $PV^{1\cdot25}$ = constant to a pressure of 0·7 MN/m². Determine:

(a) the mass of steam present,
(b) the work transfer,
(c) the change of internal energy,
(d) the heat exchange between the steam and surroundings, stating the direction of transfer.

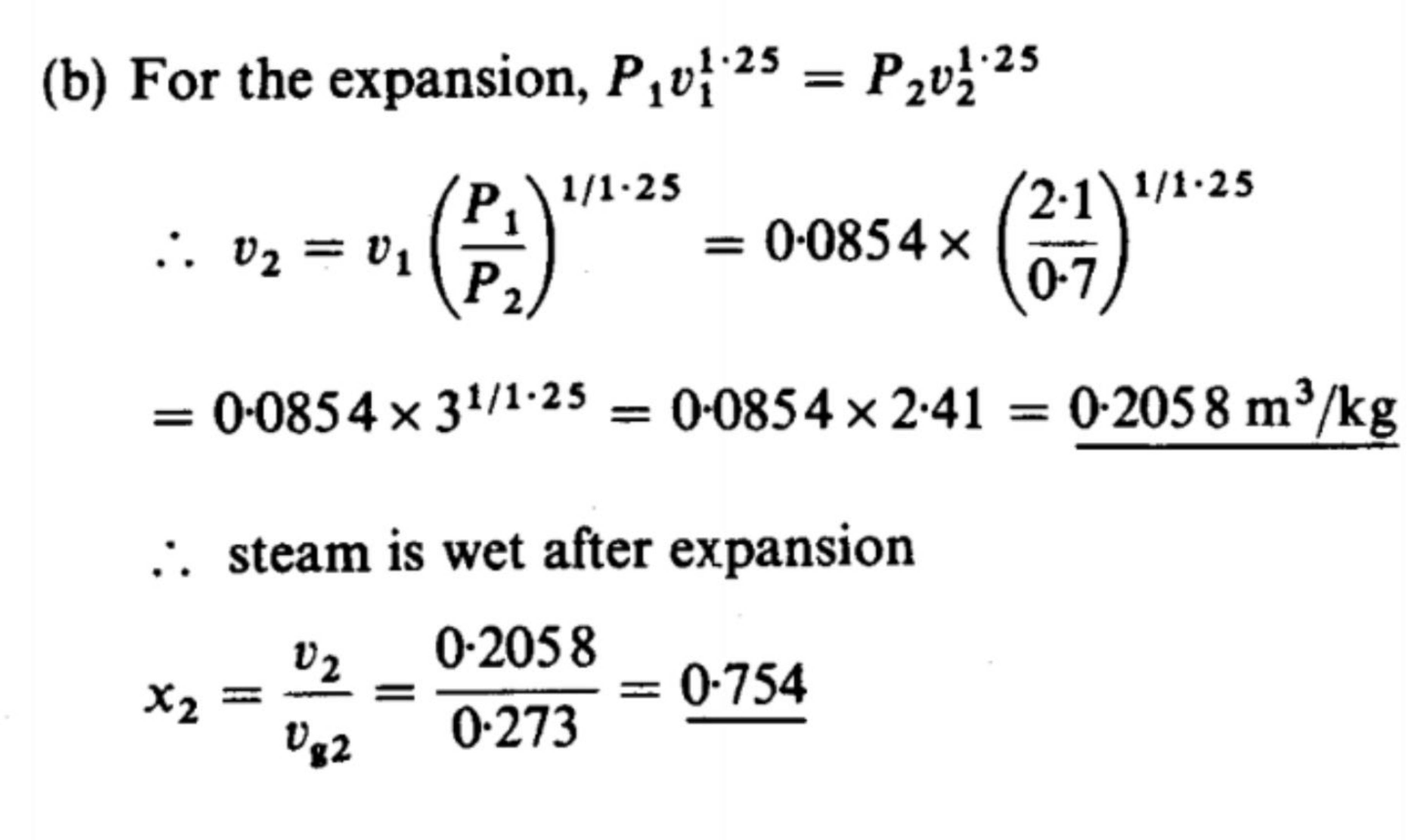
EXTRACT FROM STEAM TABLES

Press MN/m²	Sat. temp. t_f °C	Spec. enthalpy kJ/kg h_f	h_{fg}	h_g	Spec. vol. v_g m³/kg
0·7	165	697·1	2064·9	2762·0	0·273
2·1	214·9	920·0	1878·2	2798·2	0·0949

(a) Specific volume of steam at 2·1 MN/m² and 0·9 dry

$$= v_1 = x_1 v_{g1} = 0{\cdot}9 \times 0{\cdot}0949 = \underline{0{\cdot}0854 \text{ m}^3/\text{kg}}$$

$$\therefore \text{ mass of steam present} = \frac{0{\cdot}427}{0{\cdot}0854} = \underline{5 \text{ kg}}$$



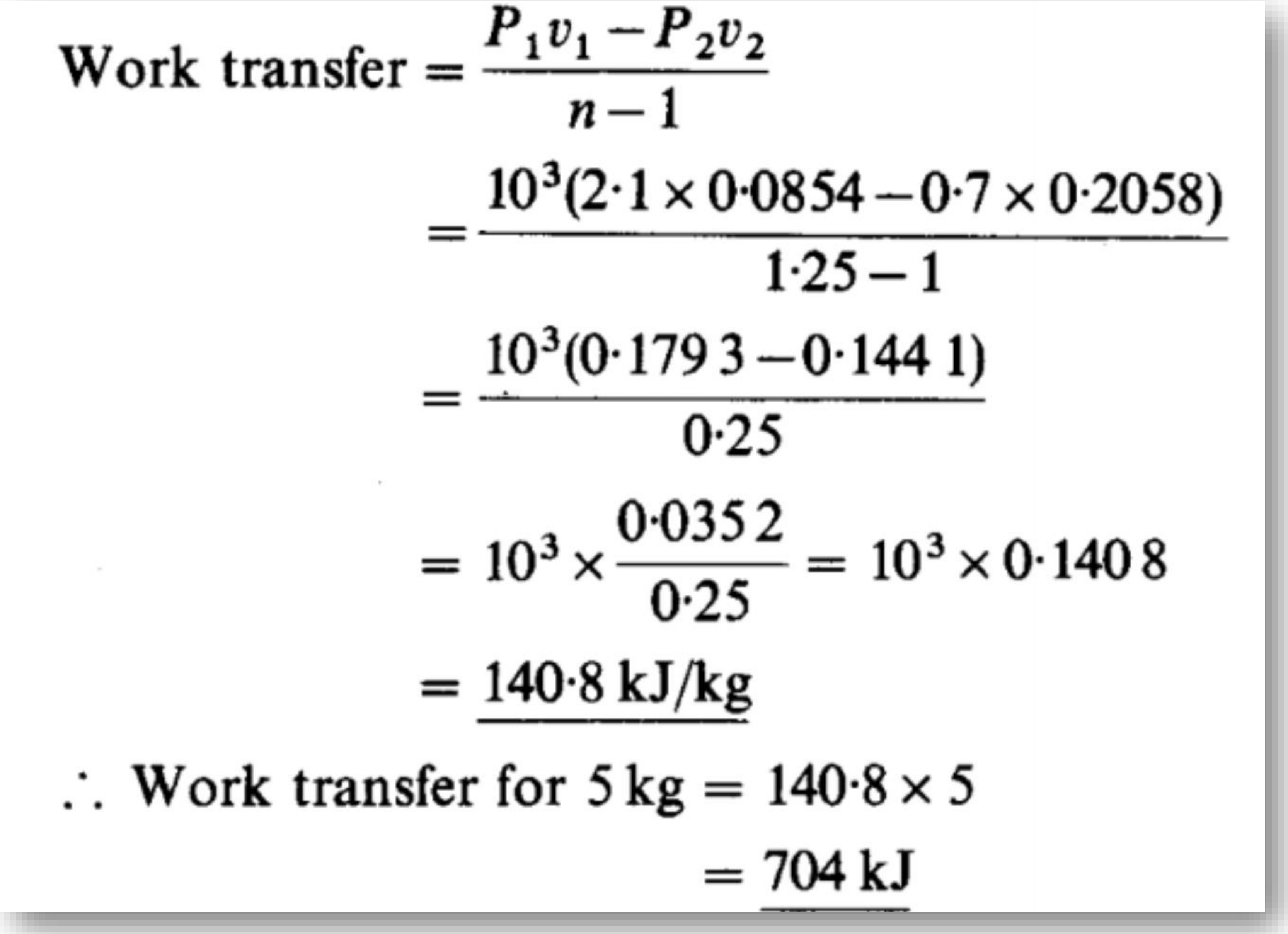
(b) For the expansion, $P_1 v_1^{1\cdot25} = P_2 v_2^{1\cdot25}$

$$\therefore \quad v_2 = v_1 \left(\frac{P_1}{P_2}\right)^{1/1\cdot25} = 0\cdot0854 \times \left(\frac{2\cdot1}{0\cdot7}\right)^{1/1\cdot25}$$

$$= 0\cdot0854 \times 3^{1/1\cdot25} = 0\cdot0854 \times 2\cdot41 = \underline{0\cdot2058 \text{ m}^3/\text{kg}}$$

$\therefore$ steam is wet after expansion

$$x_2 = \frac{v_2}{v_{g2}} = \frac{0\cdot2058}{0\cdot273} = \underline{0\cdot754}$$



$$\text{Work transfer} = \frac{P_1v_1 - P_2v_2}{n-1}$$

$$= \frac{10^3(2{\cdot}1 \times 0{\cdot}0854 - 0{\cdot}7 \times 0{\cdot}2058)}{1{\cdot}25 - 1}$$

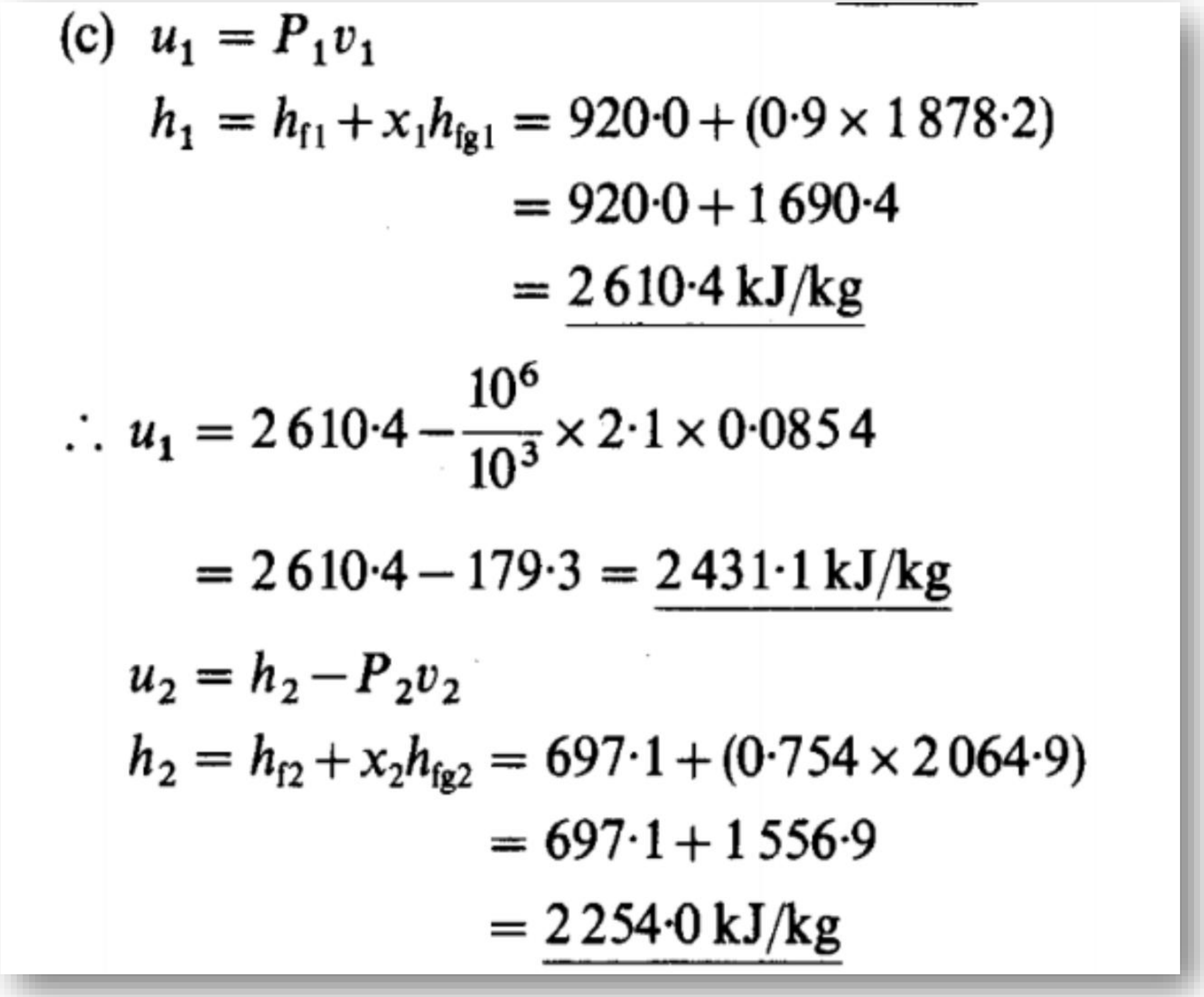
$$= \frac{10^3(0{\cdot}179\,3 - 0{\cdot}144\,1)}{0{\cdot}25}$$

$$= 10^3 \times \frac{0{\cdot}035\,2}{0{\cdot}25} = 10^3 \times 0{\cdot}140\,8$$

$$= \underline{140{\cdot}8\ \text{kJ/kg}}$$

$$\therefore\ \text{Work transfer for 5 kg} = 140{\cdot}8 \times 5$$

$$= \underline{704\ \text{kJ}}$$



(c) $u_1 = P_1 v_1$

$$h_1 = h_{f1} + x_1 h_{fg1} = 920{\cdot}0 + (0{\cdot}9 \times 1\,878{\cdot}2)$$

$$= 920{\cdot}0 + 1\,690{\cdot}4$$

$$= \underline{2\,610{\cdot}4 \text{ kJ/kg}}$$

$$\therefore u_1 = 2\,610{\cdot}4 - \frac{10^6}{10^3} \times 2{\cdot}1 \times 0{\cdot}0854$$

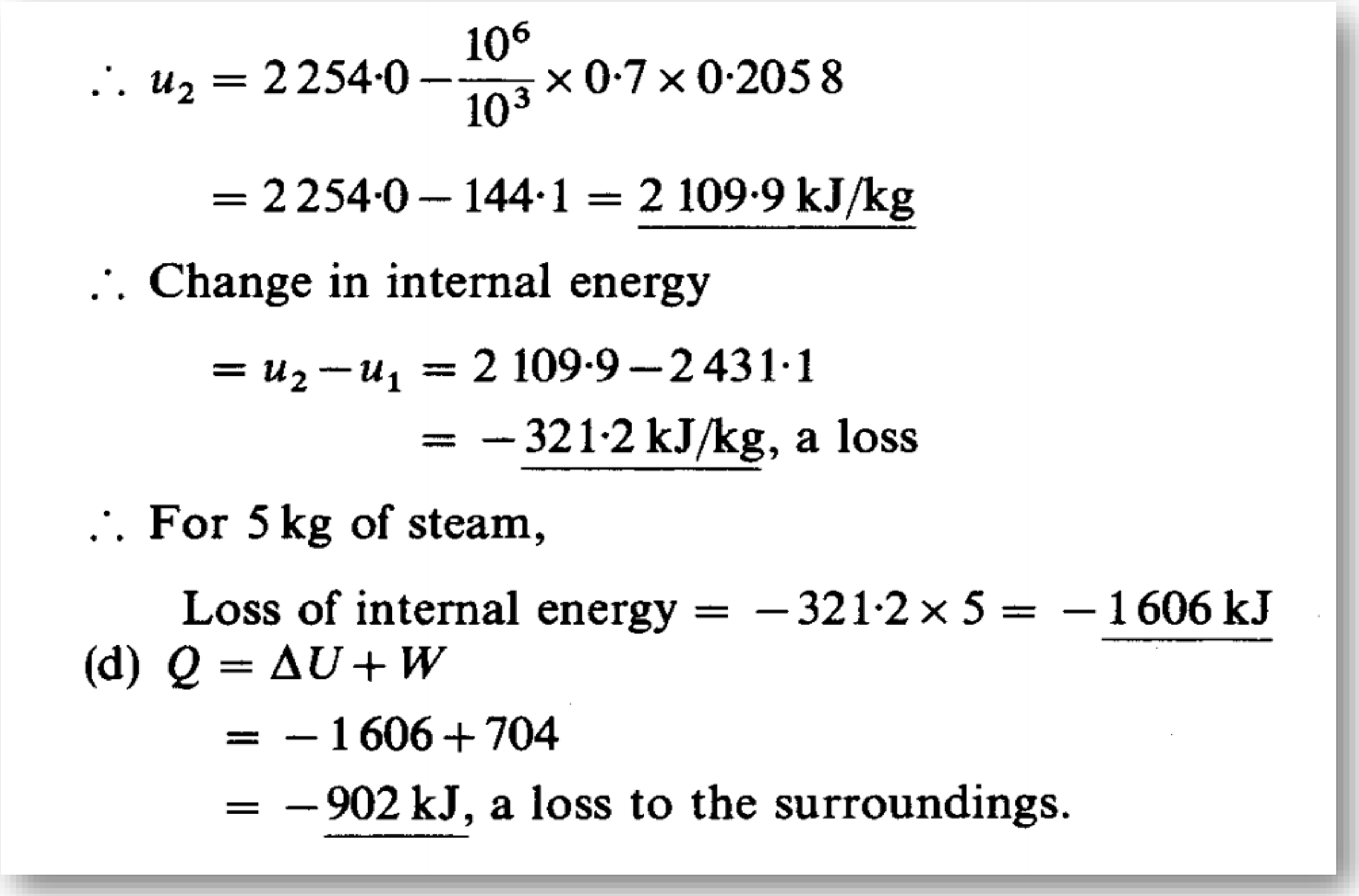
$$= 2\,610{\cdot}4 - 179{\cdot}3 = \underline{2\,431{\cdot}1 \text{ kJ/kg}}$$

$$u_2 = h_2 - P_2 v_2$$

$$h_2 = h_{f2} + x_2 h_{fg2} = 697{\cdot}1 + (0{\cdot}754 \times 2\,064{\cdot}9)$$

$$= 697{\cdot}1 + 1\,556{\cdot}9$$

$$= \underline{2\,254{\cdot}0 \text{ kJ/kg}}$$



$$\therefore\ u_2 = 2\,254{\cdot}0 - \frac{10^6}{10^3} \times 0{\cdot}7 \times 0{\cdot}205\,8$$

$$= 2\,254{\cdot}0 - 144{\cdot}1 = \underline{2\,109{\cdot}9\ \text{kJ/kg}}$$

∴ Change in internal energy

$$= u_2 - u_1 = 2\,109{\cdot}9 - 2\,431{\cdot}1$$

$$= -\underline{321{\cdot}2\ \text{kJ/kg}},\ \text{a loss}$$

∴ For 5 kg of steam,

$$\text{Loss of internal energy} = -321{\cdot}2 \times 5 = -\underline{1\,606\ \text{kJ}}$$

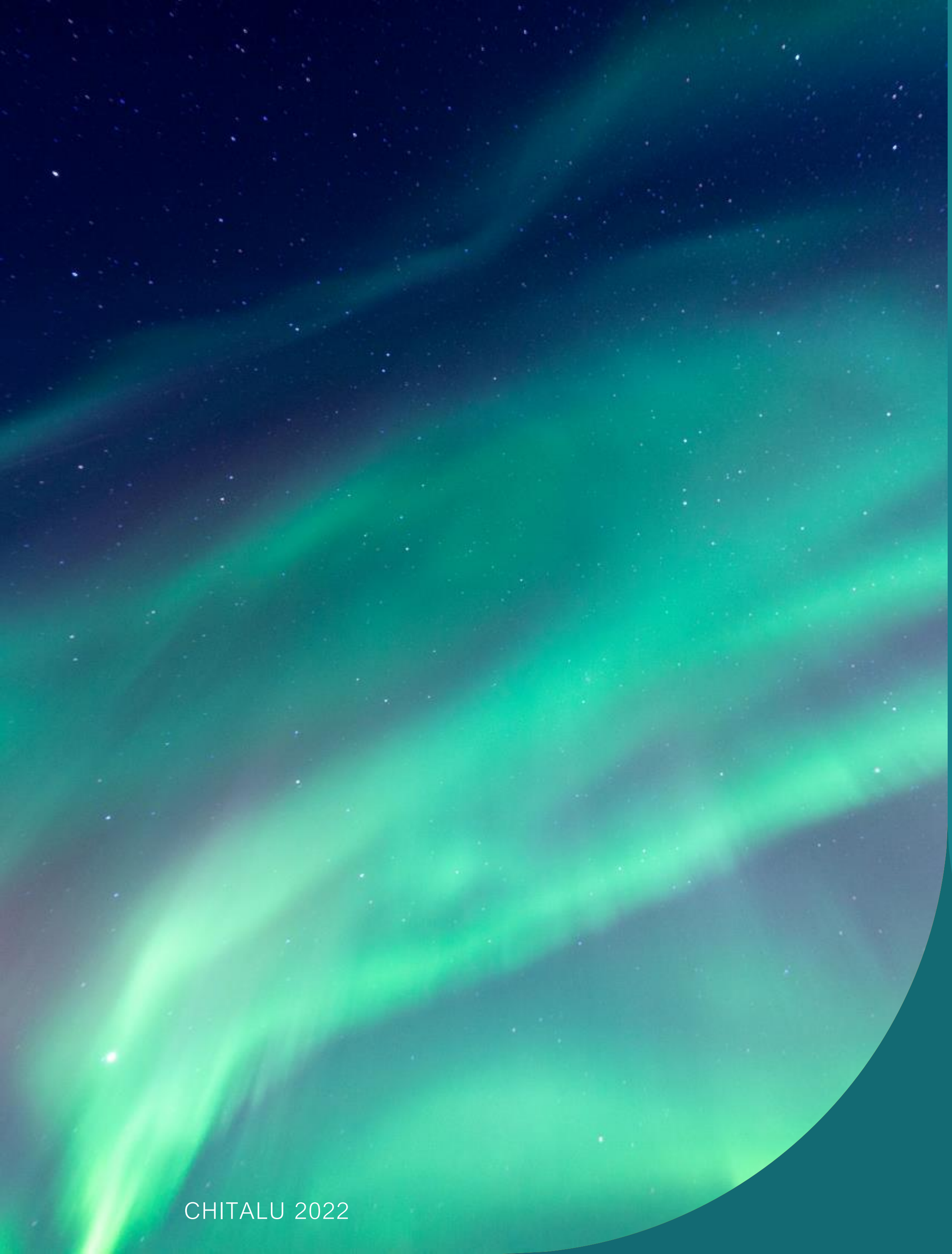
(d) $Q = \Delta U + W$

$$= -1\,606 + 704$$

$$= -\underline{902\ \text{kJ}},\ \text{a loss to the surroundings.}$$

“Science owes more to the steam engine than the steam engine owes to science”

Lawrence Joseph Hendersen



Thank You

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