

COURSE 225
HEAT & THERMODYNAMICS

MODULE 3
ENTROPY, THROTTLING AND MOLLIER DIAGRAM

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Heat and Thermodynamics

MODULE 3

ENTROPY, THROTTLING AND MOLLIER DIAGRAM

Course Objectives

1. Given a calculator and a set of S.I. steam tables, you will be able to perform the following calculations:
 - (a) Determination of final dryness fraction of steam expanded isentropically.
 - (b) Initial dryness fraction of steam prior to throttling.

Enabling Objectives

1. Illustrate a series of processes associated with the steam turbine on a Mollier diagram, which the student has sketched.

ENTROPY, THROTTLING AND MOLLIER DIAGRAM

The conception of "Entropy" presents a difficulty because it does not represent anything tangible or anything that has an immediate physical significance.

Entropy means 'spread' and any increase of entropy, increases the spread of energy, and as a result, lowers the availability of that energy for doing useful work.

If we had two different quantities of liquid, both having the same amount of heat but at different temperatures, the liquid at the higher temperature would have less entropy than the liquid at the lower temperature. Although the energy levels are the same, there is less energy available from liquid at the lower temperature.

In any real process, the entropy increases. In a completely ideal process, entropy stays constant. The process when entropy stays at the same value is called an ISENTROPIC process and provides a useful base to compare the performance of practical systems with the ideal performance.

I am sure you will be glad to know that we will not concern ourselves with entropy beyond a simple state. You may recall in Module 2 'Steam Tables,' that the only columns we did not look at were those headed "Specific Entropy."

When looking at the simple use of entropy, we can use it in exactly the same way as we did enthalpy, i.e.,

entropy of saturated steam is S_g

entropy of saturated liquid is S_f

entropy of wet steam is $S_f + qS_{fg}$.

Example

Saturated steam enters a low pressure turbine at 200°C and is exhausted at a pressure of 6 kPa(a). Determine the dryness fraction of the steam leaving the low pressure turbine if the expansion is ideal, i.e., isentropic.

Before we look at any values, the whole question revolves around the fact that the value of entropy before the steam expands is exactly the same as after the expansion.

The steam prior to expansion is saturated at a temperature of 200°C. The entropy will be S_g at 200°C, which from Table 1, is 6.4278 kJ/kg°C. (The units for entropy are the same as those for specific heat capacity.)

After expansion the steam will be 'wet' and we do not know the value of 'q', the dryness fraction. The steam is 5 kPa(a). Using Table 2,

$$S_f = 0.5209 \text{ kJ/kg}^\circ\text{C}$$

$$S_{fg} = 7.8104 \text{ kJ/kg}^\circ\text{C}$$

If the entropy is to be constant during the process, the initial entropy is equal to the final entropy.

$$\text{i.e., } S_{g200} = S_f(0.06 \text{ bar}) + qS_{fg}(0.06 \text{ bar})$$

$$\text{thus } 6.4278 = 0.5209 + q \times 7.8104$$

$$5.9069 = q \times 7.8104$$

$$\text{therefore, } q = \frac{5.9069}{7.8104} = 76.6\%$$

Do these examples and compare your answers at the end of the module.

Q3.1 Saturated steam at 160°C is allowed to expand isentropically until it is rejected to a condenser at pressure of 1 bar. Determine the dryness fraction of the steam at the exhaust to the condenser.

Q3.2 Steam which is 4% wet at 15 bar is expanded, isentropically to 60°C. Determine the dryness fraction of the final steam condition.

Q3.3 Saturated steam is expanded isentropically to 36°C where the dryness fraction is 87%. Determine the temperature of the initial steam.

* * * * *

Throttling

This is a process where a compressible fluid expands from one pressure to a lower pressure without doing any mechanical work. This is the process which occurs through the governor steam valves on the turbine when the governor steam valves are not full open. The smaller the percentage opening the greater the throttling effect becomes.

There is a major problem with the throttling process which is not obvious. When throttling takes place, the enthalpy of the fluid remains constant, ie, the enthalpy before the partially closed governor steam valve is equal to the enthalpy after the valve. This is true because the process occurs at high speed and there is no time for heat to pass through the containment walls. Secondly, there is no reduction of enthalpy due to work, because there is no work done. Sounds fair enough doesn't it? The problem is that although the enthalpy is the same, the entropy has increased in this process and we cannot get as much work out of the steam. This factor becomes of major consideration when considering the control of governor steam valves. Suppose we have a turbine which has four governor steam valves. If they all open at the same time then all four valves will be throttling the steam until the valves are fully opened when minimum throttling occurs. This method of control is called "throttle governing" and produces loss of efficiency if operating at any load other than full load. In peak load stations we use "nozzle governing" where the valves open one after the other, so that at any point in time there is, in principle, no more than one valve which is throttling the steam.

A significant change occurs with steam that is wet when throttled to a lower pressure.

A look at the temperature enthalpy diagram will help illustrate the condition.

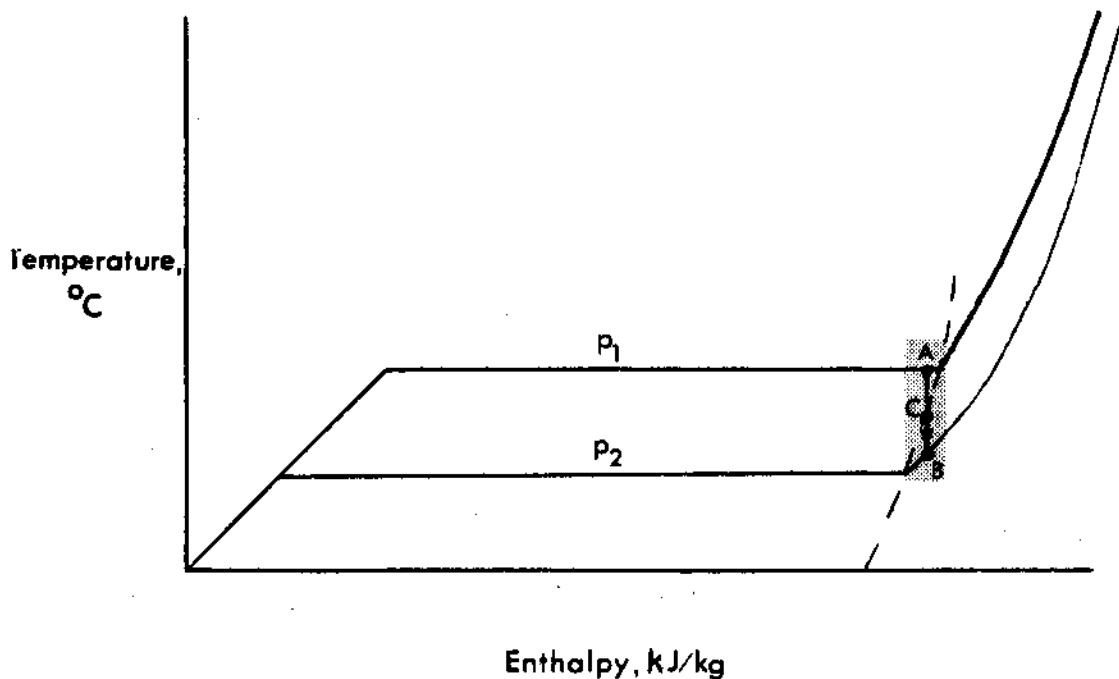


Fig. 3.1

Suppose at point A we have steam which has a small moisture content and exists at pressure P_1 . If we throttle the steam to a lower pressure P_2 , the enthalpy will remain constant and condition of the steam will be at point B.

The saturation line for the steam is not vertical and we can see that as the pressure falls, during the throttling process, the steam becomes dryer until it becomes saturated at point 'C' and then becomes superheated steam at point B. Do not forget the enthalpy has not changed.

Why is this event of any significance? During performance tests and commissioning of steam turbines using wet steam, it is essential to check the steam quality against design value to ensure that the turbine does not suffer severe erosion damage because of excessive levels of moisture.

You know that you have wet steam and you know the temperature and pressure. Is it any problem determining the dryness fraction of this steam? Sure there is. Knowing only the temperature and pressure you could have anything from saturated liquid through to saturated vapour. The missing factor is the value of enthalpy and with the given information, pinpointing this quantity is impossible.

However - if we could throttle the wet steam to a lower pressure and produce superheated steam, then knowing the pressure and temperature at this point would allow us to look up the enthalpy in Table 3 of the steam tables. Once we have found the enthalpy, which remains constant, we can determine the dryness fraction of the wet steam.

Here is an example - wet steam is throttled from a pressure of 40 bar to a pressure of 0.1 bar when the temperature is 100°C . Determine the dryness fraction of the initial wet steam.

Using Table 3, at 100°C and a pressure of 0.1 bar, the enthalpy of the superheated steam is 2688 kJ/kg.

We know that the enthalpy was constant and by using $h = h_f + qh_{fg}$ we can find 'q'.

Using Table 2, at 40 bar $h_f = 1087.4$ kJ/kg and $h_{fg} = 1712.9$ kJ/kg.

The enthalpy of the steam is 2688 kJ/kg.

Thus $2688 = 1087.4 + q \times 1712.9$

$1600.6 = q \times 1712.9 \text{ kJ/kg}$

$$q = \frac{1600.6}{1712.9}$$

$$= 93.4\%$$

Do these problems and check your answers at the end of the module.

Q3.4 Wet steam at 154°C is throttled to atmosphere at 1 bar and the temperature is measured to be 125°C. Determine the dryness fraction of the wet steam.

Q3.5 Initially wet steam at 15 bar is throttled to produce steam at 75°C and a pressure of 5 kPa(a). Determine the dryness fraction of the wet steam.

* * * * *

Mollier Diagram

This chart may be thought of as a graph of steam table values, with some other information added. Although there are many calculations that may be effectively performed using the diagram, we shall not be concentrating on this use of the diagram.

The temperature enthalpy diagram is limited in what it can show is happening in a process and this is the major benefit of looking at a Mollier diagram. We are going to use the diagram to describe the process and use the steam tables to make any calculations that are necessary.

Let us examine the information which is presented on the diagram.

Axes

The diagram is a plot of enthalpy against entropy and for most purposes we can ignore the entropy values.

Saturation Line

The saturation line lies between wet steam and superheated steam regions as shown. Anything below the line is wet steam and anything above the line is superheated steam.

Constant Moisture Lines

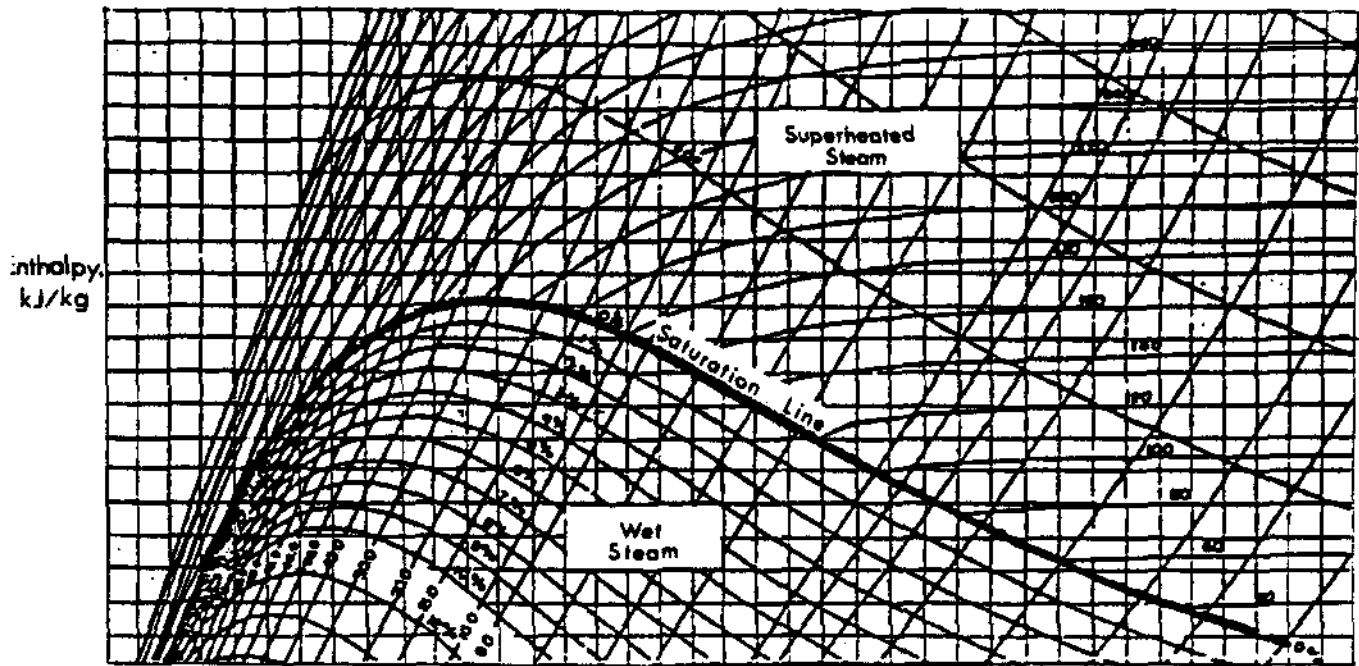
These lines run somewhat parallel to the saturation line in the wet steam region. The moisture content increases as the constant moisture lines become further away from the saturation line.

Constant Superheat Lines

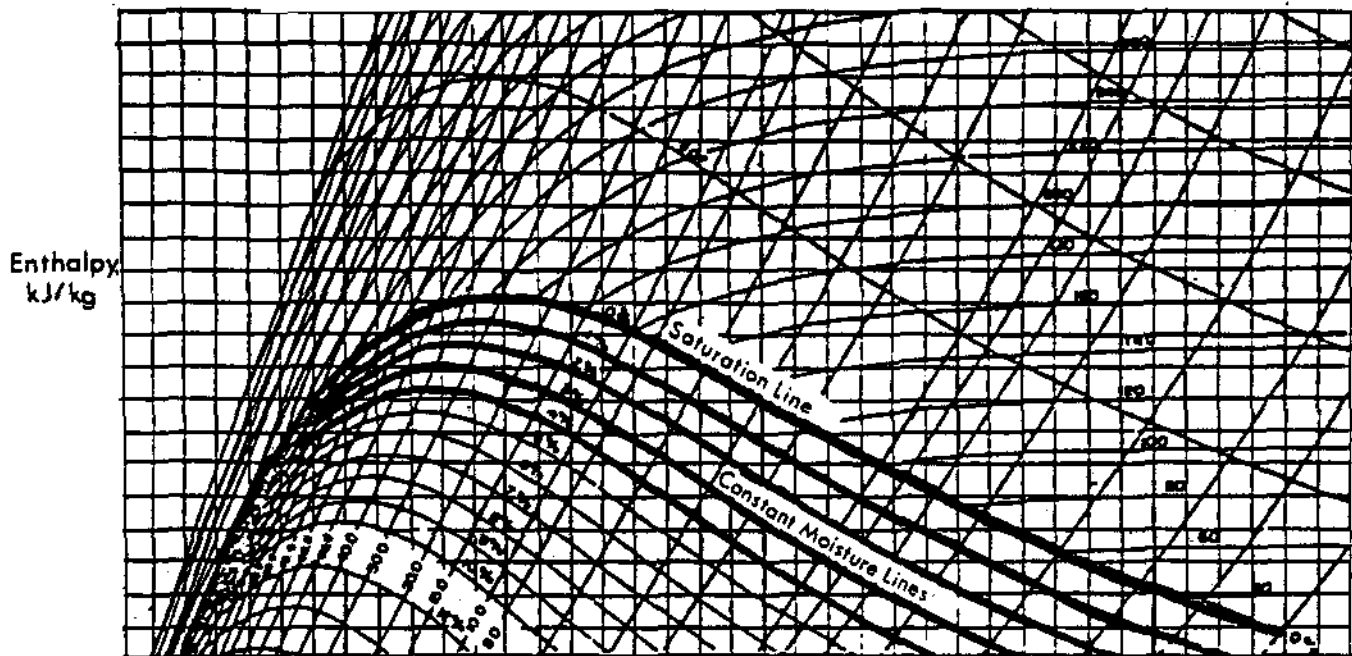
These lines follow a similar shape to the saturation line but are in the superheat region. The first line represents a condition which is 50°C above the saturation temperature at that pressure.

Lines of Constant Pressure

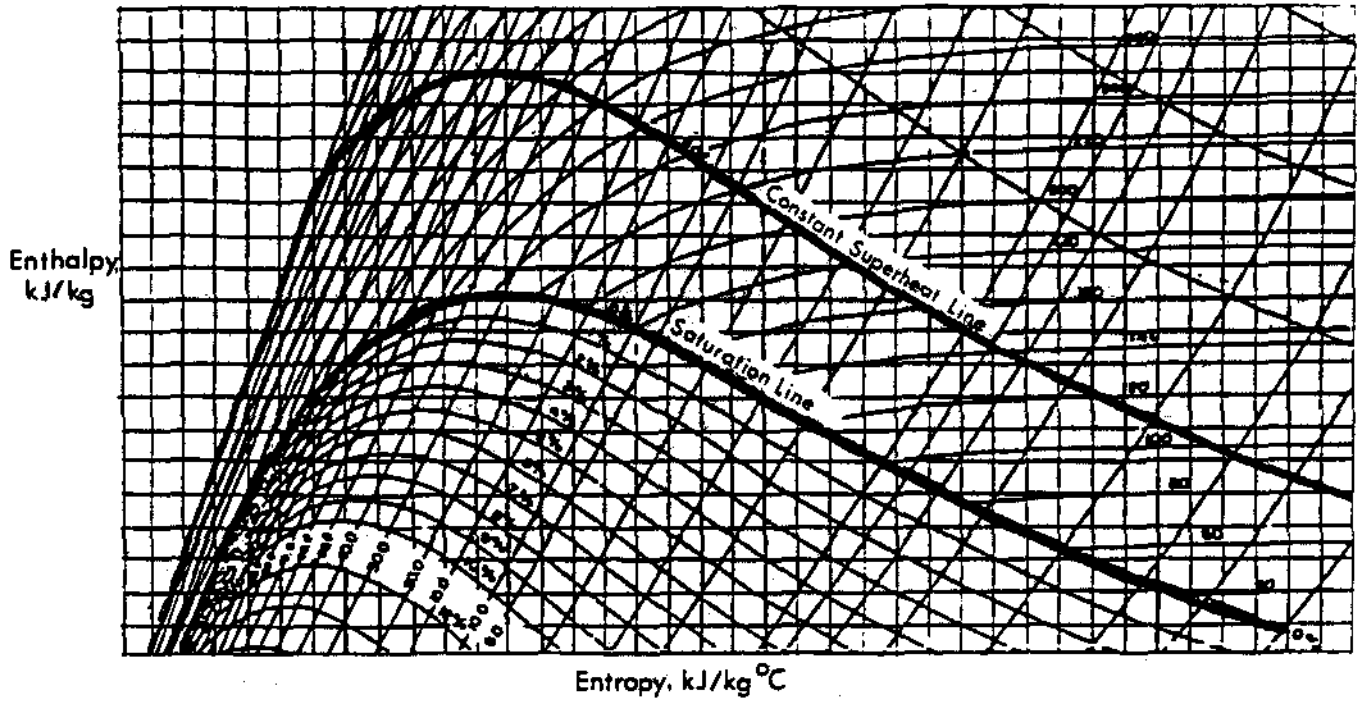
These lines run from the bottom left of the diagram towards the top right hand corner.



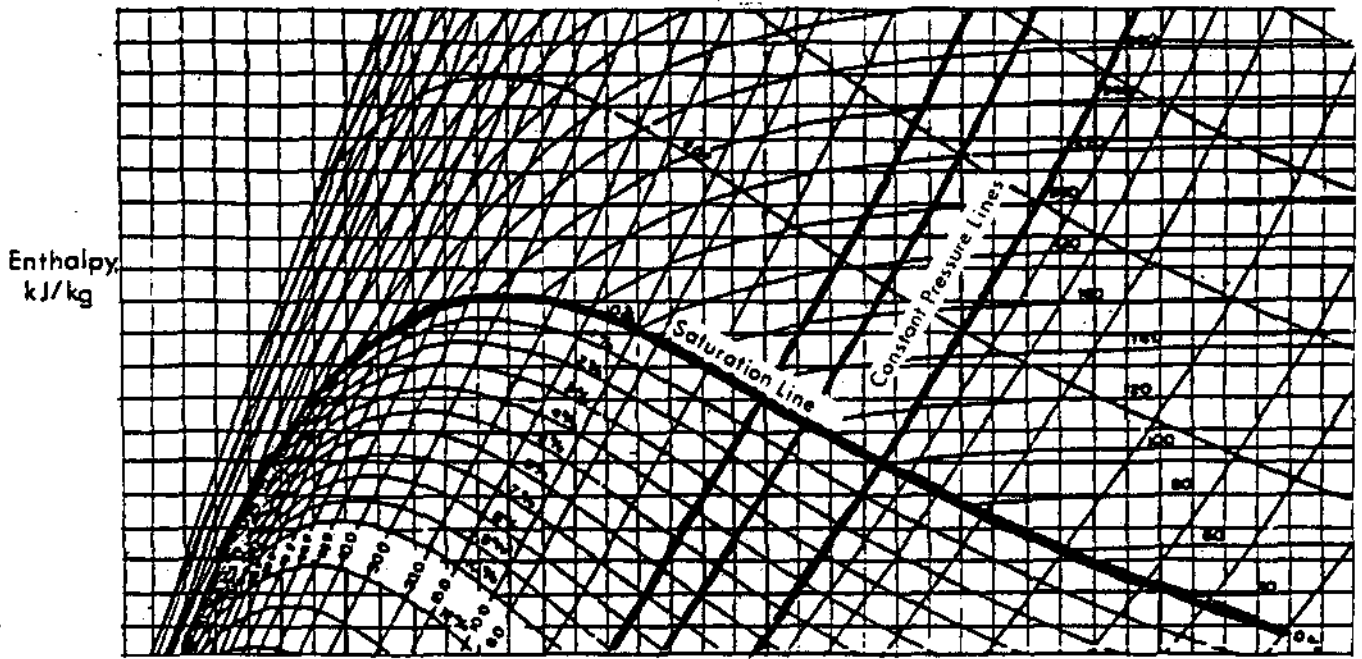
Entropy, kJ/kg °C
Fig. 3.2



Entropy, kJ/kg °C
Fig. 3.3



Entropy, kJ/kg °C
Fig. 3.4



Entropy, kJ/kg °C
Fig. 3.5

Lines of Constant Temperature

In the wet steam region the lines of constant temperature and constant pressure are parallel. This is because all the time the water is at saturation conditions, ie, saturated liquid through to saturated vapour, the temperature remains constant. Above the saturation line the constant temperature line moves over to the right as shown below.

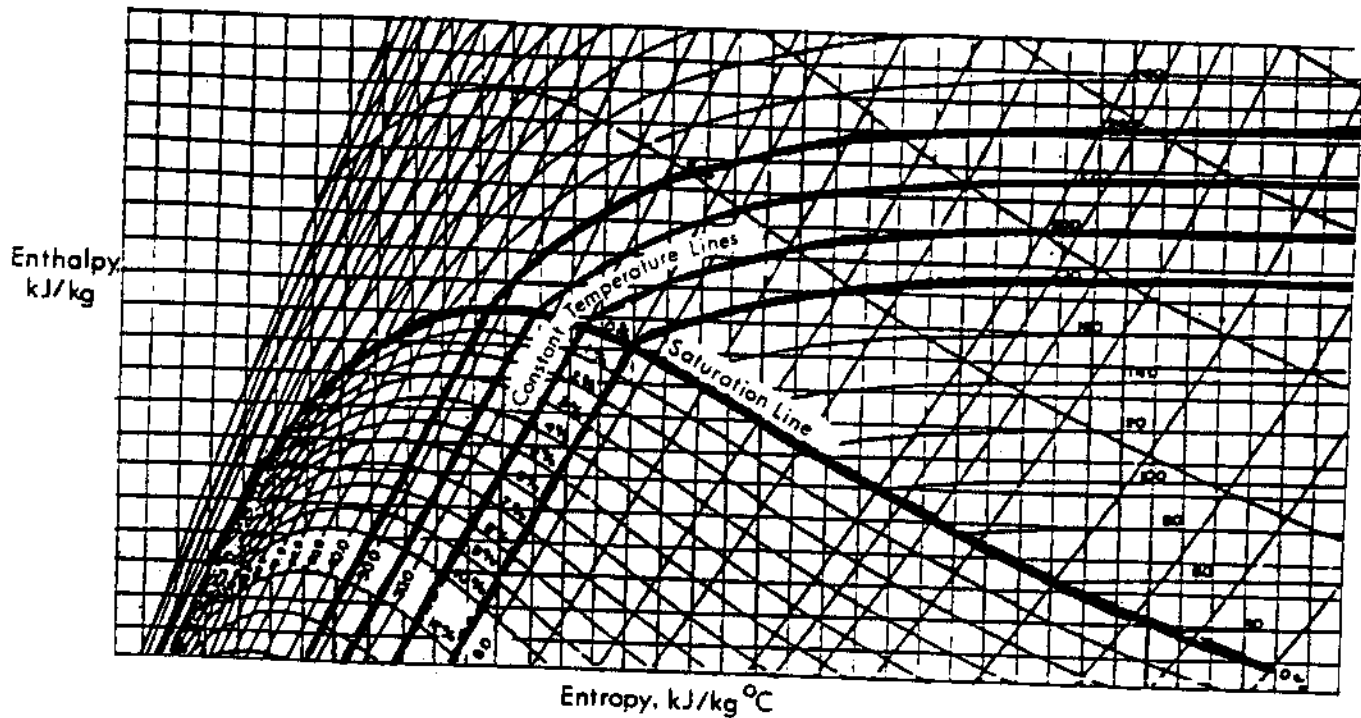


Fig. 3.6

Before we look at how we can use this array of lines, do the following exercise and compare with the diagram at the back of the module.

Q3.6 Using the Mollier diagram, given at the beginning of the module, as a guide, sketch the following:

- (a) Draw and label the axes required for the Mollier diagram.
- (b) Draw the saturation line.
- (c) Draw a single constant moisture line.
- (d) Draw a single constant superheat line.
- (e) Draw a single constant pressure line.
- (f) Draw a single constant temperature line.

* * * * *

We must examine a few processes to see how they are displayed on the Mollier diagram.

Suppose we consider a typical steam turbine in a nuclear station and plot the various points. You remember when we looked at "entropy" we said that in the real world the entropy always increases. If you watch the progress on the Mollier diagram you will see this is true.

Expansion of Steam in the HP Turbine

If we look at the initial steam condition entering the high pressure turbine where the steam is saturated and at 250°C we have the starting point for the process.

The steam is saturated so the point must lie on the saturation line. If you examine the lines of constant temperature you will find that the intervals are every 20°C. Consequently 250°C will lie between the lines representing 240°C and 260°C:

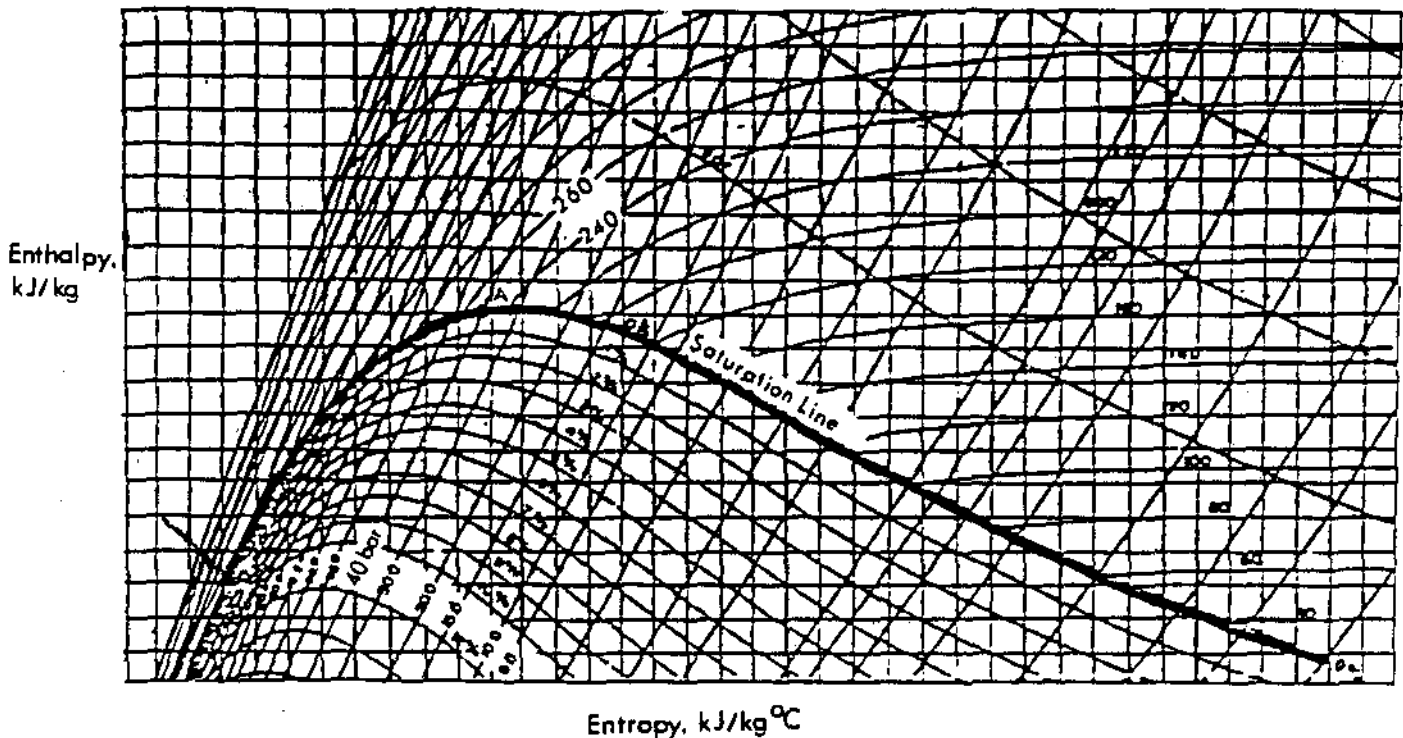


Fig. 3.7

The initial operating point is where the 250°C temperature line intersects the saturation line. If you look at the pressure line that passes through 'A' you will see that the saturation pressure is 40 bar. On the enthalpy axis, the enthalpy of the steam is represented by H_A .

The steam is expanded to a lower pressure in the high pressure turbine, down to a pressure of 10 bar. The moisture of the steam leaving the high pressure turbine is 10%. This makes the plotting of the second point very easy. If we follow the constant pressure line for 10 bar up until it intersects with the 10% constant moisture line, this is the operating condition of the turbine exhaust.

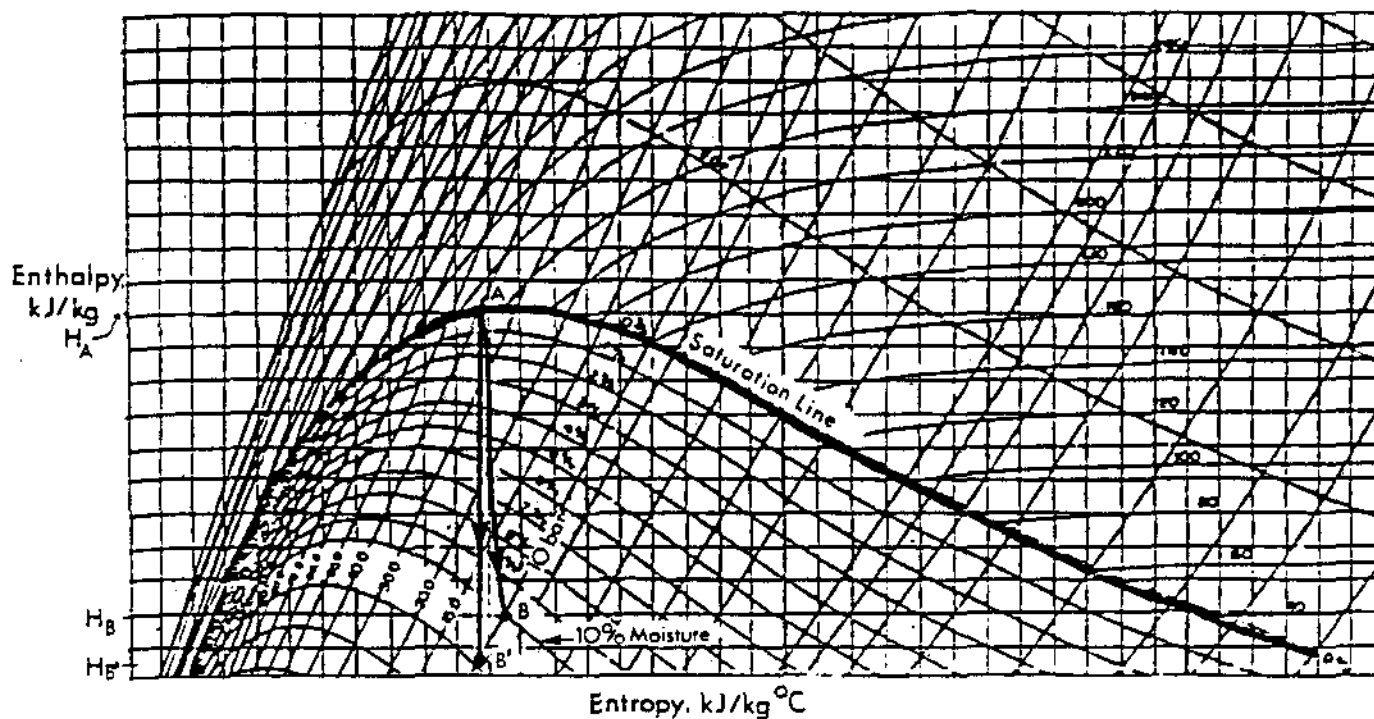


Fig. 3.8

The temperature at 'B' is the saturation temperature for a pressure of 10 bar which from the diagram is 180°C. You will notice that point B is further to the right of the diagram than point B' because entropy has increased due to surface and fluid friction. In the ideal case the entropy would remain constant and instead of expanding to point B the steam would have expanded to point B'.

The maximum amount of work available from the turbine would be the enthalpy difference between points A and B', ie, $H_A - H_{B'}$. In practice the work available was less than the ideal and only equal to the enthalpy difference $H_A - H_B$.

From the information that we used, you can see that we could calculate the enthalpy drop either by using tables, as we have already seen, or by using the scales on the Mollier diagram.

Moisture Separation

This part of the process can be a stumbling block if we are not careful. There are several things happening at once, some real and some apparent.

Ignoring the pressure drop through the moisture separator, we can show moisture separation as taking place at constant pressure. Before we get into detailed discussion, take a look at the separation process on the Mollier diagram.

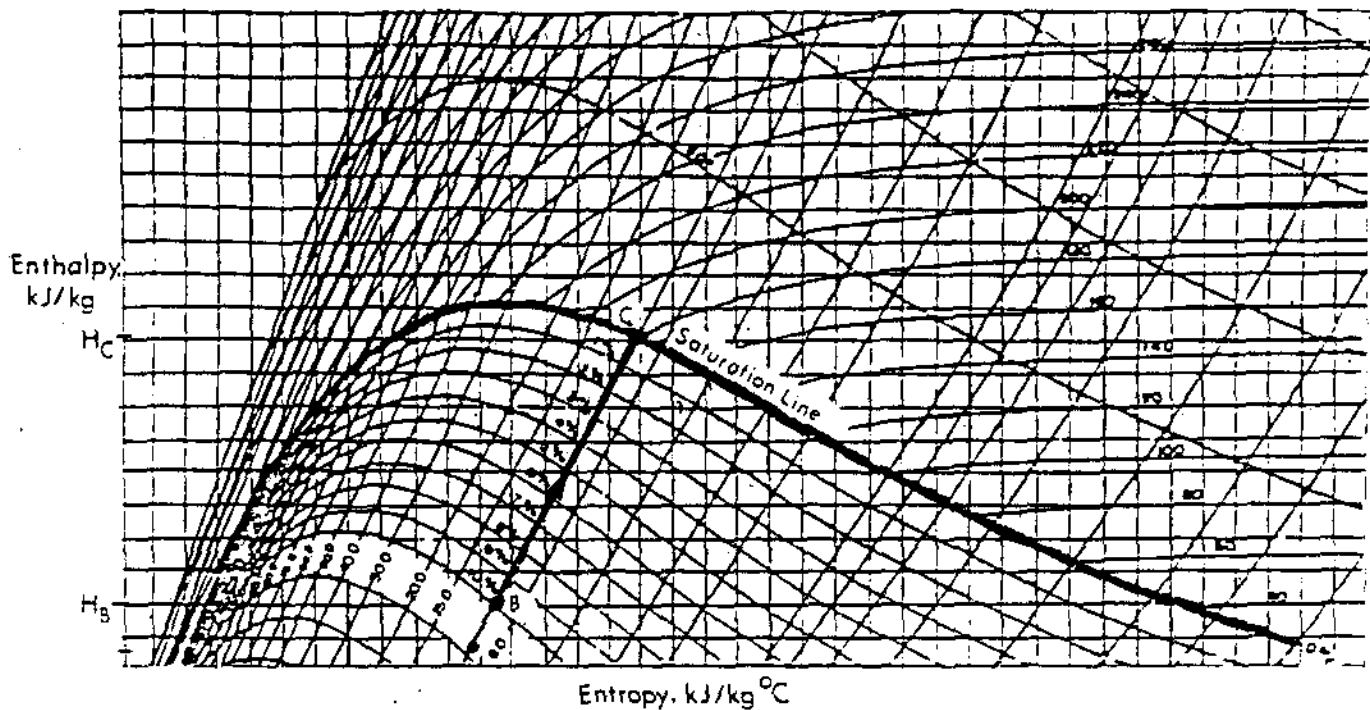


Fig. 3.9

The pressure remains constant and the process proceeds from condition B where the steam is 10% wet to condition C where the steam is saturated.

Looking across at the enthalpy scale you will see that the enthalpy has risen from H_B to H_C . So we must obviously have added some heat - not true. In fact we removed some heat. If this is so, how is it that the enthalpy appears to have increased - good question.

The answer is fairly simple. The quantity of "steam" at B is not the quantity of steam at C. Suppose we have 10 kg of steam at point B that is 10% wet. This is really the same as saying we have 9 kg of saturated steam and 1 kg of saturated water. Let us put some figures in to make this point. Let $h_g = 2700$ kJ/kg and $h_f = 700$ kJ/kg.

Then the average enthalpy of this mixture is

$$\frac{(9 \text{ kg} \times 2700 \text{ kJ/kg}) + (1 \text{ kg} \times 700 \text{ kJ/kg})}{10 \text{ kg}}$$

$$= \frac{24300 + 700}{10}$$

$$= 2500 \text{ kJ/kg}$$

When we pass the wet steam through the moisture separator we removed 1 kg of saturated liquid, ie, the low grade water and now the enthalpy of the working fluid which is saturated steam, is 2700 kJ/kg, an increase of 200 kJ/kg. BUT the overall quantity of steam has now been reduced by 10%. This is the pitfall when negotiating this part of the process. You must make sure that you change the flowrate after the moisture separation to account for the mass of liquid removed. If the steam leaving the moisture separator is saturated and the steam was x% wet, then the reduction in steam flow as a result of moisture separation is also x%.

Reheat

Again for purposes of illustration assume that there is no pressure drop through the reheater. Heating is taking place at constant pressure, so the process will continue to follow the constant pressure line.

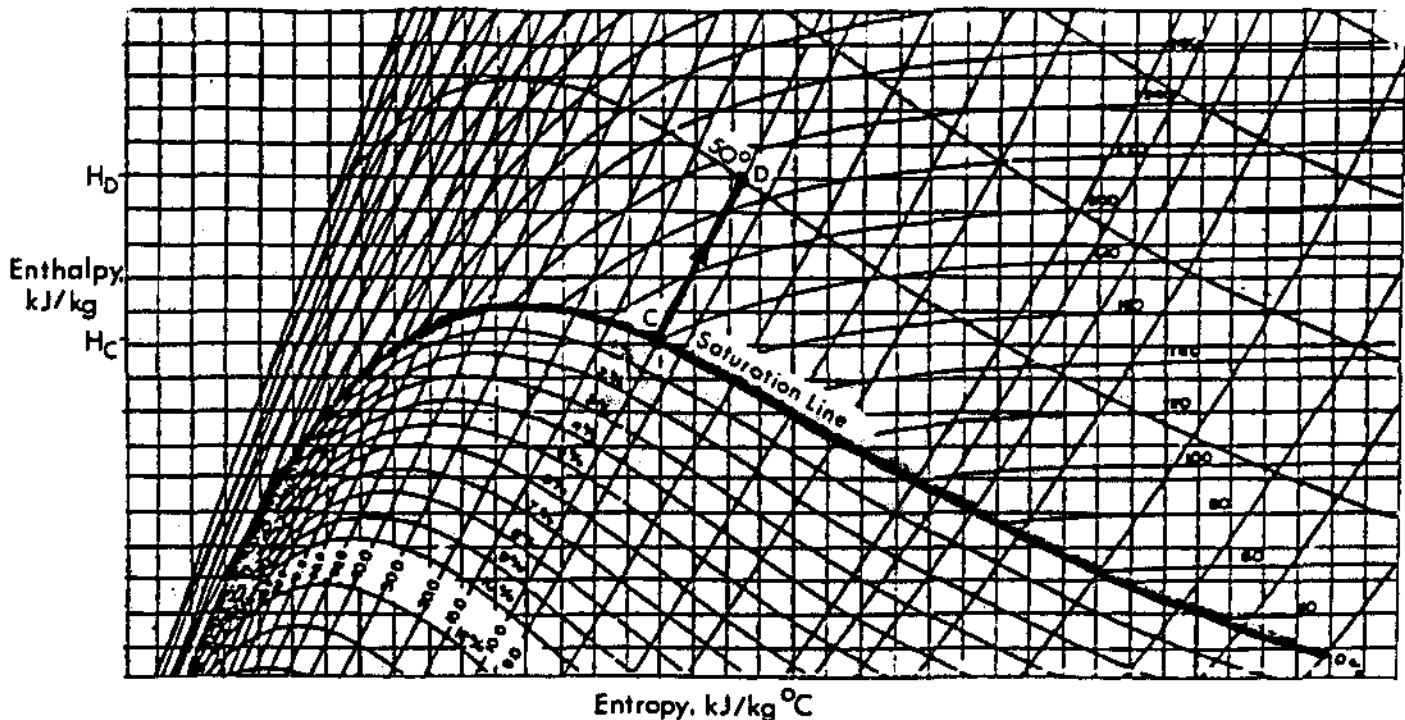


Fig. 3.10

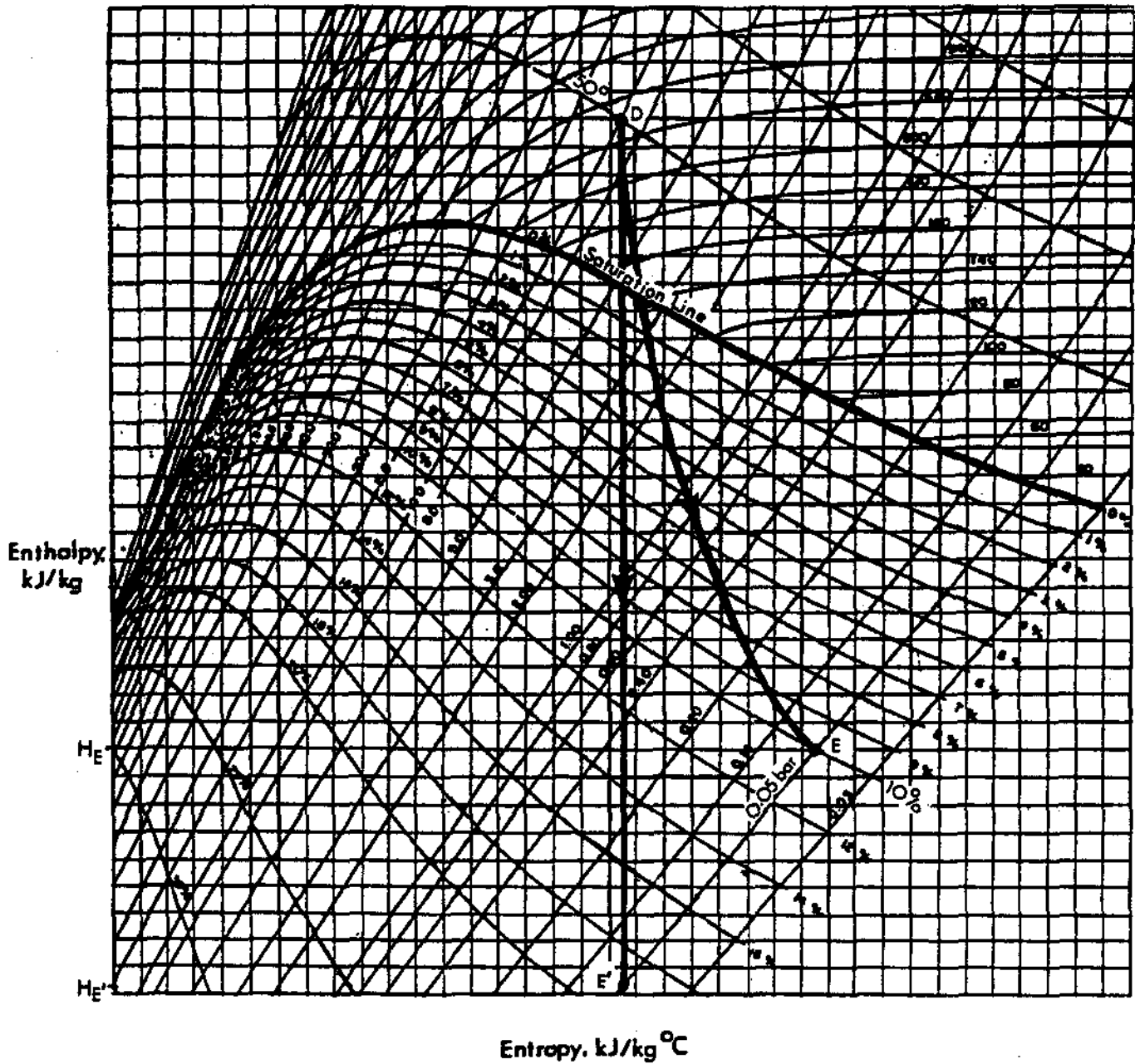
Before we leave point 'C' we did not mention that the temperature did not change throughout the moisture separation process and is of course the saturation temperature corresponding to a pressure of 10 bar and $t_s = 180^\circ\text{C}$.

The addition of heat from the reheater is going to raise the temperature above the saturation temperature and produce superheated steam. For ease of illustration assume that the reheater adds 50°C of superheat. The operating point 'D' occurs where the constant pressure line intersects the constant superheat line of 50°C . The temperature of the steam is now $180 + 50 = 230^\circ\text{C}$. The change in enthalpy of the steam is $H_D - H_C$ which is equal to the heat lost by the reheater.

Expansion in the Low Pressure Turbine

The expansion of the steam in the low pressure turbine is the same in principle to the expansion in the high pressure turbine, the only difference being that the steam is initially superheated.

The steam will expand to condenser pressure, say 5 kPa(a) and the condition will be 10% moisture. If we plot this point on the diagram, this represents the end of the steam process before condensation occurs.

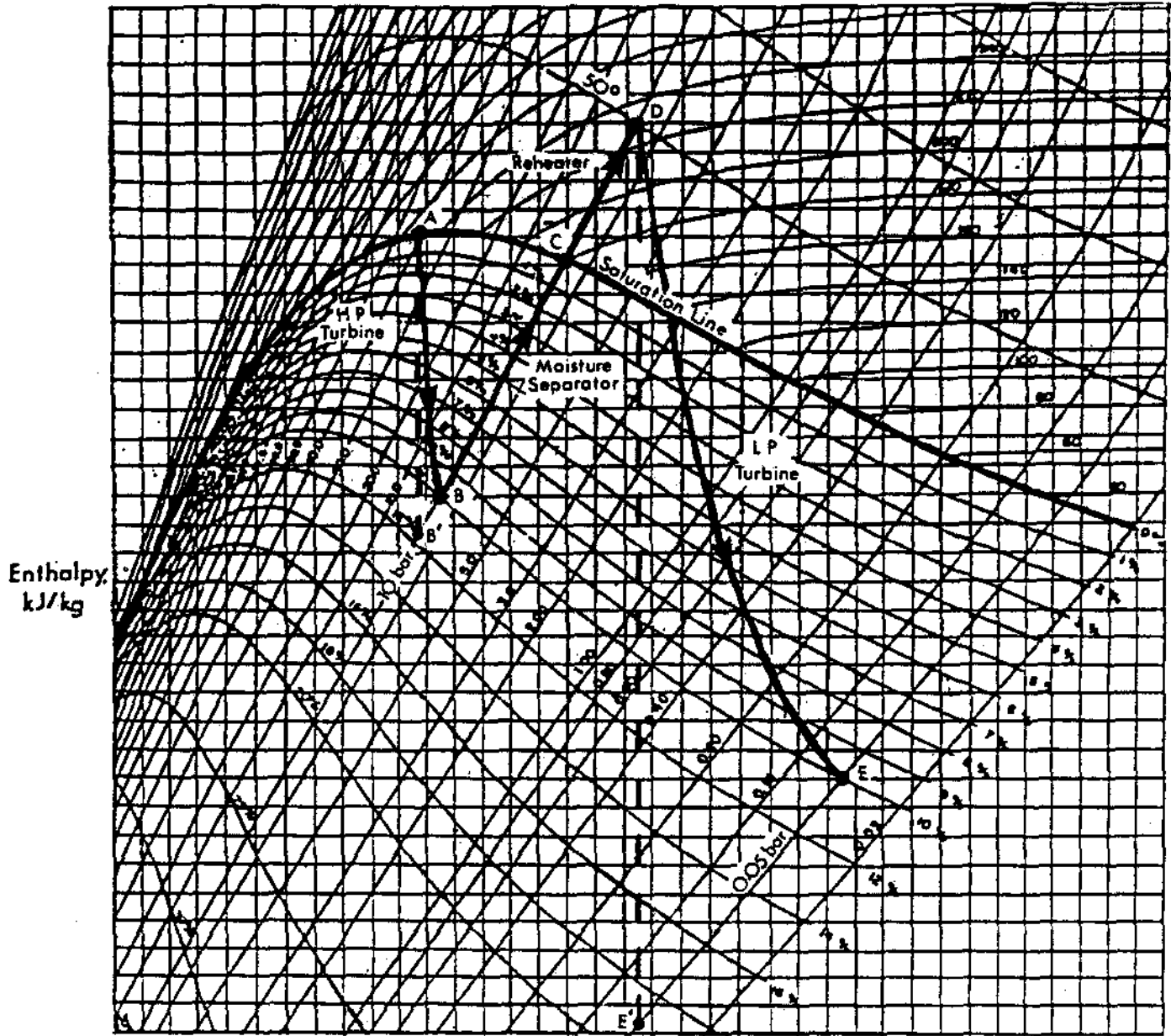


Entropy, kJ/kg °C

Fig. 3.11

If the expansion in the low pressure turbine had been ideal, i.e. had there been no friction, then entropy would have been constant and the available work from the low pressure turbine would have been equal to $H_D - H_{E'}$.

Using the Mollier diagram to illustrate the complete process, we can see the trends in changes of enthalpy, moisture, etc, and when used in conjunction with the steam tables it provides a good graphical aid to help solve the problem.



Entropy. kJ/kg °C

Fig. 3.12

Do these problems and check your answers at the end of the module.

Q3.7 Sketch your own Mollier diagram to illustrate the following series of processes: A high pressure turbine uses saturated steam at 240°C and exhaust the 10% wet steam to a moisture separator at 160°C. The separator produces 2% wet steam and is followed by a reheater which produces 40°C of superheat. The superheated steam expands in a low pressure turbine to 10% moisture at 35°C.

Q3.8 Explain how your sketch would change if you had to show the condensation process in the condenser associated with question Q3.7.

Q3.9 The mass flowrate of steam into the high pressure turbine, in question Q3.7 is 900 kg/s. Determine the mass flow into the reheater.

* * * * *

Throttling

We have already looked at this process using enthalpy values from the steam tables. The process may be clearly shown on the Mollier diagram.

Remember that throttling is a constant enthalpy process, so on the Mollier diagram this is represented by a horizontal line.

An example will illustrate the process. Steam at 40 bar with 3% moisture is throttled to 2 bar. Determine the final temperature of the steam and the degree of superheat.

Before we look at the diagram, we know that by throttling wet steam to a low enough pressure we can produce not only saturated steam, but superheated steam.

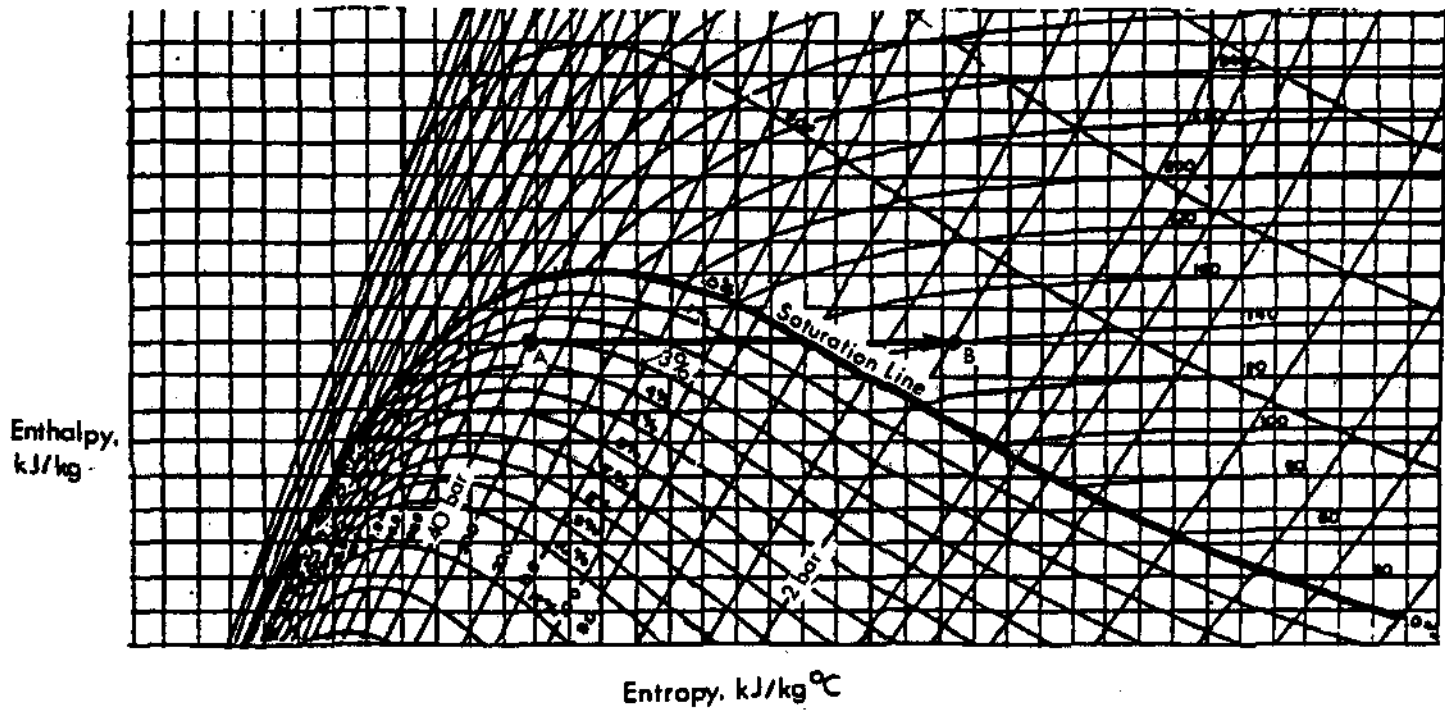


Fig. 3.13

As the steam is throttled from point A, to the lower pressure at point B, the quality changes from wet steam to superheated steam at a temperature of 140°C which, from the diagram, is roughly 20°C above the saturation temperature and therefore there are 20°C of superheat.

This looks like a convenient way of producing superheated steam and perhaps we should use this technique to produce superheated steam entering the high pressure turbine. It can be done thermodynamically without any difficulty.

Suppose we take the saturated steam at 250°C , which is the normal condition of steam entering the high pressure turbine, and produce superheated steam by throttling it to 1 bar prior to entry to the turbine. All the time the heat content remains constant.

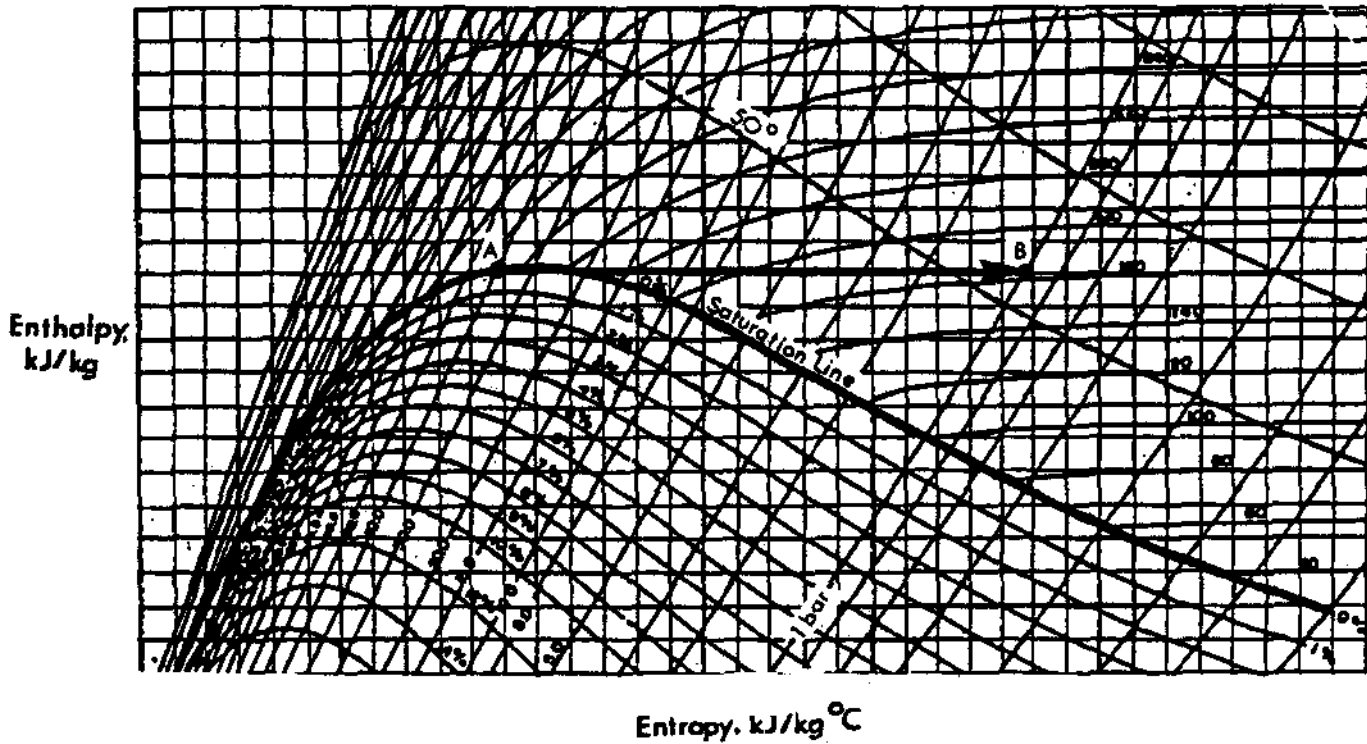


Fig. 3.14

This process produces steam which is well superheated with a temperature around 65°C above the saturation temperature so there are no problems of excessive moisture.

Q3.10 Why don't we take advantage of this process? There is no loss of enthalpy and we have steam which is well superheated - how can we go wrong. Analyze this situation and in a few lines write down why you think we do not use this as a solution to the moisture problems in our turbines. Check your answer at the end of the module.

MODULE 3 - ANSWERSQ3.1

The whole process takes place at constant entropy, i.e. the initial entropy is equal to the final entropy.

The initial condition is saturated steam at 160°C. From Table 1, S_g at 160°C = 6.7475 kJ/kg°C.

The final condition is wet steam at 1 bar, the dryness fraction is unknown.

At 1 bar S_f = 1.3027 kJ/kg°C
and S_{fg} = 6.0571 kJ/kg°C

$$\begin{aligned} S_{1 \text{ bar}} &= S_f + qS_{fg} \\ &= 1.3027 + q \times 6.0571 \text{ kJ/kg°C} \end{aligned}$$

Equating the initial and final conditions,

$$S_{g160} = S_{1 \text{ bar}}$$

Substituting 6.7475 = 1.3027 + q x 6.0571 kJ/kg°C

$$5.4448 = q \times 6.0571$$

$$\text{hence } q = \frac{5.4448}{6.0571} = \underline{89.9\%}$$

Q3.2

Again we know that the entropy remains constant throughout the process and that the initial and final entropies are equal.

The initial condition is 4% wet steam at 15 bar and using Table 2 we can determine the entropy using

$$S = S_f + qS_{fg}$$

$$S_f = \text{at 15 bar} = 2.3145 \text{ kJ/kg°C}$$

$$S_{fg} = \text{at 15 bar} = 4.1261 \text{ kJ/kg°C}$$

$$S = 2.3145 + 0.96 \times 4.1261 \text{ kJ/kg°C}$$

$$= 2.3145 + 3.9611$$

$$= \underline{6.2756 \text{ kJ/kg°C}}$$

The final condition will be wetter steam than 4% at 60°C.

$$S_f \text{ at } 60^\circ\text{C} = 0.8310 \text{ kJ/kg}^\circ\text{C}$$

$$S_{fg} \text{ at } 60^\circ\text{C} = 7.0798 \text{ kJ/kg}^\circ\text{C}$$

Equating initial and final conditions we get:

$$6.2756 = 0.8310 + q \times 7.0798 \text{ kJ/kg}^\circ\text{C}$$

$$5.4446 = q \times 7.0798$$

therefore, $q = 76.9\%$

Q3.3

Again we know that the entropy is constant throughout and we can determine the value of entropy at the final condition using

$$S = S_f + qS_{fg}$$

Using Table 1, at 36°C $S_f = 0.5184 \text{ kJ/kg}^\circ\text{C}$

$$\text{and } S_{fg} = 7.8164 \text{ kJ/kg}^\circ\text{C}$$

$$\text{Thus } S = 0.5184 + 0.87 \times 7.8164$$

$$= 0.5184 + 6.8003 \text{ kJ/kg}^\circ\text{C}$$

$$= \underline{7.3187} \text{ kJ/kg}^\circ\text{C}$$

We know that the entropy is constant so this value of 7.3187 kJ/kg°C is also the initial value.

If we look at S_g , because we are told that the initial steam condition is saturated, in Table 1, we will be able to find the value of t_s which most nearly has a corresponding value of $S_g = 7.3187 \text{ kJ/kg}^\circ\text{C}$.

The nearest value is $S_g = 7.3196 \text{ kJ/kg}^\circ\text{C}$ at $t_s = \underline{103^\circ\text{C}}$.

Q3.4

The final condition of the superheated steam allows us to pinpoint the enthalpy. Using Table 3, 125°C is halfway between the quoted values, so at a pressure of 1 bar and a temperature of 125°C, h is

$$\frac{2776 + 2676}{2} = \underline{2726} \text{ kJ/kg}$$

This enthalpy remains constant.

Using Table 1 we can find the values of h_f and h_{fg} at 154°C which are 649.4 kJ/kg and 2100.6 kJ/kg respectively.

Using $h = h_f + qh_{fg}$ we get

$$2726 = 649.4 + q \cdot 2100.6 \text{ kJ/kg}$$

$$2076.6 = 1 \times 2100.6$$

$$1 = \frac{2076.6}{2100.6}$$

$$= \underline{98.9\%}$$

Q3.5

Again the final condition is the key to the solution. Using Table 3, 75°C is in between the stated values. At a pressure of 5 kPa(a) and a temperature of 75°C ,

$$h = \frac{2594 + 2688}{2} = \underline{2641} \text{ kJ/kg}$$

This enthalpy remains constant and allows 'q' to be determined using $h = h_f + qh_{fg}$. Using Table 2, h_f and h_{fg} at a pressure of 15 bar are 844.7 kJ/kg and 1945.2 kJ/kg respectively.

Using $h = h_f + qh_{fg}$ we get

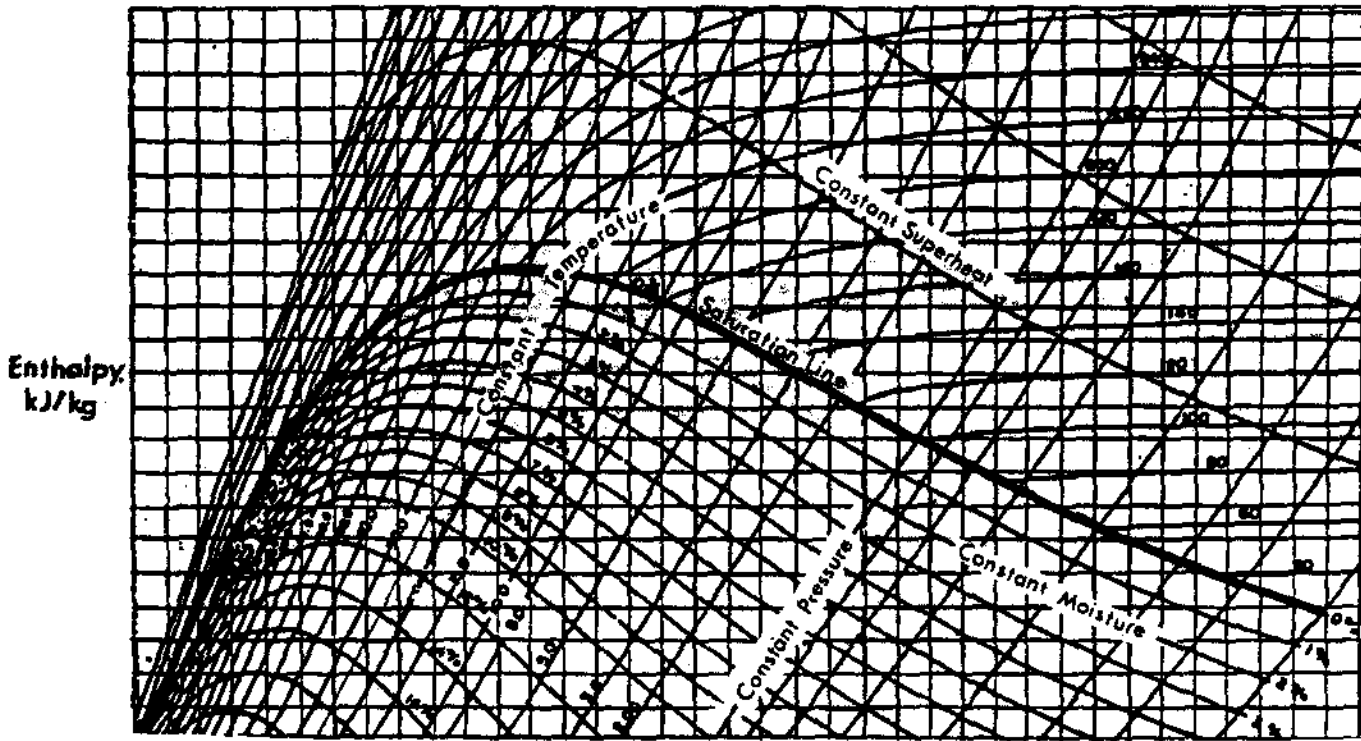
$$2641 = 844.7 + q \times 1945.2 \text{ kJ/kg}$$

$$1796.3 = q \times 1945.2$$

$$q = \frac{1796.3}{1945.2}$$

$$= \underline{92.3\%}$$

03.6



Entropy, kJ/kg °C
Fig. 3.15

03.7

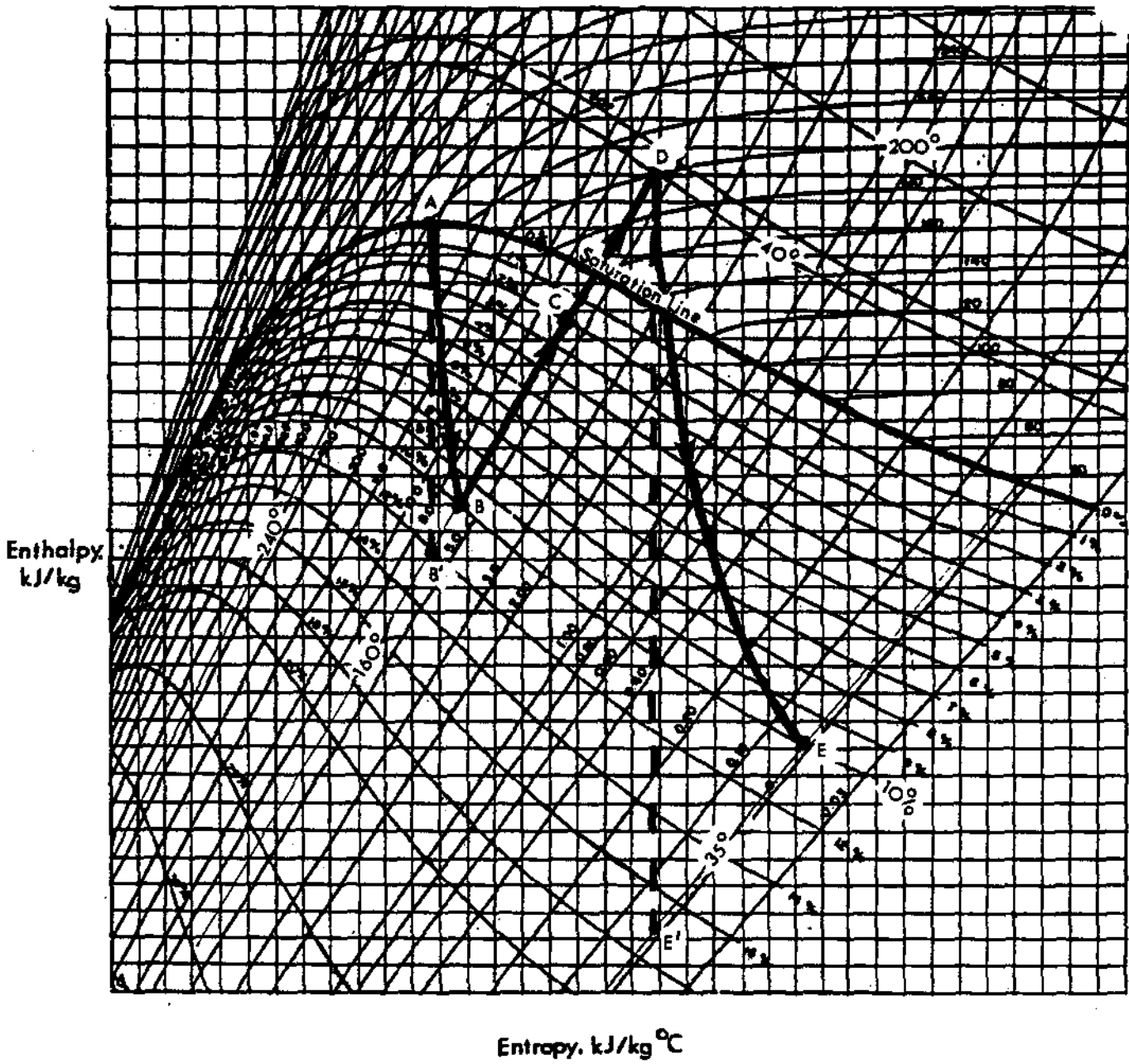


Fig. 3.16

Process A - B

Initial condition is saturated steam at 240°C. Expansion in the high pressure turbine, allowing for frictional effects, takes the process to the right of point B' at a moisture level of 10%.

Process B - C

The moisture separator, assuming no pressure drop, removes moisture from 10% to 2%. The temperature remains constant at the saturation temperature of 160°C.

Process C - D

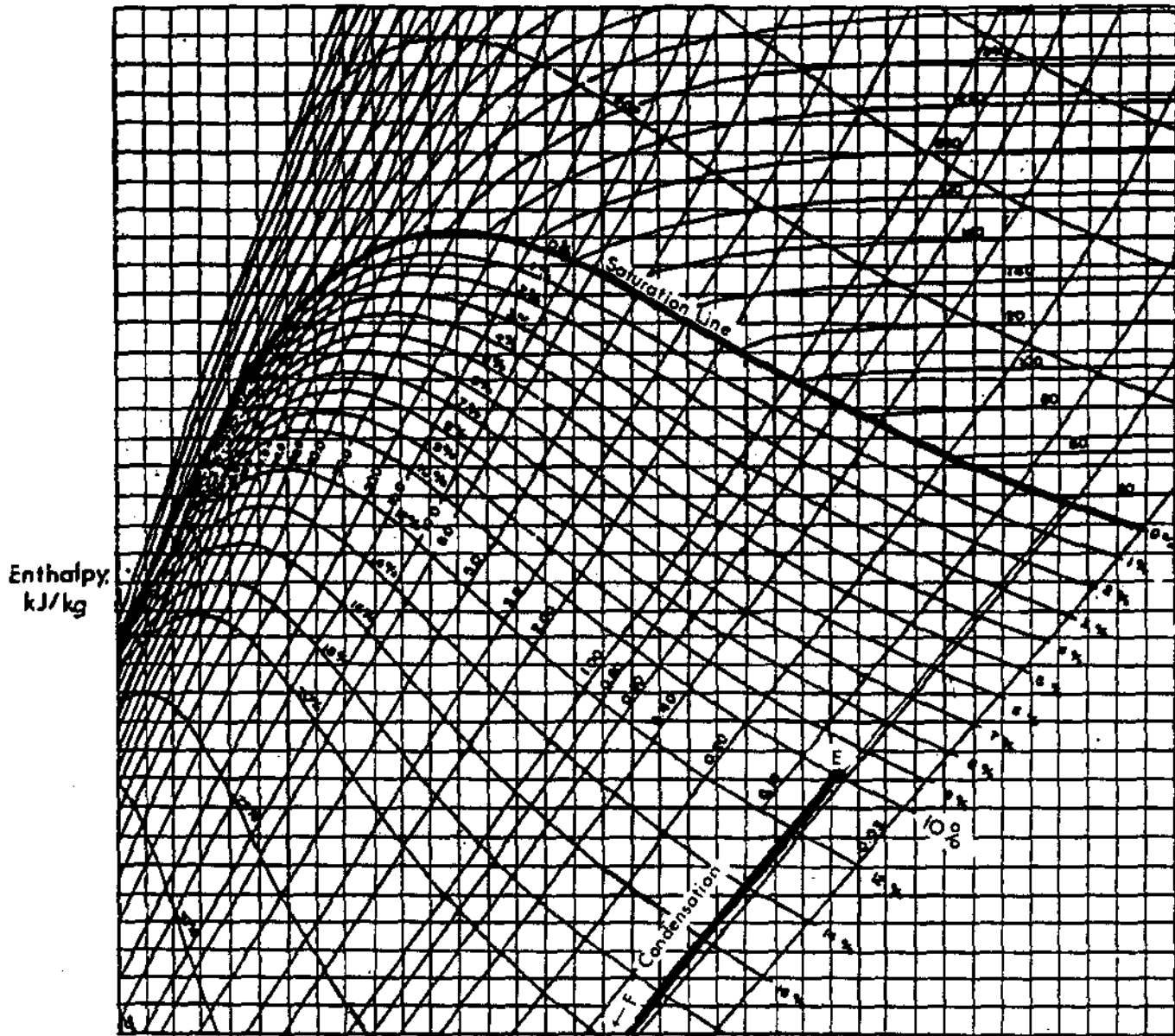
Again assuming no pressure loss in the reheater, the enthalpy of the steam is increased at constant pressure, initially up to the saturated steam condition, after which further addition of heat raises the temperature from 160°C to 200°C.

Process D - E

The superheated steam expands in the low pressure turbine and allowing for friction takes the process to the right of point E' where the final temperature is 35°C and the moisture level is 10%.

Q3.8

If the condensation process was illustrated on the Mollier diagram this would take place at constant pressure and temperature while the latent heat was being removed. The process would move down the constant pressure/temperature line to some point off the diagram when the moisture would be 100%, i.e., at the saturated liquid line.



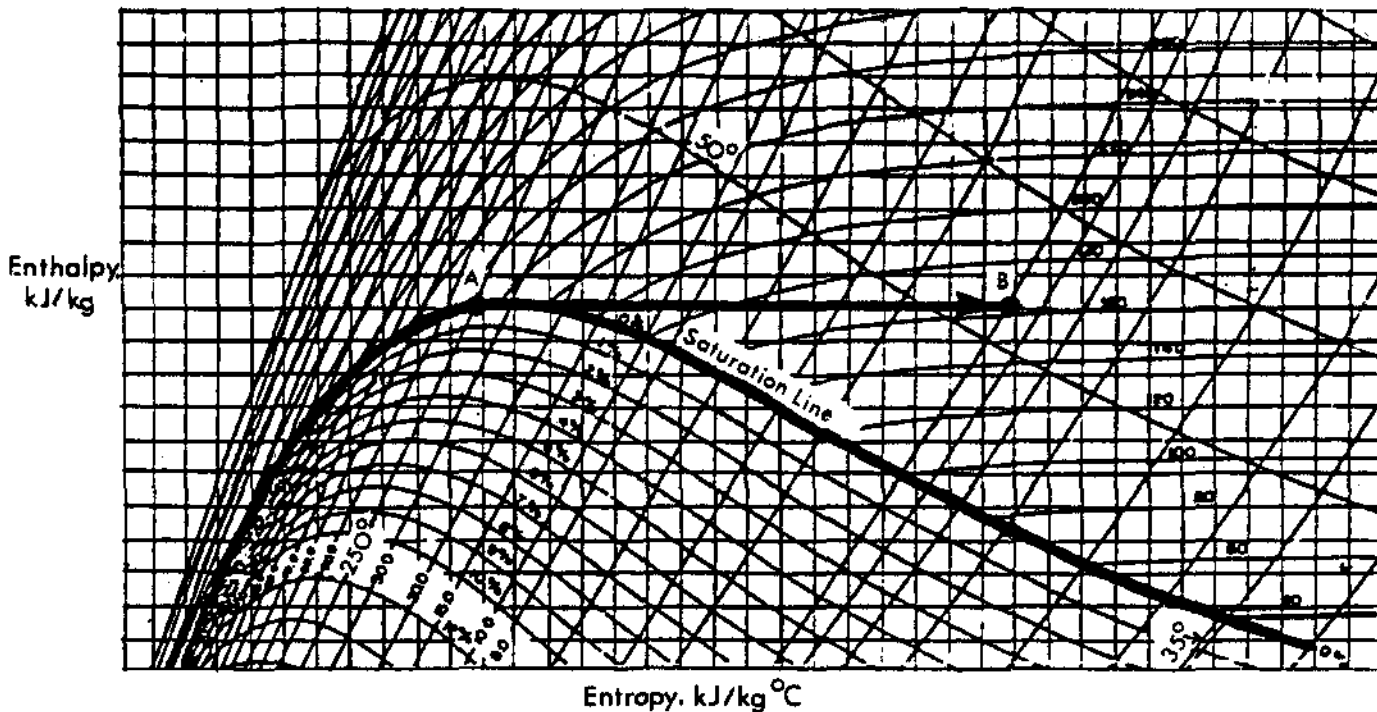
Entropy, kJ/kg °C
Fig. 3.17

Q3.9

The change in mass flow occurs in the moisture separator where the dryness fraction is increased from 90% to 98% by removing the moisture droplets. Consequently 8% of the working fluid has been removed and the flow into the reheater = 0.92×900 .

$$= 828 \text{ kg/s.}$$

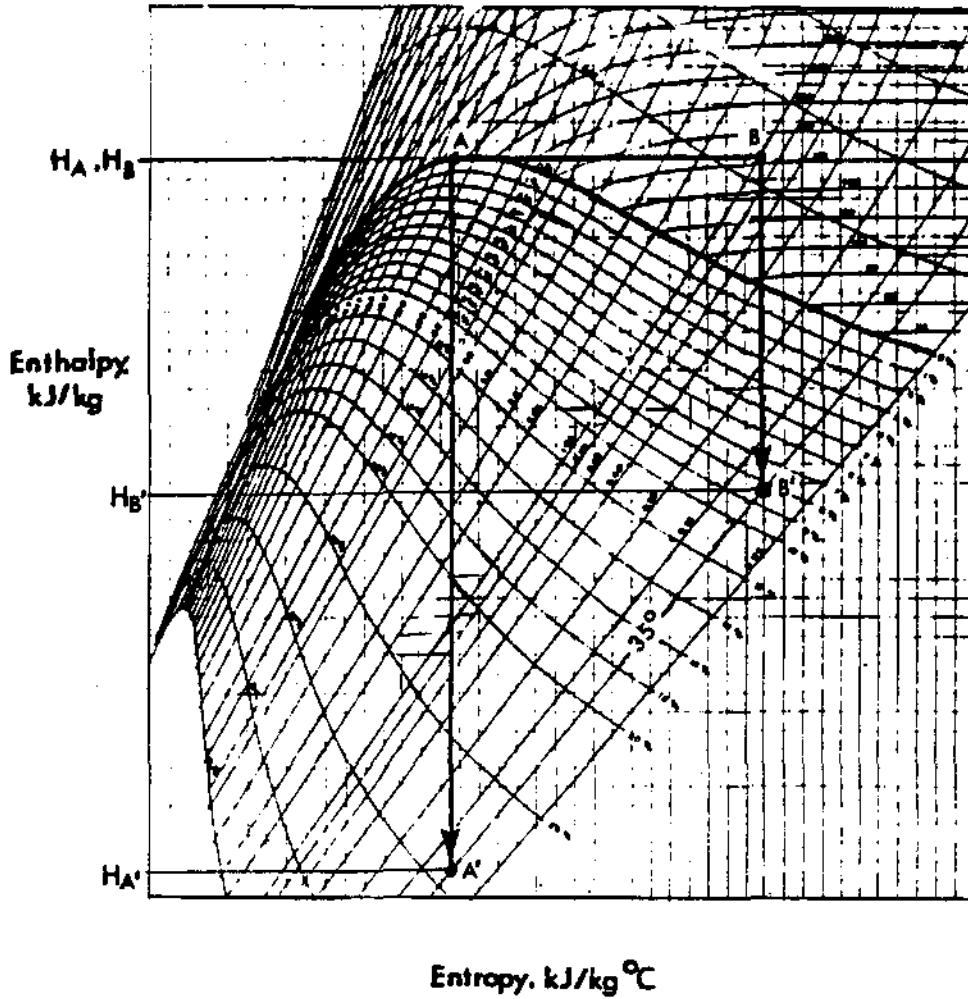
Q3.10



Entropy, $\text{kJ/kg}^\circ\text{C}$
Fig. 3.18

The enthalpy at points A and B is the same. The amount of work that is available depends upon the change of enthalpy. In practice we expand the steam in the turbine to a temperature which is dictated by the cooling water supply. Assume that the turbine exhaust is at 35°C . The enthalpy drop from the initial condition to the constant temperature line will indicate the work available.

If we consider the process from point A, the enthalpy drop is $H_A - H_{A'}$. Similarly, if we consider the enthalpy drop at point B, the value is $H_B - H_{B'}$. You can see that although the enthalpy is the same, the work available is decreased as a result of the throttling process increasing the unavailable part of the enthalpy. If the enthalpy $H_B - H_{B'}$ was only 50% of $H_A - H_{A'}$, then the steam flowrate would have to be doubled to achieve the same power output using the throttling technique.



Entropy, kJ/kg °C

Fig. 3.19

Note: This reasoning is greatly simplified because it assumes isentropic expansion in the turbine and this is unrealistic.