Turbine and Auxiliaries - Course PI 34

THE MOLLIER DIAGRAM AND THE TURBINE PROCESSES

Objectives

1. Sketch a Mollier diagram from memory. Label the following on your sketch:

   (a) constant enthalpy lines
   (b) constant entropy lines
   (c) saturation line
   (d) constant temperature lines
   (e) constant pressure lines
   (f) constant moisture content lines
   (g) constant degree of superheat lines

2. On the sketch of a Mollier diagram that you have drawn, illustrate these turbine processes:

   (a) expansion in the high pressure turbine
   (b) moisture separation
   (c) reheat
   (d) expansion in the low pressure turbine

3. Explain how moisture separation and reheat each:

   (a) increase the enthalpy of the steam at the LP turbine inlet
   (b) reduce the moisture content of the steam at the LP turbine outlet

4. Define throttling and, using a Mollier diagram, explain how throttling of the steam supplied to the turbine affects:

   (a) the pressure, temperature and moisture content of the steam at the turbine inlet
   (b) the amount of heat which can be converted into mechanical energy by the turbine.

Mollier Diagrams and The Turbine Set

This module deals with the turbine process. When you have finished the module, you should be aware of the major equipment of the turbine set and you should be able to show the turbine process on a Mollier diagram.

Mollier Diagrams

The Mollier diagram is a very useful tool. It can be used to depict the various processes associated with the turbine set. It may also be used quantitatively for various calculations. Your consideration of Mollier diagrams in this course will be limited to a qualitative look at the turbine set.

A Mollier diagram for water is shown in Figure 6.1. The axes of the diagram are enthalpy and entropy. Remember that enthalpy is the heat content of water above 0°C reference point.

Entropy is harder to explain since it has no physical significance. For our purposes, entropy can be considered as an indicator of the availability of heat energy to do work. Say we have two substances that have the same heat content, but one substance is at lower temperature than the other. The amount of work that can be done by the lower temperature substance is less than the work that can be done by the higher temperature substance. The entropy of the lower temperature substance is greater than that of the other substance. Thus, the greater the entropy, the less work is available from a given amount of heat.

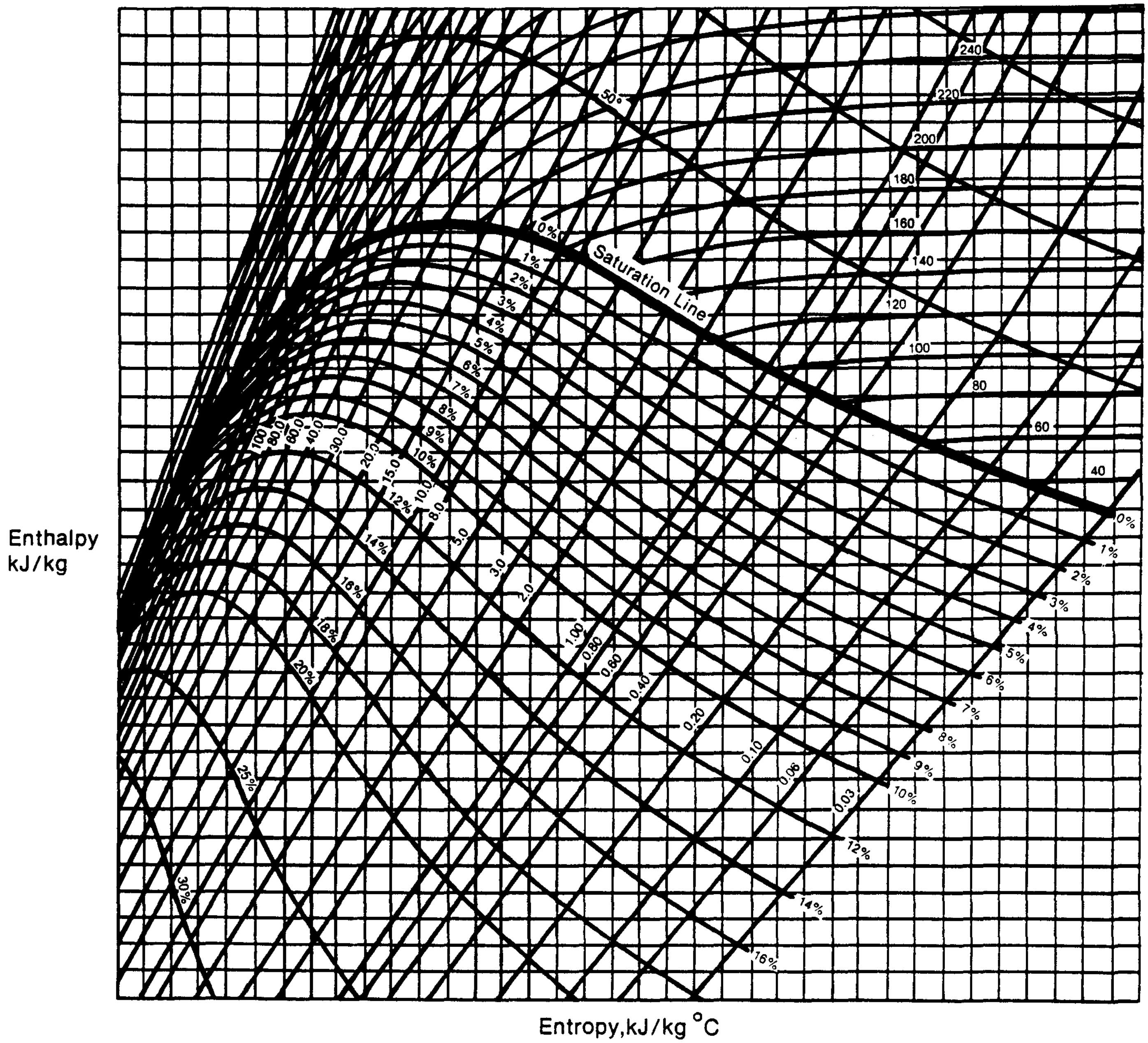
Enthalpy
kJ/kg
Entropy,kJ/kg °C
Saturation Line
50°
240
220
200
180
160
140
120
100
80
60
40
0%
1%
2%
3%
4%
5%
6%
7%
8%
9%
10%
12%
14%
16%
18%
20%
25%
30%
100
80.0
60.0
40.0
30.0
20.0
15.0
10.0
8.0
5.0
3.0
2.0
1.00
0.80
0.60
0.40
0.20
0.10
0.06
0.03

Figure 6.1

The Mollier diagram for water deals with three states of water: saturated steam, wet steam, and superheated steam. On Figure 6.2, the darker line marked <u>saturation line</u> represents saturated steam at different conditions of temperature and pressure. Superheated steam is represented <u>above</u> the saturation line. Wet steam is represented <u>below</u> the saturation line.

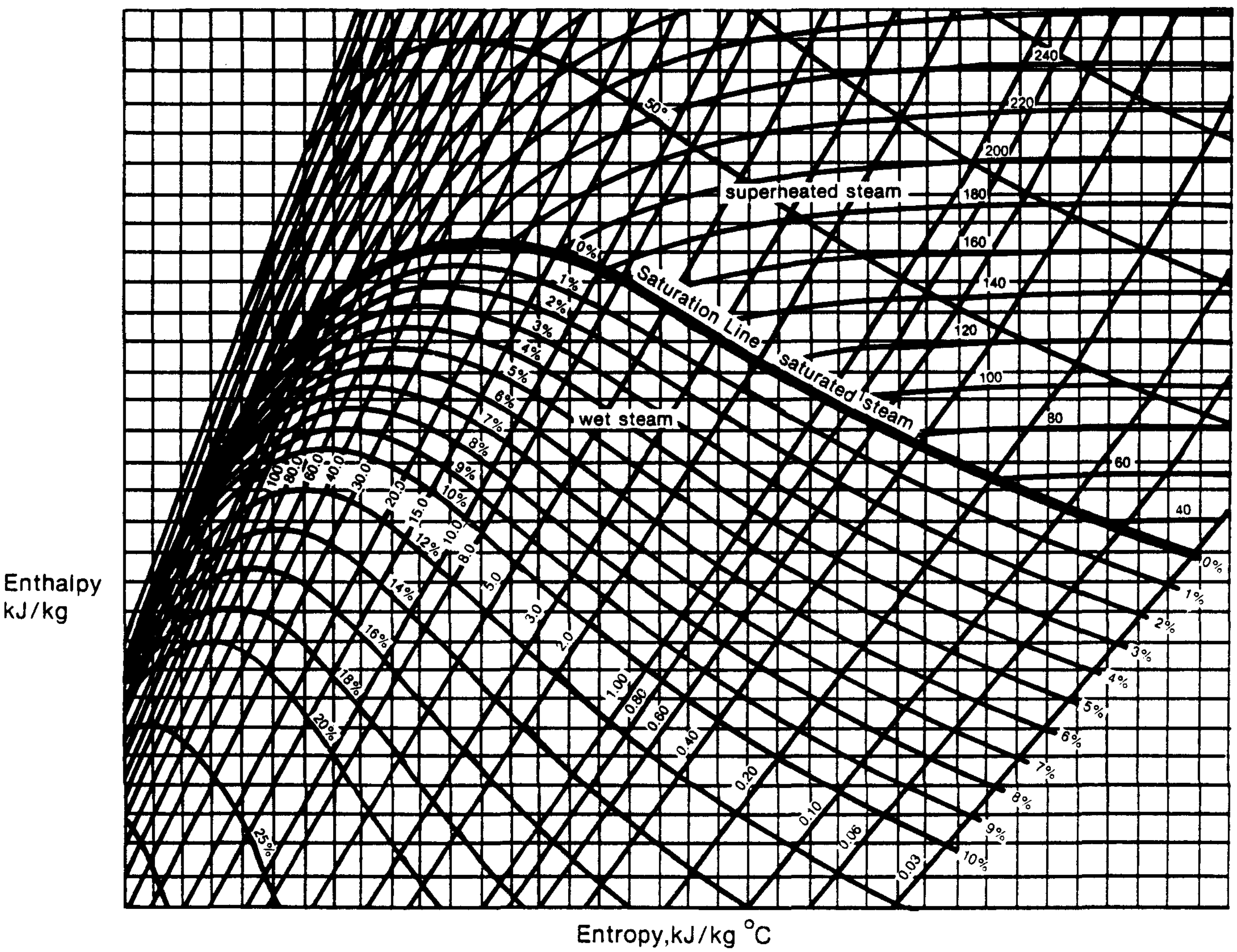

Figure 6.2

Besides enthalpy and entropy, there are other variables shown on a Mollier diagram.

Figure 6.3 shows a Mollier diagram with constant temperature lines indicated.

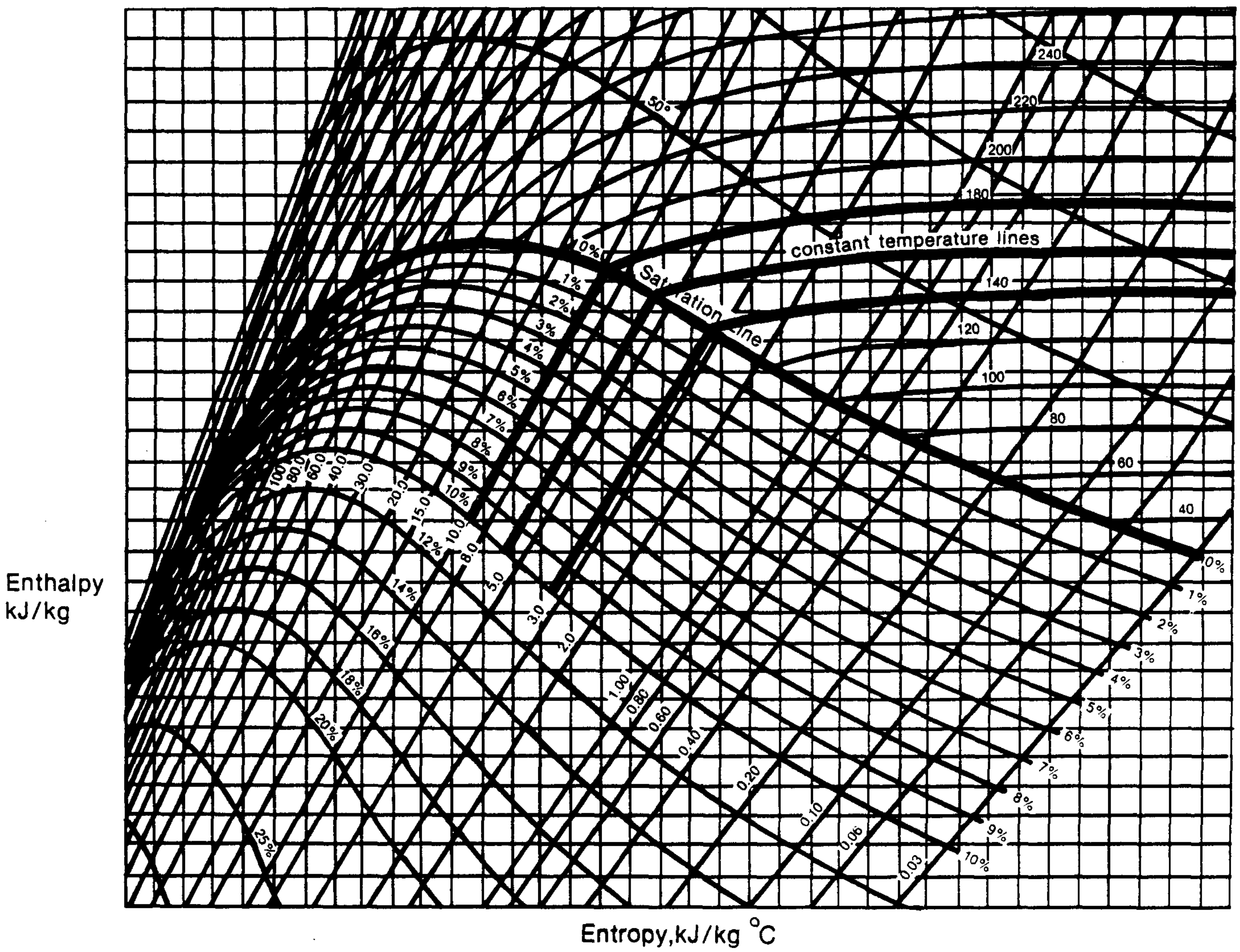

Figure 6.3

Figure 6.4 shows constant pressure lines. Note that the constant pressure lines and constant temperature lines are parallel in the wet steam region, but not in the superheated steam region. This is because for saturated conditions (e.g. wet steam) the temperature remains constant at constant pressure as heat is added. For conditions which are not at saturation (e.g. superheated steam) the temperature does not remain constant as heat is added at constant pressure.

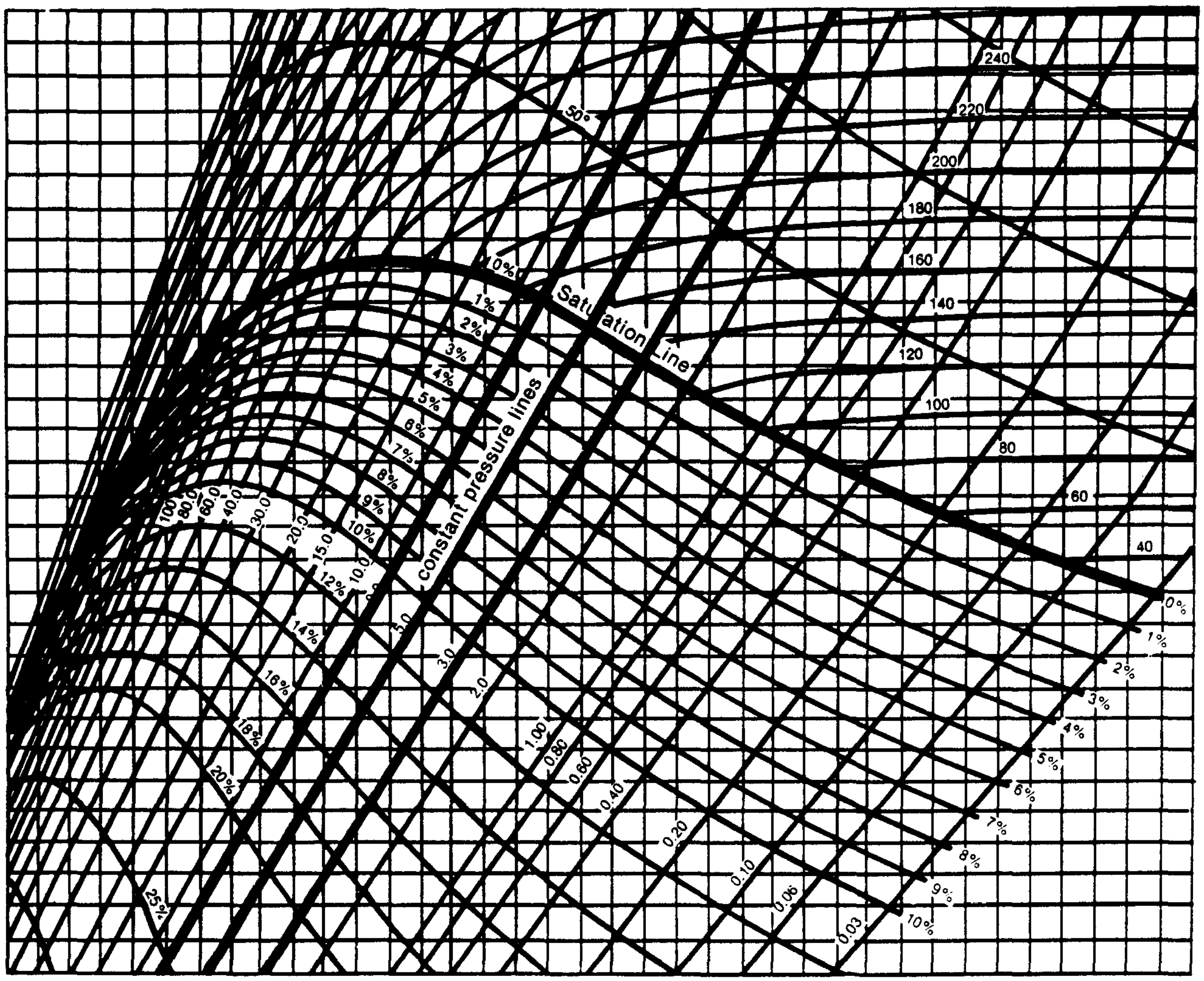

Figure 6.4

Figure 6.5 shows constant moisture content lines. These show wet steam at different temperatures and pressures that have the same percent moisture.

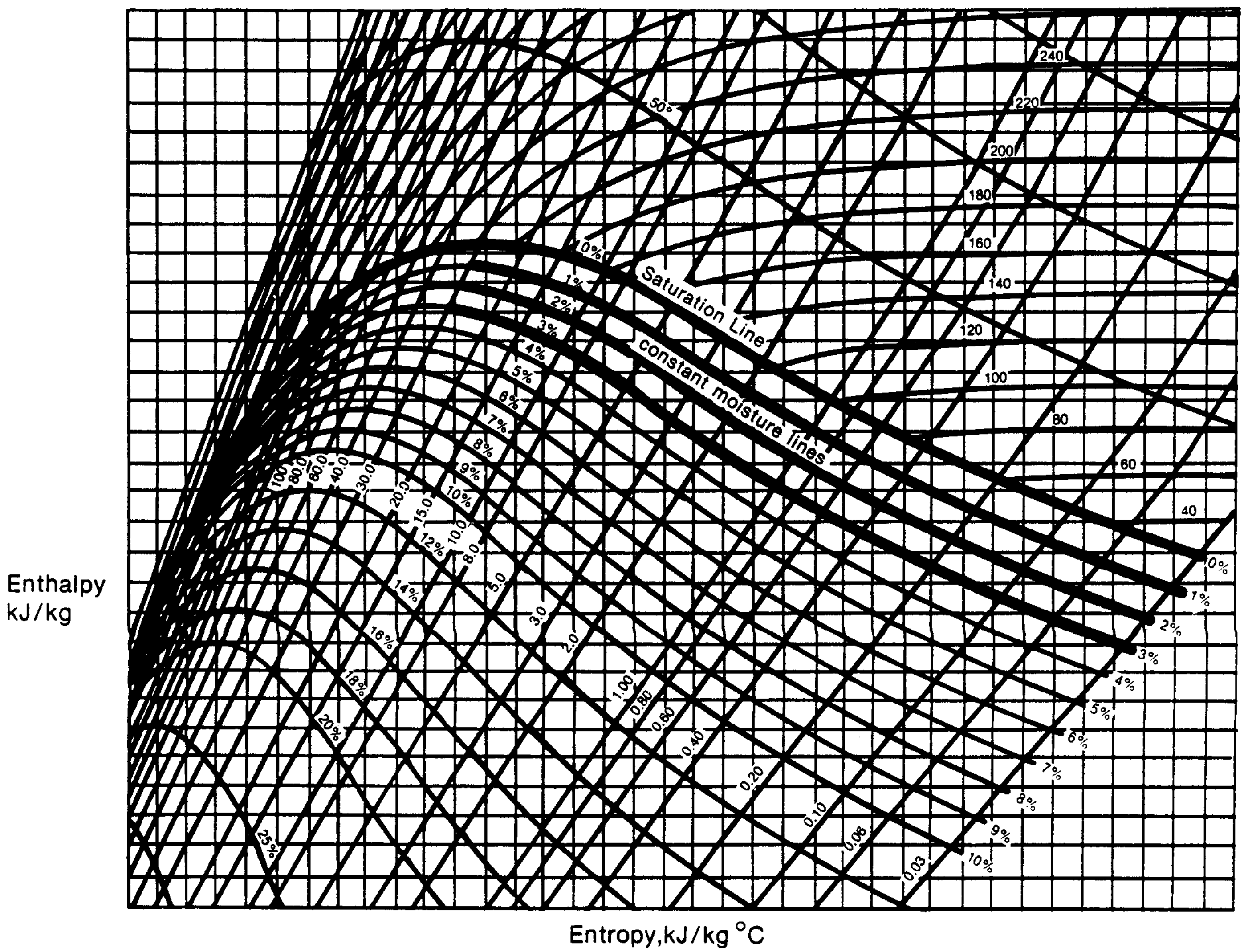

Figure 6.5

Figure 6.6 shows constant degree of superheat lines. These show superheated steam at different temperatures and pressures that are at constant temperature difference above the saturation temperature.

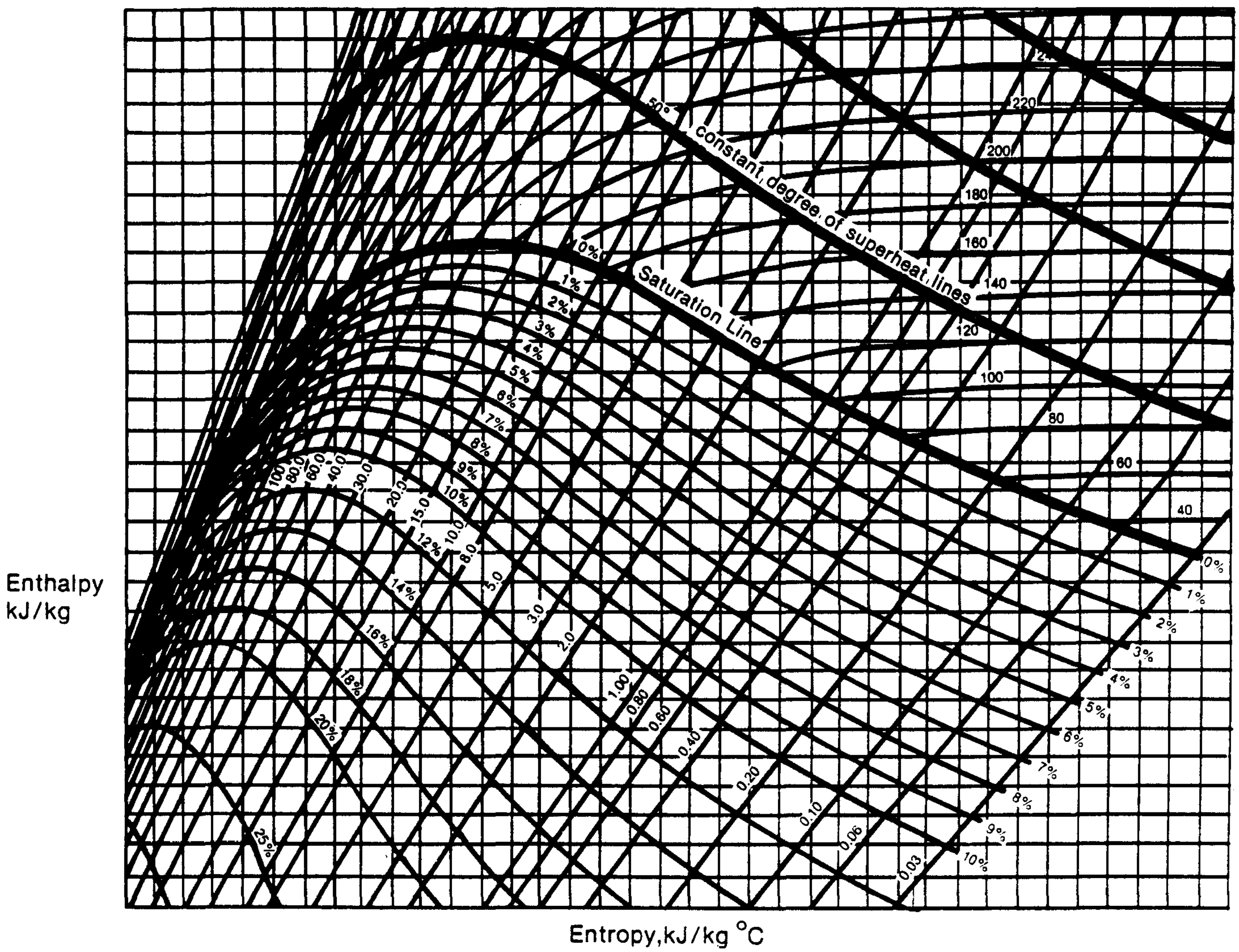

Figure 6.6

→ Answer the following question in the space provided, then check your answer with the "TEXT ANSWERS".

6.1) From memory, sketch and label a Mollier diagram for water. Your labels should include the following:

(a) constant enthalpy lines
(b) constant entropy lines
(c) saturation line
(d) constant temperature lines
(e) constant pressure lines
(f) constant moisture content lines
(g) constant degree of superheat lines

The Turbine Process

The turbine set of a large CANDU unit is shown in Figure 6.7. Note that this diagram is somewhat simplified for clarity.

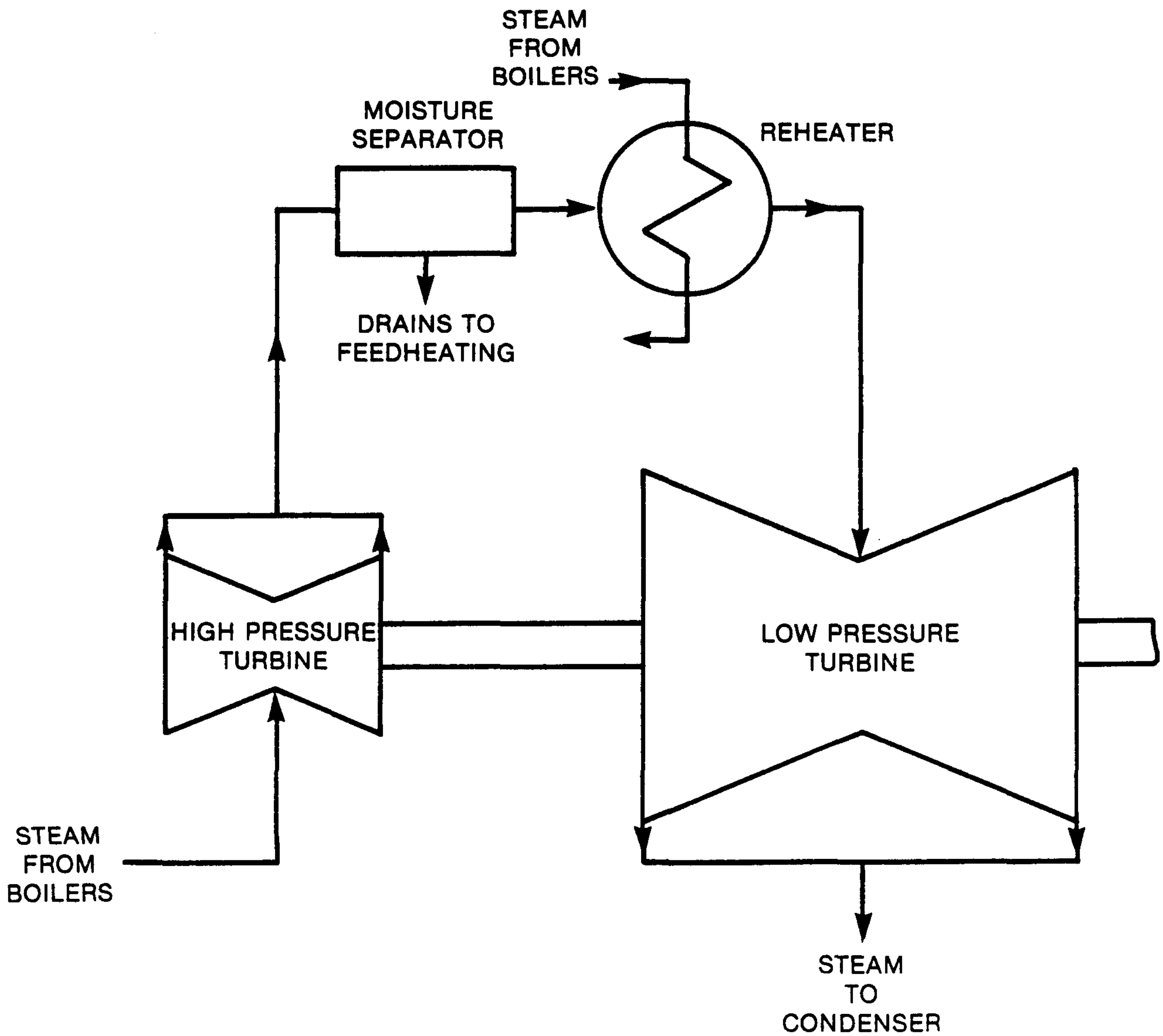

Figure 6.7

Saturated steam at about 250°C and 4 MPa(a) comes from the boilers to the high pressure (HP) turbine. As the steam flows through the turbine, its pressure and temperature drop. The effect of these changes is to turn the turbine shaft - i.e. some of the heat energy of the steam is converted into shaft mechanical energy.

As the steam supplied to the turbine is saturated, the heat which is extracted from the steam is a portion of the latent heat of vaporization. The effect of this is that the steam starts to condense and as it flows through the turbine more and more moisture is produced. Finally, at the outlet of the HP turbine, the steam typically has a moisture content of about 10% and pressure of about 800 kPa(a) with a corresponding saturation temperature in the order of 170°C. This part of the overall process is shown (from A to B) on Figure 6.8

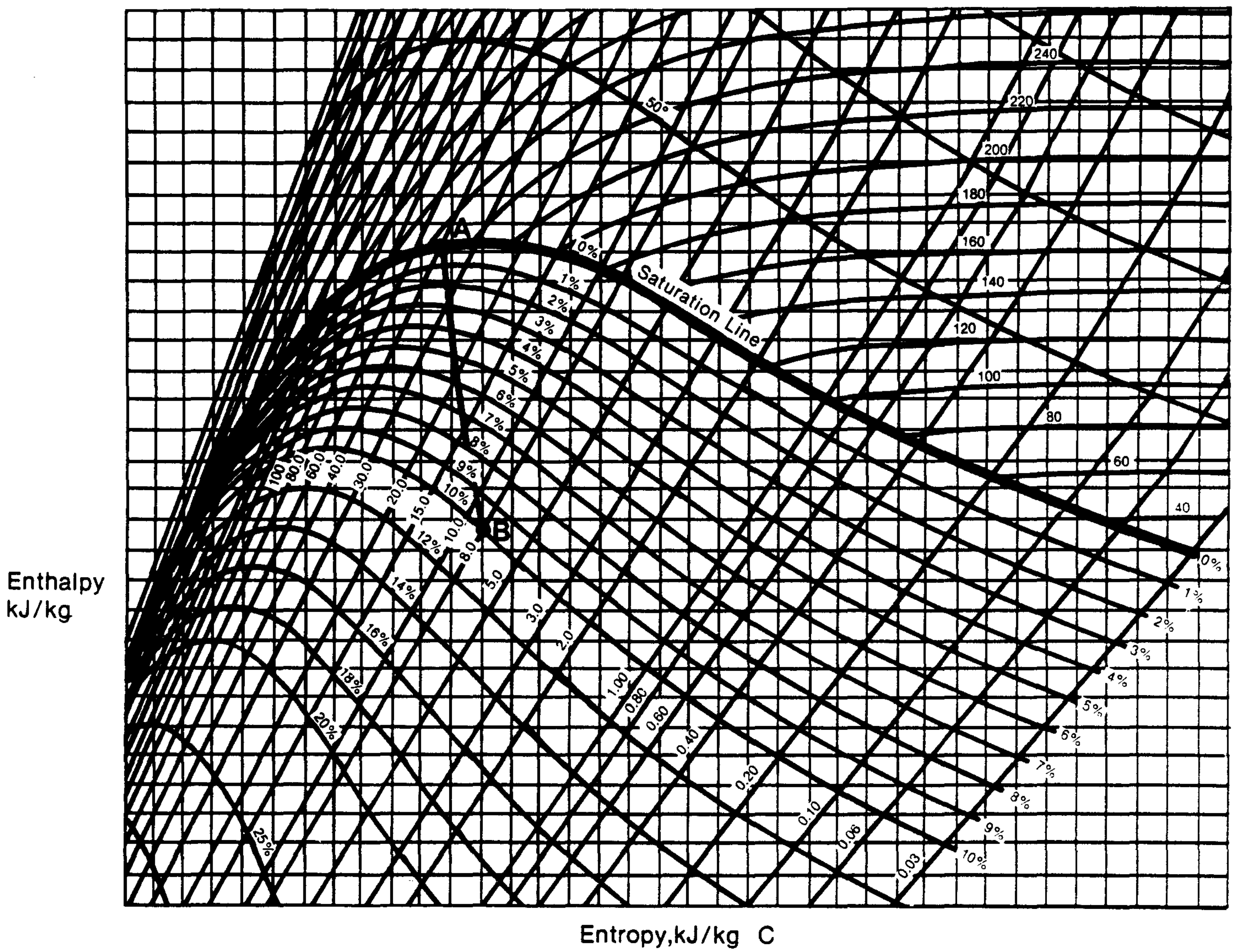

Figure 6.8

Why is the steam taken out of the turbine at this point? The reason lies in the moisture content. At moisture levels above about 10%, erosion caused by the impingement of the liquid droplets on moving parts becomes unacceptable. The steam must have the moisture removed before it can be used to produce more power. This is accomplished in the moisture separator. Liquid is physically removed from vapor in the separator. The steam at the moisture separator outlet is essentially saturated at about 170°C and 800 kPa(a). The separation process is shown (from B to C) on Figure 6.9.

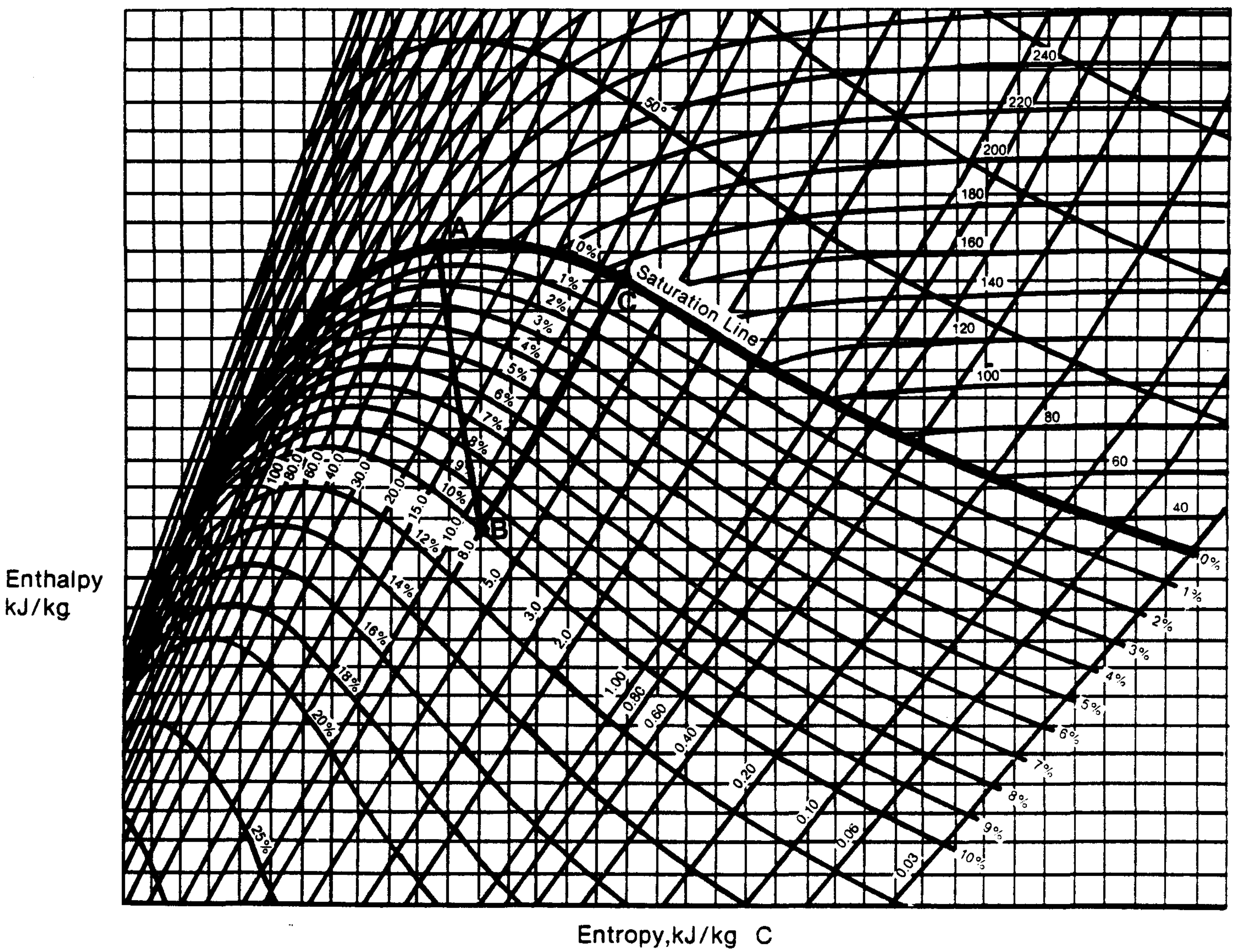

Figure 6.9

Note that the steam enthalpy has increased. How can this be true? Has any heat been added to the steam to increase its enthalpy? The answer is no, no heat has been added. The enthalpy has gone up because the moisture has been removed. Remember that enthalpy is heat content per kg of water above 0°C. The enthalpy of wet steam is a weighted average of saturated liquid enthalpy and saturated steam enthalpy. If we remove the liquid from the wet steam, the heat content per kg of the fluid that remains will be higher. However, there will be fewer kilograms of fluid after separation than before. Thus, the total heat contained in the steam leaving the moisture separator is certainly smaller than that in the steam entering, since some heat is contained in the water separated by the moisture separator.

→ Answer 6.2 before you proceed. Check your answer with the one in the "TEXT ANSWERS".

6.2) Explain how moisture separation increases the steam enthalpy of the steam exiting the HP turbine.

The steam could now enter the LP turbine and generate more mechanical energy. The problem with this is that condensation would start immediately, and before the steam could reach the design exit conditions (i.e. 30°C and 4 kPa(a)) its moisture content would be completely unacceptable. In fact, if you look at Figure 6.10 and follow the dotted line from C (moisture separator exit conditions) to D' (30°C and 4 kPa(a)), you will see that the moisture content will be about 15%. This value, however, would be much smaller than the moisture content of the steam at the LP turbine exhaust if no moisture separator were used so that steam could flow from the HP turbine directly to the LP turbine. Such a process is shown on Figure 6.10 as Line B-D" and you can see that the moisture content would be about 21%.

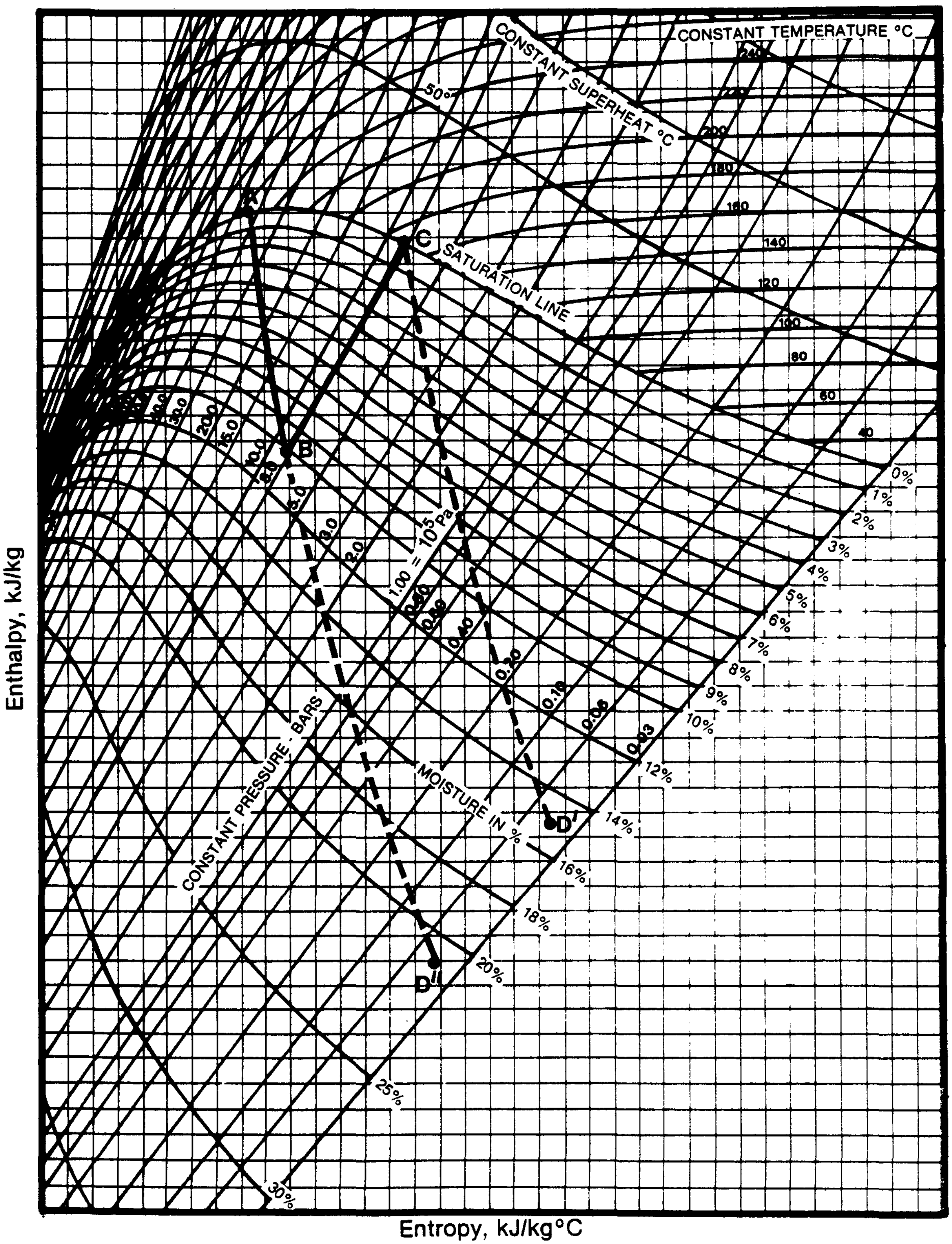
CONSTANT TEMPERATURE °C
CONSTANT SUPERHEAT °C
50°
200
180
160
140
120
100
80
60
40
SATURATION LINE
A
B
C
D'
D''
10.0
8.0
5.0
3.0
2.0
1.00 = 10⁵ Pa
0.40
0.20
0.10
0.06
0.03
CONSTANT PRESSURE - BARS
MOISTURE IN %
0%
1%
2%
3%
4%
5%
6%
7%
8%
9%
10%
12%
14%
16%
18%
20%
25%
30%
Enthalpy, kJ/kg
Entropy, kJ/kg°C

Figure 6.10

The steam leaving the moisture separator is then put through a shell and tube heat exchanger called the reheater in order to avoid moisture problems. The reheater uses live steam (taken from the main steam line before the HP turbine) to heat the steam coming from the moisture separator. Since this steam enters the reheater saturated at 170°C, as it is heated it becomes superheated steam. The exit temperature of the steam is about 235°C and the pressure is about 800 kPa(a). The reheating process is shown in Figure 6.11 from C to D.

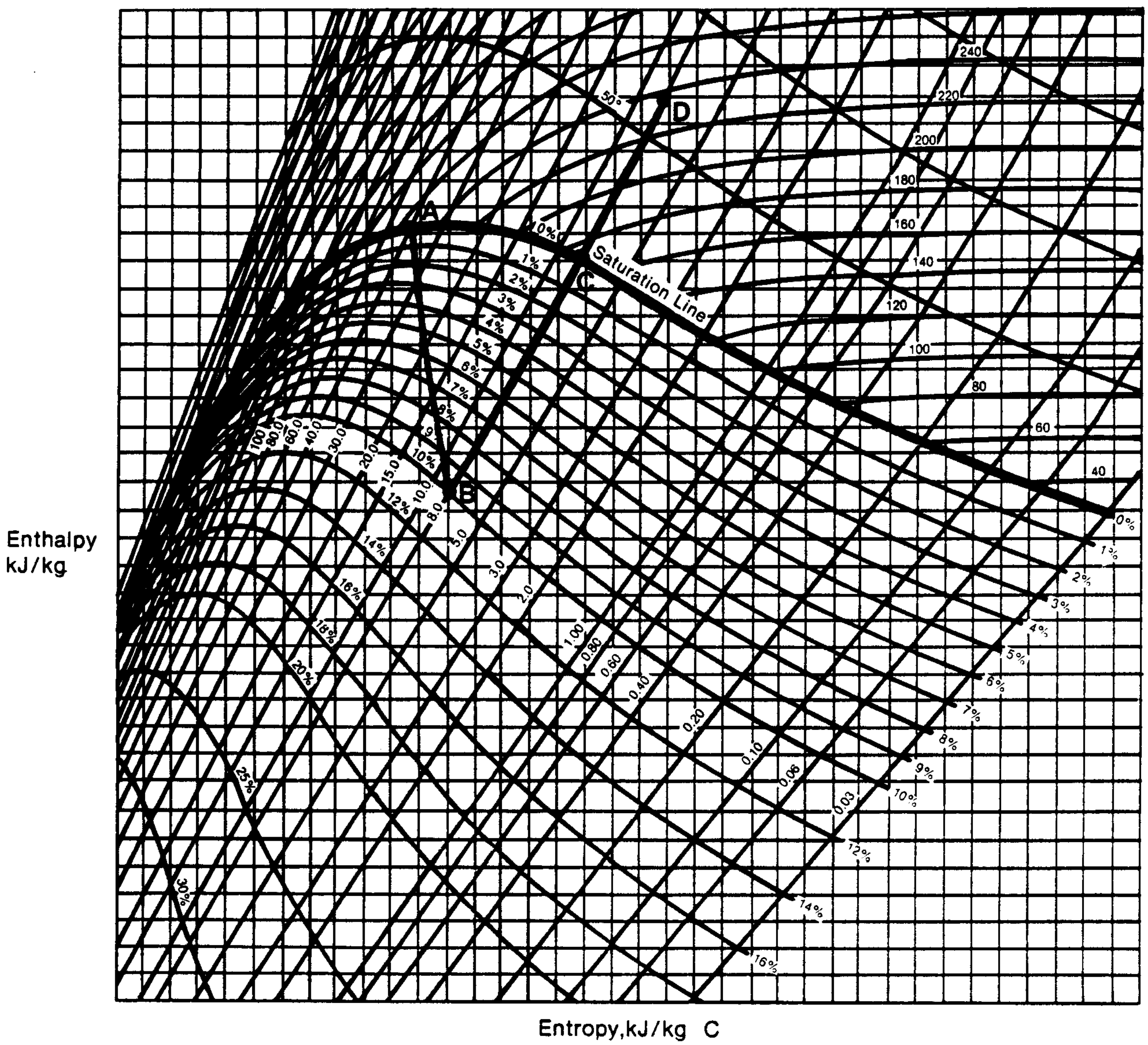

Figure 6.11

→ Answer question 6.3 in the space provided, then check your answer with the "TEXT ANSWERS".

6.3) Explain how reheat increases the enthalpy of the steam coming from the moisture separator.

The steam now enters the low pressure (LP) turbine. It expands, cools, and condenses, generating shaft mechanical energy as it flows. At the LP turbine exit the steam is typically about 10% wet at 30°C and 4 kPa(a). This part of the process is shown in Figure 6.12 from D to E.

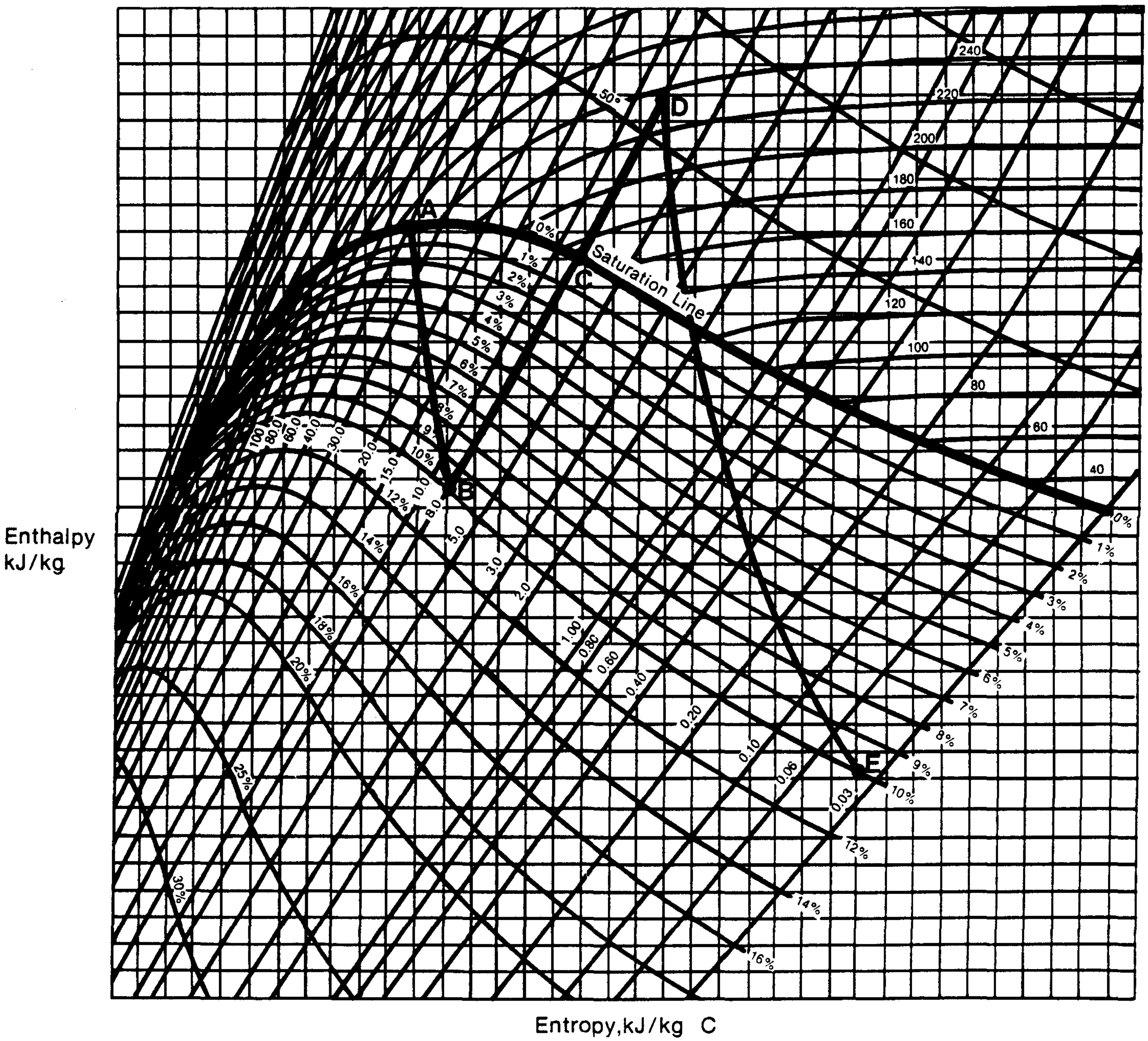

Figure 6.12

→ Answer the following question in the space provided, then check your answer with the one in the "TEXT ANSWERS".

6.4) Sketch a Mollier diagram from memory. On it, show the overall turbine process, including:

(a) high pressure turbine
(b) moisture separator
(c) reheater
(d) low pressure turbine

6.5 On the Mollier diagram you have already sketched, show how the moisture separator and reheater reduce the moisture content of the steam at the LP turbine outlet.

Throttling

This is a process where a compressible fluid expands from one pressure to a lower pressure but no mechanical work is done. Although, throttling occurs to a certain extent in any pipeline (especially if it is long), partially open valves are one place where the process is most noticeable.

When throttling takes place, the enthalpy of the fluid remains constant. This is true because:

(a) no mechanical work is done by the fluid,
(b) there is no heat loss because the flow occurs at high speed and there is no time for heat to pass through the valve casing or pipe walls. Often they are lagged with thermal insulation which makes heat transfer even more difficult.

Since the enthalpy of a throttled fluid does not change, throttling can be shown on a Mollier diagram as a horizontal line. Figure 6.13 shows throttling of wet steam. As you can see, the steam pressure and temperature are reduced. The moisture content of the steam is reduced as well and, if throttling is sufficiently large, superheated steam can be produced.

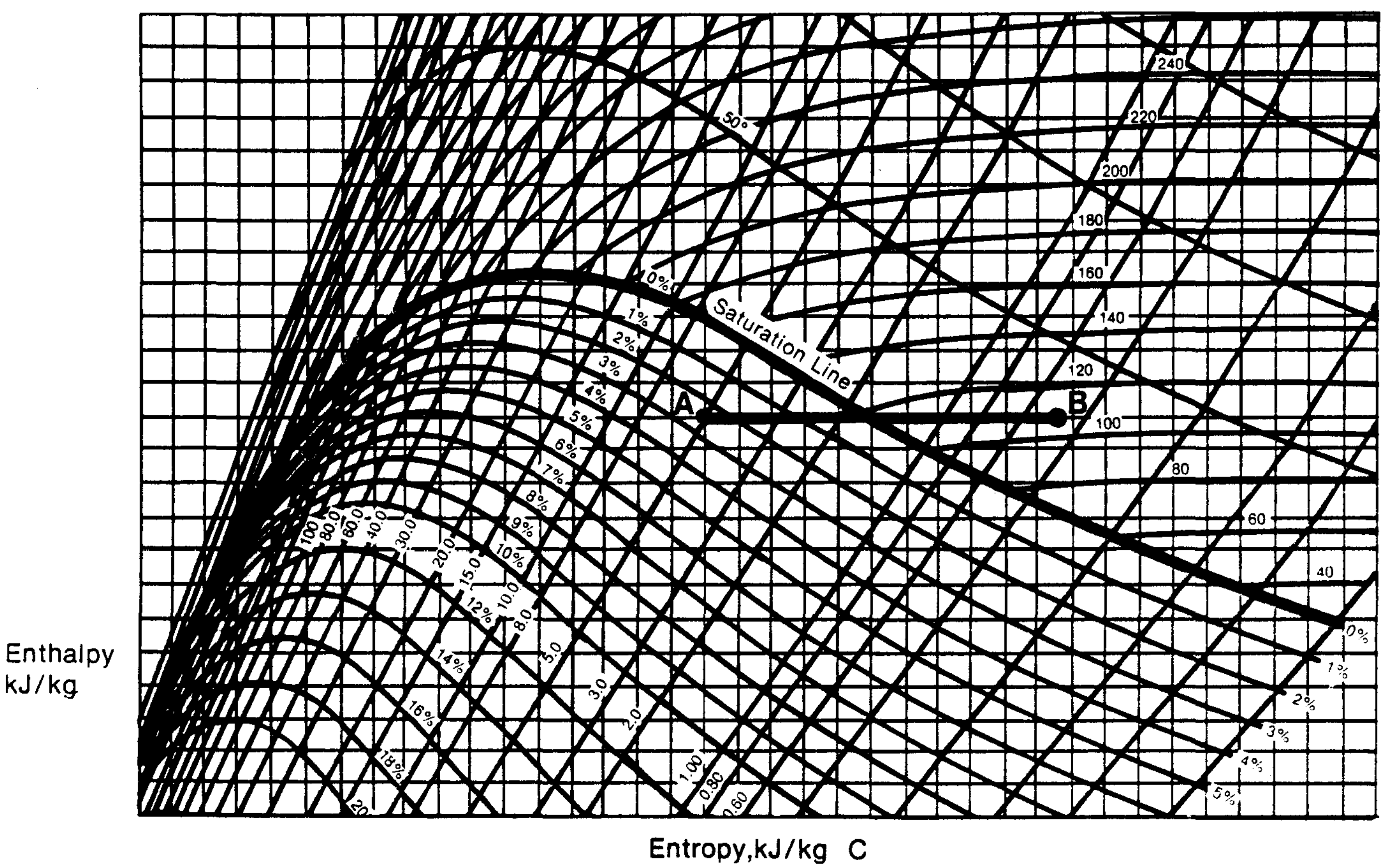

Figure 6.13

In CANDU stations, a typical place where throttling occurs is in the governor steam valves located at the HP turbine inlet. These valves are used to control steam flow to the turbine and they are partially closed at partial load conditions. The smaller the percentage opening, the greater the throttling effect. Less steam at a lower pressure and temperature gets into the turbine and thus its power is reduced.

Throttling of steam by the governor steam valves is illustrated on Figure 6.14. As you can see, the temperature and pressure of the steam drop and it becomes superheated.

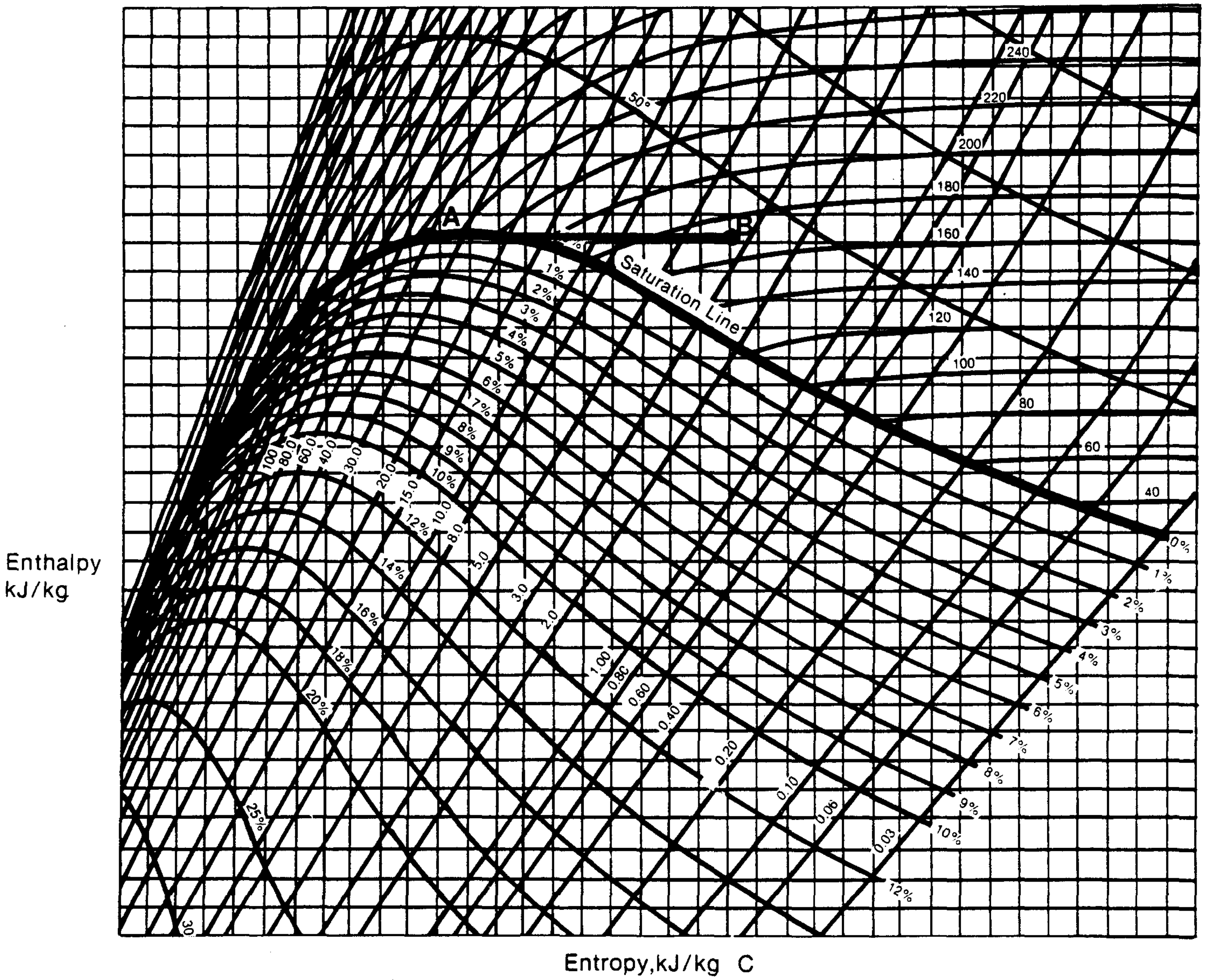

Figure 6.14

This looks like a convenient and simple method of producing superheated steam and thus avoiding, or at least reducing, the problems caused by moisture in the steam. So, why is this method not used in our CANDU stations?

To answer the question, recall what entrogy is and note that during throttling the entropy of the fluid increases. This means that less work is available from the heat contained in the steam. This is shown on Figure 6.15 which illustrates the simplest possible case of an ideal turbine (no friction losses) without a moisture separator and reheater. Line A-B illustrates the turbine process in the case when the governor steam valves are fully open so that throttling of the steam is negligible. Line C-D shows the turbine process when the valves are partially open so that the steam is throttled before entering the turbine. In the latter case, much less heat energy can be extracted from the steam and converted into mechanical work. This reduction in work is the reason why throttling is not used to produce superheated steam at the turbine inlet.

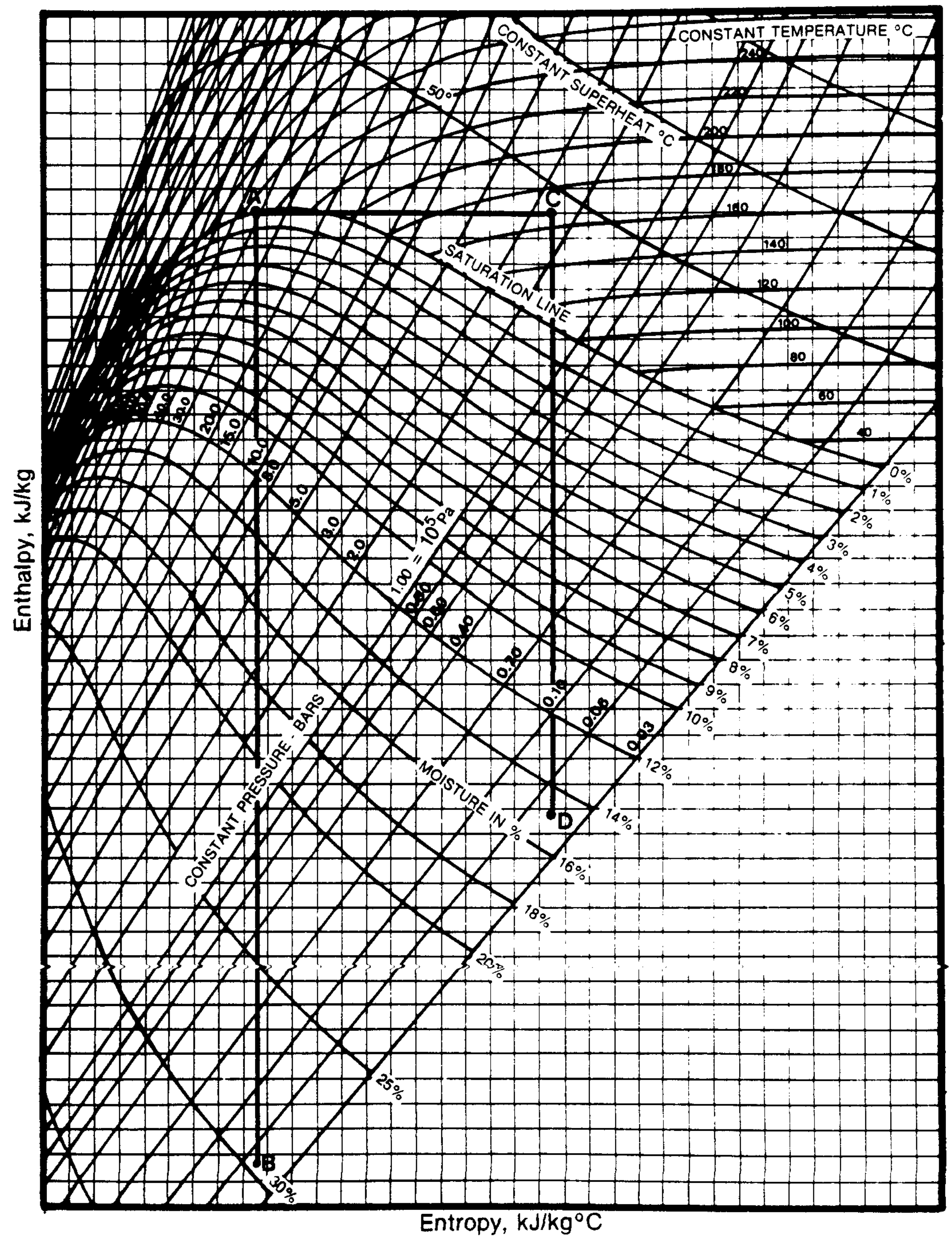
CONSTANT TEMPERATURE °C
CONSTANT SUPERHEAT °C
SATURATION LINE
CONSTANT PRESSURE, BARS
MOISTURE IN %
1.00 = 10^5 Pa
A
B
C
D
50°
240
220
200
180
160
140
120
100
80
60
40
0%
1%
2%
3%
4%
5%
6%
7%
8%
9%
10%
12%
14%
16%
18%
20%
25%
30%
Enthalpy, kJ/kg
Entropy, kJ/kg°C

Figure 6.15

6.6 Define throttling and, using a Mollier diagram, explain how throttling of the steam supplied to the turbine affects its:

(a) pressure
(b) temperature
(c) moisture content

6.7 Using a Mollier diagram, explain how throttling of the steam supplied to the turbine affects the amount of heat which can be converted into mechanical work by the turbine.

→ You have now completed module 6. If you are confident you can answer the objectives, obtain a criterion test and answer it. If you feel you need more practice, consult with the course manager.

PI 25-6 TEXT ANSWERS

6.1) Your diagram should have the same shape and labels as Figure 6.16:

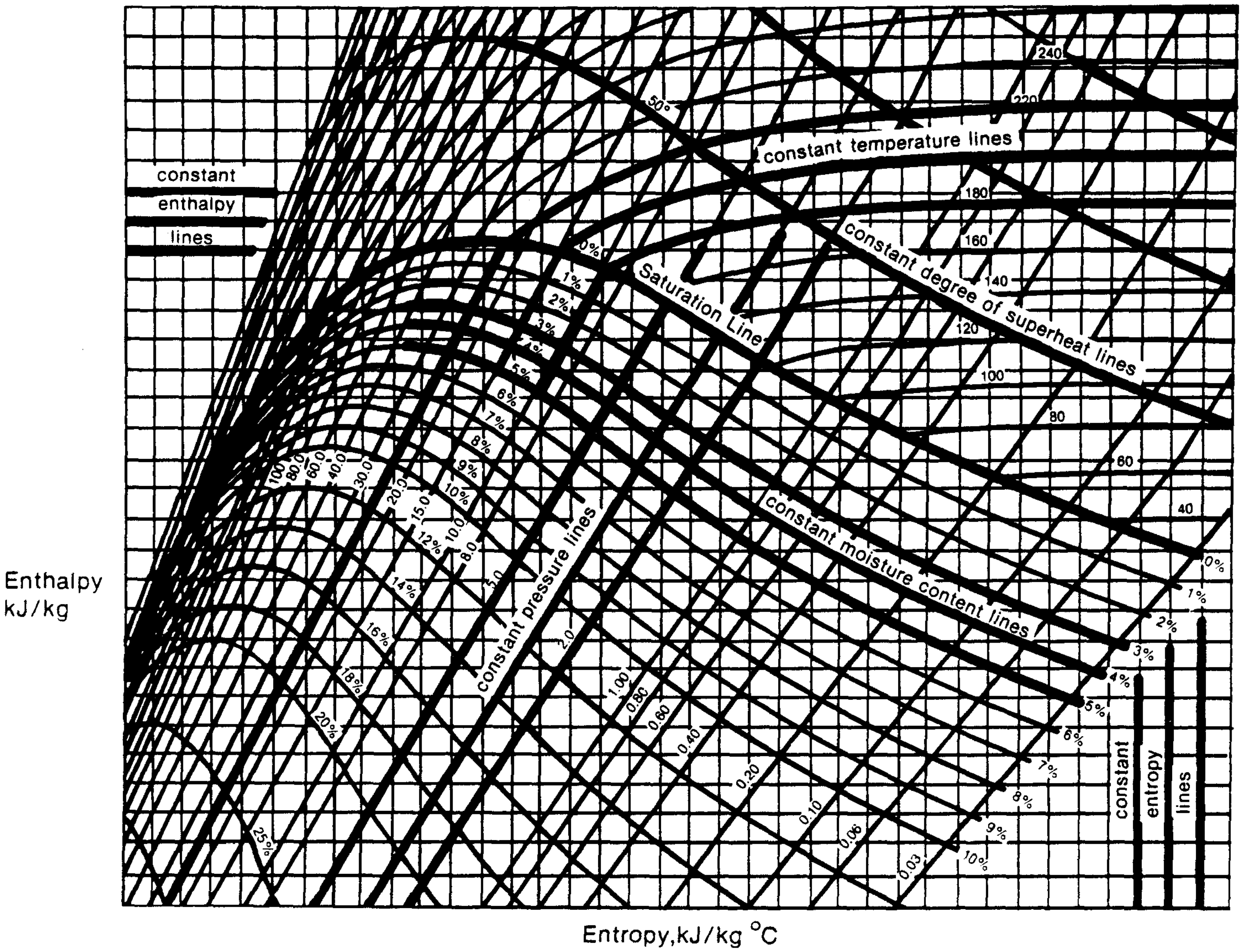

Figure 6.16

6.2) Moisture separation increases the enthalpy of the steam coming from the hp turbine by removing the liquid portion of the wet steam. The fluid that remains after the separation is essentially saturated steam, and the heat content per kg of fluid remaining will be higher. The mass flow rate of fluid, however, drops by the amount of moisture removed. Thus the enthalpy of the steam has increased, while the amount of flow has decreased.

6.3) Reheating increases the enthalpy of the steam coming from the moisture separator using live steam (at 250°C) from the main steam line before the hp turbine. The live steam condenses in the reheater, giving up enough heat to heat the saturated steam at 170°C and 800 kPa(a) to produce superheated steam at about 235°C and 800 kPa(a).

6.4) Your answer should look like Figure 6.17.

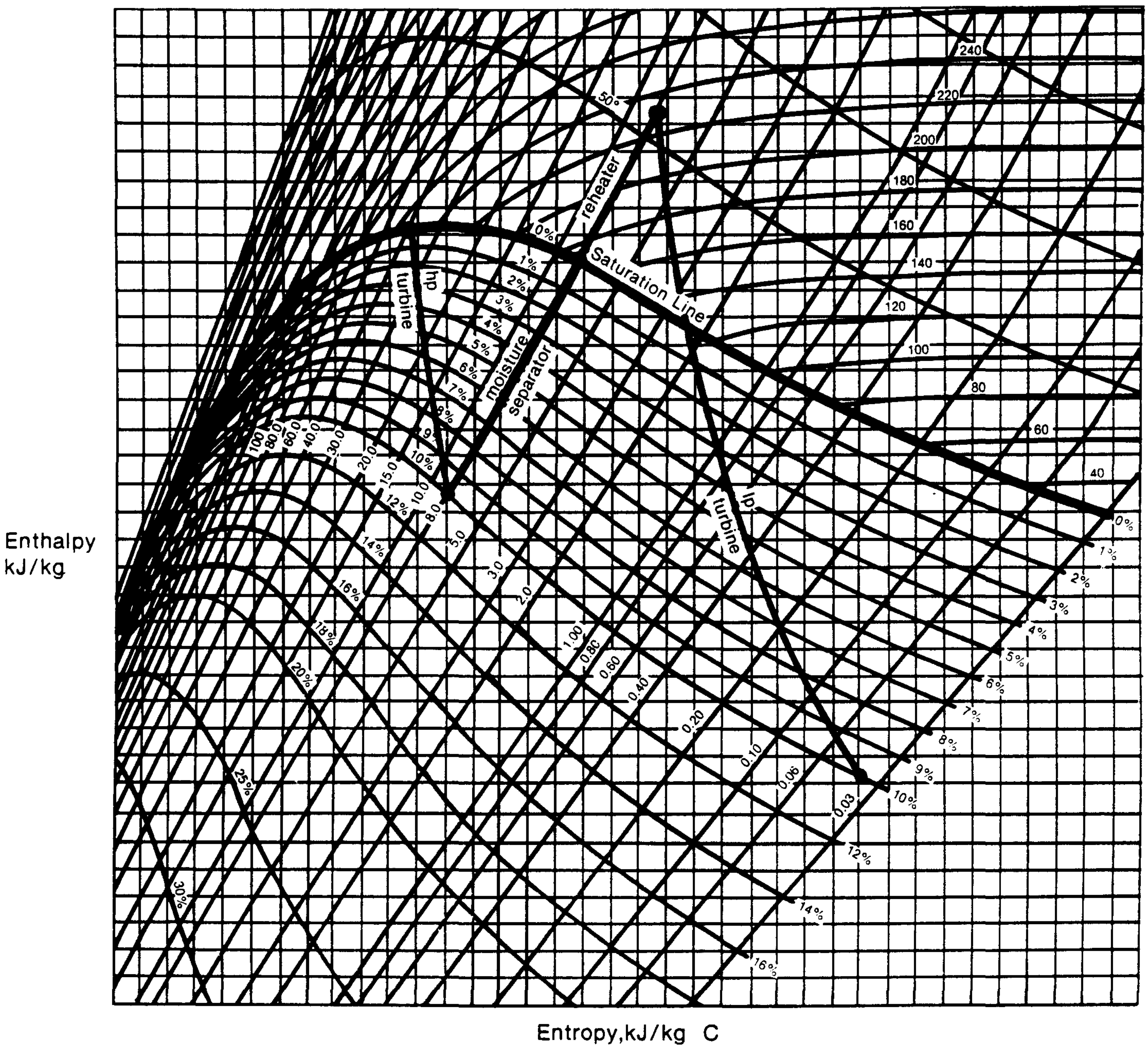

Figure 6.17

6.5 Your answer should look like Figure 6.18:

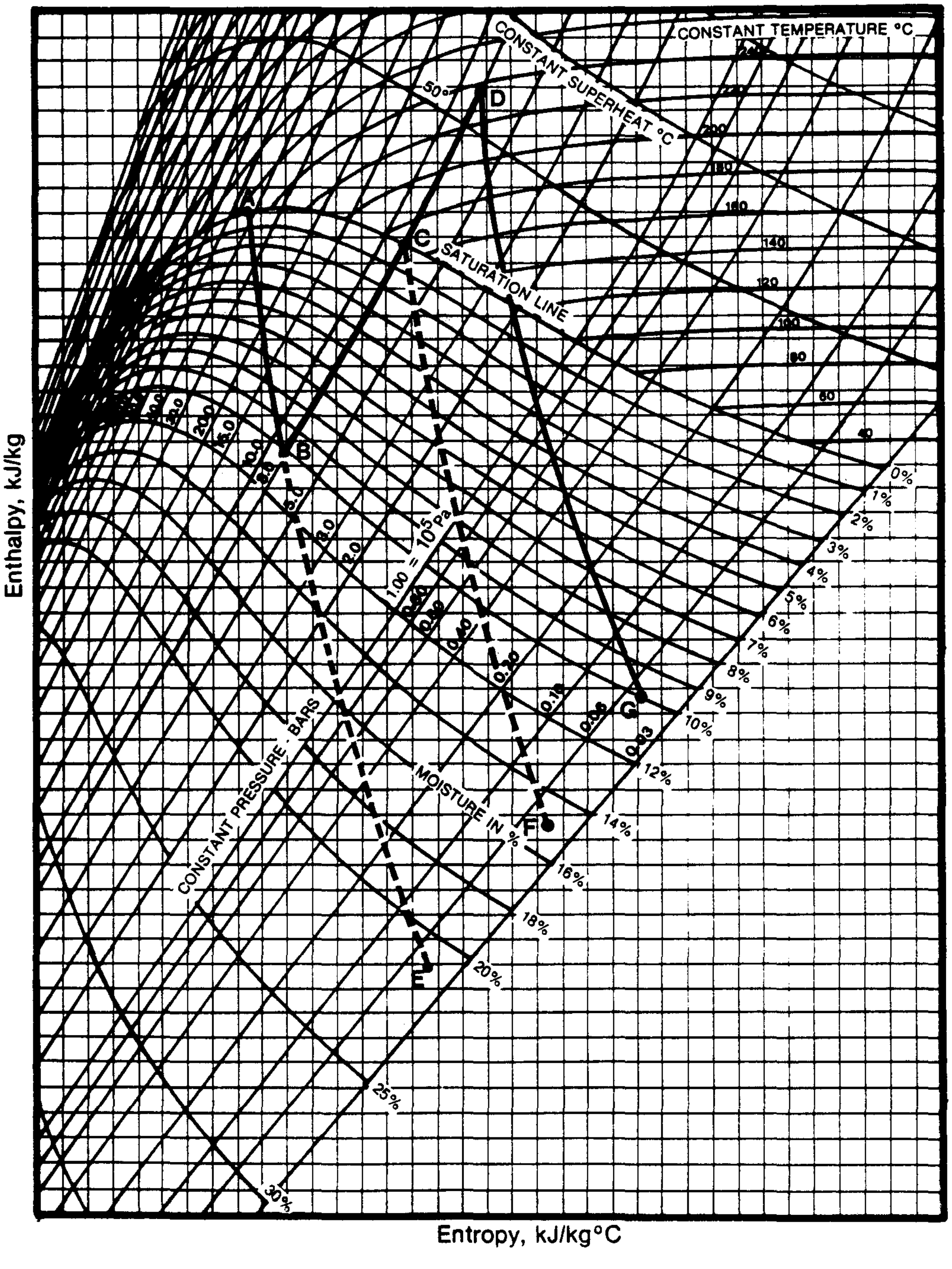

Figure 6.18

As the diagram shows, using a moisture separator allows the moisture content of the steam at the LP turbine exhaust to be reduced from about 21% to about 15%. Using a moisture separator followed by a reheater allows a further reduction of the moisture content to about 10%.

6.6 Throttling is a process which occurs when a compressible fluid expands from one pressure to a lower pressure, and no mechanical work is done. During this process the enthaply of the fluid remains constant.

Throttling of the steam supplied to the turbine is shown on Figure 6.19.

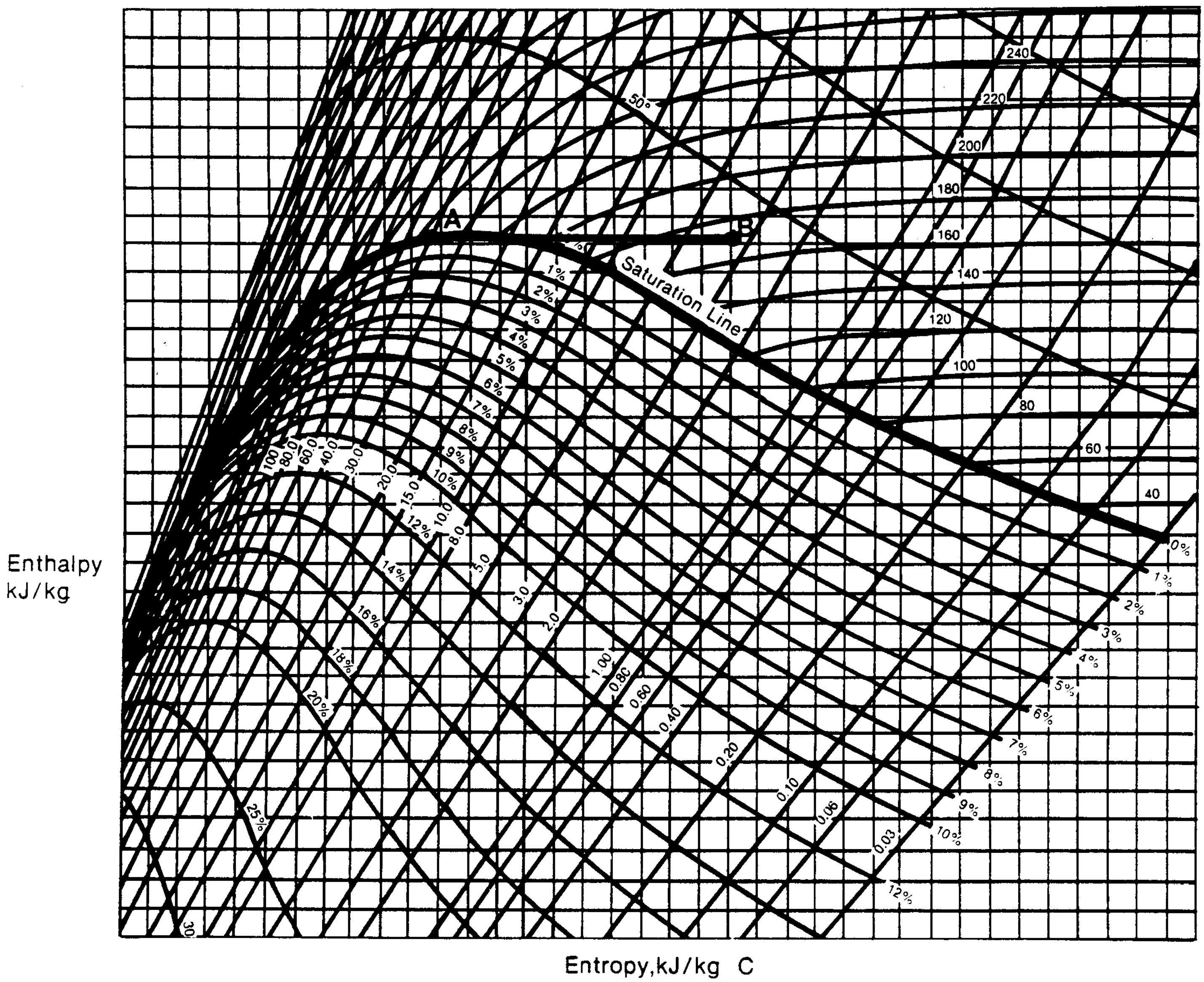

Figure 6.19

As the diagram shows, both the pressure and temperature of the steam are reduced, and it becomes superheated (its moisture content is certainly zero).

6.7 Your answer should look like Figure 6.20

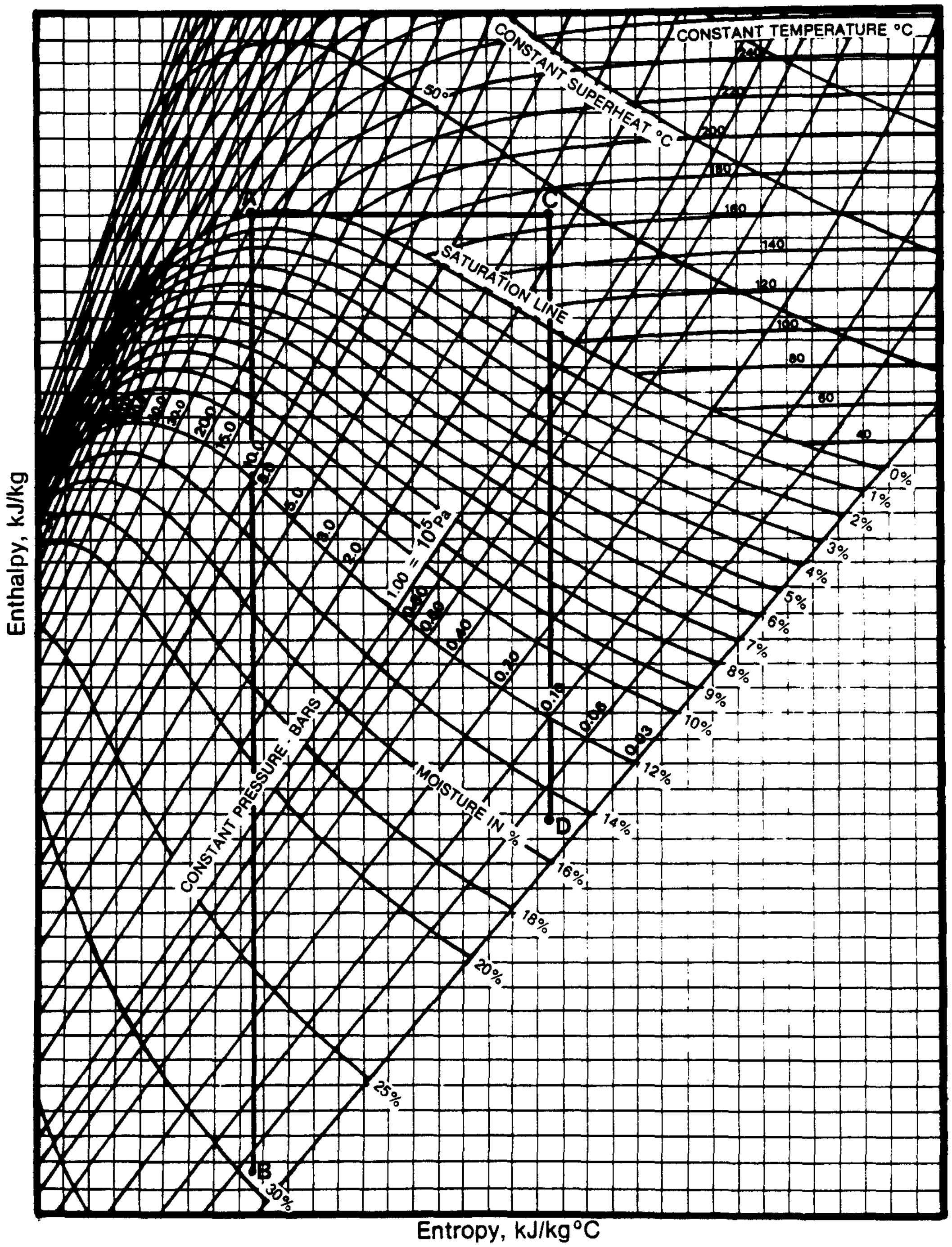

Figure 6.20

As the diagram shows, throttling of the steam supplied to the turbine reduces the amount of heat which can be converted into mechanical work by the turbine ($h_A - h_B > h_C - h_D$).