ROLPHTON

NUCLEAR TRAINING CENTRE

COURSE PI 25

NUCLEAR TRAINING COURSE

COURSE PI 25

HEAT AND THERMODYNAMICS

Index

Heat and Thermodynamics - Course PI 25

COURSE PROCEDURES

PI 25, Heat and Thermodynamics, is a self-pacing course designed to give you some basic concepts, terms, and skills that will be useful to you mainly as support for other initial training courses. You will also find that many of the concepts presented in this course will be useful as basics during your career in the Nuclear Generation Division of Ontario Hydro.

There are 8 modules in the course (including this course procedures module); they are listed on the cover sheet which is the first page of the course materials.

You should proceed according to the course map shown on page 2, that is, start with this module, then proceed to module PI 25-1. After you have completed module 1 (as outlined below) you may proceed to either module PI 25-2 or PI 25-3. You must complete both modules PI 25-2 and PI 25-3 before you proceed to module PI 25-4, ie, you must do all the prerequisite modules as shown on the course map before moving upwards on the map. Once you have satisfactorily completed Module PI 25-7 you will be issued a credit in PI 25.

A module consists of six parts:

1. Objectives - these tell you exactly what you must be able to do to satisfactorily complete the module.

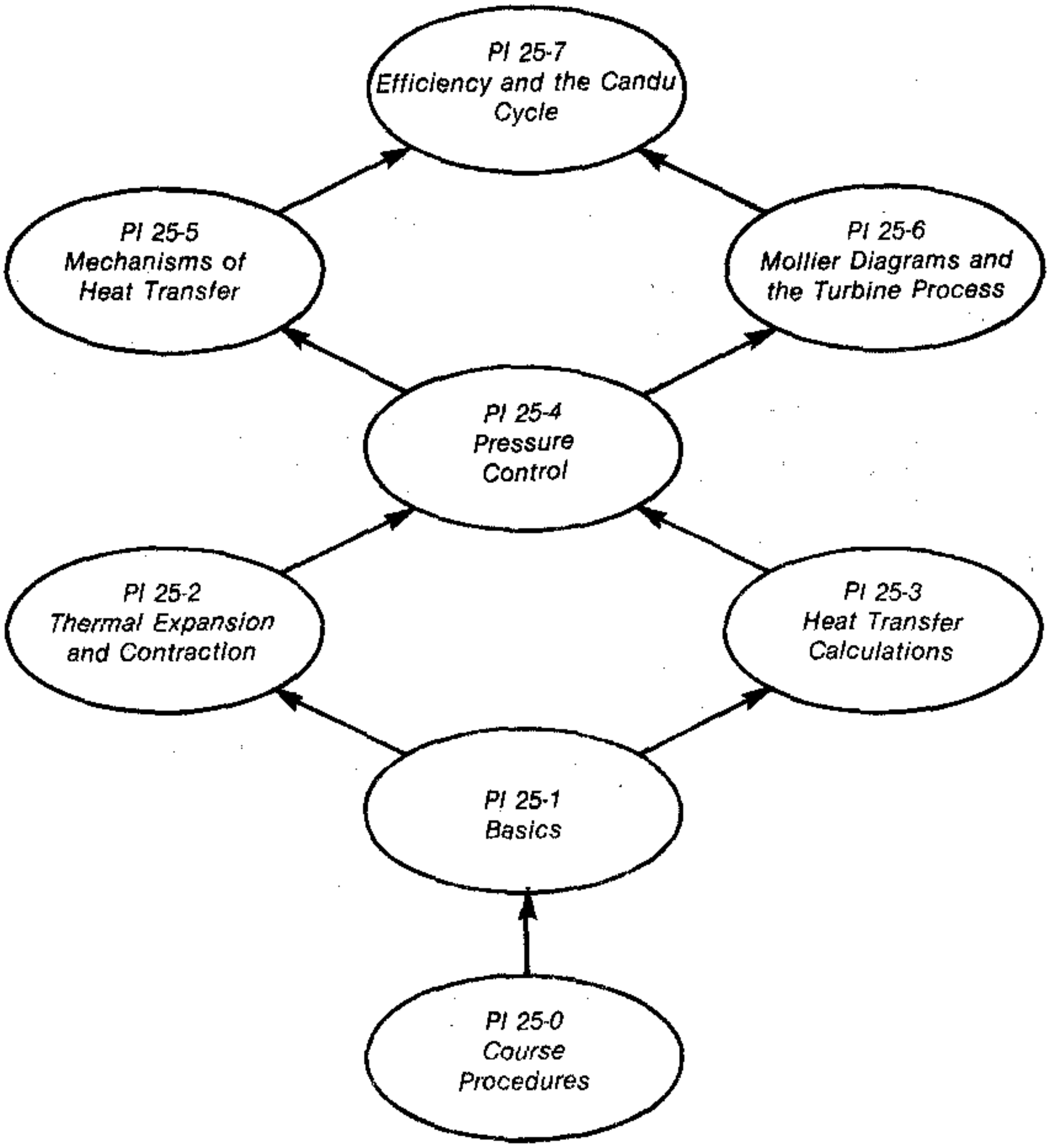
2. Text - this gives you enough information so that you are able to practise the performance called for in the objectives.

3. Assignment Questions - these are questions that should give you enough practice so that you can perform the objectives satisfactorily.

4. Text Answers - these are suggested answers to the assignment questions that you can use to correct your assignment answers.

5. Criterion Test - this is used to test exactly the objectives given at the beginning of the module.

PI 25 COURSE MAP



6. Self Evaluation - these are suggested answers to the criterion test questions, so that you and the course manager (if available) can diagnose any problem areas that may occur.

Now, answer the following question: "Will there be an instructor's (course manager's) assistance available to you while you study the course?"

If your answer to this questions is "YES", then skip to section B on page 4.

If your answer is "NO", read section A immediately below.

A. INSTRUCTOR'S ASSISTANCE UNAVAILABLE

After reading this section, you should proceed with each of the other modules as follows:

1. Read the objectives. If you are confident you can perform exactly as they state, then take the criterion test corresponding to the module. You can find all criterion tests at the end of the course notes.

2. If you are not sure that you can do the tasks the objectives call for, you should start reading through the module. As you progress through the module you will encounter directions. They are marked by using an arrow (——→), and they normally deal with assignment questions.

3. Do the assignment questions in accordance with the directions.

4. Check each of your answers to the assignment questions with the corresponding suggested answer in the "TEXT ANSWERS" section. Each module has its "TEXT ANSWERS" immediately following the module text. Make sure that you do enough assignment questions so that you become confident you can complete the criterion test correctly.

5. Once you are confident, complete (from memory unless otherwise stated) the criterion test corresponding to the module.

6. Find, at the very end of the course notes, the self-evaluation corresponding to the module. Compare your answers to those in the self-evaluation. If you find any discrepancies between the content of your answers and those in the self-evaluation, think the subject matter over once more before you conclude that you are competent. You may also consider consultation with your supervisor and/or workmates.

7. If you are happy with your answers, proceed to the next module according to the course map. After having completed module PI 25-7, collect all the criterion tests and give (mail) them to the training person responsible for this course at the site training centre (ie, ENTC, RNTC, or WNTC). Candidates at Head Office should mail the criterion tests to RNTC. Do not forget to do this otherwise you will not be issued a credit in this course.

You are now ready to begin Module PI 25-1. Proceed at a pace that is comfortable to you and enjoy studying.

B. INSTRUCTOR'S ASSISTANCE AVAILABLE

The first thing you should do is to remove the last section of the notes which contains a set of criterion tests and self-evaluations. Give this set to the course manager. He will administer these tests and self-evaluations so that you will get each of them at a proper time. This will enable the course manager to monitor your progress, check your answers, and provide you with additional assistance if necessary.

Then, after reading the remaining portion of this section you should proceed with each of the other modules as follows:

1. Read the objectives. If you are confident you can perform exactly as the objectives state, then consult with the course manager. The manager will ask you a few questions to ensure that you are ready for the criterion test. Once satisfied, he will give you the test.

2. If you are not sure that you can do the tasks that the objectives call for (or if you have not satisfied the course manager that you are ready for the test), you should start reading through the module. As you progress through the module you will encounter directions. These directions are marked by using an arrow (⟶),

3. Do the assignment questions in accordance with the directions.

4. Check each of your answers to the assignment questions with the corresponding suggested answer in the "TEXT ANSWERS" section. Each module has its "TEXT ANSWERS" immediately following the module text. Make sure that you do enough assignment questions so that you become confident you can complete the criterion test correctly. If you have done all the assignment questions in a module and you are not confident, consult with the course manager for more practice.

5. Once you are confident, obtain a criterion test and complete it (from memory unless otherwise started).

6. Obtain the self-evaluation and compare your answers to those in the self-evaluation, noting any discrepancies.

7. Show your test to the course manager and discuss the discrepancies that you have noted.

8. At this point the course manager will either sign you off on the module checklist or he will dianose some problems and give you directions to enable you to meet the objectives satisfactorily.

9. Once the module is signed off, proceed to the next module according to the course map.

You are now ready to begin Module PI 25-1. Proceed at a pace that is comfortable and that will allow you to complete the course in the allotted time.

D. Taylor
J. Jung

Heat and Thermodynamics - Course PI 25

BASICS

Objectives

1. Define:

    (a) Heat
    (b) Temperature
    (c) Enthalpy

2. State the meaning of each of the following as it applies to water:

    (a) Saturation temperature
    (b) Subcooled liquid
    (c) Saturated liquid
    (d) Wet steam
    (e) Saturated steam
    (f) Superheated steam
    (g) Sensible heat
    (h) Latent heat of vapourization

3. Sketch a temperature vs. enthalpy diagram for water at constant pressure. Label the following on your sketch:

    (a) Saturation temperature
    (b) Subcooled liquid region
    (c) Saturated liquid
    (d) Wet steam region
    (e) Saturated steam
    (f) Superheated steam region
    (g) Sensible heat region
    (h) Latent heat region

4. Given steam tables and values representing the temperature, pressure, and enthalpy of water, identify each set of values as one of:

    (a) Subcooled liquid
    (b) Saturated liquid
    (c) Wet steam
    (d) Saturated steam
    (e) Superheated steam

5. Given steam tables and values representing water with all but one of the initial and final conditions of temperature, pressure, enthalpy, and, if appropriate, quality specified, determine the unknown value.

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This module has two main purposes: to give you some definitions and skills which are basic to this PI 25 course, and to make you familiar with terms that you will hear in other courses here at RNTC and in the stations themselves. As you read through the module, you will come to various assignment questions.

→ Answer these questions in the spaces provided, then check your answers with those found in the "TEXT ANSWERS" section at the end of the module. If you have any questions, about either your answers or the ones in the "TEXT ANSWERS" section, please feel free to consult with the course manager.

Heat

Heat is a form of energy in a substance. The amount of heat in a substance is dependent on the temperature of the substance, on the type of substance, and its state, and on the mass of the substance.

Temperature

Temperature measures the ability of a substance to lose or gain heat energy when compared with another substance.

Are temperature and heat the same? To answer this question, imagine the small square ("A") in Figure 1.1 to be 1 kg of liquid water at 100°C and atmospheric pressure. The large square ("B") represents 1 kg of steam at 100°C and atmospheric pressure. If we allow the water and the steam to come into contact with each other, will any heat be transferred?

The answer is no - they are at the same temperature.

Do the water and the steam have the same amount of heat energy in them?

Again the answer is no - the steam must have more heat because it is in the form of a vapour, since this will be developed more fully later, the production of steam requires further addition of heat to the water.

Thus temperature and heat are not the same. Whereas heat is a form of energy, temperature is a rough indicator of the level of heat that a substance possesses.

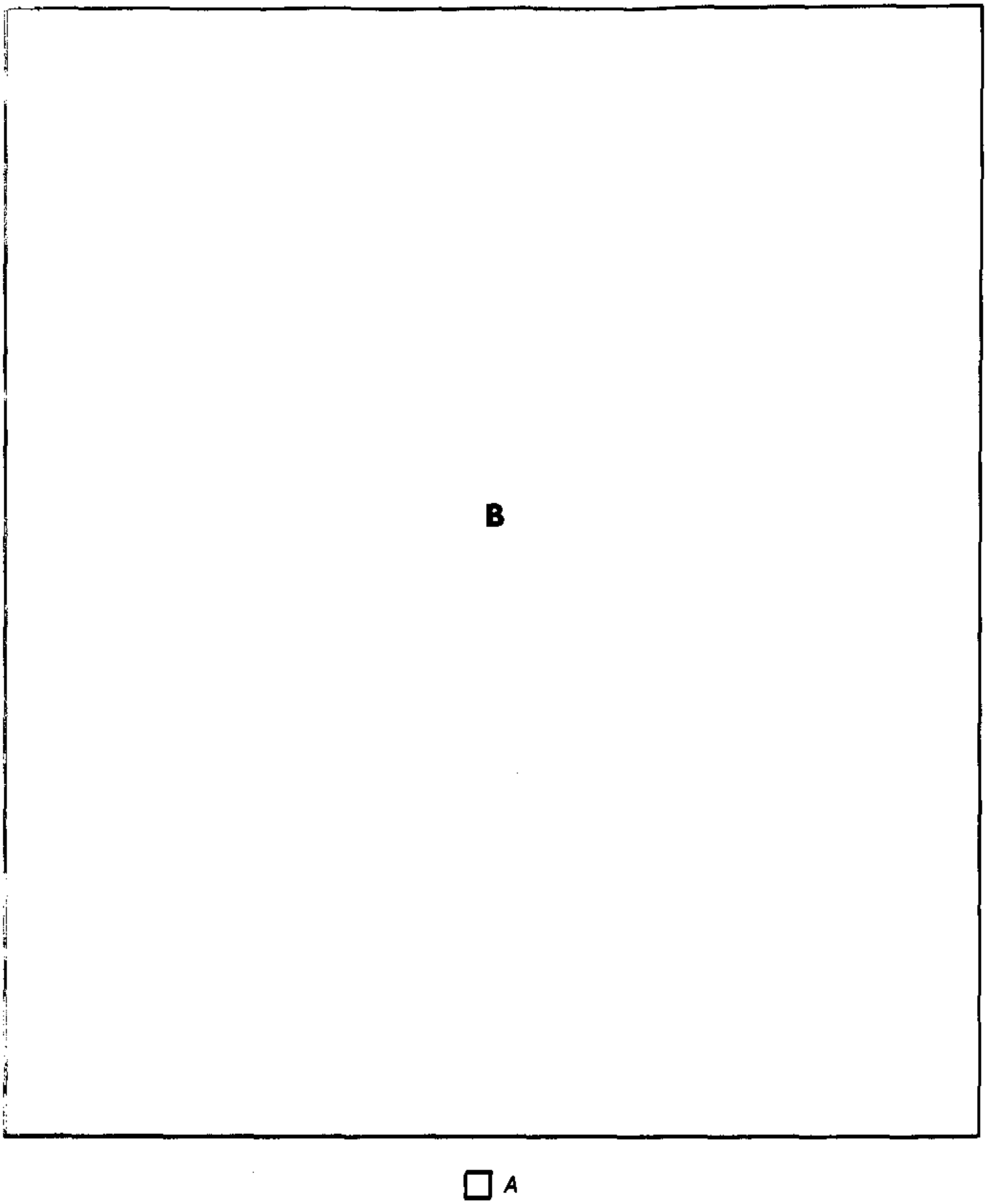


Figure 1.1

Enthalpy

For our purposes, enthalpy is defined as the total heat per kilogram of substance, measured above an arbitrary reference point. For water, the reference point is 0°C.

This definition allows us to determine quantitatively how much heat must be added to water (or how much heat can be removed from water) in various parts of the thermodynamic cycle which represents a CANDU station. The symbol for enthalpy that is used in this text is h. The unit of enthalpy is kJ kg^{-1}.

→ Answer the following questions from memory in the spaces provided, then check your answers with those in the "TEXT ANSWERS" section. Once you are satisfied with your answers, proceed to the next section, Water.

1.1) Define:

(a) Heat

____

____

(b) Temperature

____

____

(c) Enthalpy

____

____

Water

Water and heavy water are the main heat transfer media in a CANDU generating station. In the primary heat transport (PHT) system, heavy water is used to remove the heat produced by the fission of fuel in the reactor. The heavy water flows through a number of boilers, where the heat taken from the reactor is transferred through boiler tubes into light water. The light water cycle is called the secondary heat transport system. The heat added to the light water produces steam - the working fluid of the CANDU system. Some of the heat added to the steam is used in the turbine set to produce shaft mechanical power. The balance of this heat is removed in the condenser by lake water (called condenser cooling water) passing through the condenser tubes. The steam condenses and is recirculated to the boilers via a number of feedheaters, where it is heated in order to minimize thermal stressing in the boilers. The heat for this feedheating is supplied using steam and water from various parts of the secondary heat transport system.

The behaviour of water with respect to heating is thus a very important aspect of a CANDU unit. Much of the rest of this course will be concerned with this behaviour.

To begin, look at Figure 1.2. This graph of temperature vs. enthalpy for water represents the changes that water undergoes as it is heated at constant pressure, starting with liquid at 0°C.

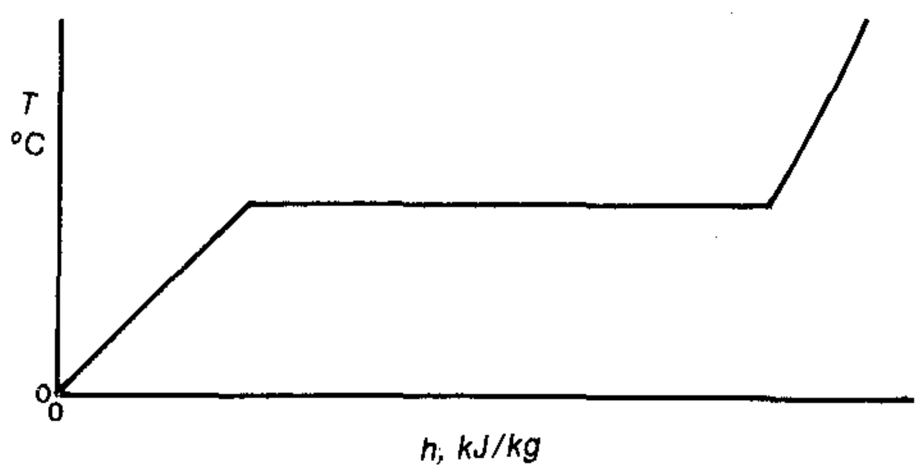


Figure 1.2

As the liquid is heated, its enthalpy increases. Initially, the liquid temperature also increases. At a certain temperature, depending on the pressure, some molecules of the water will have enough energy to change state and become vapour.

This process is, of course, boiling. The temperature at which boiling occurs for a given pressure is the saturation temperature, T_S.

Liquid that is below the saturation temperature for a given pressure is called subcooled liquid. Figure 1.3 shows the subcooled liquid region on a temperature - enthalpy diagram.

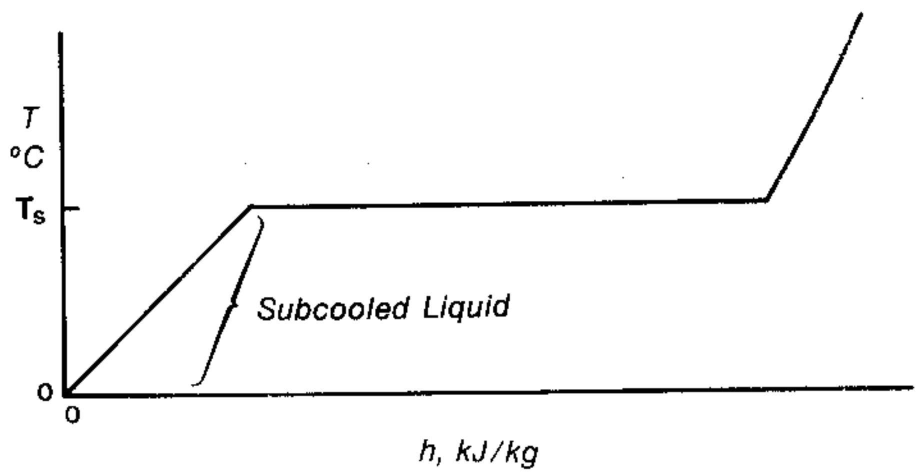


Figure 1.3

As subcooled liquid is heated, it will eventually reach the saturation temperature. If conditions are properly controlled, at this point there will be liquid at the saturation temperature, with no boiling occurring. This liquid is called saturated liquid. Figure 1.4 shows saturated liquid on a temperature - enthalpy diagram.

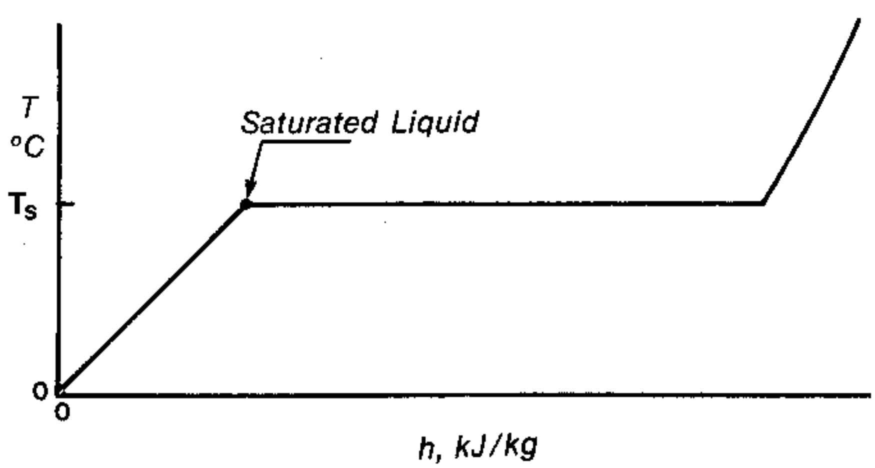


Figure 1.4

While boiling is happening, both vapour and liquid are present. Any mixture of liquid and vapour at the saturation temperature for a given pressure is called wet steam. Figure 1.5 shows wet steam on a temperature enthalpy diagram.

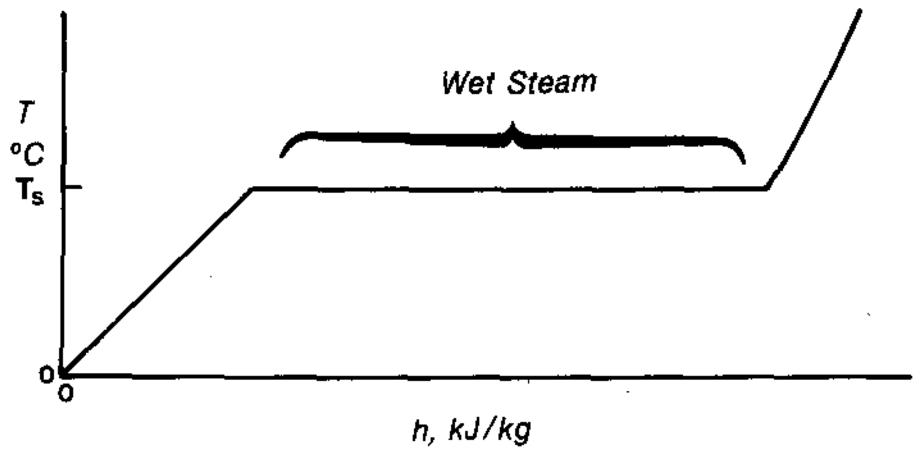


Figure 1.5

At some point all the liquid will have changed to vapour, but the vapour is still at the saturation temperature for that pressure. This is saturated steam. Figure 1.6 shows saturated steam on a temperature - enthalpy diagram.

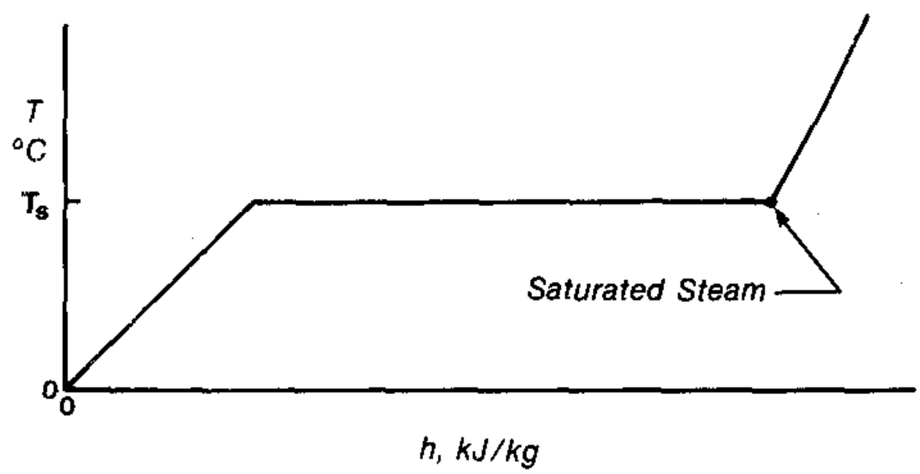


Figure 1.6

If saturated steam is heated, the temperature will rise. Any steam that is above the saturation temperature for a given pressure is called superheated steam. You can see the superheated steam region in Figure 1.7.

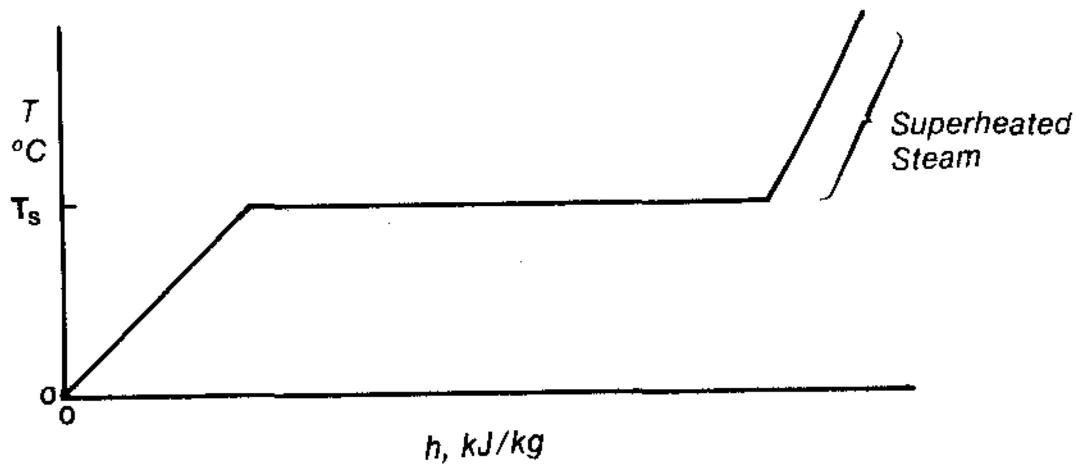


Figure 1.7

On these diagrams, any heat added that produces a temperature change is called sensible heat. The sensible heat regions are shown in Figure 1.8.

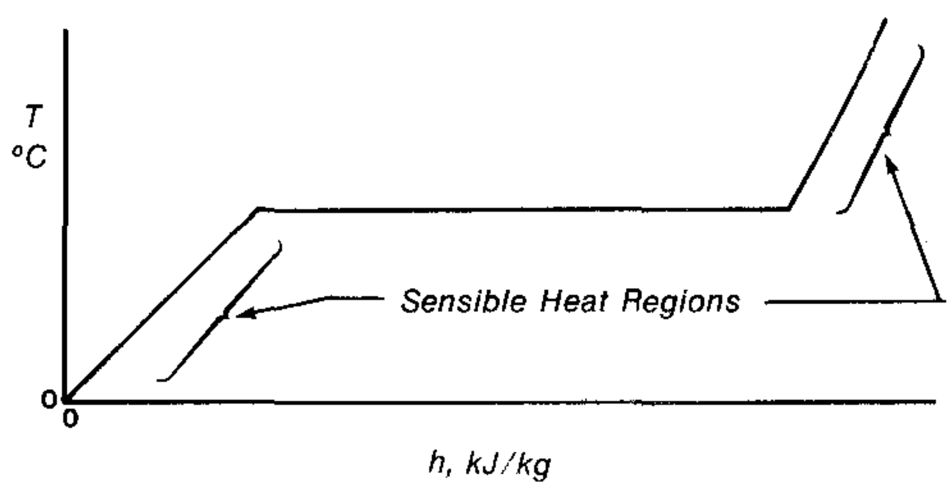


Figure 1.8

The heat added to completely boil one kilogram of fluid at constant temperature is called the latent heat of vapourization, L_V. This is shown in Figure 1.9.

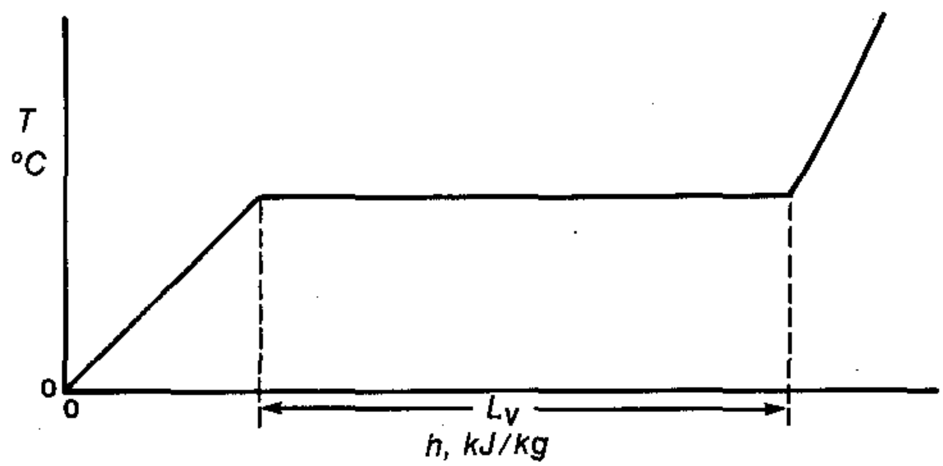


Figure 1.9

→ Try these assignment questions. Answer from memory in the space provided, then check your answer with those in the "TEXT ANSWERS" section.

1.2) State the meaning of each of the following as it applies to water:

(a) Saturation temperature: ______________________

____

(b) Subcooled liquid: ______________________

____

(c) Saturated liquid: ______________________

____

(d) Wet steam: ______________________

____

(e) Saturated steam: ______________________

____

(f) Superheated steam: ______________________

____

(g) Sensible heat: ______________________

____

(h) Latent heat of vapourization: ______________________

____

____

1.3) Sketch a temperature vs. enthalpy diagram for water at constant pressure, starting at 0°C. Label the following on your sketch:

(a) Saturation temperature
(b) Subcooled liquid region
(c) Saturated liquid
(d) Wet steam region
(e) Saturated steam
(f) Superheated steam
(g) Sensible heat region
(h) Latent heat region

Steam Tables:

This section deals with identifying the "states" of water (i.e. subcooled liquid, saturated liquid, wet steam, saturated steam, and superheated steam) given values that represent water at a certain temperature, pressure, and enthalpy. In order to be able to identify these states, you must be able to read the steam tables and to use the information presented in them.

⟶ Locate the copy of "Steam Tables in SI Units" and turn to page 1.4 in Table 1. The information you will be using is contained in the first five columns on the left side of the page.

The extreme left hand column lists saturation temperatures in even increments. The units are °C. Next to each saturation temperature is listed a pressure in bar (1 bar = 100 kPa(a)). This is the pressure at which water will boil for the given saturation temperature, or the saturation pressure.

1.4) For example, look at the 100°C entry. What is the saturation pressure for water to boil at 100°C? ________

⟶ Answer this question in the space provided and check your answer with the one in the "TEXT ANSWERS" section before proceeding.

The third column from the left is headed "h_f", which stands for the enthalpy of saturated liquid at the given saturation temperature. Find h_f for water at 100°C. The enthalpy is 419.1 kJ/kg. This means that 1 kg of water at 1.013 bar must have 419.1 kJ of heat added to it to raise it from 0°C to 100°C.

The <u>fifth</u> column from the left is headed "h_g" - this is the enthalpy of saturated steam at the given saturation temperature. Thus, to change 1 kg of water at 0°C to saturated steam at 100°C (and 1.013 bar) it is necessary to add 2676.0 kJ of heat.

The fourth column from the left, headed "h_{fg}", is not strictly an enthalpy. It is a difference of enthalpies: $h_g - h_f$. This is the latent heat of vapourization at the given saturation temperature.

1.5) What is the latent heat of vapourization of water at 100°C? ____________________

⟶ Answer this question in the space provided before proceeding and check your answer with the one in the "TEXT ANSWERS".

The information in the above example can be shown on a temperature-enthalpy diagram:

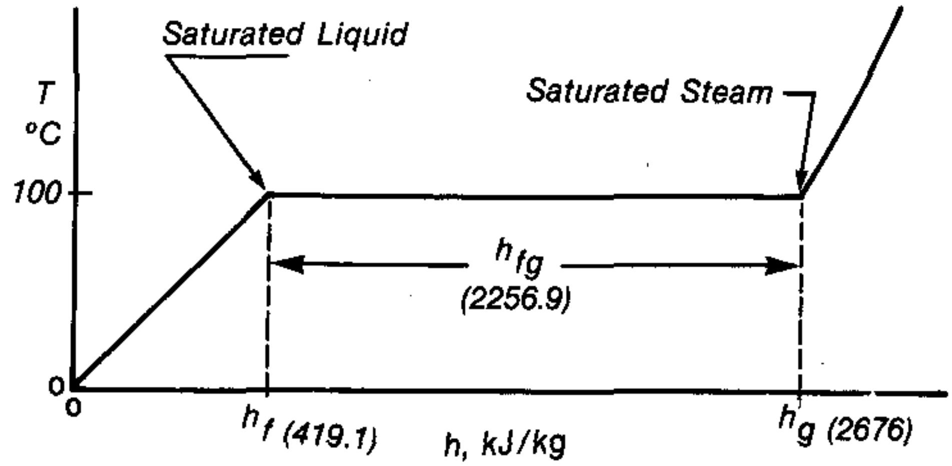


Figure 1.10

Now, compare Table 2 with Table 1.

1.6) What is the difference between the two tables?

____

⟶ Answer this question and check your answer with the "TEXT ANSWERS" section before you proceed.

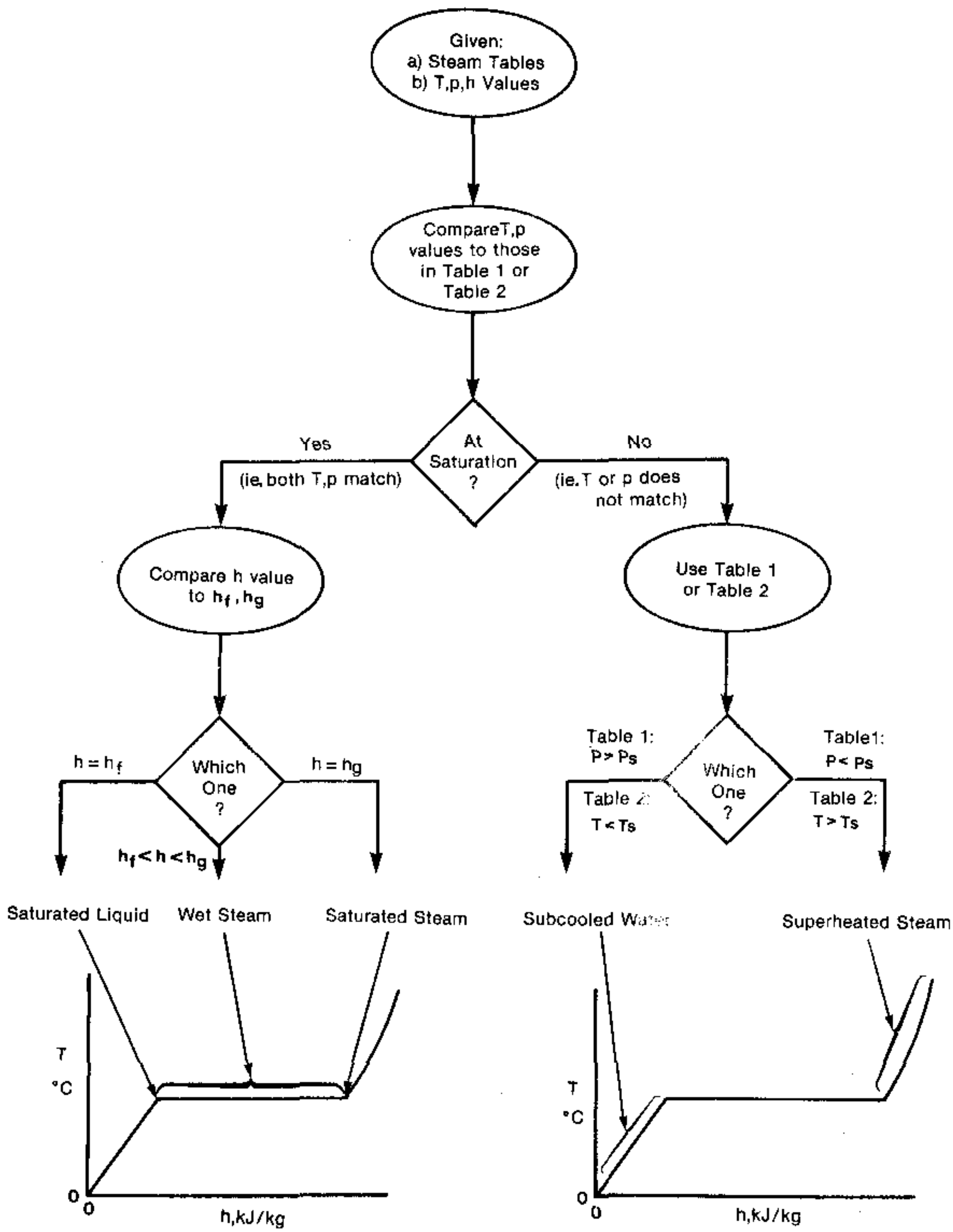

Given:
a) Steam Tables
b) T,p,h Values
CompareT,p values to those in Table 1 or Table 2
At Saturation ?
Yes
(ie, both T,p match)
No
(ie.T or p does not match)
Compare h value to h_f, h_g
Use Table 1 or Table 2
Which One ?
$h = h_f$
$h = h_g$
$h_f < h < h_g$
Table 1: P > Ps
Table 2: T < Ts
Table1: P < Ps
Table 2: T > Ts
Saturated Liquid
Wet Steam
Saturated Steam
Subcooled Water
Superheated Steam
T °C
0
h,kJ/kg

Figure 1.11

Identifying States:

If you are given a set of temperature, pressure and enthalpy values that represents water, how could you use the steam tables to go about identifying the state of water?

You can use a decision making process which is represented by Figure 1.11.

→ Use this diagram and your steam tables to follow these examples:

Identify the following as one of subcooled liquid, saturated liquid, wet steam, saturated steam, or superheated steam:

(A) 100°C, 1.013 bar, 1575.0 kJ/kg

The first thing to do is decide whether the example is at saturation or not. Look at the given temperature and pressure. Compare these values to those given in either Table or Table 2. (In this first example, since the given temperature matches an entry in Table 1, and since the given pressure does not match an entry in Table 2, you should use Table 1.) If both the given temperature and pressure match the saturation values in the appropriate table, then the example is at saturation.

→ Answer these questions now, then compare your answers with those in the "TEXT ANSWERS" section.

1.7) Look at 100°C in Table 1 and compare the given pressure to the saturation pressure. Is this example at saturation? ________________

1.8) Of the 5 states of water, 2 can now be eliminated.

Which two? ________________

Why? ________________

1.9) You now have 3 choices, each at 100°C and 1.013 bar. How can you choose between them? ________________

____

Since the given enthalpy (1575.0 kJ/kg) is greater than h_f but less than h_g, the water in this example has more heat added to it from 0°C than saturated liquid but less than saturated steam. In other words, the water must be boiling but it cannot be completely vapour. This example represents wet steam.

(B) 225 °C, 8 bar, 2894.5 kJ/kg

1.10) (a) Is this example at saturation? ______________

(b) Why? ______________________________

1.11) Which of the 5 states of water can now be eliminated?

____

→ Answer questions 1.10 and 1.11 before proceeding, then check your answers with those in the "TEXT ANSWERS".

There are two ways to proceed from this point - use Table 1 or Table 2. Either way can be used, depending on your preference.

Using Table 1: The saturation pressure for water to boil at 225 °C is 25.501 bar.

1.12) (a) What effect does raising the pressure have on the saturation temperature for water? ______________

____

(b) What effect does lowering the pressure have on the saturation temperature for water? ______________

____

→ Answer these questions, then check them before proceeding.

Since the given pressure, 8 bar, is less than 25.501 bar, the saturation temperature of the example must be less than 225°C. This example is thus above the saturation temperature for the given pressure, that is, it is superheated steam.

Using Table 2: The saturation temperature for water at 8 bar is 170.415 °C. Since the given temperature, 225 °C, is higher than the saturation temperature at the given pressure, this example must be superheated steam.

Now it's time to practice for yourself.

→ Using steam tables and Figure 1.11 answer question 1.13 in the spaces provided, then check your answers against those in the "TEXT ANSWERS".

1.13) State whether each of the following represents subcooled liquid, saturated liquid, wet steam, saturated steam, or superheated steam:

(a) 54°C, 0.15 bar, 2599.2 kJ/kg ____________________

(b) 210°C, 20 bar, 897.9 kJ/kg ____________________

(c) 170°C, 7.92 bar, 1241.2 kJ/kg ____________________

(d) 179°C, 9.8 bar, 758.7 kJ/kg ____________________

(e) 300°C, 30 bar, 2995 kJ/kg ____________________

Basic Calculations Using Steam Tables

In this section you will be given sets of values representing water as it is heated or cooled from one set of conditions to another. Using the steam tables, you will be asked to do simple calculations to determine an unknown variable.

→ Locate your copy of the steam tables and use them to follow the worked examples and to try some practice questions:

Example 1:

Water at 60°C is heated to produce water at 95°C. Determine the heat that must be added per kilogram of water heated.

Answer:

If we can find the enthalpy of the water at the initial and final conditions, we can say that the difference in enthalpies, Δh, between the two conditions is the amount of heat that must be added per kilogram.

Liquid water is an incompressible fluid. As such, its enthalpy will not vary significantly with pressure. Thus, if we know the water temperature, we can assume that the enthalpy of the liquid is essentially the same as that of saturated liquid at the same temperature.

The enthalpy of water at 60°C can be assumed to be the same as h_f at 60°C, or 251.1 kJ/kg from Table 1, and the enthalpy of water at 95°C can be assumed to be h_f at 95°C, or 398.0 kJ/kg.

The amount of heat added in this case is:

$$\Delta h = h_{f_{95°C}} - h_{f_{60°C}}$$
$$= 398 - 251.1$$
$$= 146.9 \text{ kJ/kg}$$

This can be represented on a temperature vs. enthalpy diagram as follows:

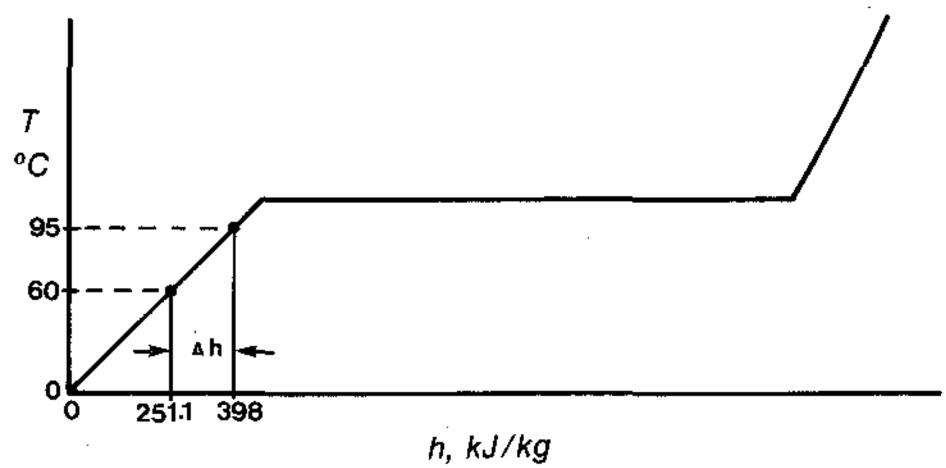


Figure 1.12

Example 2:

Water at 176°C enters a boiler. The boiler produces 1000 kg/s of saturated steam at 254°C. What is the rate of heat addition in the boiler?

Answer:

The process is represented by Figure 1.13:

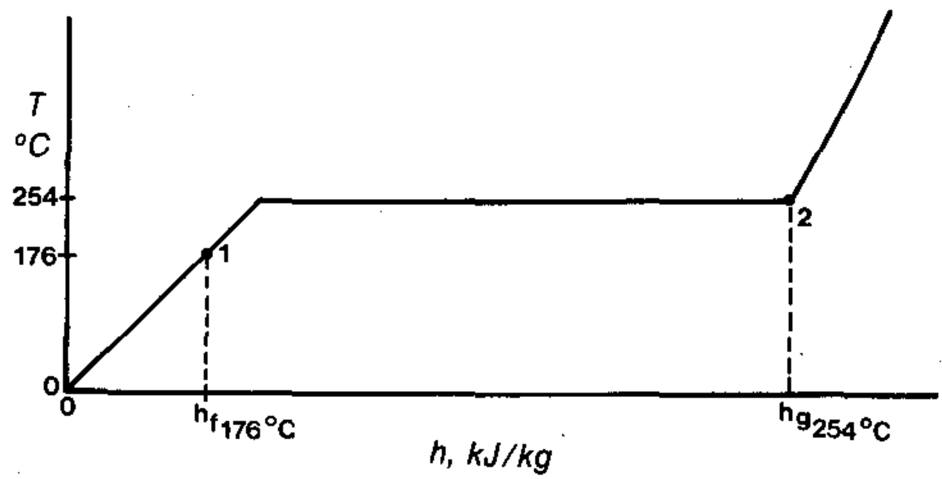


Figure 1.13

Here, condition 1 is water at 176°C and condition 2 is saturated steam at 254°C.

Δh is the difference between $h_{g254°C}$ and $h_{f176°C}$

$$\Delta h = h_{g254°C} - h_{f176°C}$$

$$= 2799.1 - 745.5$$

$$= 2053.6 \text{ kJ/kg}$$

Since there are 1000 kg/s of steam generated, the rate of heat addition is 1000 x Δh, or

$$1000 \times 2053.6$$

$$= 2{,}053{,}600 \text{ kJ/s}$$

1 watt is equal to 1 J/s by definition. Thus the rate of heat addition may be expressed as 2,053,600 kW or 2053.6 MW.

⟶ Before you proceed, try the following questions. Answer them in the space provided, then check your answers with those in the "TEXT ANSWERS".

1.14) How much heat must be added per kilogram to raise the temperature of liquid water from 60°C to 250°C? (Assume that the liquid is pressurized sufficiently to remain liquid).

1.15) What is the heat removal rate if 33.0 kg/s of saturated steam at 120°C is condensed to form water 103°C?

Wet Steam

→ Use Figure 1.14 to answer the following questions. Write your answers in the space provided, then check them with the *"TEXT ANSWERS" before you proceed.*

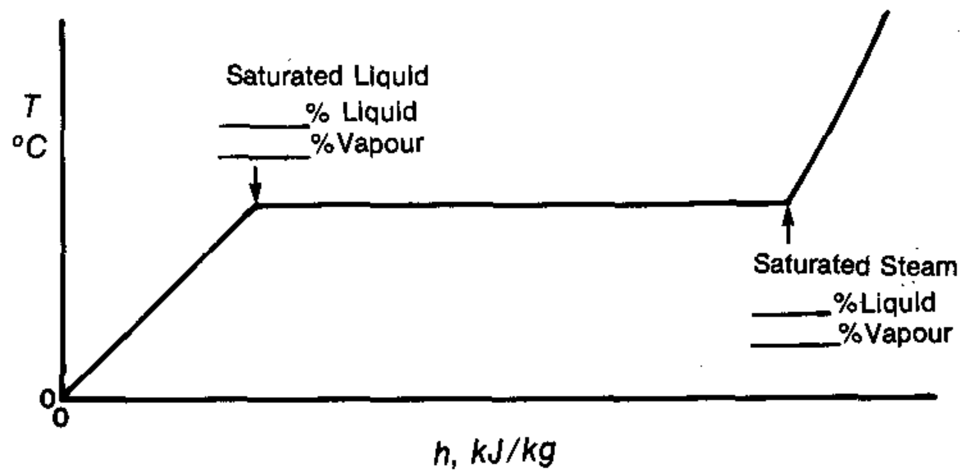


Figure 1.14

1.16) For saturated liquid, what percentage of the fluid is:

(a) liquid?

(b) vapour?

1.17) For saturated steam, what percentage of the fluid is:

(a) liquid?

(b) vapour?

→ (Write the percentages on Figure 1.14 in the appropriate spaces.)

1.18) On Figure 1.14, mark the point that represents wet steam with 75% vapour and 25% steam by mass.

1.19) How much of the latent heat must be added to the saturated liquid to produce the wet steam in question 1.18? ____________________

1.20) *How could you determine the enthalpy of the wet steam* from question 1.18? ____________________

____

Note: The steam from question 1.18 is commonly referred to in a variety of ways. It could be called wet steam (quality = 75%); 25% wet steam, wet steam with moisture content 25%, or wet steam with dryness fraction 0.75.

Generally, to determine the enthalpy of wet steam (h_{ws}) add the enthalpy of saturated liquid (at the same temperature) to the fraction of the latent heat of vapourization (again at the same temperature) that corresponds to the steam quality:

i.e. $h_{ws} = h_f + q\, h_{fg}$

where q = steam quality, represented as a fraction.

⟶ Answer the following questions in the space provided before proceeding, then check your answers with those in the "*TEXT ANSWERS*".

1.21) Determine the enthalpy of 25% wet steam at 130°C.

1.22) Wet steam at 50°C has enthalpy 2450 kJ/kg. Determine the moisture content of this steam.

1.23) Saturated liquid at 14 bar is heated to produce 10% wet steam. How much heat is added per kg of wet steam produced?

1.24) How much heat is removed from 5 kg of wet steam (moisture content = 21%) at 140°C to produce water at 110°C?

1.25) If 2.28×10^4 kJ of heat are added to 10 kg of water at 65°C to produce wet steam at 95°C, what is the quality of the steam produced?

→ The first module is now complete. Read the objectives for this module again. If you are confident you can perform the objectives, obtain the PI 25-1 Criterion Test and complete it. If you feel you need more practice in any area, see the course manager.

PI 25-1 TEXT ANSWERS

1.1) (a) Heat:

A form of energy in a substance, depending on the temperature, type, state and mass of the substance.

(b) Temperature:

A measure of the ability of a substance to lose or gain heat when compared with a second substance.

(c) Enthalpy:

The total heat per kg of substance, measured above an arbitrary reference point.

1.2) (a) Saturation Temperature:

The temperature at which boiling occurs for a given pressure.

(b) Subcooled Liquid:

Liquid water below its saturation temperature.

(c) Saturated Liquid:

Liquid water at the saturation temperature. No boiling has yet occurred.

(d) Wet Steam:

A mixture of liquid and vapour at the saturation temperature.

(e) Saturated Steam:

100% vapour at the saturation temperature.

(f) Superheated Steam:

Vapour at a temperature above its saturation temperature.

(g) Sensible Heat:

Heat added that results in a change in temperature.

(h) Latent Heat of Vapourization:

Heat added to boil 1 kg of water at constant temperature.

1.3)

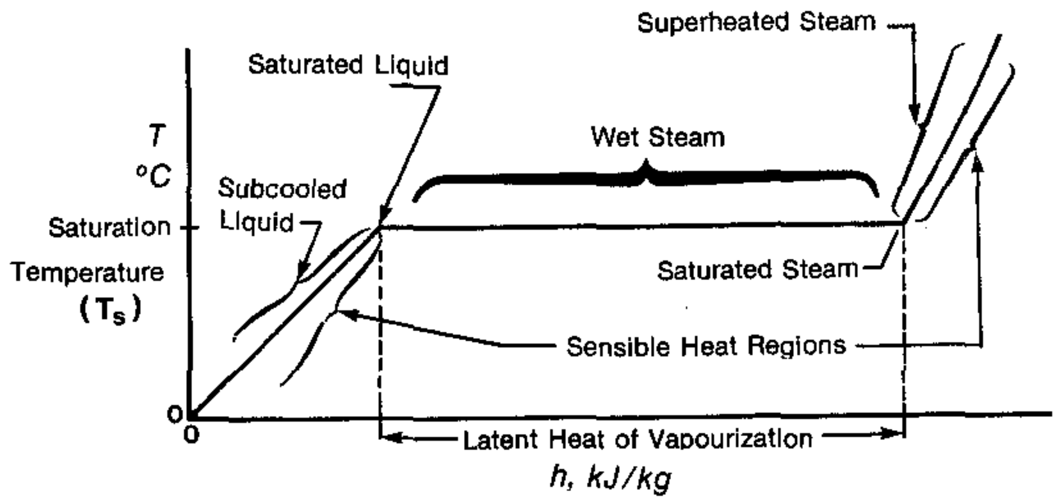


Figure 1.15

1.4) The saturation pressure for 100°C is 1.013 bar, or 101.3 kPa(a).

1.5) The latent heat of vapourization for water at 100°C is 2256.9 kJ/kg.

1.6) Table 1 has even increments of temperature as the initial variable, while Table 2 has even increments of pressure as the initial variable.

1.7) Yes, this example is at saturation - that is, the given temperature and pressure (100°C, 1.013 bar) match values in Table 1. (Note: On Figure 1.11, you have now picked the left branch).

1.8) (a) Subcooled liquid and superheated steam can be eliminated.

(b) These two states cannot be at saturation by definition, thus they can be eliminated.

1.9) Compare the given enthalpy to h_f and to h_g. Since the given value states the amount of heat added to water from 0°C, it can be compared to the saturated liquid and saturated steam enthalpies to fix the state.

1.10) (a) No.

(b) In this case either Table 1 or Table 2 is appropriate, since there is an entry to match 225°C in Table 1 and an entry to match 8 bar in Table 2.

From Table 1, the saturation pressure for 225°C is 25.501 bar (not 8 bar).

From Table 2, the saturation temperature for 8 bar is 170.415°C (not 225°C).

Looking at Figure 1.11, you have now picked the right hand branch.

1.11) Since saturated liquid, wet steam, saturated steam are at saturation, they can now be eliminated.

1.12) (a) Raising the pressure increases the saturation temperature.

(b) Lowering the pressure decreases the saturation temperature.

1.13) (a) Saturated Steam

In either Table 1 or 2, 54°C and 0.15 bar match saturation values (53.997°C can be rounded off to 54°C). Thus this example is at saturation. Comparing the given enthalpy, 2599.2 kJ/kg, to h_f and to h_g in Table 1 or 2, you will find the given enthalpy equals h_g. This must be saturated steam.

(b) Subcooled Liquid

Comparing 210°C and 25 bar to either table should indicate that this example is not at saturation.

If you used Table One:

The saturation pressure for water to boil at 210°C is 19.007 bar. The given pressure, 20 bar, is greater than 19.077 bar; thus the saturation temperature for the example must be more than 210°C. Since the example is at 210°C at 20 bar, the state must be subcooled water.

If you used Table Two:

The saturation temperature for water at 20 bar is 212.375°C. The given temperature, 210°C, is less than the saturation temperature. This must be subcooled liquid.

(c) Wet Steam:

Table One is the best choice for this example, since Table 2 does not have 7.92 bar listed. When you compare the given temperature and pressure, 170°C, 7.92 bar, to the values in Table 1, you should find they match. This example is thus at saturation. The given enthalpy, 1241.2 kJ/kg, is more than h_f (719.1 kJ/kg), and less than h_g (2767.1 kJ/kg). This means the correct answer is wet steam.

(d) Saturated Liquid:

The given temperature and pressure, 179°C, 9.8 bar, match the values in Tables 1 and 2 (rounding 9.798 bar to 9.8 bar). This example is at saturation. The given enthalpy, 758.7 kJ/kg, equals h_f - so the state is saturated liquid.

(e) Superheated Steam:

Comparing 300°C and 30 bar with the values in either table should indicate that the example is not at saturation.

If you used Table One:

The saturation pressure for water to boil at 300°C is 85.927 bar. Since the given pressure, 30 bar, is less than 85.927 bar, the saturation temperature must be less than 300°C. Since the water is above the saturation temperature at the given pressure, this is superheated steam.

If you used Table Two:

The saturation temperature for water to boil at 30 bar is 233.841°C. Since the given temperature, 300°C, is greater than the saturation temperature for 30 bar, the state is superheated steam.

1.14) This process can be represented as shown in Figure 1.16.

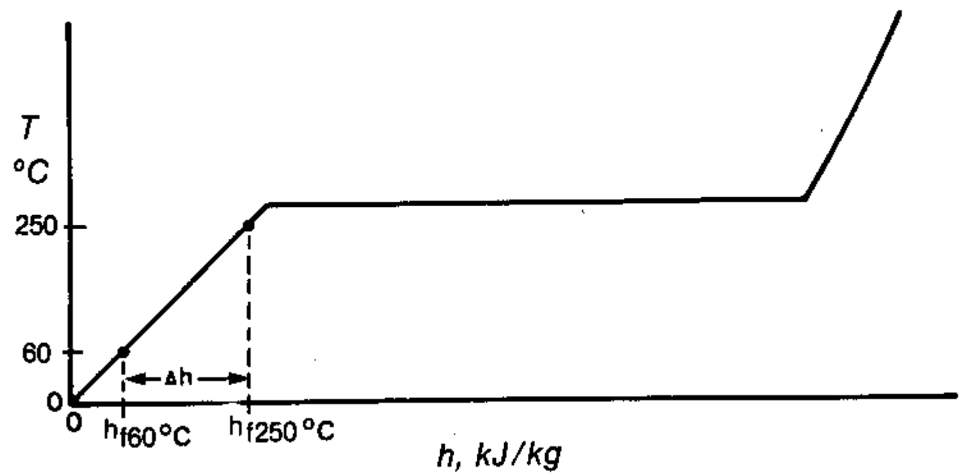


Figure 1.16

Here $\Delta h = h_{f_{250°C}} - h_{f_{60°C}}$

From Table 1, $h_{f_{250°C}}$ = 1085.8 kJ/kg

and $h_{f_{60°C}}$ = 251.1 kJ/kg

Thus, Δh = 1085.8 - 251.1

= 834.7 kJ/kg

1.15) The process can be represented as shown below:

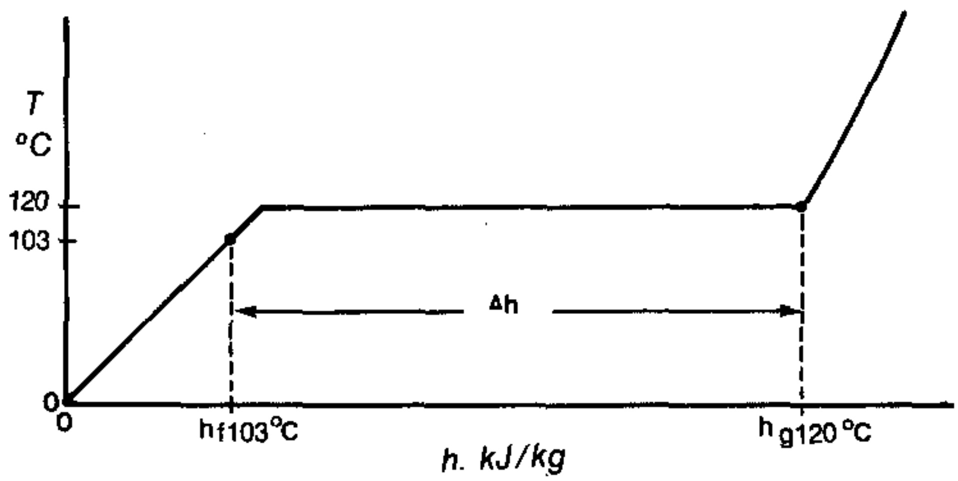


Figure 1.17

In this case, $\Delta h = h_{g120°C} - h_{f103°C}$

From Table 1, $h_{g120°C}$ = 2706.0 kJ/kg

and $h_{f103°C}$ = 431.7 kJ/kg

Thus, Δh = 2706.0 - 431.7

= 2274.3 kJ/kg

For a 33.0 kg/s flow, the heat removal rate will be 33.0 x 2274.3 = 7.51×10^4 kW.

1.16) (a) 100% is liquid.

(b) 0% is vapour.

1.17) (a) 0% is liquid.

(b) 100% is vapour.

1.18)

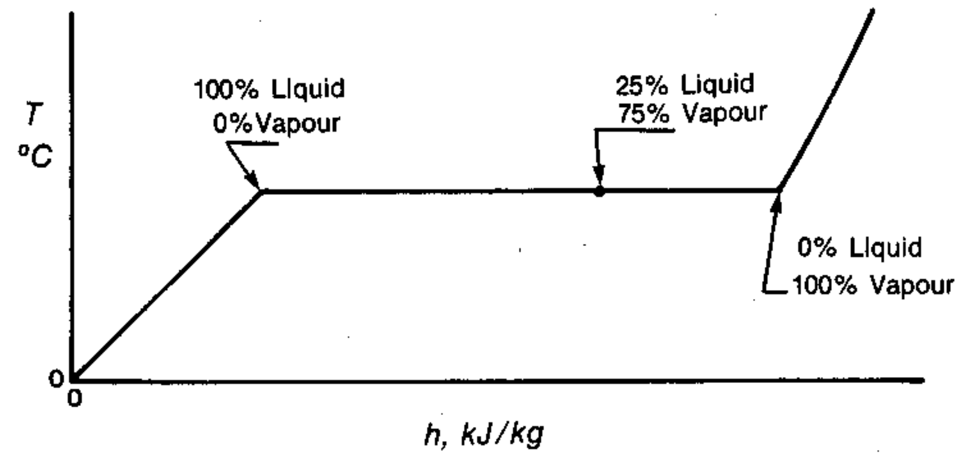


Figure 1.18

1.19) To change saturated liquid to wet steam (75% vapour and 25% liquid), 75% of the latent heat must be added.

1.20)

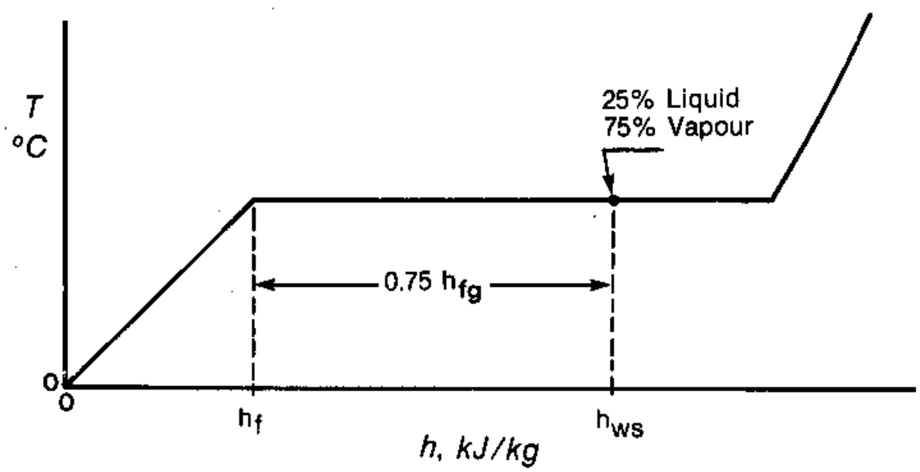


Figure 1.19

To obtain the enthalpy of the wet steam (h_{ws}), consider the following:

First, the water must be heated from 0°C to produce saturated liquid. The heat added can be expressed as h_f.

Secondly, 75% of the latent heat is added to produce the wet steam. This can be expressed as 0.75 h_{fg}.

Thus, the enthalpy of the wet steam is the sum of h_f and 0.75 h_{fg}:

$$h_{ws} = h_f + 0.75\ h_{fg}$$

(Remember that enthalpy for water is by definition the heat added from reference point <u>0°C</u>.)

1.21) "25% wet steam" is steam with quality 75%.

At 130°C, h_f = 546.3 kJ/kg

and h_{fg} = 2173.6 kJ/kg

Thus h_{ws} = 546.3 + 0.75 x 2173.6

= <u>2176.5 kJ/kg</u>

1.22) In this question you are asked to calculate the moisture content of the steam. You can use the enthalpy of the wet steam to determine the steam quality, and then find the moisture content using the quality:

$$h_{ws} = 2450 \text{ kJ/kg}$$

At 50°C from Table 1 h_f = 209.3 kJ/kg

and h_{fg} = 2382.9 kJ/kg

Thus, 2450 = 209.3 + q x 2382.9

$$\text{and } q = \frac{2450 - 209.3}{2382.9} = 0.940$$

The quality is 94.0%; the moisture content must be 100 - 94.0 = <u>6.0%</u>.

1.23) In this case, Δh is $h_{ws} - h_{f_{14bar}}$. Since there is no mention of temperature change, we will assume the wet steam to be at 14 bar. This is shown on Figure 1.20:

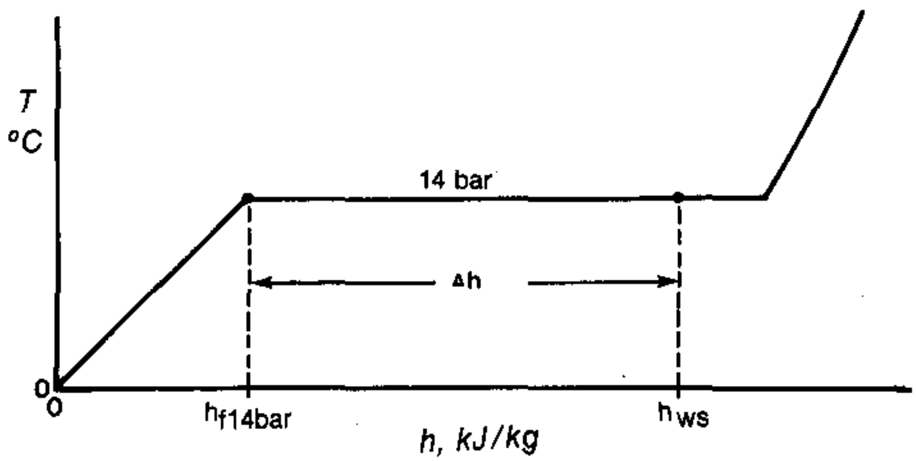


Figure 1.20

By inspection of Figure 1.20, you will see that Δh is the same as the percentage of latent heat added to the saturated liquid. Since the steam is 10% wet, 90% is the percentage of latent heat added.

From Table 2, $h_{fg_{14\ bar}} = 1957.7$ kJ/kg

Therefore, $\Delta h = 0.90 \times 1957.7$

$= 1761.9$ kJ/kg

1.24) This example involves condensing steam and cooling it. The change in enthalpy, Δh, is:

$$h_{ws_{140°C}} - h_{f_{110°C}}$$

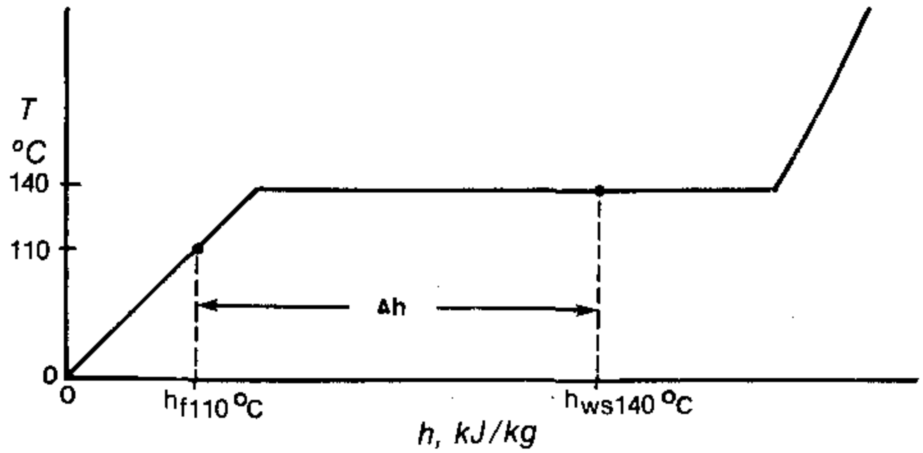


Figure 1.21

From Table 1, $h_{f_{140°C}}$ = 589.1 kJ/kg

and $h_{fg_{140°C}}$ = 2144.0 kJ/kg

Since the moisture content is 21%, the dryness will be 79%.

Thus $h_{ws_{140°C}}$ = 589.1 + 0.79 x 2144.0

= 2282.86 kJ/kg

From Table 1, $h_{f_{110°C}}$ = 461.3 kJ/kg

Thus, Δh = 2282.86 - 461.3

= 1821.56 kJ/kg

The heat removed from 5 kg of steam is

5 x 1821.56 = 9.11×10^3 kJ.

1.25) This example is somewhat different than the others, in that the unknown variable is the steam quality.

The process can be represented as in Figure 1.22:

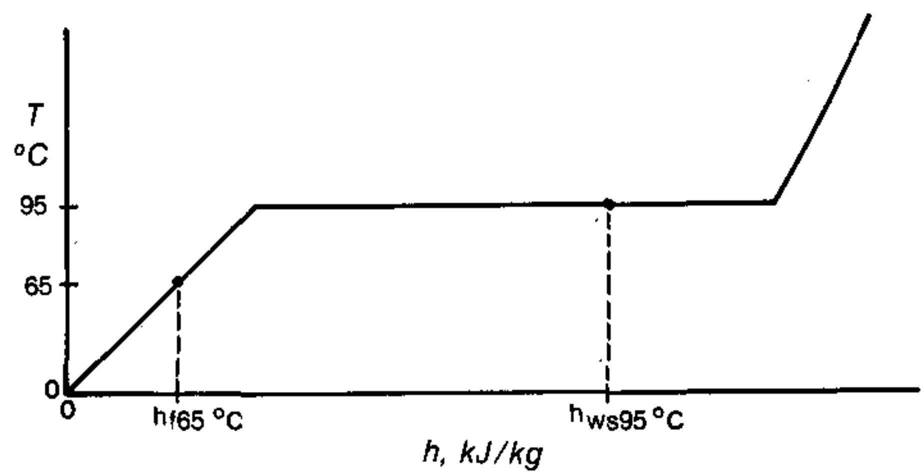


Figure 1.22

The quantity of heat added for 10 kg of water is 2.28 x 10^4 kJ. Thus the change in enthalpy is (Δh) is:

$2.28 \times 10^4 \div 10 = 2.28 \times 10^3$ kJ/kg.

Δh can also be expressed as $h_{ws95°C} - h_{f65°C}$

This can be expanded:

From Table 1, $h_{f65°C} = 272.0$ kJ/kg

$h_{f95°C} = 398.0$ kJ/kg

$h_{fg95°C} = 2270.2$ kJ/kg

Thus, $\Delta h = (398.0 + q \times 2270.2) - 272.0$ kJ/kg

Substituting, $2.28 \times 10^3 = (398.0 + q \times 2270.2) - 272.0$

So q = 0.949,

or the steam quality if 94.9%.

Heat and Thermodynamics - Course PI 25

EXPANSION AND CONTRACTION

Objectives

1. Given all variables but one, use $\Delta L = L_o \alpha \Delta T$ to determine the unknown variable.

2. Given a sketch of a bimetal strip and the coefficients of linear expansion of the metals in the strip, state in which direction the strip will bend as it is heated or cooled. Briefly explain why the strip will bend in the stated direction.

3. Given values representing initial and final conditions of a unit mass of water or heavy water and appropriate tables, determine the ratio representing the volume change that will occur as the water or heavy water goes from the initial to the final condition.

   The changes may be any of the following:

   (a) Liquid at one temperature to liquid at another temperature.

   (b) Vapour (saturated or wet) at one pressure to vapour (saturated or wet) at another pressure.

   (c) Liquid at a given temperature to vapour (saturated or wet) at the same temperature.

   (d) Vapour (saturated or wet) at one temperature to liquid at the same temperature.

4. Explain the terms shrink and swell as they apply to:

   (a) A liquid that is changing temperature while remaining liquid.

   (b) Water in a boiler that is experiencing step increases or decreases in steam flow rate.

5. Explain why the programmed level of water in the boiler changes as power is changed.

6. Explain how steam entering the condenser at a CANDU station can be at about 30°C and 4 kPa(a).

Most substances expand when heated and contract when cooled. The behaviour of substances due to heating and cooling must be taken into account in the design and operation of a CANDU generating station. In this module you will be learning some methods of predicting how metals will behave when they are heated or cooled. You will also be determining volumetric changes that various states of water undergo as they are heated or cooled.

Linear Expansion and Contraction:

Generally, when we consider the behaviour of metal fabricated parts as heating or cooling occurs, we are concerned only with changes in one dimension.

We call this behaviour linear expansion or linear contraction - the change in length a substance undergoes as it is heated or cooled.

The amount of expansion/contraction a particular object undergoes is proportional to three factors:

(1) the change in temperature the object undergoes. This temperature difference (between the initial and final temperatures) is measured in °C and is labelled ΔT. The larger the temperature difference, the greater the expansion or contraction.

(2) the original length of the object, L_o. The longer the original length, the more expansion or contraction.

(3) the substance the object is made of. Different substances will expand/contract different amounts, even if they have the same original length and if they undergo the same temperature difference. This behaviour is quantified by measuring the amount of expansion/contraction of each substance per unit length per °C temperature change. The measurement is known as the "coefficient of linear expansion," α.

The dimensions of the coefficient are length, length^{-1}, temperature^{-1}; since the length dimensions cancel, the unit for the coefficient is °C^{-1}.

The combination of the above three factors can be used to predict the amount of expansion or contraction that a metal will undergo. If we label the amount of expansion/contraction ΔL,

$$\text{then } \Delta L = L_o \alpha \Delta T.$$

The use of the above equation to predict the behaviour of metals with heating or cooling is an approximation. It is a valid approximation because:

(1) the expansion and contraction processess due to heating and cooling are sensibly reversible; that is, if a metal is heated, then cooled to its original temperature it will expand, then contract to its original length.

(2) the coefficients of expansion vary only slightly over the range of temperatures normally experienced in our stations.

You will be asked to use $\Delta L = L_o \alpha \Delta T$ in two ways:

a) in solving simple numerical examples.

b) in predicting the behaviour of bimetal strips.

Let's look at (a) first.

(a) Numerical Examples

→ Answer the following questions in the spaces provided, then check your answers with those in the "TEXT ANSWERS" section.

2.1) The steam supply line to Bruce Heavy Water Plant "A" (BHWP-A) has a pipe run that is 655 m long at 25°C. The pipe is made of carbon steel ($\alpha = 10 \times 10^{-6}$ °C^{-1}) and when steam is being supplied to BHWP-A the pipe temperature is 190°C. Determine the amount of expansion the pipe undergoes.

2.2 The low pressure (LP) turbine shaft at BNGS-B is 51.2 m long at 25°C. If the linear expansion coefficient is 11×10^{-6} °C^{-1} and the average shaft temperature at power is 105°C, what is the amount of expansion of the shaft?

2.3) A stainless steel sleeve ($\alpha = 16 \times 10^{-6}$ °C^{-1}) is to be installed on a shaft with an interference fit. To accomplish this the sleeve is to be heated until it slides easily over the shaft. If the sleeve has 0.55 m diameter at 20°C and if it must be heated until its diameter is 0.552 m, to what temperature should it be heated?

b) **Bimetal Strips:**

A bimetal strip is a common device used as a thermal switch or as a thermometer. In its most basic form, it can be represented as shown in Figure 2.1:

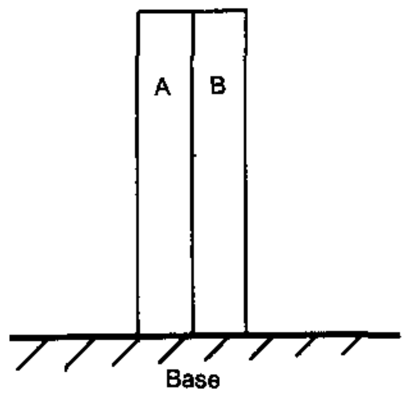


Figure 2.1

Two different metals, A and B, are joined firmly together, then fastened to the base.

2.4) If A is brass ($\alpha = 18 \times 10^{-6}\ °C^{-1}$) and B is carbon steel ($\alpha = 10 \times 16^{-6}\ °C^{-1}$), what will happen to the strip if it is heated uniformly 5°C?____________________

____.

2.5) Explain why the strip will behave as in question 2.4.

____

____

→ Answer the above questions before you proceed, then check your answers with those in the "TEXT ANSWERS" section.

You should now be able to predict the behaviour of a bimetal strip as it is heated or cooled, and you should be able to briefly explain this behaviour.

→ Try question 2.7, then check your answer with the one in the "TEXT ANSWERS" section. You should now be able to do the first two objectives for this module. If you feel you need any more practice, see the course manager.

2.7) Towards which contact will the strip shown in Figure 2.2 move as it is cooled? Briefly explain why.

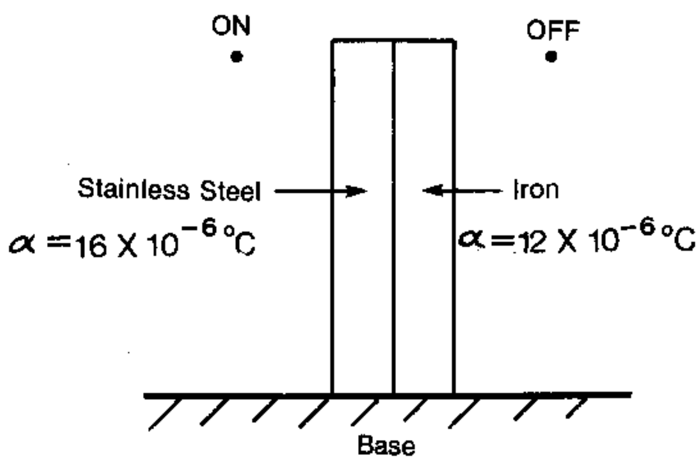


Figure 2.2

Volumetric Expansion and Contraction:

Almost all fluids expand upon heating and contract when cooled. When we consider the behaviour of fluids with respect to thermal expansion/contraction, we are concerned with changes in volume. We call this behaviour volumetric expansion or volumetric contraction.

Since water and heavy water are the working fluids of CANDU generating units, we will only consider the behaviour of these two substances in this module.

→ Locate your copies of "Steam Tables in SI Units" and "Heavy Water Steam Tables" and refer to them as indicated.

The steam tables for water and for heavy water include entries for specific volume - that is, the volume per kilogram of fluid. You will be using these entries to predict the ratio of change of volume when water is changed from one given set of conditions to another.

— Turn to Table 1 in the "Steam Tables in SI Units". The entries you will be using are found in the first four columns on the right side of the page. The column on the extreme right is the given saturation temperature. The column headed V_f is the specific volume of saturated liquid at the given saturation temperature. The column headed V_f is the specific volume of saturated steam at the given saturation temperature. The column headed v_{fg} is the change in volume as water is boiled at the given saturation temperature. The unit of specific volume in these tables is dm^3/kg, or ℓ/kg.

→ Now turn to Table 1 in the "Heavy Water Steam Tables". The entries in these tables differ in two ways:

(a) they represent the specific volume of heavy water, in m^3/kg.

(b) they are located on the left side of the page.

You will be using these tables to determine the initial and final values of specific volume for water and heavy water that are undergoing various changes. To determine the ratio of any volume change, divide the larger specific volume by the smaller one.

→ Try the following practice questions, then check your answers with those in the "TEXT ANSWERS" before proceeding.

2.8) Determine the ratio of the change in volume as water at 254°C is boiled to produce saturated steam at 254°C.

2.9) Determine the ratio of the change in volume as liquid heavy water at 60°C is heated to produce liquid heavy water at 260°C.

How can you determine the specific volume of wet steam? The answer is to treat it in exactly the same way as you did the enthalpy of wet steam: to the specific volume of the saturated liquid add the product of the steam quality and the change in volume from liquid to vapour. This can be expressed as follows:

$$V_{ws} = V_f + q\, V_{fg}$$

where V_{ws} is the specific volume of the wet steam.

⟶ Answer the following questions before you proceed. Check your answers with those in the "TEXT ANSWERS" section .

2.10) Determine the ratio of the change in volume of steam going through the turbine set at PNGS-A. The steam enters the set saturated at 250°C and leaves the set 10% wet at 33°C.

2.11) Determine the ratio of the change in volume in the condenser at BNGSA. Steam (moisture content 12%) at 30°C enters the condenser and is condensed to form water at 30°C.

→ If you are confident you can do objective (3) at this point, proceed to the next section in this module. If you feel you need more practice, obtain some extra questions from the course manager.

Shrink and Swell

The terms shrink and swell are commonly used terms that are applied to the change in volume of water in two specific circumstances in a CANDU station.

1. Shrink and Swell in a Liquid System

The first circumstance deals with the primary heat transport (PHT) system. This system removes heat from the fuel and transports it to the boilers, where the heat is transferred to light water to produce steam. The heavy water in the PHT system is in the range of 250°C to 300°C when the unit is "at power" (i.e. ready to produce power) and it is highly pressurized (9 to 10 MPa(a)) so that vaporization will not occur.

After a lengthy shutdown, the PHT average temperature is about 60°C. As it is brought up to the operating temperature range, the heavy water will undergo a 25% expansion (as you calculated in question 2.9). This change in volume as the average PHT system temperature is increased is referred to as swell in the PHT system.

Conversely, as the system is taken from "at power" state to "cold pressurized" (i.e. 60°C and 9 to 10 MPa(a)) it will undergo a 25% contraction. This decrease in volume as the PHT average temperature is decreased is known as shrink in the PHT system.

Note that shrink and swell tend to occur any time the PHT average temperature changes.

2. Shrink and Swell in a Boiler:

When a CANDU boiler is operating, boiling is occurring throughout most of the liquid. The fluid in the boiler is thus a mixture of vapour and liquid. Since the vapour has approximately 40 times the liquid volume per kilogram at boiler conditions, it contributes significantly to the volume of fluid in the boiler. This volume is monitored by measuring the liquid level in the boiler. As the amount of vapour in the fluid varies, the liquid level will vary.

Consider an operating boiler that experiences a step increase in steam flow - that is, the steam flow out of the boiler is instantly increased by a certain amount.

2.12 What will happen to the pressure in the boiler?

2.13 (a) What will happen to the boiler level?

(b) Why will this occur?

→ Answer questions 2.12 and 2.13 in the space provided, then check your answers with those in the "TEXT ANSWERS". If you have any questions at this point, consult with the course manager.

This increase in level due to a very rapid or step increase in steam flow from the boiler is called swell in the boiler. It can be a significant amount: for example, at PNGSA for a steam flow increase corresponding to a change in power from 0% to 100% at the rate of 1%/s, the swell is 0.66 m.

Now consider an operating boiler that undergoes a step decrease in steam flow.

2.14) What will happen to the pressure in the boiler?

2.15) (a) What will happen to the boiler level?

(b) Why will this happen?

⟶ Answer questions 2.14 and 2.15 before you proceed, then check your answers with those in the "TEXT ANSWERS".

The decrease in level due to a a very rapid or step *decrease in steam flow from the boiler is called* <u>*shrink*</u>. *The* worst case shrink occurs when the unit is at 100% full power and a turbine trip occurs with no corresponding reactor trip. At PNGS-A the shrink would be 1.5 m in this case.

Both shrink and swell occur only during transitions following a very rapid change in the steam flow from the boiler. When the boiler pressure is constant, neither shrink nor swell occurs.

⟶ Answer the following questions before you proceed, then compare your answers with those in the "TEXT ANSWERS".

2.16) Explain shrink and swell as they apply to:

(a) the PHT D_2O as its temperature is changed.

(b) water in the boiler that experiences a step increase or decrease in steam flow rate.

Boiler Level Control:

The level of water in the boiler is controlled automatically when the unit is at power. The level is maintained at a minimum when the unit is at 0% full power. As the unit is taken from 0% to 100% power, the level in the boiler is continually increased. When the unit is at 100% power the level is maintained at a maximum value.

There are two reasons for this change in programmed level with power changes:

(1) As power increases, more and more steam is produced. Since the steam appears from within the liquid and since there is an expansion of about 40 times on vaporization, as more steam is produced the apparent volume of the liquid increases and thus the boiler level increases. The programmed level must take this effect into account. If the boiler level were maintained constant as power increases, the mass of water contained in the boiler would be reduced. Should a loss of feedwater condition occur, the heat sink capacity for the PHT system would be reduced and the boiler water inventory boiled off in a shorter time.

(2) The most likely change in steam flow at low power levels is an increase. This will cause swell, and if the level were high to begin with, there would be a chance of liquid being forced into the steam lines. This would cause serious problems in the turbine.

The most likely change in steam flow at high power levels is a decrease. This will cause shrink. If the boiler level is low before the shrink occurs, the drop in level could uncover the top section of the boiler tubes with subsequent deposition and baking of solids on the hot, dry tubes. This deposition would permanently impair heat transfer and increase corrosion rate.

The boiler level is thus kept low at low power levels and high at high power levels to avoid the problems mentioned above. The level setpoint changes are mainly due to the shrink and swell considerations mentioned in (2) above.

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

2.17) Explain why the programmed level of water in the boiler changes with power changes.

Condenser Conditions

The condenser's main purpose is to change the vapour exiting the turbine set to a liquid so it can be returned to the boilers. An additional benefit (better unit efficiency) occurs because the steam that enters the condenser can be maintained at a high vacuum. (For the explanation of this benefit see module PI 25-7). The purpose of this section is to explain how condenser conditions can be maintained.

The vacuum is a result of using cold lake water as the condensing fluid. The lake water temperature is seasonally variable between 0°C and about 20°C. The lake water flowing through the condenser tubes will condense the steam on the shell side at about 30°C. At this temperature, steam decreases in volume by about 25,000 times (refer to question 2.11 for details). It is this large change in volume that maintains a very low pressure.

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

2.18) Explain how steam entering the condenser of a CANDU unit can be at about 30°C and 4 kPa(a).

→ Read over the objectives for this module. If you are confident you can perform these objectives now, obtain the PI 25-2 criterion test and answer the questions on it. If you feel you need more practice, consult with the course manager.

PI 25-2 TEXT ANSWERS

2.1) In this question,

L_o is 655 m

α is 10×10^{-6} °C^{-1}

ΔT is 190 - 25 = 175°C

Thus, $\Delta L = 655 \times (10 \times 10^{-6}) \times 175 =$ 1.15 m. How could this expansion be accommodated?

2.2) Here,

L_o is 51.2 m

α is 11×10^{-6} °C^{-1}

ΔT is 105 - 25 = 80°C

Thus, $\Delta L = 51.2 \times (11 \times 10^{-6}) \times 80 =$ 0.045 m (or 4.5 cm)

2.3) Here, you are looking for the final temperature. If you first determine the temperature difference, the final temperature can be calculated quickly.

$\Delta L = 0.552 - 0.55 = 0.002$ m

$L_o = 0.55$ m

$\alpha = 16 \times 10^{-6}$ °C^{-1}

Thus, $0.002 = 0.55 \times (16 \times 10^{-6}) \times \Delta T$

$\Delta T = 227$ °C

$\therefore$ the final temperature is 20 + 227 = 247°C.

2.4) The strip will bend towards the right.

2.5) The original lengths of the two materials are the same and both substances undergo a 5°C temperature difference. The behaviour of the strip thus depends on the coefficients of linear expansion of the two metals. Since the coefficient for brass is greater than that for carbon steel, the brass will become longer. The only way this situation can occur in this strip is if the strip bends as shown in Figure 2.2.

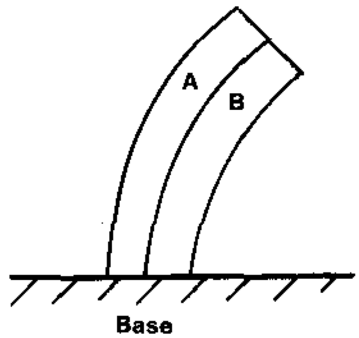


Figure 2.3

"A" is longer than "B" since it is on the outside of the arc.

2.6) The strip will bend towards the left as it is cooled. (Since the coefficient for brass is greater than the coefficient for carbon steel, the brass will contract more. It would have to be on the inside of the arc that would be formed.).

2.7) The strip will move towards the ON contact as it is cooled. Since the linear expansion coefficient for stainless steel is greater than that of iron, as cooling occurs the stainless steel will become shorter - that is, it must be on the inside of the arc. This will move the strip towards the ON contact.

2.8) You should assume the water at 254°C to be saturated liquid. This is a reasonable assumption unless the pressure is very much higher than the saturation pressure. Thus the specific volume of water at 254°C is

$V_{f_{100°C}} = 1.2607\ \ell/\text{kg}$ (From Table 1, "Steam Tables in SI Units")

The volume of saturated steam at 100°C is:

$V_{g_{100°C}} = 46.692\ \ell/\text{kg}$ (From Table 1, "Steam Tables in SI Units"

The ratio of the change in volume is:

$$46.692 \div 1.2607 = \underline{37.0 \text{ times}}.$$

(This is representative of the change in volume at BNGS-A: in general, water expands about 40 times in a CANDU boiler as it changes from liquid to vapour).

2.9) The specific volume of liquid heavy water will also be assumed to be the same as the saturated liquid volume at the same temperature.

Thus, the specific volume of liquid heavy water at 60°C is:

$$v_{f_{60°C}} = 0.000916 \text{ m}^3/\text{kg},$$

and the specific volume of liquid heavy water at 260°C is:

$$v_{f_{260°C}} = 0.001157 \text{ m}^3/\text{kg},$$

Hence, the ratio of the change in volume is:

$$0.001157 \div 0.000916 = \underline{1.26 \text{ times}}$$

(The heavy water in the primary heat transport system undergoes approximately the same expansion as you have just calculated. A couple of rhetorical questions:

What would happen if this volume increase could not be accommodated in the system?

How could the expansion be accomodated?

(You should be able to answer these questions after you have completed module 4.)

2.10) The specific volume of saturated steam at 250°C is:

$$v_{g_{250°C}} = 50.037 \ \ell/\text{kg}$$

The specific volume of 10% wet steam at 33°C is:

$$v_{ws} = v_{f_{33°C}} + q\, v_{fg_{33°C}}$$

$$= 1.0053 + 0.90 \times 28040.9$$

(remember $q = 1 - 0.10 = 0.90$)

$$= 25237.8 \ \ell/\text{kg}$$

The ratio of the change in volume is:

$$25237.8 \quad 50.037 = \underline{504 \text{ times}}.$$

(This represents the expansion of steam at PNGS-A as it goes from the inlet to the turbine set to the outlet at the condenser.)

2.11) The specific volume of the 12% wet steam at 30°C is:

$$V_{w_s} = V_{f_{30°C}} + q\, V_{fg_{30°C}}$$

$= 1.0043 + 0.88 \times 32927.9$ (remember $q = 1 - 0.12 = 0.88$)

$= 28977.6$ ℓ/kg

The specific volume of the water at 30°C is:

$$V_{f_{30°C}} = 1.0043 \text{ ℓ/kg}$$

The ratio of the change in volume is:

28977.6 ÷ 1.0043 = <u>28853 times</u>

2.12) When the steam flow suddenly increases, the pressure in the entire boiler (on the light water side) will <u>decrease</u>.

2.13) (a) The boiler level will suddenly rise.

(b) This rise will occur because more vapour is suddenly produced, causing the apparent volume of liquid in the boiler to increase, and thus also the level.

2.14) When the steam flow suddenly decreases, the pressure in the entire boiler (on the light water side) will <u>increase</u>.

2.15) (a) The boiler level will suddenly drop.

(b) When the pressure increases, the boiling process ceases. The vapour bubbles that are present in the liquid will condense, and the apparent volume of the liquid in the boiler will decrease. This will cause the level to drop.

2.16) (a) As the PHT D_2O temperature increases, the liquid will expand. This expansion is called swell.

As the PHT D_2O temperature decreases, its volume will decrease. This is called shrink.

(b) When the boiler is operating, the apparent volume of liquid in the boiler is not only due to the volume of liquid, but also due to the volume of vapour present within the liquid.

If the steam flow from the boiler experiences a very rapid or step increase, the pressure in the boiler will drop. The boiling rate will increase, causing more vapour to be present in the liquid. The apparent volume of the liquid will increase, and the boiler level will suddenly go up. This is called swell in the boiler.

If the steam flow experiences a very rapid or step decrease, the pressure in the boiler will increase. The vapour present in the liquid will condense, causing the apparent volume of liquid to suddenly decrease. This causes a drop in boiler level which is called shrink.

2.17) The programmed level in the boiler increases with power increases and it decreases with power decreases. There are two reasons for these level changes:

(a) There is a natural variation in the apparent volume of liquid in the boiler. The more boiling that occurs, the more vapour is present in the liquid. Since the vapour has a higher specific volume than the liquid, the volume of the mixture increases with increasing amounts of vapour. Thus the level will increase with increasing power (and increasing boiling). The opposite effect occurs with power (and boiling) decreases. If the boiler level were maintained constant as power increases, the boiler water inventory would be reduced. This would decrease the heat sink capability and the boiler water would boil off in a shorter time, should a loss of feedwater occur.

(b) The boiler level is changed <u>more than</u> would naturally occur. This is done to minimize the possible effects of shrink and swell in the boiler.

At low power levels, the most likely steam flow change is an increase (as power is raised). This will cause swell to occur. The boiler level is maintained low to minimize the danger of carrying over liquid in the steam lines.

At high power levels the most likely steam flow change is a decrease (as power is dropped). This will cause shrink to occur. The boiler level is maintained high to prevent uncovering of the top section of the boiler tubes which would result in deposition of solid on the hot dry tubes. This would permanently impair heat transfer and increase corrosion rate.

2.18) The steam is maintained at about 30°C and 4 kPa(a) by using cold lake water to condense the steam. Lake water at a maximum temperature of about 20°C flows through condenser tubes. This will enable the temperature of the condensing steam to be about 30°C. At this temperature the steam decreases in volume about 25,000 times - this decrease maintains the pressure at about 4 kPa(a).

Heat and Thermodynamics - Course PI 25

HEAT TRANSFER CALCULATIONS

Objectives

1. Given steam tables and values representing a feedheater or condenser with all variables but one specified, determine the unknown variable.

2. Given heavy water tables and values representing reactor channel inlet and outlet tempertures, channel flow rates of heavy water, and the number of reactor channels, determine the reactor thermal power, assuming there is no boiling in the channels.

Heat Transfer Calculations:

At some point in your career with Ontario Hydro you may be asked to perform calculations involving a heat balance. This module should provide you with the basic skills to do the calculations. The module also introduces some terms and situations that are common both in other initial training courses and in the stations.

Feedheater/Condenser Calculations

In a CANDU generating station there are many heat exchangers. Two of the major types of heat exchangers are the feedheater and the condenser.

Feedheaters are generally shell and tube heat exchangers. Their function is to heat the light water (called feedwater) that is being returned to the boilers from the condensers. The feedwater flows through a number of tubes in each feedheater. Steam is extracted from the turbine set to heat the feedwater. The steam, which is usually saturated or wet, is condensed in the shell side of each feedheater. A simplified view of a feedheater is shown in Figure 3.1:

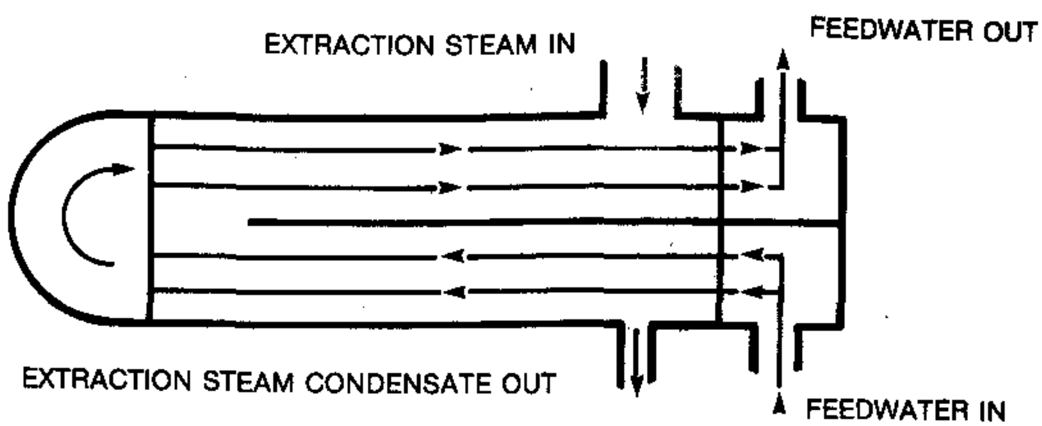


Figure 3.1

The condenser receives wet steam which is exhausted from the turbine set. This steam is condensed using cold lake water which flows through thousands of tubes in the condenser. A simplified view of the condenser is shown in Figure 3.2:

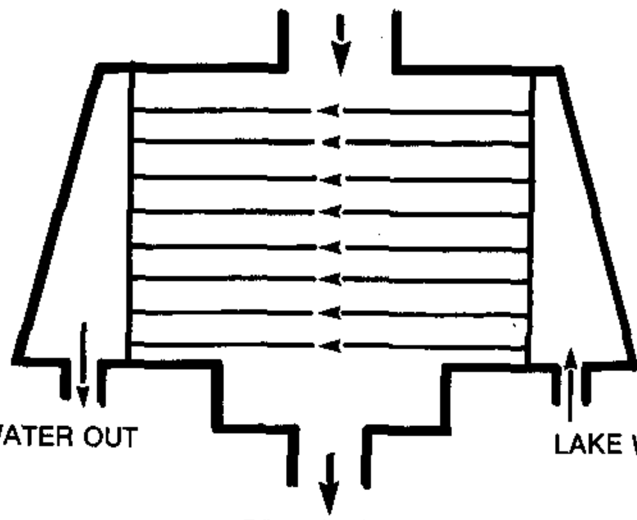


Figure 3.2

Both types of heat exchangers normally operate at steady state. Assuming no heat losses, there is thus a heat balance achieved - the rate of heat loss from the steam side is equal to the rate of heat addition to the water side.

This can be expressed as follows:

$\dot{Q}_L = \dot{Q}_G$,

where $\dot{Q}_L$ is the rate of heat lost, in kW.

and $\dot{Q}_G$ is the rate of heat gained, in kW.

The rate of heat transfer, $\dot{Q}$ is the product of the mass flow rate, $\dot{m}$ (in kg/s), and the change in enthalpy, Δh (in kJ/kg), that occurs.

The heat balance can be rewritten as:

$$(\dot{m}\,\Delta h)_L = (\dot{m}\,\Delta h)_G$$

→ *Locate your copy of "Steam Tables in SI Units".* *Answer* question 3.1 in the space provided before you proceed, then check your answer with the one in the "TEXT ANSWERS".

3.1) A feedheater heats feedwater from 85°C to 120°C. 80 kg/s of extraction steam (saturated at 125°C) is used to heat the water. The extraction steam condensate exits the feedheater at 125°C.

(a) Sketch a temperature vs. enthalpy diagram to show the feedwater heating process.

(b) Sketch a temperature vs. enthalpy diagram to show the extraction steam condensing process.

(c) Determine the flowrate of feedwater heated.

Question 3.1 represents the least complicated heating situation - where water is heated solely by condensation of saturated steam. Generally, the steam entering the feedheater or condenser is wet steam.

→ Answer question 3.2 in the space provided and check your answer with the one in the "TEXT ANSWERS" before you proceed.

3.2) 750 kg/s of steam (12% wet at 30°C) is exhausted from the turbine set to the condenser. The steam is condensed, and the condensate leaves at 30°C. 37,000 kg/s of lake water is used to condense the steam. If the water enters the condenser at 15°C, determine the temperature of the water leaving it.

Question 3.2 deals with a condenser. In CANDU stations the main condensers are designed to prevent subcooling of the condensate. The feedheaters, however, normally operate with subcooled extraction steam condensate.

→ Answer the following questions before you proceed. Check your answers with those in the "TEXT ANSWERS".

3.3) 71.2 kg/s of extraction steam (66.6% wet at 60°C) is used to heat feedwater from 27°C to 59°C. If the extraction steam condensate leaves the heater at 28°C, what is the feedwater flowrate?

3.4) At 25% power, heater #5 at BNGS-A is designed to use 29.4 kg/s of extraction steam (71.3% wet at 132°C). If 335 kg/s of feedwater enters the heater at 118°C and the extraction steam condensate leaves the heater at 119°C, what is the outlet feedwater temperature?

→ You should now be able to do the first objective of this module. If you feel you need more practice, please consult with the course manager.

Reactor Thermal Power Calculations

Most of the heat output of the reactor is transferred to the boilers. This is done by the PHT heavy water. This heavy water flows through a number of pressure tubes which contain the fissioning fuel. The D_2O then flows through the boiler and is pumped back to the reactor.

The amount of heat that is transferred to the boilers is called the reactor thermal power output. The purpose of this section is to provide you with the skill of estimating this output.

If you knew the power output of one pressure tube and the number of pressure tubes, you should easily be able to determine the total power. This determination will be an estimate since conditions vary from one pressure tube to another.

Certain pressure tubes are fully instrumented - that is, the flow of D_2O and the inlet and outlet temperatures are measured. Using these values, the thermal power of one pressure tube, $\dot{Q}_{PT}$, can be calculated.

Here, $\dot{Q}_{PT}$ will be the product of the mass flow rate, $\dot{m}$, and the change in enthalpy, Δh, of the D_2O:

$$\dot{Q}_{PT} = \dot{m}\,\Delta h$$

⟶ Locate your copy of the "Heavy Water Steam Tables". Use them to answer the following questions, then compare your answers with those in the "TEXT ANSWERS".

3.5) D_2O enters a pressure tube at 251°C and exits at 296°C. The flow of D_2O in the tube is 24 kg/s.

(a) What is the change in enthalpy of the D_2O as it goes through the pressure tube?

(b) Determine the power output of the pressure tube.

3.6) 25 kg/s of D_2O flows through a pressure tube. The inlet and outlet D_2O temperatures are 248°C and 290°C. If there are 388 pressure tubes in the reactor, determine the reactor thermal power output.

→ Once you have completed question 3.6 satisfactorily, you should be able to do the second objective of this module. If you are confident you can do this, obtain a criterion test and complete it. If you feel you need more practice before you attempt the test, please consult with the course manager.

3.1) (a)

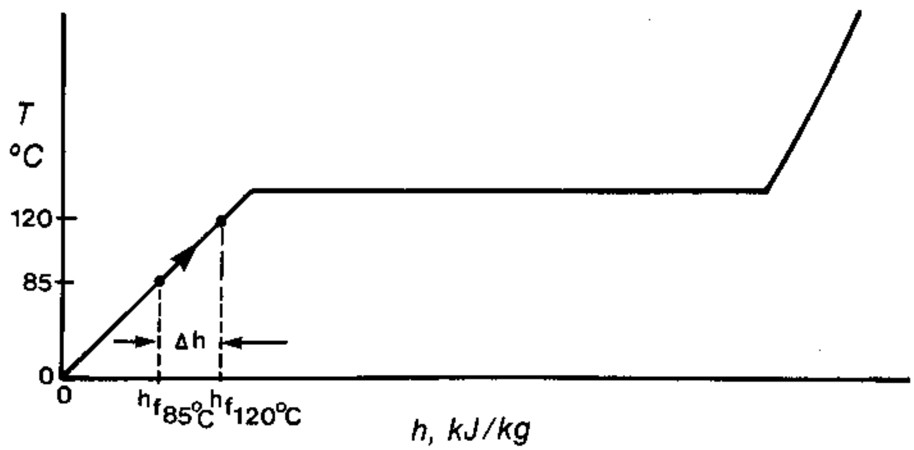


Figure 3.3

(b)

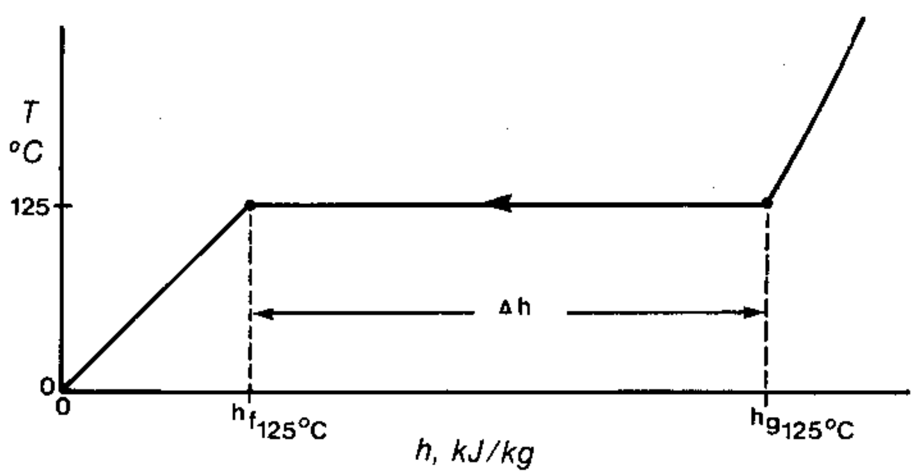


Figure 3.4

(c) As shown in (b), Δh for the steam side is:

$$h_{g125°C} - h_{f125°C}$$

This is the same as $h_{fg125°C}$.

As shown in (a), Δh for the feedwater side is:

$$h_{f120°C} - h_{f85°C}$$

Thus,

$$\dot{m}_L(h_{fg125°C}) = \dot{m}_G(h_{f120°C} - h_{f85°C}),$$

where $\dot{m}_L$ is the mass flow of extraction steam, and $\dot{m}_G$ is the mass flow rate of the feedwater.

$$80(2188.0) = \dot{m}_G(503.7 - 355.9)$$

$$\dot{m}_G = \underline{1180 \text{ kg/s}}$$

3.2) In this question, the steam side of the condenser can be shown as on Figure 3.5:

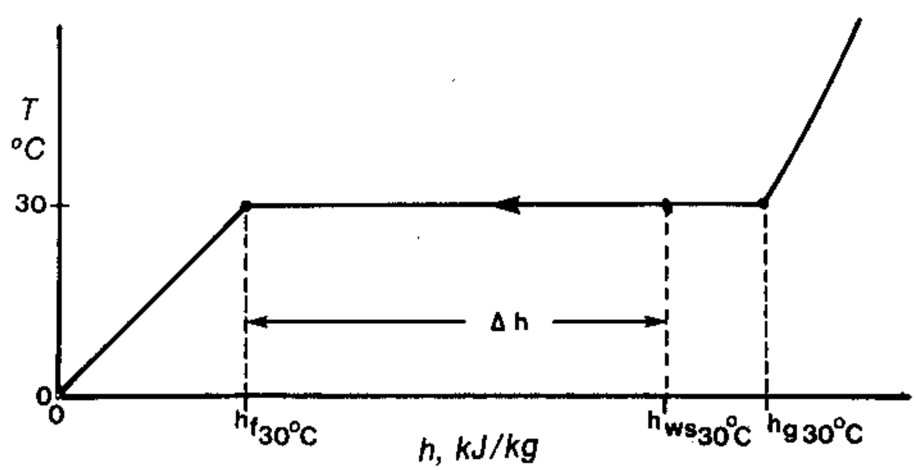


Figure 3.5

Here $\Delta h = h_{ws30°C} - h_{f30°C}$

For the lake water side, $\Delta h = h_{f?} - h_{f15°C}$, as shown on Figure 3.6:

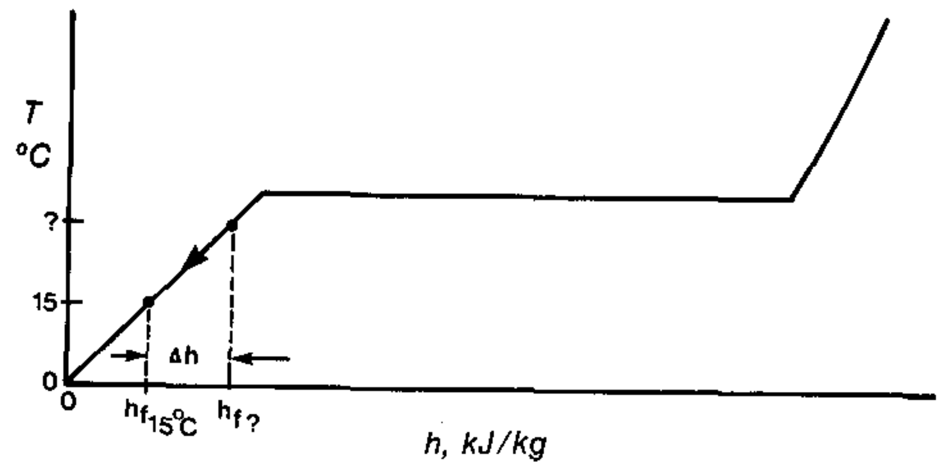


Figure 3.6

Thus, $\dot{m}_L(h_{ws30°C} - h_{f30°C}) = \dot{m}_G(h_{f?} - h_{f15°C})$

$h_{ws30°C}$ must be determined:

$h_{ws30°C} = h_{f30°C} + qh_{fg30°C}$ where $q = 1 - 0.12 = 0.88$

$\dot{m}_L(h_{f30°C} + 0.88\ h_{fg30°C} - h_f\ 30°C) = \dot{m}_G(h_{f?} - h_{f15°C})$

$\dot{m}_L(0.88\ h_{fg30°C}) = \dot{m}_G(h_{f?} - h_{f15°C})$

$750(0.88 \times 2430.7) = 37{,}000(h_{f?} - 62.94)$

$h_{f?} = 106.3$ kJ/kg

How can you use $h_{f?} = 106.3$ kJ/kg to find the water temperature?

The answer: Use enthalpy and look in either Table 1 or Table 2 of "Steam Tables in SI Units".

From Table 1, $h_{f25.5°C} = 106.9$ kJ/kg. There is no value near 106.3 kJ/kg in Table 2. Thus the outlet water temperature is about 25.5°C (assuming that the enthalpy of water varies little with pressure).

3.3) In this question the extraction steam condensate is subcooled:

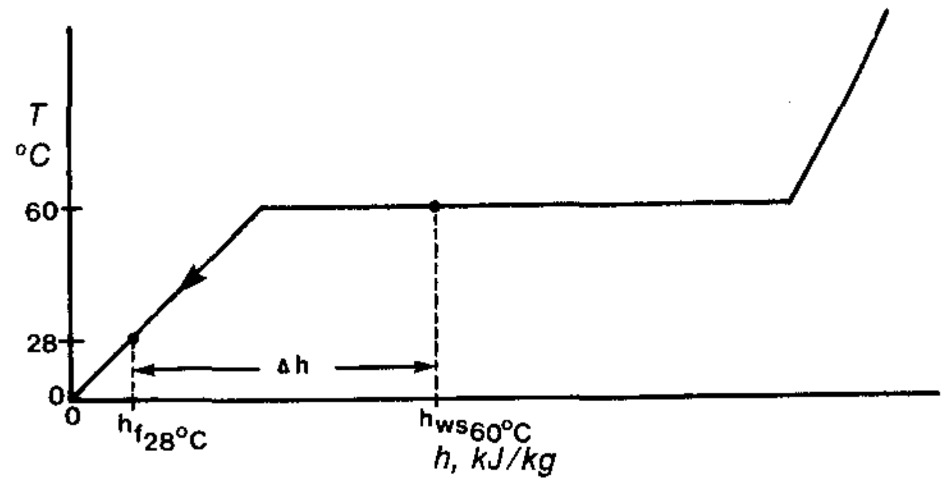


Figure 3.7

Here, $\Delta h = h_{ws60°C} - h_{f28°C}$

On the feedwater side,

$\Delta h = h_{f59°C} - h_{f27°C}$, as in Figure 3.8

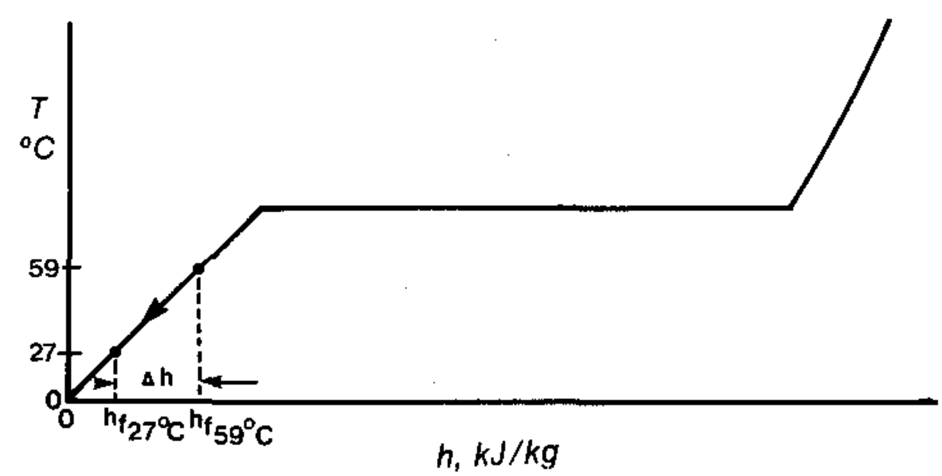


Figure 3.8

Thus, $\dot{m}_L(h_{ws_{60°C}} - h_{f_{28°C}}) = \dot{m}_G(h_{f_{59°C}} - h_{f_{27°C}})$

$h_{ws_{60°C}} = h_{f_{60°C}} + (1 - 0.666)h_{fg_{60°C}}$

$= h_{f_{60°C}} + 0.334\ h_{fg_{60°C}}$

$\dot{m}_L(h_{f_{60°C}} + 0.334\ h_{fg_{60°C}} - h_{f_{28°C}}) = \dot{m}_G(h_{f_{59°C}} - h_{f_{27°C}})$

$71.2(251.1 + 0.334 \times 2348.6 - 117.3) = \dot{m}_G(246.9 - 113.1)$

$\dot{m}_G$ = 490 kg/s

3.4)

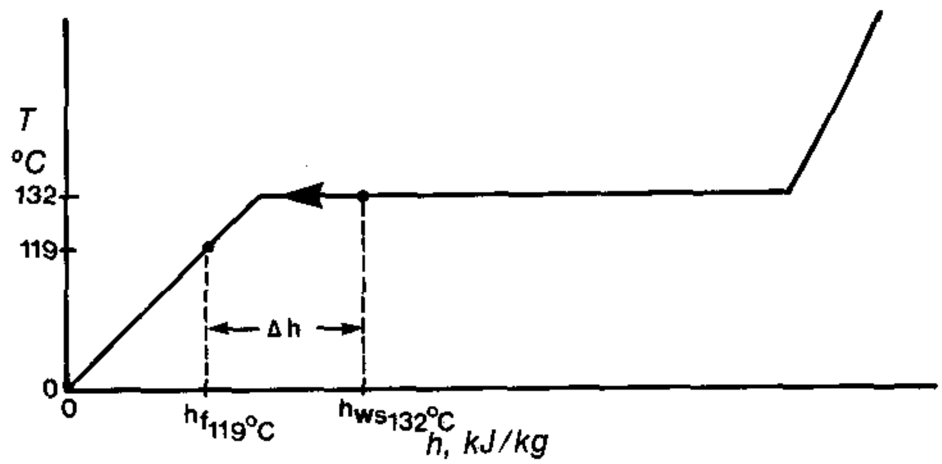


Figure 3.9

The enthalpy difference on the steam side is:

$h_{ws_{132°C}} - h_{f_{119°C}}$

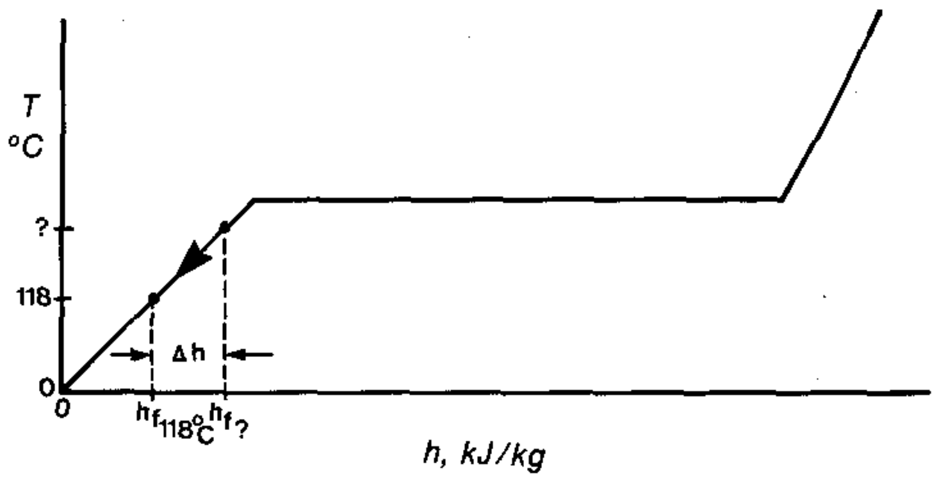


Figure 3.10

The enthalpy difference on the feedwater side is:

$h_{f?} - h_{f118°C}$

Thus, $\dot{m}_L(h_{ws132°C} - h_{f119°C}) = \dot{m}_G(h_{f?} - h_{f118°C})$

$h_{ws132°C} = h_{f132°C} + (1 - 0.713)h_{fg132°C}$

$= h_{f132°C} + 0.287\ h_{fg132°C}$

$\dot{m}_L(h_{f132°C} + 0.287\ h_{fg132°C} - h_{f119°C}) = \dot{m}_G(h_{f?} - h_{f118°C}$

$29.4(554.8 + 0.287 \times 2167.8 - 499.5) = 335\ (h_{f?} - 495.2)$

$h_{f?} = 554.5$ kJ/kg

From Table 1, using 554.5 kJ/kg, the outlet feedwater temperature is 132 °C.

3.5) (a) From the "Heavy Water Steam Tables", Table 1,

$h_{f251°C} = 1057.07$ kJ/kg

$h_{f296°C} = 1287.07$ kJ/kg

Thus $\Delta h = 1287.07 - 1057.07$

$= 230$ kJ/kg

(b) The power output of the pressure tube is the product of the mass flow rate and the Δh of the D_2O:

$\dot{Q}_{PT} = 24 \times 230$

$= 5520$ kW

3.6) From the "Heavy Water Steam Tables",

$\Delta h = h_{f290°C} - h_{f248°C}$

$= 1254.49 - 1042.68$

$= 211.81$ kJ/kg

The power output per channel, Q_{PT},

$25 \times 211.81 = 5295.25$ kW

The reactor thermal power output is:

$388 \times 5295.25 = 2.05 \times 10^6$ kW

(or 2050 MW)

Heat and Thermodynamics - Course PI 25

PRESSURE CONTROL

Objectives

1. Describe the effects resulting from:

   (a) too high primary heat transport pressure
   (b) too low primary heat transport pressure

2. Given a simplified system diagram, explain how the heat transport system pressure is controlled using:

   (a) the feed and bleed system
   (b) the pressurizer system

3. State why controlling boiler pressure is important.

4. List the three main heat sinks for the boiler in a CANDU station.

5. Briefly explain how the boiler pressure can:

   (a) remain constant as power increases
   (b) fall as power increases,

   and how this affects the PHT fluid average temperature.

Controlling the pressure of the PHT system and of the boiler is very important in the CANDU station. In this module you will be examining the reasons for controlling the pressure and you will be introduced to the means of pressure control in two areas: the primary heat transport system and the boiler.

Primary Heat Transport Pressure Control

The PHT system operates at high pressures and temperatures - in the range of 8.5 to 10 MPa(a) and 250 to 300°C. The high pressures are necessary to maintain the heavy water in a liquid state.

If the PHT pressure becomes too high, there is a possibility of rupture in the PHT system. This would be a loss of coolant accident.

If the PHT pressure becomes too low, either of two effects may occur:

(a) Boiling in the pressure tubes will begin, due to the continuing production of heat by the fuel as the pressure drops to the saturation value. If sufficient vapour is produced so that the fuel elements are covered with a vapour film, the fuel temperature will rise drastically. This will lead to fuel failure and significant releases of fission products in the PHT system.

(b) Cavitation in the main PHT circulating pumps will occur. This leads to reduction in flow (with less cooling of the fuel) and to pump damage.

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

4.1) Describe the effects resulting from:

(a) too high PHT pressure.

(b) too low PHT pressure.

There are two main ways that PHT pressure is controlled in NGD: using a feed and bleed system or using a pressurizer system (in conjunction with a feed and bleed system).

Feed and Bleed System

A much simplified version of the feed and bleed system is shown in Figure 4.1:

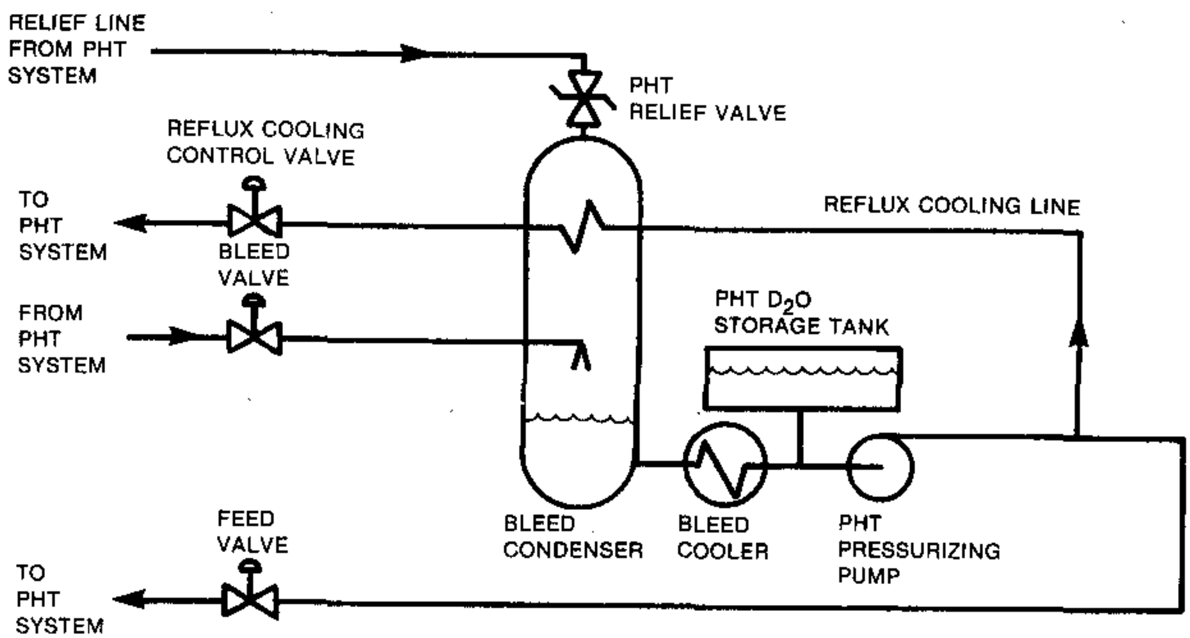


Figure 4.1

The PHT pressure is controlled from becoming too high in two ways:

(a) Under normal operating conditions the bleed valve lowers the PHT pressure by admitting more D_2O from the primary heat transport system to the bleed condenser than is returned to the system. The bleed condenser is a vessel with a mixture of D_2O liquid and vapour at saturation conditions. Controlling the D_2O temperature in this vessel will also control its pressure (that is, if the vapour temperature is lowered, the pressure must drop, and if the vapour temperature is raised, the pressure must rise). The bleed condenser temperature and pressure are lowered by a reflux cooling line, which is controlled by the reflux cooling control valve. The reflux cooling D_2O is cooled by the bleed cooler.

(b) Under abnormal conditions, i.e. if a PHT pressure rise cannot be controlled via the bleed valve, there is a relief line from the PHT system which will activate relief valves leading to the bleed condenser. If the relief valves do not control the pressure increase, reactor power will be reduced. If the power reduction does not control the pressure increase the reactor will be tripped.

The PHT pressure is controlled from dropping too low by the use of the feed valve. The PHT pressurizing pump provides high pressure D_2O at its outlet. There is a constant flow from this pump into the PHT system through the reflux cooling line. The pressurizing pump also supplies the feed valve which admits D_2O to the PHT system as necessary to maintain the PHT pressure. If the system pressure cannot be maintained using the feed valve, the reactor is tripped.

In summary, the normal variations of pressure (due mainly to PHT shrink and swell) are controlled by a balance between the operation of the bleed valve and the feed valve (taking into account the effect of flow through the reflux cooling line). The bleed condenser is used as a sink of low pressure to ensure flow through the bleed valve; the PHT pressurizing pump provides a source of high pressure to ensure flow through the reflux cooling line and feed valve.

⟶ Answer question 4.2 in the space provided before you proceed. Check your answer with the one in the "TEXT ANSWERS". If you have any questions at this point, consult with the course manager.

4.2) For the system shown below, explain how the heat transport system pressure is controlled.

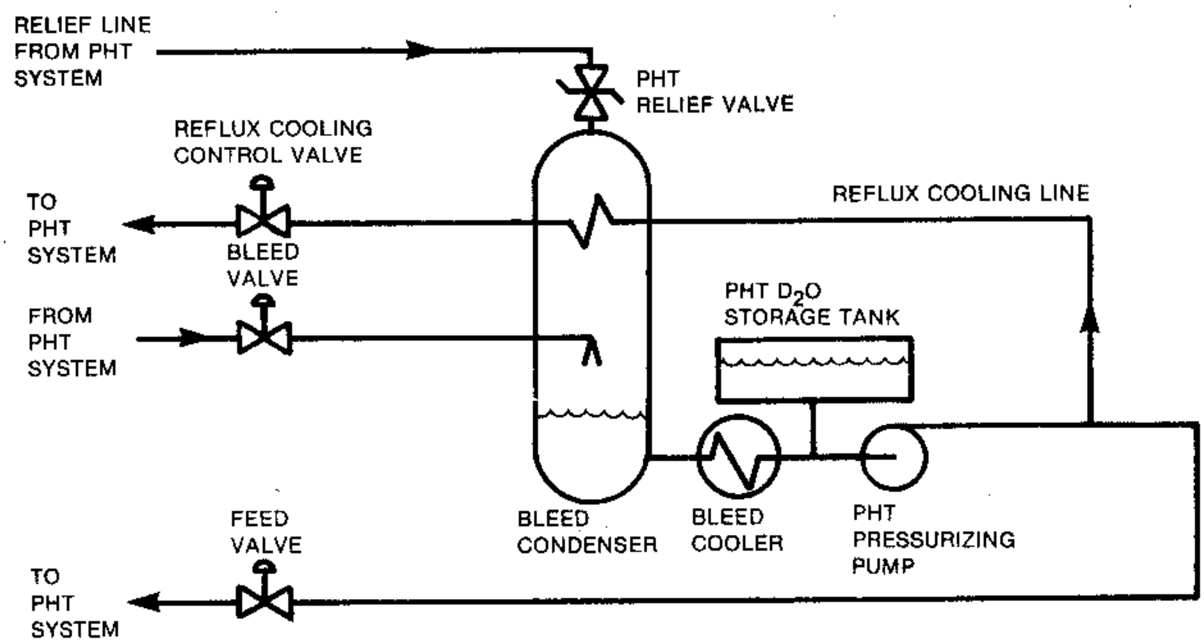


Figure 4.2

Pressurizer System:

A simplified version of the pressurizer sytem is shown in Figure 4.3.

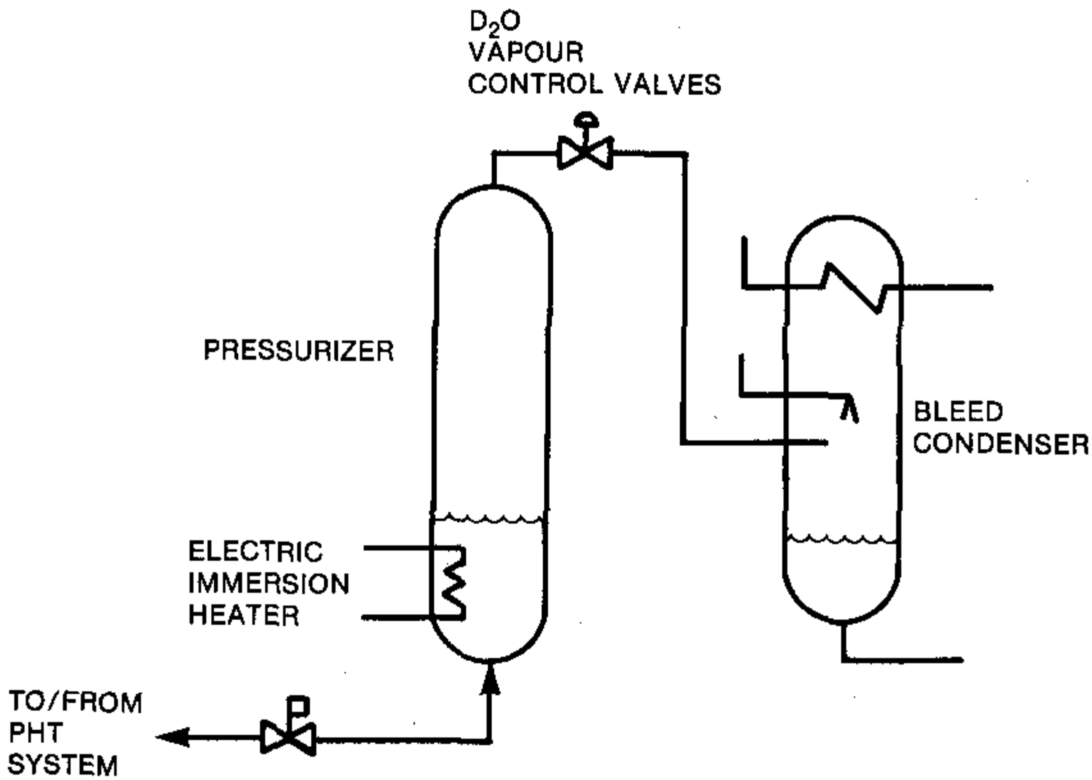


Figure 4.3

The pressurizer is connected to the PHT system by a liquid line. This connection can either supply D_2O to the PHT system or remove D_2O from the system.

Under normal operating conditions, if the PHT pressure drops (say due to shrink), the immersion heater in the pressurizer will increase the temperature and thus the pressure of the D_2O vapour and liquid in the vessel. This will increase the PHT pressure via the connecting line.

If the PHT pressure increases (say due to swell) the D_2O vapour control valves will act to admit D_2O vapour from the pressurizer to the bleed condenser. This will lower the PHT pressure by removing D_2O from the PHT system to the pressurizer.

(Normally, in addition to the pressurizer, there is a feed and bleed system installed. Besides providing a low pressure sink for the pressurizer, this feed and bleed system is used to pressurize and depressurize the PHT system, from atmospheric to normal operating range.)

⟶ Answer the following question, then compare your answer to the one in the "TEXT ANSWERS".

4.3) For the pressurizer system shown below, explain how the PHT system is controlled.

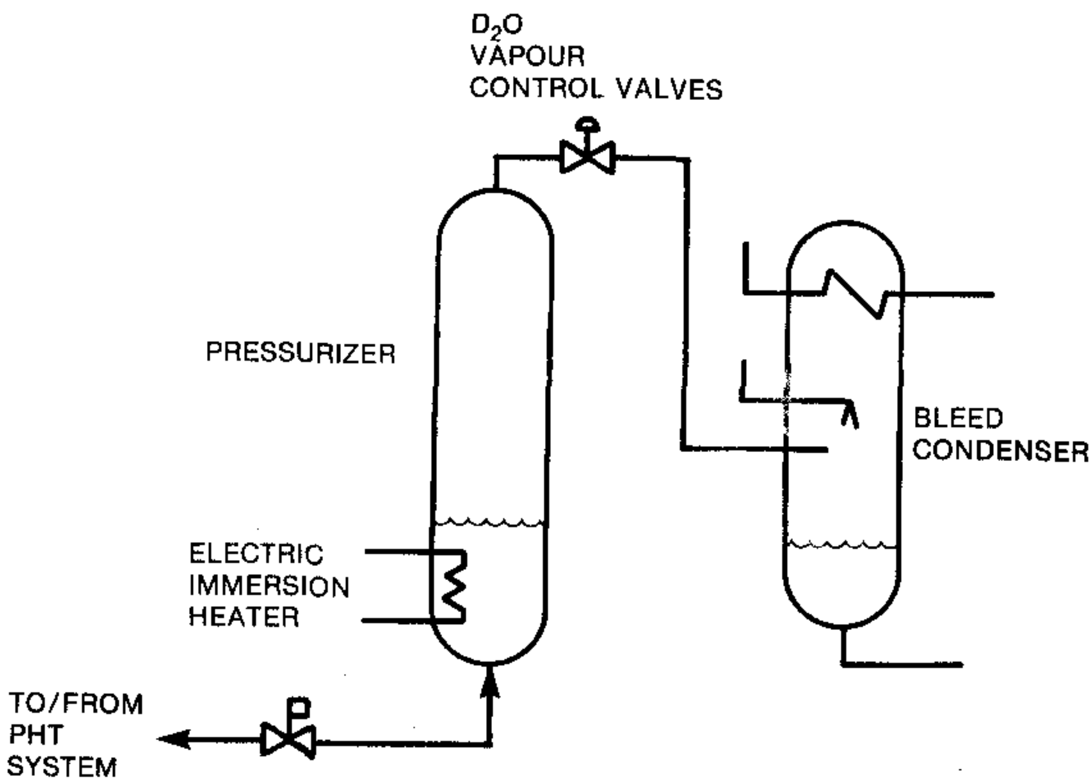


Figure 4.4

Boiler Pressure Control

The boilers are the main heat sink for the heat generated in the reactor. This heat is added to the water in the boilers by the PHT system to produce steam. The steam removes heat from the boilers as it flows out.

It is very important to match the addition of heat to the boilers with the removal of heat from them. If the reactor power (ie, the heat input) is greater than the heat removed by the steam flow, then boiler temperature and pressure both increase. The opposite happens if the reactor power is less than the heat removed by the steam. Either temperature or pressure can be used to indicate conditions in a boiler because the boiler is operating at saturation. Pressure is a variable that can be measured easily and quickly; thus boiler pressure is used to control the match between heat input to the boiler and heat output from the boiler.

The boilers in turn must have heat sinks in order to continue to function as the main reactor heat sink. The three main heat sinks for the boilers are:

(a) the turbine set

(b) the condenser

(c) the atmosphere

Note that under normal circumstances heat is removed from the boilers via steam to the turbine set and condenser. If the turbine set or the condenser are unavailable, the steam can be rejected to atmosphere to allow heat removal from the boilers.

→ Answer the following questions before you proceed. Check your answers with those in the "TEXT ANSWERS".

4.4) State why controlling boiler pressure is important.

4.5) List the three main heat sinks for the boiler in a CANDU station.

Boiler pressure is controlled in the large stations using the Boiler Pressure Control (BPC) program of a digital control computer. There are two different types of BPC program:

(a) boiler pressure is held constant as power is increased

(b) boiler pressure is lowered as power is increased

In the first case, the pressure in the boilers is held constant at all power levels. Power is increased by increasing steam flow from the boiler. Effectively, reactor power becomes less than the heat removed by the steam which causes the boiler pressure to drop. In order to keep it constant, the BPC program increases reactor power so that heat input matches heat output.

The result of this power increase is a change in the PHT D_2O average temperature. The amount of heat transferred from the PHT D_2O to the light water in the boiler is a function of the temperature difference between the average temperature of each of the two substances. In order to increase power, more heat must be transferred. Since boiler pressure (and thus temperature) is maintained constant, the average PHT temperature must rise as power is increased.

In the second case, the pressure in the boilers is lowered when power is increased. This is done to keep the PHT D_2O average temperature constant through the whole power range and thus, to reduce PHT D_2O shrink and swell. When the reactor power increases (which tends to increase the D_2O temperature, and boiler temperature and pressure), the BPC program increases steam flow from the boiler. This flow is increased so much that boiler pressure can be lowered. This is associated with a decrease in boiler temperature so that the temperature difference between the PHT D_2O and the light water can be increased. Therefore, more heat can be transferred despite the constant temperature of the PHT D_2O.

⟶ Answer the following in the space provided, then check your answers with those in the "TEXT ANSWERS".

4.6) Briefly explain how boiler pressure can remain constant as power increases, and how this affects the PHT D_2O average temperature.

4.7) Briefly explain how boiler pressure can fall as power increases, and how this affects the PHT D_2O average temperature.

→ You have now completed PI 25-4. If you feel confident you can do the objectives for this module, obtain a criterion test and answer the questions on it. If you feel you need more practice before attempting the test, consult with the course manager.

PI 25-4 TEXT ANSWERS

4.1) (a) The main effect of a very high pressure in the PHT sytem is the possibility of a rupture, which would cause a loss of coolant accident.

(b) The first effect of too low a pressure in the heat transport system is boiling of D_2O in the pressure tubes. *This could lead to fuel failure and release* of fission products if the boiling becomes enough to lead to vapour film formation around the fuel.

The second effect is cavitation in the main heat transport circulating pumps. This will cause reduction in PHT flow and in fuel cooling, and it may lead to pump damage.

4.2) The PHT pressure is controlled in this feed and bleed system by a balance in flow through the bleed valves and the feed valves (and including the reflux cooling flow).

The bleed valves act to lower the PHT pressure by admitting D_2O from the heat transport system to the bleed condenser. The bleed condenser will lower the temperature and pressure of any bleed flow that occurs. Condensing action is maintained by the reflux cooling line. The bleed cooler acts to maintain the reflux cooling line temperature low.

The feed valves act to raise the PHT pressure by admitting high pressure D_2O to the heat transport system. The PHT pressurizing pump is the source of high pressure D_2O.

4.3) The pressurizer acts to raise or to lower PHT pressure through the same connecting line.

In order to raise the pressure, electric immersion heaters heat the liquid in the pressurizer vessel. The PHT pressure is increased via the connecting line.

In order to lower the pressure, D_2O vapour is admitted from the pressurizer to the bleed condenser by the D_2O vapour control valves. Liquid D_2O will be removed from the heat transport system to the pressurizer and the PHT pressure will be lowered.

4.4) Boiler pressure is used to control the match between heat input to the boiler from the reactor and heat output from the boiler in the steam. This match is critical; thus boiler pressure control is important.

4.5) The three main heat sinks for the boiler in a CANDU station are the turbine set, the condenser, and atmosphere.

4.6) At stations where boiler pressure is maintained constant, power is increased by first increasing steam flow from the boilers. This would tend to lower boiler pressure. The BPC program increases reactor power to maintain constant boiler pressure, while the PHT D_2O average temperature changes.

4.7) At stations where boiler pressure changes, power is increased by first increasing reactor power. This would tend to increase boiler pressure. The BPC program increases steam flow so much that boiler pressure and temperature in fact decrease, allowing an increase in power while at the same time keeping PHT average temperature constant.

Heat and Thermodynamics - Course PI 25

MECHANISMS OF HEAT TRANSFER

Objectives

1. Briefly explain heat transfer by:

   (a) conduction
   (b) natural convection
   (c) forced convection
   (d) radiation.

2. State the factors that affect the rate of heat transfer by each mechanism from (1).

3. Briefly describe two examples of each mechanism from (1) in a CANDU generating station.

March 1984

In this module you will be considering the four mechanisms by which heat can be transferred: conduction, convection - both natural and forced, and radiation. It is by combinations of these mechanisms that electricity generation in a CANDU station is made possible.

Conduction

Heat transfer by conduction involves the movement of heat energy without a net mass movement. In effect, heat is passed through a substance from one molecule to the next with no overall movement of the substance from one place to another.

There are four factors that affect the rate of conduction:

(1) The type of substance involved. Since the structures of different substances are different, heat energy will be passed through these substances with varying degrees of difficulty. This effect is expressed by the thermal conductivity.

(2) The surface area of the substance that is conducting heat. As area increases, so does rate of conduction.

(3) The temperature difference across the substance. Heat will be transferred through the substance as long as there is a high temperature source on one side of the substance and a low temperature sink on the other side. The larger the temperature difference, the higher is the rate of conduction.

(4) The thickness of the substance. As the distance between the high temperature side and the low temperature side increases, the rate of conduction decreases.

Thermal conductivity of substance is normally expressed in watts conducted per square meter of surface per metre thickness per degree Celsius temperature difference.

⟶ Answer questions 5.1 and 5.2 in the space provided, then check your answers with those in the "TEXT ANSWERS".

5.1) Briefly explain heat transfer by conduction.

5.2) State the factors that affect the rate of conduction.

→ Answer question 5.3 in the space provided before you proceed. Discuss your answer with someone else in the class or with the course manager.

5.3) Briefly describe two examples of conduction in a CANDU station.

Convection

Heat transfer by convection is heat transfer due to movement of a fluid. Typically, the fluid gains heat as it flows past a higher temperature surface. The fluid then transports the heat from the surface as it flows.

Convection is divided into two types: natural and forced.

Natural Convection

In natural convection, the flow of fluid is accomplished by density differences that occur as the heat is transferred. As the fluid is heated, it expands and becomes less dense. Under the influence of gravity this less dense fluid will rise and be replaced by cooler, more dense fluid. A flow is set up which transfers heat as the flow occurs.

There are three factors that influence the rate of heat transfer by natural convection:

(1) The area of the surface in contact with the fluid. As this area increases, so does the rate of convection.

(2) The temperature difference between the surface and the fluid. As this difference increases, the rate of heat transfer increases.

(3) A heat transfer coefficient that expresses specific conditions associated with the substances in the system. Examples of the conditions expressed are: amount of turbulence in fluid, conductivity of the fluid, fluid density, slope of the surface, fluid viscosity, etc. As the coefficient increases, so does the rate of heat transfer.

→ Answer the following questions in the space provided. Check your answers for questions 5.4 and 5.5 with those in the "TEXT ANSWERS". For question 5.6, discuss your answer with someone else in the class or with the course manager before you continue.

5.4) Briefly explain heat transfer by natural convection.

5.5) State the factors that affect the rate of heat transfer by natural convection.

5.6) Briefly describe two examples of natural convection in a CANDU station.

Forced Convection

Forced convection involves fluid movement due to external means. The fluid flow is usually accomplished using a mechanical device such as a pump, fan, blower, or compressor.

The factors that influence the rate of heat transfer by forced convection are the same as those you considered in natural convection: surface area, temperature differential, and heat transfer coefficient.

5.7) Briefly describe heat transfer by forced convection.

5.8) State the factors that affect the rate of heat transfer by forced convection.

5.9) *Briefly describe two examples of heat transfer by* forced convection in a CANDU station.

→ Answer the above questions in the space provided. Check your answers to the first two questions with those in the "TEXT ANSWERS". Discuss your answer to question 5.9 with someone else in your class or with the course manager before you proceed.

Radiation

Heat transfer by radiation can be described as emission of electromagnetic energy from a substance that is at a higher temperature than its surroundings. This energy usually *is in the infrared part of the electromagnetic spectrum.*

There are three factors that affect the rate of heat transfer by radiation:

1) The surface area presented by the emitting substance to the surroundings. The larger the surface area, the higher the rate of heat transfer by radiation.

2) The temperature differential between the substance and the surroundings. This differential is expressed by the difference between the fourth powers of the absolute temperatures of the substance and the surroundings. Note that as the temperature of the substance increases relative to the surroundings, the rate of heat transfer by radiation increases more and more quickly.

3) A property of the emitting substance called emissivity. The emissivity is influenced by such things as surface colour and smoothness. The higher the emissivity the greater the rate of heat transfer by radiation.

(Note that heat can not only be emitted but also be absorbed due to radiation.)

⟶ Answer questions 5.10, 5.11, and 5.12 in the space provided before you proceed. Check your answers for questions 5.10 and 5.11 with those in the "TEXT ANSWERS". Discuss your answer to question 5.12 with someone from your class or with the course manager.

5.10) Briefly explain heat transfer by radiation.

5.11) State the factors that affect the rate of heat transfer by radiation.

5.12) Briefly describe two examples of heat transfer by radiation in a CANDU station.

→ You have now completed module 5. If you feel confident you can answer the objectives, obtain a criterion test and complete it. If you feel you need more practice, go back and answer the assignment questions on separate paper. Check your answers with the "TEXT ANSWERS" and with your own corrected answers in the module.

PI 25-5 TEXT ANSWERS

5.1) Heat transfer by conduction is the transfer of heat energy from one particle to the next through a substance. There is no net movement of mass in conduction.

5.2) The factors that affect rate of conduction are:

(a) thermal conductivity (which expresses the type of substance)

(b) surface area of the conducting substance

(c) temperature difference between the hot and cool sides of the conducting substance

(d) thickness of the conducting substance.

5.3) Discuss your answer with the course manager.

5.4) Heat transfer by natural convection is heat transfer by fluid movement, where the fluid movement is due to density differences that occur as heat is tranferred.

5.5) The factors that influence the rate of heat transfer by natural convection are:

(a) surface area of the substance in contact with the fluid

(b) temperature difference between the surface and the fluid

(c) heat transfer coefficient (which is influenced by the conditions of the system).

5.6) Discuss your answer with the course manager.

5.7) Forced convection is a means of transferring heat by fluid movement, where the movement is caused by some external means. Examples of external means are pumps, fans, blowers and compressors.

5.8) The factors that affect the rate of heat transfer by forced convection are:

(a) surface area of the substance in contact with the fluid

(b) temperature difference between the surface and the fluid

(c) heat transfer coefficient (expressing the conditions of the system).

5.9 Discuss your answer with the course manager.

5.10 In heat transfer by radiation, the particles of a substance emit electromagnetic energy because they are at a higher temperature than their surroundings. This energy, usually in the infrared light range, transfers heat from the substance.

5.11) The factors which affect the rate of heat transfer by radiation are:

(a) surface area of the emitting substance

(b) temperature difference between the fourth power of the absolute temperature of the emitting substance and the fourth power of the absolute temperature of the surroundings

(c) emissivity of the surface of the emitting substance (expressing colour, texture, etc.).

5.12) Discuss your answer with the course manager.

Heat and Thermodynamics - Course PI 25

MOLLIER DIAGRAMS AND THE TURBINE PROCESS

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 a sketch of a Mollier diagram that you have drawn, illustrate the overall turbine process, including

   (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 <u>throttling</u> 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

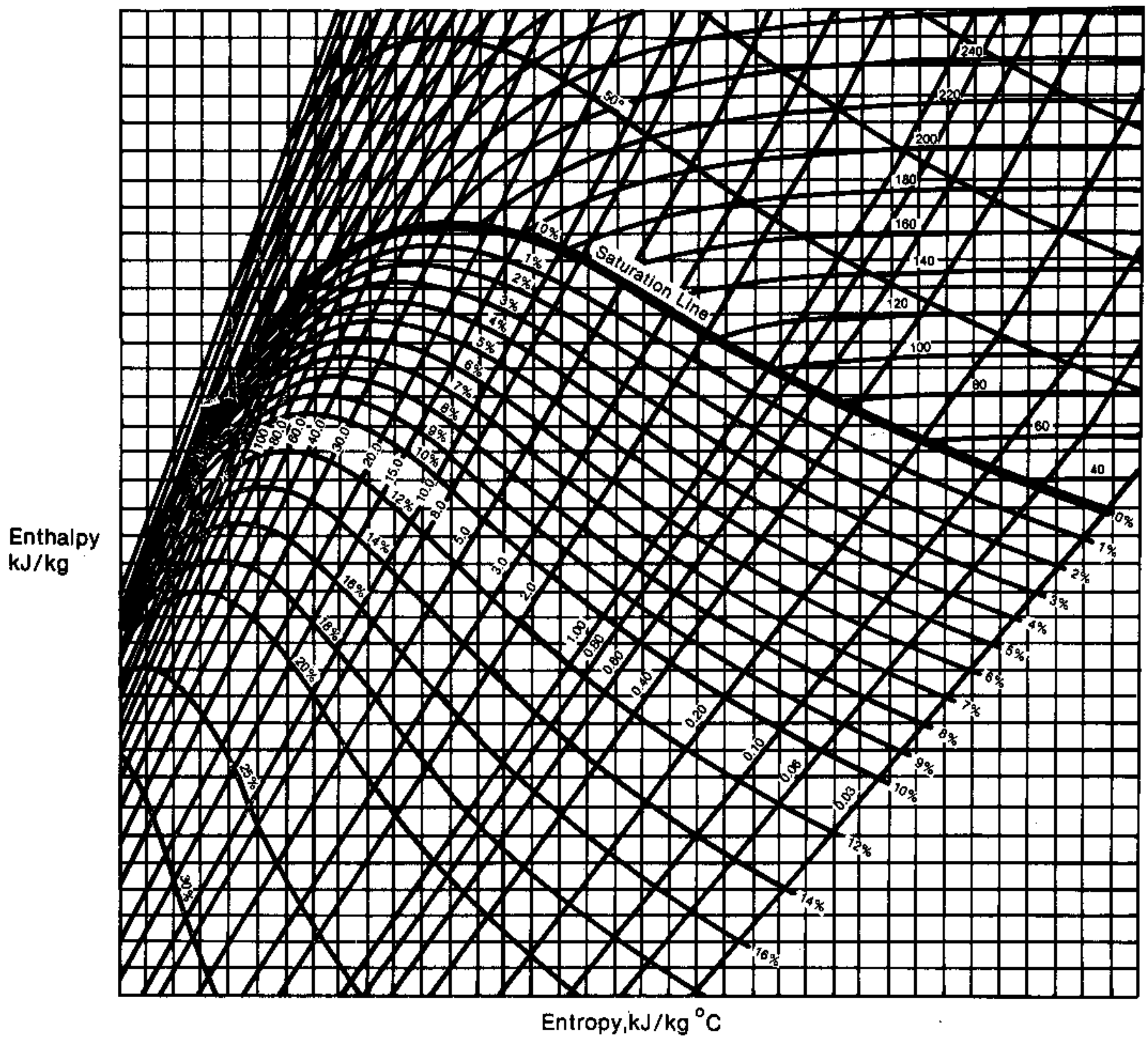
This module deals with the turbine process. When you have finished the module, you should be aware of the major equipment of the turbine set and you should be able to show the turbine process on a Mollier diagram.

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
0%
1%
2%
3%
4%
5%
6%
7%
8%
9%
10%
12%
14%
16%
18%
20%
25%
30%
50°
240
220
200
180
160
140
120
100
80
60
40
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 saturation line represents saturated steam at different conditions of temperature and pressure. Superheated steam is represented above the saturation line. Wet steam is represented below the saturation line.

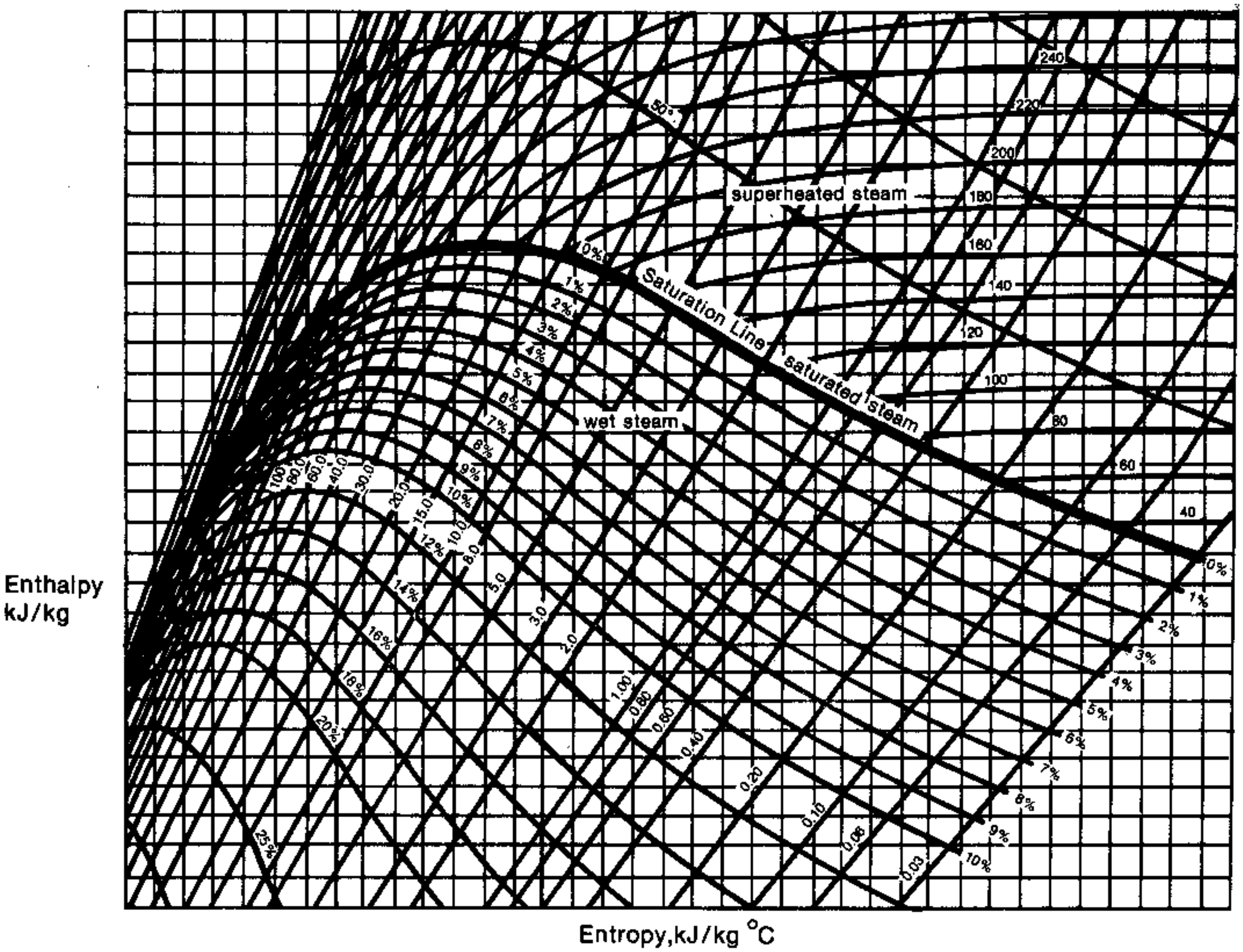


Figure 6.2

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.

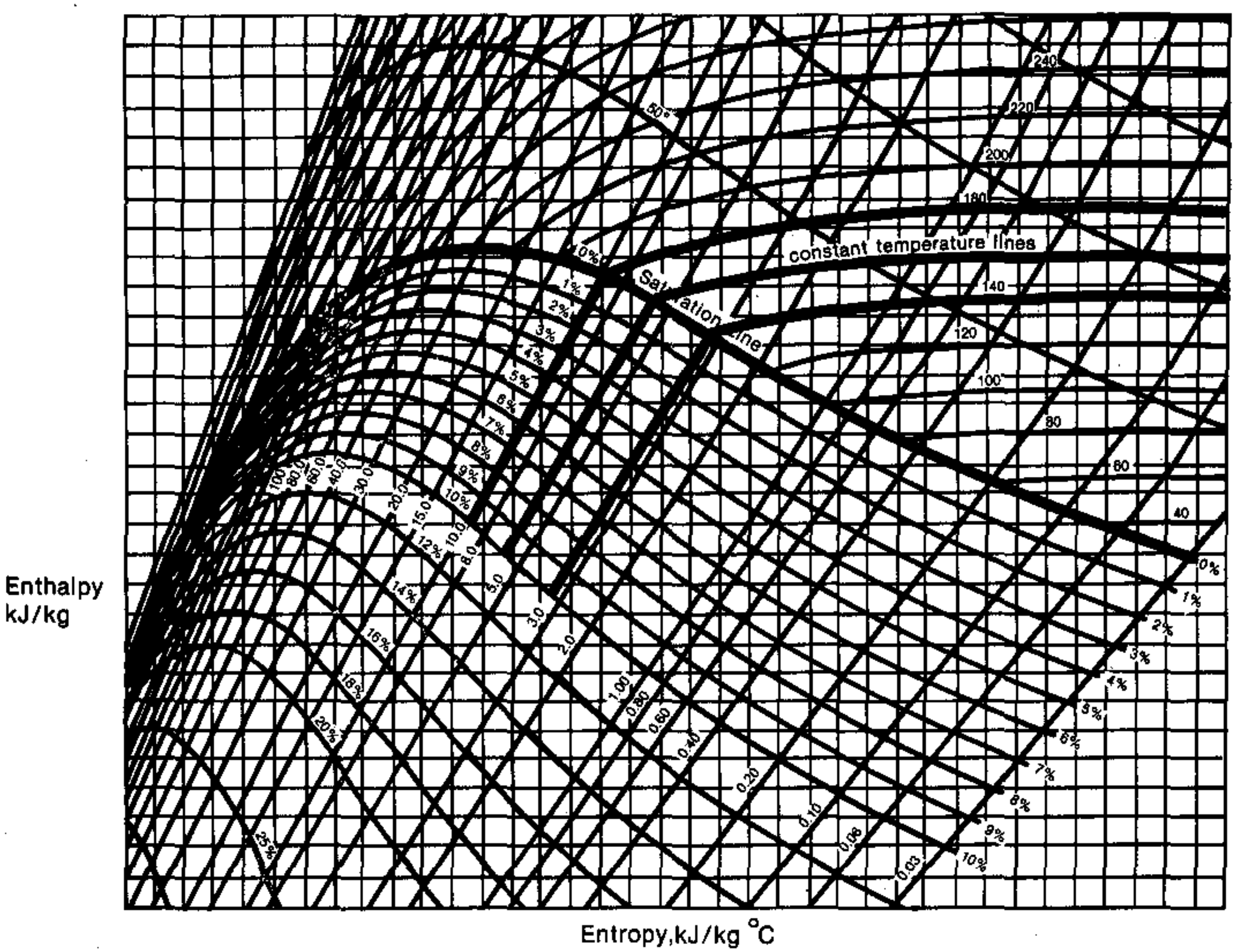


Figure 6.3

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.

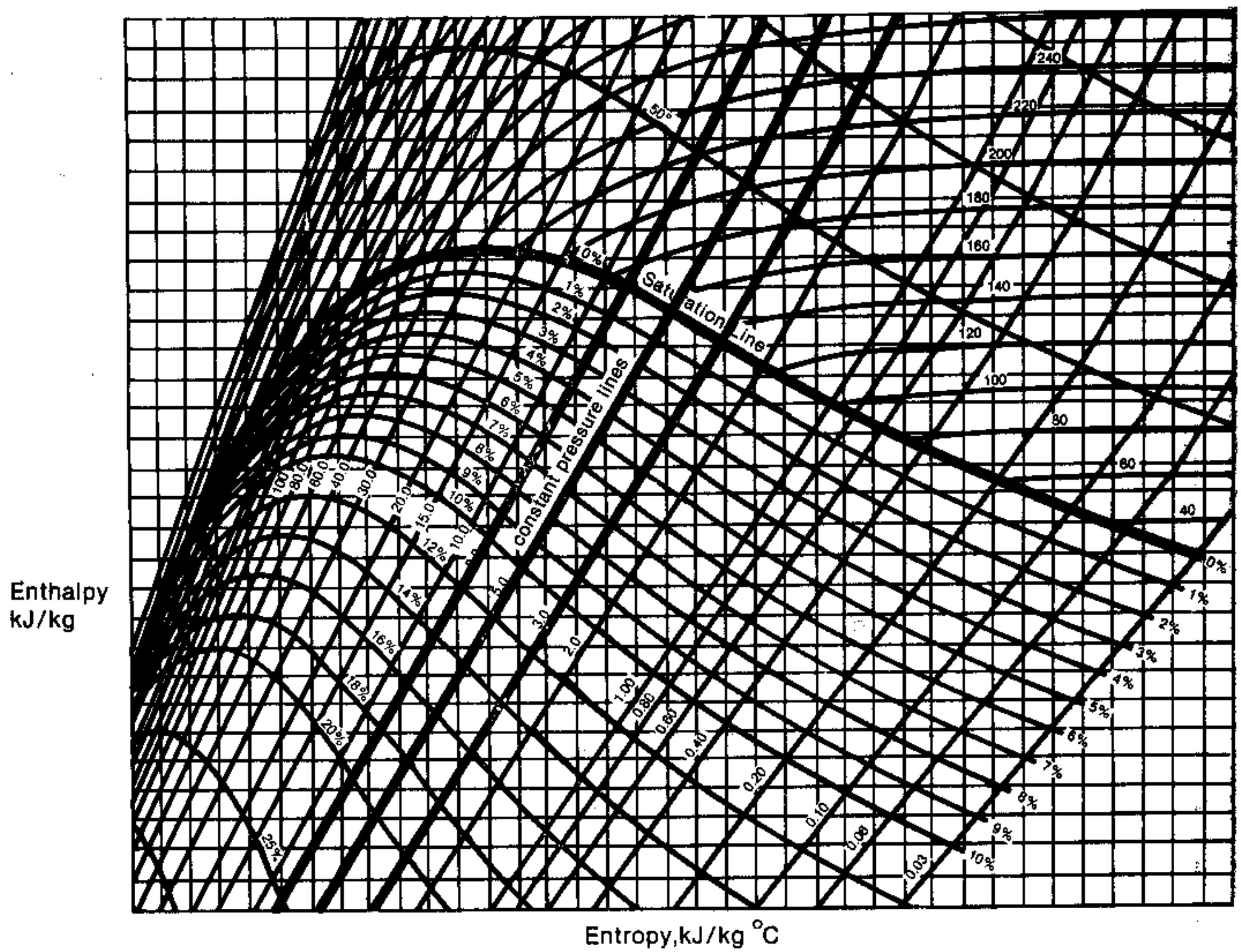


Figure 6.4

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

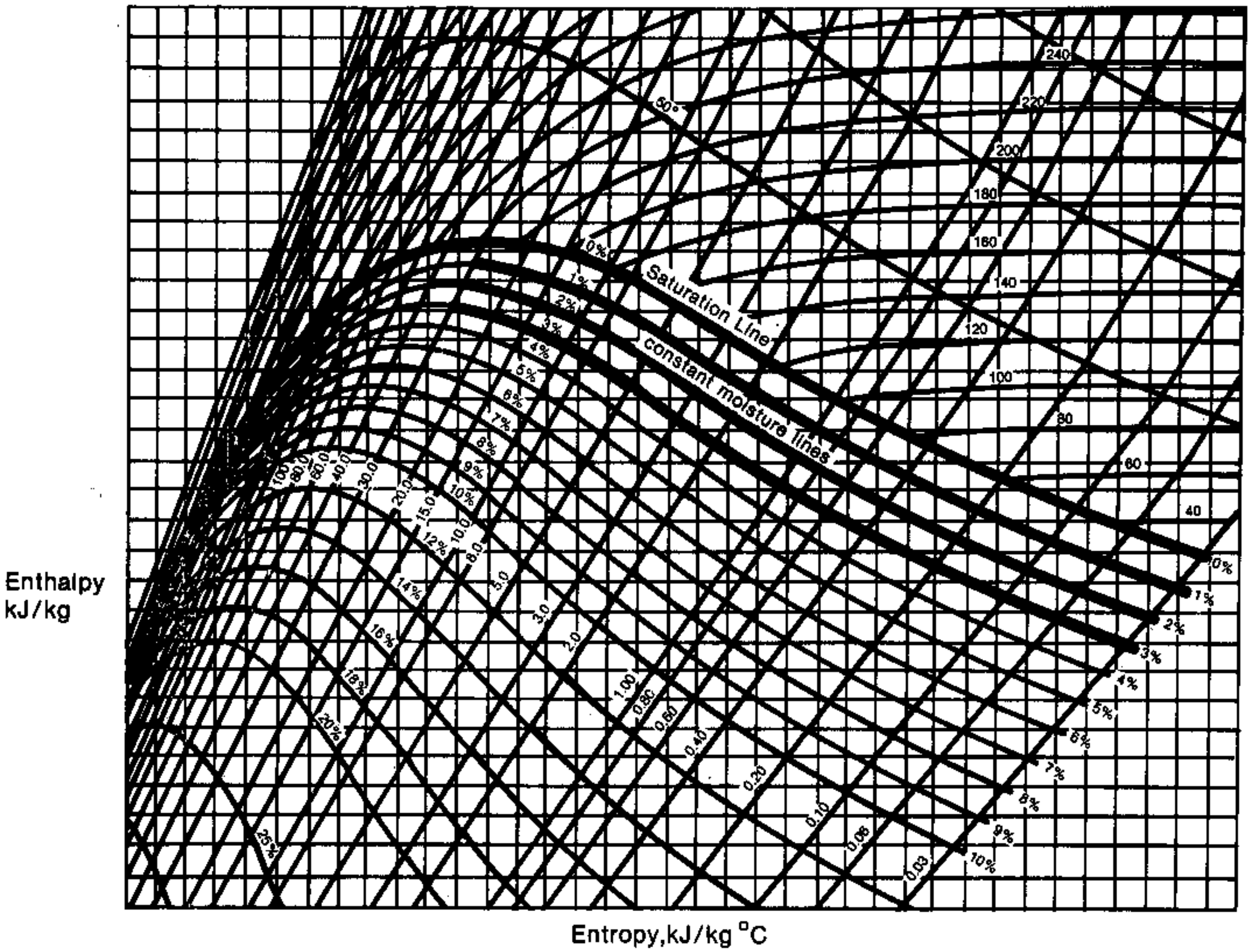


Figure 6.5

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.

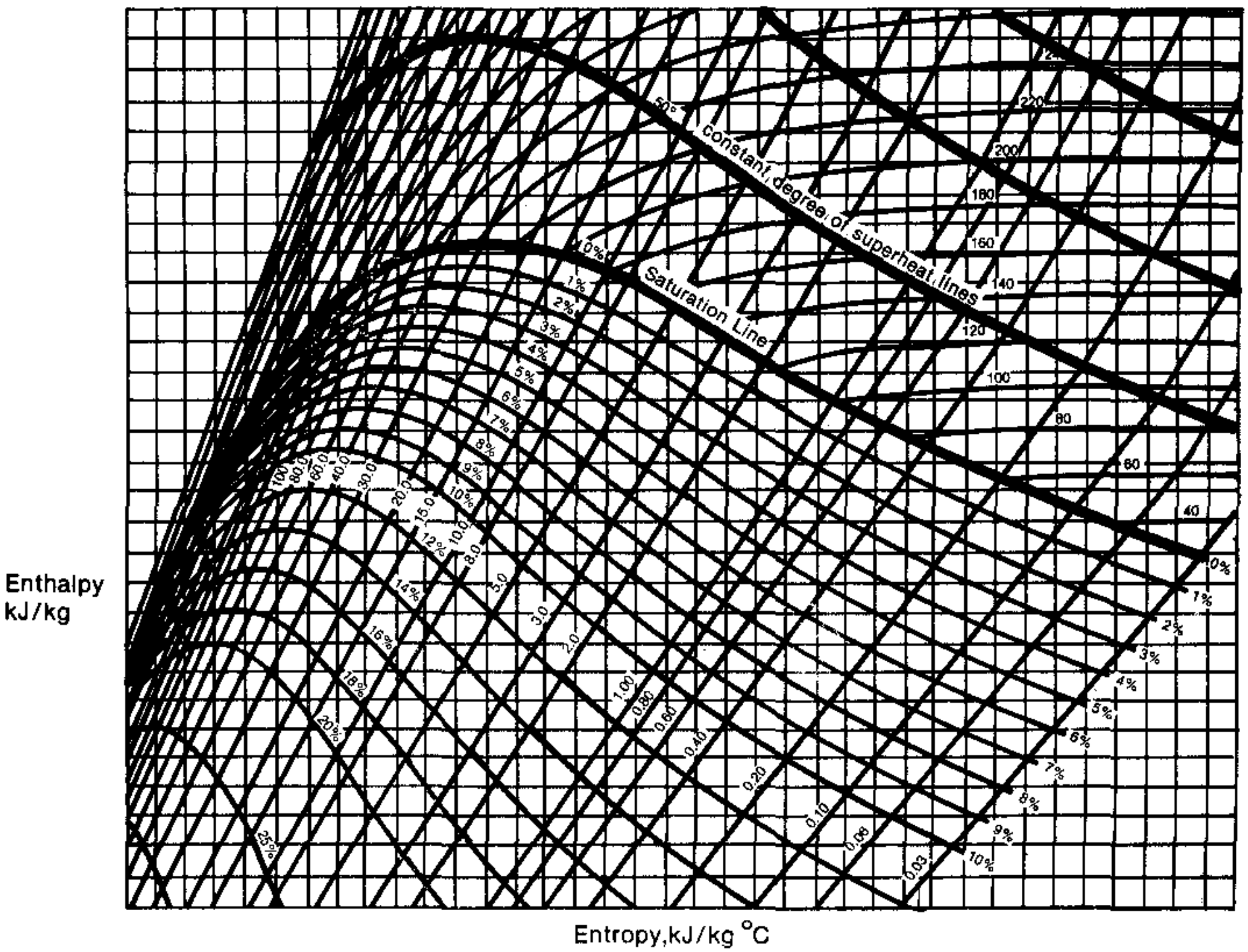


Figure 6.6

→ 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.

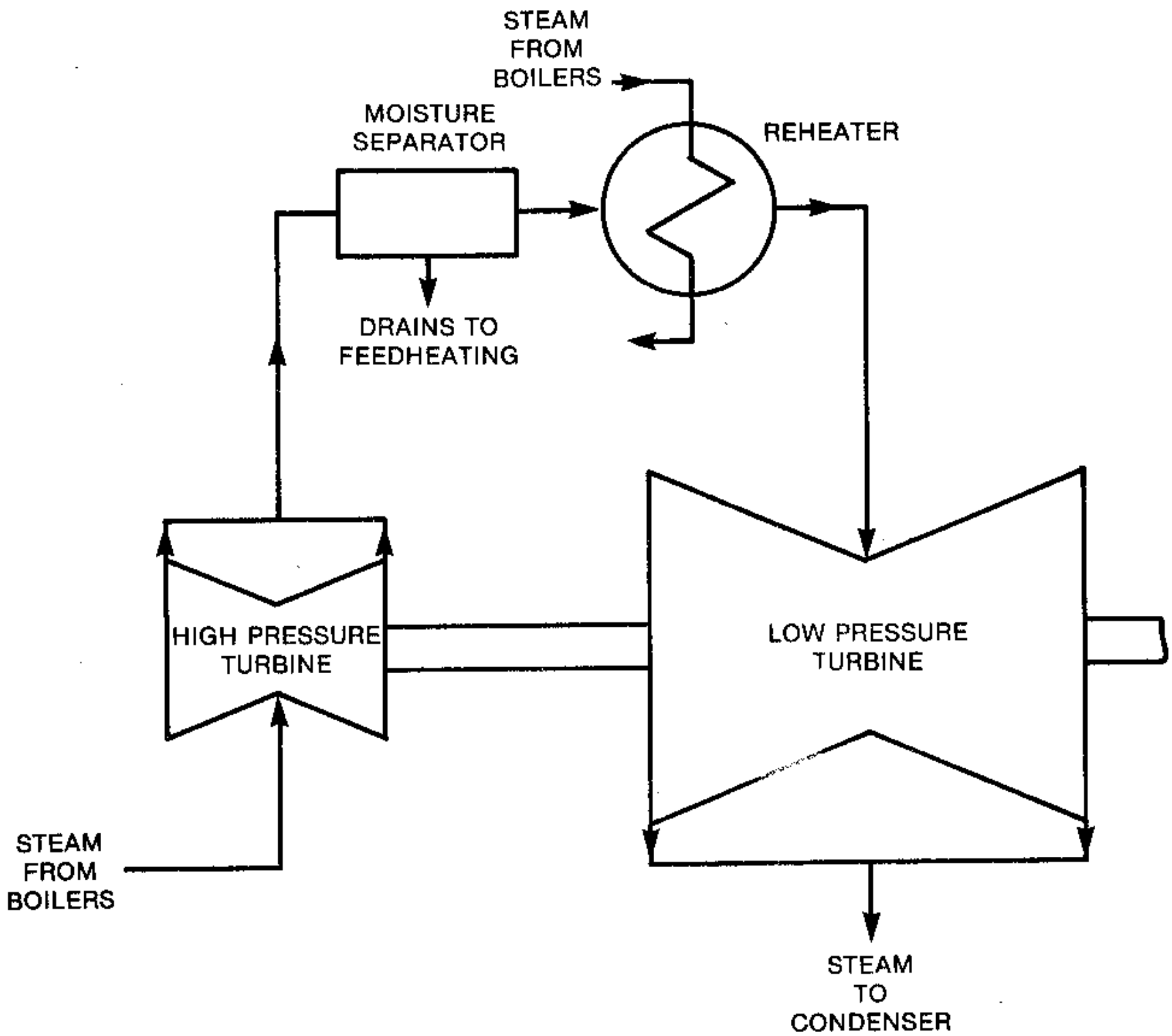


Figure 6.7

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

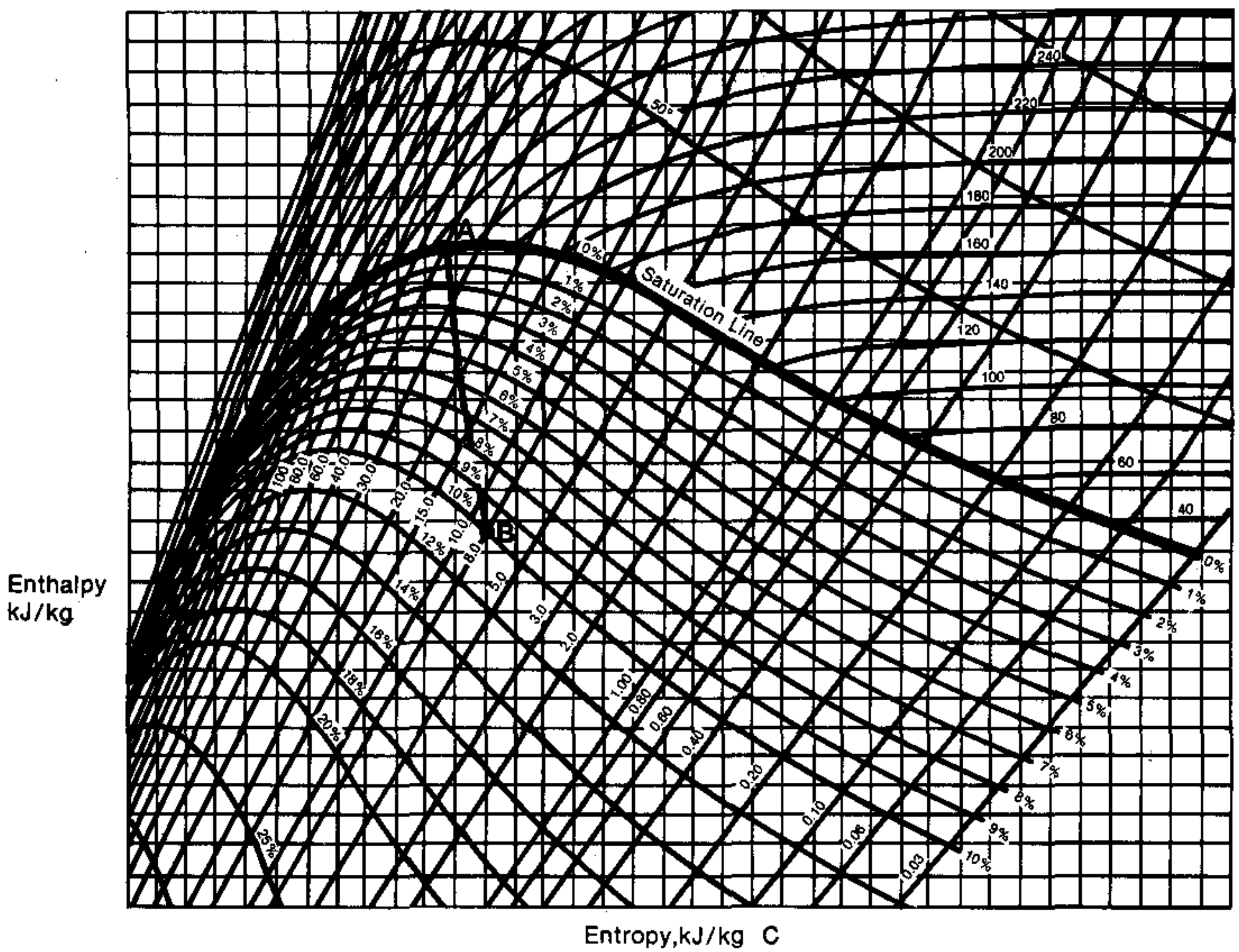


Figure 6.8

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.

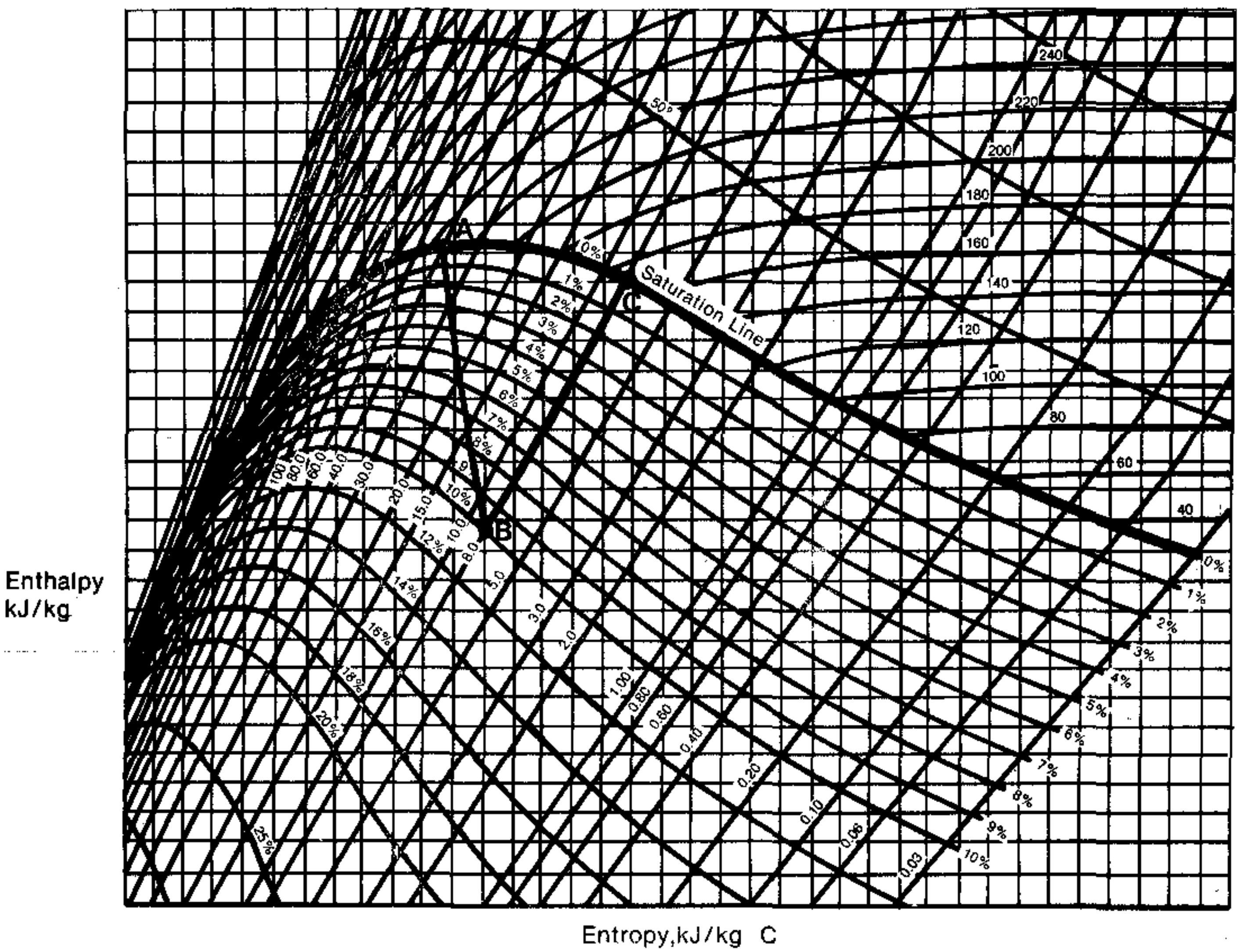


Figure 6.9

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%.

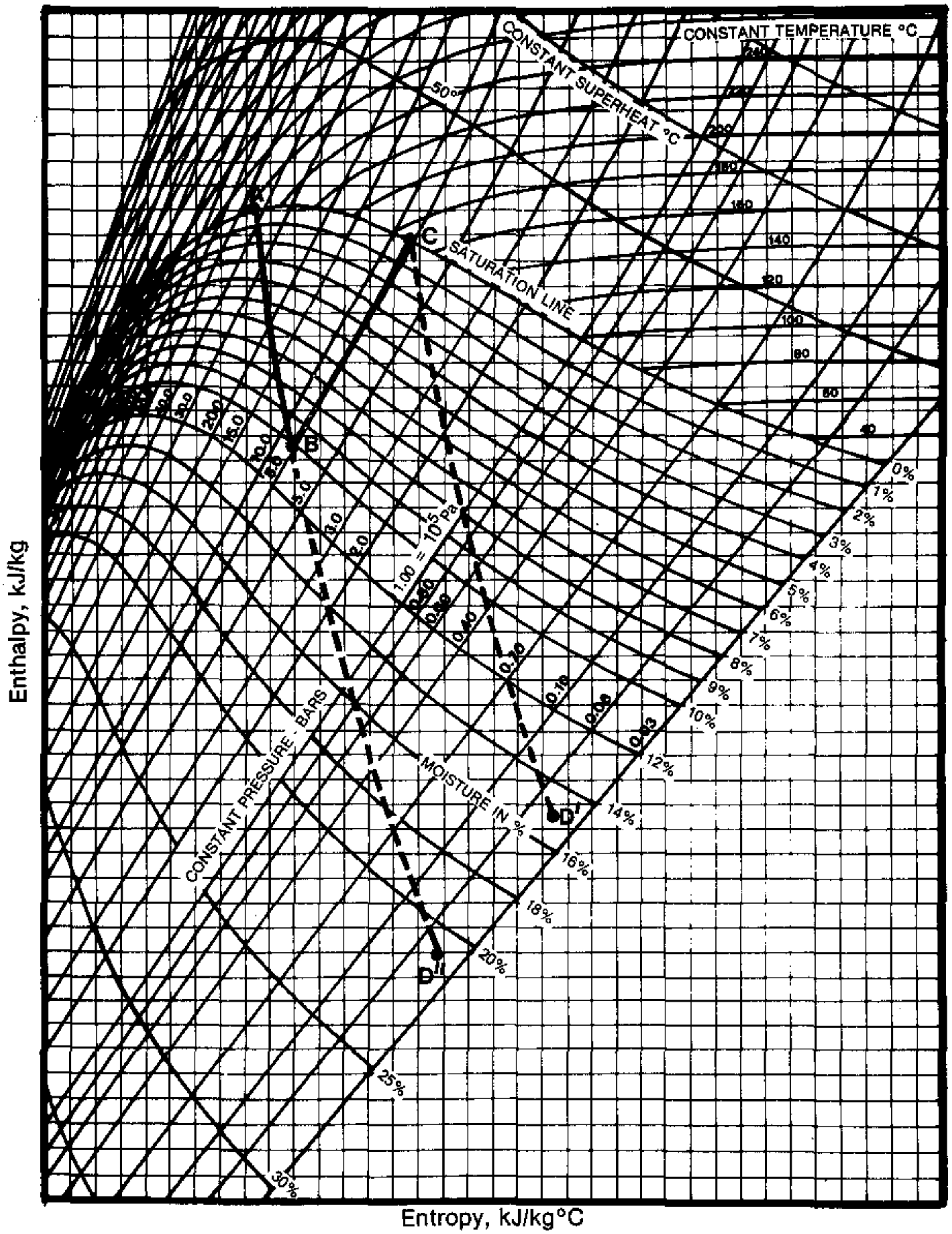

CONSTANT TEMPERATURE °C
CONSTANT SUPERHEAT °C
50°
200
180
160
140
120
100
80
60
40
A
C
SATURATION LINE
B
40.0
30.0
20.0
15.0
10.0
5.0
3.0
2.0
$1.00 = 10^5$ Pa
0.60
0.50
0.40
0.20
0.10
0.06
0.03
0%
1%
2%
3%
4%
5%
6%
7%
8%
9%
10%
12%
14%
16%
18%
20%
25%
30%
CONSTANT PRESSURE - BARS
MOISTURE IN %
D'
D''
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.

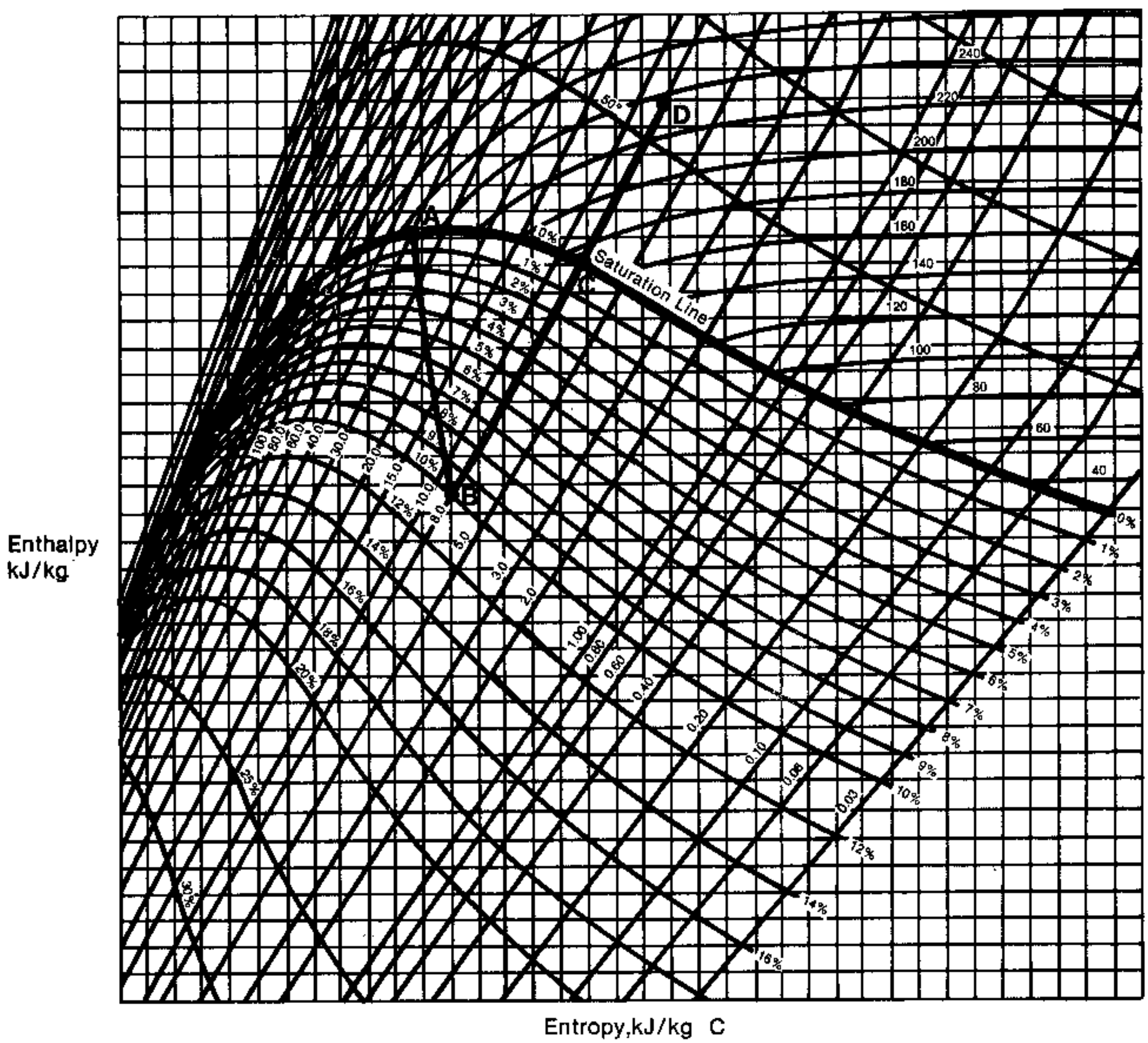


Figure 6.11

→ 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.

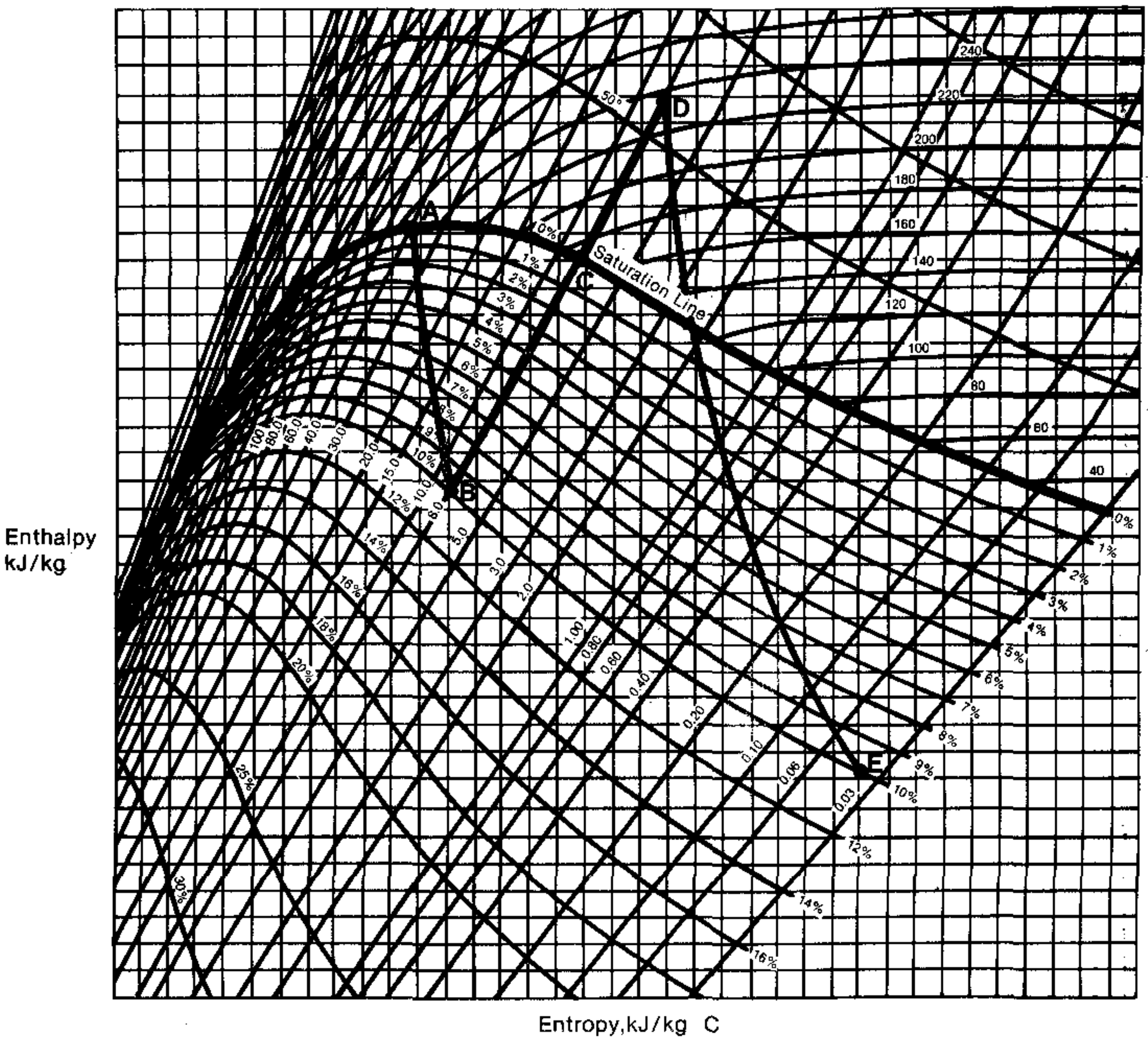


Figure 6.12

→ 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.

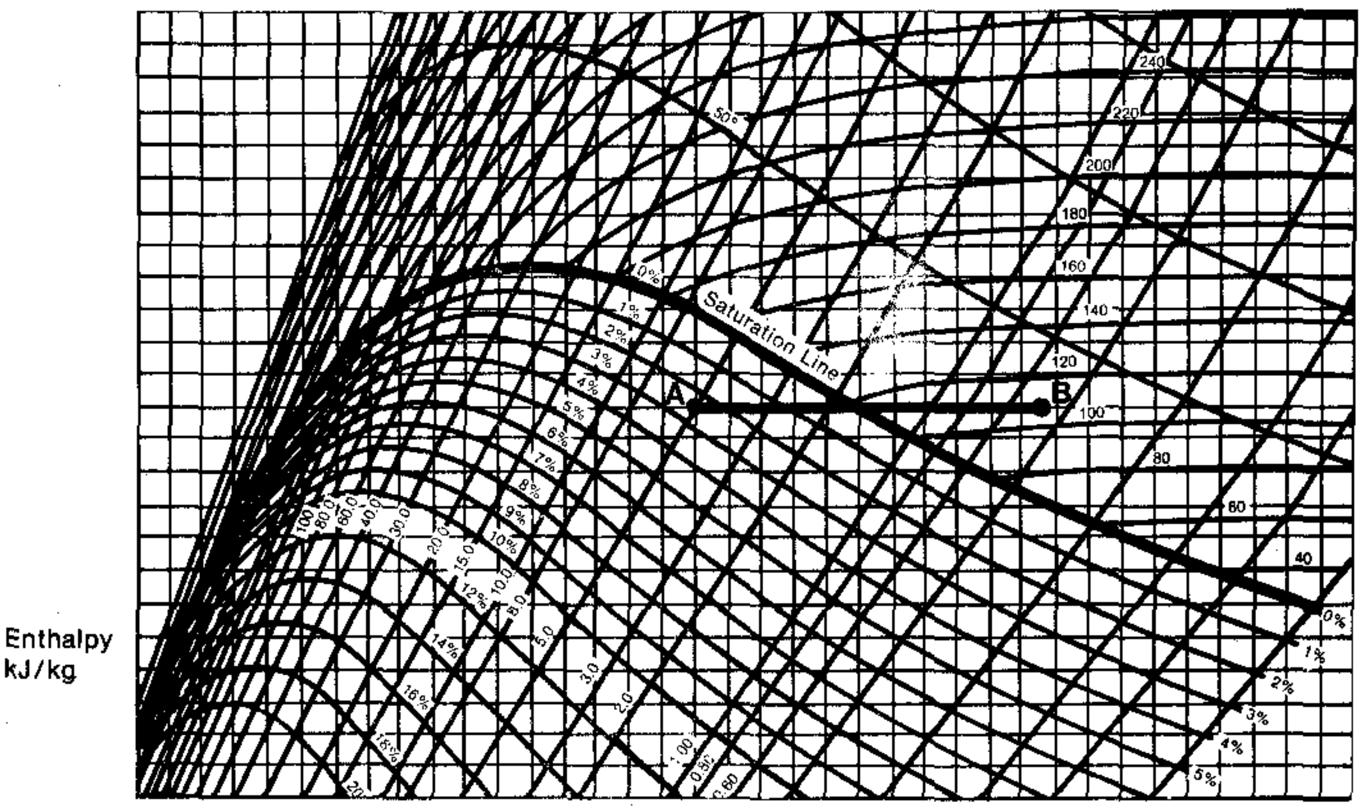


Figure 6.13

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.

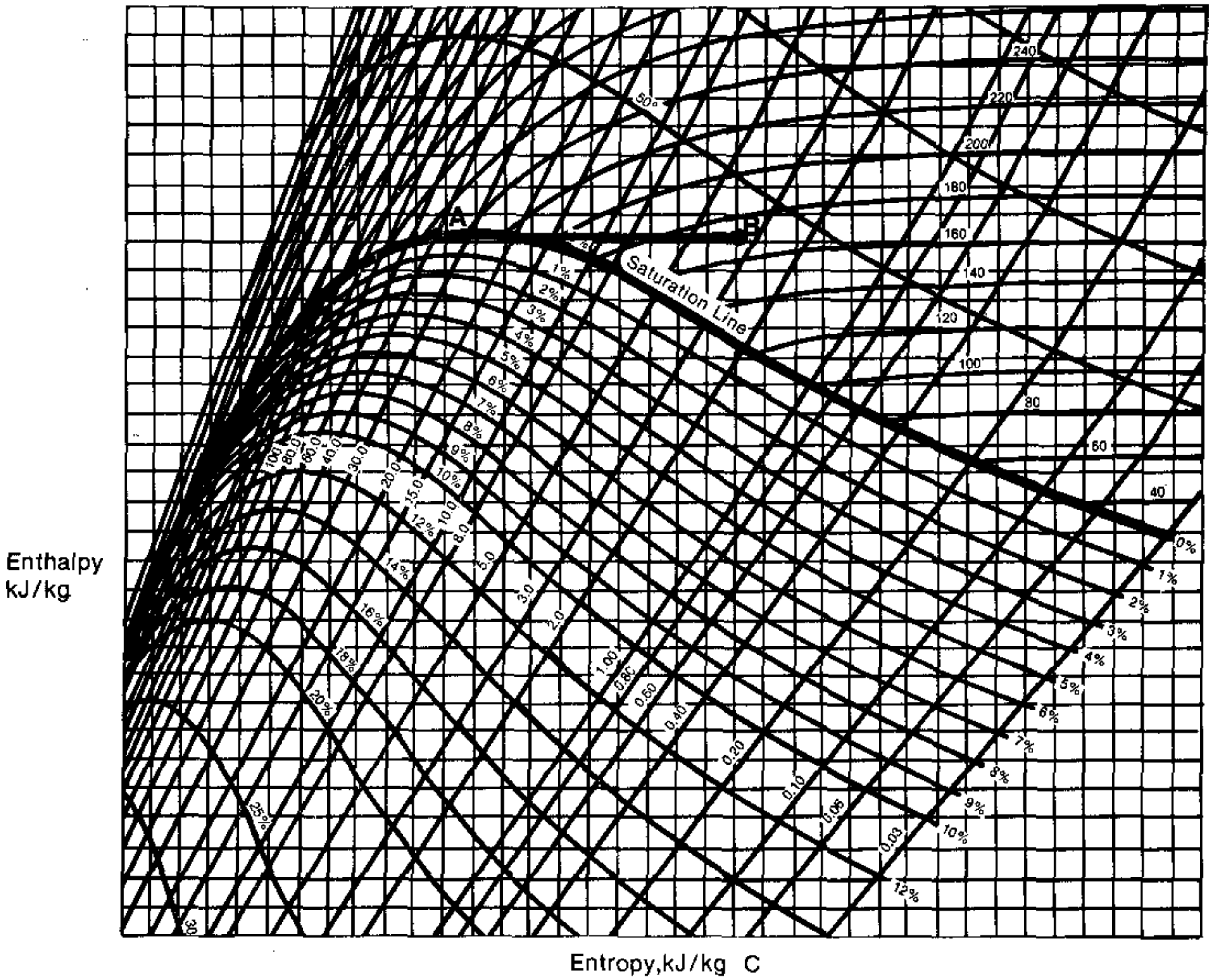


Figure 6.14

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.

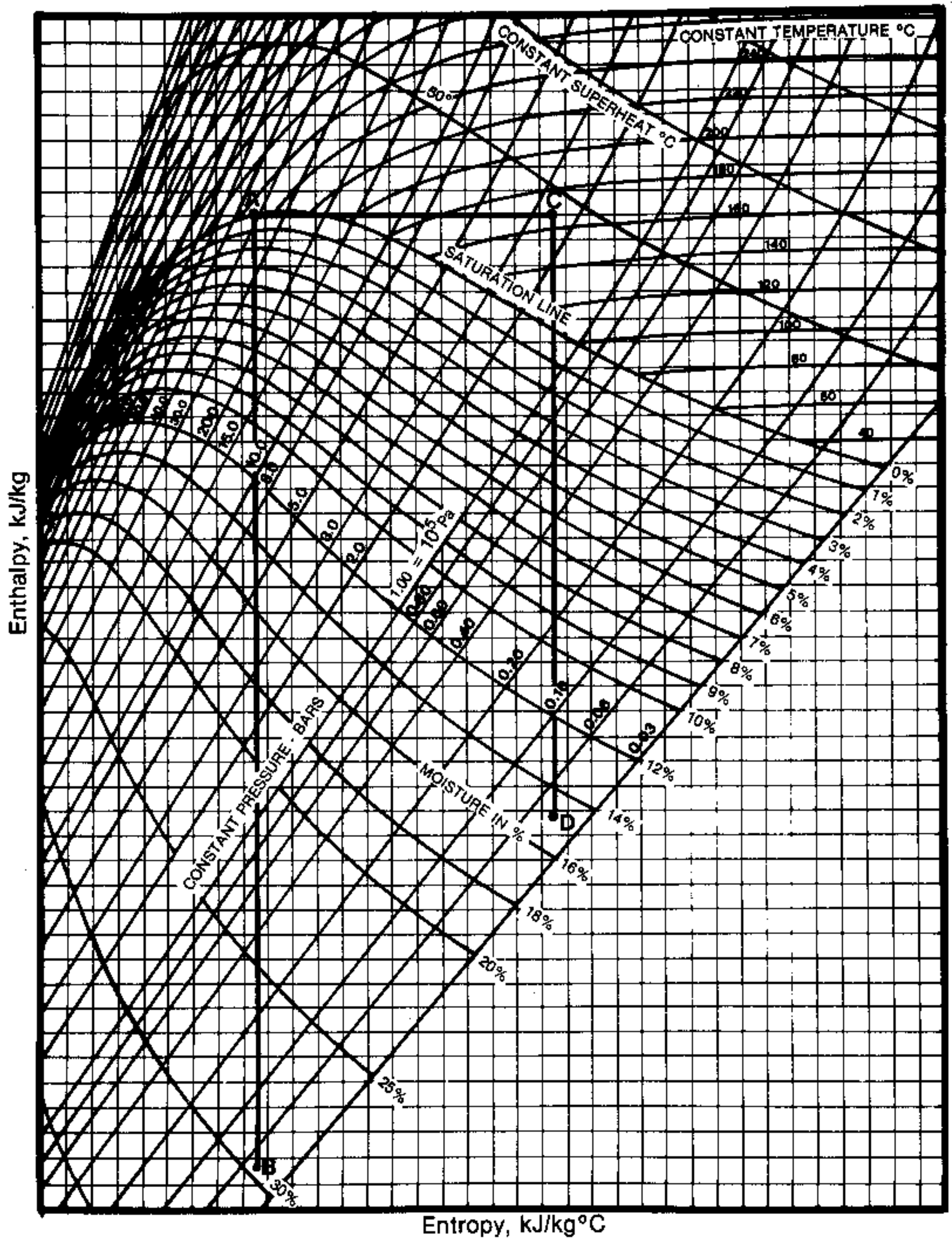

CONSTANT TEMPERATURE °C
CONSTANT SUPERHEAT °C
SATURATION LINE
CONSTANT PRESSURE - BARS
MOISTURE IN %
A
B
C
D
Enthalpy, kJ/kg
Entropy, kJ/kg°C
1.00 = 10^5 Pa
0%
1%
2%
3%
4%
5%
6%
7%
8%
9%
10%
12%
14%
16%
18%
20%
25%
30%

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:

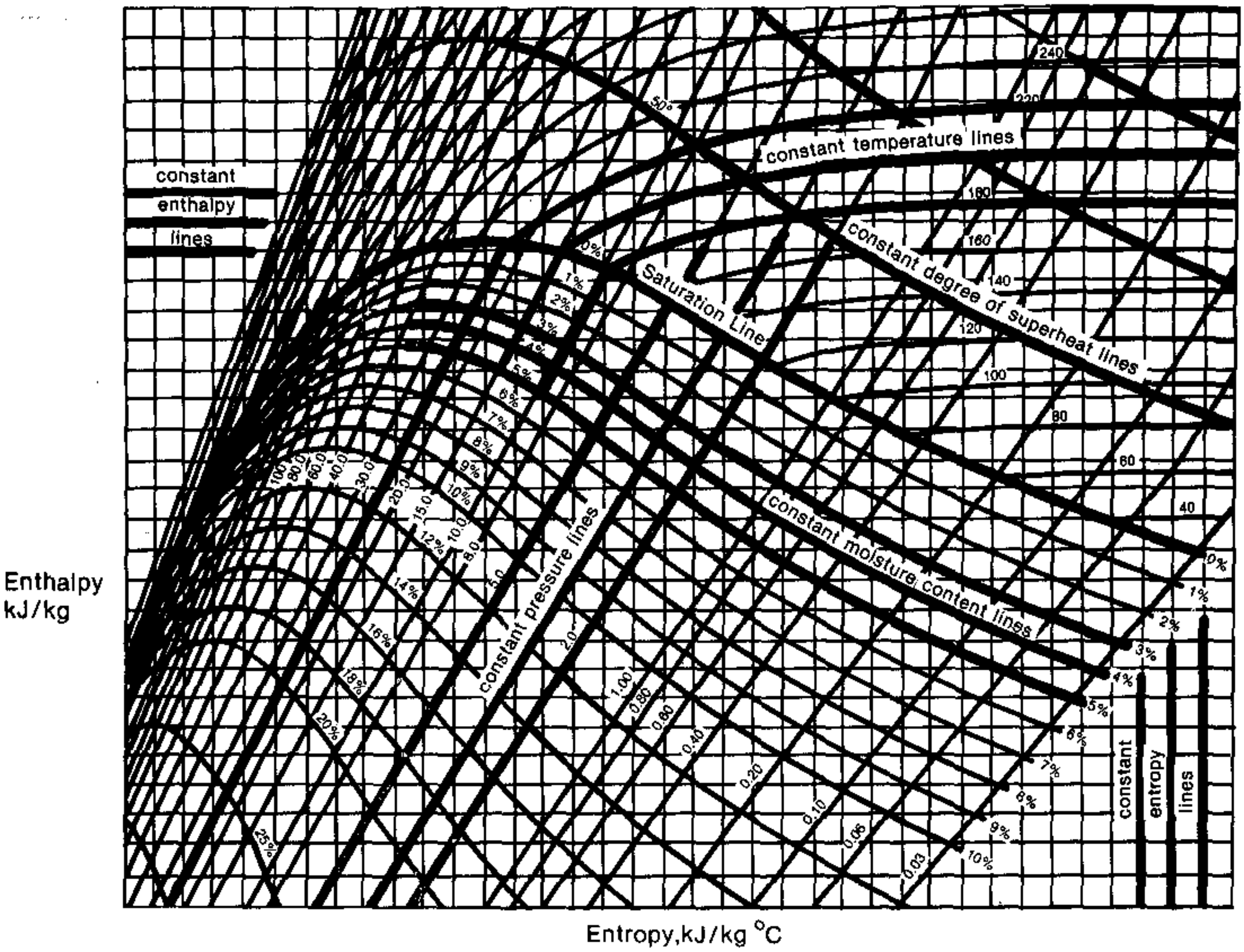


Figure 6.16

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.

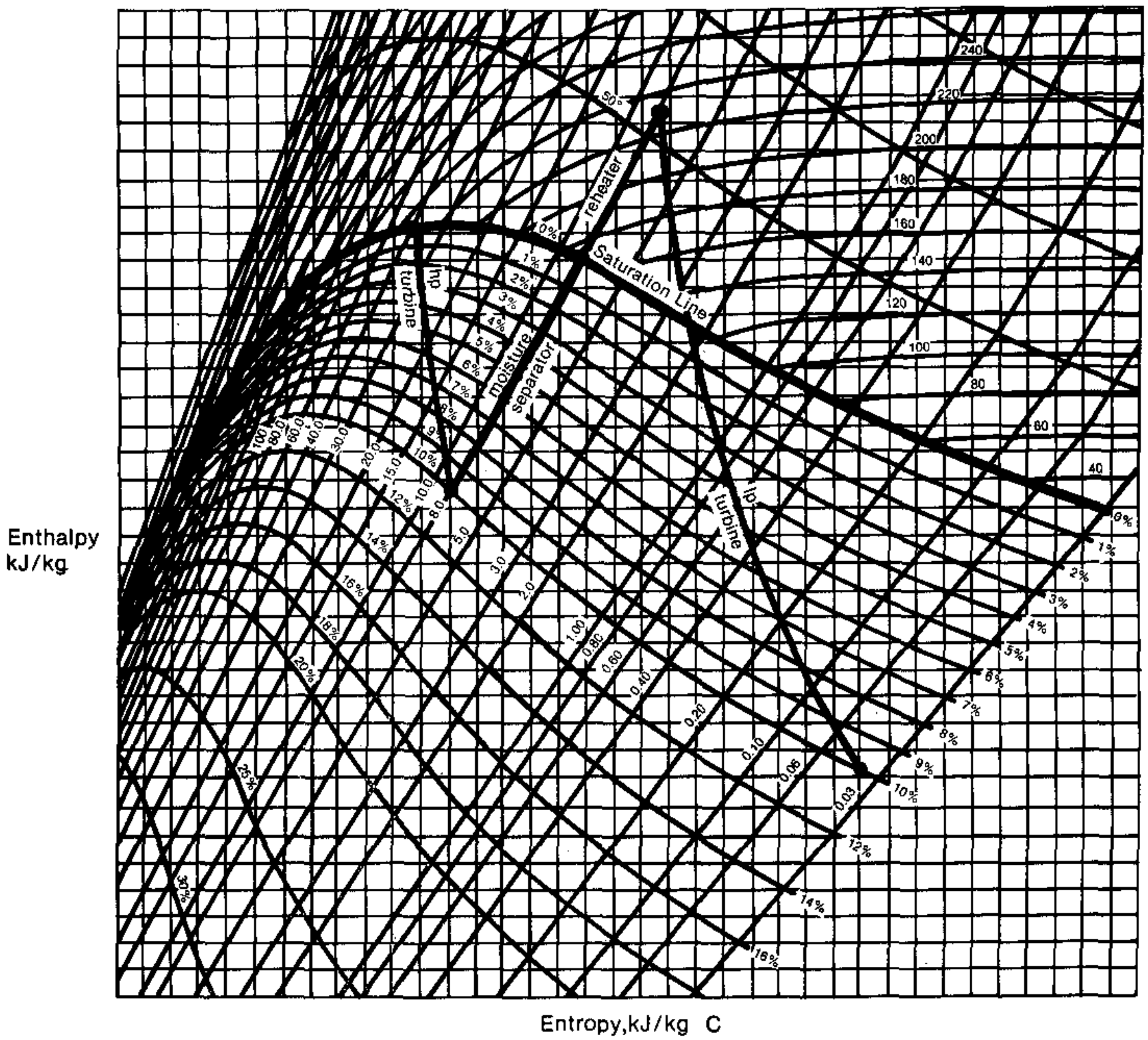


Figure 6.17

6.5 Your answer should look like Figure 6.18:

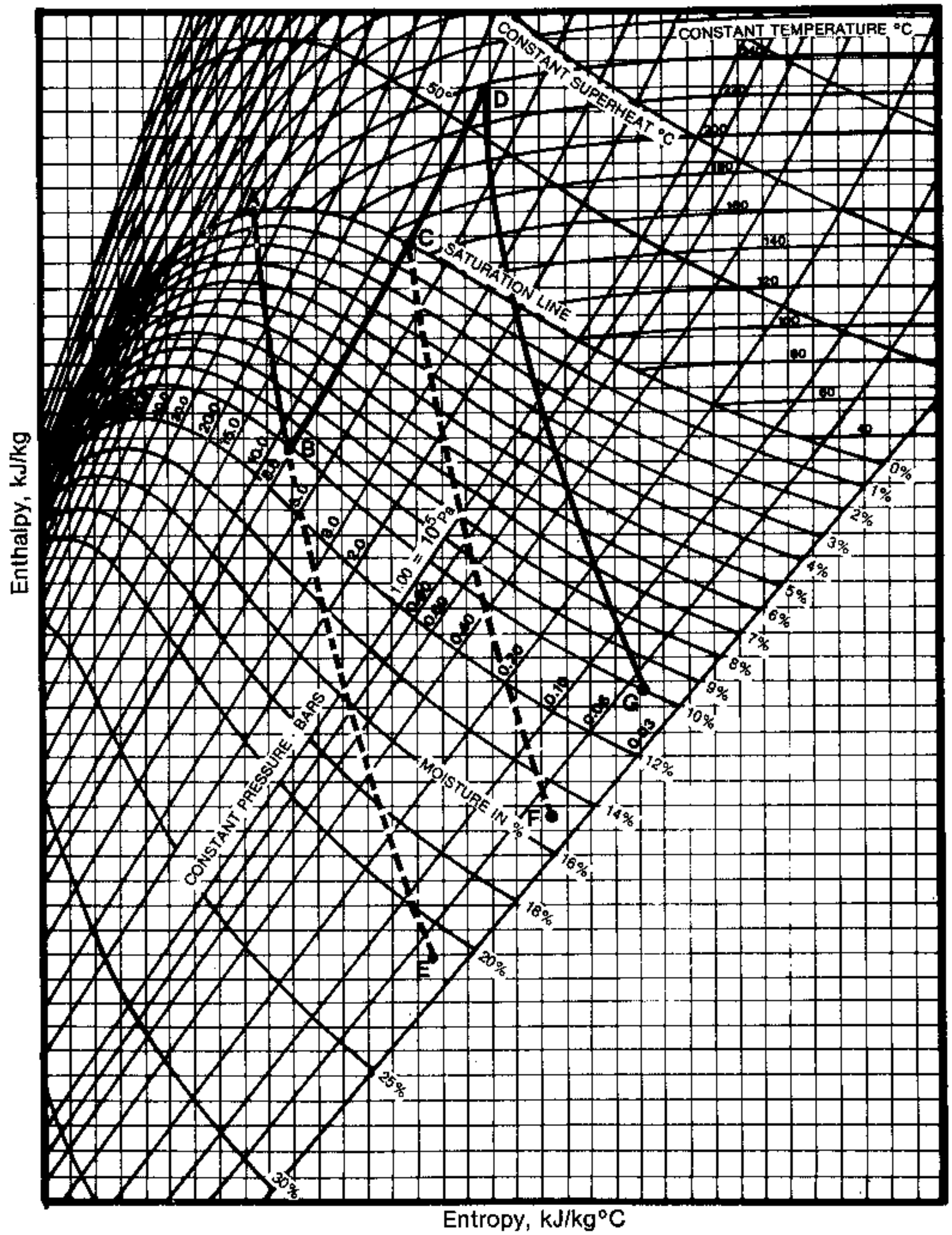


Figure 6.18

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.

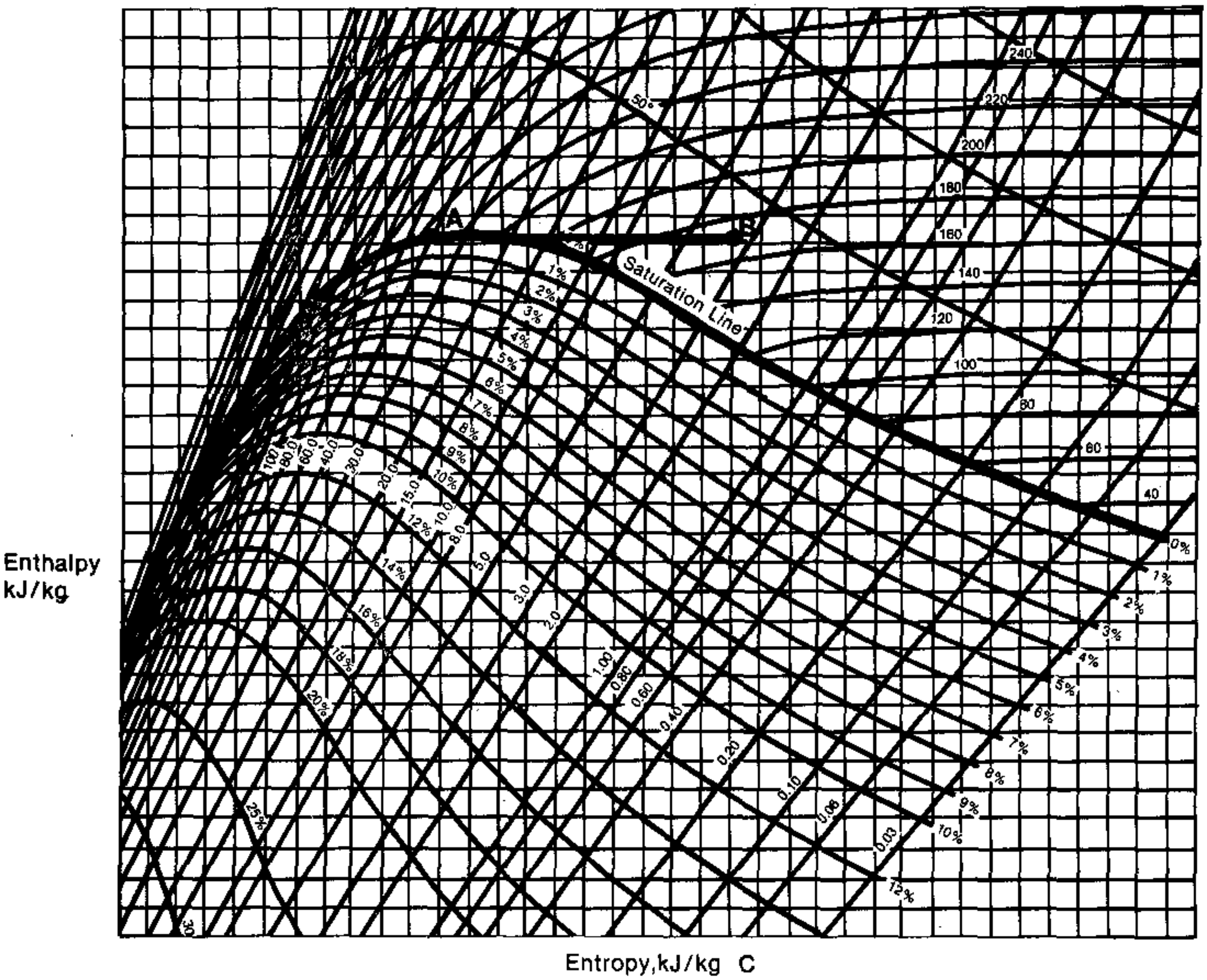


Figure 6.19

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

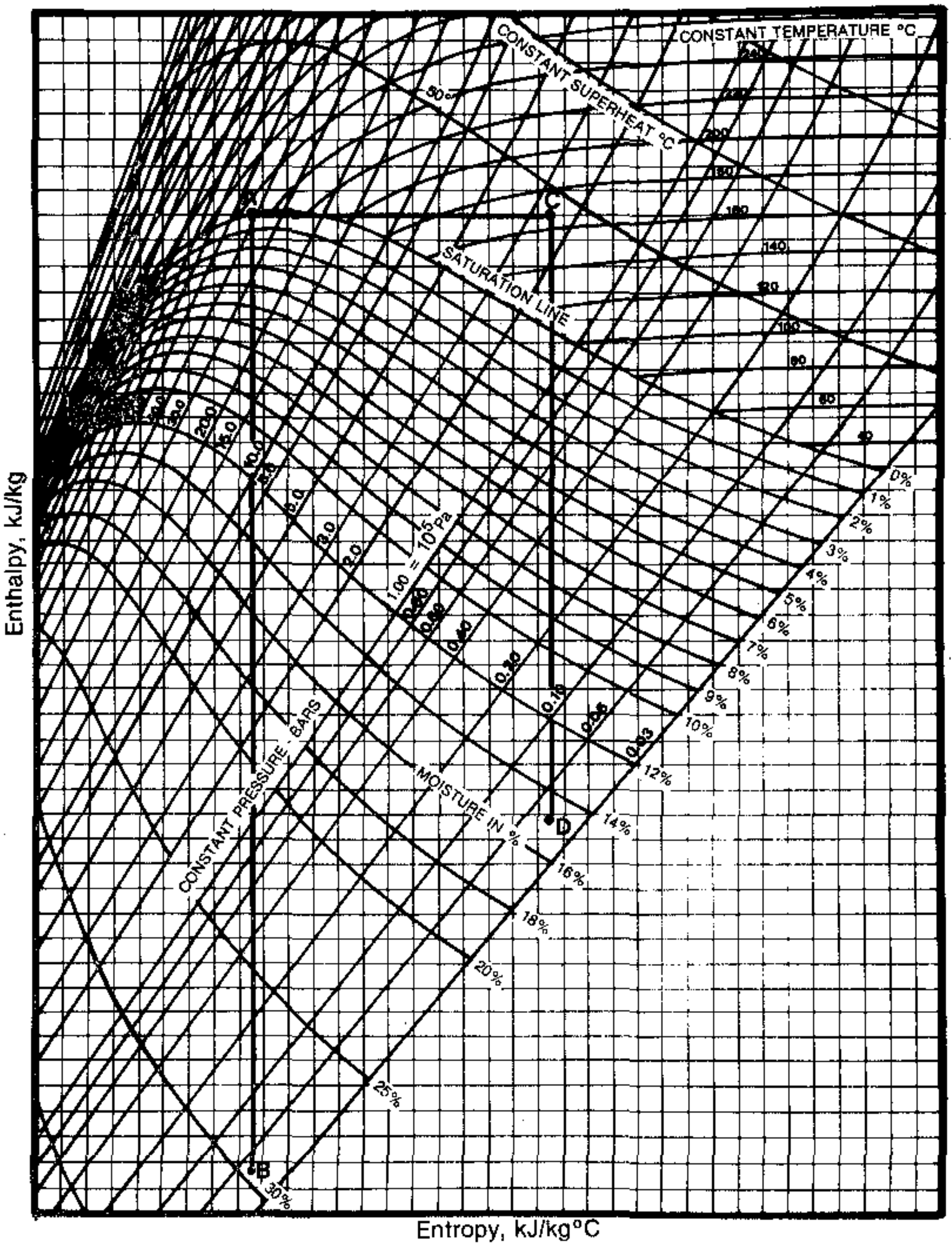


Figure 6.20

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 ($h_A - h_B > h_C - h_D$).

Heat and Thermodynamics - Course PI 25

EFFICIENCY AND THE CANDU CYCLE

Objectives

1. Define:

   (a) efficiency
   (b) thermal efficiency

2. Given all inputs and outputs of a system, determine the thermal efficiency.

3. (a) Explain how the thermal efficiency of the CANDU cycle can be improved by raising boiler pressure.
   (b) State the main limitation on the improvement in (a).

4. (a) Explain how the thermal efficiency of the CANDU cycle can be improved by lowering condenser pressure.
   (b) State two limitations on the improvement in (a).

5. (a) Explain how the thermal efficiency of the CANDU cycle can be improved by superheating in the boiler.
   (b) State the main limitation on the improvement in (a).

6. (a) Explain how the thermal efficiency of the CANDU cycle can be improved by:

      i) reheating between the high and low pressure turbines.
      ii) using extraction steam for feedheating.

   (b) State the main limitation on each improvement in (a).
   (c) State two practical benefits of each improvement in (a).

7. (a) Explain how the thermal efficiency of the CANDU cycle can be improved by moisture separation.

   (b) State the practical benefit of moisture separation.

Module Seven deals with efficiency. After definitions and simple calculations are dealt with, the rest of the module concerns the thermal efficiency of the CANDU cycle. The intent of this module is to make you aware of various considerations that have been taken into account in order to make CANDU generating stations as efficient as possible.

Efficiency can be defined as output divided by input, often expressed as a percentage value. This definition can apply to many things: the efficiency of heat transfer in the boilers, the efficiency of a pump, the efficiency of a turbine, etc. So that you can consider the thermodynamic cycle that represents a CANDU unit, we will define a particular type of efficiency - thermal efficiency.

The thermal efficiency of a system is defined to be the net work output of the system divided by the total heat input to the system, often expressed as a percentage. The net work output is the work produced by the system minus the work put in to the system in order to make it operate.

→ Answer questions 7.1 and 7.2 in the space provided before you proceed, then check your answers with the "TEXT ANSWERS".

7.1) Define the following:

(a) Efficiency: ______________________________

____

(b) Thermal efficiency: ______________________

____

7.2) 2390 MW of heat are added in the boilers of a CANDU unit. If the unit produces 788 MW of electricity and if 5.5 MW are put in to pump the feedwater from the condenser to the boilers, what is the thermal efficiency of the cycle?

→ At this point you should be able to do the first two objectives for this module. If you feel you need more practice, consult with the course manager.

CANDU Cycle Thermal Efficiency

The secondary heat transport system is the thermodynamic cycle of a CANDU unit. It is this system that the heat produced by nuclear fission is used to produce shaft mechanical energy. Needless to say, it is important that the thermal efficiency of this cycle be as high as can be reasonably achieved. This section deals with the cycle thermal efficiency of a CANDU unit - how it can be maximized and what practical limits are imposed on it.

Boiler Pressure

The pressure (and with it the temperature) of steam produced in the boiler should be as high as possible. Overall, as the saturation temperature and pressure of the steam leaving the boiler are raised, the ratio of net work output to heat input is increased. In other words, the higher the temperature and pressure of the steam, the higher the proportion of heat energy made available to produce work.

There is an upper limit on steam temperature (and thus pressure) in the CANDU system. This upper limit is imposed because of considerations involving the fuel and fuel sheath. The hotter the steam to be generated in the boilers, the hotter the PHT D_2O must be. This results in an increase in the surface temperature of the fuel in the reactor. The fuel is uranium dioxide (UO_2) manufactured in cylindrical pellets. As UO_2 is a ceramic material, its thermal conductivity is very low and the pellet core temperature is therefore much higher than the surface temperature. The temperature profile of a fuel pellet, including the sheathing, is shown in Figure 7.1.

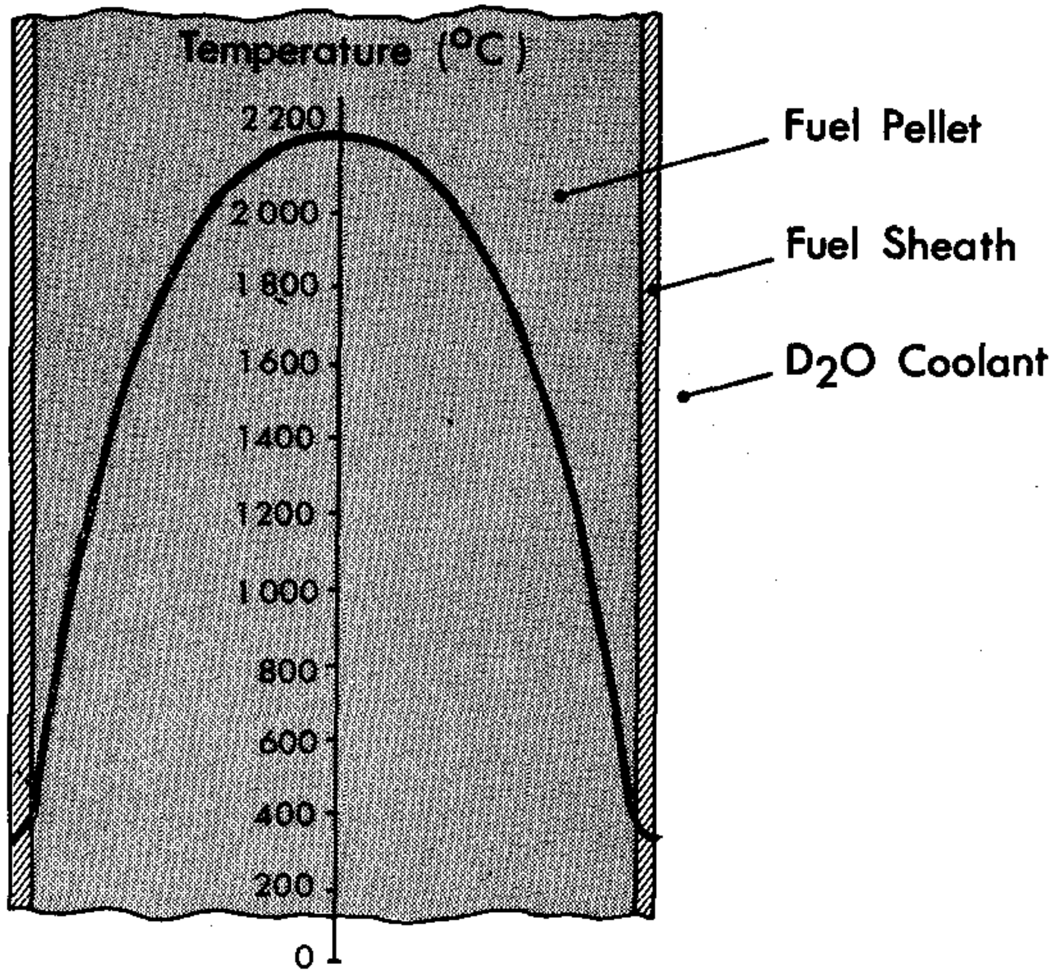


Figure 7.1

Note that temperatures in the order of 2000-2200°C occur in the centre of the fuel in order to produce 250-260°C steam. If higher steam temperatures were used, the pellet temperature would have to increase, and the danger of release of fission products due to fuel sheath failure would significantly increase. Thus the steam temperature is limited to a maximum of about 250-260°C.

→ Answer the following questions before you proceed. Check your answers with those in the "TEXT ANSWERS".

7.3 Explain how the thermal efficiency of the CANDU cycle can be improved by raising boiler pressure.

7.4) State the limitation on the improvement in thermal efficiency due to raising boiler pressure.

Condenser Pressure

The pressure (and temperature) of steam entering the condenser from the LP turbine should be as low as possible. As the pressure and temperature at the LP turbine outlet decrease, the work that has been extracted from the steam increases. The ratio of net work output to heat input increases significantly because of the extra work made available. Thus the thermal efficiency increases.

There are two main limitations on lowering the condenser pressure:

(a) The temperature of the condenser cooling water (CCW) is the main limitation. The water used to condense the steam is lake water. In summer the temperature of the CCW at the condenser inlet is about 20°C. Remember from Module PI 25-2 that this leads to steam temperature about 30°C in the condenser. It is interesting to note that as the CCW temperature drops with the approach of winter, the CANDU cycle efficiency increases.

(b) The lower the condenser pressure and temperature, the higher the moisture content of the steam leaving the LP turbine. Remember that moisture content above about 10% is undesirable. Without the use of moisture separation, reheating, feedheating, and some other features (which you will consider in PI 34), the moisture content of steam entering the condenser at 30°C would be 21%. Moisture content would have to be reduced in order to have a low condenser pressure.

→ Answer the following questions in the space provided, then check your answers with those in the "TEXT ANSWERS".

7.5) Explain how the thermal efficiency of the CANDU cycle can be improved by lowering condenser pressure.

7.6) State two limitations on the improvement in question 7.5.

Superheating

Superheating steam in the boilers (ie, heating the steam to a temperature higher than the saturation temperature for the steam pressure) will increase cycle thermal efficiency. Here is an extra heat input required to superheat the steam but the ratio of available work from this steam to the total heat input required is increased. Thus the overall cycle thermal efficiency is increased.

The main limitation on superheating is the limit of 250-260°C imposed by the fuel and fuel sheath considerations mentioned in raising boiler pressure. Superheated steam at 250-260°C could be produced, but it would be at a lower pressure than saturated steam at the same temperature. The ratio of available work to heat input would be less because of the lower pressure.

Another option would be to use a fossil-fuelled superheater. The price of such fuel is, however, the main reason why fossil-fuelled superheaters are not used.

→ Answer questions 7.7 and 7.8 in the space provided, then check your answers with those in the "TEXT ANSWERS".

7.7) Explain how the thermal efficiency of the CANDU cycle can be improved by superheating in the boiler.

7.8) State the main limitation of the improvement due to superheating.

Reheating

Remember that reheating between the HP turbine and the LP turbine produces superheated steam entering the LP turbine. As a result, the moisture content of the steam in the LP turbine is reduced and the turbine efficiency is therefore, increased. Thus, the ratio of net work output to heat input, ie, the cycle thermal efficiency, is increased.

The main limitation on reheating is due to the temperature of the live steam used to heat the main steam. This live steam is taken from the steam leaving the boiler, so it is limited to about 250-260°C.

Although reheating to higher temperatures could be achieved by means of fossil-fuelled reheaters, economical considerations (fuel price) make this option unattractive.

→ Answer the following questions before you proceed. Check your answers with those in the "TEXT ANSWERS".

7.9) Explain how the thermal efficiency of the CANDU cycle can be improved by reheating between the high pressure and low pressure turbines.

7.10) State the main limitation on the improvement due to reheating.

Reheating provides practical benefits besides an increase in cycle thermal efficiency; these benefits are the main reason reheating is done. The first benefit is a reduction in moisture content in the steam as it goes through the LP turbine. The result of having drier steam is that the steam can be utilized to a lower temperature and pressure. This allows a lower condenser pressure to be used and this reduction itself also improves the cycle thermal efficiency.

The second benefit of reheating is that the steam flow is smaller to produce a certain power. Remember that reheating increases the enthalpy of the steam before it enters the LP turbine. The steam can produce more work than steam that has not been reheated, and thus less flow is necessary to produce a certain power.

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

7.11) State two practical benefits of reheating.

Feedheating

The water that is returned from the condenser to the boilers is heated from about 30°C to about 175°C. There are two reasons for this feedheating:

(1) If the water is returned to the boilers (which operated at about 250°C) at 30°C, large thermal stresses will occur in the boilers. To reduce these stresses, the water must be preheated.

(2) Less fuel is burned to produce a given amount of power, since most of the sensible heat needed to change the temperature of the water from condenser conditions to boiler conditions comes from feedheating.

Generally, steam is extracted from the turbine to heat the feedwater in the feedheaters. Using the extraction steam increases CANDU cycle thermal efficiency. The increase is due to the use of the heat energy of the steam.

If the extraction steam is not extracted, but allowed to continue through the turbine, it would produce some work and then enter the condenser. In the condenser about 90% of the latent heat of the steam is rejected to the lake as the steam is condensed.

When the extraction steam goes to the feedheater, the work that it could produce in the turbine is lost. However, the steam condenses in the feedheater and its heat is given up to the feedwater. Thus, at the expense of the loss of some work production, a significant amount of heat is conserved within the cycle. This conservation reduces the heat input in the boilers and the ratio of net work output to heat input, ie, the cycle thermal efficiency, is increased.

The increase in thermal efficiency depends on the number of feedheaters used and the pressures at which the steam is extracted from the turbine. The larger the number of feedheaters, the larger the increase in efficiency. However, the gain in efficiency due to installing each successive feedheater gets smaller and smaller. For a given number of feedheaters, it is possible to calculate optimal pressures for the extraction steam so that the increase in the thermal efficiency will be maximum.

The main limitation on the improvement due to using extraction steam for feedheating is economic. Using a larger number of feedheaters makes it possible to achieve a larger increase in the cycle thermal efficiency, however, it increases the capital costs. At some point there is a balance between the benefit from efficiency increase and costs incurred. In a CANDU station this occurs when 5-6 feedheaters are used and the feedwater is heated to about 175°C.

→ Answer the following questions, then check your answers with those in the "TEST ANSWERS".

7.12) Explain how using extraction steam for feedheating can improve the thermal efficiency of the CANDU cycle.

7.13) State the main limitation on the improvement in efficiency due to using extraction steam for feedheating.

Using the extraction steam for feedheating also provides practical benefits. The first is a reduction in moisture content of the steam in the turbine. When wet steam flows through the turbine, it has a very swirling motion. Centrifugal forces are exerted both on vapor and water droplets but due to the difference between their densities, the liquid is centrifuged outwards, ie, towards the turbine casing. As extraction steam is removed from the casing, its moisture content is much larger than the average moisture content of the steam flowing through the turbine. The result of this is a reduction in moisture content in the turbine.

The second benefit has to do with the amount of steam extracted. Up to 30% of the steam flow is removed from the turbine set for feedheating. This reduction in steam flow through the low pressure turbine enables a smaller, and therefore less costly, low pressure turbine to be used.

——► Answer questions 7.14, then check your answer with the one in the "TEXT ANSWERS".

7.14) State two practical benefits of using extraction steam for feedheating.

Moisture Separation

Moisture separation causes a significant increase in cycle thermal efficiency. The main effect of moisture in the steam is a tendency to retard the motion of the turbine blades; this causes a loss in work production in the turbine. Reducing the moisture content allows the turbine to produce more work for the same heat input. Thus the cycle thermal efficiency is improved.

The practical benefit of moisture separation is the same as the first benefit listed in reheating: moisture separation reduces the moisture content of the steam going through the LP turbine, which allows a lower condenser pressure to be used without exceeding the maximum acceptable moisture content of the steam at the turbine exhaust (about 10-12%).

⟶ Answer the following questions before you proceed. Check your answers with those in the "TEXT ANSWERS".

7.15) Explain how moisture separation can increase the thermal efficiency of the CANDU cycle.

7.16) State the practical benefit of moisture separation.

→ You have now completed the last module of PI 25. If you feel you can answer the objectives for this module, obtain a criterion test and answer it. If you are not confident at this point, please consult with the course manager.

PI 25-7 TEXT ANSWERS

7.1) (a) Efficiency - output divided by input, often expressed as a percentage.

(b) Thermal Efficiency - net work output of a system divided by total heat input to the system, often expressed as a percentage.

7.2) The heat input in this question is 2390 MW.

The net work output is 788 - 5.5 = 782.5 MW.

The thermal efficiency is (782.5 ÷ 2390) x 100 = 32.7%

7.3) As boiler pressure is raised, the steam temperature and pressure both increase. As they increase, the ratio of work available to heat input increases. This will increase the ratio of net work output to heat input, ie, the thermal efficiency of the cycle.

7.4) The main limitation is a maximum achievable steam temperature of about 250 -260°C, imposed by fuel and fuel sheath considerations.

7.5) As the steam pressure and temperature in the condenser are lowered, the work produced in the turbine increases. The ratio of net work output to heat input, ie, the thermal efficiency, increases.

7.6) The increase in efficiency due to lowering condenser pressure is limited by the temperature of the lake water used as the condenser coolant and by the maximum allowable moisture content in the LP turbine.

7.7) If superheating is done in the boiler, the steam will have a higher amount of work available to heat input ratio. The thermal efficiency of the cycle can thus be increased.

7.8) The main limitation on superheating in the boiler is 250-260°C temperature limit due to the material considerations of the fuel and fuel sheath.

7.9) Reheating between HP and LP turbines increases cycle thermal efficiency by providing superheated steam to the LP turbine. As the moisture content of the steam in the turbine is reduced, the turbine efficiency increases, and therefore the cycle thermal efficiency is increased.

7.10) The main limitation on improving cycle thermal efficiency by reheating is the live steam temperature. The live steam is taken from the main steam flow from the boilers; its temperature is limited to 250-260°C.

7.11) Reheating reduces moisture content in the lp turbine, which allows a low condenser pressure to be maintained. Also, the steam flow is less with reheating to provide a given power than the flow without reheating - thus the whole secondary system size is smaller and less costly.

7.12) Using extraction steam for feedheating increases CANDU cycle thermal efficiency because, at the expense of some loss of work production, a large amount of heat is conserved with the cycle. This heat is conserved because the steam is condensed by feedwater rather than by lake water. The ratio of net work output to heat input is increased because much less heat input is required.

7.13) The limitation on the efficiency improvement due to the use of extraction steam for feedheating is economic. It is the balance between the increasing cost of the equipment and the increasing gain in efficiency as the number of feedheaters increases.

7.14) The first benefit of using extraction steam for feedheating is that moisture content in the LP turbine is reduced. The second benefit is that the size of the turbine set is reduced due to smaller flow through the outlet portion of the turbine.

7.15) The effect of moisture separation is that less work is lost in the turbine (the work lost being due to retardation of the moving blades because of liquid impingment). The LP turbine thus has a higher work output for the same heat input, and the cycle thermal efficiency increases.

7.16) The practical benefit of moisture separation is that a low condenser pressure can be maintained without exceeding the maximum acceptable moisture content of the steam at the LP turbine exhaust (about 10-12%).

Heat and Thermodynamics - Course PI 25

CRITERION TESTS

PI 25-1 - CRITERION TEST

1. Define:

   (a) heat
   (b) temperature
   (c) enthalpy

2. State the meaning of each of the following as it applies to water:

   (a) saturation temperature
   (b) subcooled liquid
   (c) saturated liquid
   (d) wet steam
   (e) saturated steam
   (f) superheated steam
   (g) sensible heat
   (h) latent heat of vaporization

3. Sketch a temperature vs enthalpy graph for water at constant pressure. Label the following on your sketch:

   (a) saturation temperature
   (b) subcooled liquid region
   (c) saturated liquid
   (d) wet steam region
   (e) saturated steam
   (f) superheated steam region
   (g) sensible heat region
   (h) latent heat region

4. State whether each of the following represents subcooled liquid, saturated liquid, wet steam, saturated steam, or superheated steam. You may use steam tables as an aid.

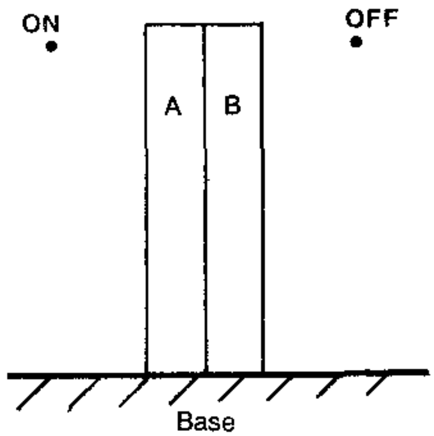
   (a) 190°C, 10 bar, 2802.0 kJ/kg
   (b) 144.5°C, 4.1 bar, 1864.3 kJ/kg
   (c) 295°C, 86 bar, 1317.3 kJ/kg
   (d) 29°C, 0.04 bar, 121.4 kJ/kg
   (e) 65°C, 0.25 bar, 568.1 kJ/kg
   (f) 222°C, 24.1 bar, 2800.5 kJ/kg

5. How much heat is added to 10 kg of water at 95°C to produce 13% wet steam at 194°C?

PI 25-2 - CRITERION TEST

1. A pipe run is 500 m long at 20°C. The pipe is carbon steel (α = 10 x 10^{-6} °C^{-1}) and it operates at 200°C normally. What is the amount of expansion that occurs as the pipe goes from 20°C to 200°C?

2. A bimetal strip is shown below. If A is iron (α_A = 12 x 10^{-6}°C^{-1}) and B is brass (α_B = 18 x 10^{-6} °C^{-1}), towards which contact will the strip move as it is heated? Briefly explain why.



3. Determine the ratio of the change in volume that occurs as steam (10% moisture content) at 33°C is condensed to water at 33°C.

4. Explain shrink and swell as they apply to:

   (a) a liquid (eg, the PHT D_2O) as its temperature is changed
   (b) water in a boiler that experiences a step increase or decrease in steam flow.

5. Explain why the programmed level of water in the boiler changes as power changes.

6. Explain how steam entering the condenser at a CANDU station can be at about 30°C and 4 kPa(a).

PI 25-3 - CRITERION TEST

1. The high pressure feedheater at BNGS-A uses 151 kg/s of extraction steam at 173°C (moisture content = 70.5%) to heat 1070 kg/s of feedwater. The extraction steam condensate exits the feedheater at 155°C. If the feedwater enters the heater at 149°C, to what temperature is it heated?

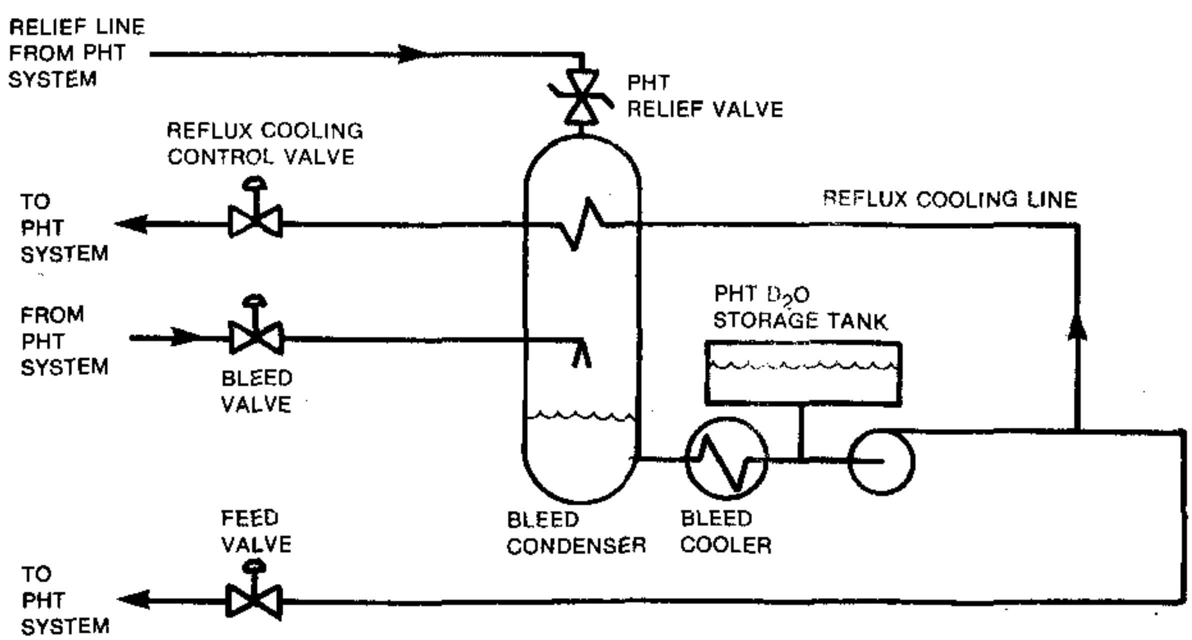
2. 24 kg/s of D_2O is heated from 244°C to 300°C as it flows through a pressure tube. Assuming the D_2O remains liquid, determine the reactor thermal power output if there are 412 pressure tubes in the reactor.

PI 25-4 - CRITERION TEST

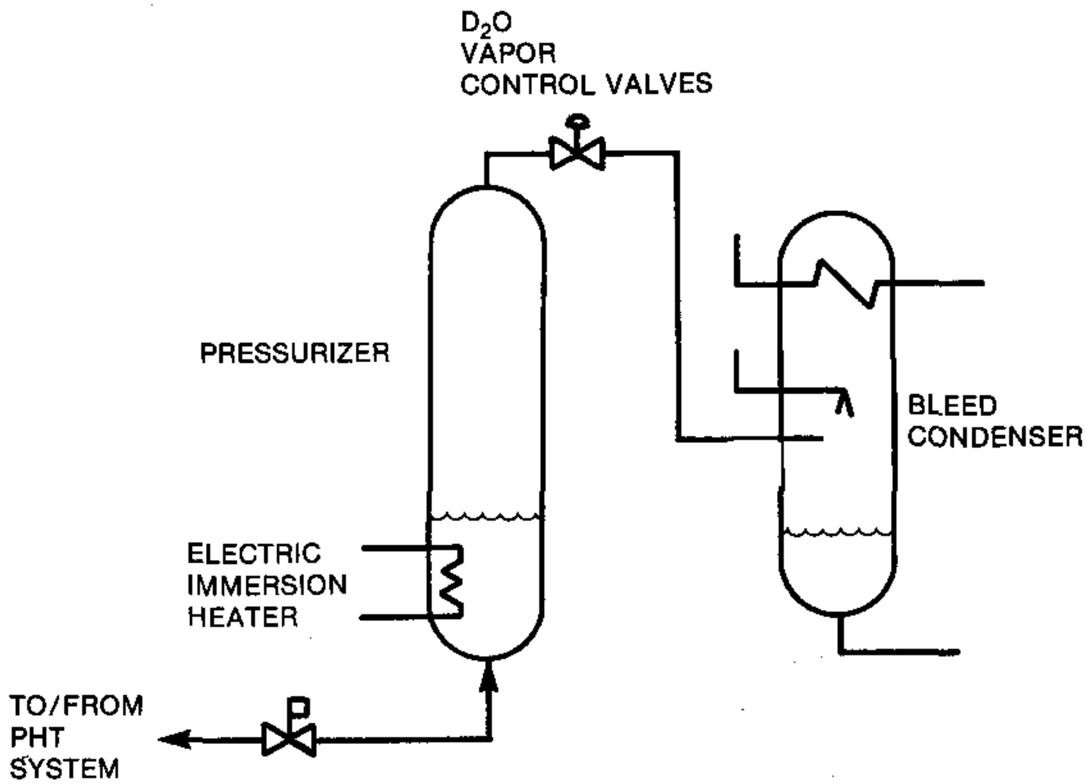
1. Describe the effects resulting from:

   (a) too high heat transport pressure
   (b) too low heat transport pressure

2. For the system shown below, explain how heat transport system pressure is controlled.



3. For the system shown below, explain how heat transport system pressure is controlled.



4. State why controlling boiler pressure is important.

5. List the three main heat sinks for the boiler in a CANDU station.

6. Briefly explain how the boiler pressure can:

   (a) remain constant as power increases
   (b) fall as power increases

   and what the effect is, in each case, on the PHT D_2O average temperature.

PI 25-5 - CRITERION TEST

1. Briefly explain heat transfer by:

   (a) conduction
   (b) natural convection
   (c) forced convection
   (d) radiation

2. State the factors that influence the rate of heat transfer by each mechanism in Question 1.

3. Briefly describe two examples of each mechanism from Question 1 in a CANDU generating station.

PI 25-6 - CRITERION TEST

1. Sketch a Mollier diagram from memory, and include the following labels 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 your sketch from Question 1, show the overall turbine process, including:

   (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 increase the enthalpy of the steam flowing to the LP turbine.

4. Explain how moisture separation and reheat each each reduce the moisture content of the steam at the LP turbine outlet.

5. Define throttling.

6. Explain, using a Mollier diagram, 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

PI 25-7 - CRITERION TEST

1. Define:

   (a) efficiency
   (b) thermal efficiency

2. 2450 MW of heat are added in the boilers of a CANDU unit. The unit produces 796 MW of electricity and 6 MW are input to pump feedwater from the condenser to the boilers. Determine the thermal efficiency of the cycle.

3. (a) Explain how the thermal efficiency of the CANDU cycle can be improved by raising boiler pressure.
   (b) State the main limitation on the improvement in (a).

4. (a) Explain how the thermal efficiency of the CANDU cycle can be improved by lowering condenser pressure.
   (b) State two limitations on the improvement in (a).

5. (a) Explain how the thermal efficiency of the CANDU cycle can be improved by superheating in the boiler.
   (b) State the main limitation on the improvement in (a).

6. (a) Explain how the thermal efficiency of the CANDU cycle can be improved by:

      i) reheating between the high and low pressure turbines.
      ii) using extraction steam for feedheating.

   (b) State the main limitation on each improvement in (a).
   (c) State two practical benefits of each improvement in (a).

7. (a) Explain how the thermal efficiency of the CANDU cycle can be improved by moisture separation.
   (b) State the practical benefit of moisture separation.

Heat and Thermodynamics - Course PI 25

SELF EVALUATION ANSWER SHEET

PI 25-1 - SELF EVALUATION ANSWER SHEET

1. (a) Heat is a form of energy in a substance. The energy depends on the temperature of the substance, the type of substance, its state and the amount of mass involved.

   (b) Temperature is a measure of the ability of a substance to lose or gain heat when compared to another substance.

   (c) Enthalpy is the total heat per kg of substance, measured above a reference point.

2. (a) Saturation temperature - the temperature at which boiling occurs for a given pressure.

   (b) Subcooled liquid - liquid water at a temperature lower than the saturation value.

   (c) Saturated liquid - liquid at the saturation temperature; no vapor present.

   (d) Wet steam - liquid and vapor existing as some mixture at the saturation temperature.

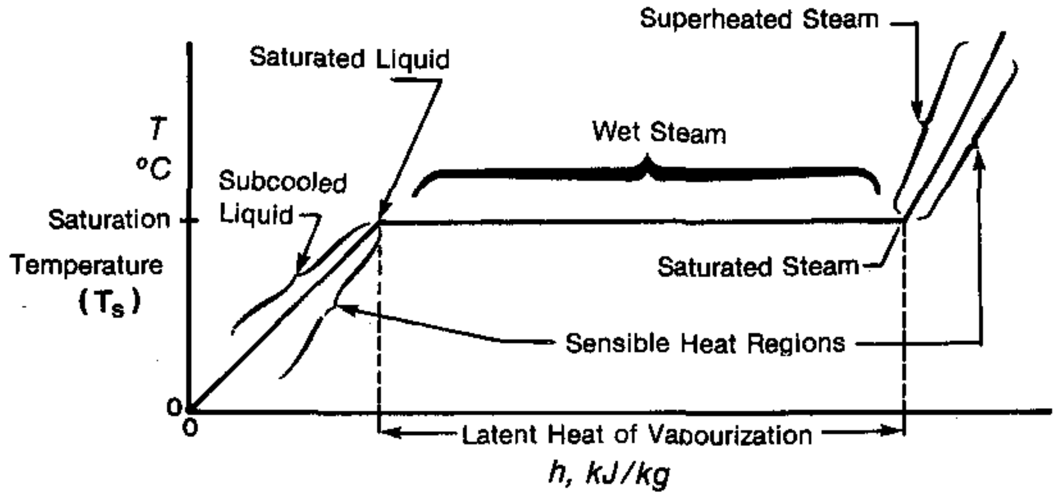
   (e) Saturated steam - vapor at the saturation temperature; no liquid is present.

   (f) Superheat steam - vapor at a temperature higher than the saturation value.

   (g) Sensible heat - heat added or removed that results in a change in temperature.

   (h) Latent heat of vaporization - heat added to boil/kg of liquid at constant temperature.

3.



4. (a) superheated steam
   (b) wet steam
   (c) subcooled liquid
   (d) saturated liquid
   (e) wet steam
   (f) saturated steam

5. Here, $\Delta h = h_{ws} - h_{f_{95°C}}$

and, $h_{ws} = h_{f_{194°C}} + (1 - 0.13)\ h_{fg_{194°C}}$

$= h_{f_{194°C}} + 0.87\ h_{fg_{194°C}}$

Thus, $\Delta h = h_{f_{194°C}} + 0.87\ h_{fg_{194°C}} - h_{f95°C}$

$= 825.4 + 0.87 \times 1961.7 - 398.0$

$= 2134.1$ kJ/kg

The heat added is $Q = m\Delta h = 10 \times 2134.1 = \underline{2.13 \times 10^4 \text{ kJ}}$

PI 25-2 - SELF EVALUATION ANSWER SHEET

1. Here, $L_o = 500$ m

$\alpha = 10 \times 10^{-6}$ °C^{-1}

$\Delta T = 200 - 20 = 180$°C

Thus, $L = L_o \alpha \Delta T = 500 \times 10 \times 10^{-6} \times 180$

$= \underline{0.9 \text{ m}}$

2. The switch will move towards the ON contact as it is heated. This is because the linear expansion coefficient is greater for brass than for iron; since the strip is heated, the brass will be longer. The brass must be on the outside of the arc formed, and the strip will bend to the left.

3. The volume of the wet steam is:

$v_{WS} = v_{f33°C} + (1 - 0.10)\, v_{fg33°C} = 1.0053 + 0.90 \times 28040.9$

$= 25240$ ℓ/kg

The volume of the water is:

$v_{f33°C} = 1.0053$ ℓ/kg

The ratio is 25240 ÷ 1.0053 = 25,100 times.

4. (a) As the liquid is heated (and its temperature increases) it will expand. This is swell.

As the liquid is cooled (and its temperature decreases) its volume will decrease. This is shrink.

(b) The apparent volume of water in an operating boiler is due to the volume of liquid <u>plus</u> the volume of vapor contained in the liquid at <u>any</u> instant.

If the steam flow experiences a rapid increase, the boiler pressure suddenly decreases, the rate of vapor production increases, and the apparent volume of water in the boiler will increase. This causes the boiler level to suddenly increase. This increase is apparent volume and level is known as swell in the boiler.

If the steam flow experiences a rapid decrease, the boiler pressure will suddenly increase. The vapor present in the liquid will condense, and the apparent volume of water will suddenly decrease. This decrease and the consequent drop in boiler level is called shrink in the boiler.

5. The programmed boiler level increases as power increases and it decreases as power decreases. There are two reasons for this:

   (a) As the amount of boiling changes, so does the level. The more boiling that occurs, the more vapor is present with the liquid. The volume of water increases, and the level does also. The reverse is true as less boiling occurs. In order to maintain a constant mass of water in the boiler, the level setpoint must be increased.

   (b) The programmed level is changed <u>more</u> than would naturally occur (as in (a)). This is done to accommodate shrink and swell. Thus, since at a low power level swell is likely to occur, the programmed level setpoint is low. At high power levels, when shrink is likely to occur, the programmed level setpoint has been increased.

6. The use of cold lake water enables the condenser to be at 30°C and 4 kPa(a). The water flows through the condenser tubes at a maximum about 20°C, thus condensing the steam on the outside of the tubes at about 30°C. While condensing at this temperature, the steam decreases in volume in the order of 25,000 times. This will maintain the pressure at about 4 kPa(a).

PI 25-3 - SELF EVALUATION ANSWER SHEET

1. The enthalpy difference on the steam side is:

$$h_{ws173°C} - h_{f155°C} = h_{f173°C} + (1-0.705)\ h_{fg173°C} - h_{f155°C}$$
$$= h_{f173°C} + 0.295\ h_{fg173°C} - h_{f155°C}$$

The enthalpy difference on the feedwater side is:

$$h_{f?} - f_{f149°C}$$

Thus, $\dot{m}_L\ (h_{f173°C} + 0.295\ h_{fg173°C} - h_{f155°C}) = \dot{m}_G(h_{f?} - h_{f149°C})$

$$151\ (732.8 + 0.295 \times 2037.7 - 653.8) = 1070\ (h_{f?} - 627.8)$$

$$h_{f?} = 723.8\ \text{kJ/kg}$$

The exit temperature is about 171°C.

2. For one pressure tube:

$$\dot{Q}_{PT} = \dot{m} \times (h_{f300°C} - h_{f244°C})$$
$$= 24 \times (1309.23 - 1023.64)$$
$$= 6854.16\ \text{kJ/s}$$

The reactor thermal power output is:

412 x 6854.16 = 2820 MW

PI 25-4 - SELF EVALUATION ANSWER SHEET

1. (a) The effect of too high a pressure in the heat transport system is the possibility of rupture, leading to a loss of coolant accident.

   (b) There are two effects of too low a heat transport pressure:

   (i) The D_2O could reach saturation conditions and boil. This boiling, if it leads to vapor film formation around the fuel, could result in fuel failure and release of fission products to the PHT system.

   (ii) The PHT main circulating pumps may cavitate. The cavitation can result in impairment of flow and loss of fuel cooling, and it can result in damage to the circulating pumps.

2. Pressure control is established in this feed and bleed system by means of a balance in flow between the bleed valves and the feed valves, taking into account the reflux cooling flow.

   The bleed valves tend to lower the PHT pressure by admitting D_2O from the PHT system to the bleed condenser. The bleed condenser pressure is maintained lower than PHT pressure by cooling via the reflux cooling line, and the reflux cooling flow is cooled by the bleed cooler.

   The feed valves tend to raise the PHT pressure by admitting high pressure D_2O from the PHT pressurizing pump outlet to the PHT system.

3. This system uses a pressurizer to control PHT pressure. Raising and lowering pressure is accomplished using the same connecting line from the PHT system to the pressurizer.

   Raising pressure is done using electric immersion heaters in the pressurizer. The heaters raise the temperature and pressure of the D_2O in the pressurizer, and then in the PHT system via the connecting line.

   Lowering pressure is accomplished by removing D_2O vapor from the pressurizer to the bleed condenser using the D_2O vapor control valves. The pressure in the pressurizer drops, and the PHT system pressure drops via the connecting line.

4. *Boiler pressure control is important because boiler* pressure is the variable used to control the match between the reactor heat input to the boiler and the heat output from the boiler as steam flow.

5. The three main heat sinks for the boiler in a CANDU station are: the turbine set, the condenser, and the atmosphere.

6. (a) In the case of maintaining constant boiler pressure, power is increased by first increasing steam flow from the boilers. This would tend to lower the boiler pressure. To maintain it constant, the BPC program causes the reactor power to increase so that heat input matches heat output. Since the boiler pressure is constant so is the boiler temperature. Therefore, increasing power, ie, the amount of heat transferred in the boilers, causes the PHT D_2O average temperature to rise.

   (b) In the case of variable boiler pressure, power is *increased by first increasing the reactor power.* This would tend to raise the boiler pressure. However, the BPC program increases the steam flow from the boilers so that heat output matches the increased heat input. This increase in the steam flow causes the boiler pressure to fall. This results in a corresponding decrease in boiler water temperature so that larger ΔT exists between the PHT D_2O and the boiler water. Thus more heat can be transferred in the boiler while maintaining the PHT D_2O average temperature constant.

PI 25-5 - SELF EVALUATION ANSWER SHEET

1. (a) Heat transfer by conduction involves heat transfer from one molecule to the next through a substance, with no net transfer of mass.

   (b) Heat transfer by natural convection is heat transferred due to fluid movement, which occurs because of density differences established as heat is transferred.

   (c) Forced convection is heat transfer by fluid movement, which is due to some external means (eg, pumps, fans, blowers).

   (d) Heat transfer by radiation involves the emission of electromagnetic waves (mainly infrared light) from a high temperature object. The energy emitted transfers heat from the object.

2. The factors affecting each mechanism are as shown:

   (a) Conduction:

   (i) thermal conductivity of the conducting substance
   (ii) surface area of the conducting substance
   (iii) temperature difference across the conducting substance
   (iv) thickness of the conducting substance.

   (b) Natural convection:

   (i) surface area in contact with the fluid
   (ii) temperature difference between the surface and the fluid
   (iii) heat transfer coefficient of the system.

   (c) Forced convection:

   (i) surface area in contact with the fluid
   (ii) temperature difference between the surface and the fluid
   (iii) heat transfer coefficient of the system.

(d) Radiation:

(i) surface area of the emitting object

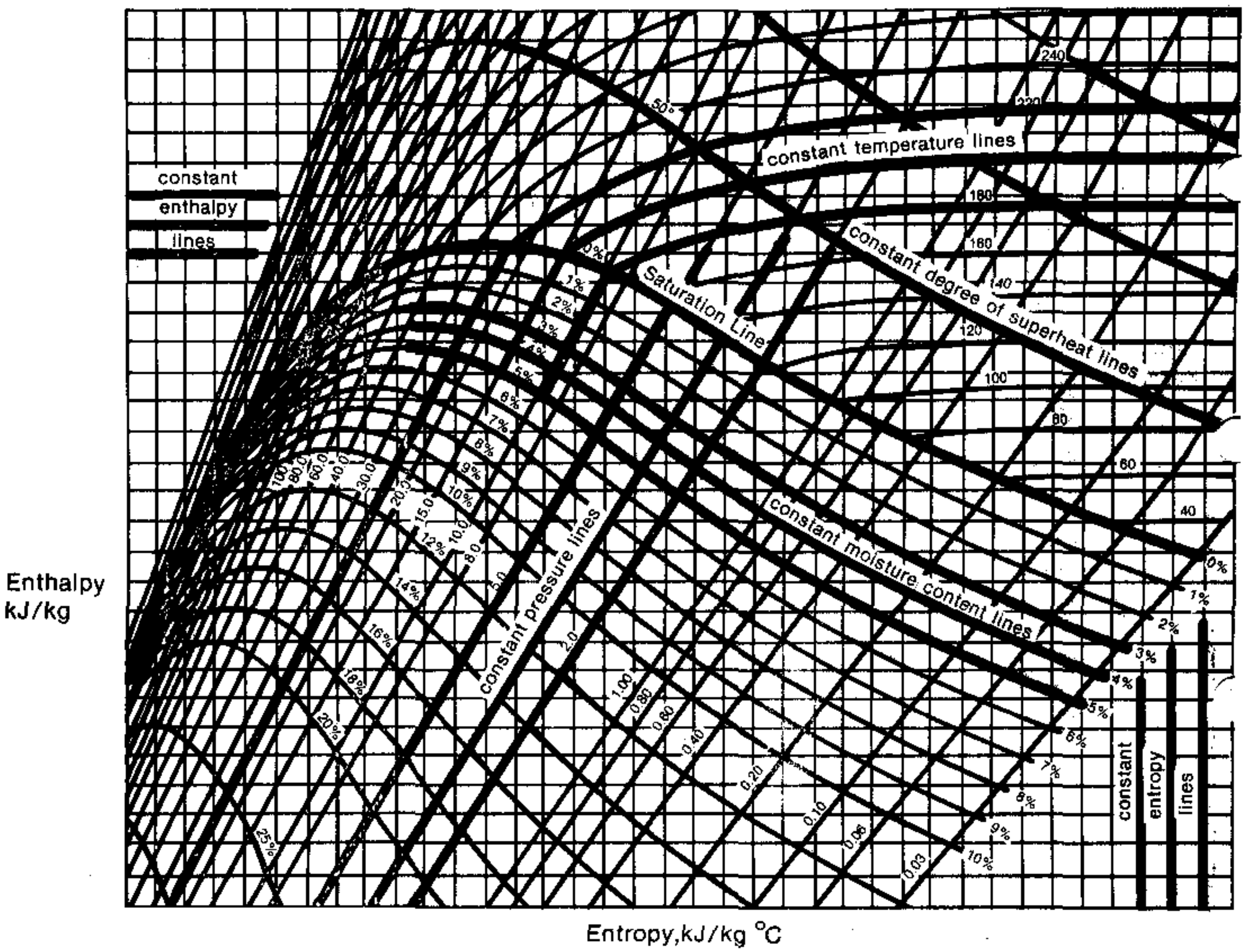
(ii) the difference between the fourth power of the absolute temperature of the object and the fourth power of the absolute temperature of the surroundings

(iii) emissivity of the surface of the object.

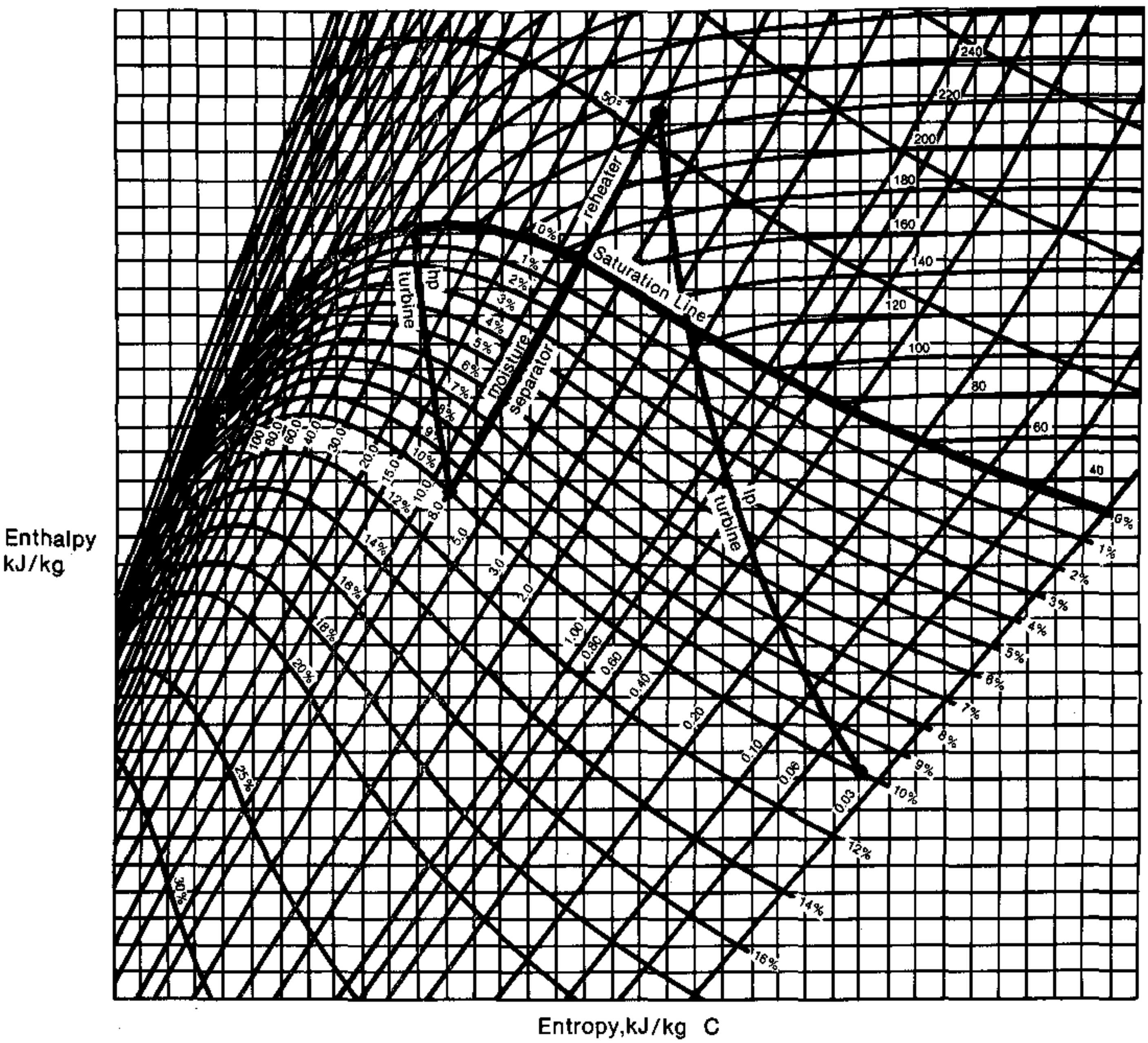
3. Discuss your answers with the course manager before you proceed.

PI 25-6 - SELF EVALUATION ANSWER SHEET

1. Your diagram should be similar to the one shown:



2. Your answer should be similar to the one below:



3. The steam entering the moisture separator is wet. Its enthalpy is in fact a weighted average of saturated liquid and saturated steam enthalpies. The separator removes the liquid portion of the wet steam; thus the enthalpy (ie, heat content per kg of fluid) will increase. The flow of fluid going to the LP turbine has decreased at the same time.

Reheating uses live steam (at 250-260°C) from the main steam line to heat the steam flowing to the LP turbine. Thus, the steam enthalpy is increased.

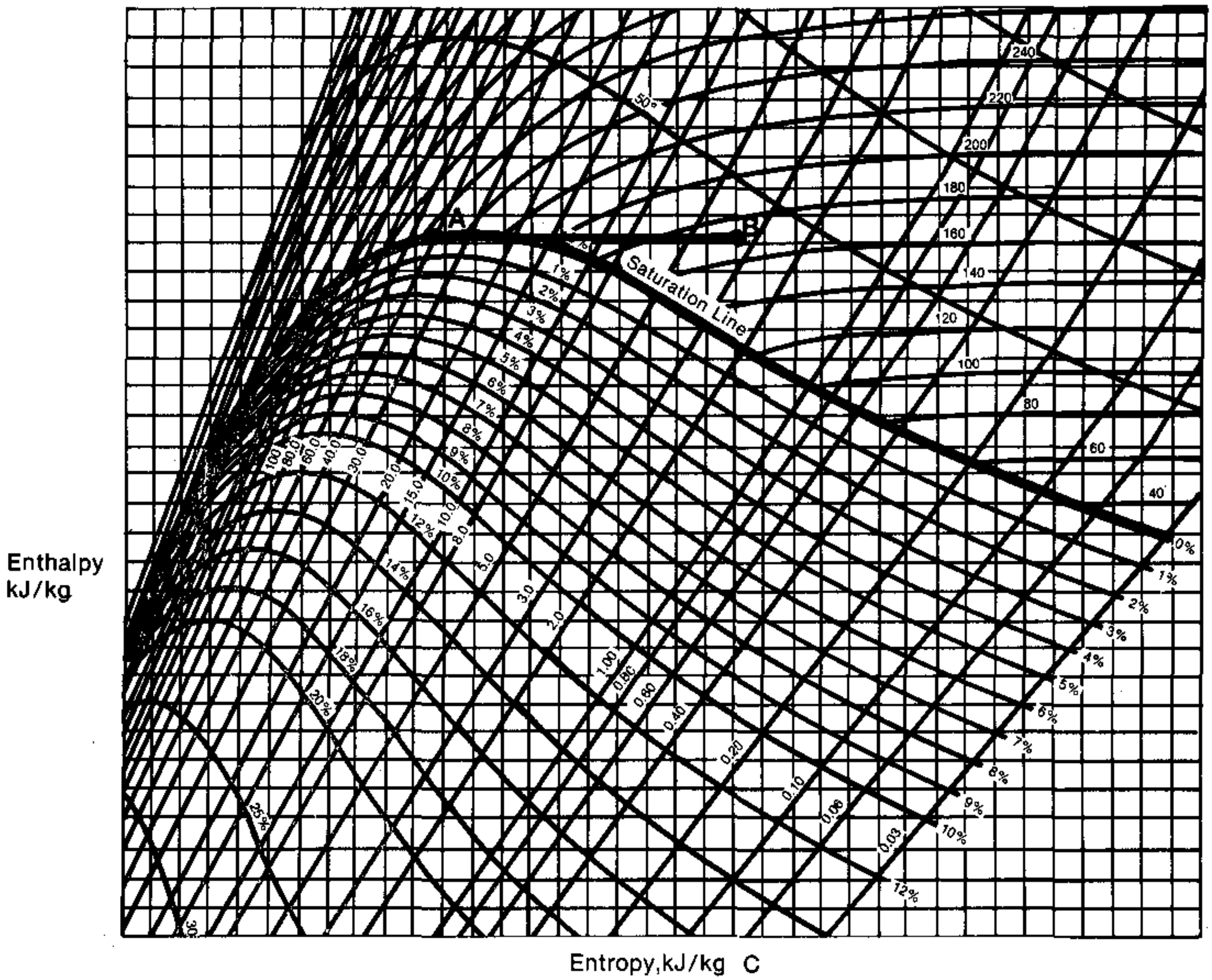
4. Moisture separation reduces the moisture content of the steam exhausted from the HP turbine from about 10% to nearly zero. As the steam at the LP turbine inlet has less moisture, then the moisture content of the steam at the LP turbine outlet can be reduced.

   Reheating allows the LP turbine to be supplied with superheated steam so that production of moisture can be postponed until the latter portion of the LP turbine. Therefore, the moisture content of the steam at the turbine outlet is reduced more than in the case of using moisture separation alone.

5. Throttling is a process which occurs when a compressible fluid (eg, steam) flows through a valve or a pipeline from one pressure to a lower pressure. During this process no mechanical work is done and practically no heat is lost, so that the enthalpy of the fluid remains essentially constant.

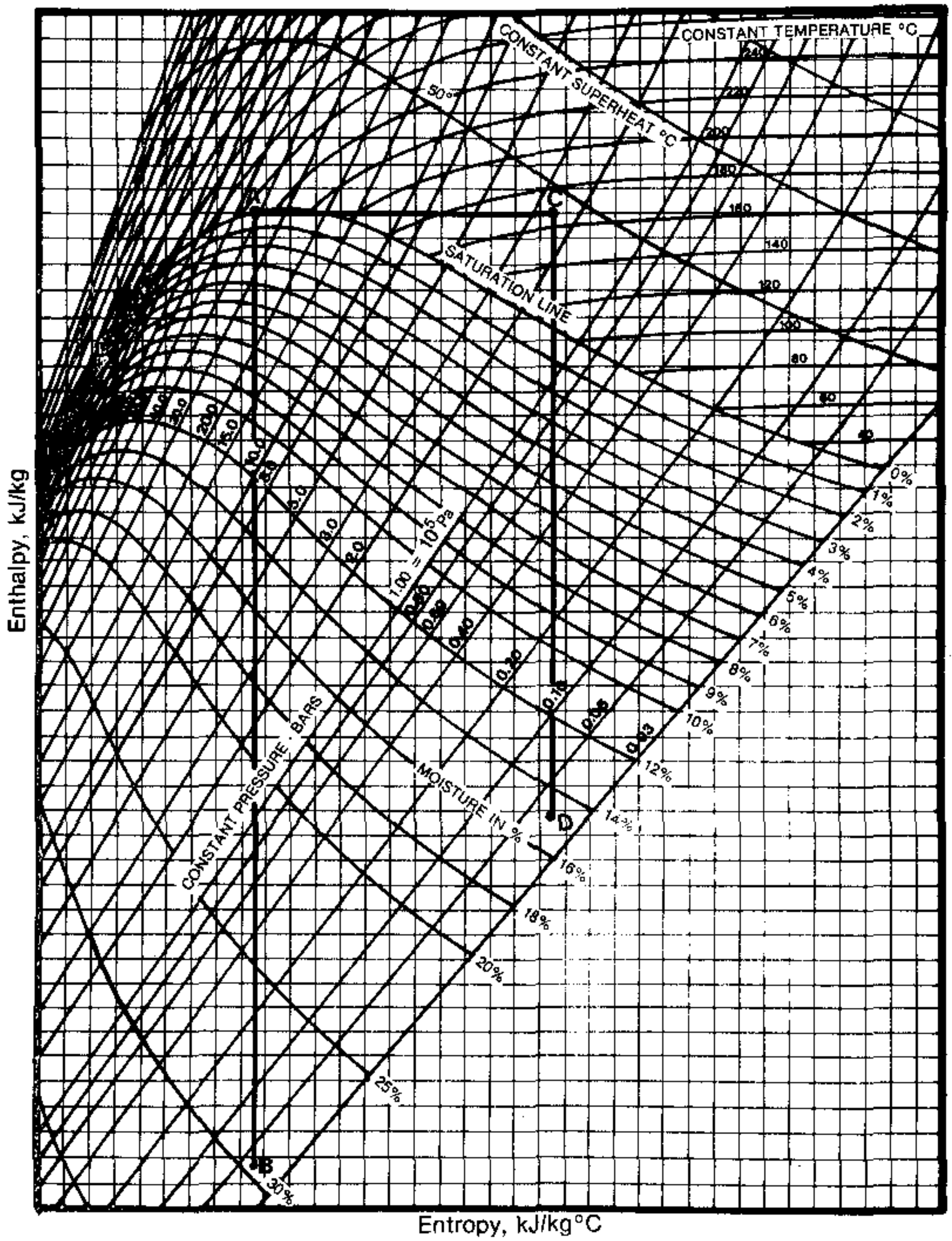
Your answer should be similar to the one below:

(a)



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

(b)



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 ($h_A - h_B > h_C - h_D$).

PI 25-7 - SELF EVALUATION ANSWER SHEET

1. (a) Efficiency - output divided by input, often expressed as a percentage.

   (b) Thermal efficiency - net work output of a system divided by total heat input to the system, often expressed as a percentage.

2. The net work output here is 796 - 6 = 790 MW.

   The heat input is 2450 MW.

   The thermal efficiency is (790 ÷ 2450) x 100 = 32.2%.

3. (a) As boiler pressure (ie, steam pressure) is increased, so is the steam temperature. As this occurs, the ratio of work available to heat input increases, and the thermal efficiency increases.

   (b) The main limitation is a maximum steam temperature (about 260°C) in the boilers, which is imposed by fuel and fuel sheath considerations.

4. (a) As condenser pressure (and temperature) are lowered, the work produced in the turbine increases. The ratio of net work output to total heat input, ie, the thermal efficiency of the cycle, thus increases.

   (b) The limitations on the efficiency improvement in (a) are:

      (i) the temperature of the cooling water is the same as lake temperature.

      (ii) the moisture content in the LP turbine has a limit (about 10-12%).

5. (a) Superheated steam produced in boilers increases the ratio of available work to heat input, and thus also the thermal cycle efficiency.

   (b) The main limitation is the steam temperature (about 250-260°C) imposed by fuel and fuel sheath considerations.

6. (a) (i) Reheating provides superheated steam to the LP turbine, and the work available to heat input ratio per kg of steam flow in the turbine increases.

(ii) Use of extraction steam for feedheating allows recovery of the heat contained in the steam (which would be rejected to the lake if the steam flowed through the turbine) at the expense of some loss of work output. The ratio of work produced to heat input (ie, the thermal efficiency of the cycle) is increased.

(b) (i) Live steam temperature, which in turn has a 250-260°C limit, is the main limitation on reheating.

(ii) The limitation on feedheating is economic. As the number of feedheaters increases, there is a point at which the cost of equipment outweighs the gain in efficiency.

(c) (i) Two practical benefits of reheating are a reduction of moisture content in the LP turbine and a smaller steam flow (and thus smaller equipment) needed to produce a given power.

(ii) Two practical benefits of using extraction steam for feedheating are a reduction of moisture content in the turbine and a reduction in turbine size due to smaller flow through the outlet portion of the turbine.

7. (a) Moisture separation allows less work loss due to moisture droplets in the LP turbine. This allows the turbine to produce more work for the same heat input, and the thermal efficiency increases.

(b) The practical benefit of moisture separation is that a lower condenser pressure can be used without exceeding exhaust steam moisture limits.