125

HEAT & THERMODYNAMICS

MODULE B.3.1

CONDENSER PERFORMANCE

Heat & Thermodynamics

MODULE B.3.1

CONDENSER PERFORMANCE

Course Objectives

1. You will be able to explain four advantages of using a condenser instead of rejecting the exhaust steam to atmosphere from a steam turbine.

2. You will be able to explain the changes which occur to pressure and temperature when steam or CCW flowrate conditions change in the condenser.

3. You will be able to list a sequence of steps designed to eliminate the causes of increased condenser pressure. You will be able to explain the reasoning for each step.

4. You will be able to explain two undesirable consequences for each of the following conditions:

   a) operating the condenser above design pressure
   b) operating the condenser below design pressure.

5. Given condenser conditions relating to steam and cooling water, you will be able to calculate either the CCW flow or the steam flow.

In this module, we will be looking at condenser performance and examining some of the basic concepts of condenser operation. In many respects, the feedheater and condenser have a lot in common. They both remove heat from steam using a liquid coolant.

Why do we need a condenser? It's a simple question that has a more complicated answer. You may say that the condenser is in the design to allow the cycle efficiency to be optimized. That's not altogether true! The fact that we do use a condenser does allow us to maximize the efficiency of the cycle, but that is not the prime reason for using a condenser.

If we did not bother to collect the exhaust from the turbine and return it to the system, the costs of operating a unit would be very high.

We would be throwing away hot demineralized water at the rate of around 1000 kg every second. This is obviously an impractical situation. The size of the water treatment plant and storage would be enormous.

It is an advantage to retain the working fluid within the system. The need for phenomenal quantities of treated water is eliminated and some of the remaining heat in the cooling fluid is recovered.

After the steam turbine, the working fluid is returned to the boiler for heating. The boiler is at a much higher pressure than the turbine exhaust so we must raise the pressure of the working fluid to a higher pressure than the boiler in order that the working fluid can flow into the boiler.

This creates a basic problem. The exhaust steam from the turbine exhaust has a very large volume, even at atmospheric pressure and the easiest way of raising the pressure of the exhaust steam is to use a compressor. The problem with this concept is that the compressor would be extremely large, due to the large steam volume, and would consume vast quantities of power.

If we could reduce the volume of the working fluid and pump liquid instead of vapour, the problems would be much more acceptable.

The condenser allows the volume of the working fluid to be reduced dramatically; a reduction in volume of around 28000 to 1, ie, 1 kg of steam at low condenser pressure occupies around 28000 liters. When condensed, the final volume is 1 liter.

The price that we have to pay for this reduction in working fluid volume is that we must reject around 66% of the total reactor power or sensibly twice the turbo-generator power. This heat which appears in the CCW is the latent heat of vapourization from the turbine exhaust steam which had to be removed for condensation to saturated liquid to occur. We do manage to keep the remaining sensible heat in the resulting condensate in the condenser hotwell.

Before we move on, answer the question below and check your answer with the notes at the end of the module.

B.3.1.1

Explain the function of the condenser and describe three advantages that arise from a plant design using a condenser.

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Cycle Efficiency

Having made a decision to use a condenser, we are now faced with another problem. At what temperature should the condenser operate?

Thermodynamically, we can get the best use from the steam when the temperature difference between the steam in the steam generator and the steam in the condenser is at maximum.

In practice, the type of nuclear fuel that is used dictates that the steam temperature is around 250°C as we will discuss in more detail in Module B.1. When we look at making the exhaust temperature in the process as low as possible, we find that there are constraints on this option as well.

It is a fact that we cannot condense the exhaust steam at a lower temperature than the cooling water. In the summer time, the CCW inlet temperature may be fairly high in relation to winter when the temperature may hover around the freezing mark. These two conditions represent the range of temperature that we would expect to see. In practice, the system is designed around some temperature between the two extremes.

Suppose the mean temperature, ie, the average between the CCW inlet and outlet temperatures, was 15°C. Does this mean that the temperature of the steam in the condenser will be 15°C under operating conditions? The answer is that if condensation is to occur, the latent heat of vapourization has to "flow" from the condenser steam space to CCW system. Therefore, there has to be a temperature difference between the steam and the average CCW temperature.

In practice, the lowest temperature in the condenser is around 33°C and this is the temperature for which the condenser heat transfer will be designed.

The potential cycle efficiency is now fixed based upon a maximum temperature of 250°C steam and an exhaust temperature of 33°C. Obviously, these temperatures will vary from station to station but the principle is still válid.

You can see now why I said that having the condenser to maximize the efficiency wasn't altogether the true picture. We needed the condenser to return the working fluid to the steam generator, and having made that choice, we then were able to optimize the efficiency.

Answer the following question and check your answer with the notes at the end of the module.

B.3.1.2

Explain why steam is not expanded to 10°C in the turbine when the CCW inlet temperature is 0°C.

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Heat Transfer

I am going to look at the condenser in exactly the same way as we examined the feedheater. I will use a single condenser tube to illustrate the ideas so that we can visualize what is happening in practice.

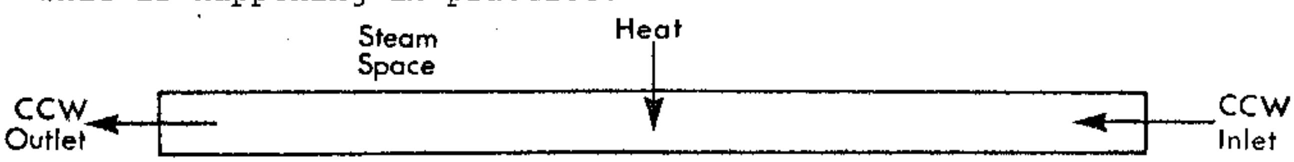

Fig. 3.1.1

Let's just take a look at the diagram. The tube represents one condenser tube through which the CCW is travelling and through the walls of which the heat flows from the steam to the CCW. The amount of heat which is able to flow from the steam space in the condenser to the CCW depends upon the difference which exists between the steam temperature and the average temperature of the CCW. In practice, the heat transfer is more complex than this but a simplistic approach will allow a clearer understanding of the concept.

The average CCW temperature = $\frac{\text{Outlet + Inlet}}{2}$.

Consider the steady state situation in the tube. The temperature in the steam space is T_s and the average temperature of the CCW is T_{wa}. T_s is greater than T_{wa} and heat is flowing from the steam space to the CCW in proportion to (T_s - T_{wa}).

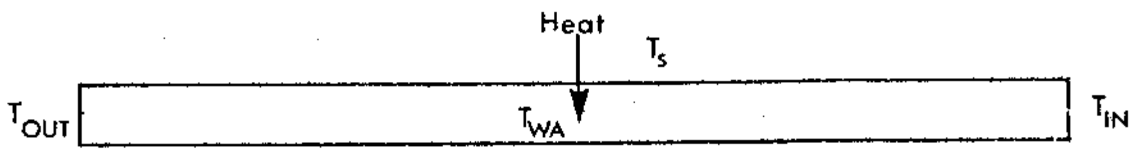

Fig. 3.1.2

The temperature rise across the condenser tube is T_{out} - T_{in}. The pressure which exists in the steam space is the saturation pressure for temperature T_s.

Let's consider several changes in the system and examine the effects on the rest of the system.

CCW Inlet Temperature Increases

Initially, the heat transferred will stay constant. Suppose the CCW inlet temperature rose by 4°C, then the outlet temperature would rise by the same amount because initially, the same amount of heat would be transferred. What happened to the average CCW temperature T_{wa}? If the inlet temperature rose by 4°C and the outlet temperature rose by 4°C, then T_{wa} would rise by 4°C.

What has happened to the temperature difference (T_s - T_{wa})? As the average CCW temperature has risen, so the temperature difference has decreased and less heat is being transferred.

Exhaust steam is still entering the condenser at the same rate but the heat rejection rate to the CCW has decreased. What will be the effect of this energy imbalance? How does it affect the condenser? The temperature in the steam space will rise. What will happen to the condenser pressure? It will rise with the rising temperature to maintain the saturation pressure corresponding to the temperature.

As the condenser pressure rises, the difference in pressure from the GSVs to the condenser decreases which means that the steam flowrate through the turbine decreases until the heat entering the condenser is once again equal to the heat leaving via the CCW system.

The changes may be reflected by recording in table form.

	Steam	CCW
Flowrate	Decrease	Same
Inlet Temp	X	Increase
Outlet Temp	X	Increase
Ave Temp	Increase	Increase
Pressure	Increase	X

Answer this question and compare your response with the notes at the end of the module.

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B.3.1.3

Explain how temperatures, pressure and flowrates are affected in a condenser when the CCW inlet temperature falls. Summarize your answer in table form.

CCW Flowrate Increases

To examine the effect of change, we initially must assume that the rest of the system remains at the same level of operation. If the CCW inlet temperature remains constant and the heat rejected from the condenser remains constant, the effect of increasing the CCW flowrate will be to lower the CCW outlet temperature. This is because with the increased flowrate, each kilogram of CCW will pick up less heat and therefore there will be less temperature rise.

The falling CCW outlet temperature lowers the average CCW temperature which increases the temperature difference between the CCW and the condenser steam space and more heat flows to the CCW. There is now an inequilibrium because heat is being removed at a greater rate than it is being supplied and the temperature in the steam space starts to fall. The condenser pressure falls with the temperature and the steam flow into the condenser increases because of the larger pressure differential across the turbine.

The system finds a new operating point with a lower CCW outlet temperature, lower condenser pressure and temperature, together with an increased steam flow.

	Steam	CCW
Flowrate	Increase	Increase
Inlet Temp	X	Same
Outlet Temp	X	Decrease
Ave Temp	Decrease	Decrease
Pressure	Decrease	X

Answer the following question and compare notes at the end of the module.

B.3.1.4

The steam flow into a condenser is increased from 50% to 100% whilst the CCW inlet temperature and flowrate remain constant. Explain the changes you would expect and list the changes in table form.

* * * * *

A condenser is designed to operate at a particular pressure. This pressure is used to optimize the turbine performance. Deviations from the design value of condenser pressure can create problems as we will see later on. One of the first indications of change in the condenser performance is a change in condenser pressure for which there may be several reasons.

Reduction of CCW Flowrate

This situation may occur because the condenser tubes are blocked or because of the loss of a CCW pump. The result will be an increased CCW outlet temperature which will raise the CCW average temperature and result in a higher temperature and pressure in the steam space. There will be no difference between the condensate temperature and the condenser exhaust temperature.

This may also be due to accumulated gas in the water boxes which may be determined by checking the vacuum priming system.

Fouling of the Heat Transfer Surfaces

Fouling is due to contaminants being deposited on the heat transfer surfaces. Contaminants may be oil, corrosion scale, or other deposits on either the CCW side or the steam side of the condenser tubes.

The effect of fouling means that a larger temperature difference is required to overcome the increased thermal resistance. The CCW outlet temperature does not change significantly, but the temperature and pressure in the steam space will have increased. There will be no difference between the condensate temperature and turbine exhaust temperature.

Change in CCW Inlet Temperature

The change in inlet temperature will be seen by a corresponding change with the CCW outlet temperature and a corresponding change in the CCW average temperature.

If the CCW inlet temperature rises, then the CCW outlet temperature and CCW average temperatures also rise. This results in an increase in pressure and temperature in the steam space. There will be no difference between the condensate temperature and the exhaust temperature.

Air Ingress

If air is drawn into the condenser, it impairs the heat transfer on the steam side because the air collects around the condenser tubes where it was left by the condensing steam. If air leakage does occur, it will reduce the cooling surface area available for condensing the steam.

The pressure in the condenser is equal to the sum of the partial pressures due to all the gases and vapours. In normal circumstances, there is so little air and other gases, the pressure is sensibly only due to the steam.

If air is now introduced, the pressure rises and the condenser pressure is due to the pressure of the steam plus the pressure due to the air. The saturation temperature for the steam only depends upon the partial pressure due to the steam. This provides a means of checking whether the increase in condenser pressure is due to air or some other cause.

If there was no subcooling, as there should not be in the condenser, the temperature of the condensate would be equal to the saturation temperature corresponding to the pressure.

If air has entered the condenser, the pressure will be higher than that indicated by the condensate temperature. If the condensate temperature was 35°C and the condenser pressure was 70 kPa(a), then there is a very strong possibility that air has entered the condenser and is impeding heat transfer. If there was no air present, the condensate temperature would be t_{sat} at 70 kPa(a), t_{sat} = 39°C.

Another indication of air ingress is a decrease in the exhaust temperature into the condenser although the condenser pressure will have risen. The greater the % air in the condenser, the more exaggerated this effect becomes.

A giveaway for air ingress is a marked increase in dissolved oxygen in the condensate.

Flooding of Condenser Tubes

If a problem of level control arises in the hotwell, the heat transfer surfaces may become flooded with condensate. This flooding produces two effects:

a) There is a significant degree of subcooling of the condensate.

b) There is a reduction in the heat transfer surface available for condensing the steam.

This event would result in an increase in temperature and pressure in the steam space. The CCW outlet temperature would be increased and the condensate would be well subcooled.

A table of changes, relative to the "normal" condenser conditions may be a useful guide to determining cause for the increase in condenser pressure. The table assumes that nothing else has changed in the system.

Changing Condition	1 CCW Inlet Temp.	2 CCW Outlet Temp.	2-1	3 Cond. Press.	4 Turbine Exhaust Temp.	5 Cond. Temp.	4-5
CCW Flowrate Decrease	Same	Incr.	Incr.	Incr.	Incr.	Incr.	Zero
Condenser Tube Fouling	Same	Same	Same	Incr.	Incr.	Incr.	Zero
CCW Inlet Temp. Increase	Incr.	Incr.	Decr.	Incr.	Incr.	Incr.	Zero
Air Ingress	Same	Decr.	Decr.	Incr.	Decr.	Decr.	Incr
Tube Flooding	Same	Incr.	Incr.	Incr.	Incr.	Decr.	Incr

B.3.1.5

The pressure in a condenser is normally 5 kPa(a) and has risen to 7 kPa(a). Describe the steps you would follow to quickly eliminate some of the possible causes for the increase in condenser pressure. Explain why you are considering each parameter.

* * * * *

Earlier in the module, I said that deviations from the design condenser pressure could result in problems. Let's examine the effect of operating with a condenser pressure lower than design, ie, a higher vacuum.

Suppose we have steam at 800 kPa(a) with 50°C superheat entering a low pressure turbine which exhausts to a condenser at a pressure of 60 kPa(a). (You will recognize that the exhaust pressure is not realistic but allows the process to be easily illustrated on the Mollier diagram.) For simplici-

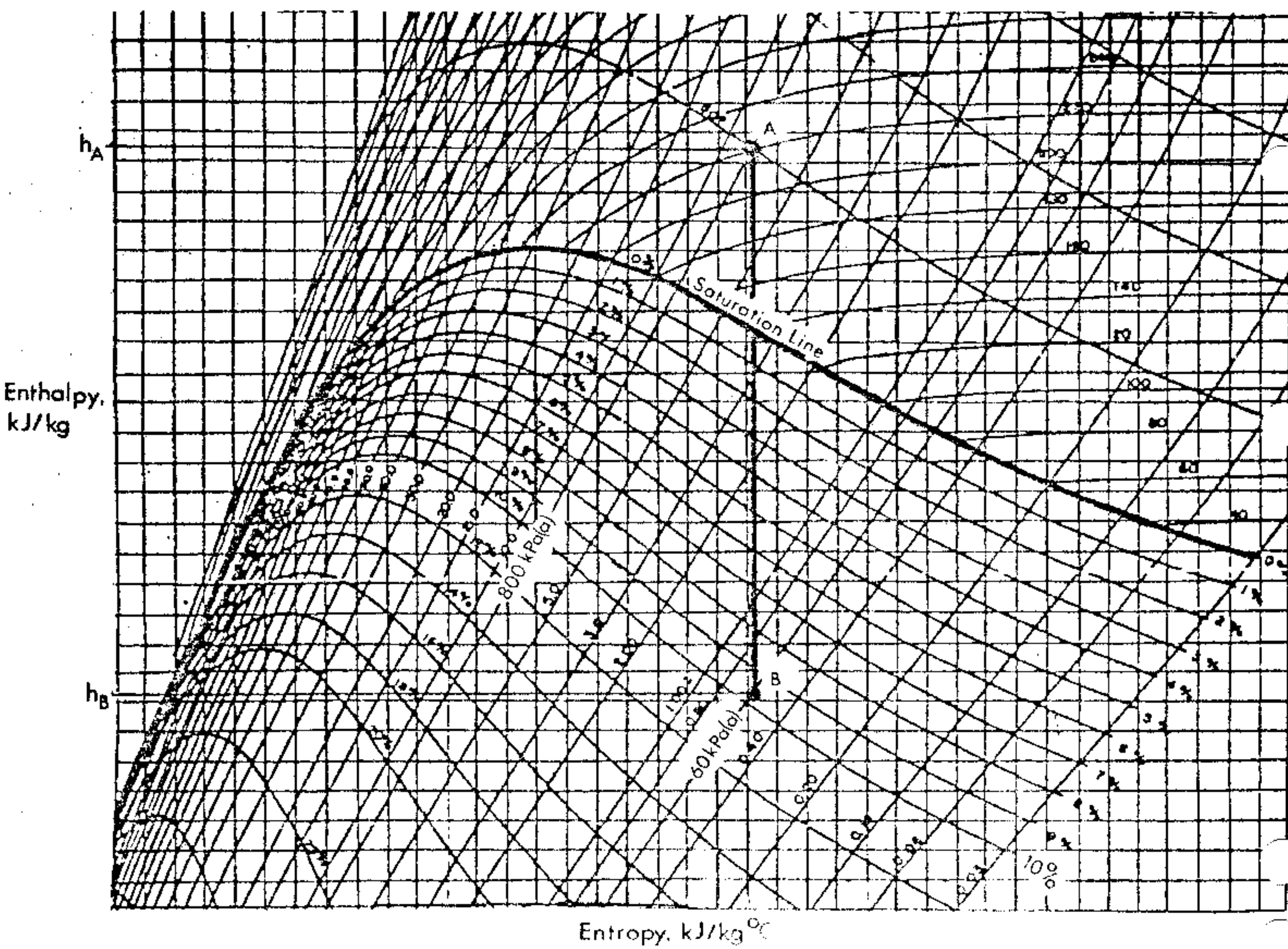

Fig. 3.1.3

ty, we'll assume that the turbine expansion is isentropic which means that the expansion is represented by a vertical line on the diagram.

From the diagram, you can see that the exhaust moisture is around 10%. The ideal work done in the turbine is equal to the enthalpy drop from point A to point B.

Thus the turbine work is:

$H_A - H_B$.

Suppose the CCW conditions are such that we can obtain a vacuum of 40 kPa(a). Let's look at the Mollier diagram and see how this changes the previous operating condition.

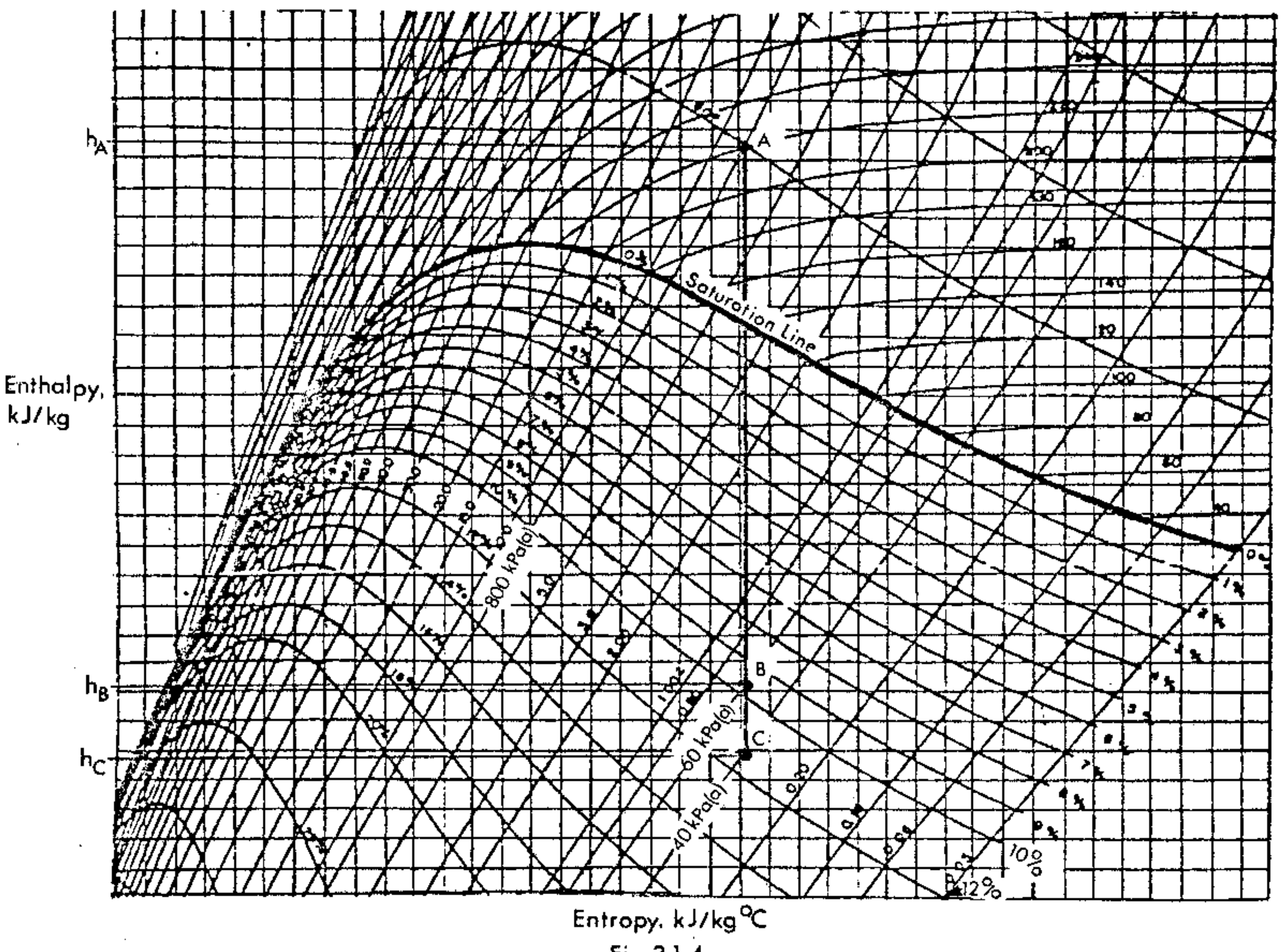

Fig. 3.1.4

There is an obvious difference when looking at the amount of enthalpy that is converted into work in the turbine. This work has increased to $H_A - H_C$ which represents an additional 13% turbine power.

A second effect of the lower condenser pressure is to increase the steam flow through the turbine which also contributes to increasing the turbine power.

Why does this present a problem operationally? You have probably already noticed the new exhaust condition from the low pressure turbine. The moisture level has increased by around 2%. If this increased moisture level is experienced for any length of time, there will be a significant increase in the rate of erosion on the turbine blading which will increase stresses and accelerate failure due to fatigue.

The second aspect of this problem is also related to blade stresses. The turbine output power has been increased due to the increased enthalpy drop through the turbine and to the increase in steam mass flowrate due to the larger pressure difference between the turbine GSVs and the condenser. This increased turbine power level puts more stress on the turbine blading and will significantly reduce blading life.

Everything has its price and the price that is paid for operating the turbine at exhaust pressures below design values is reduced blading life. This reduced blading life is due to increased stresses as a result of accelerated erosion and overpowering of the turbine.

Let's look at the other condition of operating a turbine with a higher pressure than design, ie, a lower vacuum.

From the previous example, it will be no surprise to find that the turbine power has been reduced due to:

a) a lower enthalpy drop available from the steam.
b) a reduced steam flowrate due to the lower pressure difference which exists between the GSVs and the condenser.

The loss of turbine power is obviously undesirable but the story does not end here. Less work is done per kilogram of steam which reduces the cycle efficiency.

A more immediate concern relates again to the turbine blading. The velocity of the low pressure blade tips is approaching 800 m.p.h. As the pressure of the steam in the condenser increases, so the density of the steam increases. The increase in density results in an increase in frictional effects on the turbine blading which results in heating.

Permanent blade distortion due to creep effects is significantly affected by temperature. If the temperature is allowed to rise to a critical value, the low pressure blades will permanently stretch in the radial direction and in so doing, close up the radial tip clearances.

In the event of a high condenser pressure, the vacuum unloader reduces the turbine load to control the heating effect on the long low pressure turbine blades.

If reducing the turbine power via the vacuum unloader does not have the desired effect, the vacuum trip will operate at a condenser pressure of around 25 kPa(a).

It should be restated that there is no long term advantage to be gained in operating a turbine at exhaust conditions other than those for which the machine is designed.

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

B.3.1.6

It appears that the power output of a turbogenerator may be increased to 110% of rated continuous full power. The increase in available power is dueto low CCW inlet temperatures. Describe two turbine related problems which would result from operating at this condition for any significant length of time.

B.3.1.7

If you were faced with the situation in question B.3.1.6, what would be your recommendations for operating the turbine?

B.3.1.8

Explain why a vacuum unloader and vacuum trip facilities are considered necessary protective deviceson a steam turbine exhausting to a condenser.

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Steam Flowrate and CCW Flowrate

The approach to numerical problems relating steam flow and CCW flow is exactly the same as the approach we used for the feedwater. Heat lost by the exhaust steam = Heat gained by CCW. For example, a condenser is supplied with cooling water at an inlet temperature of 4°C. The temperature rise across the condenser is 10°C.

Steam at 36°C enters the condenser at 12% moisture and a flowrate of 680 kg/s.

Assuming that there is no subcooling of the condensate, determine the CCW flowrate.

Heat Lost by Exhaust Steam

A sketch of the temperature enthalpy diagram will quickly confirm how much heat is lost by the steam.

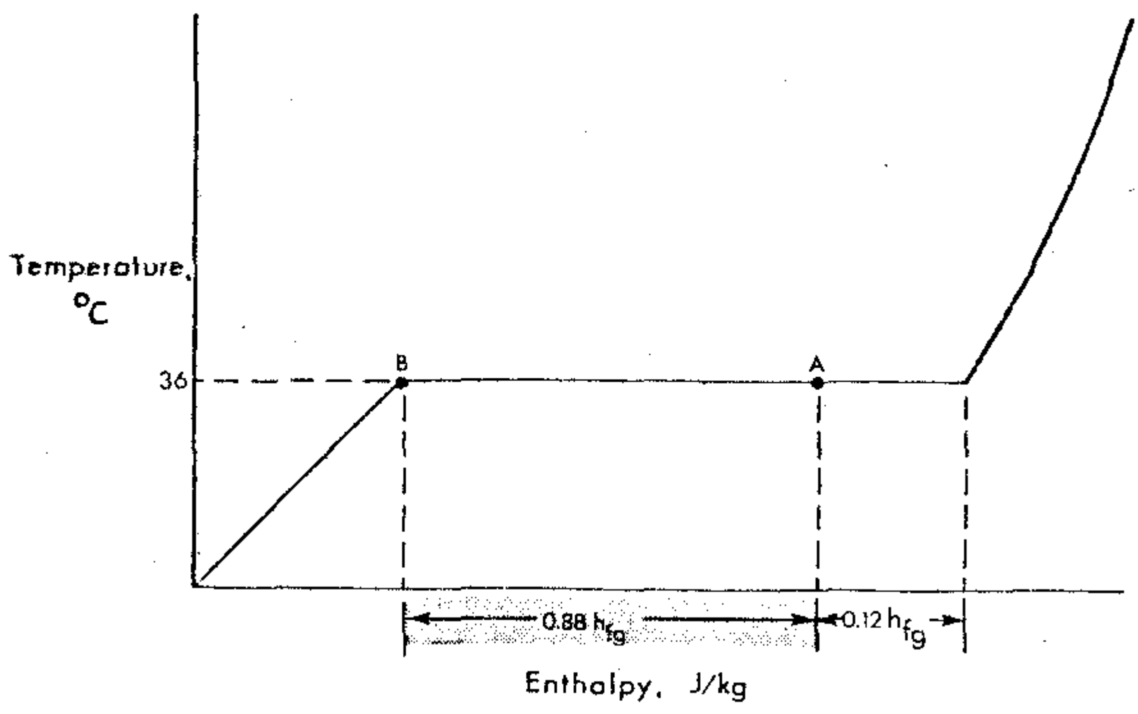

Fig. 3.1.5

At point A, the steam has lost 12% of its latent heat because it is 12% moisture. The condensate is not subcooled and is therefore, saturated liquid at 36°C.

From the diagram, we can see that the heat to be removed from 1 kg of steam is the remaining latent heat, ie, 0.88 $h_{fg_{36}}$.

From Table 1 $\qquad h_{fg}$ at 36°C = 2416.4 kJ/kg

$$0.88 \times 2416.4 = 2126.4 \text{ kJ/kg.}$$

The total heat lost by the steam per second is found by multiplying the heat lost per kg by the mass flowrate 2126.4 x 680 = 1445952 kJ per second.

Under steady state conditions, this is the heat gained by the CCW.

Heat gained per kilogram of CCW is the enthalpy of the liquid at the outlet temperature (4 + 10 = 14°C) less the enthalpy of the liquid at the inlet temperature (4°C).

$$\text{Heat gained} = h_{f_{14}} - h_{f_4}$$

$$= 58.75 - 16.80$$

$$= 41.95 \text{ kJ/kg.}$$

Every kilogram of CCW picks up this amount of heat in the condenser until the total of 1445952 kJ has been removed every second. If 1 kg removes 41.95 kJ of heat, then 1445952/41.95 kg of CCW are required to remove 1445952 kJ of heat = 34468 kg.

Every second 34468 kg of CCW are required to remove the heat lost by the condensing steam.

Try these examples and check your answers at the end of the module.

B.3.1.9

A condenser operates at a pressure of 6 kPa(a) and receives steam at a flowrate of 710 kg/s which is 92% dry. The CCW outlet temperature is 12°C and the temperature rise across the condenser is 10°C. Assuming no subcooling of the condensate, determinethe CCW flowrate required.

B.3.1.10

45 x 10^3 kg/s of CCW flow through a condenser with an inlet temperature of 3°C. The CCW temperature rise is 9°C.

Saturated steam is condensed to saturated liquid at 35°C. Determine the steam flow into the condenser.

* * * * *

This completes the module on condenser performance. When you feel you are ready for the test, ask the course/shift manager. When you have written the test, ask for the self-evaluation sheet and look at the notes. Discuss your answers with the course/shift manager and when you are both satisfied, have the manager sign your progress summary sheet.

Proceed to Module B.4.2 or B.2.

Answers

MODULE B.3.1

CONDENSER PERFORMANCE

B.3.1.1

It is obviously wasteful to reject the working fluid from a system at the end of a process. This is particularly true if the fluid has some economic value, eg, contains some heat and has already been processed as in the water-treatment plant.

Having made the decision to retain the working fluid at the end of the process and return it to the system presents a problem. The exhaust at the end of the process is a mixture of water as vapour and liquid. How do you pump this mixture into the steam generator? You could use a compressor but because of the very large specific volume of exhaust steam, the size of the compressor would be equal to the size of the turbine and probably consume more power than the turbine produces.

So we can use a pump. The only problem is that most pumps are designed to handle liquids and not liquid/vapour mixtures. The only way that we can produce liquid is to condense the steam by removing the remaining latent heat of vapourization. This is the reason for the condenser to change the state of the working fluid from vapour to liquid, thereby reducing the volume significantly and allowing the working fluid to be pressurized using a conventional pump.

Three immediate benefits that arise from using the condenser are:

1. Use of a small pump instead of a compressor as already stated.

2. Some of the turbine exhaust heat is recovered as sensible heat in the condensate.

3. A significantly reduced treated water usage and plant incurs a much lower capital and operating expense.

B.3.1.2

There are two aspects of this question. The first point is that there has to be sufficient temperature difference between the Steam and the CCW to be able to reject the heat from the steam to achieve condensation. In practice, the rough difference is 25°C above the mean CCW temperature. This is only a guide but it serves to illustrate that this temperature difference does not exist in the question as stated.

The second point concerns the seasonal variation of CCW temperature. Suppose the condenser design was fine tuned to achieve the stated performance.

As the temperature of CCW inlet rose in the summer, the CCW flowrate would have to be increased in proportion to compensate. In practice, there would be insufficient CCW capacity and the unit would have to be derated. So we would have gained during the winter but lost that advantage during the summer.

B.3.1.3

We can apply exactly the same rationale as before. Initially, the heat rejected from the steam in the condenser will remain constant. As the CCW inlet temperature falls, so the CCW outlet temperature will also fall. At the same time, the average CCW temperature will fall.

The effect of the lower average CCW temperature will increase the temperature difference between the steam in the condenser and the CCW and more heat will flow to the CCW.

There is now an imbalance. The CCW is removing more heat than is being supplied to the condenser and the average temperature in the condenser falls. As a result of the falling temperature, the pressure in the condenser also drops.

The effect of the lower condenser pressure is to increase the pressure difference between the GSVs and the condenser and more steam flows.

The system settles out with lower CCW temperature, lower condenser temperature and pressure and a larger steam flowrate to the condenser.

	Steam	CCW
Flowrate	Increase	Same
Inlet Temp	X	Decrease
Outlet Temp	X	Decrease
Ave Temp	Decrease	Decrease
Pressure	Decrease	X

B.3.1.4

As soon as the steam flow into the condenser starts to increase, there will be an imbalance in the heat input to the condenser and the heat rejected to the CCW. As a result of the increased steam flow to the condenser, the temperature in the steam space will start to rise because with the existing temperature differences between the steam and the CCW, the CCW is not able to remove the extra heat energy.

As the temperature in the steam space rises, so the temperature difference between the steam and the CCW increases. This increased differential allows more heat to flow to the CCW and is seen by a higher CCW outlet temperature.

This temperature in the condenser continues to rise until the temperature difference between the steam and the CCW rises to a level when all the extra heat energy is being transferred to the CCW. The condenser pressure will, of course, rise with the temperature in the steam space.

	Steam	CCW
Flowrate	Increase	Same
Inlet Temp	X	Same
Outlet Temp	X	Increase
Ave Temp	Increase	Increase
Pressure	Increase	X

B.3.1.5

In this exercise, we are not concerned with the remedial action to be taken. Knowing the possible causes of the loss of back pressure, the procedure is essentially to rule out as many options as we can. A word of caution - in practice, conditions may be greatly different upon closer examination than at first glance. The fact that a possible cause for the high pressure is determined in this exercise, does not mean that you stop before completion. There may be more than one cause. Having identified the probable causes, someone would then have to calculate whether these probable causes would account for the total change in condenser pressure. We don't have to do this part of the exercise.

a) So let's start the exercise. Before we stride into the problem, we have to have a reference from which to work. The safest reference is to check the CCW inlet temperature. If this has increased, then this will account of some or all of the pressure increase due to the increase in average CCW temperature and therefore an increase in the steam space average temperature. If the CCW inlet temperature is the same as before the pressure rise, this option is eliminated.

b) The next possibility is so obvious that we often forget to consider it! Has the turbine power changed? Has there been a reduction in steam extracted from the turbine? An increase of 10% steam flow will raise the CCW outlet temperature by approximately 1°C if the full CCW flowrate is passing through the condenser.

The increased steam flowrate would have produced an imbalance in the energy into the condenser/energy out of the condenser. As a result, the average temperature in the steam space would have increased to transfer a greater quantity of latent heat to the CCW system.

If the steam flow has not increased, this option is eliminated.

c) Has the CCW flowrate through the condenser dropped? This could be due to a CCW pump having tripped or tube blockage occurring.

If all the temperatures apart from the CCW inlet temperature have increased including the condensate temperature, then having followed the process to this point, this is a likely cause. You must watch that the condensate temperature increases as well because this option is very similar in its effect to that of flooding the tubes with the exception of the condensate temperature.

The reduced flowrate would result in a higher CCW outlet temperature and therefore a higher CCW average temperature. This would mean that the steam space temperature would have to rise to maintain the same temperature difference in order to transfer the same quantity of heat to the CCW.

d) The next possibility is that of air ingress. If this has occurred, the air will act as an insulating blanket and reduce the heat transfer in the condenser which will be seen by a lower CCW outlet temperature. This will occur even though the condenser pressure has risen. It is quite likely that the partial pressure of the steam will have fallen as well and this would reduce the temperature of the steam space in the condenser but the condensate temperature would be below that of the condenser exhaust temperature. The real giveaway is a marked jump in the dissolved oxygen level in the feedwater.

e) Tube flooding is a possibility but does not happen very often. The giveaway for tube flooding is a significant drop in the condensate temperature leaving the hotwell. The subcooling has resulted from the condenser tubes being immersed in the condensate.

f) Tube fouling that impedes the heat transfer, as opposed to tube blockage which restricts the CCW flow, is unlikely to happen suddenly. This situation usually deteriorates with time. However, it is conceivable that an oil slick could be drawn in through the CCW system or some similar contamination could occur within the steam side of the condenser.

In this situation, you would not expect to see any significant change on the CCW circuit. The problem is one of higher thermal resistance to the transfer of the same amount of heat from the steam to the CCW. This resistance is overcome with a higher temperature difference between the steam and the CCW which results in the higher condenser pressure.

If you followed this exercise and did not find at least one possibility for the increased condenser pressure, you should consider checking the validity of the readings you are using. There are some things which we have to accept and I have accepted that the increase in condenser pressure indication was real and not a fault on the data system.

B.3.1.6

There are two turbine related problems which will arise from operating a turbine above full rated power due to a lowering of condenser pressure.

The lower condenser pressure allows more work to be extracted from the steam which looks like something for nothing. However, the only way that more heat may be extracted from the steam is to allow more latent heat to be removed and more steam to condense in the turbine. The increased moisture will accelerate erosion of the blading and will result in premature fatigue failure of the turbine blading.

In the second aspect we are concerned with the increased work done by the blades due to the drop in condenser pressure and the extra steam flow which arises as a result of the larger pressure difference between the GSV and the condenser.

The extra work from the turbine increases the mechanical loading on the blades. This extra loading will result in premature blade failure as a result of the higher stresses.

B.3.1.7

Before you can make a recommendation, you must to sure that you know why the turbine unit is now operating in this condition.

The turbine is operating at full rated power and because the CCW conditions have changed, we now have the opportunity of overpowering the turbine which may be desirable in the very short term but is undesirable in principle. How can we restore the condition to 100% power at design vacuum?

If you feel you want to advocate reducing turbine power to 100%, RESIST this temptation!

Let's have a look at this situation from the start. How did the turbine conditions change in the first place? Quite simply - the CCW inlet temperature dropped which lowered the average CCW temperature and allowed more heat to be removed from the condenser than was being supplied by the steam.

If we reduce the turbine load, will the condenser pressure increase or decrease? Reducing the amount of heat entering the condenser will cause an even greater mismatch between heat lost by exhaust steam and heat gained by the CCW. In this situation, the condenser pressure would fall further as the average temperature in the condenser approached the CCW inlet temperature. The moisture in the exhaust steam would also rise.

The solution to the condition is to reverse the effect of the CCW inlet temperature. If each kilogram is capable of removing more heat, then to maintain the previous operating condition the condenser needs a lower CCW flow. How this is achieved in practice depends upon the condenser design. It may be possible to reduce the number of CCW pumps on the unit or it may be possible to reduce the CCW flow from the water boxes with a CCW outlet valve.

Whichever technique is employed, a reduction of CCW flow will restore the turbine power to 100% at design vacuum.

B.3.1.8

If the pressure in the condenser starts to rise, this is an obvious indication of a mismatch between the heat being rejected by the exhaust steam and the heat being gained by the CCW.

In this case, the heat being rejected by the steam exceeds the heat being gained by the CCW. As a result the temperature and pressure rise in the condenser.

The tips of the low pressure blades are travelling around 800 mph and the frictional skin heating effects on the rotating blades become very significant as the temperature and pressure rise.

The centrifugal force is trying to elongate the moving blades. As the temperature of the blades rises, the resistance to elongation becomes less. If the blades did stretch, they would close the radial blade clearances with the turbine casing and the results could be catastrophic.

To prevent this event occurring, we try and restore the equilibrium across the condenser by reducing the amount of steam entering the condenser. This is done in practice using the vacuum unloader which reduces the oil pressure to the GSVs. If the pressure continues to rise in spite of the vacuum unloader action, then the turbine is tripped on condenser high pressure using the vacuum trip at which point the heating of the low pressure turbine blades ceases.

B.3.1.9

The heat lost by the condensing steam is equal to the heat by the CCW.

Heat Lost by the Condensing Steam

A sketch of the temperature/enthalpy diagram is of help in presenting the initial and final steam conditions.

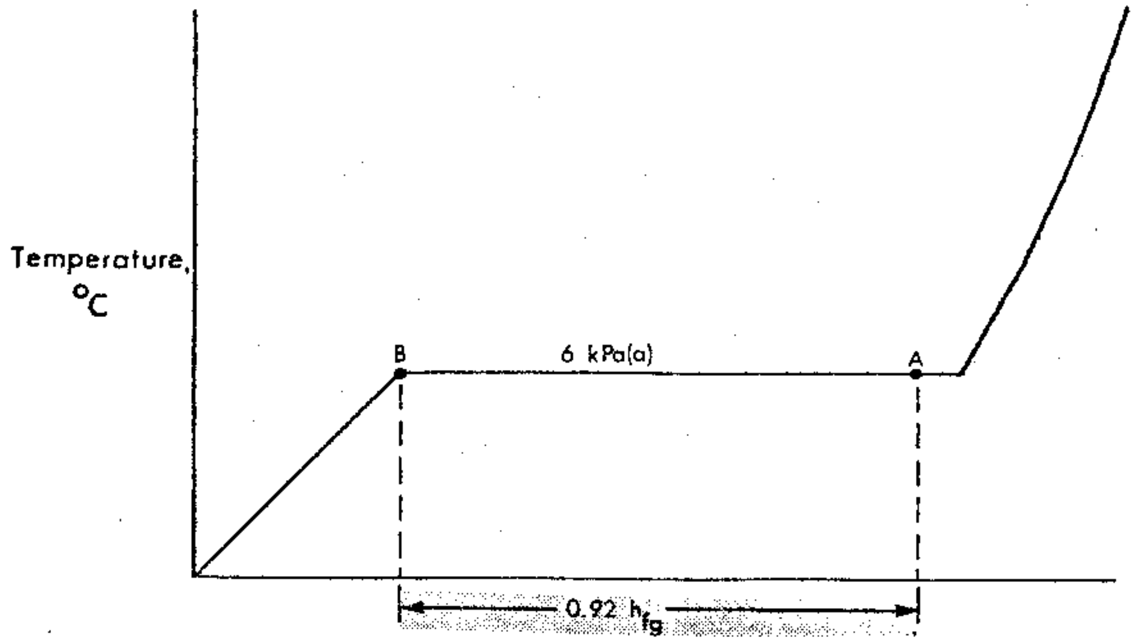

Fig. 3.1.6

The steam entering the condenser at point A, has already lost 8% of its latent heat of vapourization. The condensate at point B is saturated liquid when it leaves the condenser. The heat which has been removed between points A and B is the remaining latent heat of vapourization at 6 kPa(a).

From table 2, h_{fg} at 6 kPa(a) = 2416 kJ/kg

Heat lost per kg of steam = 0.92 x 2416

= 2222.7 kJ.

Total heat lost by steam in the condenser equals the change in enthalpy (2222.7 kJ/kg) multiplied by the mass flowrate (710 kg/s).

Total heat lost per second = 2222.7 x 710

= 1578131 kJ.

This heat is gained by the CCW. The outlet temperature is 12°C and the inlet temperature is 2°C (12°C - 10°C).

Thus heat gained per kilogram of CCW = $h_{f_{12}} - h_{f_2}$

$= 50.38 - 8.39$

$= \underline{42}$ kJ/kg.

Every kg of CCW removes 42 kJ of heat until 1578131 kJ have been removed every second.

CCW flow required to remove 1578131 kJ = $\frac{1578131}{42} = \underline{37584}$ kg/s.

B.3.1.10

This time we know the CCW flow and have to find the steam flow. The approach is exactly the same.

Heat gained by CCW = Heat lost by steam.

Heat Gained by CCW

Outlet temperature = 12°C (3°C + 9°C).

Inlet temperature = 3°C.

Heat gained per kg of CCW = $h_{f_{12}} - h_{f_3}$

$= 50.38 - 12.60$

$= 37.8$ kJ.

Total heat gained by CCW equals enthalpy rise (37.8 kJ) multiplied by the CCW flowrate (45×10^3 kg/s).

Total heat gained by CCW = $37.8 \times 45 \times 10^3$

$= 1.7 \times 10^6$ kJ/s.

This is equal to the heat lost by the condensing steam in the condenser. The heat lost is uncomplicated in this example.

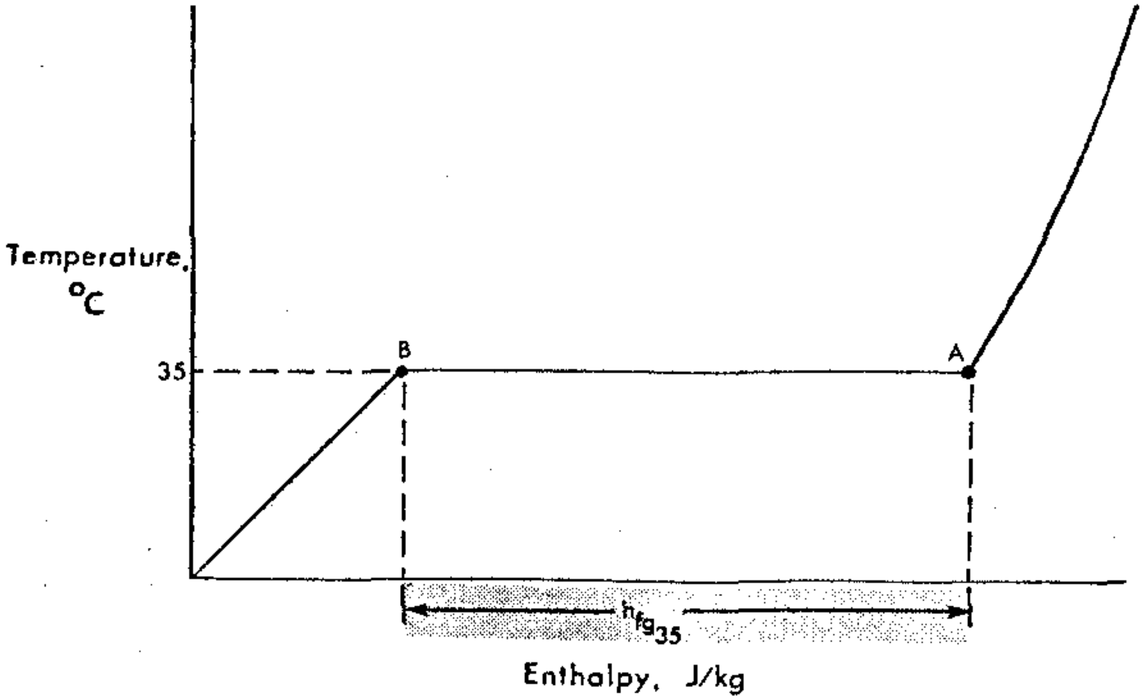

Fig. 3.1.7

The steam enters the condenser as saturated steam at point A and leaves as saturated liquid at point B. The heat which has been removed in the condenser is all the latent heat of vapourization at 35°C.

From table 1 h_{fg} at 35°C = 2418.8 kJ/kg.

This heat is gained by the CCW and steam is continually condensed giving up 2418.8 kJ/kg until 1.7×10^6 kJ of heat are transferred to the CCW every second.

The steam flow required to transfer 1.7×10^6 kJ/s

$$= 1.7 \times 10^6/2418.8 \text{ kg/s}$$

$$= \underline{703} \text{ kg/s.}$$

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