COURSE 225

HEAT & THERMODYNAMICS

MODULE 6

CONDENSER PERFORMANCE

Revised	Verified	Verified
A. Wadham J. Jung E. Abdelkerim	Trng Supt ENTC	Trng Supt WNTC
	Date 88-05-30	Date 88-07-29

0036k3

Heat & Thermodynamics

MODULE 6

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.

CONDENSER PERFORMANCE

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, more, in fact, than the turbine could produce.

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 turbogenerator 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.

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

* * * * *

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 8. 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 the 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 about 28°-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 valid.

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.

Q6.2 Explain why steam is not expanded to 10°C in the turbine when the CCW inlet temperature is 0°C.

* * * * *

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.

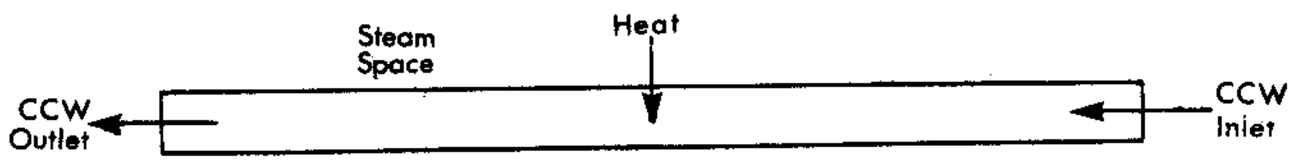


Fig. 6.1

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 $(T_s - T_{wa})$.

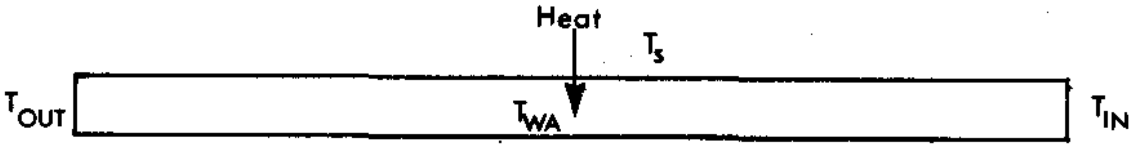


Fig. 6.2

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.

<u>CCW Inlet Temperature Increases</u>

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 and the available enthalpy decreases. However, the steam flowrate essentially remains constant because the increase in condenser pressure will be of the order of a few kPa compared to a pressure difference of the order of 4 MPa between GSVs and the condenser. This is assuming condenser pressure has not reached a level at which the vacuum unloader operates.

The changes may be reflected by recording in table form.

	Steam	CCW
Flowrate	Same	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.

Q6.3 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. The system finds a new operating point with a lower CCW *outlet temperature, lower condenser pressure and temperature*, and essentially the same steam flow.

	Steam	CCW
Flowrate	Same	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.

Q6.4 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, a pressure chosen to optimize turbine performance and feedwater cycle efficiency. Deviations from the design value of condenser pressure can create problems, as we will see later on. Such deviations can be caused by any of 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. Another possibility is reduction of CCW flow due to accumulated gas in the water boxes (which can be confirmed by checking the vacuum priming system).

The result of reduced CCW flow will be an increase in CCW outlet temperature, and hence an increase in CCW average temperature. This will, in turn, cause steam temperature and pressure to go up in order to maintain a constant ΔT between the steam and cooling water sides. Turbine exhaust temperature will increase, as will condensate temperature. These effects are summarized in the Table 1 on page 9.

Fouling of the Heat Transfer Surfaces

Fouling is caused by contaminants being deposited on the heat transfer surfaces. Contaminants can be algae, corrosion scale, oil or other deposits on either the CCW side or the steam side of the condenser tubes.

Fouling reduces the heat transfer coefficient for the condenser tubes, and therefore forces up the steam space temperature (and pressure) in order to maintain the same heat transfer rate across the tubes. As in the case of a CCW flow reduction, turbine exhaust temperature and condensate temperature will both increase. There will, however, be no discernible change on the cooling water side (Table 1 - page 9).

Change in CCW Inlet Temperature

Cooling water inlet temperature will vary with the season and the weather conditions. An increase in CCW inlet temperature will result in a corresponding increase in CCW outlet temperature, and hence an increase in average temperature on the cooling water side. Steam side temperature and pressure will increase to compensate. Turbine exhaust and condensate temperatures will both increase.

Air Ingress

Since the condenser operates at a pressure below atmospheric, leaks will allow air to enter rather than allowing steam to escape. If air is drawn into the condenser it will impair heat transfer from the steam side by "blanketing" the condenser tubes and reducing the transfer coefficient. Steam space temperature and pressure will rise in order to maintain the heat transfer rate, while conditions on the cooling waterside should show no significant change. Turbine exhaust temperature will increase, as will condensate temperature - but there will be a ΔT between these two values, with condensate temperature lower than it should be.

This rather unexpected effect arises as follows. In normal operation, very little air enters the condenser. One air extraction pump has no difficulty extracting it, and its effect is very small. As the leak rate increases, however, the air - in addition to impeding heat transfer across the tubes - begins to collect in the region of the condenser where steam pressure is lowest (ie, near the suction of the air extraction pumps).

Now, according to Dalton's Law of partial pressures, the temperature of the steam at any point in the condenser is dependent only on the partial pressure of the steam, not on the total pressure of the steam and air. At the turbine exhaust, the quantity of steam is much greater than the quantity of air, so the steam temperature at that point will be very close to the saturation temperature corresponding to total condenser pressure. If the latter were 7.0 kPa(a), for example, steam temperature would be 39°C.

At the extraction pump suction, however, the ratio of steam to air is much lower, the actual value depending on how bad the air inleakage is. If the ratio were 50:50, and the pressure was 6.0 kPa(a) at that point, the partial pressure of the steam would be only 3.0 kPa(a); any condensate forming there would have a saturation temperature of only 24°C. Naturally, only a relatively small quantity of condensate of such low temperature will be produced, because there isn't much steam in that region. There will be enough, however, to keep the overall condensate temperature from rising as high as the overall pressure would lead us to expect. In other words, the condensate will appear to be subcooled.

Apparent condensate subcooling is not the only characteristic feature of air inleakage. The level of dissolved oxygen in the condensate will increase as more air leaks into the condenser, and of course the load on the air extraction pump will increase, too. In fact, if the standby pump cuts in during normal operation, this can almost always be taken as a sign of worsening air inleakage.

Flooding of Condenser Tubes

If a problem of level control arises in the condenser hotwell, the lower heat transfer surfaces may become covered by condensate. This flooding will reduce the heat transfer surface available for condensing the steam. This will result in an increase in steam space temperature and pressure.

Since some tubes are flooded the cooling water causes subcooling of the condensate. The sensible heat removed from the condensate is small in comparison with the latent heat of vapourization and no noticeable increase in CCW outlet temperature will be experienced.

For example, to condense steam at 5 kPa(a) with a moisture content of 10% requires heat removal of 2 180 kJ/kg. To subcool the condensate by 5°C approximately 21 kJ/kg of extra heat must be removed, ie, 1% more. (Subcooling by much more than this is not possible as it is limited by CCW inlet temperature.) If the CCW temperature differential was 10°C at full power, then 1% more heat removal would change the temperature differential by 0.1°C which is not easily detectable.

Table 1 shows changes (relative to "normal" condenser conditions) which can be used as a guide in determining the cause for any increase in condenser pressure. The table assumes that the regulating system will attempt to keep turbine-generator output constant and the GSV opening remains unchanged.

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

Table 1

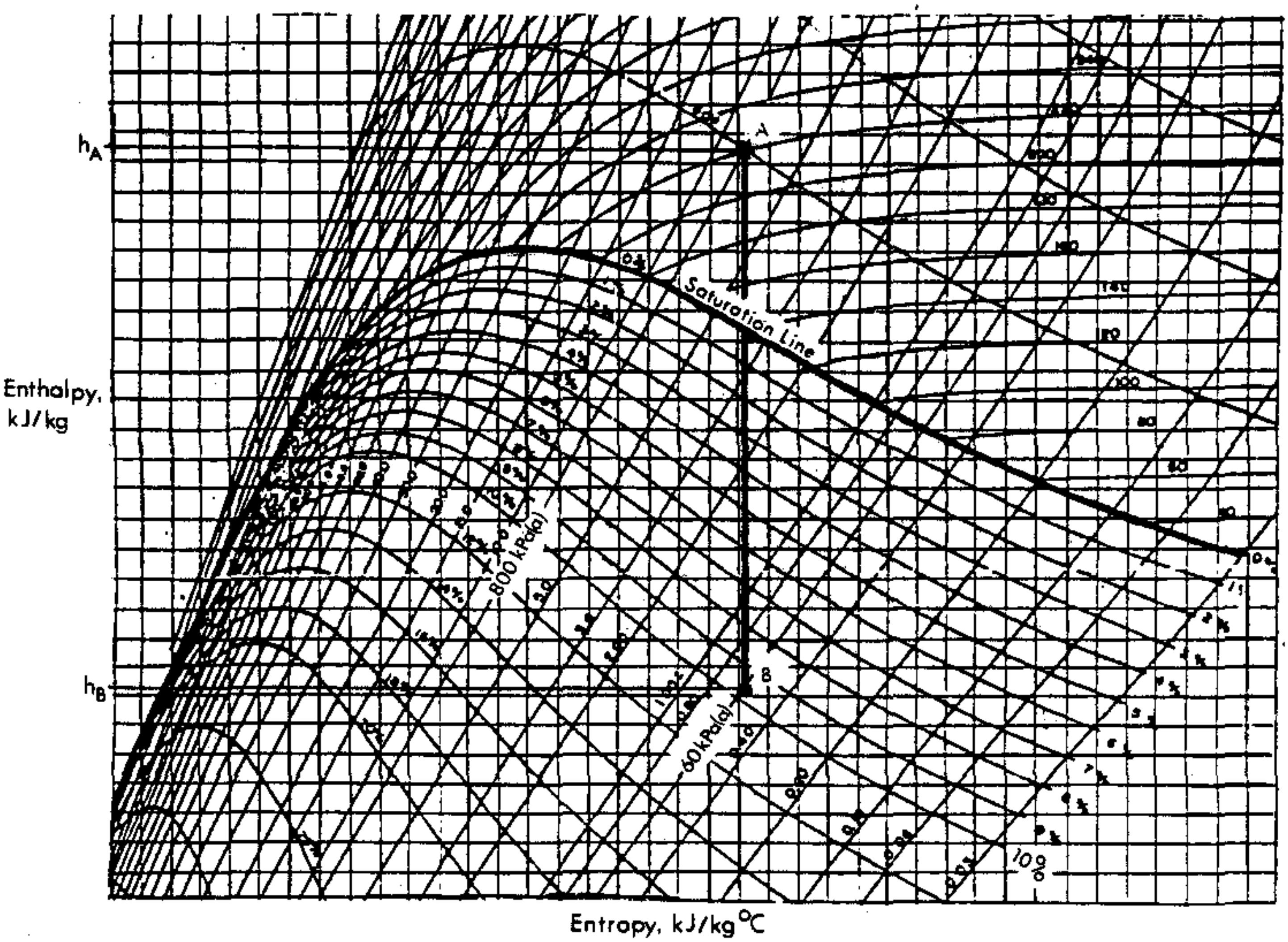
*May not be measurable.

Q6.5 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 simplicity, we'll assume that the turbine expansion is isentropic which means that the expansion is represented by a vertical line on the diagram.



h_A
h_B
Enthalpy, kJ/kg
Entropy, kJ/kg°C
Saturation Line
800 kPa(a)
60 kPa(a)
A
B

Fig. 6.3

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.

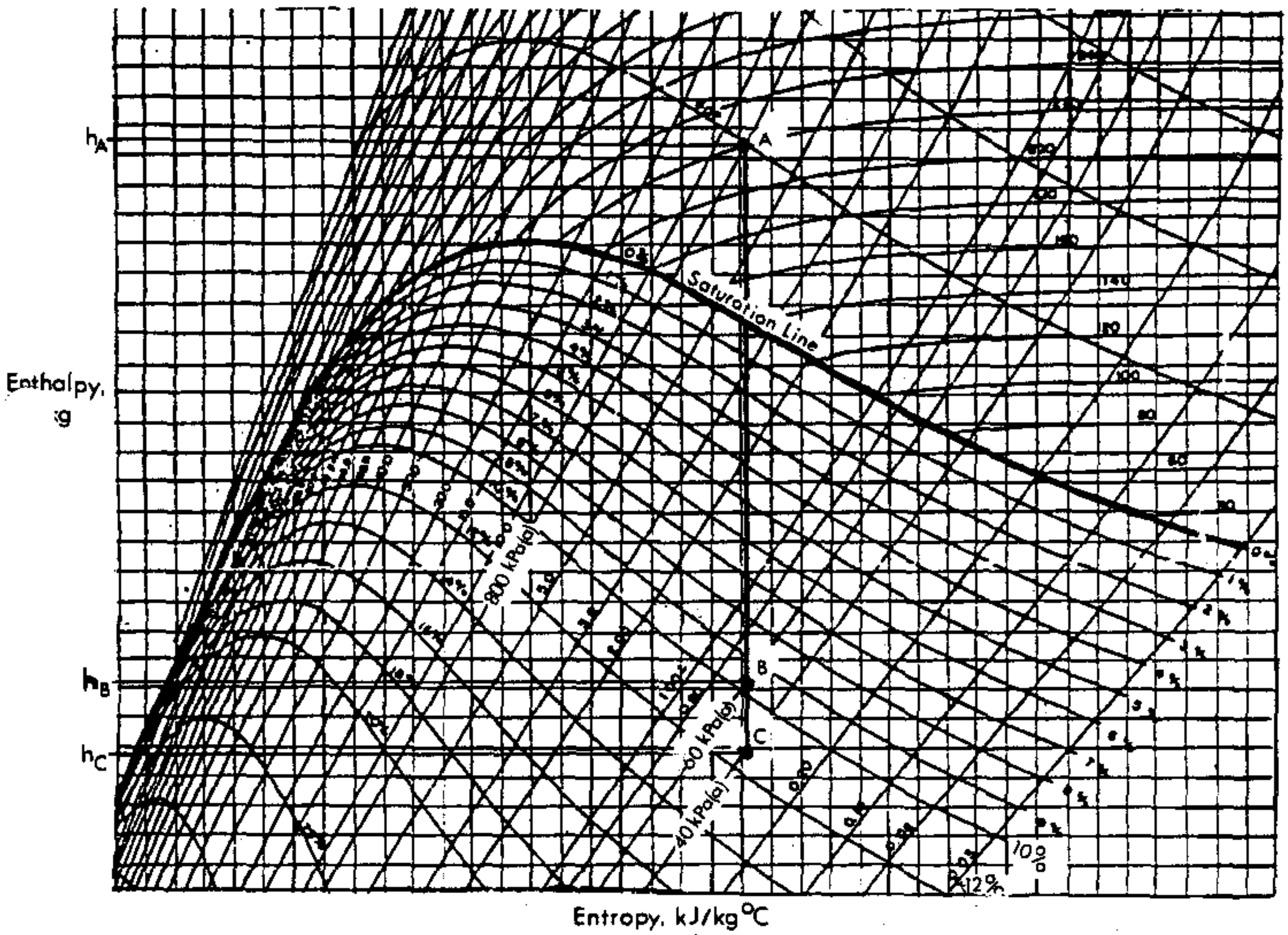


Fig. 6.4

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.

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 increased flow induced vibration.

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. 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 component life. This reduced life is due to increased stresses as a result of accelerated erosion and overpowering of the last stage of the turbine. Condenser tubes would experience considerable erosion and flow induced vibration.

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 lower enthalpy drop available from the steam. A reduced steam flowrate due to the lower pressure difference which exists between the GSVs and the condenser will only become noticeable if condenser pressure goes very high and the unloader fails to operate.

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.

Thermal expansion of the blading can close up the radial tip clearances which would cause rubbing and consequent damage. Heating of blades is a problem at low power where the cooling effects from steam flow are much reduced.

The vacuum unloader reduces the turbine load in the event of a high condenser pressure.

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 if full steam flow is maintained 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.

Q6.6 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 due to low CCW inlet temperatures. Describe two turbine related problems which would result from operating at this condition for any significant length of time.

Q6.7 If you were faced with the situation in question Q6.6, what would be your recommendations for operating the turbine?

Q6.8 Explain why a vacuum unloader and vacuum trip facilities are considered necessary protective devices on a steam turbine exhausting to a condenser.

* * * * *

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.

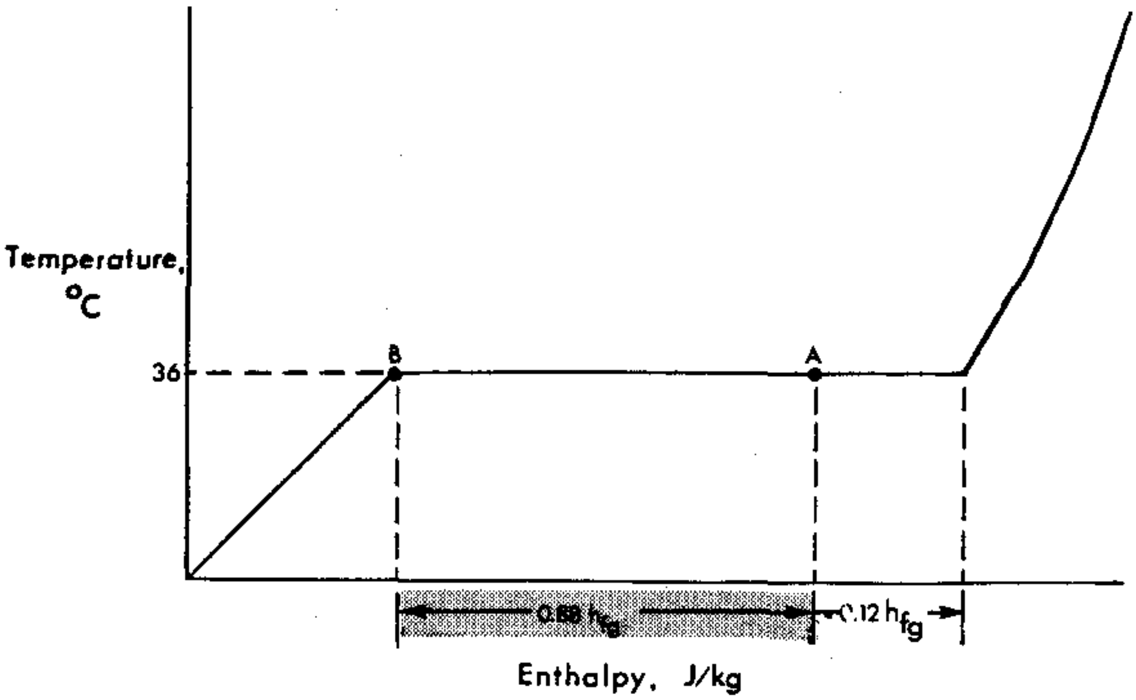


Fig. 6.5

At point A, the steam has lost 12% of its latent heat because it is 12% moisture. The condensate is <u>not</u> 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_{fg36}

<u>From Table 1</u> 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,

ie 2126.4 x 680 = <u>1445952</u> 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).

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

= 58.75 - 16.80

= 41.95 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 = 34468 kg of CCW are required to remove 1445952 kJ of heat.

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.

Q6.9 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, determine the CCW flowrate required.

Q6.10 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.

* * * * *

MODULE 6 - ANSWERS

Q6.1

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 comparable to the size of the turbine and will 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. Creating a high vacuum at the turbine exhaust thereby improving cycle efficiency.
3. A significantly reduced treated water usage and plant incurs a much lower capital and operating expense.

Q6.2

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 10°-15°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.

Q6.3

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 hence the enthalpy drop across the turbine.

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

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

Q6.4

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.

The 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

Q6.5

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 for 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 as well as the condensate temperature increasing, 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 coefficient. Condenser temperature and pressure will rise to compensate, and condensate temperature will also go up - though not as much as expected. The effect of the partial pressure of air in the condenser will make it appear as if the condensate is subcooled in comparison to the higher turbine exhaust temperature. An additional giveaway to air ingress will be a marked increase in the dissolved oxygen concentration 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.

Q6.6

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 condenser tubes and flow induced vibration will result in premature fatigue failure of the components.

Q6.7

Before you can make a recommendation, you must ensure 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 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.

Q6.8

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 400-500 m/s and the frictional skin heating effects on the rotating blades become very significant as the temperature and pressure rise.

Thermal expansion elongates the moving blades. As the temperature of the blades rises, and the blades stretch, they may close the radial blade clearances with the turbine casing and the results could be catastrophic.

Unloading is carried out to reduce the heat transfer load on the condenser and prevent a further increase in pressure. Overheating becomes more troublesome when steam flow is reduced.

Q6.9

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

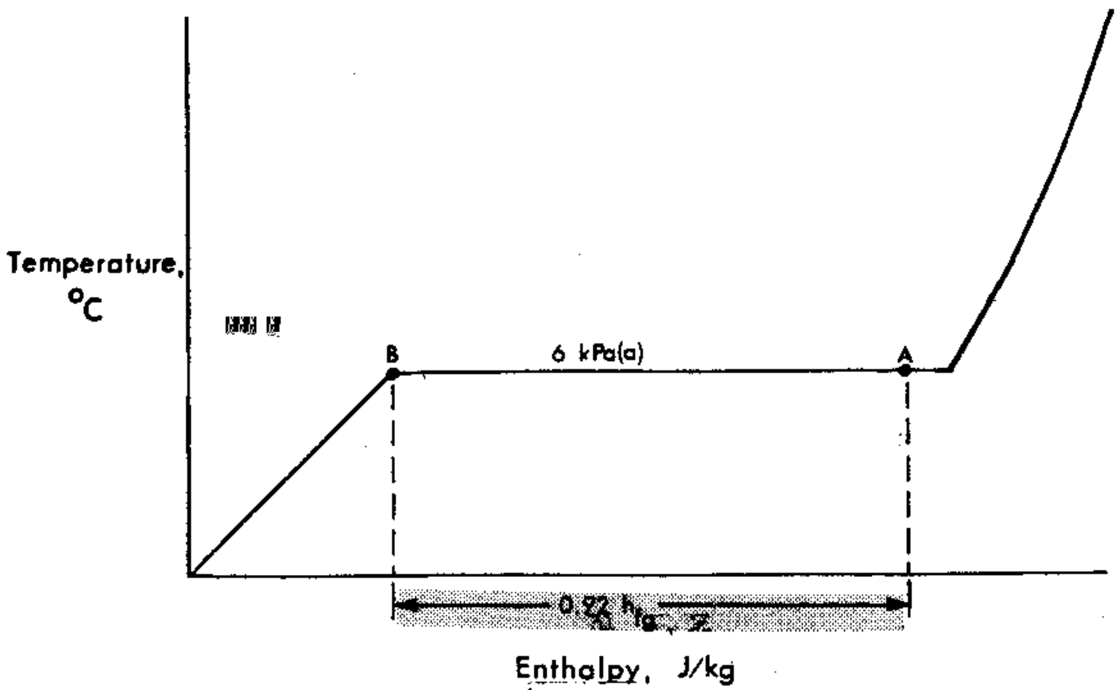


Fig. 6.6

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

= 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 = $\frac{1578131}{42}$ = 37584 kg/s.

Q6.10

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 x 10^3 kg/s).

Total heat gained by CCW = 37.8 x 45 x 10^3

= 1.7 x 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.

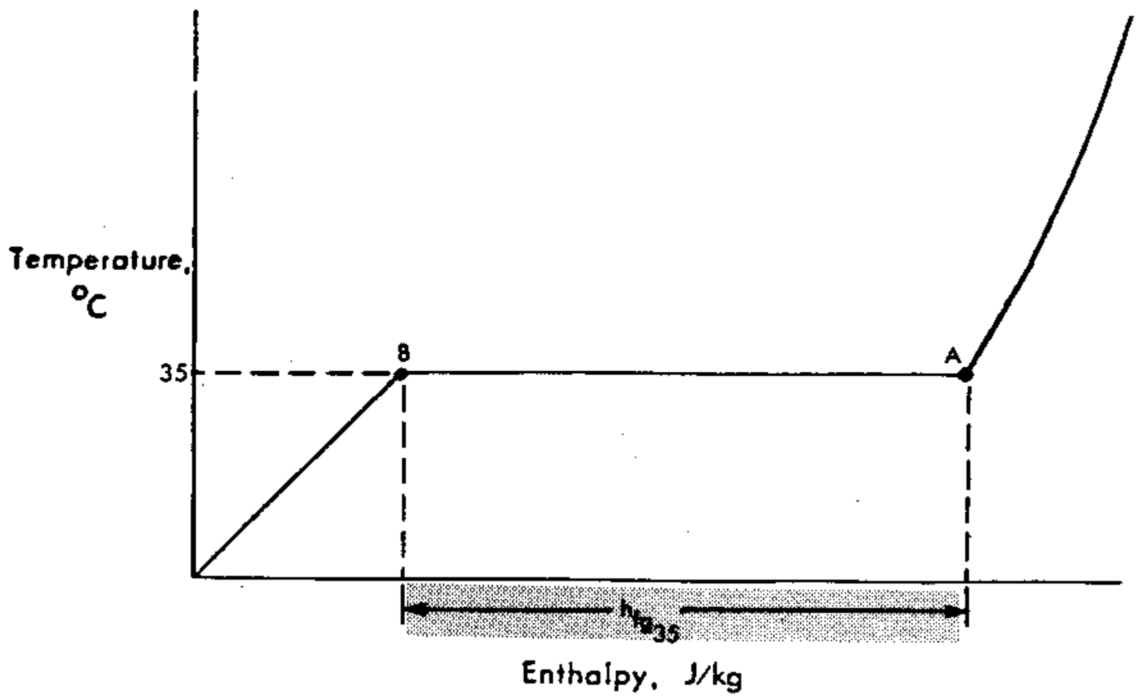


Fig. 6.7

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 x 10^6 kJ of heat are transferred to the CCW every second.

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

= 1.7 x 10^6/2418.8 kg/s

= 703 kg/s.