Turbine and Auxiliaries - Course PI 34

EFFICIENCY OF THE CANDU TURBINE CYCLE

Objectives

1. (a) Explain how the thermal efficiency of the CANDU turbine cycle can be improved by raising boiler pressure.

   (b) State the main limitation on the improvement in (a).

2. (a) Explain how the thermal efficiency of the CANDU turbine cycle can be improved by lowering condenser pressure.

   (b) State two limitations on the improvement in (a).

3. (a) Explain how the thermal efficiency of the CANDU turbine cycle can be improved by superheating in the boiler. .

   (b) State the main limitation on the improvement in (a).

4. (a) Explain how the thermal efficiency of the CANDU turbine 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).

5. (a) Explain how the thermal efficiency of the CANDU turbine 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: ____________________

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(b) Thermal efficiency: ____________________

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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.

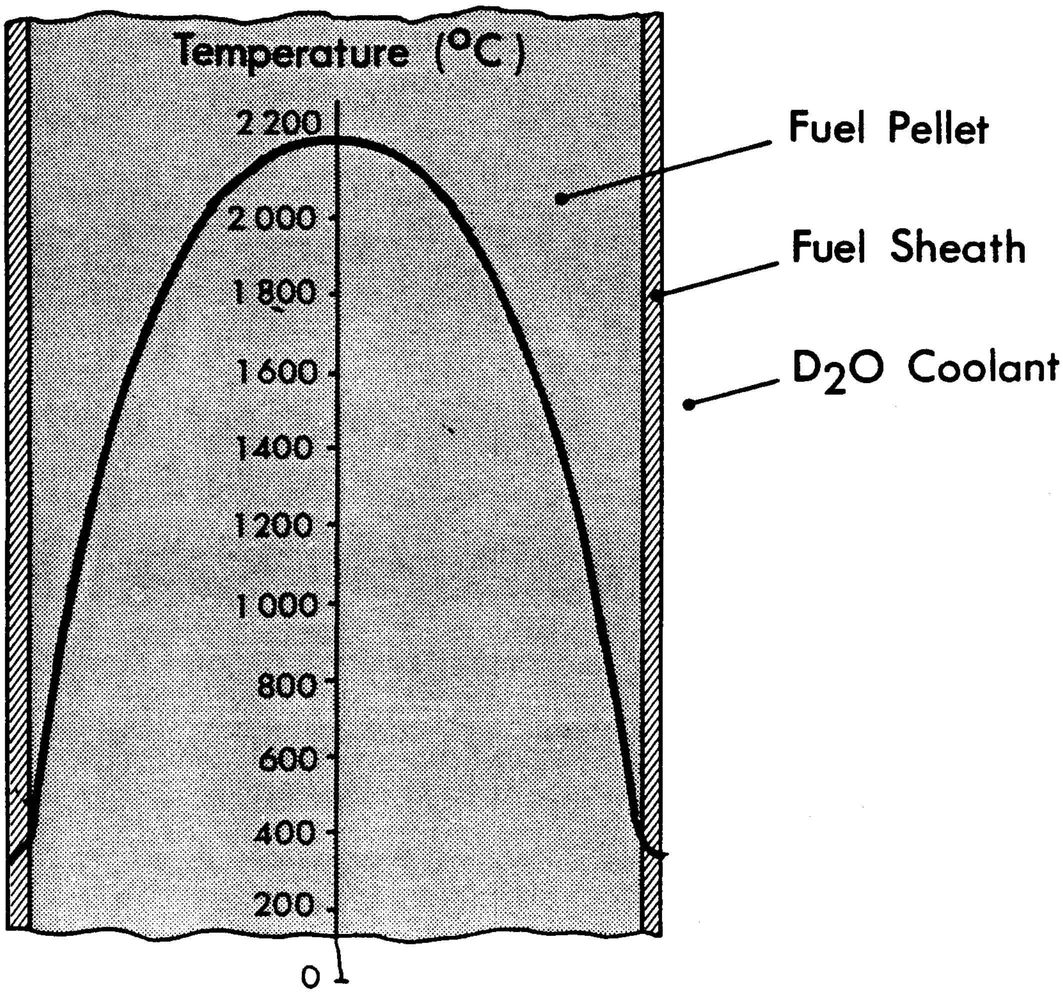

Figure 7.1

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%).