

HEAT AND THERMODYNAMICS

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OBJECTIVES

This module covers the following areas pertaining to thermodynamics:

- Introduction
- Heat and Thermodynamics – The Basics
- Reactor and Heat Transport System Normal Operation
- Heat Transport System Component Operation

Introduction

- Define terms, and give units of measurement: temperature, specific heat, enthalpy, specific enthalpy, entropy and specific entropy.
- Describe heat transfer processes
- State the factors which affect the rate of heat transfer
- Describe the manner in which the heat transfer rate is affected: radiation, conduction, and convection.

Reactor and Heat Transport System Normal Operation:

- Explain the relationship between reactor power and the inlet to outlet header differential temperature and steam quality
- Describe heat transfer processes from fuel to coolant
- Compare their effectiveness: single-phase convection, sub-cooled nucleate boiling, saturated/bulk boiling, transition/partial film boiling, full film boiling
- Define the term dryout as it pertains to a fuel bundle in a reactor
- Describe dryout in a fuel channel experiencing two phase flow
- Define critical heat flux (CHF) and critical channel power (CCP)
- Explain the reason limits are applied to bundle, channel and reactor power
- Explain why channel boiling results in a reduction in coolant mass flow rate
- Explain the shape of the temperature profile curve across a fuel element, sheath and coolant
- Describe how the shape of the temperature profile curve changes for increase in reactor power and the onset of coolant boiling up to dryout
- Explain the expected changes in the temperature-enthalpy graphs for system changes: reduction in coolant flow rate, reduction in system pressure, increase in bulk reactor power, changes in axial flux distribution and increase in coolant inlet temperature

Heat Transport System Component Operation:

- Describe the operating principles of the bleed condenser, including the need for both reflux and spray cooling
- Describe the operating principles of the pressurizer
- Explain how the pressurizer stabilizes pressure transients
- Explain boiler steady state and transient shrink and swell
- Explain how control of boiler pressure is used to control the balance of energy flow from the primary to the secondary systems
- Explain the relationship between boiler pressure and reactor coolant temperature
- Explain how HT system warm-up and cool-down are achieved by raising and lowering boiler pressure

HEAT AND THERMODYNAMICS – THE BASICS

2.0 INTRODUCTION

Thermodynamics is the branch of physical science that deals with heat and related processes. A part of thermodynamics that is especially relevant to power plants focuses on the laws governing heat transfer from one location to another and transformation of energy from one form into another. Examples of such processes would be the heat transfer in a steam generator or the conversion of heat into work in a steam turbine.

A CANDU nuclear power plant is, from a thermodynamic point of view, a complex mixture of thermodynamic systems connected together in such a way as to produce a significant electrical output. Through a review of basic terms, concepts and laws of thermodynamics, this module will help you understand the material presented in the other modules and, ultimately, the thermodynamic processes occurring in a CANDU nuclear power station.

In thermodynamics, a clear definition of a thermodynamic system is necessary. For example, a system could be as simple as a bicycle pump or as complex as the CANDU reactor itself. Parameters such as volume, temperature, pressure, internal energy, enthalpy, and entropy are used to define the state of a system. We will see how parameter changes impact our thermodynamic systems as we progress through this module.

2.1 BASIC DEFINITIONS AND UNITS

2.1.1 Internal Energy

A body is said to possess energy if it is capable of doing work. Such a definition used in mechanics arises from the fact that most forms of energy can be transformed into work. A moving body possesses energy, known as kinetic, due to its motion. A rock elevated above the ground possesses potential energy due to its position with respect to the ground. Potential energy can also exist when two bodies are connected with a spring.

Other forms of energy include electrical, magnetic, chemical and nuclear. Energy can be transformed from one form to another to make it more suitable for a particular use. For instance, a nuclear reactor converts nuclear energy into heat; the turbine converts heat into mechanical energy, and the generator converts mechanical energy into electrical energy.

Internal energy of a thermodynamic system is the total amount of energy contained in the system. In general, the internal energy of a substance is made up of two parts: kinetic energy due to molecular motion and potential energy arising from molecular dispersion.

The kinetic energy of a molecule is associated with its motion – the faster the molecule moves, the more kinetic energy it possesses. To get a feel for the potential energy of molecules, picture them in your mind as spheres connected by imaginary springs. The springs symbolize the forces acting between individual molecules and the energy stored in these imaginary springs is the potential energy of the molecules.

The symbol for internal energy is U and in the International System (SI) it is measured in joules (J) or kilojoules (kJ). $1\text{kJ}=1000\text{J}$.

Internal energy is a variable that characterizes the state of a thermodynamic system. While it would be very difficult to calculate the total amount of internal energy possessed by a substance, a thermodynamic process is only concerned with a change in internal energy.

Total internal energy is defined relative to a certain reference condition at which the internal energy is arbitrarily assumed to be zero. We use a similar concept to measure the gravitational potential energy (elevation) of a given object (which is sometimes assumed to be zero at the Earth's surface).

2.1.2 Enthalpy and Specific Enthalpy

A more useful system variable for this course is enthalpy. Enthalpy (H) is the sum of internal energy and the product of pressure and volume of the system.

$$H = U + p \cdot V$$

In a thermodynamic system with fixed volume and pressure, enthalpy has the same meaning as internal energy and it is also measured in kilojoules (kJ). The reference condition regarding enthalpy differs from one substance to another. For water (H_2O), the reference condition is defined at a temperature of approximately 0.01°C and a pressure of approximately 0.61 kPa(a) . This is the only combination of pressure and temperature at which ice, water and vapour can stably exist together. The condition is referred to as the triple point. Every substance has its own triple point. At the triple point enthalpy of the substance is considered to be 0.

The enthalpy contained in one kg of a substance is known as specific enthalpy (h). Specific enthalpy depends on the material, its pressure, temperature and state. Specific enthalpy data for light and heavy water can be found in steam tables. Specific enthalpy (h) is measured in kJ/kg.

Notes

Therefore, taking the value of (h) and multiplying it by the mass, one can obtain the value of enthalpy (H).

$$H = m \cdot h$$

2.1.3 Work

Work (W) is the product between force and displacement.

If we look at the common bicycle pump, we can easily understand the way work is used in thermodynamics. When the piston is displaced, work (W) is simply the product of force (F) multiplied by distance (d):

$$W = F \cdot d$$

In mechanics, the definition of pressure (p) is force divided by the surface area (S) of the piston:

$$p = \frac{F}{S} \quad \text{and} \quad F = p \cdot S$$

The change in volume is equal to:

$$\Delta V = S \cdot d \quad \text{and} \quad d = \frac{\Delta V}{S}$$

Therefore, from the above, we get the relationship used for defining work in thermodynamics:

$$W = p \cdot \Delta V$$

Work is connected with changes of internal energy or enthalpy, and is also measured in kilojoules (kJ).

2.1.4 Heat

Historically, heat was considered to be a fluid that can spontaneously flow from a hot body to a cold body. It had a special unit of measurement called a calorie. We now have a better understanding of heat; as such we know that heat is just another form of energy. Heat is a measure of the internal energy change in a thermodynamic system when no work is performed.

For practical purposes, and given the way enthalpy is defined, heat is also equal to the change in enthalpy of a system when no work is performed. We will learn more about this later. When work is performed, the change of internal energy is the sum of both heat and work. The symbol for heat is (Q) and its unit of measurement is also kilojoules (kJ).

2.1.5 Temperature

Temperature is a physical quantity characterizing the degree of hotness or coldness of a body. When two parts of a thermodynamic system are in thermal contact, heat is transferred between the parts. We say that heat is transferred spontaneously from the hotter part toward the cooler part. This continues until we reach an equilibrium state where the contacting parts exist at the same temperature.

Temperature Scales

Many physics variables have different units of measurement. For example we measure distance in miles or km and mass in pound or kg. Temperature also has different units of measurement. They are called temperature scales. The most common is the Celsius scale. When measured in degrees Celsius ($^{\circ}\text{C}$), the symbol for temperature is (t). At atmospheric pressure, 0°C and 100°C represent the freezing and boiling points of water, respectively. Hence, there are 100 equal divisions between the freezing point and the boiling point of water at this set pressure. The scale is then extended above 100°C and below 0°C in the same equal divisions.

The absolute or Kelvin temperature scale has been derived from the behaviour of gases subject to cooling. It has been found that, under constant volume and mass conditions, gas pressure decreases with falling temperature at a constant rate.

An extrapolation of this trend for an ideal gas indicates that the pressure would drop to zero at a temperature of -273.15°C . This lowest possible temperature sets the zero point on the Kelvin scale. Degree Kelvin (1 K) is the unit of measurement and the symbol for absolute temperature is (T).

The size of a Kelvin degree is equal to the size of a Celsius degree. Hence the temperature conversion from one scale to the other is very simple, i.e.:

$$T(K) = t(^{\circ}\text{C}) + 273.15$$

or

$$t(^{\circ}\text{C}) = T(K) - 273.15$$

2.1.6 Entropy and Specific Entropy

Entropy is an important thermodynamic parameter. The symbol for entropy is (S).

Notes

If a process can be exactly reversed it is called reversible and is designated as ideal. In real life, no process can be exactly reversed.

Just like temperature, the entropy of a system can only be defined for equilibrium states. In any event we are only interested in changes in entropy.

Entropy is the measure of the heat ΔQ exchanged by the system with its surroundings at constant temperature T , in an ideal reversible process. The change in entropy of the system is:

$$\Delta S = \frac{\Delta Q}{T}$$

Thus we can conclude that the unit of measurement for entropy is kJ/K.

Specific entropy(s) is the entropy of 1 kg of the substance and it is measured in kJ/(kg.K), hence:

$$S = m \cdot s$$

A process in which no heat is exchanged with the surroundings is called adiabatic, or isentropic (entropy stays the same).

In an ideal turbine, friction and heat losses are absent and, therefore, no heat is transferred between the steam and the surroundings. We say that in the ideal turbine, the steam is subject to an adiabatic and reversible process in which part of its enthalpy is transformed into work without losses. While this kind of processes cannot occur in reality, they do serve as a benchmark to evaluate the quality of real processes.

In a real turbine, heat exchanged (due to losses and friction) is not zero; hence, less work is done by the enthalpy of the steam.

In irreversible (real life) processes, the entropy of the steam increases. In simple terms: If the entropy of a system increases, less work is done for a given amount of enthalpy. From which we can deduce that the entropy of a system is connected with the amount of heat that produces work.

2.1.7 Sensible and Latent Heat; Specific Sensible and Latent Heat

When heat is transferred to a system, a change of internal energy occurs. This change can affect the kinetic energy of the molecules, their potential energy, or both. The heat transfer may or may not be associated with a phase change as discussed below.

We can define two types of heat: sensible and latent. Sensible heat causes a temperature change but the body does not change its phase. Latent heat causes a phase change with no change in temperature.

A substance can change its phase during several processes. The two most common are boiling (or condensation when the direction of heat transfer is reversed) and melting (or freezing). Therefore, latent heat is further divided into latent heat of boiling (or vapourization) and latent heat of melting (or freezing).

Lets start by taking a closer look at sensible heat. The amount of sensible heat (Q) transferred to or from a body causing its temperature to change from an initial value, t_{in} , to a final value, t_{fin} , is calculated as follows:

$$Q = m \cdot c \cdot \Delta t = m \cdot c \cdot (t_{fin} - t_{in})$$

where:

m = the mass of the body expressed in kg;

c = the specific heat capacity of the body's material (defined below);

Δt = the temperature change caused by the heat transfer;

t_{fin} = final temperature;

t_{in} = initial temperature.

In this formula, Δt is positive when $t_{fin} > t_{in}$, which happens when heat is transferred to the body. In the opposite case, heat removal, Δt is negative. Therefore, (Q) is positive when the body is gaining energy and negative when the body is losing energy through heat transfer. This sign convention allows us to mathematically express the direction of heat exchange relative to the body.

The specific heat capacity is the amount of heat, expressed in kJ, which must be transferred to or from 1 kg of a given material to cause its temperature to change by 1°C. Hence, the unit of measurement is kJ/(kg°C). The word specific, used in this and other terms we will use later, refers to 1kg.

Notes

Table 1* lists the Specific Heat Capacity for some common materials.

Material	Specific heat capacity, kJ/(kg °K)
Aluminium	0.88
Copper	0.39
Steel	0.63
Water**	4.19
Oil	1.97
Vapour (at 101.3 kPa)	2.02
Air (at 101.3 kPa)	1.01
Hydrogen** (at 101.3 kPa)	14.5

Table 1
Specific Heat Capacity for Various Materials

* Specific heat capacity is slightly dependent on temperature. The values in the table are valid for a temperature range of approximately 0-100°C. For vapour and gases, specific heat capacity is very dependent upon pressure. The higher the pressure the larger the number of molecules, hence heat capacity in a given volume.

** NOTE: As seen in table 1, water and hydrogen have particularly large specific heat capacities making them good coolants.

Now lets take a closer look at latent heat. The latent heat (Q), associated with a given change of phase for a given body, can be calculated as the product of the body's mass (m) and the specific latent heat of melting (l_m) or boiling (vapourization) (l_v) as the case may be.

These specific latent heats are measured in kJ/kg, and specify the amount of heat needed to cause a given change of state of 1 kg of a given material with no change in its temperature. The heat received by m kg of a substance when boiling or melting is:

$$Q = m \cdot l_v \quad \text{or} \quad Q = m \cdot l_m$$

For consistent sign convention, as discussed earlier, latent heat is positive when it is supplied to the body (melting and boiling), and negative when it is removed (freezing or condensation).

For a given substance, the specific latent heat of melting is practically constant, but the specific latent heat of boiling depends on pressure as discussed earlier. The values quoted in the table below are valid for standard atmospheric pressure (101.3 kPa).

Material	Boiling point, °C	Specific latent heat of vapourization (kJ/kg)
Helium	-269	21.0
Hydrogen	-253	452
Ammonia	-33.3	1370
Water	100	2260
Hydrazine	114	1440

Table 2
Specific Latent Heat of Vapourization for Various Materials

In table 2, water has the highest specific latent heat of vapourization. Again, this makes water a good coolant even when boiling occurs.

Let's move on and look at a formula, which can be used for both sensible and/or latent heat:

$$Q = m \cdot \Delta h$$

This formula connects heat exchanged by the system with its mass and the change in specific enthalpy.

2.1.8 Summary of the Key Concepts in Section Basic Definitions and Units

- Enthalpy is a measure of the quantity of energy contained in a thermodynamic system.

Notes

- Specific enthalpy is the total amount of enthalpy contained in 1 kg of a given substance and is measured at a certain reference condition. The reference point is the triple point of the substance. Tables identifying specific enthalpy at different temperatures and pressures are available for common materials including light and heavy water.
- When the system changes its state, the enthalpy, and the internal energy change. If an exchange of energy occurs between the system and the surroundings, this can be work, heat, or both.
- Heat is a measure of internal energy, or enthalpy, exchanged between a system and its surroundings when no work is performed.
- Internal energy (U), enthalpy (H), work (W), and heat (Q) are all measured in kJ.
- When two parts of a thermodynamic system come into thermal contact, heat is transferred between them until equilibrium is reached, i.e., until there is no temperature differential.
- Two scales of temperature are commonly used in this course, Celsius and Kelvin. One degree from each scale has the same size (one hundredth of the temperature between freezing and boiling of water at atmospheric pressure), but the origin is different. The Celsius scale uses (0 °C) as its origin, which is the freezing point of water at atmospheric pressure. The Kelvin scale uses (0 K) as its origin - a point called absolute zero. 0 K is equal to $-273.15\text{ }^{\circ}\text{C}$.
- When heat is exchanged between the system and its surroundings at constant temperature during a reversible process the variation of entropy S of the system is the ratio between the amount of heat exchanged and the absolute temperature.
- $$\Delta S = \frac{\Delta Q}{T}$$
- Specific entropy of a substance s is defined as the ratio between entropy and mass m of the substance, entropy per kg.
- When entropy of the system increases, the amount of work that can be obtained from the system decreases.
- Sensible heat causes a change in temperature but the body does not change its phase. Latent heat – further divided into latent heat of condensation (boiling or vapourization) and latent heat of freezing

(melting) – causes a change in phase, but no change in temperature as long as constant pressure is maintained.

2.2 THERMODYNAMIC PROPERTIES OF VAPOUR AND WATER

As previously stated, every substance can be found in three phases: solid, liquid or gas. By adding or removing heat and/or work into the thermodynamic system the substance may experience a phase change.

2.2.1 Behaviour Under Applied Heat

Light and heavy water are the two most common fluids in CANDU stations. It is, therefore, important to understand how heat transfer affects them. In this section, we will examine how these fluids behave when heat is added or removed. As stated in Section 2, when heat is transferred to a system, its internal energy and enthalpy change. This is accompanied by a change in temperature and/or phase.

Figure 2-1 illustrates the changes that occur in 1 kg of water due to heat transfer under constant atmospheric pressure.

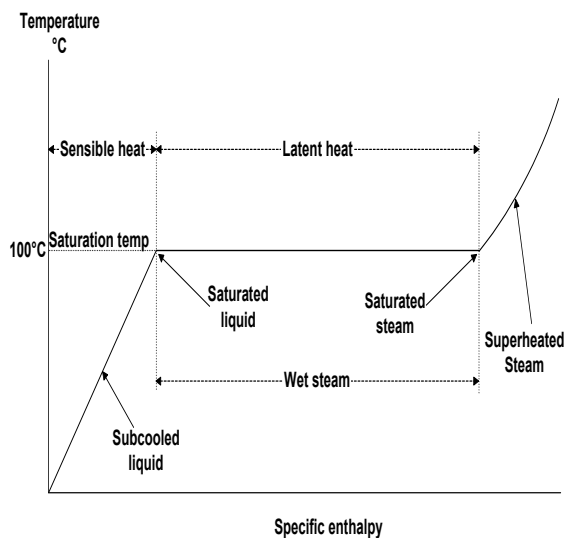


Figure 2-1
Heating of H₂O at Atmospheric Pressure

From this graph, and our everyday experience, we know that adding heat to cold water initially raises its temperature and the process continues until boiling begins at 100 °C. Prior to boiling the water is designated subcooled. Further addition of heat will cause boiling to continue but with no change in temperature.

Notes

In this situation, we have water and vapour mixture designated as wet steam. When boiling is complete, the temperature will rise again as more heat is added. In this situation, we have superheated steam.

If we remove heat, we simply reverse the process, noting that condensation occurs at the same temperature, namely 100° .

In the next section we will identify and define all the states of the fluid and associated terms.

2.2.2 Definitions

Saturation Temperature

Saturation temperature (t_s) is the temperature at which boiling or condensation occurs and it depends on the system pressure - the higher the pressure, the higher the saturation temperature (t_s). Their relationship is discussed later in the module.

Saturation temperature can also be defined as the highest temperature at which liquid, at a given pressure, can stably exist. While very fast heating can raise liquid temperature above (t_s), this state is unstable and evokes violent boiling. Similarly, (t_s) is the lowest temperature at which vapour can stably exist.

Saturation Pressure

Saturation pressure (p_s) corresponds to a saturation temperature. It is the pressure at which boiling or condensation occurs at a given temperature.

Alternatively, we can express (p_s) as the lowest pressure at which a liquid at a given temperature can stably exist. Similarly, (p_s) is the highest pressure at which vapour at a given temperature can stably exist. (The effects of reducing a liquid's pressure below (p_s) and raising a vapour's pressure above (p_s) will be discussed later in the module.)

Sub-Cooled Liquid

Sub-cooled liquid is a liquid that has not received enough heat for the temperature to reach its saturation point. Consequently, this liquid exists at a temperature below (t_s).

Saturated Liquid

Saturated liquid is a liquid that exists at the saturation temperature. We use the term saturated because the liquid is saturated with heat, i.e., it cannot absorb any more heat without the liquid starting to turn into vapour.

Saturated Vapour

Saturated Vapour is vapour totally void of liquid and it exists at its saturation temperature (t_s) corresponding to a given pressure (that's why we call it saturated). The boiling process is complete and no more heat has been added.

Wet Vapour

Wet vapour is a mixture of vapour and liquid that exists at the saturation temperature. If there is a lot of liquid in the mixture, the condition of the vapour will be close to saturated liquid. If there is little liquid in the vapour, the condition will be close to saturated vapour. Another way of describing wet vapour is to say that it is vapour that has received some, but not all, of the latent heat of vapourization.

Superheated Vapour

Superheated vapour is vapour that has received all its latent heat and has been further heated so that its temperature is above (t_s).

2.2.3 Critical Point and Effects of Pressure On Saturation Conditions

The process illustrated in Figure 2-1 was at atmospheric pressure. Figure 2-2 shows two more similar processes at higher pressures: 1 MPa(a) and 10 MPa(a) respectively.

Notes

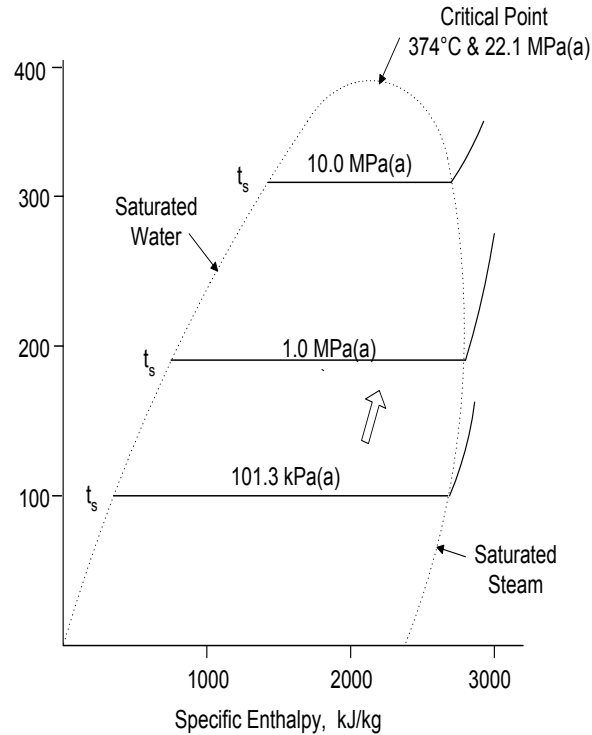


Figure 2-2
Pressure Effect on Saturation Conditions

The illustrated saturation curve ties together the points that correspond to the states of saturated water and saturated vapour for a broad range of pressure. Based on this Figure, we will answer the following questions:

What happens to the saturation temperature as the pressure increases?

What happens to the specific enthalpy of the saturated liquid as the pressure increases?

What happens to the latent heat of vapourization as pressure increases?

What happens to the specific enthalpy of saturated vapour as pressure increases?

Question #1

For any defined saturation temperature there is a corresponding saturation pressure and vice versa. As the pressure increases, so does the saturation temperature until it reaches approximately 374°C at a pressure of about 22.1 MPa(a). At this point, some major changes occur, which we will discuss shortly.

Question # 2

The specific enthalpy of the saturated liquid rises with pressure.

Question # 3

The value of latent heat falls as the pressure rises. At a pressure of approximately 22.1 MPa(a), the value of latent heat is zero. At this enormous pressure (over 220 times higher than atmospheric!), vapour is compressed so much that its molecules are as close to one another as they are in water. From a molecular viewpoint, there is no difference between the two states and that's why no energy is needed to move from one state to the other.

This unusual state is termed the Critical Point (CP), and it occurs at a critical pressure of $\cong 22.1$ MPa(a) and critical temperature of $\cong 374^\circ\text{C}$. As stated earlier above the critical temperature substances are only found in gas form. For lower temperatures, the substance can be a liquid or a vapour depending on its pressure and temperature.

Question # 4

As the pressure increases, the specific enthalpy of the saturated vapour increases. However, if we take a closer look we will see that this enthalpy reaches a maximum of approximately 2802 kJ/kg at a saturation pressure of approximately 3.2 MPa(a). The specific enthalpy then falls, with increasing pressure, to a value of about 2107 kJ/kg at the critical point.

It is now time to explain what happens to a subcooled liquid, a wet vapour, and a superheated vapour when we change pressure at constant enthalpy.

Sub cooled Liquid

When pressure increases at constant enthalpy, the saturation temperature will rise increasing the differential temperature between it and the temperature of sub-cooled liquid.

When pressure decreases, the saturation temperature falls until it reaches the actual liquid temperature. At this point the liquid is no longer subcooled. As the pressure continues to fall, the actual liquid temperature is greater than the saturation temperature and boiling will start. In this process sensible heat is transformed into latent heat producing wet vapour.

Wet vapour

When pressure increases at constant enthalpy, we will see different effects depending upon the condition of the vapour and our pressure range.

Notes

If the pressure stays below 3.2 MPa(a), which corresponds to the maximum value of specific enthalpy for saturated vapour, a pressure increase will translate into increased moisture content. If our starting point is relatively wet steam, the end product may very well be subcooled water.

If the pressure increase takes us above 3.2 MPa(a), we will see different affects dependant upon the initial moisture content. If the vapour is relatively wet we will see an increase in moisture content and temperature and we may end up with subcooled liquid. On the other hand, if the vapour is very dry we may see an increase in quality and temperature and even end up with superheated vapour/steam.

When pressure decreases at constant enthalpy the process is reversed.

Superheated vapour

If our pressure stays below 3.2 MPa (a) a pressure increase will lead to a rise in saturation temperature and corresponding reduction in degrees of superheat. If the process continues we will see a change in phase.

If on the other hand our starting pressure is above 3.2 MPa(a) a rise in pressure will cause a rise in saturation temperature but as can be seen in Figure 2-2 the enthalpy required to produce saturated vapour starts to decline with pressure hence our steam will stay well superheated.

2.2.4 Vapour Quality and Moisture Content

Wet vapour is a mixture of water droplets and vapour, both existing at the saturation temperature. There are two methods to express the composition of wet vapour.

Vapour quality (also known as dryness fraction), (q).

The dryness fraction is a ratio of the mass of vapour in a mixture to the total mass of liquid plus vapour, i.e.:

$$q = \text{Mass of vapour} / \text{Mass of vapour and liquid}$$

Vapour quality is dimensionless, although it may be expressed as a percentage. The range of vapour quality is 0 to 1.

$q = 0$ when no vapour is present, i.e., the fluid is a saturated water.

$q = 1$ when no liquid is present, i.e., when the fluid is a saturated vapour.

Moisture Content (also known as vapour wetness), (m_c). This parameter is defined as a ratio of the mass of liquid to the total mass of liquid plus vapour, i.e.:

m_c = Mass of liquid / Mass of vapour and liquid

The sum of vapour quality and moisture content equals 1 (or 100%), i.e.: $q + m_c = 1 = 100\%$. Therefore, once you know one of these parameters, you can easily calculate the other.

2.2.5 Summary of the Key Concepts -Thermodynamic Properties of Vapour and Water

- Saturation temperature is the temperature at which boiling or condensation occurs at a given pressure. Similarly, saturation pressure is the pressure at which these processes occur at a given temperature. The higher one of these parameters is the higher the other one will be, although the relationship is not proportional.
- In a stable state, a liquid can be sub-cooled or saturated. A liquid is sub-cooled when its temperature is lower than the saturation temperature, which means that pressure is above the saturation pressure.
- A liquid is saturated when its temperature equals the saturation temperature (or pressure equals the saturation pressure) and there is no vapour present.
- In a stable state, vapour can be saturated or superheated. Vapour is saturated when its temperature equals the saturation temperature, or pressure equals the saturation pressure and there is no liquid present. Vapour is superheated when its temperature is above the saturation temperature, which means that its pressure is below the saturation pressure.
- Wet vapour is a mixture of liquid and vapour that exists at the saturation pressure and temperature. The composition of wet vapour can be expressed as vapour quality (dryness fraction) or moisture content (vapour wetness).
- Vapour quality is the ratio of the mass of vapour over the total mass of the wet vapour.
- Moisture content is equal to the ratio of the mass of liquid over the mass of the wet vapour.
- The sum of vapour quality and moisture content equals 1.

2.3 THERMODYNAMIC LAWS

The timeless dream of humankind was to produce work without consuming anything. A machine capable of doing such is called a perpetual motion machine.

James Watt invented the first relatively modern practical work engine. This engine produced work by consuming fuel. Fuel was burned and transformed into heat. Heat was transferred to a fluid (called working fluid) and then heat was transformed into work. The fact that heat (or another form of energy) is needed to produce work in an engine is the essence of the first thermodynamic law.

In Watt's engine however, not all heat was transformed into work; some of it was released into the surrounding atmosphere.

Sadi Carnot proved that there is a limit to the amount of heat that can be transformed into work, as we will always lose some heat to the surroundings. This discovery is also connected with the known fact that heat cannot, of its own accord, transfer from a lower temperature body to a higher temperature body. This is the essence of the second thermodynamic law.

Historically, the development of thermodynamics was related to the study of work engines and the above principles. Later, it was proven that all thermodynamic processes (such as heat transfer, heat exchange, etc.) obey the two laws.

A more general formulation of the laws was then derived.

2.3.1 The First Law of Thermodynamics

The first thermodynamic law is the formulation of a more general law of physics (the law of conservation of energy) for thermodynamic processes. Simple put:

Energy* cannot be created or destroyed; it can only be transformed from one form into another.

*However in processes involving nuclear transformation, energy E and mass m are related by the famous Einstein equation $E = mc^2$ (where c is the speed of light). Hence mass can be transformed into energy and vice-versa.

When a thermodynamic system is in a particular state it is characterized by system parameters such as pressure, temperature, volume, enthalpy, entropy, etc. When system parameters change, the system can exchange heat, and/or work with its surroundings.

The way internal energy, work, and heat were defined in the section on Basic Definitions and Units, allows us to understand the first thermodynamic law:

During a transformation, the change in the internal energy of a system is equal with the sum of work and heat exchanged by the system with its surroundings.

$$\Delta U = \Delta Q + \Delta W$$

Where: ΔQ and ΔW are positive if they are transferred into the system and negative if they are released by the system.

To apply the first law of thermodynamics to a cyclic process we have to remember that internal energy is a system variable. In a cyclic process, the system returns at the same state, hence there is no change in its internal energy. In this case, work produced by the system equals the heat exchanged by the system:

$$\Delta W = - \Delta Q$$

When PHT coolant receives heat from the core, its internal energy changes. If we neglect the expansion of coolant, work is zero and the first law becomes:

$$\Delta U = \Delta Q = \Delta H$$

If we apply the first law to a mass of coolant that changes phase, i.e., boiling occurs, work can no longer be neglected. If the phase change takes place at constant pressure, work is:

$$\Delta W = -p \cdot V$$

The minus sign indicates that work is done by the system. The first law then becomes:

$$\Delta U = \Delta Q - p \cdot V \quad \text{or} \quad \Delta U + p \cdot V = \Delta Q$$

As $H = U + p \cdot V$ we obtain

$$\Delta H = \Delta Q$$

In the more complicated case when both pressure and volume of the coolant change, the work exchanged with the system is equal to the sum of two terms. One is the expansion work (or work of the flow) i.e., work done to overcome the external pressure and the second one, work (W')

Notes

done to overcome other external forces, for example work needed to rotate the turbine. In this case, the first law can be written by combining the expansion work with the internal energy:

$$\Delta H = \Delta Q + \Delta W'; \text{ or}$$

$$H_2 - H_1 = Q_{in} - Q_{out} + W'_{in} - W'_{out}$$

and by rearranging, we get:

$$H_1 + Q_{in} + W'_{in} = H_2 + Q_{out} + W'_{out}$$

2.3.2 The Second Law of Thermodynamics

There are two formulations used for the Second Law of Thermodynamics. The formulations are equivalent, but apply in different processes. One is connected with heat engines and the other with heat transfer.

It is not possible to convert all the heat supplied to a heat engine into useful work.

Heat cannot be naturally transferred from a colder body to a hotter body.

Applying formulation (A) to a heat engine, we can determine that all the heat supplied to the engine cannot be converted into work. The ratio between the work obtained and the heat supplied to the engine is called thermal efficiency.

$$\eta = \frac{W_{produced}}{Q_{supplied}}$$

Each heat engine uses a fluid to take heat from a hot source, transform a part of this heat into work, and release the rest to a cold source. This fluid is called the working fluid. A heat engine performs a cyclic process (at the beginning of each cycle the working fluid inside the engine is in the same thermodynamic state, including its internal energy, enthalpy, pressure and volume). Applying the first law to this processes, ΔU is zero, and hence work produced:

$$-\Delta W = \Delta Q$$

Where: ΔQ is the difference between heat supplied (Q_1) to the engine and heat released (Q_2) by the engine to its surroundings. Therefore:

$$\eta = \frac{Q_1 - Q_2}{Q_1} \quad \text{or} \quad \eta = 1 - \frac{Q_2}{Q_1}$$

Carnot, proved that Q_2 cannot be zero and that, the ratio Q_2/Q_1 is equal to the ratio T_2/T_1 , - where T_1 represents the absolute temperature of the hot source and T_2 the absolute temperature of the cold source. Therefore, the maximum thermal efficiency of a heat engine is:

$$\eta = 1 - \frac{T_2}{T_1}$$

Formulation (B) reflects the fact that heat sink temperatures must be lower than heat source temperatures in order to naturally transfer heat from the heat source to the heat sink. The refrigerator seems to contradict this law, but it does not. A refrigerator consumes energy in order to accomplish the transfer.

Heat transfer processes are critical to CANDU operations; consequently we will see many examples throughout the text.

2.3.3 Summary of Key Concepts in Section Laws of Thermodynamics

The First Thermodynamic Law is based upon a more general law of physics, the law of conservation of energy, as applied to thermodynamic processes.

During a transformation, the change in the internal energy of a system is equal with the sum of work and heat exchanged by the system with its surroundings.

The Second Law of Thermodynamics has two equivalent formulations. They both apply to any thermodynamic process:

Formulation (A):

It is not possible to convert all the heat supplied to a heat engine into useful work.

Formulation (B):

Heat cannot naturally be transferred from a colder body to a hotter body.

2.4 HEAT TRANSFER

In terms of heat transfer we defined temperature as the parameter that characterizes the state of equilibrium. Heat can only be transferred between parts of a system or between systems when there is a temperature difference.

Notes

When heat is transferred to a substance, the substance may change its temperature, its phase, or both. When the substance changes its temperature, the following equation applies:

$$Q = m \cdot c \cdot \Delta T$$

For a flowing fluid the equation becomes:

$$\dot{Q} = \dot{m} \cdot c \cdot \Delta T$$

When a substance changes its phase or both, the following equation must be used:

$$Q = m \cdot \Delta h \text{ or } \dot{Q} = \dot{m} \cdot \Delta h .$$

The mechanisms and the rate of heat transfer will be explained in this section.

2.4.1 Radiation

Particles of a substance emit electromagnetic energy in the infrared range. This radiant energy transfers heat from the substance. This process occurs at all temperatures above absolute zero - the higher the temperature, the higher the rate of heat emission.

At the same time, as a body emits thermal radiation, it also absorbs and reflects the radiation emitted by other bodies in its vicinity. When the rate of emission equals the rate of absorption, the rate of heat transfer by radiation is zero because the body is neither gaining nor losing heat.

Radiation is the only heat transfer mechanism that can function in a perfect vacuum. While conduction and convection need molecules to transfer heat from one location to another, radiation uses photons to achieve it. Photons can move easily through gases and steam. Solids, however and, to smaller extent liquids, absorb and reflect photons. In other words, thermal radiation does not penetrate solids and liquids. Thus, for practical purposes, radiation only occurs where a vacuum, or a layer of a gas or steam, separates the objects involved in heat transfer.

An example of heat transfer by radiation is the heat transferred through a vapour film surrounding a fuel bundle during excessive coolant boiling/dryout.

Another example of a process where radiation significantly contributes to heat transfer is in the annulus gas system where heat is transferred from a

pressure tube to its calandria tube. Forced convection also contributes to the heat transfer in this situation.

The rate of heat emission by radiation depends on:

surface area, A;

absolute temperature, T;

type of the material;

surface finish (for example dull and rough surfaces emit more radiation);

darkness (a black body emits the most of radiation).

The rate of emission is expressed as:

$$\dot{Q} \propto A \cdot T^4$$

This equation is given for illustration purposes. Some factors are omitted for simplicity. Symbol \propto denotes proportionality.

The rate of heat transfer due to radiation between two objects increases dramatically with their differential temperature, ΔT . This is very different from conduction and convection where the heat transfer rate is proportional to ΔT .

In conclusion, radiation can be neglected when ΔT is fairly small and/or heat transfer occurs in a solid or liquid. If however the temperature differential is large and heat transfer occurs in a vapour or gas environment, radiation can become the predominant heat transfer mechanism.

2.4.2 Conduction

Conduction involves heat transfer with no transfer of mass. Heat is transferred from one part of a body to another part, or to another body in physical contact with it. Transfer is achieved via kinetic energy from molecule to molecule. Molecules move during this process, but their displacements are imperceptible. For example, in solids, molecules vibrate about fixed points with no mass transfer from one location to another.

Conduction occurs mainly in solids. In fluids, it is usually insignificant in comparison with convection. However, if we stop or restrict fluid movement, heat transfer by conduction will be dominant.

Notes

Examples of such situations would include small bubbles of gases trapped within Styrofoam insulation or air/moisture trapped between the fibres of fibreglass insulation.

In CANDU stations, conduction is a very common heat transfer mechanism. For example, it takes place in the tubes or plates of heat exchangers, piping walls and the casings and rotors of a variety of machinery, such as pumps and turbines. Conduction also occurs inside reactor fuel pellets.

The rate of heat transfer by conduction is dependent on the ability of the material to conduct heat, the area through which heat is flowing, A , the temperature differential from the hot side to the cold side, ΔT , and the wall thickness, L . The following formula shows this relationship:

$$\dot{Q} = k \cdot \frac{A}{L} \cdot \Delta T$$

The applicability of this equation is restricted to flat surfaces, constant thickness, constant temperatures and constant thermal conductivity within the temperature range.

In this equation, the material's ability to conduct heat is expressed by k . This parameter is called thermal conductivity and is measured in $\text{W/m}^\circ\text{C}$. From the physical perspective, thermal conductivity specifies the heat transfer rate (in W) through a plate with area of 1m^2 , 1m thick, across which a uniform 1°C temperature differential exists. Thermal conductivity changes quite significantly with temperature. For gases, it also increases with rising pressure.

Table 1.4 lists thermal conductivity values for some common materials under standard atmospheric conditions.

Material	Thermal conductivity, W/m°C
Aluminium	220
Admiralty brass	110
Carbon steel	55
Titanium	22
Stainless steel	15
UO ₂	3.4*
H ₂ O	0.64
D ₂ O	0.62
Hydrogen	0.17
Air (dry)	0.03

Table 4
Thermal Conductivity

*For UO₂ temperature is assumed to be 1000 °C.

With reference to the table we can make the following observations:

Metals are much better heat conductors than liquids, which, in turn, are better than gases.

The thermal conductivity of UO₂ is the smallest of all the solids listed in the table.

In other words, our fuel is a rather poor heat conductor. This has safety implications, as we will see later.

Notes

Hydrogen has a thermal conductivity several times as large as that of air – this is one of the reasons why hydrogen is used for generator cooling.

The thermal conductivity of stainless steel is a few times smaller than that of carbon steel. As a result, large temperature gradients are produced during welding. This is one of the reasons why stainless steel is more difficult to weld than carbon steel.

2.4.3 Convection

Convection involves heat transfer that is accomplished by the movement of a fluid. As the fluid moves, it carries heat with it. Because convection relies on transfer of molecules from one place to another, it only occurs in fluids that are free to move. It does not occur in solids and is usually negligible in fluids that are trapped. Convection can be either natural or forced as explained below:

Forced Convection

This type of convection uses pressure differences to force the fluid to move. The pressure differences are generated by equipment, such as pumps, fans, and compressors. This type of convection is very common in our plants.

For example, the condenser cooling water is pumped through the condenser, where it picks up heat from the inner surface of the condenser tubes and discharges this heat into the lake. Or, when the heat transport system (HTS) pumps are running, the reactor coolant picks up heat from the outer surface of the fuel bundles and carries it into the boilers where it gives off the heat to the inner surface of the boiler tubes.

Natural Convection

In natural convection, there are no external means forcing the fluid to flow, e.g., no running pump. The movement of the fluid is caused by density and/or pressure differences produced in the fluid due to heat transfer.

The movement of the fluid is caused by density differences coupled with gravity. The denser hence, heavier fluid descends, forcing the lighter fluid upwards.

In our stations, natural convection is less common, but it does occur. For example, as boiler water is heated, it turns into steam. The steam rises through the water to the top of the boiler carrying the heat extracted from the reactor coolant.

Thermosyphoning is also an example of natural convection. This occurs in the HTS when all HT pumps are lost. This is an extremely important topic, which will be discussed in more detail in a later module.

The extraction steam flow to a feed heater is another example of natural convection. The steam gives off heat to the outer surface of the feed heater tubes and condenses. As the steam condenses, its volume decreases drastically lowering the feed heater shell pressure somewhat below the pressure located at the turbine end of the extraction steam piping. It's this pressure difference that maintains the steam flow.

Regardless of the type of convection, the rate of heat transferred to or from an object is proportional to the temperature differential between the object and the fluid, ΔT , the surface area exposed to the fluid, A , and the fluid's ability to convect heat. This ability is characterized by a convective heat transfer coefficient, h . Hence:

$$\dot{Q} = h \cdot A \cdot \Delta T$$

The convective heat transfer co-efficient specifies the rate of heat transfer between a moving fluid and a 1m^2 surface due to a uniform 1°C temperature differential between the two. Hence, the unit of measurement is $\text{W}/\text{m}^2\text{C}$. The value of this co-efficient depends on a number of physical properties such as fluid density, specific heat capacity, thermal conductivity, and viscosity, which, in turn, depend on the type of fluid. They all vary with temperature. For gases and vapours, pressure is also a significant factor because it affects the fluid's density, i.e., the number of molecules per unit volume.

Finally, the co-efficient depends on the fluid's velocity - the faster the fluid flows, the higher the heat transfer rate. The relationship between the fluid's velocity and the convective heat transfer co-efficient is not proportional and a change in the fluid's velocity causes a much smaller change in the co-efficient.

Notes

Because there are so many variables, it is very difficult to accurately determine the value of the coefficient. Table 5, lists the approximate ranges for this coefficient for various fluids and convection conditions.

Condition		Convective heat transfer coefficient $W/m^2^{\circ}C$
Natural convection	Gases	5 –30
	Water	100 –900
Forced convection	Gases	10 –300
	Water	300 –11,000
	Liquid metals	6,000 – 110,000
Phase change	Boiling liquids	3,000 – 60,000
	Condensing vapours	6,000 – 110,000

**Table 5
 Convective Heat Transfer Coefficient**

Based on the data in the table, we note that in terms of heat transfer:

Gases are less effective than water, which in turn is less effective than liquid metals;

Normally, forced convection is more effective than natural convection; and

Boiling and condensing are very effective due to vigorous mixing of molecules that occur at the surface in contact with the fluid.

2.4.4 Heat Transfer by Vapour Condensation

This particular kind of heat transfer is the basic principle of operation of condensers and feed heaters.

Heat transfer from saturated vapour differs substantially from heat transfer, by convection, from gases. When a saturated vapour touches a surface, which is cooler than the vapour, condensation immediately takes place-transferring heat to the cooling surface. The condensation process produces a liquid film over the cooling surface. Subsequent heat transfer takes place through this film. The thickness of this film has a marked influence on the heat transfer rate, since the laminar flow of the liquid film permits only conduction as a medium of heat transfer. On the other hand, the thermal conductivity of water is small. All other conditions being equal, the greater the film thickness, the slower the heat transfer rate.

The thickness of the film is also influenced by viscosity of the liquid. The viscosity decreases as the temperature increases. (As we already know the saturation temperature increases with pressure). Finally, the thickness is influenced by the roughness of the surface. The rougher the surface the thicker the liquid film.

It should be noted that if excessive air/gas builds up in the shell of a steam condensing heat exchanger it decreases the heat transfer rate. The air/gas blankets some tubes and acts like insulation effectively decreasing the heat transfer coefficient. To transfer a given quantity of heat in this situation the steam temperature must rise to compensate for the reduced heat transfer coefficient. This leads to an increase in shell pressure. The air/gas in-itself will exert a pressure that according to Dalton's law causes a further pressure increase.

$$P_c = P_{steam} + P_{gas}$$

In a condenser or condensing heat exchanger, excess air/gas should be removed from the steam flow by using vacuum pumps/air ejectors.

2.4.5 Summary of Key Concepts in Section Heat Transfer

The rate of heat transfer to or from a substance can be expressed as the product of mass flow rate and the change in specific enthalpy. This covers changes in both temperature and phase.

When no change of phase occurs the heat transfer rate can be expressed as the product of mass flow rate, specific heat capacity, and temperature differential between inlet and outlet.

There are three main mechanisms of heat transfer: conduction, convection, and radiation. Convection is further subdivided into forced and natural.

Conduction involves heat transfer with no transfer of mass and occurs within a body or is transferred between bodies in physical contact.

Notes

Convection involves heat transfer through the movement of a fluid and can occur naturally or is forced by a pump or other device.

Radiation is electromagnetic energy emitted in the infra-red range. The process is only effective at elevated temperatures in a vacuum, gas or steam environment.

In reality, conduction, convection and radiation all occur in any given body. However, in heat exchangers the heat transfer via radiation is usually negligible. Hence, the heat transfer can be expressed by one equation, which combines conduction and convection. Namely:

$$\dot{Q} = U \cdot A \cdot \Delta T_m$$

Where:

U = overall heat transfer coefficient;

A = surface area of the heat exchanger;

ΔT_m = mean temperature differential over the surface area.

This is a universal equation, which covers changes in temperature and state between two fluids.

Vapour condensation is an effective heat transfer mechanism applied to steam condensing heat exchangers.

Excess air/gas inside the shell of a steam condensing heat exchanger decreases the heat transfer rate and should be removed using vacuum pumps/air ejectors.

2.5 REVIEW QUESTIONS – THE BASICS

1. Define each of the following terms and state typical units of measurement.
 - a. Temperature
 - b. Specific heat
 - c. Enthalpy
 - d. Specific enthalpy
 - e. Entropy
 - f. Specific Entropy

2. Heat energy can be transferred from one place to another through four (4) processes. Name, describe and state the factors that affect each process each process.

3. Define the following terms:
 - a. sub-cooled liquid;
 - b. saturated liquid;
 - c. saturated vapour;
 - d. superheated vapour;
 - e. wet vapour;
 - f. moisture content;
 - g. vapour quality/dryness;
 - h. sensible heat;
 - i. latent heat of vapourization / condensation;
 - j. saturation pressure;
 - k. saturation temperature.

4. Given t-h diagrams, showing various constant pressure lines, identify and explain the meaning of the following terms:
 - a. critical point;
 - b. saturated liquid line;
 - c. saturated vapour line;
 - d. liquid, vapour and gas regions

REACTOR AND HEAT TRANSPORT SYSTEM NORMAL OPERATION

3.0 INTRODUCTION

This section will discuss the thermodynamics of the heat transport system. In particular, we are concerned with heat removal from the fuel. If the fuel is not kept cool fuel fails can result and fission products will be released into the heat transport system.

A simplified diagram of the heat transport main circulating system is shown in Figure 3-1.

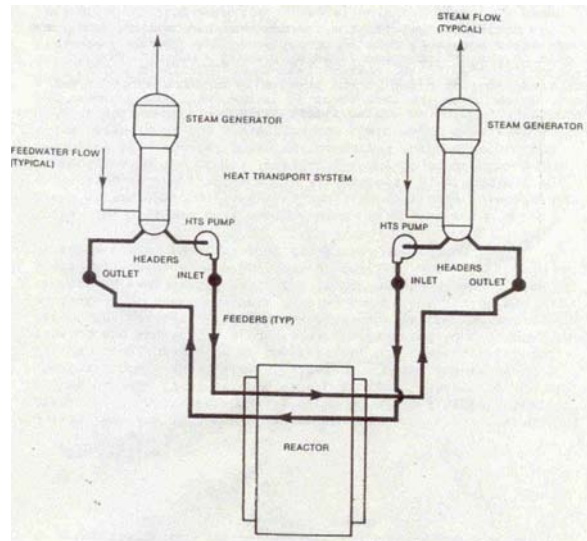


Figure 3-1
Simplified Heat Transport Main Circulating System

The Heat Transport System (HTS) is a reversible heat accumulator. Heat is transferred from fuel to the heavy water, where it is stored for a short period. From the heavy water, heat is then transferred to the steam generator.

In Figure 3-1, we can see that HTS has a bi-directional coolant flow. Namely, the coolant flows through adjacent reactor channels in opposite directions. The thermodynamic processes associated with the heat transfer from the PHT coolant to the steam generators will be described later.

3.1 REACTOR THERMAL POWER

Heat energy is produced during the fission and decay processes within the reactor. This heat is removed from the reactor by various means. Since the purpose of the reactor is to produce heat to make electricity, most of the heat is used to produce boiler steam, which in turn is used to drive the turbine.

3.1.1 Definition

Thermal power is defined as the heat produced by the source per unit of time. Specifically,

Reactor thermal power is defined as heat produced by the reactor per unit of time.

Reactor thermal power is the sum of neutron power, decay heat power and pump heat power minus the thermal power lost in the moderator, end-shields, piping, etc.

Although fission reactions produce the power generated in the nuclear reactor, the relationship between reactor thermal power and neutron power, or neutron flux, is not always proportional. There are three processes that contribute to this:

The heat produced by radioactive decay of the fission products in the core.

A mature reactor has a fission product inventory of approximately 6%. This represents the heat generated by beta and gamma decay. The level of decay heat falls away very quickly once the reactor is shutdown.

Heat generated by fluid friction in the coolant channels.

Approximately two-thirds of the pressure drop, hence heat input, in the HTS occurs in the fuel channels. This input, several MWs, depends exclusively on the coolant flow rate and is, therefore, independent of the reactor power.

The coolant loses heat to the moderator. The total amount of heat lost is proportional to the difference in temperature between the coolant and the moderator.

As explained above, the relationship between the reactor thermal power and neutron flux is not linear. For example, at full power 93 % of the heat comes directly from the fission process, 6 % from the decay of fission products and 1 % from the HTS pumps.

Notes

Under these conditions, approximately 95% of the total power is transferred to the HTS and the remaining 5% is transferred to the moderator.

When reactor power is raised from 50% to 100%, the ratio of decay heat to neutron power will immediately drop to half. After which the decay heat level will slowly increase with the build up of fission product inventory. As stated earlier, the level of pump heat is directly proportional to the coolant flow rate consequently it should not change. The heat lost in the moderator will increase a little since the average temperature of the coolant rises with reactor power.

After the reactor is shut down, the main heat sources are:

Decay heat. Immediately after shutdown, it is approximately 6% of the full power level. After a few hours, it will fall to about 1%.

Pump heat. As stated earlier this is simply a function of coolant flow rate.

The majority of the heat transfer will take place through the boiler steam rejection, however some heat will be transferred into the moderator. The total heat transfer rate falls over time, with decay heat.

3.1.2 Thermal Power Calculation

The purpose of performing a reactor heat balance is to be able to accurately calibrate the neutron flux detectors because they are used as the primary means of measuring reactor power for both control and shutdown.

A heat balance is an accurate calculation of the heat produced in the reactor by accounting for all heat removal and addition pathways.

The pathways used in the calculation are:

Steam/feed water/boiler water: Heat is transferred in to the feedwater in the pre-heaters and into the boiler water in the boilers to produce steam. Both sensible heat and latent heat appear in the calculation. The heat added is calculated from feedwater flow measurements, feedwater temperature (up-steam of the pre-heaters) and boiler pressure (used to calculate saturation temperature and latent heat). The temperature and flow of the, incoming, second stage reheater drains is also included.

Moderator: Heat generated in the moderator is calculated as a fixed fraction of the heat transport heat since no flow measurement instruments are installed. The fraction is approximately 5%.

End-shield and shield tank: Heat is generated in the end-shields and shield tank. The heat rejected is calculated from measurements of flow and differential temperature.

Feed and Bleed: Heat is rejected in the bleed cooler. The heat rejected is calculated from measurements of feed and bleed flow and differential temperature

Constant factors: There are several other heat energy rejection and addition paths. These tend to be relatively constant at all power levels and hence are grouped together. The factors include:

- Heat transport pump energy
- Heat losses from hot piping
- Heat rejected through boiler continuous blow-down

Steam dryness fraction correction. (The calculation of boiler heat addition assumes the steam is dry on exit from the boiler. Tests have shown that the steam actually contains approximately 0.1% moisture).

Figure 3-2 illustrates these pathways.

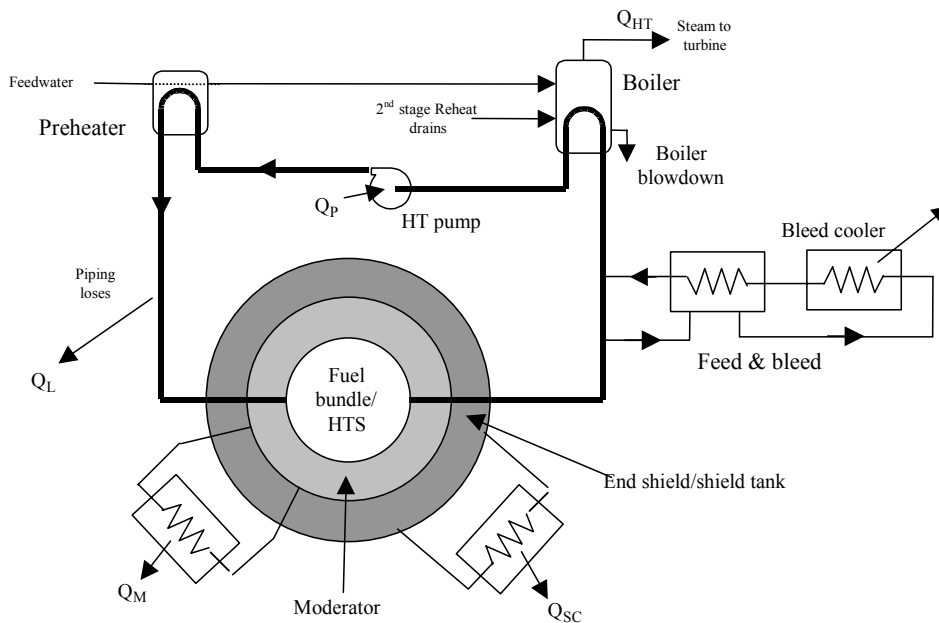


Figure 3-2
Schematic of Reactor Thermal Power Pathways

Reactor thermal power is given by the following equation:

$$RTP = Q_{HT} + Q_M + Q_{SC} + Q_{FB} + Q_{CF}$$

Notes

Where:

Q_{HT} is the heat added to the feedwater in the boilers and pre-heaters. It is calculated by calculating the enthalpy added to the feedwater and 2nd stage reheat drains as it becomes steam.

Q_M is the heat rejected via the moderator heat exchangers.

Q_{SC} is the heat rejected via the end-shield heat exchanger.

Q_{FB} is the heat rejected via the bleed cooler.

Q_{CF} accounts for the various constant heat sources such as piping losses, heat added via the heat transport pumps and losses associated with boiler blow-down.

In practice, the data for the heat balance is generated in the DCCs.

3.1.3 Reactor Power and Temperature Differential

Some reactors allow boiling in some channels; others are kept sub-cooled at all times. Boiling increases the heat transfer to a point improves fuel cooling. This is discussed in a future section. A water and steam mixture carries more heat than pure water. Calculations show that a channel with saturated liquid at the outlet at a temperature of 311°C and a pressure of 10 MPa and a 61°C rise across it will have 16.5% less heat in the fluid than a channel with the same inlet and outlet temperatures and pressures but a 4% steam quality.

Although a little boiling improves heat transfer a lot actually reduces it so where it is allowed the amount of boiling is limited. It is also more difficult to see power changes or low flow conditions in boiling channels. The outlet temperature of the channel does not change with increases in channel power or with increases in flow. The quality of the steam increases, but this is difficult to see. In a non-boiling channel the energy flow can be calculated by the following formula

$$\dot{Q} = \dot{m} \cdot c \cdot \Delta T .$$

However is boiling is allowed temperature the ΔT stays the same across the channel until all of the liquid is boiled away.

$$\dot{Q} = \dot{m} \cdot \Delta h$$

3.1.4 Summary of Key Concepts in Reactor Thermal Power

Reactor thermal power is the sum of neutron power, decay heat power, and pump heat power minus the thermal power lost primarily in the moderator.

The relationship between the thermal power and the factors listed above is not linear.

At full reactor power: 93% of the heat comes from neutron power, 6% from decay heat power, and 1% from pump heat power. Approximately 5% of this heat is lost in the moderator. Hence, the coolant removes 95% of the power.

Immediately after a reactor shutdown, the major heat source is decay heat. After a few hours, this changes and pump heat becomes predominant.

The heat transferred by the coolant depends on:

Coolant mass flow rate

For non boiling channels - Coolant differential temperature, inlet to outlet

For boiling channels - Coolant specific enthalpy change, inlet to outlet

3.2 MODES OF FUEL COOLING

During reactor operation, the fuel sheath is heated on one side by the fuel and cooled on the other by the PHT coolant. The rate of heat transfer per unit area of the fuel sheath is called heat flux, which is normally expressed in kW/m^2 . In a CANDU reactor, the heat flux varies from one location to another, depending on the local neutron flux. The magnitude of the heat flux has a profound effect on reactor safety and the manner in which the coolant removes heat from the fuel sheath.

3.2.1 Heat Transfer Processes

To understand how various operating conditions affect reactor safety, we will examine the effects of heat flux on fuel sheath temperature. This will be done relative to the coolant saturation temperature, and mode of cooling.

Initially, we will make the following simplified assumptions:

- the heat flux is uniform along the fuel channel
- the HTS pumps maintain the normal coolant flow rate

Notes

- normal coolant pressure and reactor inlet header temperature are maintained.

Later, we will discuss the effects of normal and abnormal flux distributions, and various abnormal coolant conditions.

For simplicity, we will focus our attention at the channel outlet. In addition, we will assume that one fuel element runs the entire length of the channel. At our focus point, the coolant will contain the maximum amount of heat.

Figure 3-3 illustrates the relationship between the heat flux, fuel sheath temperature, and various modes of fuel cooling.

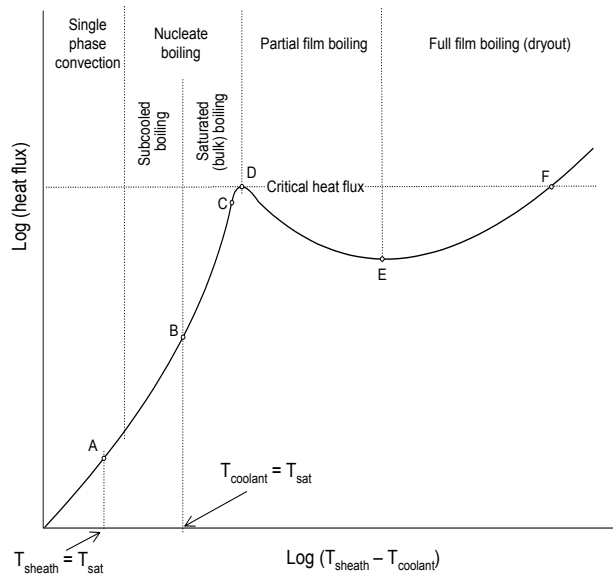


Figure 3-3
Coolant Boiling Profile

When our heat flux is relatively small, the coolant is sub-cooled, hence heat transfer occurs through forced, single-phase convection. At a certain heat flux, the sheath temperature reaches the coolant saturation temperature, but the coolant is still sub-cooled (point A in Figure 3-3).

As fuel power increases, the heat flux increases, and the sheath temperature will rise. However, even when the sheath temperature slightly exceeds the saturation temperature no boiling occurs. Under such conditions, the sub-cooled coolant quickly removes the heat generated by the fuel. But as our sheath temperature continues to rise, with increasing power, nucleate boiling begins.

This is characterized by the formation of bubbles at specific nucleation sites on the sheath. These nucleation sites are microscopic imperfections, such as cavities and scratches, on the sheath surface.

The coolant in contact with these sites is saturated, but the bulk of the coolant remains slightly subcooled. As bubbles leave the surface, partly due to their buoyancy, and partly due to forces exerted by the flowing liquid, mixing occurs. This allows the colder liquid to contact the sheath surface and hence increases the convective heat transfer coefficient.

As the coolant away from the sheath is slightly subcooled, the vapour bubbles will condense. However the latent heat transferred will add heat to the fluid and its temperature will rise. When the bulk coolant temperature remains below its saturation temperature, the boiling is classified as subcooled nucleate boiling.

When the bulk coolant temperature reaches its saturation temperature, (point B in Figure 3-3), the generated bubbles no longer condense. At this point the boiling is classified as saturated nucleate boiling or bulk boiling.

As we continue to increase power, the boiling action becomes more vigorous. Under such conditions convective heat transfer becomes increasingly effective. It will however reach a maximum value and then starts to decline. This occurs because the fraction of liquid coolant near the sheath's surface progressively decreases, as the fraction of vapour progressively increases. Because vapour has poorer heat transfer properties than liquid, the heat transfer coefficient will start to decrease (point C in Figure 3-3).

(we refer to this condition as excessive nucleate boiling. In this situation a small increase in heat flux can cause dryout, hence fuel failure).

As we continue to increase power, we will reach the maximum heat flux (point D in Figure 3-3) that nucleate boiling can transfer. This heat flux is known as the Critical Heat Flux (CHF).

A slight increase in heat flux above the CHF will cause some vapour bubbles to coalesce, forming an unstable vapour film over parts of the sheath. This vapour film will break down, be replaced by violent boiling, and will again re-establish, but not necessarily in the same location. This is referred to as departure from nucleate boiling, and starts what is called partial film boiling.

In this situation, convective heat transfer decreases as thermal radiation begins to take effect.

Notes

However at these relatively low temperatures, thermal radiation is not very effective, and hence there is a net loss in heat transfer/heat flux.

The coolant is now removing less heat than the fuel is producing. Hence heat is absorbed in the fuel/fuel sheath, causing a sharp rise in their temperatures. Consequently more vapour is produced leading to a further reduction in heat flux and subsequent fuel/fuel sheath temperature.

Under these conditions we will very quickly reach a point when the sheath no longer has any liquid contact, and is completely covered by a vapour film (point E in Figure 3-3). While the liquid-vapour interface is very turbulent, the film is stable in the sense that it covers the fuel sheath all the time.

The vapour contacting the sheath is superheated. The hot vapour and the heat radiated off the sheath vapourize any coolant before it can penetrate the film and reach the surface of the sheath. This state is called full film boiling. The heat flux from the sheath is still less than the heat input, and the temperature of the sheath will continue to rise.

As sheath temperature rises, the rate of heat transfer through radiation increases significantly and becomes the dominant means of heat transfer. The heat flux will now begin to increase until thermal equilibrium is restored. This situation is shown as point F in Figure 3-3.

The transition from maximum nucleate boiling (point D) to full film boiling (point F) occurs very quickly. It only takes a few seconds because the mass and hence, thermal capacity of a fuel pencil is very small.

When thermal equilibrium is re-established the heat is being removed at the expense of extreme fuel and fuel sheath temperatures. These extreme temperatures may result in fuel centerline melting and fuel sheath damage. In the next section, we will describe this in more detail.

So far, we have focused our attention at the end of a fictitious fuel element. Now it is time to move on and examine what happens upstream. When the heat flux is high enough to produce full film boiling at the channel outlet, other modes of cooling are present in the channel. This situation is shown in Figure 3-4. In this case, we have assumed normal coolant pressure, flow, and channel inlet temperature. However we still assume constant heat flux down the length of the channel. The significance of these assumptions will become apparent later.

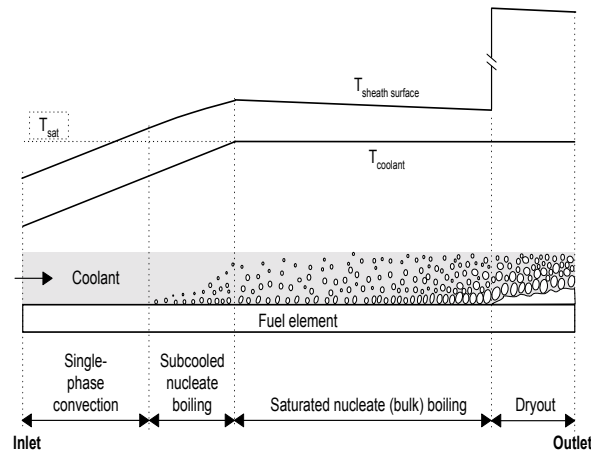


Figure 3-4
Temperature Profiles and Various Modes of Cooling of a Fuel Element

With reference to Figure 3-4 we should note:

The differential temperature between the coolant and the fuel sheath start to converge when boiling commences. This is associated with the increase in the convective heat transfer coefficient as explained earlier.

The saturation temperature falls as we progress down the channel. This is related to frictional, hence pressure losses

At the end of the saturated nucleate boiling phase the fuel sheath temperature rises dramatically. This is associated with the formation of the vapour film and subsequent loss in heat transfer.

When the sheath temperature reaches its maximum value, thermal equilibrium has been re-established.

When dry vapour patches exist on the fuel sheath, we have entered into dryout.

We should also note that dryout occurs at the point where our actual heat flux exceeds the CHF. When our heat flux approaches the CHF, we jeopardise fuel integrity. At this point we enter into excessive nucleate boiling. Its termed excessive because a small change in the heat flux, due to on-power refuelling, xenon transients, etc., could quickly lead to fuel dryout, and probable fuel damage.

Notes

3.2.2 Critical Heat Flux and Critical Channel Power

Since prevention of fuel dryout is closely associated with the CHF, it is important to understand the major factors affecting the CHF. Namely: the degree of coolant sub-cooling, coolant quality (when boiling takes place), and coolant velocity or flow rate.

Coolant Sub-cooling - It takes more heat flux to develop a vapour film when the coolant is significantly subcooled. Hence, when the coolant sub-cooling is larger, the CHF is also larger. The temperature differential between saturation temperature of the coolant and the actual temperature of the coolant is called subcooling margin (SCM). Typical the SCM at the reactor inlet under normal operating conditions is between 40 and 50 °C.

Vapour Quality - It takes less heat to form a vapour film when there is more vapour present in the coolant entering a fuel pencil. Hence, the CHF decreases with increasing coolant quality.

Coolant Velocity - Convection is enhanced when the fluid flows faster. Hence increasing velocity raises the CHF.

Now lets enter the real world and see what happens to the coolant as it travels though a fuel channel.

In a fuel channel the CHF progressively decreases towards the channel outlet as the degree of sub-cooling declines, and where appropriate, coolant quality rises. The coolant sub-cooling and quality profile in the channel depends on coolant pressure, flow rate, inlet temperature, and the heat flux profile. During normal operation, the actual heat flux profile in a fuel channel is significantly below the CHF. However, during some abnormal conditions, the two profiles can intersect as shown in Figure 3-5.

The actual heat flux curve is simplified, as it does not show local flux depressions caused by reactivity control devices such as absorber rods and/or liquid zone compartments.

It should be noted that dryout might only occur in one channel location. For example, the actual heat flux part way down a channel may be greater than CHF whilst the actual heat flux further downstream falls below it. This occurs because the heat flux generated in the downstream bundle(s) is too low to sustain film boiling. Simply put the turbulent coolant flow breaks apart the vapour film that existed on the bundles in dryout, allowing coolant to wet the sheath of the downstream fuel bundle(s).

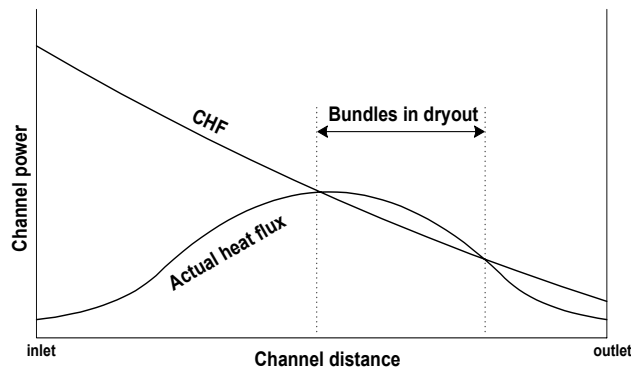


Figure 3-5
Dryout in a Fuel Channel

Before we leave this section we should note that:

Dryout does not develop simultaneously over the whole surface of a fuel bundle. For one thing, the neutron flux and hence, the heat flux varies axially and radially in a fuel bundle. In addition the coolant flow is not distributed uniformly across the bundle; hence, some fuel elements get the lions share of the total flow. The actual heat flux and CHF curves shown in Figures 3-5 and subsequently 3-9 to 3-14 represent the worst-case situation. We should also note that dryout can even occur at decay heat levels if abnormal coolant conditions exist.

The dryout scenario described above is not the only possible one. For example, if the channel flow rate is very low, stratification of steam and water can develop such that the upper fuel pencils would be engulfed in steam (hence, in dryout), whereas the lower ones would be submerged in water.

We should also make the distinction between dryout and voiding. They are not synonymous. Voiding can be considered an extreme case of dryout. Dryout exists when a thin vapour film separates liquid coolant from the fuel sheath. Voiding exists where the vapour film occupies all the available space.

Finally we will define Critical Channel Power (CCP). CCP is defined as the minimum channel power at which the CHF is reached in any location within the channel, i.e., any part of any fuel element in the channel. As with the CHF, the CCP is not a fixed value. It varies according to bundle power/flux distribution and channel coolant conditions. CPP will be used extensively in station specific training.

Notes

3.2.3 Coolant Boiling

In the previous section, we learned that limited nucleate boiling improves convection of heat from the fuel sheath to the coolant. Thus, a given coolant flow-rate can accommodate an increase in channel power.

Coolant boiling also has disadvantages.

Firstly: As discussed, excessive nucleate boiling reduces the margin to dryout. In the extreme case, dryout can occur.

Secondly: For a given pressure differential between the reactor inlet and outlet headers, the channel flow-rate decreases with increasing coolant quality. This occurs as a result of increased flow resistance. Flow resistance is affected by two major factors: fluid velocity and coolant viscosity. When boiling starts, the coolant volume increases dramatically. The increased volume results in increased velocity. As friction losses are proportional to the velocity squared flow resistance increases significantly.

In terms of viscosity, steam has a smaller viscosity than water, hence a lower flow resistance. However, the effect of velocity prevails. Therefore, the net effect of boiling is increased flow resistance resulting in a corresponding reduction in the channel flow rate.

A simple, but fairly accurate, rule of thumb can be applied: for a constant pressure differential between the channel inlet and outlet, the coolant flow rate decreases by about 1% per 1% boiling (by mass) at the channel outlet.

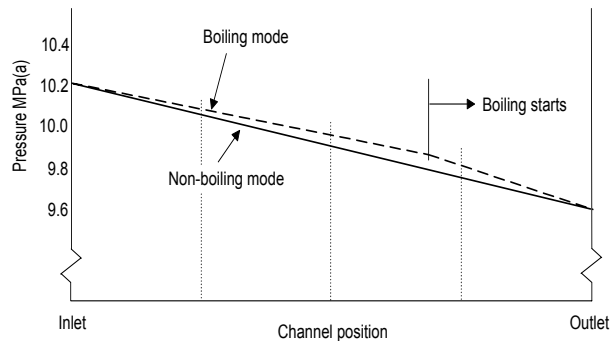


Figure 3-6
Pressure Profile in a Boiling and Non-Boiling Channel

In reactor channels designed to boil, the outlet coolant quality is very small even at full power. Hence, the effects noted above are insignificant.

However, under certain abnormal conditions significant boiling can occur at the channel outlet. Under such conditions, the resultant reduction in the flow rate can impair fuel cooling. Figure 3-6 shows two pressure profiles in a channel, one without boiling and one with significant boiling.

In the non-boiling pressure profile, the pressure decrease along the channel is almost linear. In the boiling mode pressure profile, a linear relationship exists until the onset of boiling. Once boiling starts, the pressure drops off at a faster rate.

To prevent inappropriate boiling within a fuel channel, power limits are applied. These limits are established to prevent dryout occurring in any fuel element. In addition, the total reactor power level is limited. This value can never exceed the capability of the boilers/heat sink.

3.2.4 Summary of Key Concepts in Modes of Fuel Cooling

When no vapour is present within the coolant, heat transfer from the fuel sheath to the coolant occurs through single-phase convection.

When the fuel sheath temperature rises above the coolant saturation temperature, sub-cooled nucleate boiling occurs. Under such conditions, the bulk of the coolant is sub-cooled. Vapour bubbles are produced at discrete nucleation sites, and condensed by the sub-cooled liquid. Mixing of the liquid by the vapour bubbles enhances convective heat transfer.

As the fuel sheath temperature continues to rise, the bulk coolant temperature will reach the saturation temperature. At this point, saturated nucleate or bulk boiling takes place and the vapour bubbles produced do not condense.

With further power increases, so much vapour is produced that it becomes difficult for the liquid to reach the sheath. This limits the heat flux during nucleate boiling.

The maximum heat flux that can be transferred under nucleate boiling conditions is termed the Critical Heat Flux (CHF).

From this point on, any increase in heat flux results in a heat transfer crisis. The heat flux decreases as vapour bubbles coalesce, forming an unstable vapour film. The film breaks down and re-appears, but not necessarily in the same place. This condition is termed partial film boiling.

As the heat transfer rate through the film is reduced below the rate of heat production in the fuel, fuel and sheath temperatures rise dramatically. Under such conditions, a stable vapour film is quickly established over the whole sheath surface.

During partial film boiling convective heat transfer declines. At the same time, radiative heat transfer increases due to the rising sheath temperature.

Notes

The condition at which a stable vapour film is established is termed full film boiling. Any liquid heading towards the sheath gets vapourized before it can contact the sheath. Fuel and sheath temperatures continue to rise until equilibrium is established. Equilibrium is established when the heat production rate matches the heat removal rate. Temperatures, at this point, may result in fuel and/or fuel sheath damage.

Dryout encompasses partial and full film boiling, and occurs when the actual heat flux exceeds the CHF. Once we reach dryout, fuel integrity is compromised.

The CHF rises as coolant sub-cooling and velocity increase and falls with increasing coolant quality. In a fuel channel, the CHF decreases towards the channel outlet. The CHF profile in a channel depends on: coolant pressure, flow rate, inlet temperature, and neutron flux distribution.

When a bundle in a channel is in dryout, the adjoining bundle(s) may not be. In such a case, the heat flux in these areas will be below the CHF.

The channel power at which the CHF is reached in any part of any fuel pencil in the channel is termed Critical Channel Power (CCP). Like the CHF, the CCP depends on: coolant pressure, flow, inlet temperature, and neutron flux distribution.

To accommodate the expanding volume caused by boiling, the velocity of the coolant increases. Increased velocity causes increased flow resistance. Increased flow resistance causes a reduction in flow rate. Channel flow rate decreases by about 1% per 1% increase in coolant quality.

Power limits are applied independently to the reactor, fuel channels, and fuel bundles.

3.3 TEMPERATURE PROFILES IN THE REACTOR CORE

In normal operation, a large temperature distribution exists within the reactor core. In the most heavily loaded areas the fuel centreline temperatures reach approximately 2000⁰C. Coolant temperature increases between the reactor inlet and outlet headers. At the outlet header the coolant temperature is approximately 300⁰C.

To ensure fuel integrity and prevent the release of radioactivity to the environment, fuel pellet, and sheath temperatures must be maintained within acceptable limits. Excessive fuel overheating must be prevented.

3.3.1 Fuel Temperature Profile

Figure 3-7 shows a typical fuel/fuel sheath temperature profile under normal operating conditions.

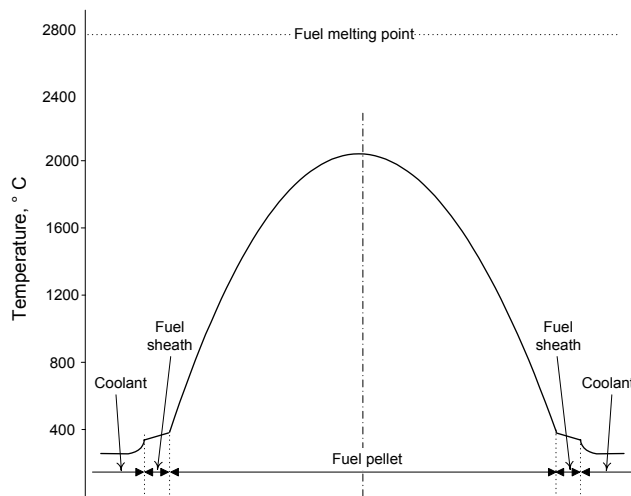


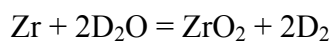
Figure 3-7
Fuel Element Temperature Profile

Figure 3-7 clearly illustrates the poor thermal conductivity of the ceramic fuel. Assuming normal coolant conditions, the fuel centreline temperature is around 1900-2000°C whereas the sheath temperature is in the order of 300-350°C. As the UO₂ fuel pellets and the zirconium sheath melt at approximately 2700-2800°C, and 1800-1900°C respectively, there is a substantial safety margin prior to failure.

In reality the safety margin is a little lower as radiation reduces the melting temperatures and the ductility of the zirconium fuel sheath.

Abnormal operating conditions can lead to excessive fuel and/or sheath temperature. If we experience excessive fuel temperatures the fuel will begin to melt. As molten fuel does not trap gaseous fission products, such as iodine, fuel melting is considered to be a barrier breach. In the extreme case, molten fuel could reach the sheath and melt it. In this case the second barrier has been breached, allowing radioactivity to enter the PHT coolant.

Overheating of the fuel sheath can result in damage even if no fuel or fuel sheath melting occurs. At high temperatures (above 1100°C), the zirconium in the fuel sheath reacts rapidly with steam. The reaction shown below produces a brittle zirconium oxide and explosive deuterium gas:



Notes

The rapid oxidation of zirconium produces heat at a rate comparable to the decay heat. This extra heat results in further increases in sheath temperature. When we combine the temperature increase with sheath embrittlement, due to oxidation and irradiation, sheath failure could occur.

Increasing the fuel temperature will increase the pressure inside the sheath. This occurs due to the expansion of the fuel pellets and the fission product gases. Normally under such conditions, coolant pressure prevails, pressing the sheath onto the fuel surface. This maintains good heat conductance from the fuel to the sheath. If there is a loss of coolant accident (LOCA) however, coolant pressure can drop below the pressure exerted by the hot fuel and gases. This can result in fuel sheath failure as explained below.

The released gases can form a thin film between the fuel and the sheath. The insulating effect of this film would cause a step increase in the fuel surface temperature (see Figure 3-8). If the sheath has not been excessively oxidized or embrittled by neutron irradiation, it will balloon, reducing pressure and preventing any release of fission products.

Although fission products have not been released, the deformation of the fuel bundle may make it difficult to remove. When the sheath is brittle however, it may crack and release fission products to the HTS. The above description does not cover all possible damage mechanisms. It does however stress the importance of protecting both the fuel and the sheath from excessive temperature and shows that damage can occur even without fuel or sheath melting.

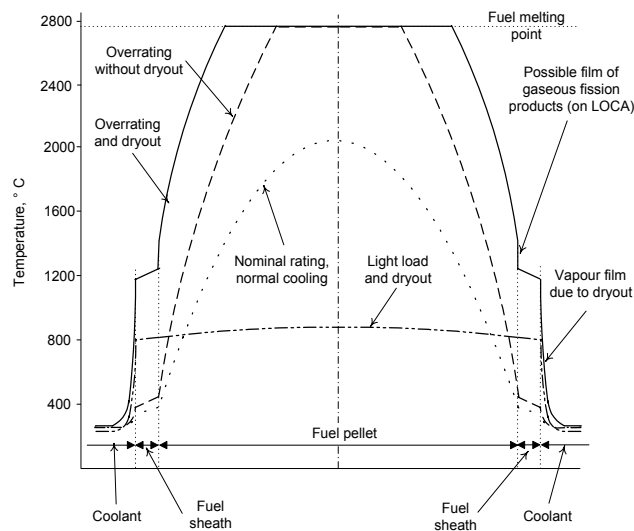


Figure 3-8
Fuel Temperature Profile during Various Conditions

The various conditions that can lead to fuel overheating can be grouped into two categories, fuel overrating, and/or inadequate cooling. Either can result in fuel melting and/or dryout as can be seen in Figure 3-8.

Without dryout, heat transfer from the fuel to the coolant is via conduction and convection. Therefore, the individual ΔT s across the fuel pellet, across the fuel sheath and between the sheath and the coolant are approximately proportional to bundle power.

If significant overrating occurs close to the channel inlet, fuel melting can occur without dryout. This is not the case near the channel outlet, as the actual heat flux is much closer to the CHF. In this location dryout will occur prior to fuel melting.

As stated earlier, if cooling is impaired, dryout can occur even at the decay heat level. In such instances, although the temperature profile across the fuel pellet is flat, the sheath would overheat. However we are very unlikely to get fuel melting. Safety analyses indicate that, at the decay heat level, fuel melting would require a total loss of coolant flow combined with a loss of emergency coolant injection and a loss of moderator cooling. In fact at the decay heat level fuel melting would only occur after the moderator D_2O had boiled off.

3.3.2 Coolant Temperature and Heat Flux Profile

We are now in a position to examine five abnormal conditions that can lead to fuel overheating. The first three conditions: low coolant pressure, low coolant flow and high reactor inlet header temperature, are associated with impaired fuel cooling. The last two conditions: excessive bundle power and excessive channel power, relate to excessive heat production in the fuel.

Low Coolant Pressure

A sustained low coolant pressure can be caused by a LOCA, or a malfunction, of the HTS pressure control system.

For example, the feed valves may fail closed or the pressurizer steam relief valve may fail open (as happened during the infamous accident at Three Mile Island). A transient drop in pressure can be caused by coolant shrink and can happen, for example, on a reactor trip. (Other causes of low pressure will be addressed later)

Coolant saturation temperature falls with dropping pressure. This reduces the amount of subcooling as boiling will occur at a lower temperature and, where boiling is already active, it will increase.

Notes

In both cases, the CHF decreases. So, as pressure is reduced, the CHF profile decreases, possibly leading to dryout.

For simplicity, we will ignore the reduction in the channel flow rate and possible increase in fuel thermal power associated with boiling. We will also assume that the pressure loss is not large enough to cause HTS pump cavitation. Under these assumptions, the coolant temperature profile does not change before boiling occurs. Figure 3-9 shows the effects of a pressure decrease on coolant temperature, saturation temperature, and the CHF.

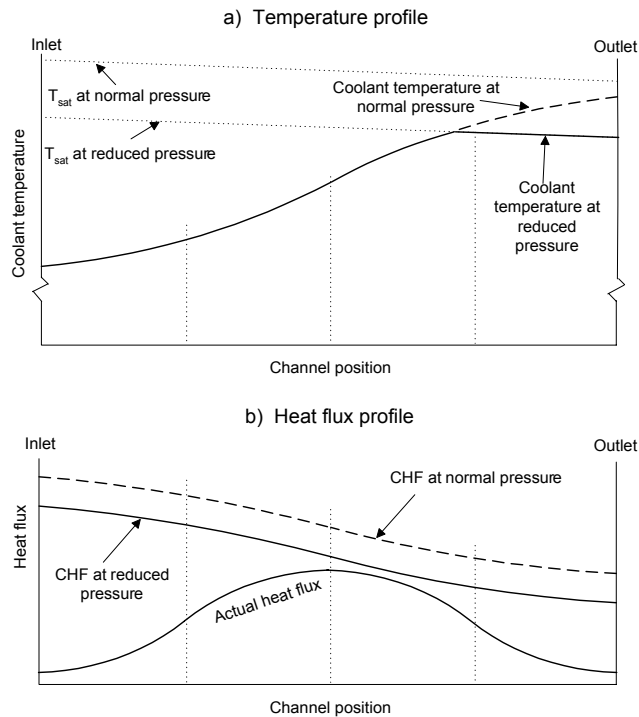


Figure 3-9
Effects of Low Coolant Pressure

With reference to Figure 3-9, we should note that the saturation temperature decreases towards the channel outlet. This decrease is roughly proportional to the fall in coolant pressure /friction losses.

The pressure loss is substantial, > 1 MPa, because the coolant has to flow through tight passages between the fuel elements.

We should also note that the coolant temperature profile rises faster at the centre of the channel. This is not surprising as it coincides with the highest thermal power. Incidentally, if we ignore fuel burn-up, the channel thermal power, and thus, the actual heat flux is directly proportional to the neutron flux.

If boiling occurs in a channel, all subsequent locations past that point will be subjected to a liquid/vapour mixture. In this case, the coolant temperature will decrease towards the channel outlet due to the decrease in pressure. Steam quality will increase as heat energy is added to the coolant from the fuel and, to a small extent, via frictional heating. In addition, the pressure drop will cause some of the coolant to flash to steam. Even if boiling does not occur in the channel, the pressure drop at the outlet feeder may cause some flashing to occur.

The decrease in the CHF along the channel reflects the reduced level of sub-cooling and, possibly, some boiling. During normal operation, the margin to dryout is quite substantial (the margin is about 30-40% of the actual heat flux). However, a drop in coolant pressure decreases this margin. In Figure 3-9, dryout does not occur but, as can be seen, the heavily loaded bundles in the third quartile of the channel are very close to dryout.

Low Coolant Flow

Channel Δp , hence flow rate, is essentially fixed by the reactor inlet and outlet header pressures. Channel flow can be reduced in several ways, for example, a HT pump trip, pump cavitation, or a channel flow blockage.

Let's consider what would happen if we were to gradually reduce coolant flow rate in a non-boiling channel. If this occurred the amount of heat produced per kilogram of coolant would increase, as can be seen in the following equation:

$$\rightarrow \downarrow \uparrow$$
$$\dot{Q} = \dot{m} \cdot \Delta h$$

This translates into a faster coolant temperature rise along the channel. As the flow is progressively reduced, sub-cooled nucleate boiling will begin at the outlet of the channel and will progress into saturated nucleate boiling.

NOTE: With the reduced velocity in the coolant channel, fewer bubbles will be swept away from the sheath surface facilitating the formation of a vapour film.

As we continue to reduce flow, boiling will move upstream in the channel, and the amount of vapour produced in the channel will progressively increase.

Notes

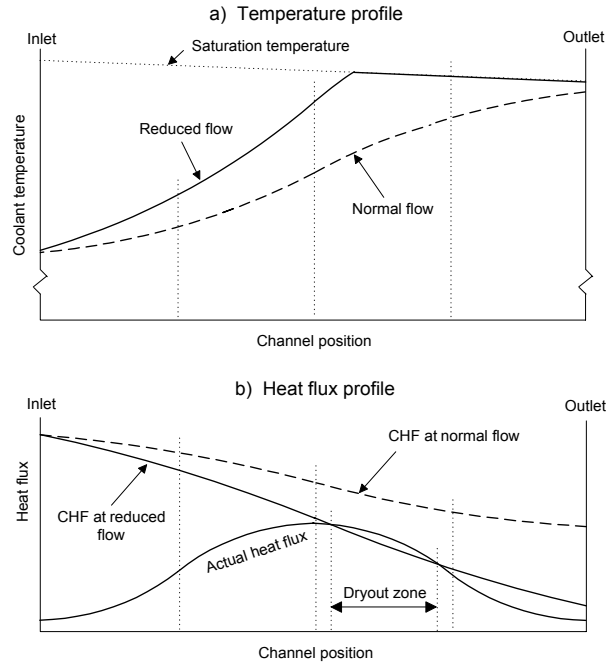


Figure 3-10
Effects of Reduced Channel Flow

Reduced channel flow rate results in a faster coolant temperature rise. Therefore, in a non-boiling channel, boiling may occur.

We should note that in a boiling channel, boiling would start earlier, due to the faster temperature rise. Hence, downstream coolant quality increases.

The combined effect leads to a progressive reduction in the CHF. When significant boiling occurs, the liquid coolant velocity falls leading to a further reduction in the CHF.

In the case shown, Figure 3-10, the CHF profile falls below the actual heat flux resulting in localized dryout. For simplicity, we will assume that the actual heat flux/bundle power stays constant despite the reduced neutron absorption in the steam environment.

High Reactor Inlet Header Temperature

A high reactor inlet header temperature, in most cases, is caused by deteriorated heat transfer conditions in the boilers. The following can cause this:

- Boiler tube fouling, plugging, or uncovering.
- A leaking boiler divider plate.
- A loss of boiler feedwater.

- Excessive reactor thermal power or abnormally high boiler pressure.

A high reactor inlet header temperature affects all the fuel channels it supplies. This causes a rise in the coolant temperature/quality profile as it progresses through the channel. In a non-boiling channel, boiling may develop.

In a boiling channel, boiling will start earlier. This results in an increase in the steam quality in the downstream part of the channel. The CHF falls in accordance with the rise in inlet temperature and we should note that if this temperature rise is significant dryout could occur.

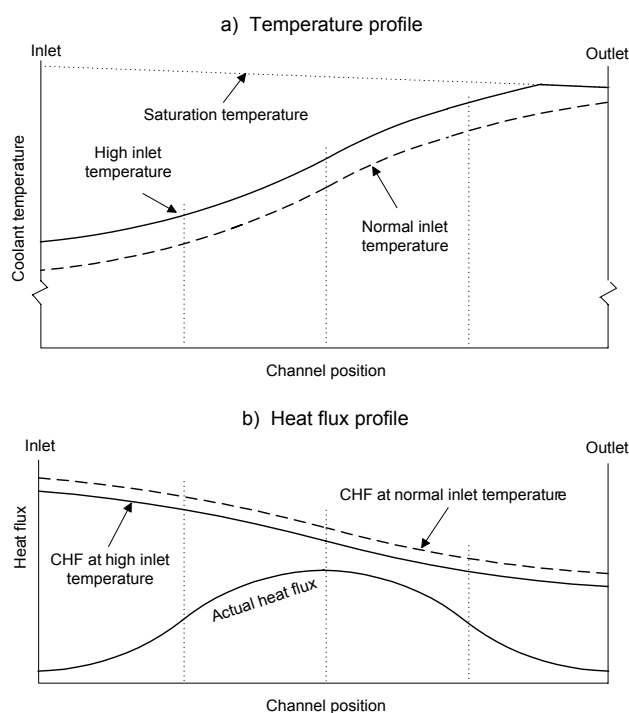


Figure 3-11
Effects of Increased Channel Inlet Temperature

Excessive Bundle Power

In this section, we will assume that the overall channel power is constant, whilst some bundles produce too much heat. Such a situation could occur given a large neutron flux tilt (e.g., due to an inadequate fuelling scheme).

For this discussion, we will assume normal coolant flow rate, pressure, and inlet temperature. As the channel power is constant; the outlet coolant temperature and quality, if applicable, will not change. However the heat flux and the coolant temperature/quality profiles will change.

Notes

Let's examine the case where neutron flux is skewed towards the channel outlet. We should note that, since the channel power has not changed, the areas below the normal and skewed heat flux curves are the same.

With reference to Figure 3-12, we can see that the local rate of temperature rise is proportional to the corresponding local heat flux.

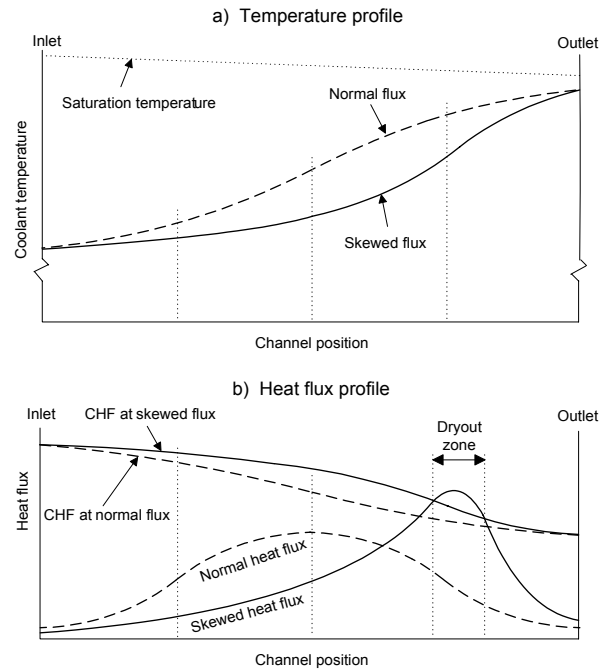


Figure 3-12
Channel with Neutron Flux Tilted to Channel Outlet

In a boiling channel, saturation conditions occur further down the channel. But once established the quality quickly increases. At any channel location, other than the inlet or outlet, coolant temperature/quality is lower than it would have been during normal operation. This is why the CHF profile is slightly higher. However, the actual heat flux in the most heavily loaded bundles can reach and exceed the CHF.

If we now look at the adjacent channel the flux shape will be skewed in the opposite direction. In this case the majority of power is produced close to the channel inlet. Again we can make the statement that the local rate of temperature rise is proportional to the corresponding local heat flux. If our example had been a boiling channel, saturation conditions would have been reached earlier. However, the steam quality would then increase at a slower rate up to its normal outlet value. All of the above statements support the fact that, apart from the channel inlet and outlet, the CHF profile is slightly lower than normal.

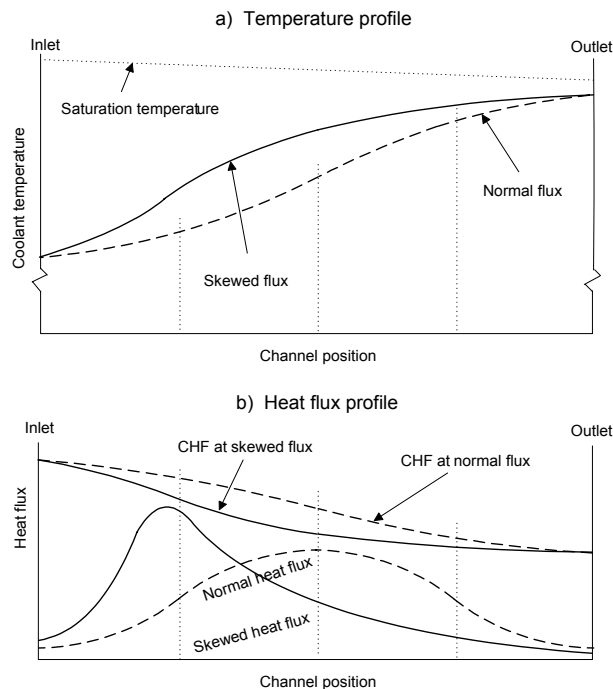


Figure 3-13
Channel with Neutron Flux Tilted to Channel Inlet

As the high power bundles are exposed to colder coolant there is less chance of reaching the CHF. However as stated earlier the integrity of these bundles are still in question.

Given the above we would not be surprised to hear that we impose both channel and bundle power limits. This protects us against reaching the CHF during abnormal flux situations.

Excessive Channel Power

In this scenario, we will assume normal coolant flow rate, pressure, and inlet temperature. We will also assume a normal symmetrical, but significantly higher flux shape

As each bundle produces more heat, the coolant temperature will rise at a faster rate. In this situation boiling may occur, or in the case of boiling channels it will increase. The increased coolant temperature/steam quality will produce a lower CHF profile. This combination, high heat flux/low CHF, may cause local dryout (see Figure 3-14).

Notes

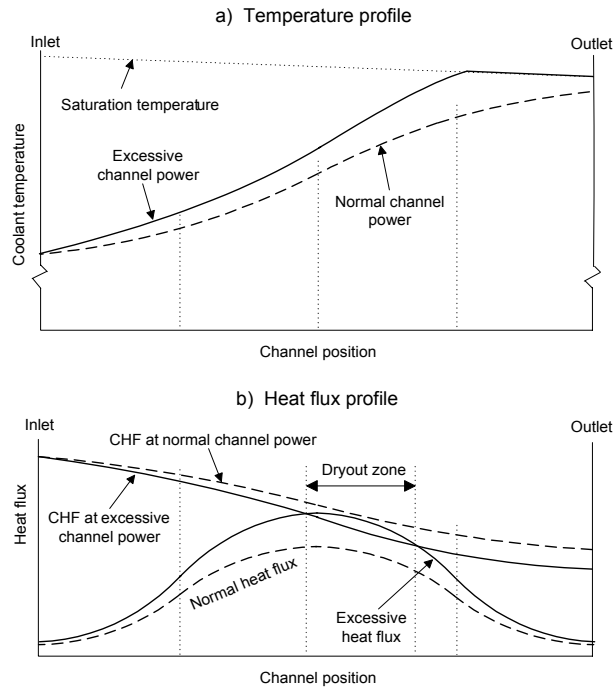


Figure 3-14
Effects of Excessive Channel Power

3.3.3 Summary of Key Concepts in Temperature Profiles in the Reactor Core

Without dryout, the fuel/fuel sheath temperature profile is approximately proportional to the bundle power. The low thermal conductivity of the ceramic fuel results in a high ΔT across the fuel pellet.

Fuel overrating and/or dryout can result in excessive fuel and/or sheath temperatures, possibly leading to fuel/sheath damage.

The following abnormal conditions can lead to fuel overheating:

low coolant pressure,

low coolant flow,

high reactor inlet header temperature,

excessive channel power,

excessive bundle power (due to skewed neutron flux).

Low coolant pressure lowers the saturation temperature profile, reducing coolant sub-cooling in the non-boiling part of the channel.

Under these conditions, a non-boiling channel can start to boil. In addition, in a boiling channel, the coolant quality increases. These changes can result in dryout.

Low coolant flow causes a faster temperature rise through the channel, similar to the previous case, coolant sub-cooling decreases at a faster rate, and if boiling begins, coolant quality increases. The reduced CHF profile increases the risk of dryout.

High reactor inlet header temperature also reduces coolant sub-cooling. The impact is similar to that seen for the case of low coolant pressure.

When a large neutron flux tilt occurs, some fuel bundles can be overrated, even when normal channel power is maintained. A large flux tilt towards the channel outlet slows down the rate of temperature rise in the inlet part of the channel where the flux is lower. Coolant sub-cooling is somewhat increased and, in boiling channels, boiling begins later. Therefore, the CHF profile is slightly elevated. The heat flux in the heavily loaded bundles in the outlet part of the channel however, increases far more than the CHF. These bundles may be subject to dryout.

When the neutron flux is tilted towards the channel inlet, coolant temperature increases at a faster rate and, in boiling channels, boiling starts earlier. The CHF profile is therefore lower. Since the heavily loaded bundles are located close to the inlet part of the channel, where the CHF is relatively high, they may experience fuel melting without dryout.

Excessive channel power promotes dryout in two ways:

the actual heat flux profile in the channel is higher

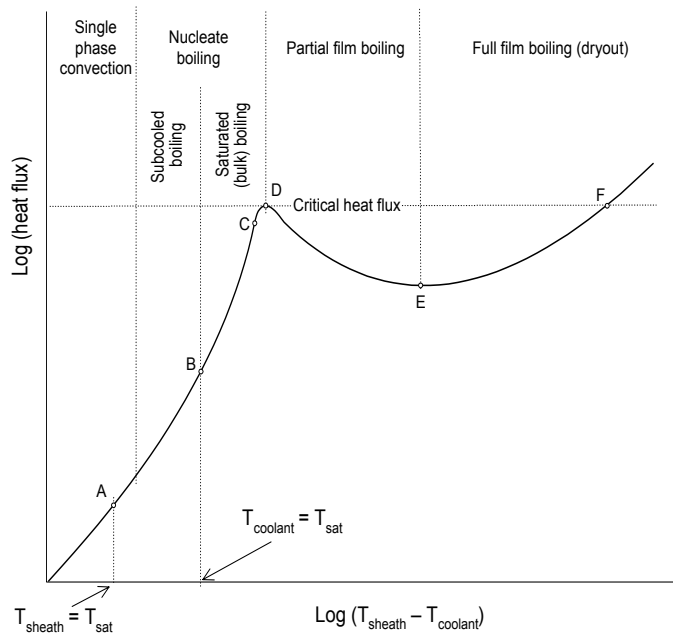
the CHF profile is lower due to the reduced degree of subcooling and coolant quality increase.

Both occur because the coolant picks up more heat per kg as it travels through the channel.

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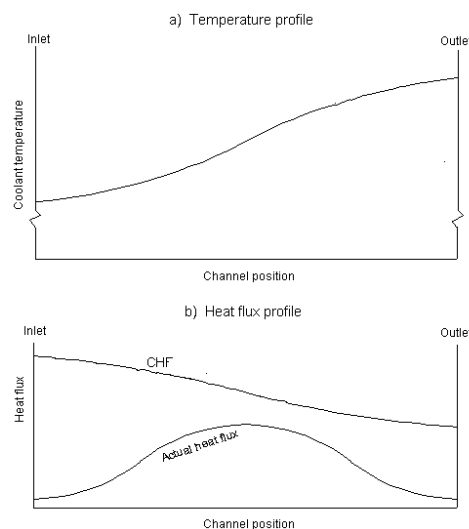
3.4 REVIEW QUESTIONS – HEAT TRANSPORT SYSTEM

1. A CANDU reactor has some boiling allowed in the reactor. Boiling does not occur until the power level of the reactor reaches 95% FP (full power). If one were measuring the output temperature and mass flow rate of a boiling channel explain what would be observed as the reactor power is raised from 0 to 100% full power. Briefly explain your observations
2. The following diagram is a plot of Log(heat flux) vs. Log ($T_{\text{sheath}} - T_{\text{coolant}}$).



- a. For each of the following regions of the graph state the name of the region and explain the major methods of transferring heat from the fuel sheath to the bulk coolant.
 - i. Origin to A
 - ii. A to B
 - iii. B to D
 - iv. D to E
 - v. E to F
- b. Define the term critical heat flux and state the point on the graph where the critical heat flux has been reached.
- c. Define the term dryout and state the region(s) on the graph where dryout is occurring.

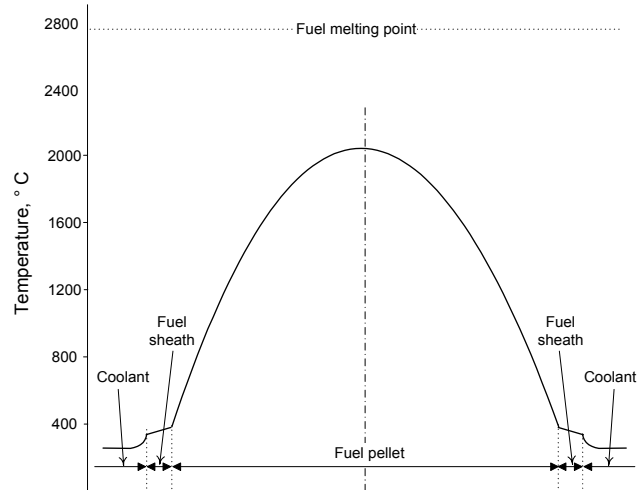
3. Describe dryout in a channel that is experiencing two phase flow
4. What is the major heat transfer process for transferring heat from the fuel to the coolant during dryout?
5. Define the terms critical heat flux and critical channel power.
6. State three factors that affect the critical heat flux in a channel and describe how each affects the CHF.
7. A reactor has limits on bundle power, channel power and reactor power. Explain why these limits exist.
8. Explain why the mass flow rate is reduced in a channel where boiling is occurring.
9. The drawing below shows the temperature profile, the flux profile and the CHF for the channel. For each of the following conditions sketch the changes that will occur in the temperature, CHF curves and actual flux curves. Indicate the channel position where dryout will first occur if the condition is severe enough. .
 - a) High reactor power
 - b) High reactor inlet header temperature
 - c) Low heat transport pressure
 - d) Low flow in the channel
 - e) Flux tilt to the inlet
 - f) Flux tilt towards the outlet
 - g) Low coolant temperature



Notes

10. The following graph is the temperature profile across a fuel pencil and the nearby fuel coolant.

- a. Explain the shape of the curve.
- b. Explain how the shape of the curve will change for each of the following conditions.
 - i. Over rating without dry out
 - ii. Overrating with dryout
 - iii. Dryout at a low power level



HEAT TRANSPORT SYSTEM COMPONENT OPERATION

4.0 INTRODUCTION

In the previous section, we described thermodynamic processes inside the reactor core, reactor channels, and fuel bundles. We also defined dryout, critical heat flux, and critical channel power. We explained why limits are applied to reactor thermal, reactor channel and fuel bundle power. We also explained why it is important to keep the Primary Heat Transport (PHT) system coolant temperature and pressure within defined limits.

Before we address abnormal operating conditions, we will explain how we control the heat transport system pressure.

4.1 PRIMARY HEAT TRANSPORT SYSTEM PRESSURE CONTROL

PHT system pressure has to be controlled within specified limits. If we go outside these limits, we jeopardise reactor safety. For example, low pressure impairs fuel cooling and may result in severe PHT system pump cavitation or even vapour locking.

Two different methods of PHT system pressure control are used in our stations. One is based solely on a feed and bleed system whilst the other uses a pressurizer in addition to a feed and bleed system.

At PNGS, there are no designated boiling channels. Hence, the PHT system is designated solid because no compressible vapours are present. A change in volume occurs due to the volumetric expansion or contraction of the reactor coolant, which is a function of temperature. The control scheme is designed to keep the average PHT coolant temperature constant during load changes. As such, under normal operating conditions the feed and bleed system effectively controls PHT coolant pressure.

Now lets take a look and see how it does so. The feed-and-bleed system can be seen in Figure 4-1. Coolant is bleed from the system via bleed valves connected to the PHT system pump suction headers. In order to maintain pressure, pressurizing pumps return the feed to the PHT system.

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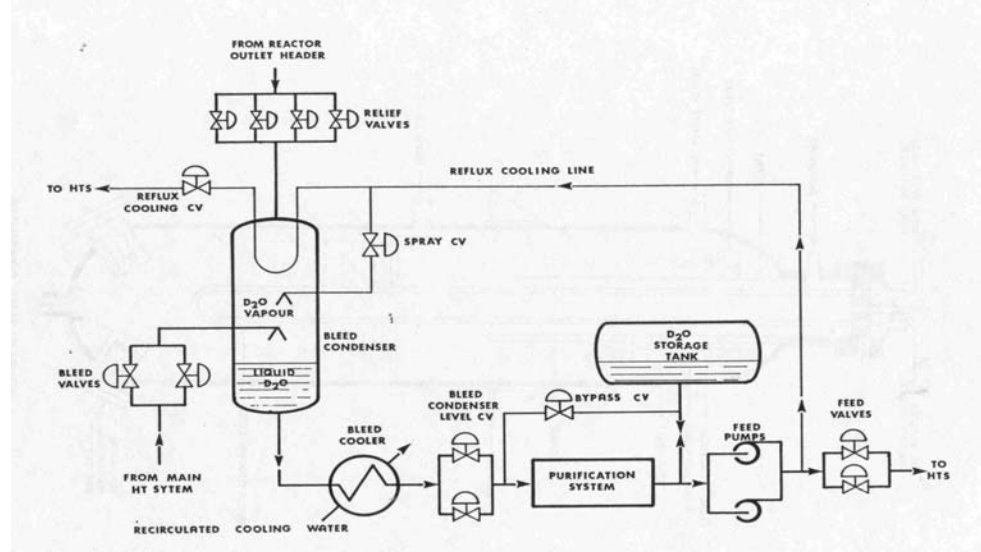


Figure 4-1
Simplified Feed and Bleed Pressure Control System

The bleed flow is directed to the bleed condenser. It is then fed through a bleed cooler on route to a purification system. After the coolant has been purified, it is fed back into the PHT system via pressurizing pumps. A large D₂O storage tank is connected to the feed and bleed system between the purification system and the feed pumps. This storage tank performs the following functions:

Stores D₂O to make up for leakage;

Accommodates coolant shrink and swell;

Provides a net positive suction head to the pressurizing pumps.

Under steady state conditions, PHT system pressures are constant and as such, the feed flow equals the bleed flow.

We should note that the bleed condenser is no more than a steam condensing heat exchanger. Having said this lets move on and see how it operates.

4.2 BLEED CONDENSER

Hot bleed, at the PHT coolant temperature, is admitted into the bleed condenser, where it flashes to vapour. The condenser removes latent heat from the coolant and in so doing changes its phase from vapour into liquid.

The bleed condenser is maintained at a set pressure. This is achieved by varying the flow of cool heavy water through the condenser reflux cooling tube (see Figure 4-2). If however, the bleed condenser pressure rose substantially above the set point, cool D₂O would be sprayed directly into the condenser. This process efficiently condenses the contained vapours, and hence quickly reduces bleed condenser pressure.

Although it is very efficient, spray cooling serves as the back up to the normal reflux cooling line. There are two reasons for this, namely spray cooling:

Increases the load on the purification system, due to recycling previously purified water; and

Increases the concentration of non-condensable gases within the bleed condenser.

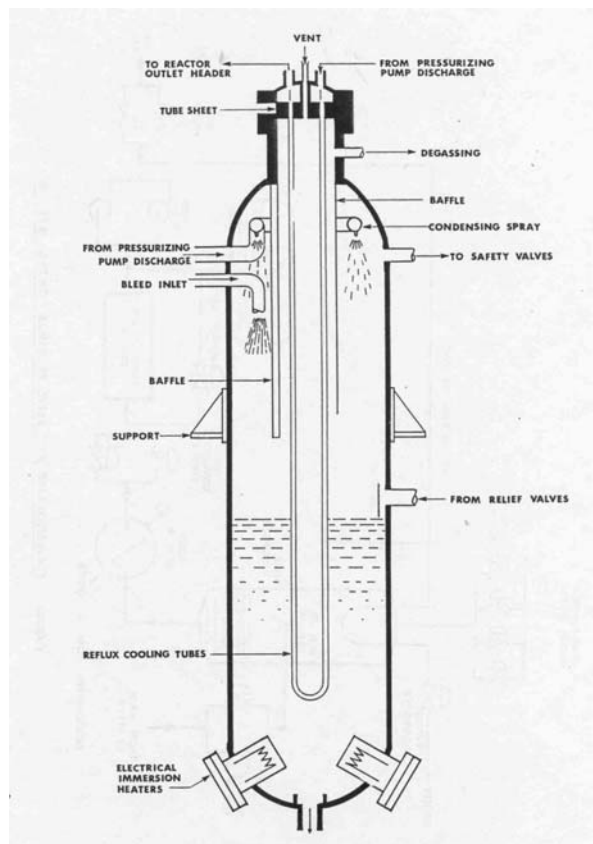


Figure 4-2
Bleed condenser

The bleed condenser also provides pressure relief for the PHT system. If the PHT system pressure is abnormally high, motorized pressure relief

Notes

valves open and discharge PHT coolant directly into the bleed condenser. The bleed condenser itself is protected from over-pressurisation by incorporating relief valves.

4.2.1 Non-Condensable Gases In Bleed Condenser

Non-condensable gases enter the bleed condenser through the cooling spray as noted above and through normal operation where the incoming bleed flashes into vapour. The presence of non-condensable gases in a steam condensing heat exchanger has two negative effects. They:

reduce the local heat transfer rate; and

increase the steam pressure hence temperature.

The condenser design dictates the temperature profile. In the turbine condenser, the highest temperature is at the top and the lowest is at the point of air extraction. We should note that at this point we have the highest concentration of non-condensable gases.

In the bleed condenser, the non-condensable gases collect at the top of the vessel. Dalton's Law tells us that we will have the lowest vapour pressure at the point where the non-condensable gases exert the highest pressure, i.e., at the top.

Due to the tube blanketing, associated with the non-condensable gases, the rate of heat transfer to the coolant will start to fall. Consequently condenser pressure and temperature will rise. In response to the pressure rise, the reflux cooling flow rate will increase.

However, as the non-condensable gases continue to accumulate, the maximum reflux flow will not be able to control the pressure/temperature rise. At this point, the reflux cooling spray valves will open. As explained earlier, this has negative consequences; hence, the only viable solution is to remove the non-condensable gases. This is done through the degassing orifice.

Before we move on, we should note that a significant build up of non-condensable gases, effectively reduces the heat transfer coefficient, hence heat transfer efficiency of our heat exchange process.

4.3 PRESSURIZER

BNGS and DNGS are equipped with a pressurizer (see Figure 4-3). The pressurizer is a large, vertical vessel, which incorporates a steam space above the saturated water line. The water level set point is ramping up with rising reactor power.

Coolant shrinks and swells, associated with power manoeuvres and limited transients are accommodated within the pressurizer.

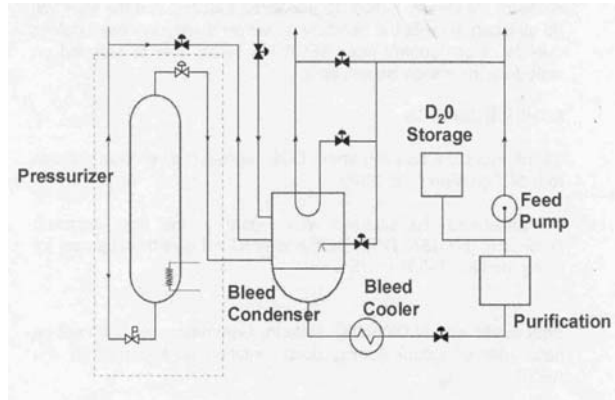


Figure 4-3
Pressure and inventory control

However, the pressurizer cannot accommodate coolant swell and shrink associated with PHT system warm-up and cool-down. In this case transferring the coolant into or out of the D₂O storage tank accommodates the corresponding inventory change. During these operations, the pressurizer is isolated from the PHT system circuit.

Under normal operation, the PHT system pressure is controlled to maintain the highest reactor outlet header pressure at its set point. This is achieved by controlling the vapour pressure, hence temperature in the pressurizer.

As the pressurizer is connected to the reactor outlet header (ROH) via a long pipe, the water in the pressurizer and the pipe are essentially stagnant. Therefore, its temperature can differ from that in the ROH so that, by controlling this temperature, we can control the vapour pressure and hence, PHT system pressure.

Normally, one or two electric immersion heaters maintain the temperature during steady state operation.

Generally speaking, the pressurizer controls PHT system pressure, whilst the feed-and-bleed system maintains system inventory. The later is achieved by transferring coolant to and from the D₂O storage tank in order to maintain pressurizer level at its set point.

The advantage of a pressurizer over a stand-alone feed-and-bleed system is obvious. The pressurizer has a far greater ability to cushion PHT system pressure transients as outlined below.

4.3.1 Pressurizer Level Control

Let us examine the processes that occur in the pressurizer when the PHT system pressure is rising. The higher pressure pushes some coolant from the PHT system into the pressurizer, raising its level. The rising water level compresses the vapour. Since the actual vapour pressure rises above its saturation pressure, some vapour condenses restoring saturation conditions.

The volumetric contraction that occurs during condensation allows water to enter the pressurizer. This minimizes the pressure rise into the PHT system.

If the influx of water is very large, the pressurizer level, hence pressure increase will cause the pressurizer steam bleed valves to open and direct steam from the pressurizer into the bleed condenser. This action helps us to quickly restore PHT system pressure and water level. If this does not happen the pressurizer is isolated to prevent water entering into the bleed condenser.

In case of low PHT system pressure, some liquid moves from the pressurizer into the PHT system circuit. As the pressurizer level falls, the vapour above expands and, therefore, its pressure decreases below the saturation pressure. This causes some water in the pressurizer to flash to steam, which in turn fills the voids left by the loss of liquid. This process minimizes the pressure drop.

If the pressure drop is very large, additional electric heaters are switched on to raise water temperature and, hence, the vapours pressure. If the water level continues to drop, the pressurizer is isolated to prevent vapours entering into the PHT system.

It should be emphasized that these changes of phase – from liquid to vapour or vice versa – make the pressurizer very effective in maintaining PHT system pressure.

4.3.2 Summary of Key Concepts PHT System Pressure Control

PHT system pressure has to be controlled within specified limits to ensure safe reactor operation. In a solid system, the pressures are controlled by a feed and bleed system.

When limited fuel channel coolant boiling is allowed a pressurizer is added to the feed and bleed system. The pressurizer effectively controls PHT system pressure during normal/transient operations. During PHT system warm-up and cool-down the pressurizer is isolated and the pressure is controlled via the feed and bleed system.

When the pressure in the PHT system is very high, relief valves open and directs coolant to the bleed condenser. Due to the pressure, drop the coolant entering the bleed condenser flashes to vapour. This vapour is then condensed by the reflux cooling water and/or reflux spray.

The non-condensable gases in the condenser decrease heat transfer efficiency by forming a gas blanket around the cooling pipes. Consequently, the steam temperature and pressure increase.

The pressurizer is connected to the reactor outlet header via a relatively long pipe. This configuration enables the pressurizer to effectively deal with pressure transients. As the pressurizer is a saturated vessel, containing a liquid and a vapour phase it is very effective in maintaining the PHT system pressure.

4.4 INTRODUCTION TO BOILERS

In previous sections, a detailed explanation of the thermodynamic processes encountered during normal and abnormal operation of the reactor and reactor coolant system was presented.

To safely operate our reactors an adequate reactor heat sink must be available at all reactor power levels, including zero neutron power. In normal operation, our heat sink is provided via the boilers. In this section, we will address boiler operation and thermodynamic processes encountered in the boilers.

When two thermodynamic systems at different temperatures are in thermal contact, heat is transferred from the one with the higher temperature to the one with the lower temperature. In our case heat is removed from the coolant and given to the boiler water. The enthalpy of the coolant decreases and the enthalpy of the boiler water increases accordingly.

A boiler, also called steam generator, is designed so that heat transfer takes place between boiler tube bundles (also called U bundles) and boiler water in the boiling area. If the U bundles are not completely submerged, the heat transfer area, hence heat transfer rate, hence heat sink capability decreases. Therefore, effective boiler water level control is an essential part of reactor operations.

4.4.1 Boiler Water Level

When boiling starts in the boiler, vapour bubbles are formed on the surfaces of the tubes and rise to the surface of the boiler water. These vapour bubbles occupy more space than the boiler water, for example at 4 MPa(a), the specific volume of the steam is about 40 times larger than that

Notes

of the liquid phase. Hence boiling results in a boiler level increase. This process is commonly known as boiler swell. If we have less boiling our boiler level falls, and we experience boiler shrink.

4.4.2 Steady State Shrink and Swell

During steady state operation, the boiler is in a state of thermal equilibrium. The heat rate removal by the steam flow is equal to the heat rate input via the reactor coolant.

At zero reactor thermal power, there is negligible boiling and, for simplicity, we can assume that no vapour bubbles are being formed. The following analysis assumes that constant water inventory is established and maintained throughout the whole load range. When load increases, vapour bubbles are formed, as shown in Figure 4-4.

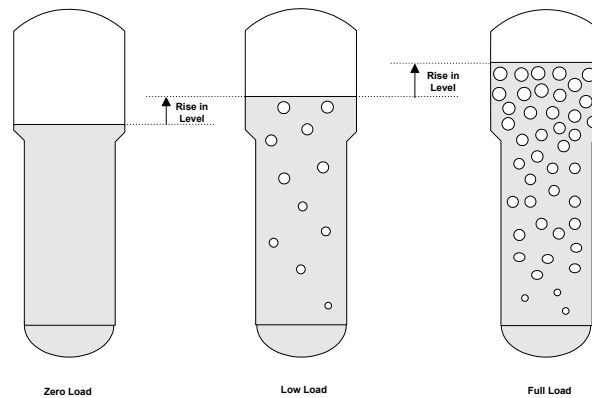


Figure 4-4
Steady State Swell

These bubbles displace the water and cause a rise in level. As the load increases, the level rises until maximum level or we reach full load conditions.

At any given constant load, there is a corresponding fixed water level associated with it. This increase in level, over and above the level in the zero power hot state, is termed steady state swell. Obviously, the largest steady state swell takes place at full reactor thermal power.

When we reduce load, the reverse analogy applies and the water level falls accordingly. At constant partial load, there is a corresponding stable water level. This decrease in level below the level at full reactor thermal power is known as steady state shrink.

Notice that steady state swell and shrink are associated with steady load operation. In practice, this also applies to slow unit loading or unloading.

Under such conditions, the transient effects discussed in the following section are negligible.

4.4.3 Transient Shrink and Swell

During unit loading, unloading and certain upset conditions – such as a reactor trip, the boiler level experiences short-lasting changes referred to as transient swell and transient shrink.

Transient swell is defined as a temporary increase in the level over and above the level which would exist at a given reactor thermal power during steady state operation.

Transient shrink is defined as a temporary drop in the level below the level corresponding to steady state operation at a given reactor power.

Both of these processes are associated with rapid changes in the total volume of the steam bubbles within the boiler water. A transient swell occurs when the volume increases quickly, whereas a transient shrink occurs during a rapid decrease in the volume.

The largest causes of transient swell and shrink are associated with rapid and large changes in reactor power and/or boiler pressure. In either case, the total volume of the steam bubbles within the boiler water changes rapidly. Reactor loading for example produces boiler swell as a result of a fast increase in the heat transfer rate within the boilers.

This is a relatively simple process, however, the effects associated with a drop in boiler pressure are more complex. A drop in boiler pressure causes some boiler water to flash to steam, which in turn, is added to that produced in the boilers, due to the heat supplied by the reactor coolant. In addition, the drop in boiler pressure is associated with an increase in vapour volume because steam is expandable. By this we mean that the specific volume of steam increases with falling boiler pressure.

These two effects combine to cause the boiler water to expand quickly in all directions. The rapid expansion has two dynamic effects, which results in an increase in down comer annulus level as illustrated in Figure 4-5. Boiler level instrumentation is connected to the down comer annulus, and not the central part of the boiler, consequently the effects noted above lead to erroneous level readings, hence level control.

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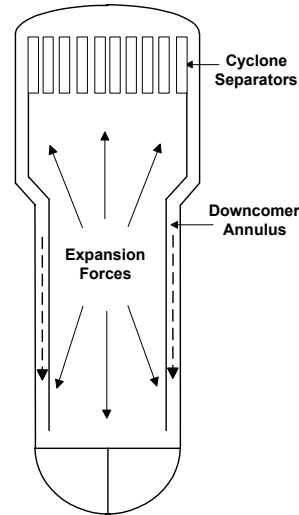


Figure 4-5
Dynamics of a Transient Swell

First dynamic effect: the flow through the cyclone separators increases as the water and steam mixture within the tube bundle is forced upwards. This enhances the flow into the down comer annulus.

Second dynamic effect: the flow of water leaving the down comer annulus is reduced. The expansion forces at the bottom of the tube bundle oppose this flow.

In addition, as the pressure falls, some water in the down comer annulus will flash to steam, which also contributes to the increased level. Note the transient swell will subside once equilibrium conditions are re-established in the boilers.

Major operational causes of a transient shrink are as follows:

A large and rapid decrease in reactor power, e.g., reactor trip or step-back

An increase in boiler pressure, e.g., turbine trip

The total volume of the steam bubbles within the boiler water decreases rapidly, either through the reduced heat transfer from the reactor coolant or through the condensation of some bubbles on rising boiler pressure. Increased boiler pressure would also compress the remaining vapour bubbles.

As the total volume of the steam bubbles collapses, two dynamic effects occur. The first decreases the flow into the down comer annulus as much less water and steam enter the cyclone separators.

The second effectively sucks the water from the bottom of the down comer annulus into the tube bundle. As a result, the water level in the down comer annulus drops.

As soon as the volume of the bubbles stabilizes, the two dynamic effects disappear and equilibrium conditions are restored.

4.4.4 Boiler Level Control

In this section, we will learn why the boiler level set-point is ramped-up with increasing reactor power.

The main reason for ramping the boiler level set-point is to accommodate the transient swell and shrink in the smallest possible boiler. This is shown in Figure 4-6 where two boilers are compared - one with a constant level set point and the other with a ramped level set point.

Both boilers hold the same water inventory at full power (thus, they provide the same post-accident heat sink for the reactor in case of a loss of feedwater incident). Obviously both boilers can accommodate the same swell and shrink. The boiler with a ramped level set point, however, has a much smaller steam drum.

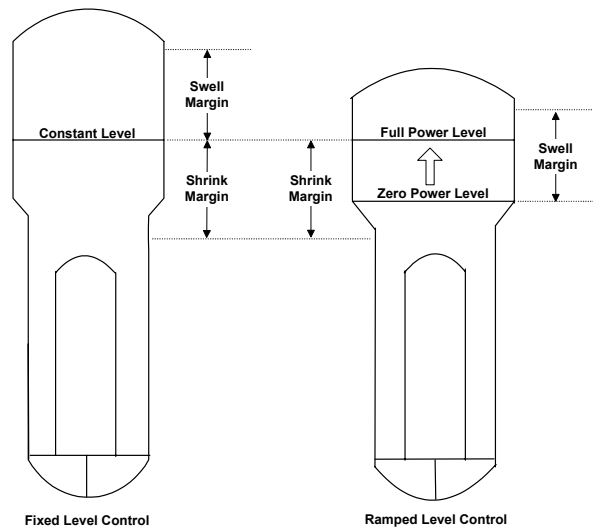


Figure 4-6
Effect of Ramped Level Control

In Figure 4-6, we can see, that at zero power, the level set point is the lowest, while at 100% FP, it reaches its maximum value. This reflects the fact that the amount of transient swell and shrink is dependent on reactor thermal power.

Notes

The largest transient swell, which can occur during power manoeuvres, will happen during fast loading from zero load. Under zero load conditions the boiler level is at its lowest and hence it can accommodate this swell. It should however be noted that no boiler is capable of accommodating the transient swell that would occur during some accident conditions, such as a major steam line break.

Similarly, the largest transient shrink will occur on a reactor trip from full load. Consequently, the boiler water level is the highest at this point. In conclusion: by ramping boiler level with power the vessel can be made smaller while still providing appropriate margins for transient swell and shrink.

4.4.5 Improper Boiler Water Level

Now lets move on and examine the adverse consequences and/or operational concerns associated with low or high boiler water level.

Low boiler level

When the boiler water level is too low, heat sink capability declines. This can have serious consequences as explained below:

A partial uncovering of boiler tubes immediately impairs heat transfer from the reactor coolant, due to the decreased effective tube surface area. This would raise the average coolant temperature, assuming constant reactor power. If no adequate protective actions are taken, excessive boiling of the reactor coolant could result, leading to fuel over-heating and subsequent fuel and fuel sheath failure.

In a worst case scenario, loss of boiler feed-water accident, the water inventory would quickly be depleted. Consequently, the operator will have less time to secure long-term cooling for the reactor fuel. If protective measures are not taken.

As a very low boiler level jeopardizes reactor safety, the reactor is set back/stepped back (depending on the situation) and finally tripped at defined set points. These forced protective actions will obviously result in lost production.

High boiler level

We will consider the following adverse consequences:

High boiler water level results in the flooding of the cyclone separators. This increases the amount of moisture carry-over, hence potential impurities, in the turbine steam.

Prolonged operation under such conditions can have severe detrimental effects on the turbine and associated systems.

If the level continues to rise slugs of water would eventually enter the steam system and hence the turbine. Under such conditions severe, even catastrophic, turbine damage could occur. At the very least the turbine would have to be subjected to an extensive inspection program.

To prevent water induction, into the turbine it is tripped on very high boiler water level. Though this protective measure is mandatory, it results in a loss of production.

4.4.6 Summary of Key Concepts In Section Boiler Water Level

At zero reactor thermal power, there is negligible vapour present within the boiler water. As load increases, vapour bubbles are formed and their concentration progressively increases with load.

The specific volume of vapour is much larger than that of water. Therefore, as vapour bubbles are formed, they displace the boiler water and cause the boiler level to rise. For a given constant load, the level is steady and above the zero load level. This increase in level is termed steady state swell.

The opposite processes occur when the load is gradually reduced. For a given constant load, the level is steady and below the full load level. This reduction in level is called steady state shrink.

Transient swell and shrink are superimposed upon steady state swell and shrink and occur during rapid load changes.

Transient swell occurs during fast reactor loading or falling boiler pressure. As the volume of the vapour bubbles within the boiler water increases quickly, two dynamic effects occur.

Firstly, some water is pushed into the cyclone separators, increasing their load and subsequent flow into the down comer annulus. Secondly, the flow of water exiting the down comer annulus is restricted. This mismatch causes the water level in the down comer annulus to rise. Hence, the indicated boiler level goes up. If the swell is caused by dropping boiler pressure, additional flashing occurs. These factors lead to erroneous level indication, hence control.

Transient shrink occurs during unit unloading and reactor upsets, such as a trip. The other major cause is associated with a fast increase in boiler pressure. This can happen during turbine unloading or certain upsets, such as a turbine trip.

Notes

As the volume of the vapour bubbles within the boiler water rapidly decreases, two dynamic effects occur. Firstly, the flow of water into the cyclone separators is reduced, causing a corresponding reduction in the water flow into the down comer annulus. Secondly, the water at the bottom of the down comer annulus is sucked into the tube bundle area. As a result, the water level in the down comer annulus drops. This also leads to erroneous level indication, hence control.

Boiler level set point is ramped up with increasing reactor thermal power. This minimizes the size of the boiler required to accommodate transient swell and shrink. The savings stem from the fact that the maximum potential for transient swell occurs at zero load, while the maximum potential for transient shrink occurs at full load.

The adverse consequences and operating concerns associated with both high and low boiler water levels are:

For low: a partial uncovering of boiler tubes, and a loss of long term cooling for the reactor fuel.

For high: flooding of the cyclone separators, and slugs of water would eventually enter the steam system and hence the turbine.

4.4.7 Boiler Pressure

To understand the relationship between the boiler pressure and system parameters, we should re-examine the operation of the boiler.

Hot, pressurized heavy water enters the bottom of the boiler and passes through tube bundles. These tube bundles are surrounded by light water, which enters the boiler shell, via the boiler feed pumps. Since the heavy water is hotter than the light water, heat is transferred from the heavy water to the light water.

The temperature of the feed water entering the boiler should be relatively close to the boiler water temperature otherwise excessive thermal shock may cause physical damage. When the feed water leaves the last feed-heater it is still much colder than the boiler water, hence, prior to entering the boilers, the water travels through pre-heaters where it is heated to the boiler's saturation temperature. Pre-heaters are either internal or external to the boiler.

After reaching the saturation temperature in the pre-heater, the water enters the boiler and covers the U tubes. Heat is transferred through the tubes to the surrounding water causing it to boil.

The produced steam (about 90% wet) then leaves the top of the water surface and passes through cyclone separators. The steam quality leaving the cyclone area is much higher, approximately 99.8% dry.

The large quantities of water, separated from the steam, flow to the outside of the boiler shell and into a downcomer annulus. The downcomer annulus is separated from the tube bundle by a shroud. The water flows down the downcomer annulus and under the bottom of the shroud where it enters the tube bundle and more steam is generated. The amount of water entering the tube bundle area from the downcomer is typically ten times higher than the amount of feedwater entering the boiler.

This re-circulation process occurs naturally through the force of gravity; i.e., the heavier water travels down the down-comer annulus forcing the lighter water surrounding the boiler tubes upwards.

Re-circulation ratio

The re-circulation ratio is defined as the number of times 1 kg of light water passes through the boiler until it is totally transformed into vapour. This number is typically around 10.

In Section 1 we noted that as pressure increases, less heat is needed to transform liquid into vapour. The equation that describes this heat transfer process can be applied to our boilers:

$$\dot{Q} = \dot{m} \cdot l_v$$

where \dot{Q} is the heat transfer rate to the boiler water from the reactor, \dot{m} is the boiler water mass flow rate and l_v is the latent heat of vaporization.

At a constant boiler pressure, the latent heat of vaporization remains constant, and the feed water to the boiler and steam flow rate from the boiler are equal and proportional to the heat transfer rate. The re-circulation ratio is not affected by the steam flow.

During warm-up, the pressure inside the boiler increases. The feed water flow is greater than the steam flow. When pressure is small the re-circulation ratio is greater than 10. As pressure approaches normal values, the feed water and steam flows tend to equalise and the re-circulation ratio approaches the normal value.

The pressure and the re-circulation ratio have normal values at the beginning of the cool-down process.

Notes

As the pressure decreases, due to an increase of the steam flow rate out the boiler compared with the feed-water flow rate into the boiler, the re-circulation ratio will increase.

4.4.8 Boiler Pressure and Heat Transfer

Boiling occurs when the temperature of the water reaches T_{sat} for a certain p_{sat} . Therefore, the pressure and the temperature inside the boiler are strictly correlated.

At all our stations, the coolant in the reactor outlet header should remain subcooled under all load conditions. This includes the case where coolant boiling occurs in some fuel channels. As the coolant does not change its phase, the following equation can be used:

$$\dot{Q} = \dot{m}_c \cdot c \cdot \Delta T$$

where:

\dot{Q} is the heat transfer rate from the coolant;

\dot{m}_c is the coolant flow rate;

c is the specific heat capacity of heavy water; and

ΔT is the change in the temperature of the coolant between headers.

As described earlier, the water from the secondary circuit is heated in feed heaters and in pre-heaters (this is done to protect the boiler against thermal stress and to increase the efficiency of the cycle). Therefore, the water from the secondary circuit will change its phase from liquid to vapour in the boiling area. Then, the heat transfer rate balance, becomes:

$$\dot{Q} = \dot{m}_c \cdot c \cdot \Delta T = \dot{m}_{H_2O} \cdot \Delta h_{H_2O}$$

In a steady state situation, when the amount of heat transferred to the water in the boiler is equal to the heat transferred out of the boiler by the steam, \dot{m}_{H_2O} is equal to the steam mass flow rate.

The heat, released by the coolant in the boiler, equals the heat received by the boiler water. But how much of this heat is exchanged between the two systems? Let us take a closer look.

The heat-transfer rate is described by the equation:

$$\dot{Q} = U \cdot A \cdot \Delta T_m$$

where:

\dot{Q} is heat transfer rate in the boilers, closely related to reactor thermal power;

U is overall heat transfer coefficient;

A is effective boiler tube surface area, and

ΔT_m is the average D₂O-to-H₂O temperature differential in the boilers.

If the boiler tube bundle is covered with water and there is no tube fouling or plugging, the minor changes in U that occur due to changes in the quantity of vapour bubbles in the boiler can be neglected. In this situation, we assume no changes occur in the parameters U and A, and hence the only parameter that can change is ΔT_m .

If the boiler water temperature increases for the same coolant temperature, ΔT_m decreases and the amount of heat transferred decreases.

If the boiler water temperature decreases for the same coolant temperature, the amount of heat transferred increases.

A change in boiler pressure will change the T_{sat} in the boiler. Therefore, by controlling the pressure inside the boiler, the amount of heat transferred is controlled. Regulating the steam mass flow rate controls boiler pressure. Hence, the heat transfer rate out of the boiler is proportional to the steam mass flow rate.

When the heat taken out of the boiler decreases, the steam pressure in the boiler increases. If the boiler pressure increases, T_{sat} will increase, and less heat will be transferred to the boilers. This causes the HTS coolant temperature to rise. We will address this situation in more detail when we discuss HTS warm up.

If heat transferred out of the boiler increases, the boiler pressure decreases. T_{sat} will decrease and more heat will be transferred from the coolant to the secondary system and its temperature will fall.

Notes

4.4.9 Boiler Pressure during PHT System Warm-Up And Cool-Down

In this section, you will learn how and why changes in boiler pressure affect the mean reactor coolant temperature during PHT system warm-up/cool-down. This is achieved via the Boiler Pressure Control (BPC) program.

During PHT system warm-up or cool-down, the BPC program controls boiler pressure by adjusting the rate at which boiler steam is discharged to atmosphere or the turbine condensers, depending on the station. AT PNGS, steam is discharged to the atmosphere using the steam reject valves (SRVs). This process increases the consumption of make-up water.

At BNGS and DNGS, steam can be discharged to the condensers and/or the atmosphere. This is done via the condenser steam discharge valves (CSDVs) and the atmospheric steam discharge valves (ASDVs), respectively. Normally, the CSDVs are used to conserve makeup water. However, these valves may not always be available or their opening may be restricted under certain conditions, e.g., very poor condenser vacuum.

Varying the steam discharge rate changes the rate at which heat is rejected in the boilers. If the heat rate supplied to the boilers coincides with this heat rate, we have balanced conditions where the boiler pressure and temperature are constant.

During warm-up, the heat transfer rate to the atmosphere is less than that supplied by the reactor and PHT system pumps. Therefore, the boiler water, steam, and metal temperatures increase. As the temperature of boiler water and steam rises, the mean temperature differential across the boiler tubes will decrease. Thus, heat removal within the boilers begins to decline. In this situation, we have more heat added to the PHT system (from the pumps and the reactor) than is being rejected in the boilers. Therefore, the reactor coolant temperature must rise.

If we assume constant reactor power, the mean temperature differential across the boiler tubes will return to its original value prior to the boiler pressure increase, i.e.:

→ → → →

$$\dot{Q} = U \cdot A \cdot \Delta T_m$$

At the new equilibrium, the increase in T_{mD_2O} will match the increase in T_{mH_2O} , as can be seen when we expand ΔT_m :

$$\rightarrow \quad \uparrow \quad \uparrow$$

$$\Delta T_m \cong T_{mD_2O} - T_{mH_2O}$$

The faster the increase in boiler pressure, the faster the warm-up rate of both the PHT system and the boilers. To increase the warm-up rate, we simply decrease the steam discharge flow rate. Conversely, to decrease the warm-up rate, we increase the steam discharge flow rate. It takes a large amount of heat to accommodate the thermal losses and raise the temperature in the hundreds of tonnes of metals and water that is contained within the PHT system and the boilers. Hence, to affect the desired rate of warm-up, the heat input to the PHT system must increase with temperature.

In practice, the PHT system pumps can provide this heat during the early stages of warm-up when the equipment is relatively cool and, therefore, heat losses (through thermal insulation and with boiler blow-down) are small. However, in the final stages of warm-up, the reactor must provide some of the required heat.

Obviously, in the cool-down scenario, the thermal mismatch is in the opposite direction, i.e., we reject more heat than we supply via the reactor and the PHT system pumps. The resultant changes in boiler pressure, T_{mH_2O} , T_{mD_2O} and ΔT_m , are opposite to those that occur during warm-up. To increase the rate of cool-down, BPC increases the rate of steam discharge. Conversely, to reduce the rate of cool-down, we simply reduce the rate at which steam is discharged.

In most cases, the reactor is tripped during cool-down. The combined decay and PHT system pump heat add up to approximately 5% of full reactor thermal power. Therefore, ΔT_m is very small, and hence, $T_{mD_2O} \cong T_{mH_2O}$. For the same reason, the coolant temperature rise in the reactor is very small, and hence $T_{RIH} \cong T_{ROH} \cong T_{mD_2O}$.

As a digression, the same thermodynamic concepts apply to crash cool-downs and major steam line breaks. The major difference is associated with the rate of cool-down. It is not controlled and is obviously much larger than during normal cool-down.

Here, we will discuss a typical cool-down of the PHT system performed during a unit shutdown.

Notes

Usually, the reactor is tripped before cool-down begins. The cool-down progress is established by monitoring ROH temperature.

The cool-down should be performed at a rate (the proper rate is about $2.8^{\circ}\text{C}/\text{min}$ which equals $5^{\circ}\text{F}/\text{min}$), which is slow enough to prevent excessive thermal stresses, but fast enough to minimize:

the risk of delayed hydride cracking of pressure tubes;

demineralised water losses; and

unit downtime.

In this section, you will learn why PHT system cool-down via BPC cannot maintain the desired cool-down rate all the way down to 100°C . Instead, cool-down via the boilers ceases at 150°C to 165°C , dependant upon the station, at which point the shutdown cooling system (SCS) takes over. The processes involved are somewhat different, dependant upon the stations.

But before we discuss the station-specific differences, let us focus on one common aspect of cooling. To maintain a constant cooling rate, the steam mass flow rate must be approximately constant. But when boiler pressure decreases, so does the steam density. Hence, the volumetric steam flow rate must increase in order to maintain the desired cool-down rate.

Consequently, the valves handling the steam flow must progressively open. Once they are fully open, the rate of cool-down can no longer be maintained. After this point, the mass flow rate of steam would decrease, hence cool-down rate.

At PNGS, steam discharge is controlled via the SRVs. They would be wide open at a boiler steam temperature of about 130°C . To conserve makeup water, cool-down is switched over to the SCS at about 150°C . Of course, to minimize thermal stresses, the SCS is pre-warmed using reactor coolant.

At BNGS and DNGS, steam discharge is initially controlled via the CSDVs. These valves have no problems handling boiler steam at temperatures above $180\text{-}185^{\circ}\text{C}$, which corresponds to boiler pressure of about $1.1\text{-}1.2\text{ MPa(a)}$.

At this pressure, steam density is so low that the valves that admit steam to the turbine gland steam system and steam jet air ejectors in the condenser air extraction system are wide open.

As boiler pressure drops further, the reducing steam mass flow rate can no longer adequately supply the ejectors and glands, hence their performance deteriorates.

Under such conditions, condenser pressure increases and the maximum allowable opening of the CSDVs is restricted in an attempt to limit further pressure increases. This action is referred to as low vacuum unloading. If condenser pressure continues to rise, it will reach a set point and the CSDVs will automatically trip closed.

In any event the magnitude of vacuum unloading increases as the condenser pressure rises. Sooner or later, the CSDVs will no longer be able to maintain the desired cool-down rate.

The ASDVs help but as they are relatively small valves they cannot maintain the cool-down rate. And so, the rate of cool-down progressively decreases until the SCS takes over at about 150°C at DNGS and 165°C at BNGS.

Valving in the SCS any earlier would subject the system to excessive thermal stresses, whereas valving in the SCS any later would unnecessarily extend the cool-down period. This would lead to increased risk of delayed hydride cracking, increased consumption of demineralized water, and extended downtime.

4.4.10 Summary Of Key Concepts In Section Boiler Pressure

Heat transfer between the reactor coolant and boiler water takes place in accordance with the equation:

$$\dot{Q} = U \cdot A \cdot \Delta T_m$$

Under normal conditions, U and A are fixed, hence a change in reactor power causes a proportional change in ΔT_m .

ΔT_m is the temperature differential between the mean PHT coolant temperature and the boiler temperature. Hence as boiler temperature is tied to boiler pressure an increase in boiler pressure causes an increase in boiler water temperature. Assuming a constant heat transfer rate this would cause a corresponding increase in the mean reactor coolant temperature.

During HTS warm-up and cool-down via the boilers, T_{mD_2O} changes with T_{mH_2O} . Usually, the reactor thermal power is very small, and therefore, T_{RIH} and T_{ROH} are very close to T_{mH_2O} .

The rate of warm-up or cool-down is adjusted by varying the rate at which boiler steam is discharged to the main condensers and/or atmosphere, depending on the station.

Notes

The rate of cool-down is established to prevent excessive thermal stresses, while minimizing the risk of pressure tube hydride cracking, and reducing makeup water losses and unit downtime. At about 150-165°C, depending upon the station, cool-down is transferred from the boilers to the SCS, which is pre-warmed to minimize thermal stresses.

4.5 REVIEW QUESTIONS – HTS COMPONENTS

1. All fluid flow from the heat transport system come out of the main system to the bleed condenser.
 - a. State the purpose of the bleed condenser
 - b. Explain how the presence of non-condensable gases in the bleed condenser reduces its efficiency.
 - c. The bleed condenser has two cooling valves the reflux valve and the spray valve. Explain why two are needed and under what circumstances each supplies cooling to the bleed condenser
2. A pressurizer controls the pressure in a heat transport system. Explain how the pressurizer maintains the pressure in the system if there is a sudden reduction in heat transport pressure
3. During changes of power levels in the plant boilers undergo both transient and steady state shrink and swell. Explain these two phenomena.
4. Explain how the boiler pressure is used as the key parameter to match the generator electrical power to the reactor output.
5. Decreasing the boiler pressure will have an effect on the temperature of the reactor inlet headers. State whether the temperature will increase or decrease and explain the reasons for this change.
6. To warm up the heat transport system the reactor power is set to 4% full power and the boiler temperature is ramped up at about 2.8°C a minute. Explain how this warms up the heat transport system and brings the boilers to operating pressure.