•••POWER ENGINEERING

Fourth Class

Edition 3.5

Elementary Physical, Chemical, and Thermodynamic Principles

Part A

Unit A-2

PanGlobal
Partner in Education

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A. Ojimelukwe — **NAIT**

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PanGlobal
Partner in Education
1–1339 40 Ave NE
Calgary, Alberta
T2E 8N6

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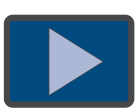</td><td>Media icons show that some form of supporting medium is available. These media may include videos, animations, 2D and 3D models, multi-views of cutaways, simulations, and more. Media elements are available to registered textbook purchasers online via MyPower Study.</td></tr>
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4th Class Edition 3.5 • Part A

UNIT A-2

Elementary Physical, Chemical, and Thermodynamic Principles

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Unit Introduction

This unit starts by describing and defining physical and chemical systems, and explains how atoms and molecules combine to form compounds, mixtures, and solutions. This is the basis for learning how and why chemical reactions occur within processes that Power Engineers manage.

The unit continues with an overview of basic thermodynamics. Thermodynamics explores the relationship between heat and work in systems where energy transfer occurs. The second chapter covers thermodynamic properties such as temperature, pressure, and specific heat within the context of two important thermodynamic laws.

The unit ends with two chapters that cover simple applications of thermodynamic principles: heat transfer methods and the thermodynamics of steam. In order to understand various heat exchanger applications, it is important to understand heat transfer modes, designs, and components. Of special importance is the effect of the heat transfer fluid on heat exchanger performance and maintenance.

The chapter on Steam Thermodynamics applies the basic principles of thermodynamics to water in its different states. The primary focus is on the main working fluid in energy plants: water in its liquid and gaseous states. To understand the thermodynamics of steam, this chapter introduces the Steam Table; its use and application is essential for Power Engineers. With this knowledge, even novice Power Engineers can operate boilers efficiently.

Some previous exposure to the study of chemistry studies may be beneficial in learning this material.

Unit Rationale

The content of this unit underpins the job of the Power Engineer. If properly applied, the knowledge in this unit will help prevent equipment failures, help control energy consumption, and keep energy plants and the natural environment safe.

Power Engineering is all about the science of thermodynamics. Boilers are heat exchangers that transfer heat from a heat source (fossil fuel, electric, nuclear, or solar) to pressurized water and steam. The energy in the steam is converted into mechanical work in a turbine.

Refrigeration evaporators are essentially boilers that operate at low temperature, with refrigerant as the working fluid. Plant equipment, including heat exchangers, compressors, and turbines operate with the basic principles of thermodynamics and fluid mechanics.

This unit will help novice Power Engineers determine the state of a working fluid and how its properties (such as temperature, pressure, specific volume, and enthalpy) explain its behaviour in specific processes. From an operational perspective, it is important for Power Engineers to understand how changes in working fluid properties influence the efficiency of plant equipment.

CHAPTER 1

Introduction to Matter and Chemistry

Learning Outcome

When you complete this chapter you should be able to:

Identify basic types of matter, their properties, and the associated chemical principles.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. *Differentiate among the physical states of matter.*
2. *Differentiate between chemical and physical changes in matter.*
3. *Classify matter as either a type of mixture or a pure substance.*
4. *Describe the purpose and uses of the periodic table using the parts of an atom.*
5. *Describe the three main ways atoms bond together: covalent, ionic, and metallic bonding.*
6. *Discuss chemical equations and their purpose.*
7. *Perform simple stoichiometric calculations.*
8. *Demonstrate how unstable compounds are combined to make stable compounds.*

Chapter Introduction

An important stage in the understanding of how to efficiently operate thermal equipment is to gain knowledge about how that equipment interacts with its environment. This interaction can be either physical or chemical. This chapter begins by describing and defining physical and chemical systems.

Chemical systems are best understood when built on a basic understanding of **molecules** and **atoms**, and the properties they display. These characteristics are presented in a standard form called the periodic table of **elements**.

The characteristics of these components are the foundation for understanding and creating chemical **reaction** equations. By using the **stoichiometry** of these equations, reactant and product amounts can be calculated, and resulting process efficiencies can be determined.

Chemical reactions provide an opportunity to understand how the environment interacts with equipment and processes. With this information, adjustments can be made to the quantities of chemical reactants to improve process efficiencies or prevent unwanted product creation. This can result in removal of harmful compounds from the environment, or replacing them with compounds that are easier and safer to manage.

As a Power Engineer, these skills are essential in order to improve efficiencies and prevent catastrophic failures but also to always work towards keeping workplaces safe. Some previous exposure to chemistry studies would be beneficial in learning this material.

Objective 1

Differentiate among the physical states of matter.

Physical States of Matter

Matter can exist in four main physical states: **solid**, **liquid**, **gas**, and plasma. Figure 1 illustrates the three most common states of matter.

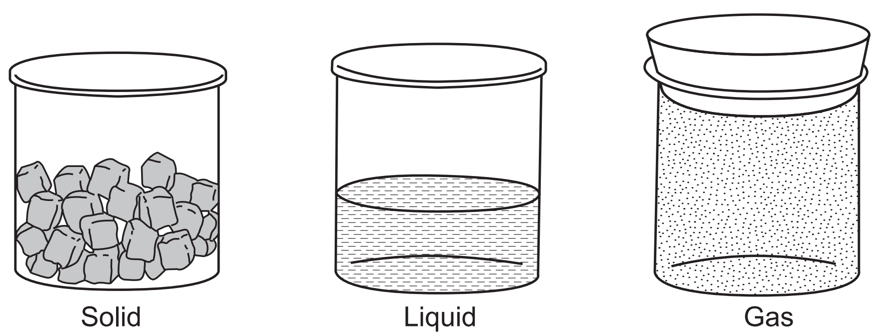
Solids have an ordered arrangement of atoms, molecules, or ions close together, giving them a rigid structure with a definite shape and volume. They have very little capability to compress or expand. Glasses are a special case of solid also called "amorphous" solids. They have a disordered molecular arrangement which are bound together sufficiently to have some rigidity.

Liquids have a definite volume, but no specific shape. Their molecules are close together but are not bound into the rigidity of a solid. They will flow around each other and will assume the shape of the container that holds them.

Gases have no fixed volume or shape because their molecules are in constant motion. They assume the shape and volume of their container. A gas consists mainly of empty space with the molecules of gas far apart from each other. Therefore, they are easily compressible to occupy a smaller volume, as well as expandable to fill a larger volume.

Plasmas are a lot like gases but many of the **electrons** are free (not bound to an atom or molecule) and are not bound by any nucleus. Plasmas are beyond the scope of Power Engineering and will not be discussed further.

Figure 1 – Solids, Liquids, and Gases



The state of matter observed for a particular substance is dependent on its temperature and pressure. At room temperature, most substances are solid; however, some are liquids and a few exist in the gaseous state.

For example, at standard room-temperature conditions and atmospheric pressure (20°C and 101.3 kPa):

- Oxygen, ammonia, carbon dioxide, and methane are gases
- Water, mercury, and bromine are liquids
- Iron and copper are solids

PHASES

A phase is one individual substance in one particular state. For example, a glass of water with ice cubes in it contains two phases: a liquid (water) and a solid (ice). The ice cubes are all considered as part of one solid phase, even though there can be many cubes dispersed through the liquid.

A mixture of water and oil contains two phases, both of them liquid. One phase is liquid water, and the other is the separate distinguishable liquid oil. Even if the mixture is stirred violently so that thousands of tiny droplets of each liquid are dispersed throughout the other, there are still only two phases present. All the water droplets are part of one liquid phase, and all of the oil droplets are part of a different liquid phase.

Changing between phases in a substance generally involves adjusting either temperature or pressure. This may change the physical interaction between the molecules in the substance but are not considered as chemical interactions.

Distinction between Gases and Vapours

A simple view of the difference between a gas and a **vapour** is that a gas is a substance that remains in the gaseous state at room conditions. A vapour is the gaseous phase of a substance that is normally liquid or solid at room conditions. The word "vapour" rather than "gas" is also generally used for any case where the liquid or solid phase is also present, or could be made to appear by increasing the pressure or cooling the system slightly.

Essentially the difference is that a gas will remain as a gas unless conditions change significantly, while vapours can change phase with minimal changes in conditions. For example, at atmospheric pressure, dropping the temperature of carbon dioxide, a gas, from +20°C to −20°C will not change its phase (but a large change to below −78.5°C will change it into a solid form). However, dropping the temperature of water vapour by 1°C can be enough to change it into liquid form.

This distinction can further be illustrated by the following examples:

a) Oxygen and helium are called gases, not vapours since each are a separate compound in one phase.

b) The gaseous phase of gasoline is called a vapour, not a gas since it is a mixture of a number of individual compounds.

c) Mothballs consist largely of the white solid, naphthalene, and the strong smell they emit is due to naphthalene vapour, not naphthalene gas.

Objective 2

Differentiate between chemical and physical changes in matter.

Properties of Matter

Matter is classified according to different characteristics or properties. Since these properties are distinct, they are used to identify and distinguish between different substances. The properties of matter are classified as:

- Chemical
- Physical

Chemical Properties

Chemical properties are only observed when there is a chemical change or reaction that occurs. Essentially, due to a change in the chemical structure of the compound something happens. These properties can be useful in classifying substances. Examples of chemical properties include:

- Heat of combustion
- Toxicity
- Flammability
- Chemical stability

For example, iron will combine with oxygen to produce rust, a new substance. Sulfur will combine with silver to produce tarnish. Magnesium will react with oxygen to produce magnesium oxide, a white powder. The chemical properties of the new substances will be different from the original properties.

Physical Properties

Physical properties are those characteristics used to describe a substance, or those properties that can be observed without a change in the composition of the matter. Physical properties include:

- Colour
- Hardness
- Density
- Boiling point
- Electrical conductivity

Although the physical appearance of the substance may change, the chemical composition is still the same.

For example, a block of ice is composed of a hydrogen and oxygen compound in the solid state. When the ice melts, its physical state changes to a liquid, but it is still chemically composed of the same hydrogen and oxygen compound.

Table 1 shows some of the chemical and physical properties of water.

Table 1 – Properties of Water

Chemical	Physical
Can be decomposed electrically into hydrogen and oxygen	Colourless
Reacts violently with metallic sodium to produce hydrogen	Boils at 100°C and freezes at 0°C
Does not react with gold	Density is 1.0 g/mL
Is a product of the combustion of hydrocarbons	Critical Point is 374°C at 22.1 MPa

Physical properties can be further subdivided, as follows:

a) An **intensive** property is one that is not dependent on the amount of matter. For example, the boiling point of water is 100°C at standard atmospheric pressure of 101.3 kPa. This is true whether boiling one litre or one thousand litres. The colour of iodine remains unchanged, regardless of its volume. All chemical properties are intensive.

b) An **extensive** property is one that is dependent on the amount of matter. Volume and mass are both examples of extensive properties.

Since no two substances have identical physical and chemical properties under the same conditions, this information is used to distinguish between them. For instance, water is the only colourless liquid that has a density of 1.00 g/mL of 1 kg/L and boils at 100°C at standard atmospheric pressure (101.3 kPa).

Changes in Matter

Changes in matter may involve the transformation from one form to another. These changes can be chemical or physical. Both changes require addition or removal of energy.

Chemical Change

Chemical change involves a change in the chemical composition of a substance. The original substances are altered and new substances are formed. Each new substance is different both chemically and physically from the original.

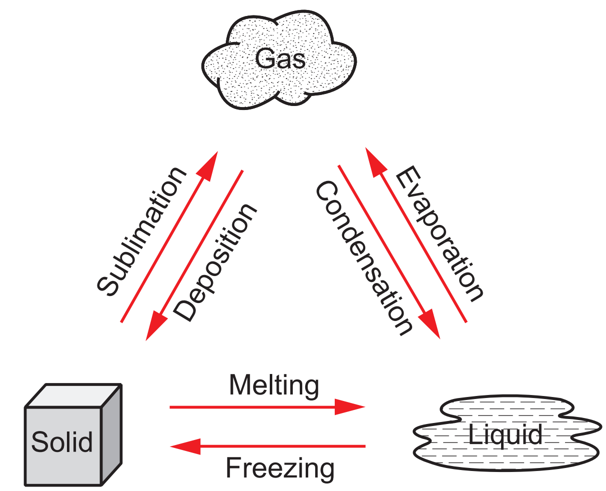
Substances display their chemical properties whenever they undergo chemical reactions. When fuel gases react with air in a combustion reaction, carbon dioxide and water are formed as products. Both differ chemically and physically from the original reactants (i.e. the fuel and the air).

Physical Change

Physical changes occur when physical properties are altered without a change in chemical composition. After the physical change, the original substances remain; therefore, no new substances are formed. A change in physical state (e.g. changes in water from a liquid to a solid or gaseous state) is perhaps the most common type of physical change.

Figure 2 depicts the six possible state changes that matter can undergo, along with the terms used to describe those changes. Most of these terms should already be familiar. The possible exceptions are sublimation, a change from a solid to a gas; and deposition, a change from a gas to a solid.

Figure 2 – Changes in Matter



There are other types of physical changes that do not involve a change of state. They include changes in the size, shape, or subdivision of matter. The grinding of coal into fine particles is an example of this type of physical change.

Behaviour of Substances in Different States

Substances exist as huge numbers of small, distinct units, called molecules.

Gas Molecules

Molecules of a gas are totally independent and move rapidly in all directions. They collide with each other or the walls of the container, without slowing down or sticking together in clumps. This type of behavior is considered perfectly elastic.

This is why gases have no definite shape or volume, and can disperse to all corners of a container. Also, different kinds of gases can spread throughout the container. All kinds of gases are completely miscible (mixable) with each other to the molecular level; over time they always form a uniform (homogeneous) mixture.

The molecules are tiny and far apart, with lots of empty space between them. This allows the gas to easily be compressed to a small fraction of its original volume (compared to liquids or solids). The pressure exerted by a gas is due to force of the molecules colliding with the wall of the container.

A compressed gas has more molecules per unit volume and a greater rate of collisions, so it exerts more pressure inside a container. As the temperature of a gas increases, the velocity of the gas molecules also increases. As a result, if gas in a container of fixed volume is heated, an increase in pressure occurs.

Liquid Molecules

Liquid molecules are much less independent. They attract each other, due to intermolecular forces, and accumulate into clumps too large to "disperse" like gas molecules. This is why liquids settle to the bottom of a container. The molecules are very close together, loosely touching, but not rigidly attached. Thus, the liquid has a definite volume, since the molecules cannot easily be pushed closer together; but no definite shape, since molecules can slide around and over each other.

Solid Molecules

Molecules of a solid are held together rigidly. The molecules are generally slightly closer together and more ordered than in liquids which is why most materials shrink when going from a liquid to a solid phase (ice is an exception to that rule as it actually expands upon freezing). They may become locked into a fixed position relative to their neighbours due to their shape, or to the strength of the attractive forces holding them against each other, so that they cannot easily revolve or slide past each other (compared to liquids or gases).

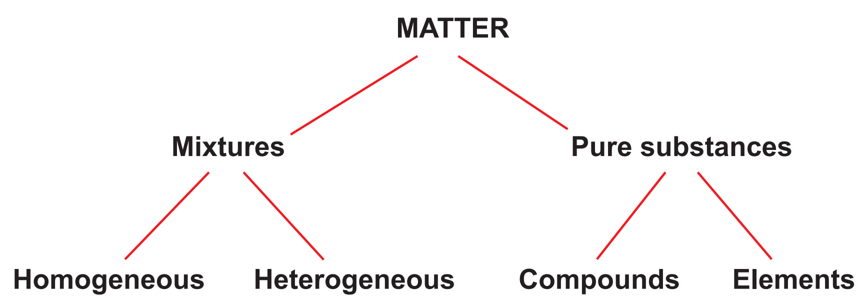
Objective 3

Classify matter as either a type of mixture or a pure substance.

Classification of Matter

Matter can be classified into two main categories, mixtures, and pure substances. They then further divide into four distinct groups, as shown in Figure 3.

Figure 3 – Classification of Matter



Mixtures

Most natural substances in the world are mixtures; that is, they are combinations of two or more pure substances that are not chemically bound to each other. The components of a mixture can therefore be separated by physical means (such as screening and distillation). Although the composition of a mixture can vary, thus leading to variation in properties, each component of the mixture retains its individual composition and properties. Two types of mixtures include:

- Homogenous
- Heterogeneous

Homogeneous Mixtures

A homogeneous mixture, also called a solution, exhibits uniform composition throughout. Therefore, a solution has only one set of properties. In terms of physical chemistry and material science, homogeneous mixtures are possible only when all the components are in the same physical state.

Flue gas is an example of a homogeneous mixture of a number of different gases. Some metal alloys (such as copper-nickel solutions) are examples of homogeneous mixtures of solid elements.

Heterogeneous Mixtures

A heterogeneous mixture has a non-uniform composition as well as differing localized properties. The substances may or may not be in the same physical state.

An oil and water emulsion is a heterogeneous mixture of one physical state, both liquids. A mixture of sand and water is a heterogeneous mixture of two different physical states, solid and liquid.

Pure Substances

A pure substance can be defined as any type of matter having a constant composition and displaying identical properties under identical conditions. There are two types of pure substances: compounds and elements.

Elements

Elements are pure substances that cannot be chemically decomposed into simpler atoms. Each atom of an element will contain the same number of **protons** in its nucleus. As of 2011, there are 118 known elements in existence. They are the building blocks of all other forms of matter. They are distributed very unevenly in the universe, with only a few predominating. Ninety-four of the elements occur naturally, while the remainders are created by decay or by synthesis in a laboratory.

Compounds

A compound is a pure substance that consists of two or more elements, chemically bound together, in fixed proportions by mass. All samples of a given substance will contain the same elements in the same proportions. This is called the Law of Constant Composition. The compounds can only be separated into their constituent elements through chemical means by which the compound is destroyed.

There are millions of compounds known in the world today, but only a small number of elements. Water, for example, is a compound composed of hydrogen and oxygen in fixed proportions. It can be broken down into these two elements by passing an electric current through it, which breaks the chemical bonds.

The physical and chemical properties of a compound are distinctly different from those of the elements from which it is composed. NaCl (table salt) is a white granular solid composed of the elements sodium (Na) and chlorine (Cl). Pure sodium is a silvery metal that reacts violently with water; pure chlorine is a green poisonous gas.

Objective 4

Describe the purpose and uses of the periodic table using the parts of an atom.

Periodic Table of the Elements

A few elements were known in ancient times (e.g. gold, silver, and copper). As early as 330 BC, Aristotle suggested that everything is made up of a mixture of root elements. Over the centuries, as studies gathered more data on the known elements and identified new ones, scientists felt it necessary to organize the large amount of information that was being gathered. To create a universal science, scientists began to give symbols to the elements with the following accepted practices:

1. The symbols assigned to each are characteristic of the element's name.

   The symbol may consist of one, two, or three letters, with the first letter capitalized. For example, calcium is symbolized Ca and hydrogen is symbolized by H.

2. The majority of these symbols have been derived from a Latin-Greek naming system. Symbols come from Latin words, such as: Na (natrium) for sodium, Pb (plumbum) for lead, and Fe (ferrum) for iron.

3. The name of each element sometimes represents its discoverer, but not all elements follow this pattern. For example, the symbol for tungsten is W because tungsten is derived from the German word wolfram.

Jons Berzelius in 1814 was one of the pioneers in this field: establishing the law of constant proportions, discovering new elements, and creating the system of symbols.

Scientists further noticed certain groups of elements possessed similar properties. They grouped these elements together in a graphical format called a periodic table (Figure 4). Dmitri Mendeleev developed the precursor to the current table around 1869.

The periodic table shows the observed properties of individual units of an element called atoms. Atoms are composed of three basic particles; the proton and **neutron** in the nucleus and the electrons surrounding it.

The periodic table provides a great deal of information about the elements, such as their mass, ionic charge, and subatomic particles (electrons, protons, and neutrons). The table also allowed scientists to accurately predict the existence of undiscovered elements based on gaps in the periodic table. Elements with similar characteristics and structures are grouped together in vertical columns called "**Groups or Families**" and horizontal rows called "**Periods.**" Some Groups also have reference names. For example Groups lA, IB, IIA and IIB (except Hydrogen) are called Metals. Group VllA elements are called Halogens.

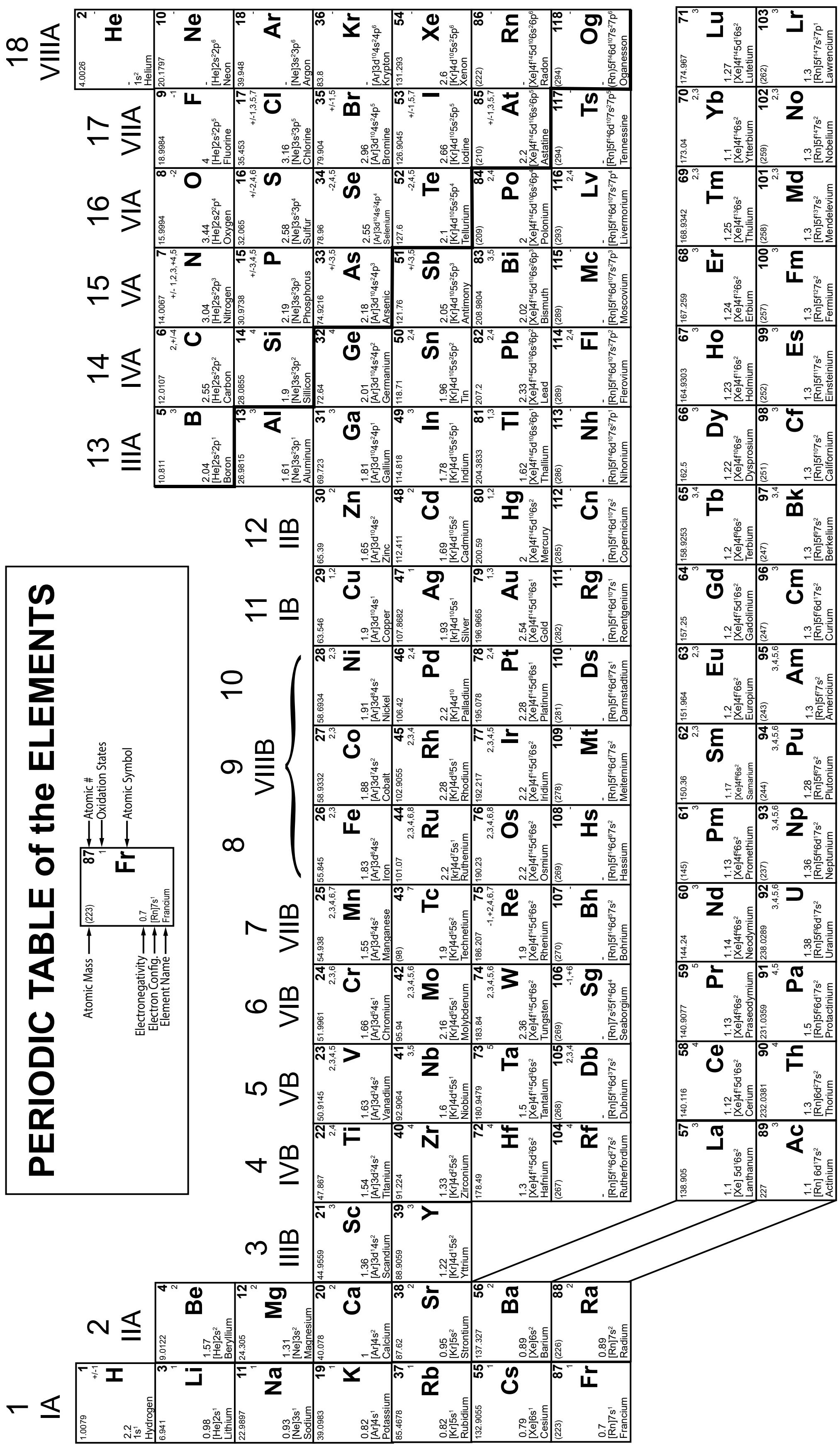
Figure 4 shows a Periodic Table of the Elements. This is the same periodic table as in the PanGlobal Academic Supplement, but made smaller here to fit the page. Refer to the PanGlobal Academic Supplement for a full-size version.

In the periodic table, each element appears in its own box. Each box contains information about the element, as follows:

a) The large letters in the center right area of the box are the "**Atomic Symbol**" of the element. The element's name is in the bottom left corner.

b) At the top right corner of each box is a number, referred to as the "**Atomic Number**." It represents the number of protons in the each atom of an element's nucleus. Other elements have different numbers of nuclear protons. There may be varying numbers of neutrons in the nucleus. For example the two stable isotopes of carbon have 6 or 7 neutrons, but always with the 6 protons. These varying forms are referred to as isotopes. Carbon isotopes are often written as C-12 and C-13. Carbon-12 is the most common isotope.

Figure 4 – Periodic Table of the Elements



Using the Periodic Table

Figure 4 shows that the atomic number for carbon (knowing its symbol is C) is 6. The number in the upper left corner is the "**Atomic Mass**" (for some elements, if the mass is uncertain, it appears in brackets). For carbon, this mass is 12.011. The atomic mass is a measure of the mass of one atom of this element. The atomic mass is essentially the sum of the mass of neutrons and protons in the nucleus plus a small contribution based on the number of electrons in the atom.

- Neutrons are neutrally charged particles (n) with an atomic mass of about 1.
- Protons are positively charged particles (+) with an atomic mass of about 1.
- Electrons are negatively charged particles (–) of negligible mass.

Each proton and neutron essentially has a mass of 1 atomic mass unit (actually about 1.0073 but close enough to 1). Each nucleus usually has an equal number of protons and neutrons. So for carbon, there are 6 protons and usually 6 neutrons, which would make a total of 12 atomic mass units. However, there are isotopes with different numbers of neutrons and protons in the nucleus. To account for this, a weighted average is used.

As a result, the atomic masses of the elements are not often nice round numbers, although they often are taken as whole numbers, (e.g. oxygen atoms are considered 16 atomic mass units even though, in theory they are 15.9994 atomic mass units).

The atomic mass of an element is used in measuring an amount of any substance. Individual atoms are very difficult to measure. Scientific convention has arbitrarily defined a measure called the "**mole**." A mole is the amount of a substance which has as many atoms or molecules as there are atoms in exactly 12 grams of the carbon isotope C-12. Twelve grams of C-12 has approximately 6.022×10^{23} atoms. Therefore, 1 mole equals 6.022×10^{23} atoms.

The number of atoms in a mole is called "**Avogadro's number.**" A quantity of matter with 1 mole of atoms will have the mass indicated on the periodic table as the "atomic mass," in grams. One kilomole of a substance will have the mass on the periodic table as the "atomic mass," in kilograms.

To further clarify, consider one mole of a different element: iron. Like any sample size equal to one mole, a mole of iron will contain Avogadro's number of atoms (6.022×10^{23}). The mass of this mole of iron will be 55.845 grams, which is its "atomic mass" as shown on the periodic table, followed by the unit "grams." If the sample of iron was increased to 1000 moles (or one kilomole), the sample size would contain 6.022×10^{26} atoms. The mass of this kilomole sample of iron would be 55.845 kg.

These masses are called the "**Molecular**" or "**Molar Mass**" and are created simply by adding the unit "gram" to the atomic mass. For carbon, the molecular mass (the mass of one mole of carbon atoms, including all its isotopes) is 12.011 grams.

As shown in Figure 5, protons (+) and neutrons (n) are in the nucleus; while the electrons (–) circle the nucleus in orbits, often called shells. The negative charge in each electron is balanced by the positive charge of a proton. The ratio of electrons to protons will therefore determine the overall charge on the atom. This charge is indicated by adding it as a superscript. For example, if an atom of Chloride has a charge of –1, its symbol will be Cl^{-1} indicating that it has 18 electrons orbiting a nucleus with only 17 protons.

Since opposites attract, the electrons are attracted to the protons in the nucleus. However, electrons also repel each other. As such, the attraction to the nucleus is balanced by the repulsion from other electrons, causing the electrons to stay a certain distance from the nucleus. That is why the orbits, or shells, are so specific. Each shell has a maximum number of electrons it can hold before it is full and the next outer shell starts to fill.

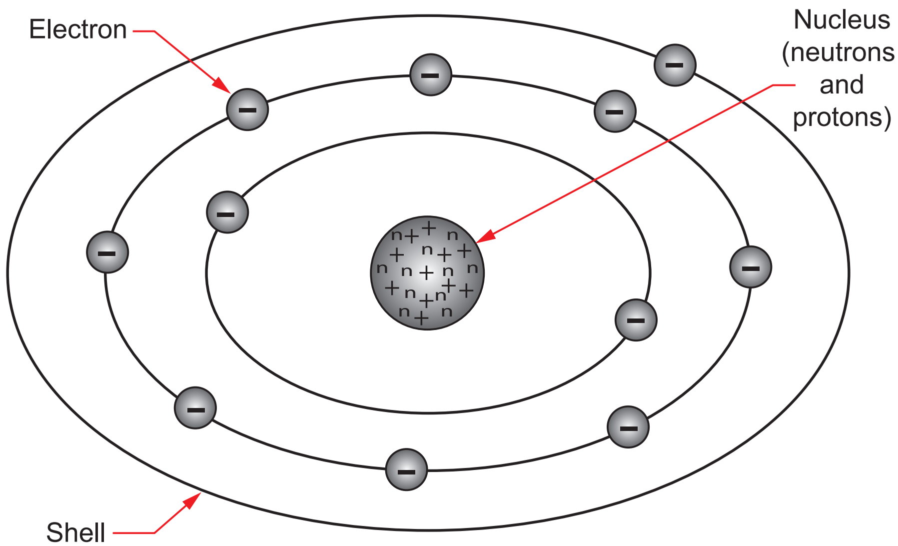
The actual location of the electrons is difficult to determine. For this reason, the "shells" represent regions where electrons are likely to be found. Therefore, it is wrong to think of electrons as following fixed "planetary orbits."

The orbital shapes vary according to the number and energy of the subatomic particles contained within. For example, orbitals containing 2 electrons are called "s" orbitals and generally have a spherical shape. The orbital shapes, and the numbers of electrons found there, are shown in the periodic table as the "**electron configuration**," shown directly above the element name. The orbital shapes are identified with the letters s, p, d and f.

Elements with higher atomic numbers have so many electrons it is impossible to show in a small box on the periodic table. For simplicity, the electron configurations shown in the periodic table name the electron configuration of a simpler element (symbol in square brackets) as the basic configuration, and adds the outer electrons which then differentiate the element in question from the simpler element.

For example, consider the noble gases of column 18. Helium has two electrons, in the first "s" orbital. Its electron configuration is $1s^2$. Neon, the next heavier noble gas, has an electron configuration $1s^2 2s^2 2p^6$. This can be simplified by saying neon's electron configuration is like helium, but with additional electrons: $[He]2s^2 2p^6$. Argon has an electron configuration of $1s^2 2s^2 2p^6 3s^2 3p^6$. It is now difficult to get all this information in a small box! So, argon's electron configuration can be simplified as: $[Ne]3s^2 3p^6$.

Figure 5 – Theoretical Concept of an Atom



"**Chemical reactions**" involve the interaction of electrons between different atoms. They do not involve interactions within the nucleus. Interactions within the nucleus are called "**nuclear reactions**", which are beyond the scope of this chapter.

Most chemical reactions occur between electrons in the outer orbital or "**valence shell**" of the atoms. The electrons in the valance shell are called "**valence electrons.**" These electrons are either removed from one atom, or shared between two or more different atoms. How much sharing occurs is mostly due to the difference in attraction between an atom's nucleus and its valence electrons.

Atoms with a higher attraction between the nucleus and outer electrons will tend to attract electrons from another atom. An element's ability to attract valence electrons is shown in the periodic table as the "**electronegativity,**" which is displayed directly above the electron configuration.

Atoms with a higher electronegativity number have a higher attraction between the nucleus and outer electrons. The opposite is true with atoms having a lower electronegativity number.

The number of electrons generally involved in chemical reactions is shown in the "**oxidation states**". These are displayed directly below the atomic number. The oxidation numbers are often shown as negative or positive indicating the electrons are generally gained (negative oxidation number) or lost (positive oxidation number) in chemical reactions.

Objective 5

Describe the three main ways atoms bond together: covalent, ionic, and metallic bonding.

Atoms, Molecules, and Ions

Atoms are the simplest structures, being comprised of protons, neutrons and electrons. The electrons are found in orbital locations that maximize atomic stability, and minimize the overall electron energy state. Such a stable configuration results from the maximum "filling" of orbital shapes with available electrons.

Orbital shapes are associated with successively higher energy levels. Atoms fill their lowest energy orbital levels first, followed by the filling of progressively higher energy levels. Most often, the highest energy levels are located furthest from the nucleus. Chemical reactions only involve the electrons in the highest energy orbital levels. These orbitals are called "valence" orbitals, and the electrons that reside there are called "valence electrons".

An electron configuration is generally more stable (has lower energy) if its valence orbital is filled. The Noble Gases (Group 18 or Group VIIIA) are examples of single atoms that have completely full valence orbitals. These gases (He, Ne Ar, etc.) are non-reactive and extremely stable, because no individual electron has sufficient energy to move to a higher orbital. This is not the case with the atoms of any other elements. To achieve stability, most atoms interact with other atoms. When atoms interact they do so by associating their valence electrons. These interactions can involve sharing electrons, capturing electrons or losing electrons. When atoms interact, and the resulting structure fills all orbitals with electrons, molecules are created.

For example:

- A Methane Molecule (CH_4) has 4 hydrogen atoms ($4 \times H$) interacting with one carbon atom (C),
- The Oxygen Molecule (O_2) has 2 oxygen atoms ($2 \times O$) interacting, and
- The Carbon Dioxide Molecule (CO_2) has 2 oxygen atoms ($2 \times O$) interacting with one carbon atom (C)

Ions are formed when a stable structure is created that could be more stable if it lost or gained electrons. Some stable ions include:

- The hydroxide ion (OH^-), which has one oxygen atom (O) interacting with one hydrogen atom (H). This structure is stable but would be more stable if it lost 1 electron.
- The ammonium ion (NH_4^+), which has one nitrogen atom (N) interacting with four hydrogen atoms ($4 \times H$). This structure is stable but would be more stable if it gained 1 electron.

Chemical Bonds

A chemical bond provides stable attraction between atoms to form chemical compounds. Atoms interact to form stable configurations. In simplest terms, atoms are most stable when the outer shell is full of electrons. The atom interacts with other atoms to achieve this by either attracting electrons, or losing electrons to other atoms.

Figure 5 shows one valance electron in the outermost shell (the valence orbital). This electron is the easiest to remove from the atom, since it is furthest away from the attraction of the nucleus.

Valence electrons are involved in the atomic bonding that forms molecules. The most common chemical bonds are covalent, ionic, and metallic.

Covalent Bond

In a **covalent bond**, the valence electrons are shared between the atoms. Each outer orbital is considered full. Each orbital has the maximum number of electrons, with credit being given for the electrons that are shared as well as those that are more immediately attached. These are fairly strong bonds and often result in hard, brittle and non conductive material, since the electrons are tightly held in the bond between the atoms.

These compounds tend to have low melting and boiling points, since individual molecules are at best weakly attracted to one another. In a similar way, covalent bonds are not soluble in water.

Schematic Diagram of Covalent Bond

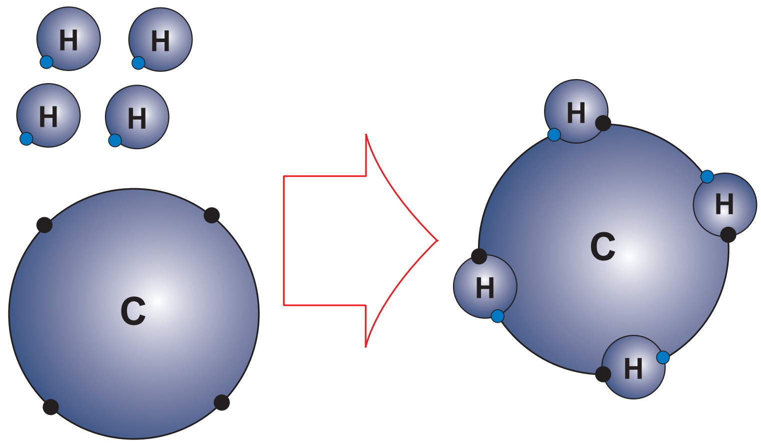
Figure 6 shows a schematic of the bond between the atoms in a methane molecule (the major component of natural gas), whereby four hydrogen atoms (H) combine with one carbon atom (C) to form a methane molecule (CH_4).

The hydrogen atoms (H) have an outer shell that can accommodate 2 electrons, but only 1 electron is present in a neutral hydrogen atom. The carbon atom's outer shell can accommodate 8 electrons, but only 4 reside in the outer shell of a neutral carbon atom. In this way, four hydrogen atoms can form covalent bonds with one carbon atom.

The 4 electrons from the hydrogen atoms (1 from each), and the 4 electrons in the carbon atom outer shell are all shared. Each of the hydrogen atoms looks like it has 2 electrons in its outer most shell, and the carbon atom looks like it has 8 electrons in its outer shell. Note that the electrons are not stationary and continue to travel through the shell; so sometimes an electron is in one of the hydrogen atom's outer shell and at other times, it is in the carbon's outer shell.

Fully Covalent (also called Non-polar Covalent bonds) only occur when atoms of the same element share electrons. Differences in electronegativity determine the covalence of any bond. Thus while the hydrogen molecule is completely covalent (zero electronegativity difference), the C—H bond is *mostly* covalent (also called Polar Covalent), having an electronegativity difference of 0.35. Because the carbon atom has a higher electronegativity number, the electrons will be attracted to the carbon atom more than the hydrogen.

Figure 6 – Theoretical Representation of a Covalent Bond



Ionic Bond

In an **ionic bond**, one or more electrons from the outer shell of one of the atoms actually move over the other atom's outer shell. This will empty the electrons in the outer shell of one atom, and maximize the electrons in the outer shell of the other one. The larger the electronegativity difference between the two atoms, the more likely they are to bond ionically.

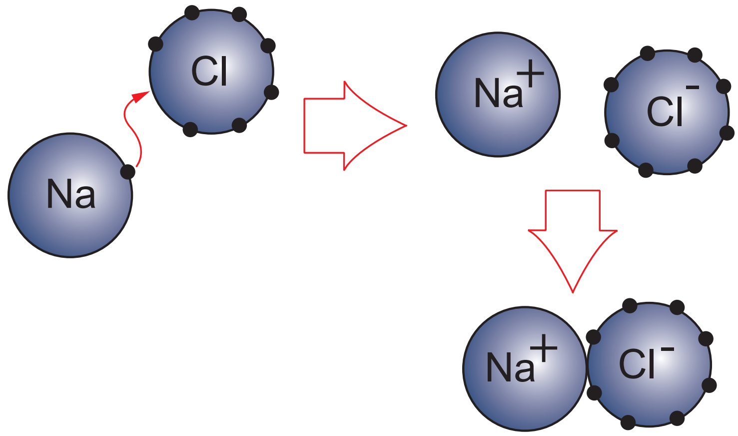
The electronegativity is essentially a measure of how strongly the electrons are attracted to the nucleus and, as a result, how strongly they are held by the atom. The larger the electronegativity of the atom, the more strongly the electrons are held.

Ionic bonds tend to create molecules that are crystalline when solid, have high melting and boiling points, conduct electricity when melted, and are soluble in water.

A common example of an ionic bond between atoms is table salt (sodium chloride or NaCl), which has an electronegativity difference of 2.23 (0.93 – 3.16). A representation of how an ionic bond forms is shown in Figure 7. The sodium ion has 1 electron in its outer most orbital, while the chlorine atom has 7 with room for 8. The pull of the chlorine atom is high enough to pry the electron away, despite the sodium trying to keep it. So the chlorine atom takes away the electron that is in the outer shell of the sodium. This fills up the chlorine atom's outer shell, but then there are more electrons (8 in the outer most, plus 10 others, for a total of 18) than protons (17) in the chlorine atom. It has a net negative charge and can be called an **anion**.

The negative charge is indicated by putting a negative sign in the superscript (Cl^-). The sodium atom then has a net positive charge (11 protons and now only 10 electrons), and can be called a **cation**. The positive charge is indicated by putting a positive sign in the superscript (Na^+). Because the cation and anion are oppositely charged, they attract each other and an ionic bond forms between them.

Figure 7 – Representation of an Ionic Bond



Covalent vs. Ionic Bonds

A number of bonding relationships exist between the fully Covalent and fully Ionic bonds. Bonds may be fully ionic, fully covalent, or somewhere in between. It may be difficult to classify some bonds as ionic or covalent. To properly classify each bond, some simple rules have been established:

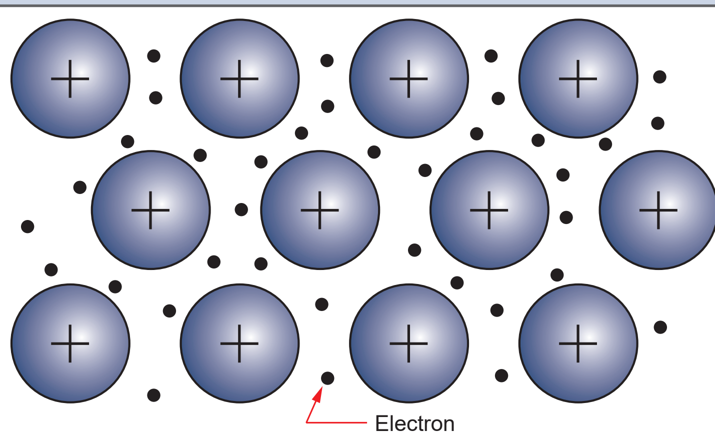
1. If the electronegativity difference (usually called ΔEN) is less than 0.5, then the bond is fully covalent.
2. If the ΔEN is between 0.5 and 1.6, the bond is considered polar covalent.
3. If the ΔEN is greater than 1.6 and a metal (such as Na, Ca, or Zn) is involved, then the bond is considered ionic.
4. If the ΔEN is greater than 2.0, then the bond is always ionic.

Metallic Bond

In **metallic bonds**, the outer most electrons of the metal atoms combine with the outer most electrons of the other metal, to form a sort of cloud of delocalized electrons. This is very different than the "atom to atom" interaction of covalent or ionic bonds.

The loss of the electrons causes the remaining part of the metal atom to become a cation (positively charged atom). This is similar to an ionic bond, but on a much larger scale. The result is a material that has high strength (due to the attraction of the cations to the cloud of electrons), good electrical and thermal conductivity, and good ductility.

Figure 8 – Schematic of Metallic Bond



Objective 6

Discuss chemical equations and their purpose.

Chemical Reactions

A chemical reaction occurs when atoms or molecules come together to form new molecules. This means that bonds between the atoms are broken and new ones formed. In this way, new molecules are formed. The substances that are initially present are called reactants or reagents. The substances that form due to the chemical reaction are called products.

A simple example of a chemical reaction is the burning of natural gas, which is mostly methane. The main reactants are methane and oxygen, which is found in the air.

Methane molecules and oxygen molecules react to form the products carbon dioxide and water. The bonds between methane's carbon and hydrogen atoms will be broken, as will the bonds between the oxygen atoms. New bonds between the carbon and the oxygen will form, as too will new bonds between hydrogen and oxygen.

Bond breaking releases energy, while forming new bonds consumes energy. In this case, more energy is released than consumed, so there is a net release of energy. That is why fire is hot. As the fuel burns, it releases energy.

Chemical Equations

Chemical reactions are effectively illustrated by creating a chemical equation. A chemical equation shows the reactants on one side and the products on the other. In between the two sides is usually an arrow ($\rightarrow$) or a double-sided arrow ($\leftrightarrow$).

The normal arrow indicates that the reaction is irreversible and will only occur in the order shown.

In the case of the double arrow, the reaction is considered an equilibrium reaction and will occur in both directions. When there a certain ratio of product to reactant is exceeded, the reaction may occur in the reverse order; essentially the product will decompose back into the reactant. The exact level at which this occurs has to do with a scientifically determined equilibrium constant.

The form of a simple chemical reaction is

$$aA + bB \rightarrow cC + dD$$

In this case a, b, c, and d are numerical coefficients. They indicate how many molecules of each substance is either required (reactants) or produced (products) in a single reaction. For this illustration, the chemical equation shows that A molecules or atoms react with B molecules or atoms to form the products C and D. The number of A molecules required is "a" and the number of B molecules is "b."

These numbers are the theoretical amounts needed and do not depend on the actual amounts present. It is important to note that chemical equations are based on molecules and not mass or volume. They show the molecular recombination of substances.

An example of a practical chemical equation, for the combustion of methane, is shown in Figure 9. This chemical equation shows the reactants on the left-hand side. It also indicates that one methane molecule (CH_4) reacts with two molecules of oxygen (O_2). The single-sided arrow indicates that this is a nonreversible reaction. The reactants will continue to react regardless of how much product is produced, as long as there is one methane molecule and two molecules of oxygen left. This would not be the case in an equilibrium equation; the reaction would only go to an equilibrium point.

In some cases, one of the reactants gets used up before the other reactants and the reaction stops. For instance, in Figure 9, if all the methane was used up, the reaction would stop, even if there was a lot of oxygen left, or if all the oxygen was used up but there was a lot of methane left. A substance that limits the reaction in that way is referred to as the **limiting reagent.**

In the example just discussed, methane would be the limiting reagent. To determine which, if any, of the reactants would be a limiting reagent, one would have to calculate how many molecules of each substance is available and consider the ratio of the numerical coefficients between the reactants.

In Figure 9, the products, carbon dioxide (CO_2) and water (H_2O) are shown on the right-hand side of the equation. For each molecule of methane and two molecules of oxygen that react, one molecule of carbon dioxide and two molecules of water will form. Figure 9 also shows that some heat will also be released along with the products. This is not usually shown in chemical equations, but is shown here as a reminder. Again, these equations are based on molecules not mass.

Next to each substance in the chemical reaction, there will often be a letter in brackets. In Figure 9, there is a (g) next to the methane (and other substances as well). This is a way for scientists to indicate the physical state of the substances in the reaction. These are not always present when a chemical equation is given. However, if they are present, "g" indicates a gas or vapour, "s" indicates a solid, "l" indicates a liquid, and "aq" indicates an aqueous solution.

Sometimes a reaction needs special conditions to occur, such as energy or a catalyst. These conditions can be noted above the reaction arrow. A catalyst is a substance which itself is not consumed within the reaction, but helps the reaction occur or makes it quicker.

Although it is not consumed, sometimes catalysts break or become poisoned, essentially rendering them ineffective, and must be replaced. In Figure 9, no special considerations are required, so there are none listed.

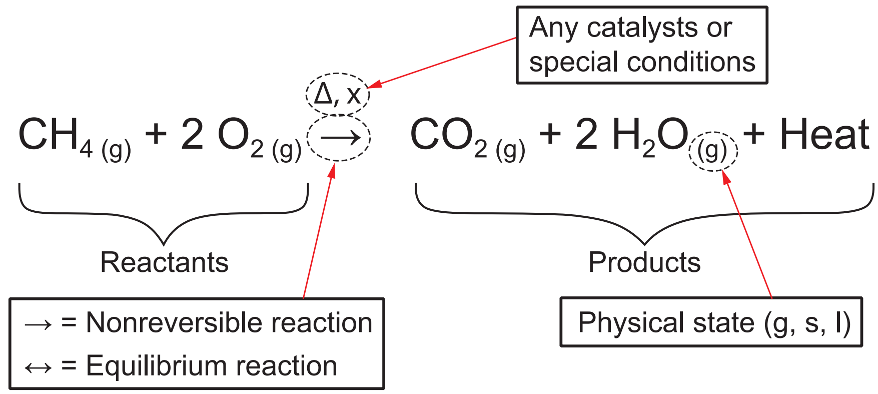
A catalytic converter in a car uses catalysts to convert carbon monoxide (CO) and nitrous oxide (NO) into less harmful products:

$$2\ CO + 2\ NO \xrightarrow{x} 2\ CO_2 + N_2$$

In this case, the presence of the catalyst $\xrightarrow{x}$ within the converter allows the reaction to occur at a quicker rate. Two molecules of carbon monoxide react with two molecules of nitrous oxide; this forms two molecules of carbon dioxide and one molecule of nitrogen.

Another example for indicating heat is applied to the chemical reaction is the $\xrightarrow{\Delta}$ symbol. In the case of the methane reacting with oxygen (combustion) this heat would be the ignition source.

Figure 9 – Example of Chemical Equation



Other Common Reactions in Power Engineering

There are common chemical reactions that occur within the Power Engineering field. Some of the equations appear in Table 2. This list is just a small sampling.

Table 2 – Common Chemical Reactions

Use	Equation	Major Constituents
Oxygen scavenging (higher pressure boilers)	$N_2H_4 + O_2 \rightarrow 2\ H_2O + N_2 \uparrow$	Hydrazine (N_2H_4)
Oxygen scavenging (lower pressure boilers)	$2Na_2SO_3 + O_2 \rightarrow 2Na_2SO_4$	Sodium sulfite (Na_2SO_3)
Passivation	$6\ Fe_2O_3 + N_2H_4 \rightarrow 4\ Fe_3O_4 + 2\ H_2O + N_2$	Protective magnetite (Fe_3O_4)
Iron Rust	$2\ Fe + 2H_2O + O_2 \rightarrow 2\ Fe(OH)_2$	Ferrous hydroxide ($Fe(OH)_2$)
Lime softening	$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2\ CaCO_3 \downarrow + 2\ H_2O$	Calcium bicarbonate ($Ca(HCO_3)_2$) Lime ($Ca(OH)_2$)
Combustion	$C + O_2 \rightarrow CO_2$	
	$S + O_2 \rightarrow SO_2$	
	$2\ H_2 + O_2 \rightarrow 2\ H_2O$	

CAUTION

In a molecular formula, when there is a subscript on an atom, it indicates how many of those atoms are found in the molecule. When the subscript is on a bracket, it indicates how many of the bracketed atoms are found in the molecule.

Chemical reaction equations are mole-based, not mass-based.

Objective 7

Perform simple stoichiometric calculations.

Stoichiometry

Stoichiometry is the component of chemistry that deals with calculations involving reactions. Chemical equations must be used to calculate the amount of reactants required or products produced. The presiding factor is that all the calculations must be made using the concept of moles since the equations are on a molecular basis.

The first step in using chemical equations is to make sure they are balanced. This means that the exact same number of atoms of each element is found in the products as they are in the reactants. For example, the equation for the combustion of methane was given in Figure 9:

$$CH_{4\,(g)} + 2\,O_{2\,(g)} \rightarrow CO_{2\,(g)} + 2\,H_2O_{\,(g)}$$

For carbon, there is one atom in the reactant side and one on the product side.

For hydrogen, there are four atoms on the reactant side and four on the product side. There are two molecules of water formed, each containing two atoms of hydrogen.

For oxygen, there are four atoms on the reactant side and four on the product side. There are two in the CO_2 molecule and one in each of the two water molecules.

Since the number of carbon, hydrogen, and oxygen atoms on both sides of the equation are equal, the equation is balanced. If this were not the case, the numerical coefficients in front of the molecules would have to be adjusted until such a balance was achieved.

The equation for combustion of methane is typical for carbon-based fuels. A carbon and hydrogen based fuel is combusted with oxygen to form carbon dioxide and water. Since boilers use air, the nitrogen component does not participate in the reaction; unfortunately, it becomes an energy loss.

Balancing an Equation

Ethanol, C_2H_5OH is another fuel and can be used as an example. The reactants for its combustion will be C_2H_5OH (ethanol) and O_2 (oxygen). The products will be CO_2 (carbon dioxide) and H_2O (water). An initial chemical equation would look something like

$$C_2H_5OH + O_2 \rightarrow CO_2 + H_2O$$

However, examining the number of atoms on each side reveals that the equation is currently unbalanced. There are two carbons on the reactant side and only one on the product side. There are six hydrogen atoms on the reactant side, but only two on the product side. The oxygen atoms are balanced (three on each side), but it is important to keep track of them throughout the balancing process because this can change.

Putting some numerical coefficients in front of the molecules can balance it. Note that the numbers should always be integers. Fractions are confusing since a portion of a molecule cannot exist.

Balancing the carbon atoms requires two carbon dioxide molecules forming. So put a 2 in front of CO_2:

$$C_2H_5OH + O_2 \rightarrow \underline{\mathbf{2}}\ CO_2 + H_2O$$

This balances the carbon atoms. To account for the six hydrogen atoms present in the reactants, three molecules of water must be produced. So, put a 3 in front of H_2O:

$$C_2H_5OH + O_2 \rightarrow 2\ CO_2 + \underline{\mathbf{3}}\ H_2O$$

Now the carbon and hydrogen atoms are balanced; however, this may have unbalanced the oxygen atoms. In this case, the oxygen atoms have become unbalanced, as there are currently three oxygen atoms on the reactant side and seven on the product side. To restore balance, put a 3 in front of the O_2. This will create seven oxygen atoms on each side and maintain the existing balances.

$$C_2H_5OH + \underline{\mathbf{3}}\ O_2 \rightarrow 2\ CO_2 + 3\ H_2O$$

Now all the atoms are balanced and the equation can be used. Other equations can be significantly more complex.

Calculating Reaction Masses

Once balanced, the equation can be used to determine how much oxygen is needed to burn a given amount of ethanol or how much carbon dioxide will be released.

As an example, if 10 kg of ethanol is burned, how much oxygen is required and how much carbon dioxide is created?

First the molecular mass of ethanol is needed so that its mass can be converted to a molar equivalent (remember chemical equations are based on molecules not mass). Using Figure 4 and the Periodic Table, the molecular mass of ethanol can be calculated.

Note: Remember that the molecular mass of an element is equal to its atomic mass (with "gram" added). The molar mass of a molecule of a substance is the sum of the molar masses of all of the atoms that makes up the substance.

Multiply the number of atoms of each element by its molecular mass. So looking at ethanol, and reading from left to right, there are 2 carbon atoms, 5 hydrogen atoms, 1 oxygen atom, and one more hydrogen atom.

$$2(12.0111)\ g/mole + 5(1.00794)\ g/mole + (15.9994)\ g/mole + (1.00794)\ g/mole = 46.06924\ g/mole$$

(Note: g/mole = kg/kmole)

So 10 kg is equivalent to:

$$\#\ of\ kmoles = \frac{mass\ (in\ kilograms)}{molecular\ mass} = \frac{10\ \text{kg}}{46.06924\ kg/kmoles} = 0.217\ kmoles$$

According to the balanced equation for the combustion of ethanol, the reaction requires three molecules of oxygen for each molecule of ethanol.

At normal pressures and temperatures, oxygen is always found in pairs (O_2). Therefore, in this case, 0.651 kmoles of oxygen (O_2) will be required (3×0.217 kmoles).

The mass of O_2 can be determined by multiplying the number of moles by its molecular mass. The molecular mass for O_2 is 2×15.9994 kg/kmole = 31.9988 kg/kmole so:

$$\begin{aligned} \textit{mass (in kilograms)} &= (\textit{\# of kmoles})(\textit{molecular mass}) \\ &= (0.651\ \textit{kmoles})(31.9988\ \text{kg/kmole}) \\ &= 20.8\ \textit{kg}\ \text{of}\ O_2 \end{aligned}$$

Using a similar process we can calculate the mass of CO_2 produced.

$$CO_2 = (1 \times 12.0111\ \text{g/mole}) + (1 \times 31.9988) = 44.0099\ \text{kg/kmole}$$

For every mole of ethanol used, two moles of carbon dioxide are formed.

In this case, since only 0.217 kmole of ethanol is burned, 2 × 0.217 kmoles = 0.434 kmoles of carbon dioxide are produced.

Finally, since its molecular mass is 44.0099,

$$\begin{aligned} \textit{The mass (in kilograms) of } CO_2 \textit{ produced} &= (\textit{\# of kmoles})(\textit{molecular mass}) \\ &= (0.434\ \textit{kmoles})(44.0099\ \text{kg/kmole}) \\ &= 19.1\ \textit{kg}\ \text{of}\ CO_2 \end{aligned}$$

Objective 8

Demonstrate how unstable compounds are combined to make stable compounds.

Operators can use their understanding of chemical reactions to improve plant efficiency and preserve equipment life, as well as to reduce maintenance. For example, dissolved oxygen in boiler water can lead to pitting and other forms of corrosion that can cause serious equipment failures. By using chemical additives to react with the oxygen, Power Engineers can help prevent corrosion and prolong boiler life. Any oxygen that is present will react with these additives to form other non-harmful molecules. This is known as oxygen scavenging. Table 2 has a couple of examples of oxygen scavenging reactions.

Under some circumstances, hydrazine can also help prevent future corrosion by converting rust in to protective magnetite (Fe_3O_4). In a similar manner sulfites (SO_3^{2-}) can be added that scavenge the oxygen to form sulfates (SO_4^{2-}):

$$2Na_2SO_3 + O_2 \rightarrow 2Na_2SO_4$$

The use of sulfites is quite popular due to their low cost.

In a similar way, sodium hydroxide (NaOH) is added to water to keep the pH levels in the 10 to 12 range. NaOH converts some of the H^+ ions present in the water to water molecules:

$$NaOH + H^+ \rightarrow Na^+ + H_2O$$

However, too much of a good thing can become bad. Caustic embrittlement and cracking can occur if the pH rises too high.

Other problems can occur in boilers due to deposition of solids. As the liquid water is boiled away, salts (specifically Ca and Mg ions) can be left behind, forming scale in combination with carbonate. To prevent this, chemicals containing phosphates are added. Solids are still formed as the phosphates combine with the salts. These solids are in the form of a sludge that does not form scale and can more easily be rid of through blowdown. The reaction is expressed as:

$$5Ca + 3PO_4 + OH = Ca_5(OH)(PO_4)_3$$

However, using too much phosphate can result in tricalcium phosphate deposits, which can be equally bad.

Chapter Summary

This chapter covered the structure of molecules and atoms. It also explained why energy is released through combustion reactions.

Given the molecular structure of a fuel, a balanced chemical reaction equation can be created. The use of the periodic table will help determine molar amounts of reactants required and the resulting products.

This concept is further expanded in other chapters dealing directly with combustion. Chemical reaction equations can also be used to describe the beneficial effects of water treatment and will be used in subsequent chapters.

Chapter 2

Introduction to Thermodynamics

Learning Outcome

When you complete this chapter you should be able to:

Explain the principles and laws of thermodynamics.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. *Define the first two laws of thermodynamics.*
2. *Define heat and specific heat, and perform sensible heat calculations.*
3. *Describe the expansion of solids and liquids.*

Chapter Introduction

Thermodynamics is the science that describes the relationship between heat, work, and the properties of thermodynamic systems. Power Engineers use their understanding of thermodynamic principles to understand and efficiently manage the conversion of one form of energy into another one, as in the conversion of energy from fossil fuels into mechanical work.

The laws of thermodynamics were developed based on the observation of thermodynamic systems. Scientists observed that work and heat are mutually convertible forms of energy. This formed the basis of the **First Law of Thermodynamics**. It was also observed that heat cannot be completely converted to work. This is the basis of the **Second Law of Thermodynamics**.

The Power Engineering field utilizes thermodynamic science in many ways. In the boiler, heat energy is released from the combustion process to turn water into steam. This energy is converted into mechanical work by using a steam turbine. In a refrigeration system, the work performed by the compressor is converted into heat, which is released from the condenser. Every piece of equipment operated by Power Engineers uses basic thermodynamic principles. This includes heat exchangers, compressors, and turbines.

This chapter presents an introduction to the two basic thermodynamic laws. It describes thermodynamic properties such as temperature, pressure, and specific heat. It also applies these laws to the process of heat transfer, and the expansion of liquids and solids.

Objective 1

Define the first two laws of thermodynamics.

The study of thermodynamics began in the 19th century, when there was a need to describe the operation of steam engines, and to determine their operating parameters. The name itself points to the relationship between **heat** and **work**.

The Power Engineer is responsible for transforming heat into mechanical energy with the use of steam or other **heat engines**. The efficient and safe management of this process is dependent on an understanding of Thermodynamics and, most importantly, the first two laws.

First Law of Thermodynamics

The First Law of Thermodynamics (also called the Conservation of Energy principle) states that the increase in **internal energy** of a closed system is equal to the heat supplied to the system minus work done by it. The basis of this law is that heat and work are mutually convertible.

Recall from the study of mechanics that work is a force applied over a distance. The First Law relates the application of heat to the work performed in a system. For example, a diesel engine heats gases within cylinders. The applied heat causes the gases to expand, forcing the pistons to move and perform work.

The First Law also relates the work done in a system to the generation of heat. A bearing supports and reduces friction between moving surfaces. However, no bearing is perfect. Some of the work causing the relative motion of the bearing surfaces is converted to heat.

On Track

A closed system is a process and related equipment, with an imaginary boundary around it. The boundary is called the system boundary. In thermodynamics, a closed system can exchange energy (as heat or work) but not matter, with its surroundings. An isolated system cannot exchange any heat, work, or matter across the system boundary.

The First Law can be stated in this general form (assuming a closed system):

The Change in Work = The Change in Heat

Or,

Net Work = Net Heat

In practice, only a part of the heat is converted into work; or only a part of the work generates heat.

For example, consider the expansion of a gas in a diesel engine cylinder. The heat is supplied intermittently, every time the cylinder "fires." Because the heat supply is intermittent, this is called a **non-flow process**. The intermittent heat supply does work by moving a piston. The internal energy of the gas in the cylinder also increases. Therefore, the First Law of Thermodynamics can be stated as:

$$\text{Heat supplied (Q)} = \text{Increase in internal energy } (\Delta U) + \text{work done (W)}$$

$$Q = \Delta U + W$$

In a boiler supplying steam to a turbine, the First Law of Thermodynamics has a similar form. In these situations, heat supply, heat transfer, and the expansion of the gas (in this case, steam) take place continuously. These processes are called **steady flow processes**. For these processes, the First Law is stated as follows:

$$Q = U + pv$$

In this expression, p is **absolute pressure** and v is volume. The expression "pv" (the product of p and v) is work done, which in this situation is called "flow energy." The internal energy plus the flow energy is equal to the **enthalpy**, represented by the letter Q.

This relationship applies in a steam boiler. As the water is heated, the internal energy increases and work is done in increasing the volume of the water. When steam is produced, the internal energy increases. Work is done to increase the volume during the change from water to steam at constant temperature.

Self-Test 1

a) In a certain process, 500 J of work is performed. 200 J of this work is converted to heat. What is the change in internal energy for the process?

b) 600 J of heat is added to a system. Then, 490 J of work is done to the same system. What is the total heat for the process?

300 J (Ans. a)
1090 J (Ans. b)

Second Law of Thermodynamics

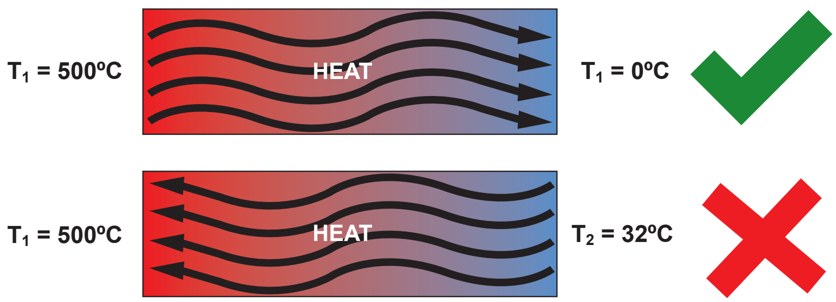
The Second Law of Thermodynamics states that, unaided, heat will flow only from a hot substance to a colder substance. This law defines the direction of energy transfer in a system. The First Law only identifies that energy transfer, conversion, and conservation occur.

Figure 1 provides a simplified illustration of the Second Law.

Side Track

Heat can be moved from a cold substance to a hot substance. However, external work must be performed. In a refrigeration system, this work is performed by the electric motor driving a compressor. This is NOT a violation of the Second Law.

Figure 1 – The Second Law of Thermodynamics



Temperature

The **temperature** of a body is a measure of the speed at which the body's molecules vibrate. A high temperature indicates high molecular vibrational speed (higher energy). A low temperature indicates low molecular vibrational speed (lower energy). A body at high temperature has the ability to transfer heat to a body at a lower temperature. Therefore, temperature differences determine the direction of the heat flow between a body and its surroundings.

For example, if a red-hot piece of metal is set on an anvil, heat will flow from the metal piece to the anvil.

Alternatively, if a block of ice is placed in an icebox, heat will flow from the contents of the icebox to the block of ice.

Heat flows naturally from a point of high temperature toward a point of low temperature. The greater the temperature difference (the temperature gradient), the greater the rate of heat transfer. As heat transfer proceeds, the temperature gradient decreases, and the rate of heat transfer slows. When thermal equilibrium exists (the temperatures equalize), heat transfer stops.

Heat is a measure of the sum quantity of internal vibrational energy in a substance. Temperature, however, is a measure of the intensity of heat in a body.

For example, the heat in a red-hot rivet is concentrated in a small mass. This results in high heat intensity with a very high temperature. Compare the heat intensity of the rivet to that of water in a low-pressure firetube boiler. The boiler has a large quantity of heat due to the large mass of water, but the heat concentration is far lower, resulting in a lower temperature.

Temperature is measured by means of a scaled instrument known as a thermometer. The scale on the thermometer is established with reference to two fixed points: the boiling point of water and the melting point of ice. The space between these fixed points is divided into equal parts. Each division is called a degree (°). The divisions also extend above and below the fixed points, in order to measure temperatures above the boiling point of water, and below the melting point of ice.

Two different temperature scales are used in the SI system: the Celsius and the Kelvin. Two other scales are common in the USA: the Fahrenheit and the Rankine scales.

Celsius

The Celsius scale considers the boiling point of water to be 100°C, and the melting point of ice to be 0°C. There are 100 divisions or degrees between these points.

Kelvin

The Kelvin scale is based on degrees Celsius. It considers **absolute zero** or 0 Kelvin (0 K) to be the lowest possible temperature (which is the same as –273°C). The degree symbol is not used with the Kelvin scale (the scale primarily used in thermodynamics).

Fahrenheit

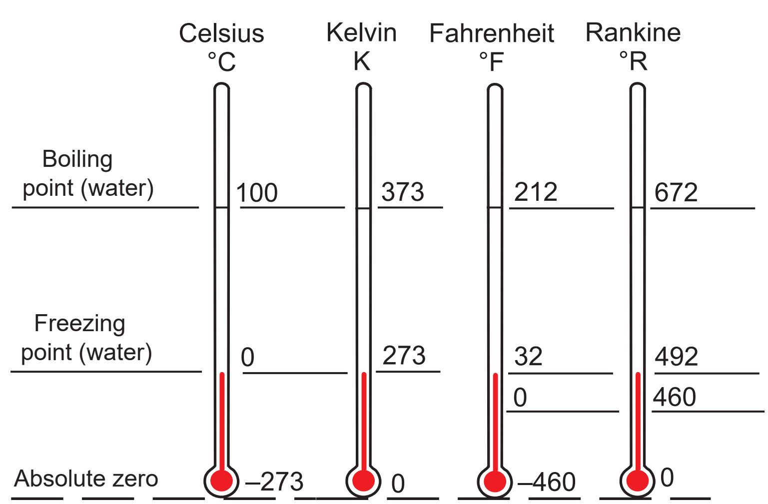
The Fahrenheit scale considers the boiling point of water to be 212°F and the melting point of ice to be 32°F. There are 180 divisions or degrees between these points.

Rankine

The Rankine scale is based on Fahrenheit divisions. It considers 0°R as the lowest possible temperature that may be theoretically achieved (absolute zero). This point is –460°F on the Fahrenheit scale.

These four scales are shown in relation to each other in Figure 2.

Figure 2 – Temperature Scales



The three fixed points used to compare the scales are:

- The boiling point of water
- The freezing point of water
- Absolute zero

On Track

The Celsius scale has 100 increments between the freezing point and the boiling point of water. The Fahrenheit scale has 180 increments between the same points. So, 100 Celsius degree increments equal 180 Fahrenheit degree increments. This means a change of 1°C equals a change of 1.8°F.

The relationships to convert temperatures between °C and °F are as follows:

To convert from °C to °F:

$$°F = 9/5\ °C + 32$$

To convert from °F to °C:

$$°C = 5/9\ (°F - 32)$$

Absolute Scales

It is important in engineering and scientific work to use a temperature scale that begins at absolute zero, the temperature at which all molecular motion is said to completely cease. These temperature scales are called absolute scales. They are particularly useful in the calculation of the behaviour of gases and vapours.

The Fahrenheit absolute scale is called the Rankine scale and begins at 492° below the melting point of ice, or 460° below zero, on the Fahrenheit scale.

The relationship between Fahrenheit and Rankine temperatures can be expressed as:

$$°R = °F + 460$$

The Celsius absolute scale is called the Kelvin scale. It begins at 273° below the melting point of ice, or 273° below zero, on the Celsius scale.

The relationship between Celsius and Kelvin temperatures can be expressed as:

$$K = °C + 273$$

On Track

The size of the degrees or divisions on both the Fahrenheit and Rankine scales are the same.

The size of the degrees or divisions on both the Celsius and Kelvin scales are the same.

The difference between absolute zero and the freezing point of water is 492 Rankine degrees, or 273 Kelvin increments. The ratio 492 to 273 is the same as 9 to 5. Therefore, a difference in temperature of 9°R is the same as 5 K.

The relationship between Rankine and Kelvin temperatures can be expressed as:

$$°R = 9/5 \times K$$

$$K = 5/9 \times °R$$

Self-Test 2

Convert the following temperatures into the other three scales.

	°C	°F	K	°R
a)	45°C			
b)		122°F		
c)				40°R
d)		–40°F		
e)	–89.2°C			
f)			273.2 K	

113°F, 318.2 K, 573°R (Ans. a)
50°C, 323.2 K, 582°R (Ans. b)
–251.1°C, –420°F, 22 K (Ans. c)
–40°C, 233.2 K, 420°R (Ans. d)
–128.6°F, 184 K, 331.4°R (Ans. e)
0°C, 32°F, 492°R (Ans. f)

Measuring Temperature

There is a wide range of instruments available for the measurement of temperature. The particular type chosen depends upon the temperatures to be measured, and the conditions under which the measurements will be made. Some of the types used in measurement of temperature are:

- Liquid-in-glass thermometers
- Bi-metal thermometers
- Pyrometers
- Infrared thermometer

Liquid-in-Glass Thermometers

The mercury or alcohol thermometer is constructed of a thick-walled glass tube with a small bore. A bulb is on one end, and the other end is sealed. Before sealing, the bulb and glass tube are completely filled with liquid at the highest temperature of the thermometer. As the liquid cools, the level drops, and a vacuum is created above the liquid. The liquid height is calibrated against temperature standards (usually the freezing point and boiling point of water).

Bimetal Thermometers

Bimetal thermometers are constructed of two dissimilar metals that are rigidly fixed together. Due to their different coefficients of linear expansions, these bimetal strips will bend when subjected to temperature changes. This movement can be transmitted directly or by linkages, to a pointer that indicates temperature on a graduated scale.

Pyrometers

The term pyrometer is used to describe instruments that measure temperatures at the surface of an object. They are typically used in temperature ranges above that suitable for other kinds of thermometers. Three common types are the thermoelectric, optical, and infrared.

Thermoelectric Pyrometer

The thermoelectric pyrometer uses a thermocouple to produce an electrical voltage which is proportional to temperature. A thermocouple consists of two wires made of different metals. The two wires are joined together at each of their ends. If one of the joints is at a higher temperature than the other, then a voltage is produced in the wires. The high temperature joint is called the hot junction, and the other joint is called the cold junction.

The voltage produced is proportional to the temperature difference between the junctions. This voltage is measured by means of a millivoltmeter, which is calibrated to read in degrees of temperature.

Optical Pyrometer

The optical pyrometer is suitable for measuring extremely high temperatures. Its operation is based on the fact that the intensity of light emitted from a hot surface varies with the temperature of that surface.

In the pyrometer, the brightness of the object to be measured is compared to the brightness of a filament. The filament brightness is produced by an electric current that heats the filament. The amount of current required to produce the necessary brightness is measured, and is proportional to the temperature of the object.

Infrared Thermometer

An infrared thermometer is a digital device capable of measuring the temperature of an object at a distance by detecting its infrared energy emissions. The radiation is directed at a thermocouple, which is capable of producing an electric current when it is partly heated. The thermocouple will generate a higher current according to the heat emitted. The current is calibrated against the temperature. This device is sometimes called a temperature gun or a laser thermometer, and is often used to detect the temperature of moving or inaccessible objects. The laser is only used for aiming purposes, and not for the actual temperature measurement.

Objective 2

Define heat and specific heat, and perform sensible heat calculations.

Heat

Heat is a form of energy which may be transferred from one body to another by virtue of a difference in temperature. If heat is added to a body, its internal energy increases. Heat only flows spontaneously from a hot body to a cold body in a closed system. If it is required to transfer heat from a cold body to a hot body (as in refrigeration), then external work is required to make the transfer.

On Track

There can be no heat transfer if there is no temperature difference between the heat source and the body under consideration.

Heat Units

The joule is the basic unit of all energy, including heat. Therefore, units of heat are expressed in joules or multiples of joules.

1 kilojoule (kJ) = 1000 J or 10^3 J

1 megajoule (MJ) = 1 000 000 J or 10^6 J

Mechanical Equivalent of Heat

Experiments have shown that one joule is equivalent to the work done by a force of one newton moving through a distance of one metre in the direction in which the force is applied. Thus, the work done is one newton metre which is equal to one joule.

1 Nm = 1 J

In other words, the unit of work is numerically equal to the unit of heat.

Sensible Heat

Sensible heat is the heat that, when added or removed from a substance, causes its temperature to change. In other words, sensible heat is heat that can be sensed or detected by a thermometer.

Latent Heat

Latent heat is heat that, when added or removed from a substance, does not cause a change in temperature. Rather, latent heat causes a substance to change state (solid-liquid, liquid-gas, or solid-gas).

Specific Heat

The **specific heat** of a substance is the quantity of heat required to raise the temperature of a unit mass of the substance by one degree. Expressed in SI units, the specific heat of a substance is the quantity of heat (in kJ) required to raise 1 kg of a substance 1 K (or 1°C). For example, the specific heat of fresh water is 4.183 kJ/kg°C (4.183 kilojoules per kilogram, per degree Celsius).

Other substances require different amounts of heat energy to have one kg of their mass raised one degree Celsius. For instance, brass has a specific heat of 0.383 kJ/kg°C, aluminum is 0.909 kJ/kg°C, and ice is 2.135 kJ/kg°C.

Heat Quantities

The quantity of heat absorbed by a substance as it increases in temperature depends on three factors.

1. Temperature rise
2. Mass of the substance
3. Specific heat of the substance

Heat quantity can be expressed in the form of a formula as follows:

$$Q = mc\,(t_2 - t_1)$$

Where

Q = Heat absorbed by the substance (kJ)

m = Mass of the substance (kg)

c = Specific heat of the substance (kJ/kg°C)

t_1 = temperature of the substance before heating (°C)

t_2 = temperature of the substance after heating (°C)

The expression "$t_2 - t_1$" can be replaced with the Greek letter Delta (Δ) followed by the letter *t*. The letter Δ is used to mean "difference in." In this case, the expression $Q = mc\,(t_2 - t_1)$ can be stated as $Q = mc\Delta t$.

On Track

When using the sensible heat formula, temperature can be expressed in either Celsius or Kelvin. However, both t_1 and t_2 must be in the same units.

Example 1

Find the quantity of heat required to raise the temperature of one kilogram of copper from 10°C to 60°C, if the specific heat of copper is 0.388 kJ/kg°C.

Solution 1

$$\begin{aligned} Q &= mc\,(t_2 - t_1) \\ &= 1\text{ kg} \times 0.388\text{ kJ/kg°C} \times (60°C - 10°C) \\ &= 1\text{ kg} \times 0.388\text{ kJ/kg°C} \times 50°C \\ &= 1\text{ kg} \times 19.4\text{ kJ /kg} \\ &= \mathbf{19.4\text{ kJ (Ans.)}} \end{aligned}$$

The quantity of heat required to raise the temperature of the water is 19.4 kJ.

Example 2

Find the quantity of heat required to raise the temperature of one litre of fresh water from 10°C to 60°C, if the specific heat of fresh water is 4.183 kJ/kg°C. Assume that 1 litre of fresh water has a mass of 1 kg.

Solution 2

$$Q = mc\,(t_2 - t_1)$$
$$= 1\text{ kg} \times 4.183\text{ kJ/kg°C} \times (60°C - 10°C)$$
$$= 1\text{ kg} \times 4.183\text{ kJ/kg°C} \times 50°C$$
$$= 1\text{ kg} \times 209.15\text{ kJ /kg}$$
$$= \mathbf{209.15\text{ kJ (Ans.)}}$$

The quantity of heat required to raise the temperature of the water is 209.15 kJ.

In Examples 1 and 2, the masses and temperature rises were the same. However, the kilogram of copper needed less than one-tenth the heat to change temperature, compared to the kilogram of water. Obviously, the higher the value of the specific heat of a substance, the greater the amount of heat required to raise the temperature of a given mass of the substance.

Table 1 lists the specific heat of some common substances.

Table 1 – Specific Heat

Substance	Specific Heat
Water	4.183 kJ/kg°C
Ice	2.135 kJ/kg°C
Copper	0.388 kJ/kg°C
Aluminum	0.909 kJ/kg°C
Brass	0.383 kJ/kg°C
Steel (Mild)	0.494 kJ/kg°C
Cast Iron	0.544 kJ/kg°C

On Track

When using the Sensible Heat Formula $Q = mc(t_2 - t_1)$, it is important to remember that the mass does not undergo a phase change (from solid to liquid, or liquid to gas) as its temperature progresses from t_1 to t_2. In other words, the formula only works in a temperature range within which the substance does not melt, freeze, vapourize, or condense. The heat determined by this formula must therefore be sensible heat.

Self-Test 3

a) It takes 492.4 J to heat 25 grams of a copper alloy from 25°C to 75°C. What is the specific heat of the alloy in J/g°C?

b) The specific heat of iron is 0.544 kJ/kg°C. How much heat is given off if the temperature of a 1.5 kg block drops from 80°C to 25°C?

c) Find the mass of a sample of water if its temperature dropped 28.8°C when it lost 870 kJ of heat. Use the specific heat of water as 4.183 kJ/kg°C.

d) A piece of copper has a temperature of 122°C. When the metal is placed in 9.22 kilograms of water at 25.2°C, the temperature of the water rises by 7.1°C. What is the mass of the metal if the heat lost from the metal is solely transferred from the copper to the water?

0.3939 J/g°C (Ans. a)
44.88 kJ (Ans. b)
7.22 kg (Ans. c)
7.87 kg (Ans. d)

Objective 3

Describe the expansion of solids and liquids.

Thermal Expansion of Plant Equipment

Almost all solids expand when undergoing a temperature increase. If a rod or pipe of a given length is raised in temperature, its increase in length will be directly proportional to its initial length, and to the rise in temperature. A rod, plate, ball, or pipe will also increase in other linear dimensions, such as circumference and diameter.

Power plant equipment is constructed of plates, tubes, pipes, shafts, and irregularly shaped castings, made of a variety of metals. During normal operation, various power plant equipment can be exposed to hot air, hot flue gas, cold air, cold water, hot water, saturated steam, or superheated steam. In each case, changes in thermal conditions causes these components to expand or contract.

The thermal expansion and contraction of equipment occurs in both an absolute and a relative sense. Boilers undergo absolute expansion in total volume as heated. To accommodate this expansion, top supported boilers are free to expand in length. Bottom supported boilers are free to expand in height. Bottom supported boilers are only fastened to the boiler room floor at one end to permit expansion in length.

Regarding relative expansion, interconnecting piping to and from the boiler also expands and contracts. The relative expansion between a boiler and its piping connections must be compensated for with various expansion joints.

Operators must be aware of the effects of thermal expansion while warming equipment, such as heat exchangers, boilers, and steam turbines. Failure to account for thermal expansion leads to restricted movement, distortion, localized stress, rubbing of rotating parts on stationary parts, and equipment failure.

Failure to consider the effects of thermal expansion can cause failure of costly power plant equipment. Here are three examples:

a) Cold firetube boilers, when fired too hard, develop complex stresses in the tube sheets, because the furnace tube expands at a faster rate than the firetubes. Over time, these stresses can loosen firetubes in their seats, crack furnace tube welds, and cause ligament cracks.

b) Hot boiler heat transfer surfaces, if contacted by cold feedwater, can rapidly contract on the cold-water side. This differential expansion between the hot and cold sides of the heat transfer surfaces creates thermal shock, which can lead to sudden brittle failure of the metal heat transfer surface.

c) When turbines warm up, rotating parts expand faster than stationary parts. The resulting differential expansion can cause turbine blades to contact each other with great force, causing tremendous destruction.

To mitigate the adverse effects of thermal expansion, equipment manufacturers provide detailed instructions on warming, cooling, and rates of load change. These, as well as site-specific operating procedures, must be followed when operating power plant equipment that may undergo temperature changes.

Linear Expansion of Solids

The increase in linear dimension due to heating is referred to as **linear expansion**. The change in length per unit length, per degree rise in temperature is known as the **coefficient of linear expansion**.

On Track

Linear dimensions include length, width, height, distance, perimeter, circumference, diameter, and radius. The linear expansion formula below is used for determining any changes in linear dimension due to temperature change.

Linear expansion is proportional to the original length, the temperature change, and a material's coefficient of linear expansion. Mathematically, this relationship is:

Change in length = Original length × Coefficient of linear expansion × Temperature difference

$$\Delta L = L\,\alpha\,(T_2 - T_1)$$

Where

ΔL = Change in length

L = Original length

α = Coefficient of linear expansion

$(T_2 - T_1)$ = Temperature difference

Example 3

What is the increase in length of a steel bar 10 m long if its temperature is increased from 20°C to 70°C? The coefficient of linear expansion of steel is 0.000012/°C or 12×10^{-6} /°C.

Solution 3

Change in length = Original length × Coefficient of linear expansion × Temperature difference

$$\Delta L = L\,\alpha\,(T_2 - T_1)$$

$$\Delta L = 10\text{ m} \times 0.000\,012/°\text{C} \times (70°\text{C} - 20°\text{C})$$

$$= 10\text{ m} \times 0.000\,012/°\text{C} \times 50°\text{C}$$

$$= \mathbf{0.006\text{ m (Ans.)}}$$

The bar increases in length by 0.006 m or 6 mm.

The answer to Example 2 (0.006 m) is difficult to visualize. It is better to state the answer as 6 mm, which is easier to visualize by looking at a ruler.

On Track

The coefficient of linear expansion gives the change in length per unit length per degree change in temperature. If the length is given in metres, the change of length will be in metres. If the length is expressed in millimetres, then the change of length will be in millimetres.

Linear expansion must be taken into account when assembling metal equipment components, which may undergo changes in temperature. This is especially important when the parts being assembled are made of different materials, with different coefficients of expansion. This means each material expands or contracts by different amounts for the same temperature change.

Coefficients of linear expansion for some common materials are listed in Table 2. Note that brass and copper expand and contract considerably more than steel does for the same temperature changes.

Table 2 – Coefficients of Linear Expansion

Material	Coefficient of Linear Expansion Between 0°C and 100°C
Steel	12×10^{-6}/°C
Copper	16.5×10^{-6}/°C
Brass	18.4×10^{-6}/°C
Aluminum	23.8×10^{-6}/°C
Cast Iron	10.4×10^{-6}/°C

Allowances must always be made to prevent parts from interfering with each other at high temperatures. When steam or feedwater piping is erected, the expected expansion is calculated. Then allowances are made with the use of expansion bends or joints.

Example 4

A spherical steel pulverizer ball is found to be 305 mm in diameter, at 8°C. When in operation, the pulverizer ball reaches 210°C. Determine the following:

a) The increase in the diameter of the pulverizer ball.
b) The final diameter of the pulverizer ball.
c) The increase in surface area of the pulverizer ball.
d) The increase in volume of the pulverizer ball.

Solution 4a

The diameter of the pulverizer ball is a linear dimension. Therefore, using the formula for linear expansion:

Change in length = Original length × Coefficient of linear expansion × Temperature difference

$$\Delta L = L\,\alpha\,(T_2 - T_1)$$

$$\Delta L = 305 \text{ mm} \times 0.000\,012/°C \times (210°C - 8°C)$$

$$= 305 \text{ mm} \times 0.000\,012/°C \times 202°C$$

$$= \mathbf{0.739 \text{ mm (Ans.)}}$$

The pulverizer ball increases in diameter by **0. 739 mm**.

Solution 4b

Final diameter = original diameter + change in diameter

= 305 mm + 0.739 mm

= **305.739 mm (Ans.)**

The final diameter of the pulverizer ball is **305.739 mm**.

Solution 4c

Change in Surface Area = Final Surface Area (A_2) – Original Surface Area (A_1)

Area of a Sphere (A) = $4\pi r^2$

Change in the Surface Area of a Sphere (ΔA) = $A_2 - A_1$

Radius (r) equals Diameter (d) divided by two.

Therefore:

$$r_1 = d_1 \div 2 = 305 \div 2 = 152.5 \text{ mm}$$

$$r_2 = d_2 \div 2 = 305.739 \div 2 = 152.87 \text{ mm}$$

Therefore:

$$\begin{aligned}
\Delta A &= A_2 - A_1 \\
&= 4\pi r_2^2 - 4\pi r_1^2 \\
&= 4\pi\,(r_2^2 - r_1^2) \\
&= 4\pi[(152.87 \text{ mm})^2 - (152.5 \text{ mm})^2] \\
&= 4\pi \times 112.83 \text{ mm}^2 \\
&= \mathbf{1417.9\ mm^2\ (Ans.)}
\end{aligned}$$

Solution 4d

Change in Volume = Final Volume (V_2) – Original Volume (V_1)

Volume of a Sphere (V) = $4/3\pi r^3$

Change in the Volume of a Sphere (ΔV) = $V_2 - V_1$

Therefore:

$$\begin{aligned}
\Delta V &= V_2 - V_1 \\
&= 4/3\pi r_2^3 - 4/3\pi r_1^3 \\
&= 4/3\pi\,(r_2^3 - r_1^3) \\
&= 4/3\pi[(152.87 \text{ mm})^3 - (152.5 \text{ mm})^3] \\
&= 4/3\pi \times 25842.1 \text{ mm}^3 \\
&= \mathbf{108247\ mm^3\ (Ans.)}
\end{aligned}$$

Self-Test 4

a) A large diameter steel steam pipe is erected at 20°C and will carry steam at a temperature of 320°C. At operating temperatures, how much linear expansion will there be in a 30 m long straight section of this steam line?

b) A circular copper rod is 20.02 mm in diameter and has to be inserted into a square hole that is 20.0 mm on each side. How much does the shaft need to be cooled to allow this operation?

c) A length of cast iron piping is 50.0 m when it carries hot water at 80°C. When the hot water is shut off, the pipe temperature drops to 20°C. Determine the final length of the cooled pipe.

d) A rod of alloy metal measures 3.521 m long at 290°C. At 373°C the rod is 3.523 m long. Determine the value of the coefficient of linear expansion for the metal.

e) A temperature control system is operated by the expansion of a zinc rod which is 200 mm long at 15°C. The control system is set to turn off the heat supply when the rod expands by 0.20 mm. Determine the temperature at which the heat turns off. Assume the coefficient of linear expansion of zinc to be 16.5×10^{-6}/°C.

0.108 m (Ans. a)
60.5°C (Ans. b)
49.97m (Ans. c)
6.84×10^{-6}/°C (Ans. d)
75.6°C (Ans. e)

Superficial (Area) and Volumetric Expansion of Solids

When a body is heated, it expands along all dimensions. Its linear dimensions of length, width, and height all increase due to the increase in temperature. In other words, the dimensions used to mathematically determine surface area or volume all increase due to the rise in temperature. The increase depends on a material's coefficient of superficial expansion or volumetric expansion. These coefficients are considered to be two times the coefficient of linear expansion for problems involving superficial expansion, and three times the coefficient of linear expansion for problems involving volumetric expansion.

Volumetric Expansion of Liquids

With the exception of water, all liquids expand in direct proportion to their change in temperature when heated. They contract similarly when cooled.

Water, though, is a special case. When cooled, its volume decreases until it reaches a temperature of about 4°C. At this temperature, water increases in volume, as it cools to 0°C, at which point it begins to freeze.

This peculiarity of water is the reason why surface water of lakes or rivers freezes, while the water below the surface does not. As the lake water is cooled below 4°C, it expands, becomes less dense, and rises to the surface. At the surface, it continues to cool until it freezes. The layer of ice formed then insulates the water below. The sub-surface water remains between 0°C and 4°C.

Liquids do not have linear dimensions. Liquids occupy the dimensions of the container they are in. Therefore, liquids only have coefficients of volumetric expansion. In general, the coefficients of volumetric expansion of liquids are greater than those of solids.

Like solids, different liquids have different coefficients of expansion. However, unlike the coefficients for solids, which are considered to be relatively constant over a broad range of temperatures, the coefficients for liquids change in value as the temperature changes. For example, the coefficient of expansion of alcohol between 0°C and 10°C is 0.0011; however, between 10°C and 60°C, it is 0.0013.

Chapter Summary

This chapter began by providing a basic understanding and application of the first two Laws of Thermodynamics. Heat is not the same as temperature, but temperature indicates heat concentration.

Heat can be converted to work, and work can be converted to heat. Neither conversion is 100% efficient. Heat is a form of energy that can be transferred or changed into other forms. The direction of heat transfer and the amount of heat transferred, over a period of time, is dependent on the size of the temperature gradient.

These principles were applied to problems involving the transfer of sensible heat:

- Heat required to change the temperature of a mass
- Thermal expansion

Mastering this content will be helpful when learning about heat transfer in thermal operating equipment.

CHAPTER 3

Introduction to Heat Transfer and Heat Exchangers

Learning Outcome

When you complete this chapter you should be able to:

Explain the modes of heat transfer and the theory of heat exchanger operation.

Learning Objectives

Here is what you should be able to do when you complete each objective:

1. Describe the three modes of heat transfer with reference to heat exchangers.
2. Discuss the general design and construction of typical heat exchangers.
3. Describe heat transfer fluids and how they affect the operation of a heat exchanger, including fouling, leakage, and vapour locking.
4. Describe heat exchanger inspection, maintenance, and operation, including placing them in service and removing them from service.

Chapter Introduction

The most important equipment Power Engineers operate are heat exchangers. The most important processes Power Engineers control involve the exchange of heat between fluids.

Heat exchangers are devices that facilitate the transfer of heat between fluids, using the thermodynamic principles of conduction, convection, and radiation. This chapter discusses heat transfer, heat exchangers, and how heat exchangers transfer heat. It also describes the most common types of heat exchanger.

Typical heat exchangers found in power plants are air intercoolers, air preheaters, condensers, steam and hot water boilers, and refrigeration plant evaporators. In fact, any process that cools or heats fluids uses heat exchangers.

Like all the equipment Power Engineers operate, heat exchangers must be operated safely and efficiently. Heat exchangers are prone to fouling, which reduces their heat transfer ability and efficiency. Many heat exchangers are pressure vessels. If over-pressurized, they can fail with disastrous consequences. So, understanding heat transfer, heat exchanger efficiency, and heat exchanger safety are very important parts of the Power Engineering field.

Objective 1

Describe the three modes of heat transfer with reference to heat exchangers.

Transfer of Heat

Heat will only flow between two bodies if they are at different temperatures. Heat always flows from a higher temperature body to a lower temperature body (the Second Law of Thermodynamics). The rate of heat flow depends on the temperature difference, and the type of material through which the flow takes place.

There are three methods by which the transfer of heat energy from one location to another takes place:

- **Conduction**
- **Convection**
- **Radiation**

Heat exchangers rely on all three of these heat transfer methods.

Conduction

Conduction involves the transfer of heat energy in two ways:

- From molecule to molecule within an individual substance.
- From the molecules of one body to those of another body in direct contact with the first body.

Higher temperature molecules have greater kinetic energy than lower temperature molecules. This energy is transferred from higher-energy molecules to lower-energy molecules by direct collision.

Consider an iron bar that has one end in contact with a flame. The other end of the bar will gradually increase in temperature due to the conduction of heat energy (molecular collisions) from molecule to molecule through the metal.

Figure 1 – Conduction

Figure 1 illustrates heat transfer by conduction. The amount of heat transferred, in kilojoules, depends on the:

a) Temperature difference between the hot and cold regions (T_1 and T_2)
b) Type of material through which the heat flows
c) Time during which heat flows
d) Thickness of the conductive material
e) Surface area of the conductive material

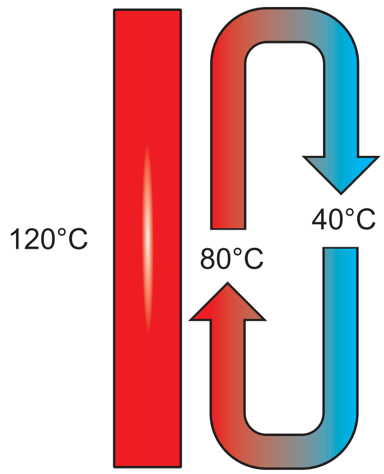
Materials with high density have closely packed molecules, which makes them good heat conductors. In these denser materials, the molecules are closer together. This permits more molecular collisions, and greater conductive heat transfer. Therefore, solids are far better heat conductors than liquids, and liquids are far better conductors than gases. Metals are extremely good conductors of heat.

Convection

The transfer of heat by convection involves the movement of matter, and the heat contained within the matter. Convection takes place only in fluids (liquids or gases). Convection cannot occur within solid material.

Figure 2 shows a fluid in contact with a hot surface. The fluid beside the hot surface is raised to a higher temperature than the remaining fluid. As it becomes hotter, the fluid adjacent to the hot surface expands in volume and decreases in density. This lower density fluid is displaced from below by cooler, denser fluid. This causes the lower density fluid to rise. The cooler, denser fluid is heated in turn, and also displaced by cooler, denser fluid. The cycle of movement (called a **convection current**) continues as long as there is a temperature difference between the hot surface and the fluid. When gravity and fluid density differences drive convection currents, the heat transfer method is called **natural convection.**

Figure 2 – Natural Convection



Natural convection is also responsible for:

- Hot gases rising up a chimney
- Air rising in a room from a radiator or convector
- Hot air balloons rising in the atmosphere

To increase the rate of heat transfer, **forced convection** is frequently used. In forced convection, the fluid is moved using pumps (in the case of liquids) or fans (in the case of gases). Hot water and chilled water circulating pumps are examples of devices that move liquid in forced convection systems.

In hot water heating systems, pumps deliver hot water to heating coils. In ice rinks, pumps deliver cold brine to coils embedded in concrete to draw heat away from the skating surface. Fans are commonly used to increase the warming effect of space heaters, by circulating room air through heating coils or radiators. Fans also contribute to the cooling effect of walk-in coolers and blast freezers.

Boiler water may be heated by either natural or forced convection. Hot water circulating pumps force water through hot water heating boilers. Most steam boilers, though, rely on natural circulation. The part of the water that is in contact with the hot tube walls or shell is heated and displaced by cooler water, which in turn is heated and displaced.

The fact that convection currents occur within a fluid must be considered when attempting to prevent the flow of heat. For example, stagnant air is a good insulator since it has fairly low conductivity. However, moving air transfers a considerable amount of heat. A cold storage room with large air spaces within its walls will gain heat by the convection currents set up in these air spaces.

Insulating material stops convection currents (and therefore convective heat transfer) by obstructing the movement of air. After convection ceases, conductive heat transfer still remains. However, because insulation materials are primarily comprised of gas, and because gas is a poor conductor, stopping convection is an effective means of reducing heat transfer.

Insulation is placed in locations where convection currents can develop, such as the open space between building studs. Foam insulation fills the space with gas bubbles held in plastic material. The trapped gas bubbles cannot freely carry away heat by developing convection currents. The plastic surrounding the bubbles is a conductor of heat, but the gas bubbles that occupy most of the foam's volume are not very conductive. Fibreglass insulation traps air between numerous glass fibres, again preventing the free movement of air. The glass fibres conduct heat; however, most of the volume of the fibreglass is air, which is a very poor conductor. Again, by stopping convection currents, heat transfer via convection is halted.

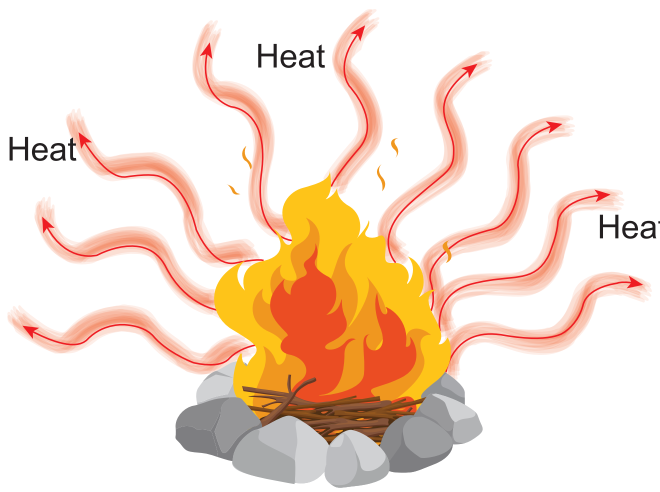
Insulating materials include fibreglass, Styrofoam, and cellulose fibre. Fibreglass and cellulose insulation are poor insulators when wet. This is because water (a far better conductor) penetrates the insulation and replaces the trapped air.

Radiation

Radiation refers to the transmission of energy via **electromagnetic waves**. All bodies emit electromagnetic radiation. The higher a body's temperature, the greater the electromagnetic emission.

Electromagnetic waves are similar to light waves; they travel in straight lines and can pass through vacuums. When they reach a body, they are absorbed, reflected, or transmitted, depending upon the nature of the body. If the waves are absorbed, they convert into heat. Because absorbed radiant heat energy increases the velocity of the molecules in the absorbing body, there is an increase in the body's heat.

Figure 3 – Radiation



The condition of a body's surface determines the amount of electromagnetic radiation absorbed or reflected. If the surface is black and rough, then the body readily absorbs radiant energy. If the surface is smooth and highly polished, most of the radiant energy reflects. Gases absorb only a small amount of radiant energy: radiant energy primarily passes through them.

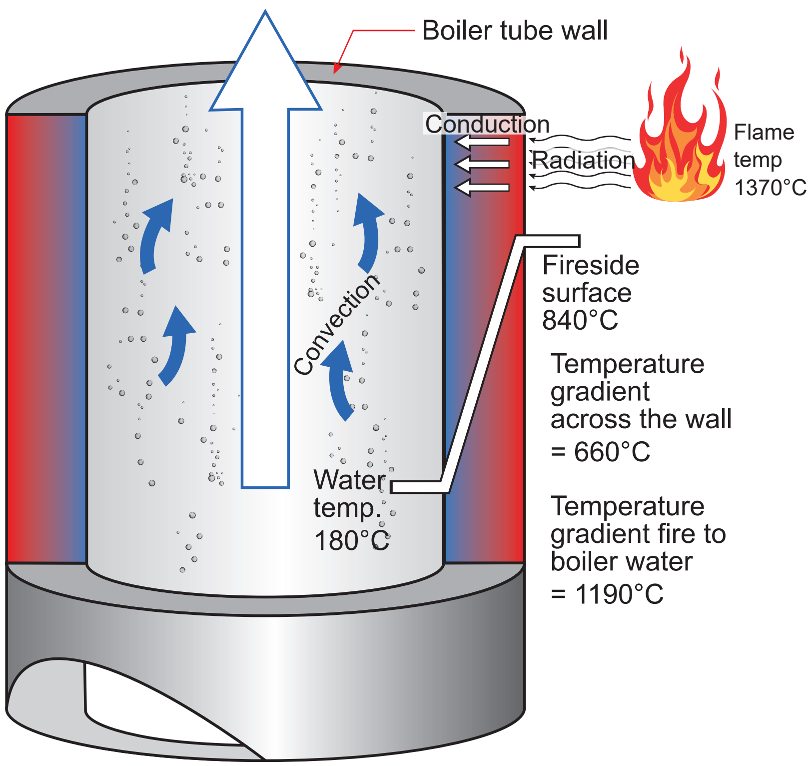
The sun, and how it supplies heat to the earth, is the best example of radiant heat transfer. The energy that leaves the sun passes through the vacuum of outer space, until it reaches the earth's atmosphere. Some radiant energy is reflected back to outer space by the atmosphere. The rest of the energy passes through the atmosphere. The atmosphere absorbs some of this radiation, and converts it to heat. The earth's surface is warmed as it absorbs the rest of the energy.

Similar events occur when the sun's rays reach the windows of a building. Some of the rays are reflected, some are absorbed by the glass, and others are transmitted through the glass. Those that are transmitted are absorbed by the contents of the room, warming them up.

Different window assemblies reflect, absorb, and transmit different proportions of the sun's radiation. Such considerations are of major concern when designing or replacing the windows in a building.

Boilers use all three of these forms of heat transfer. Figure 4 shows a cutaway of a boiler watertube. The flame, at a temperature of 1370°C, radiates heat directly to the metal surface. The metal tube wall is heated to 840°C by radiant heat transfer, and by convection of hot furnace gases. The tube wall conducts heat to the water inside. As the water increases in temperature and produces steam bubbles, it becomes less dense, and carries heat upwards in the tube due to convection.

Figure 4 – Heat Transfer in a Boiler Tube



Heat Exchanger Flow Arrangements

One way of categorizing heat exchangers is to consider the direction that fluids flow through the exchanger. Some of the common flow arrangements are:

- Parallel Flow
- Counter Flow
- Cross Flow
- Combined Cross-Counter Flow

On Track

To help understand these categories of heat exchangers, the following discussion only considers heat exchange between two fluids, separated by a conductive barrier. Although reference is usually made to "heating," keep in mind that while one fluid is increasing in temperature, the other is decreasing.

Parallel Flow

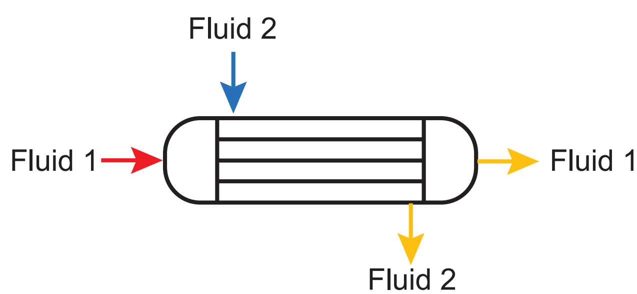
In a parallel flow heat exchanger, both heat transfer fluids travel in the same direction. Consider two fluids: Fluid 1 and Fluid 2, as shown in Figure 5. Fluid 1 is the higher temperature fluid, and transfers heat to Fluid 2.

In a parallel flow configuration, Fluid 1 and Fluid 2 both enter the heat exchanger at the same end, and travel in the same direction. At the heat exchanger inlet, the heat transfer is great, because Fluid 1 is at its highest temperature and Fluid 2 is at its lowest. At the heat exchanger outlet, the heat transfer rate is much less, because the temperature difference between Fluids 1 and 2 is also much less.

This flow arrangement may cause the heat exchanger metal to undergo **thermal shock** at the fluid inlets. This is caused by the extreme initial temperature difference between Fluid 1 and Fluid 2. As well, there can be pronounced uneven thermal expansion from one end of the heat exchanger to the other, which causes excessive stress and premature failure of the heat exchanger metal.

Parallel flow heat exchangers are useful when two fluids must be brought to nearly the same outlet temperature.

Figure 5 – Parallel Flow Heat Exchanger



Counter Flow

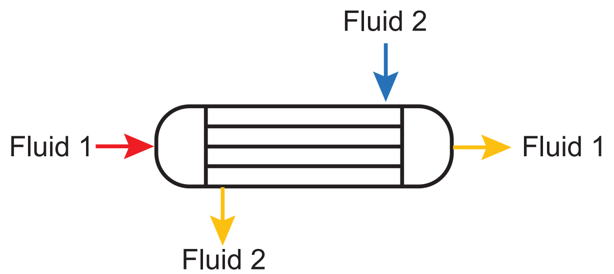
In counter flow heat exchangers, the heat transfer fluids travel in opposing directions.

Refer to Figure 6. In this configuration, Fluid 1 and Fluid 2 enter the heat exchanger at opposite ends. The heat transfer is roughly the same at the heat exchanger inlets and outlets, because the temperature differential remains consistent across the entire heat exchange surface. Therefore, counter flow heat exchangers are the most efficient.

The counter flow arrangement has three distinctive advantages over the parallel flow arrangement:

1. The uniform temperature difference between the fluids greatly reduces the risk of material failure due to thermal stress.
2. The outlet of the initially colder fluid (Fluid 2 in Figure 6) can be raised to a higher temperature than can be achieved with a parallel flow heat exchanger. This is because when the incoming hot fluid (Fluid 1) transfers its heat to the other fluid (Fluid 2) at its outlet, Fluid 1 is at its highest temperature.
3. The uniform temperature difference of the fluids within the heat exchanger produces a steadier rate of heat transfer.

Figure 6 – Counter Flow Heat Exchanger

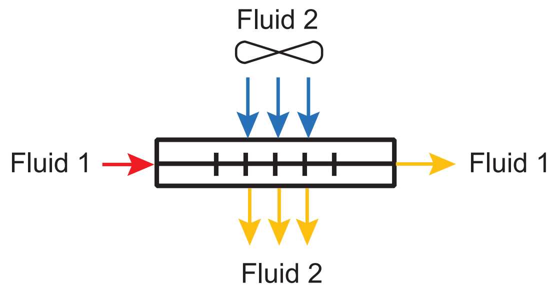


Cross Flow

In a cross flow heat exchanger, like that shown in Figure 7, Fluid 1 flows from the heat exchanger inlet to the outlet. Fluid 2 flows at a 90-degree angle to the flow path of Fluid 1.

An automotive-style radiator operates in this way. Fluid 1 is the hot engine coolant. Fluid 2 is the cooling air blown across the radiator coils.

Figure 7 – Cross Flow Heat Exchanger

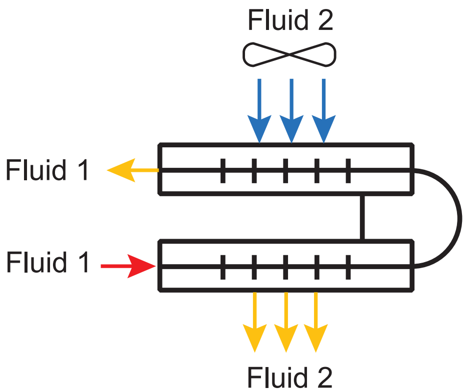


Combined Cross-Counter Flow

This type of heat exchanger (shown in Figure 8) is like a cross flow heat exchanger, except that Fluid 1 reverses flow through a second heat exchanger section. Like a counter flow heat exchanger, the temperature gradient between the two fluids – from inlet to outlet – is fairly constant. This is because the fluids first exchange heat when each are at their coolest, and continue to exchange heat as they both increase in temperature.

Boilers and utility **steam generators** often have their fluid flows and **heat transfer surfaces** arranged in this configuration.

Figure 8 – Combined Cross-Counter Flow Heat Exchanger



Examples of Heat Exchanger Applications

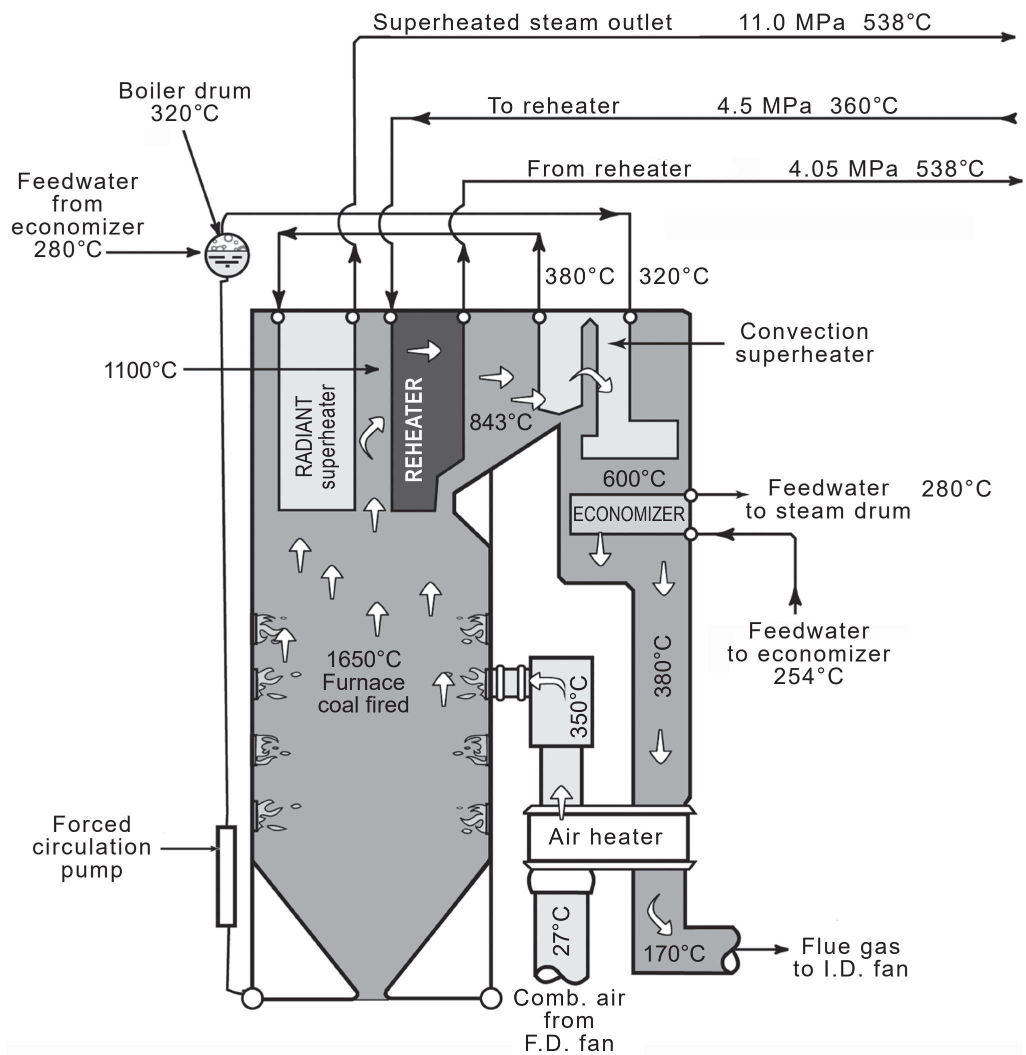
Example 1: Heat Transfer in Steam Generators

"Steam generator" is the term used to describe very large, complex boilers that have numerous heat exchange components that increase the overall efficiency of these units. Because steam generators are used by electrical utilities to generate electricity, they are often called utility boilers. A large steam generator can be used to show all three modes of heat transfer, and various flow arrangements.

Figure 9 shows a typical steam generator layout. The main heat transfer components are the:

- Boiler
- Economizer
- Superheaters
- Reheater
- Air heater

Figure 9 – Heat Transfer in a Steam Generator



The fluids that exchange heat in the steam generator are:

- **Combustion air**
- **Flue gas**
- Water
- Steam

Consider each heat transfer component individually, applying the heat transfer principles already discussed.

Boiler Section

The boiler is the main heat transfer surface of the steam generating unit. Its primary purpose is to convert water to steam. This conversion takes place inside vertical tubes filled with water, which begin at the base of the **furnace**, and terminate at the boiler **drum**. Ideally, boilers do not heat up **feedwater**; they just boil it.

The boiler section is made of hundreds of parallel **watertubes** that surround the furnace (see Figure 9). Because they surround the furnace, the watertubes receive a tremendous amount of heat. Consider the furnace temperature gradient (ΔT). This **temperature gradient** (1330°C) is the difference between the furnace temperature (1650°C) and the temperature of boiler water (320°C). With such a steep temperature gradient, it is easy to understand the tremendous rate of heat transfer in the boiler section.

Most heat in the boiler section of the steam generator is transferred by radiation. Therefore, the furnace area is called the radiant section of the boiler. The boiler tubes also receive heat through forced convection of hot furnace gas; however, compared to the radiant heat transfer, the heat transferred by convection is small. Because of this, the boiler watertubes are considered radiant heat transfer surfaces.

If considering only the convection heat transfer in the boiler, the boiler section of the steam generator can be considered a parallel flow heat exchanger. This is because the flue gases (Fluid 1) and the boiler water/steam mixture (Fluid 2) flow in the same direction. If considering only the radiant heat transfer, the boiler can be considered to be a cross-flow heat exchanger. This is because the radiant heat energy flows at right angles to the flow of the boiler water/steam mixture.

From the perspective of the **waterside**, the heat received by the water/steam mixture in the tubes is carried to the boiler drum by either forced or natural convection. Figure 9 shows that this particular boiler uses a forced circulation pump. Therefore, the circulation in this boiler is by forced convection.

Economizer

Like the boiler, the economizer is a set of tubes containing water. Unlike the boiler, the economizer does not generate steam. It merely heats feedwater. Its purpose is to recover heat from the flue gas that would otherwise go to waste.

The economizer shown in Figure 9 is a combined counter-cross flow heat exchanger, like that shown in Figure 8. Without the economizer, the flue gas temperature would be 600°C. With the economizer, the flue gas temperature is reduced to 380°C. The heat recovered raises the feedwater temperature from 254°C to 280°C. Because the feedwater temperature increases, less energy is required in the boiler to generate steam. This means less fuel needs to be burned to produce a given amount of steam (hence the name economizer).

Superheaters

Like the boiler and the economizer, the superheaters shown in Figure 9 are tubular heat exchangers. However, these heat exchangers do not contain water; they contain steam. Two kinds of superheaters are shown: a convection superheater and a radiant superheater.

Convection Superheater

The **convection superheater** receives some heat radiated from hot flue gas. However, the amount of heat transferred by radiation is minor compared to how much heat is received by convection. This is because the convection superheater is shielded from the radiant heat of the fire. The forced convection of 843°C flue gas is the main heat transfer process in this part of the steam generating unit. The convection superheater receives saturated steam from the boiler drum and raises its temperature from 320°C to 380°C. In doing so, the flue gas temperature drops from 843°C to 600°C.

Like the economizer, the convection superheater is a combined counter-cross flow heat exchanger.

Radiant Superheater

Like the boiler watertubes, the **radiant superheater** is also exposed to radiant heat. Like the boiler tubes, the radiant superheater receives its heat primarily through radiation. The radiant superheater receives superheated steam from the convection superheater at 380°C and raises the steam temperature to 538°C, for use in a steam turbine.

Reheater

The reheater shown in Figure 9 is much like a radiant superheater. In its position, it mostly receives radiant heat. However, it does receive some heat from forced convection. The reheater has greater convection heat transfer than the radiant superheater, but less convection heat transfer than the convection superheater.

Air Heater

The air heater is a unique heat transfer component because it does not transfer heat to steam or water. Rather, it adds to the steam generating unit overall efficiency by transferring waste flue gas heat to the combustion air entering the boiler furnace. During the heat transfer, the combustion air is raised from 27°C to 350°C. The flue gas drops in temperature from 380°C to 170°C.

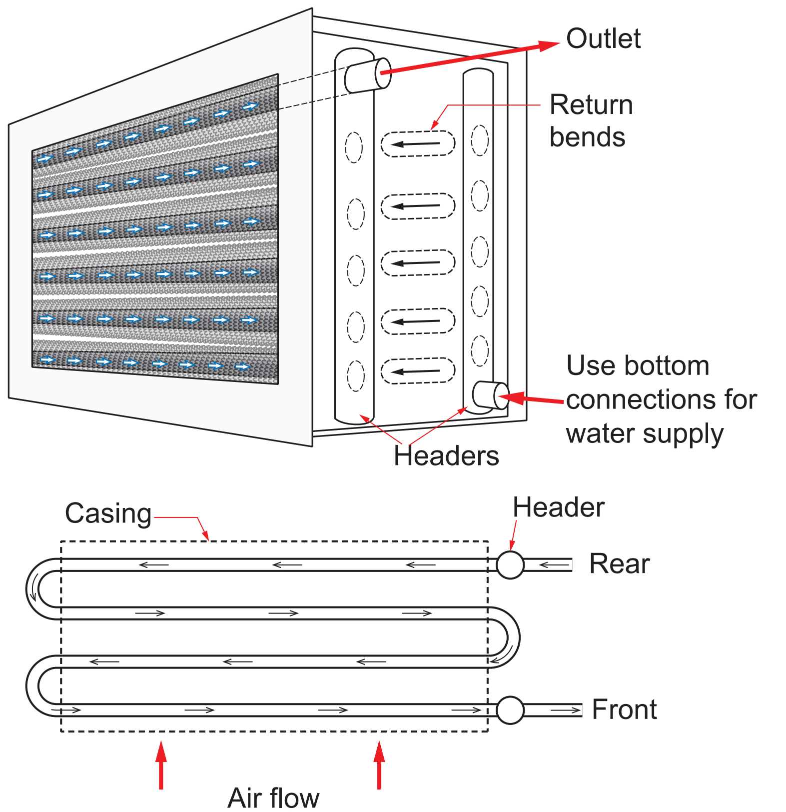
The air heater shown in Figure 9 is a counter-flow heat exchanger. Other flow configurations also exist.

Example 2: Heat Transfer in HVAC Coils

Heating and cooling coils are heat exchangers that heat or cool air, depending on the application. These tubular heat exchangers may be cross flow, combined counter cross flow or combined parallel cross flow. In all cases, a heat transfer fluid passes inside the tubes and air passes on the outside of the tubes. The heat transfer fluid may be chilled water, **refrigerant**, hot water, steam, or **glycol**. For heating, hot water and steam are most often used. For cooling, chilled water and various refrigerants are used. Glycol can be used for both heating and cooling.

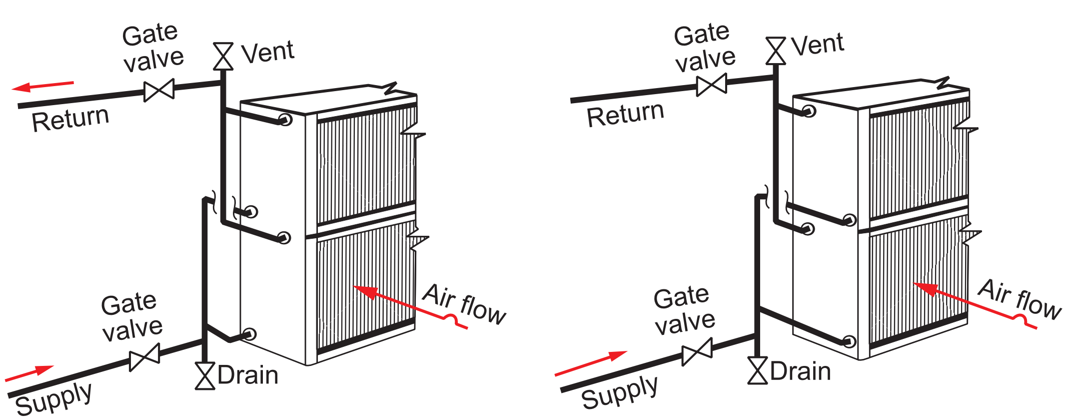
Coils may be constructed of single row coils, or multiple rows of coils with return bends. The single row coils are cross flow heat exchangers. Multiple row coils may be connected as either combination cross-counter flow or cross-parallel flow. A multiple row coil is shown in Figure 10. The bottom image shows the same coil connected as a combination cross-counter flow heat exchanger. Compare this diagram to Figure 8.

Figure 10 – HVAC Heat Exchanger



In order to obtain maximum capacity and efficiency of multiple row coils, they should be connected as cross-counter flow coils. Figure 11(a) shows another combined cross-counter flow coil arrangement. The water supply connection is located on the side of the coil where the air is leaving. The return water connection is located on the side of the coil where the air is entering. If the coil is connected for cross-parallel flow, as shown in Figure 11(b), the rated capacity of the coil will be approximately 10 to 15% lower.

Figure 11 – Coil Flow Arrangements



a) Counterflow (More efficient)

b) Parallel flow (Less efficient)

Objective 2

Discuss the general design and construction of typical heat exchangers.

Heat Exchangers

Heat exchangers transfer heat from one fluid to another. Indirect contact heat exchangers separate the heat exchange fluids with a solid barrier (such as a tube wall or metal plate). In other heat exchanger types (such as direct contact feedwater heaters), the fluids may be in direct contact.

This objective covers only tubular, shell and tube, plate, fin tube, and coil types of indirect contact heat exchangers. Boilers are special types of heat exchangers, and are examined in detail in other chapters.

These types of heat exchangers are commonly used in places such as:

- Refrigeration and air conditioning plants
- Food and beverage processing facilities
- Power generating plants
- Chemical manufacturers
- Petrochemical and petroleum refiners
- Natural gas processers

In heat transfer processes, the rate of heat transfer is proportional to the following three factors:

1. The temperature difference between the two fluids
2. A **heat transfer coefficient** between the fluids and the heat transfer surface
3. The area of the heat transfer surface

Tubular Heat Exchangers

Tubular heat exchangers transfer heat to or from the fluid that surrounds a fluid filled tube. These exchangers can have bare surfaces, or they may have fins to increase the heat transfer surface area.

Bare Tube Heat Exchangers

Bare tube heat exchangers transfer heat between the fluid that directly contacts the inside surface area of the tube and the fluid that directly contacts the outside surface area. If the inside surface area of a tube of a certain length is compared to its outside surface area, it will be seen that the inside surface area is smaller. For heat exchanger tubes, this difference is insignificant. Therefore, the heat transfer surface of a bare tube heat exchanger can be considered to be the outside surface area of the tube.

For a given temperature difference between the heat transfer fluids, a given heat transfer coefficient, and a given tube diameter, it can be seen that the only way to vary the rate of heat transfer is to modify the length of the tube. Longer tubes can transfer heat more rapidly than shorter tubes, because their surface areas increase with length. However, longer tubes are impractical. Therefore, bare tube heat exchangers use return bends to maximize the heat transfer surface, while maintaining a compact structure. Also, the number of bare tubes can be increased and the number of return bends decreased so that it is easier to pump fluid through the tubes.

An example of a bare pipe heat exchanger is shown in Figure 12. Note that it is a single tube with numerous return bends. If the number of tubes was doubled, the same heat transfer surface area would be provided, but each tube would have half the number of return bends. This would allow the fluid to flow more easily through the heat exchanger.

Bare pipe heat exchangers are used in boilers, refrigeration plants, and other places where the surfaces may easily foul due to accumulations of **ash**, **soot**, or ice. Surface **fouling** negatively affects the heat transfer coefficient, which greatly reduces the heat transfer capacity of the heat exchanger. Bare tubes are less prone to fouling, and are easier to clean when they do foul.

Figure 12 – Bare Pipe Heat Exchanger

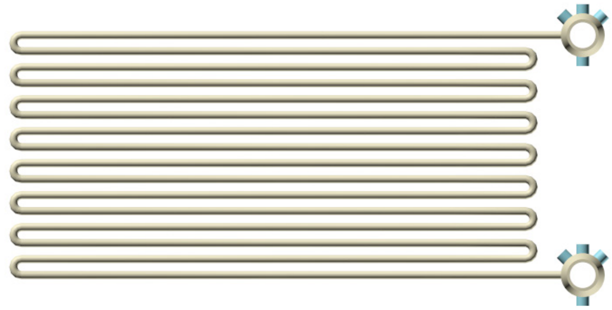
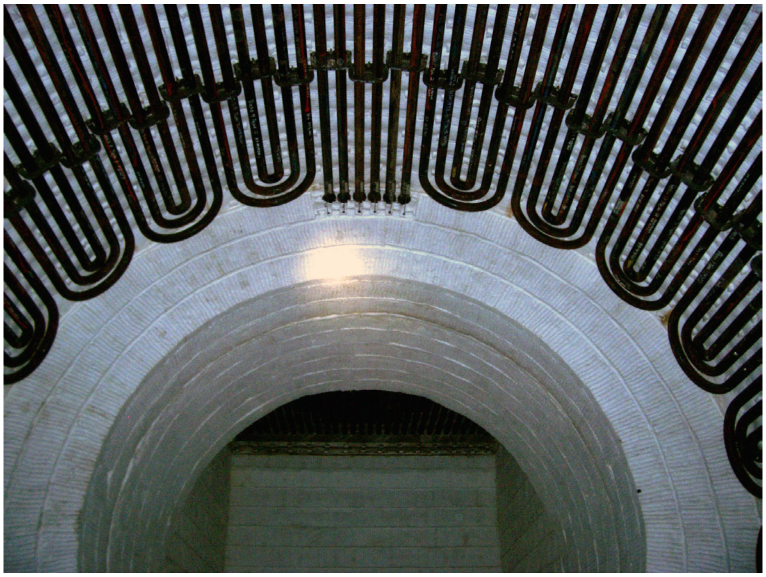


Figure 13 shows the bare watertubes of a forced-convection steam boiler. Note there are six tube circuits, each with their own return bends. Together, they cover the inside surface of the boiler.

Figure 13 – Bare Heat Exchange Tubes in a Boiler

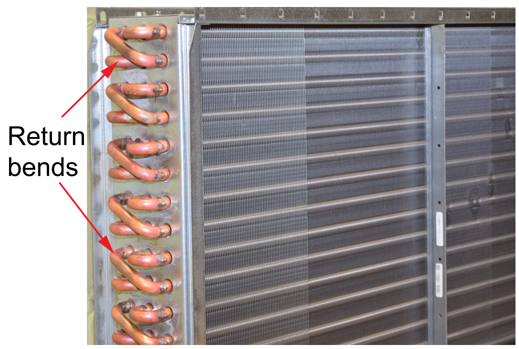


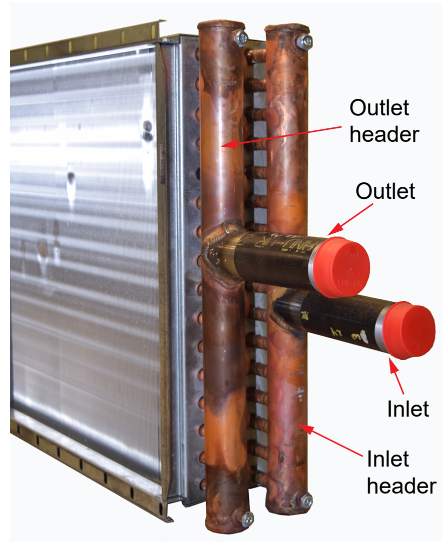
Most boiler tubes are bare pipe heat exchangers. In Figure 13, the tubes are exposed to radiant heat. The tubes conduct the heat to the boiler water, converting it to steam. Circulating pumps provide forced convection of the boiler water and steam, toward the boiler outlet.

Finned Tube Heat Exchangers

Adding fins to the tubes increases the heat transfer surface and heat transfer ability.

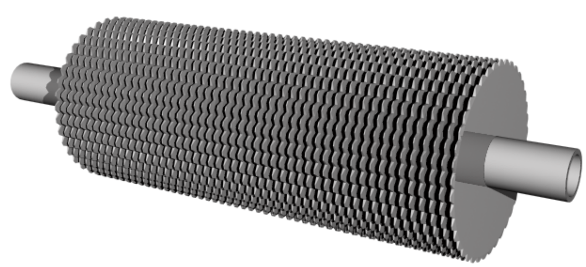
Figure 14 – Multiple Row Finned Tube Heat Exchanger Coil





The finned coil design in Figure 14 has far more heat transfer surface, but is more prone to fouling than a bare tube design. Such a heat exchanger must only be used in clean, frost-free environments to prevent fouling. Also, air filters must be installed upstream. Figure 15 shows how fins can be attached to increase the heat transfer surface area of a heat exchanger tube. By increasing the external heating surface area of the heating coils, the overall heat transfer increases accordingly.

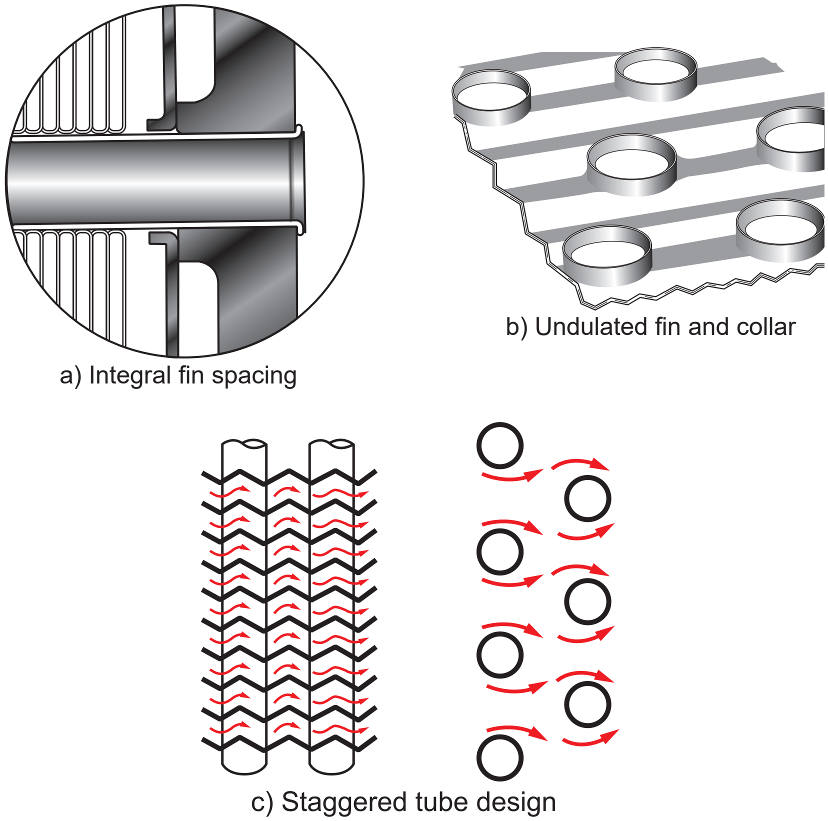
Figure 15 – Section of a Finned Tube



Heat transfer capacity of the heat exchanger increases with the number of fins per unit length of tube. However, resistance to the external flow and susceptibility to fouling are factors that limit the number of fins that can be used, and the spacing between the fins. The pressure drop across finned coils determines the power requirements of the fan motor. The greater the pressure drop across the coil, the more powerful the fan motor needed.

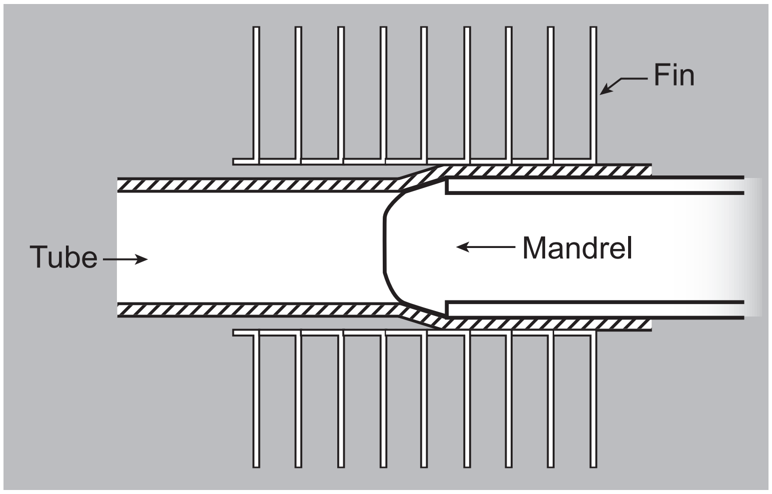
Figure 16 shows a type of fin used for staggered tube coils. The tubes are staggered to increase the contact time between the air and the heat exchange surfaces (Figure 16(c)), thus encouraging heat transfer. The fins (Figure 16(b)) are actually plates, with an undulating design. The undulations also encourage contact time between the air and the heat exchange surfaces. The left hand side of Figure 16(a) shows a cross-sectional view of a series of plates mounted on a tube. Note how the fins have regular spacing. The spacing is controlled by the height of the collars, shown in Figure 16(b).

Figure 16 – Types of Fins



In order for the fins to extend the heating surface area, the fins must be in tight contact with the tubes for conduction of heat to take place. Figure 17 shows the process for firmly attaching the fins to the heat exchanger tubes. The fins are placed loosely over the bare tubes. A **mandrel**, with a diameter larger than the tube inside diameter, but smaller than the fin collar, is forcefully drawn through each tube. This distorts the tube, and brings the tube walls into secure, permanent contact with the fin collars.

Figure 17 – Mechanical Expansion of Tube to Fin



Shell and Tube Heat Exchangers

The shell and tube heat exchanger is the most common type of heat exchanger used in industry. Shell and tube heat exchangers primarily transfer heat by convection and conduction. They can be fabricated from a wide range of metallic or non-metallic materials. Operating pressures range from full vacuum to 40 MPa. Design temperatures range from -250°C to 800°C.

Shell and tube heat exchangers have two major components: tubes (either straight, bent or coiled) and a cylindrical **shell**. The shell may be fabricated from rolled steel plate, or from sections of piping (up to DN 600). The tubes are thin walled for specific use in heat exchangers. Other components found in some (but not all) shell and tube heat exchangers are:

- **heads** (also called channels)
- **tubesheets**
- **baffles**
- **tie rods**
- spacers
- **pass partition plates**
- **expansion joints** (when required)

A E

ASME BPV Code Section VIII governs the design and construction of shell and tube heat exchangers.

Shell and tube heat exchangers are more rugged than other types of heat exchangers. However, they may not be the most efficient choice, especially for heat recovery applications, or for highly viscous fluids. Typical applications include condensers, chillers, reboilers, process heaters, and coolers.

When shell and tube heat exchangers are used with steam or other condensable fluids, the fluid is introduced in its gaseous state to the top of the shell side. The condensed fluid exits from the bottom of the shell.

When used with non-condensing fluids, the shell fluid inlet is usually at the bottom of the shell, and the outlet is at the top. The fluid in the tubes usually enters near the shell fluid outlet (counter flow). This allows a more gradual heat transfer and less shock to the exchanger.

There are many configurations of heat exchangers for many different processes. Almost all shell and tube designs are combination flow designs due to the configuration of the tubes and baffles in the shell. Most are cross-counter flow installations, though some may be cross-parallel flow.

Shell and tube heat exchanger designs include:

- U-tube
- Straight tube
- Shell and coil

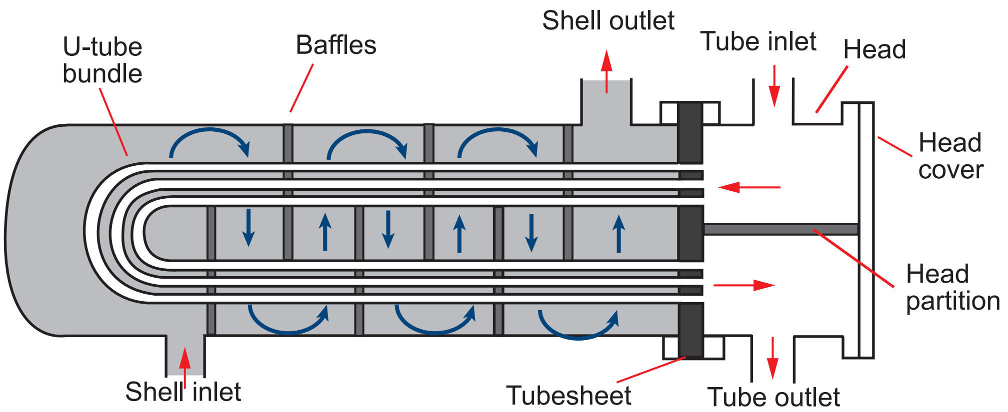
Two most common types of shell and tube heat exchangers are presented in Figures 18 and 19. These are the U-tube and straight-tube designs.

The U-Tube Heat Exchanger

Shells and tubes are often made of different materials. Shells are often steel, and tubes are often made of a copper **alloy**. Steel is used for its high strength, and copper alloys for their high thermal conductivity. However, when the heat exchanger changes in temperature, each material expands or contracts at different rates.

The U-tube heat exchanger (Figure 18) permits differential thermal expansion of the tube bundle without the need of expansion joints. The use of U-tubes also reduces the **stress** on the tubesheet, caused by restricted thermal expansion.

Figure 18 – U-Tube Heat Exchanger



Note the baffles located in the shell. The baffles have several functions:

a) They direct the fluid through multiple **passes** as the fluid flows from inlet to outlet through the shell. In doing so, the fluid in the shell contacts the entire tube bundle, maximizing contact for heat transfer to occur.

b) They slow the rate of fluid flow. This maximizes the amount of time for heat transfer to occur.

c) They support the tube bundle, so that the tubes do not carry excessive stress at the tube sheet attachment.

d) They prevent the tubes from contacting each other or the shell, so the tubes are always properly spaced, permitting fluid flow.

The head partition is an important feature of shell-and-tube heat exchangers. This solid piece directs the tube-side heat exchange fluid through the tubes. It also keeps fluid from bypassing the tube bundle and entering the outlet directly.

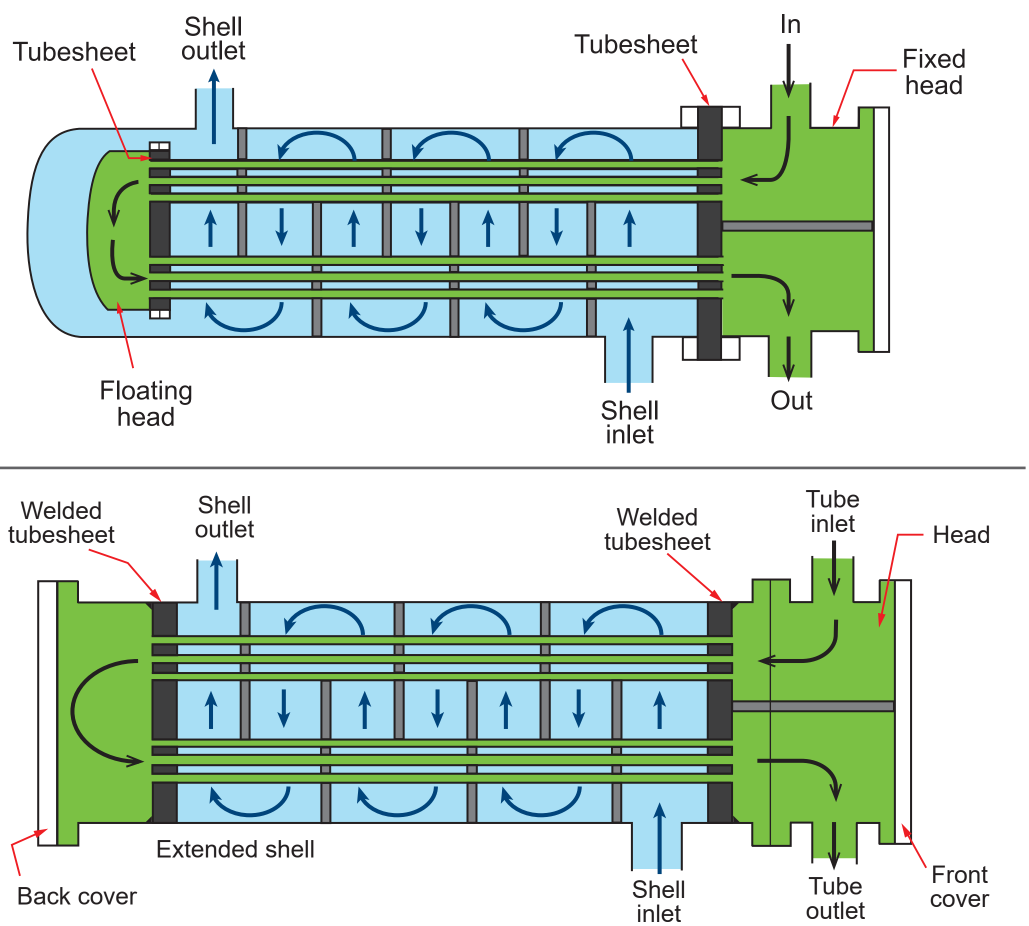
U-tube heat exchanger shells are usually designed with dished heads. This design withstands internal pressure more efficiently than flat heads.

A disadvantage of U-tube heat exchangers is that the internal tube surfaces are difficult to clean mechanically, because of the numerous bends.

Straight Tube Heat Exchanger

The straight tube heat exchanger (Figure 19) is quite similar to the U-tube heat exchanger; it too has multiple fluid passes, baffles, and head partitions. However, the straight tube heat exchanger has two tubesheets (one for each end of the tubes).

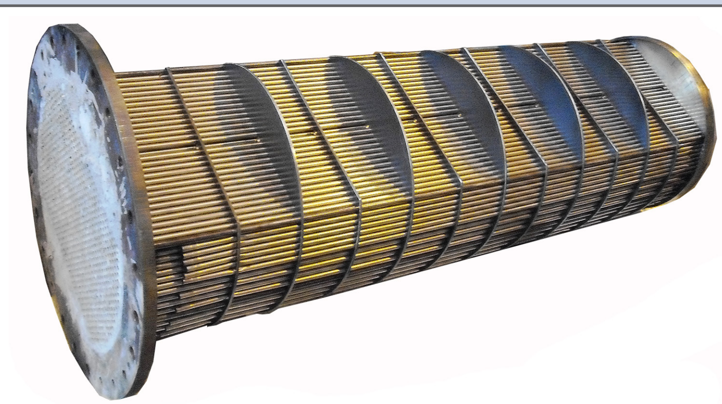
Figure 19 – Straight Tube Heat Exchanger



Straight tube heat exchangers are much easier to clean than U-tube designs, because mechanical cleaning devices can easily pass the entire length of the tube.

Figure 20 shows the tube bundle and baffles of a straight-tube shell and tube heat exchanger. Here, the tubes, baffles, and tubesheets are made of stainless steel.

Figure 20 – Straight Tube Heat Exchanger Bundle From a Lube Oil Cooler



Depending on the length of the heat exchanger, straight tube heat exchanger shells may require expansion joints to accommodate differential thermal expansion and reduce tubesheet stress. This is not an issue with floating head designs.

In general, straight tube shell and tube heat exchangers are more complex; they have more joints, gaskets, and fasteners than U-tube designs. Because of this, they have more potential leak pathways.

Shell-and-Coil Heat Exchanger

The shell-and-coil heat exchanger has a horizontal or vertical steel shell that contains a coiled tube. The shell is usually a pressure vessel made of steel, and the tubes made of copper alloy or stainless steel. The tube may be bare or finned, to increase the heat transfer surface area.

These heat exchangers are extremely compact, and make efficient use of space. Smaller types are commonly used in refrigeration service as condensers, and to cool boiler water samples (Figure 21). Larger sizes may be used to heat potable water, hot water for heating systems, and fuel oil.

Shell-and-coil heat exchangers have no gaskets, and can operate at high pressures and high temperatures. They can handle fluids that are subject to sudden and large temperature variations, such as those in steam and refrigeration systems. Many are rated up to 2500 kPa at 300°C.

These compact heat exchangers have very high heat transfer rates, especially if connected counter flow. Because the tubing is wound in a coil-shape, the tubes readily compensate for differential thermal expansion between shell and tubing.

One disadvantage of shell-and-coil heat exchangers is that they are impossible to clean mechanically. Chemical cleaning is usually the only alternative. For this reason, the "fouling" liquid is usually introduced to the shell side, and not the tubes.

Figure 21 – Shell-and-Coil Heat Exchanger Used as a Boiler Water Sample Cooler

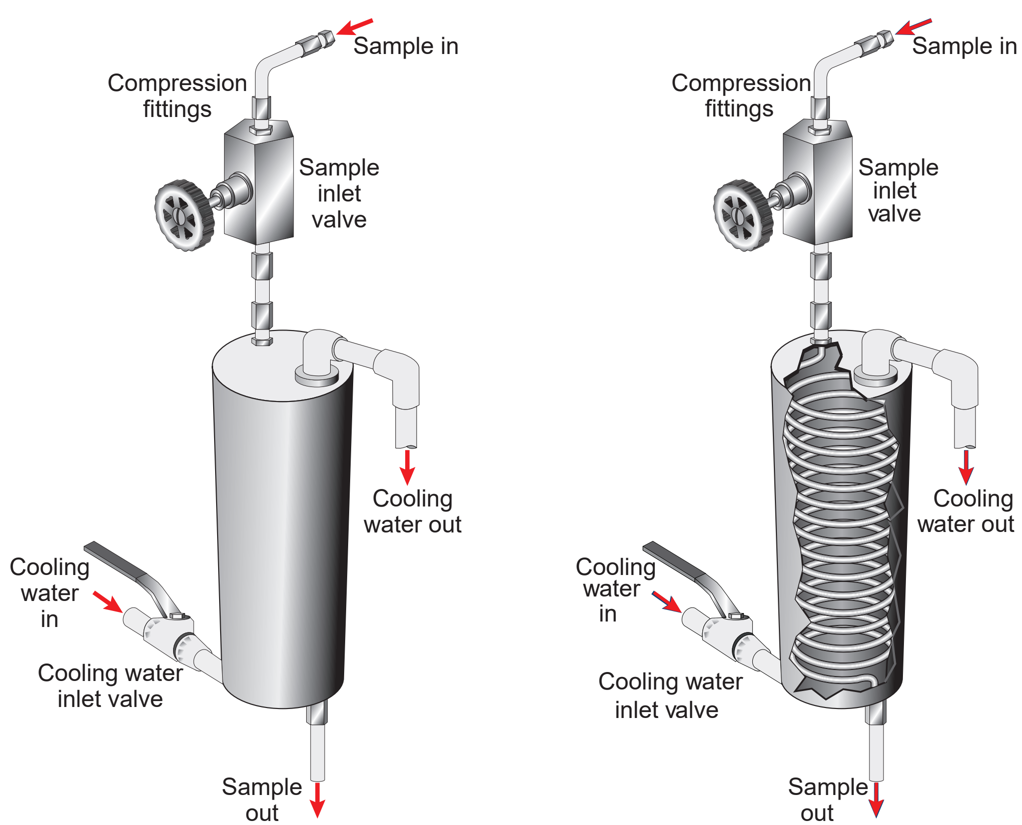


Plate Heat Exchangers

Plate heat exchangers (Figure 22) are made of a number of thin corrugated metal plates, aligned together on a carrying bar, and supported by a sturdy frame. Each metal plate has gaskets that act as barriers between the heat transfer fluids, and direct the fluids between their respective inlets and outlets. The plates are pressed together between metal end plates, using threaded rods, leaving the plates leak-tight. Because they have large heat transfer areas, relatively small plate heat exchangers can have very high heat transfer capacities.

The plate heat exchanger is more compact and lower in cost than a similar shell-and-tube heat exchanger. Recent development in gasket and brazing technology have made the use of plate type heat exchangers more widespread in industry.

Plate heat exchangers differ in the types of plates that are used, and in the configurations of those plates. Plate type heat exchangers are not usually used with steam. This is because **condensate** does not easily drain from plate heat exchangers, and the thin plates do not tolerate **water hammer**.

Figure 22 – Plate Heat Exchanger

Spiral Plate Heat Exchanger (SPHE)

Spiral plate heat exchangers are in some respects similar to plate heat exchangers. Imagine adjacent heat transfer plates, spaced evenly to permit fluids to flow between the plates. If the plates are wrapped in a spiral fashion around a central tube, the plates would take on a spiral form. The resulting heat exchanger would have the heat transfer surface area of a larger plate heat exchanger, but in a more compact form. Figure 23 shows a cross-sectional view of such a heat exchanger, including the fluid paths. Note that the fluids flow counter to each other.

Spiral plate heat exchangers are true counter-flow designs; therefore, they are very efficient at transferring heat. As well, their compact size uses space efficiently. Because the fluids are subject to centrifugal forces as they pass through the heat exchanger, the fluids tend to scrub deposits from the heat transfer surfaces. This makes spiral plate heat exchangers “self-cleaning,” reducing maintenance costs.

In addition to these advantages, spiral plate heat exchangers

- Are robust and durable
- Allow easy access for inspection or cleaning, by removing the end covers
- Have low operating cost, due to their efficient design

Spiral plate heat exchangers are becoming increasingly common in many industries.

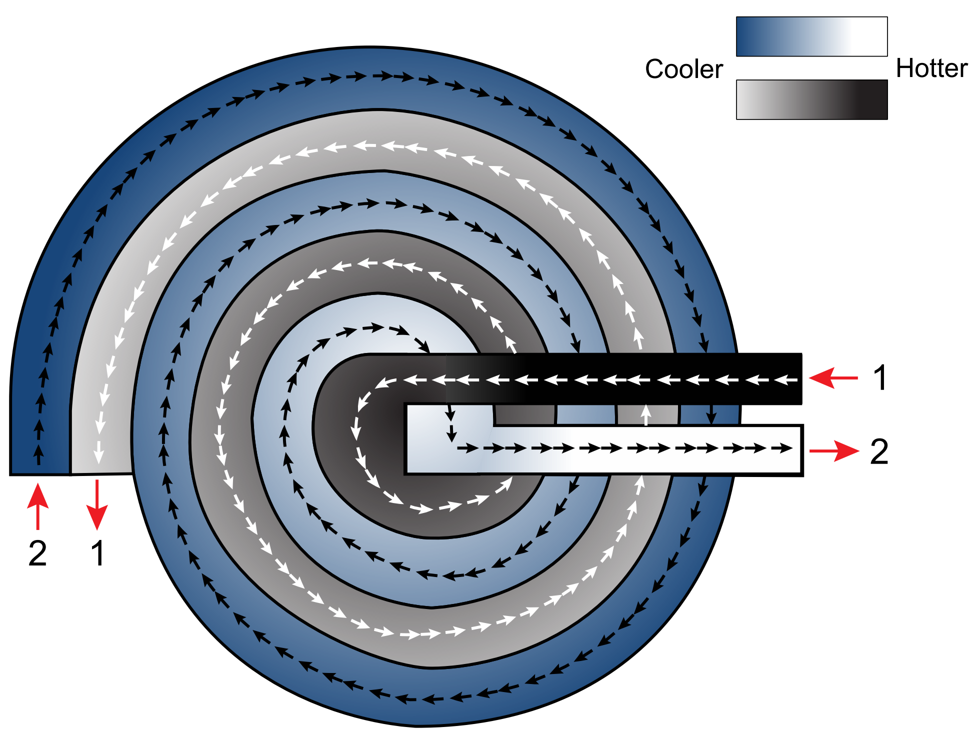
In the oil and gas, chemical and petrochemical, and mining industries, they are used as:

- Vacuum condensers
- Gas coolers
- Reflux condensers
- Vent condensers
- Evaporators
- Reboilers

In the pulp and paper industry, spiral plate heat exchangers are used to heat black and white liquor.

In water and wastewater, they are used to heat digester sludge.

Figure 23 – Cross-Section of a Spiral Plate Heat Exchanger



Objective 3

Describe heat transfer fluids and how they affect the operation of a heat exchanger, including fouling, leakage, and vapour locking.

Heat Transfer Fluids

Both gases and liquids are used as heat transfer fluids. When selecting a heat transfer fluid, the following criteria should be considered:

Coefficient of expansion – the fractional change in length or volume of a material, for a unit change in temperature.

Viscosity – the resistance of a liquid to sheer forces (and therefore to flow).

Thermal capacity – the ability of matter to store heat.

Freezing point – the temperature below which a liquid turns into a solid.

Boiling point – the temperature at which a liquid boils.

Flash point – the lowest temperature at which the vapor produced by a heated liquid can be ignited in air.

Air

Air will not freeze or boil, and is non-corrosive. However, it has a very low heat capacity, and tends to leak out of collectors, ducts, and dampers.

Water

Water is nontoxic and inexpensive. It is easy to pump because of its low viscosity. As well, because of its high specific heat, less water needs to be circulated to transfer a given amount of heat than many other transfer fluids. This reduces the required pump size and power requirements. If it has a high mineral content (i.e., "hard" water), it can deposit minerals in collector tubing and system plumbing.

Steam

Although steam is only vapourized water, it deserves separate consideration. Steam is a **two-phase** heat transfer fluid. This means that it changes from liquid to gas in a boiler, and gas to liquid in a condenser. When the steam condenses, it takes up considerably less volume, which may cause a vacuum to develop in a heat exchanger. As well, condensed steam must be able to flow unhindered from the heat exchanger into a steam trap. If the heat exchanger is prone to freezing, precautions must be taken to ensure it can be fully drained so that water pockets do not remain and freeze.

Glycol/Water Mixtures

Glycol/water mixtures have a 50/50 or 60/40 glycol-to-water ratio. **Ethylene** and **propylene** glycol are commonly called **antifreeze**. Ethylene glycol is extremely toxic and should only be used in a double-walled, closed-loop system. Propylene glycol is non-toxic. If a propylene glycol/water mixture is ***certified*** non-toxic, it can be used in single-walled heat exchangers, in applications where food-grade fluids are mandated.

Most glycols degrade at very high temperatures. Corrosion inhibitors must be added to prevent the formation of acids due to thermal degradation.

Refrigerants and Phase Change Fluids (other than water)

Refrigerants are commonly used as the heat transfer fluid in refrigerators, air conditioners, and heat pumps. They generally have a low boiling point and a high latent heat capacity. This enables a small amount of refrigerant to transfer a large amount of heat very efficiently.

Anhydrous ammonia (**ammonia** containing no water) is a very common industrial refrigerant. Due to safety considerations, it is not used in residential systems.

Heat Transfer Oils

Heat transfer oils may be used where temperatures may drop below the freezing point of glycol mixtures, or when high temperature process fluids are needed at low pressure. They are also used where the temperature must be higher than a water or glycol mixture can attain. Heat transfer oils are specially made to address viscosity, boiling, flash point, flammability, and fouling issues.

Common Concerns When Operating Heat Exchangers

Power Engineers must continually monitor heat exchangers to determine whether they are operating at peak efficiency, and to identify when heat exchangers need servicing. As well, they need to know what may occur when heat exchangers are operating incorrectly. To do this, Power Engineers typically monitor temperatures and pressures, and check for leaks.

Fouling

If there is a gradual decline in heat transfer, fouling may be occurring. Sometimes fouling becomes severe enough to plug tubes. Fouling can be caused by:

- Mineral deposits (scaling)
- Decomposition of heat exchange fluids
- Ice formation
- Soot
- Ash
- Algae
- Entrained sediments
- **Zebra mussels**

To identify fouling, Power Engineers must record the heat exchanger operating pressures and temperatures when clean, and compare these conditions over time. As well, operators must be aware of the process conditions that lead to fouling, given the process characteristics under consideration. For example, a heat exchanger cooled with lake water may foul due to zebra mussel accumulations. In an exchanger cooled with municipal potable water, zebra mussel fouling is unlikely.

Debris

Debris such as rocks, trash, wrenches, gloves, welding rods, clothing, and pencils may get into heat exchangers and cause fouling. To prevent this from occurring, **strainers** should be installed in the piping prior to the heat exchanger inlets.

Strainers are coarse filters that remove solid debris from the heat exchange fluid. This is especially important on initial installation and start-up, when piping systems often contain debris left over from construction.

Strainers should have pressure indicators on their inlets and outlets. If the differential pressure between these gauges is high, the strainer is dirty and restrictive to flow. At regular intervals, strainers must be removed, cleaned, and re-installed.

Pressure and Temperature

Heat exchangers may have pressure gauges and thermometers at their inlets and outlets. It is important to check the pressures on a regular basis, to ensure that the heat exchanger is working properly and efficiently. If an outlet pressure is lower than normal, it may be a sign of fouling. Check for dirt or scale buildup on that side of the heat transfer surface.

Fouling is indicated by either lower than normal or higher than normal outlet temperatures. The outlet temperature of the fluid being heated will be lower than normal. The outlet temperature of the fluid providing the heat will be higher than normal.

Shell-and-tube heat exchangers deserve special consideration. If the outlet pressure on the tube side is higher than normal, fluid may be bypassing the heat exchanger tubes. This could be due to a damaged head partition plate, or a poor seal between the head partition plate and the tubesheet.

If the inlet pressure on the tube side is higher than normal, the fluid flow through the tubes may be obstructed due to fouling.

In either situation, the heat exchanger should be opened up, the partition plates examined, the gaskets renewed, and the tube passages cleared. Other conditions, such as scaling and corrosion, can be assessed and addressed at this time.

Venting

Heat exchangers must be properly vented at start up. Improper venting causes poor heat transfer. Exchangers operating under a vacuum can be more of a problem than those operating under positive pressure. A vacuum sucks air into the exchanger if it is not perfectly sealed.

Vents should be located at the exchanger's highest points. The shell side is especially prone to accumulating pockets of air, or other gases. If a venting problem is suspected, the start-up procedure should be reviewed.

Proper venting, and possibly vacuum breaking, is especially important for two-phase heat exchangers (steam and condensate/water). In addition to air that may be introduced during start up, non-condensable gases can enter from the process. These gases are found most often in heat exchangers used as condensers. Vents on horizontal condensers should be located at the opposite end from the inlet.

Objective 4

Describe heat exchanger inspection, maintenance, and operation, including placing them in service and removing them from service.

Heat Exchanger Inspection

Routine inspection of heat exchangers should be carried out during regular rounds.

a) Check and record inlet and outlet temperatures of both fluid streams.

b) Check and record inlet and outlet pressures.

c) If temperatures or pressures are out of range, report or investigate.

d) Check differential pressure across strainers. If the differential pressure is excessive, recommend that they be cleaned.

e) Check for leaks at gaskets, vents, and valves. Report any leaks.

Depending on how the heat exchanger is used, it may require in-service cleaning, or out-of-service cleaning. If cleaning is necessary, consult the plant **standard operating procedures** for the required steps.

Heat exchangers may require regular tear down for inspection and maintenance. Ensure regulatory and site-specific requirements are followed.

Overpressure Protection for Heat Exchangers

Heat exchanger fluids are typically pressurized to over 100 kPag. Therefore, heat exchangers are considered pressure vessels, and must be suitably designed to withstand the pressures they encounter. In Canada and the USA, these pressure vessels are designed according to the **American Society of Mechanical Engineers Boiler and Pressure Vessel Codes** (**ASME BPVC**). The strength of the design is used to determine the heat exchanger's **maximum allowable working pressure (MAWP)**. Above this pressure, the heat exchanger pressure components may fail. Depending on the contents of the heat exchanger, the failure could be disastrous.

Heat exchangers often have two MAWPs: one for the shell and another for the tubes. **Section VIII** of the **ASME BPVC** states, *"Heat exchangers and similar vessels shall be protected with a pressure relief device of sufficient capacity to avoid overpressure in case of an internal failure."* For this reason, heat exchangers must be equipped with pressure relief valves or rupture discs. These devices open up automatically, and release enough fluid to prevent over pressurization.

The tubes in a heat exchanger may fail. This could be due to a variety of reasons, such as corrosion, vibration, thermal shock, and stress fatigue. If tube failure occurs, fluid from the high-pressure side of the exchanger may pass freely to the low-pressure side. This causes over pressurization of the low-pressure side of the exchanger. In this case, the low-pressure side must either be designed to handle this pressure excursion, or it must be equipped with safety relief devices set to protect the low-pressure side.

General Start Up and Shut Down Procedure

During the start up or shut down procedure, operators should avoid exposing the equipment to additional stresses, such as thermal shock, over pressurization, and water hammer. These additional stresses may cause leaks and other damage to the heat exchanger. Manufacturer's recommended guidelines and site-specific procedures must always be followed.

Procedures generally consider the:

a) Construction and design of the heat exchanger
b) Temperature of the incoming heating fluid
c) Temperature of the incoming fluid being heated

Usually the outlet valves on both streams will be left open on start up. In order to reduce the effects of thermal shock, it is usually best to first open the inlet valve of the fluid that is to be heated (the "cooler" fluid). Then, slowly introduce the heating medium by gradually opening its inlet valve.

If steam is the heating fluid, follow these general steps:

1. Vent the heat exchanger to remove air or other gases.
    a) Open the shell vent valve. This allows the air and non-condensable gases to escape the heat exchanger.
    b) Close the vent after the air has been removed.
2. Ensure the steam trap isolation valves are open.
3. Ensure the steam trap bypass valves are open, if applicable, to handle the start-up condensate.
4. Slowly admit the fluid to be heated. Allow it to flow through and warm the heat exchanger.
5. Open the steam valve slowly to warm up the heat exchanger and the fluid.

Heat exchangers that use steam for heat often use automatic control valves to control how much steam is admitted to the heat exchanger, in order to maintain the desired process fluid temperature. If the control valve shuts, the steam in the heat exchanger condenses and creates a vacuum. This can cause tubes to rupture, or even entire shells to collapse! Therefore, steam heat exchangers should have vacuum breakers, or combination vacuum breaker vents, installed to prevent the heat exchanger from going into a vacuum.

Shutting down a heat exchanger is typically the opposite of the start-up sequence.

Chapter Summary

This chapter covered the application of heat transfer principles to the design, application, operation, and maintenance of heat exchangers.

Objective 1 began with a description of the three modes of heat transfer: conduction, convection, and radiation. Heat exchanger fluid flow arrangements were discussed next. Examples of the heat transfer modes and flow arrangements in steam generating units and HVAC coils were given.

Objective 2 discussed bare and finned heat exchanger tubes. Various heat exchanger designs, including shell-and-tube, shell-and-coil, plate, and spiral plate heat exchangers were described. As well, some common applications were mentioned.

Various heat transfer fluids and their thermal characteristics were introduced in Objective 3. Operational considerations were discussed, including fouling, how to recognize when fouling is occurring, and what conditions may lead to fouling.

Finally, Objective 4 examined heat exchanger overpressure protection, routine inspection, and placing heat exchangers in service.

CHAPTER 4

Thermodynamics of Steam

LEARNING OUTCOME

When you complete this chapter you should be able to:

Apply the thermodynamics principles through practical applications using the steam tables and the temperature-enthalpy chart.

LEARNING OBJECTIVES

Here is what you should be able to do when you complete each objective:

1. *Describe heat as it relates to steam, water, and ice.*
2. *Explain the various columns of the steam tables.*
3. *Explain the thermodynamic principles of steam, using the steam tables.*

Chapter Introduction

In thermodynamic systems, the working media can be in different states:

- solid
- liquid
- gas
- mixed solid-liquid
- mixed liquid-gas

This chapter gives an overview of thermodynamic principles, and how they apply to water in its different states. This is important because water is the main working medium in power plants. The behaviour of water with the addition or removal of heat will be explained with the use of steam tables and the temperature-enthalpy chart.

The tables referred to in this chapter are the steam tables in the **PanGlobal Academic Supplement**.

This chapter will assist in understanding the state the working medium is in, and the main properties (such as temperature, pressure, specific volume, and enthalpy) that characterize the working medium. From an operational perspective, it is important to understand how a change of working medium properties can influence equipment efficiency. To emphasize this point, boiler efficiency will be analyzed. Power Engineers in training must be able to understand how to operate a boiler with maximum efficiency and minimum environmental impact.

Objective 1

Describe heat as it relates to steam, water, and ice.

How Heat Transfer affects Steam, Water and Ice

When heat is applied to a body or substance, the internal energy will increase, causing an increase in temperature or a change of state.

Consider how much heat energy would be required to convert 10 kg of ice at 0°C to steam at 100°C in the following heat transfer stages:

1. Ice at 0°C to water at 0°C (Latent Heat of Fusion),
2. Water at 0°C to water at 100°C (Sensible Heat), and
3. Water at 100°C to dry steam at 100°C (Latent Heat of Evaporation).

The following paragraphs track the heat addition to 10 kg of ice as it is converted step by step into steam.

Latent Heat of Fusion

When heat is supplied or taken away, causing a change in state without a change in temperature, then the heat supplied is known as latent heat.

To melt ice, latent heat of fusion must be supplied. The latent heat of fusion is the heat required to change a unit mass of solid to a unit mass of liquid at the same temperature. For example, at atmospheric pressure, the latent heat of fusion of pure ice is 335 kJ/kg. That means it requires 335 kJ of heat to change one kg of ice at 0°C into water at 0°C.

So, the heat required to melt 10 kg of ice is:

$$\begin{aligned}\text{Heat required} &= \text{Mass} \times \text{Latent heat of fusion}\\ &= 10\ \text{kg} \times 335\ \text{kJ/kg}\\ &= 3350\ \text{kJ}\end{aligned}$$

Sensible Heat

Now that the ice is melted, its temperature must be raised. When heat is supplied or taken away, causing an immediate change in temperature without changing the state, the heat is known as sensible heat.

So, the heat required to raise the temperature of 10 kg of water at 0°C to the boiling point is:

$$\begin{aligned}\text{Heat required} &= \text{Mass} \times \text{Specific heat} \times \text{Temperature difference}\\ &= 10\ \text{kg} \times 4.183\ \text{kJ/kg°C} \times (100\text{°C} - 0\text{°C})\\ &= 41.83\ \text{kJ/°C} \times 100\text{°C}\\ &= 4183\ \text{kJ}\end{aligned}$$

Latent Heat of Evaporation

The latent heat of evaporation is the heat required to change a unit mass of liquid to a unit mass of gas at the same temperature and pressure. For example, at atmospheric pressure, the latent heat of evaporation of water is 2257 kJ/kg. This means it requires 2257 kJ of heat to change every kg of pure water at 100°C into steam at 100°C.

Note: Latent heat of fusion and evaporation are found by experiment. The latent heat of evaporation varies with pressure. As the pressure increases, the latent heat of evaporation decreases.

So the heat required to convert 10 kg of water at 100°C into steam at 100°C:

$$\begin{aligned}\text{Heat required} &= \text{Mass} \times \text{Latent heat of evaporation}\\ &= 10\text{ kg} \times 2257\text{ kJ/kg}\\ &= 22\,570\text{ kJ}\end{aligned}$$

The total heat addition, then, is the latent heat of fusion plus the sensible heat plus the latent heat of evaporation. Added together, the total heat required to turn 10 kg of ice at 0°C into steam at 100°C.

$$\begin{aligned}\text{Total heat required} &= 3350\text{ kJ} + 4200\text{ kJ} + 22\,570\text{ kJ}\\ &= \mathbf{30\,120\text{ kJ (Ans.)}}\end{aligned}$$

Therefore, to convert 10 kg of ice into water at its boiling point took 3350 + 4200 = 7550 kJ or 25% of the total 30 120 kJ of heat supplied. To convert the boiling water to steam, it took 22 570 kJ, or 75% of the total 30 120 kJ of heat supplied.

In other words, it took much less heat energy to change the ice to water and to raise the water to its boiling point than it did to boil all of the water into steam. Therefore, **steam contains much more heat energy per kilogram than hot boiling water**.

Saturation Temperature

The temperature at which the change from water to steam takes place is called the boiling point or saturation temperature. This temperature depends on the pressure on the surface of the water. This pressure that exists when saturation temperature is reached is called the saturation pressure. It must always be remembered that saturation temperature is dependent on saturation pressure. Examples of the boiling point at various pressures are shown in Table 1 below and in the **PanGlobal Academic Supplement – Steam Tables, Table 1**.

Table 1 – Saturation Temperatures

Absolute Pressure	Boiling Point or Saturation Temperature
101.3 kPa	100°C
200 kPa	120.23°C
300 kPa	133.55°C
400 kPa	143.63°C

Calculations concerning steam are complex due to variations in temperature and pressure. All values of the properties of steam have been determined accurately and are listed in available and easy to use steam tables.

Similar tables are also available for most liquids and gases, such as refrigerants and industrial gases.

Saturated Steam

The change of state from water to steam takes place at the saturation temperature corresponding to the pressure acting on the water surface. Water at saturation temperature is called saturated water because it cannot hold any more sensible heat without changing state.

Further heat energy applied to saturated water will result in its conversion to steam. The steam produced is called saturated steam, because it is steam at its saturation temperature.

Saturated steam can be "wet," meaning that it contains moisture particles, or "dry," meaning that it is made only of gas. Because dry steam is only gaseous, it is invisible. To be dry, saturated water must receive all the latent heat of evaporation, per kilogram, needed to convert it to steam. At atmospheric pressure, that means exactly 2257 kJ needs to be supplied for every kilogram of saturated water.

Wet steam contains un-evaporated moisture particles that are visible to the naked eye. Wet steam is the white vapour we observe coming from a stove-top kettle. The reason it is wet is because fine water droplets leave with the gaseous steam before receiving all of its latent heat of evaporation. At atmospheric pressure, that means less than 2257 kJ were supplied for every kilogram of saturated water. For the sake of argument, it can be said that perhaps the wet steam only received 1995 kJ/kg of latent heat.

Thus, saturated steam - either dry or wet - is at the temperature of the change of state from liquid to vapour. If any heat is removed from saturated steam, it will immediately condense.

Superheated Steam

Most boilers supply saturated steam. As this steam travels through the steam lines, it condenses as it loses heat. This condensation must be continually removed from steam lines to prevent a dangerous condition called "water hammer."

To avoid or minimize heat losses, and to prevent steam condensation in steam lines, dry saturated steam can be heated to above its saturation temperature. When a gas is raised in temperature to above its saturation temperature, it is called "superheated" gas. If the superheated gas is steam, then it is called "superheated steam."

In a power plant, saturated steam is superheated by passing it through rows of tubes placed in the boiler furnace area. In these tubes, wet steam from the boiler is first dried and then superheated. Then, the superheated steam enters the main steam header. These tubes are called superheater tubes. The process of heating the steam to above its saturation temperature is called superheating.

Superheated steam will not condense until its temperature has dropped to its saturation temperature, at the corresponding saturation pressure. This means that the superheated steam can be transmitted long distances, to turbines or other equipment, without excessive condensation losses.

Buildings that use steam for heating almost always use wet or dry saturated steam. Superheated steam is used mainly in industrial facilities. These facilities have large steam generating units that supply superheated steam to turbines for power generation, or for other applications needing high temperature and high pressure steam.

Objective 2

Explain the various columns of the steam tables.

Steam Tables

The thermodynamic properties of steam vary with pressure and temperature. These thermodynamic properties include:

- the volume of gas per kilogram
- the volume of saturated liquid per kilogram
- the sensible heat of saturated liquid per kilogram
- the sensible heat of saturated gas per kilogram
- the latent heat of evaporation per kilogram

These values and others must be known to solve problems involving the use of steam. All these properties of steam have been obtained by careful experiments. The results of the experiments are listed in steam tables.

The following "Columns" refer to **Table 1 - Properties of Saturated Steam (Pressure Table)** of the **SI Steam Tables** in the **PanGlobal Academic Supplement**. The columns in the Academic Supplement's tables are not numbered. However, for this discussion, they will be referred to with numbers from left to right (Columns 1 to 13). Samples of the column headings are given below each Column sub-heading.

AS

Columns 1, 2, 3, and 4

These columns list various pressures and their corresponding temperatures, plus the specific volumes of saturated liquids and vapours.

Column 1	Column 2	Column 3	Column 4
		Specific Volume	
Absolute Pressure	Temperature	Saturated Liquid	Saturated Vapour
p	t	v_f	v_g

Column 1 lists the absolute pressure (p) in kPa.

It should be remembered that the absolute pressure is obtained using the following formula:

Absolute pressure = Gauge pressure + 101.3 kPa

Column 2 lists the corresponding saturation temperature (t) in °C for each absolute pressure.

Examine the values in columns 1 and 2. Notice that the temperature of saturated steam increases as the pressure increases. Table 2 illustrates how the boiling point of water increases as the pressure increases.

Table 2 – Boiling Point, Pressure and Temperature Relationships	
Column 1	**Column 2**
Absolute Pressure	Temperature
p	**t**
100 kPa	99.63°C
500 kPa	151.86°C
1500 kPa	198.32°C

Column 3 lists the specific volume (V_f) (volume of fluid) of the saturated liquid in cm^3/gram at each saturation temperature and pressure. The specific volume is the volume occupied by 1 gram of water at that pressure and temperature. Referring to Table 3 below, note that the specific volume of saturated water increases as the pressure and temperature increase.

Note: One cm^3/gram equals one litre/kg.

Table 3 – Pressure, Temperature and Specific Volume of Saturated Liquid		
Column 1	**Column 2**	**Column 3**
		Specific Volume
Absolute Pressure	Temperature	Saturated Liquid
p	**t**	V_f
100 kPa	99.63°C	1.0432 cm^3/g
500 kPa	151.86°C	1.0926 cm^3/g
1500 kPa	198.32°C	1.1539 cm^3/g

Column 4 lists the specific volume (V_g) (volume of gas) of the saturated steam in cm^3/gram, for each listed pressure. This is the volume occupied by 1 gram of steam at that pressure and temperature. As shown in Table 4, note that the specific volume of the saturated steam decreases with increasing pressure.

Table 4 – Pressure, Temperature and Specific Volume of Saturated Vapour		
Column 1	**Column 2**	**Column 4**
		Specific Volume
Absolute Pressure	Temperature	Saturated Vapour
p	**t**	V_g
100 kPa	99.63°C	1694.0 cm^3/g
500 kPa	151.86°C	374.9 cm^3/g
1500 kPa	198.32°C	131.77 cm^3/g

It is interesting that one gram of saturated water at 100 kPa has a volume of 1.0432 cm^3. If this water is converted into saturated steam at the same pressure, the volume becomes 1694 cm^3. The volume increases more than **1600 times** when the state changes from water to steam.

Columns 5, 6, and 7

These columns are concerned with internal energy. This is the sum of all of the energy in the atoms and molecules in a substance due to their constant motion. These columns concern more advanced topics, which will not be covered at this introductory level.

Column 5	Column 6	Column 7
Internal Energy		
Saturated Liquid	Evaporation	Saturated Vapour
U_f	U_{fg}	U_g

Columns 8, 9, and 10

These columns of the steam tables indicate specific enthalpy. Enthalpy is a measure of heat added to a unit mass of a substance.

Column 8	Column 9	Column 10
Enthalpy		
Saturated Liquid	Evaporation	Saturated Vapour
h_f	h_{fg}	h_g

Column 8 lists the liquid enthalpy (h_f) in kilojoules/kilogram of the saturated water for each pressure. The enthalpy values listed in this column refer to the amount of heat added to the water to raise its temperature from 0°C to the listed saturation temperature. It is assumed that the enthalpy of water at 0°C is zero. This is ***sensible heat*** since it raises the temperature without changing the state.

Column 9 lists the enthalpy of evaporation (h_{fg}) in kilojoules/kilogram for each pressure. In this case, the enthalpy is the heat added to the water at saturation temperature to convert it to saturated steam at the same temperature. In other words, it is the ***latent heat of evaporation***.

Column 10 lists the total enthalpy (h_g) in kilojoules/kilogram of the saturated steam for each pressure. Recall that saturated steam is fully saturated with latent heat and has no water particles present.

It should be noted that:

$$\mathbf{h_g = h_f + h_{fg}}$$

"h_g" is the total heat necessary to produce saturated steam from water at 0°C, and consists of the sensible heat plus the latent heat.

Columns 11, 12, and 13

These columns list values of entropy. These columns concern more advanced topics, which will not be covered at this introductory level.

Column 11	Column 12	Column 13
Entropy		
Saturated Liquid	Evaporation	Saturated Vapour
S_f	S_{fg}	S_g

OBJECTIVE 3

Explain the thermodynamic principles of steam, using the steam tables.

Note: All pressures given in this module are absolute unless stated otherwise.

USING THE STEAM TABLES

A | S

The **Properties of Saturated Steam – Temperature Table** lists the various saturation temperatures (Table 2 in the **PanGlobal Academic Supplement**). As in the pressure table, consider the columns as being numbered left to right.

Example 1

From the steam tables, find the following:

a) The liquid enthalpy of one kilogram of saturated water at 200 kPa
b) The enthalpy of evaporation of one kilogram of saturated steam at 200 kPa
c) The total enthalpy of one kilogram of saturated steam at 200 kPa

Solution 1

Using columns 8, 9, and 10:

a) h_f = **504.7 kJ (Ans.)**
b) h_{fg} = **2201.9 kJ (Ans.)**
c) h_g = **2706.7 kJ (Ans.)**

Table 5 – Properties of Saturated Steam – Pressure Table

Column 1	Column 2	Column 8	Column 9	Column 10
			Enthalpy	
Absolute Pressure	Temperature	Saturated Liquid	Evaporation	Saturated Vapour
p	t	h_f	h_{fg}	h_g
200 kPa	120.23°C	504.70 kJ/kg	2201.9 kJ/kg	2706.7 kJ/kg

Example 2

a) Find the sensible heat required to raise 5 kg of feedwater from 0°C to the boiling point at 300 kPa.

b) What is the boiling point at this pressure?

Solution 2

a) h_f at 300 kPa = 561.47 kJ/kg

h_f at 0°C = Zero

Therefore, the sensible heat required to raise 5 kg of water to its boiling point at 300 kPa is:

= (561.47 kJ/kg – 0) × 5 kg

= **2807.35 kJ (Ans.)**

b) From the steam tables, the boiling point or saturation temperature (t) at 300 kPa is:

= **133.55°C (Ans.)**

Values of sensible heat given in the steam tables are measured from 0°C. At 0°C, the value of the enthalpy of water is zero.

Since feedwater is not usually supplied at this low temperature, it is necessary to determine the enthalpy of feedwater at the supply temperatures.

Column 1 gives the temperature and the enthalpy can be found in Columns 8, 9, and 10.

Example 3

How much heat will be required to convert 10 kg of water at 60°C into saturated steam at 200 kPa?

Solution 3

Enthalpy of saturated steam at 200 kPa is found in Table 1 (pressure table in the PanGlobal Academic Supplement):

h_g = 2706.7 kJ/kg

Enthalpy of water at 60°C is found in Table 2 (temperature table in the PanGlobal Academic Supplement):

h_f = 251.13 kJ/kg

Therefore, heat required for 1 kg:

= $h_g - h_f$

= 2706.7 kJ/kg – 251.13 kJ/kg

= 2455.57 kJ/kg

Heat required to convert the 10 kg of water at 60°C to saturated steam at 200 kPa is:

= 2455.57 kJ/kg × 10 kg

= **24 555.7 kJ (Ans.)**

Self-Test 1

How much heat will be required to convert 15 kg of water at 80°C into saturated steam at 250 kPa?

35 729.85 kJ (Ans.)

The **Table of Properties for Superheated Steam** (Table 3 in the **PanGlobal Academic Supplement**) shows the relationships between temperature, pressure, and other thermodynamics properties. These include specific volumes and enthalpies for superheated steam (steam heated to above the saturation temperature at the corresponding pressure).

Example 4

Find the enthalpy of 5 kg of superheated steam at 500 kPa and 300°C. Also, find the degrees of superheat for steam at 500 kPa and 300°C

Solution 4

From Table 3 find the pressure of 500 kPa in the first column and the temperature of 300°C in the top row. At the intersection of these two, the enthalpy value is:

$$h = 3064.2 \text{ kJ/kg}$$

For 5 kg of steam, the enthalpy will be:

$$H = 5 \text{ kg} \times 3064.2 \text{ kJ/kg} = 15\ 321 \text{ kJ (Ans.)}$$

From Table 3, the saturation temperature at a pressure of 500 kPa is 151.86°C.

Determine the degrees of superheat:

$$300°C - 151.86°C = \textbf{148.14 degrees of superheat (Ans.)}$$

Wet Steam

Often the values given for saturated steam in the steam tables are not found in an actual steam boiler.

The steam produced by a boiler may contain particles of saturated water due to the vigorous boiling action at the water surface. This is wet steam.

Consider 1 kg of saturated water in a boiler. Allow the burner to add latent heat to the water. However, only provide the water 90% of the latent heat necessary to convert it to steam. The resulting vapour will be made of 90% dry and saturated steam (or 900 grams of steam) and 10% saturated water (100 grams of water). The water will be fine droplets mixed with the steam, causing it to be visible.

Usually, wet steam is referred to by how dry it is, and not by how wet it is. Thus, the wet steam in this example is usually referred to as "90% dry and saturated," and not "10% wet."

Example 5

If steam with a dryness fraction of 90% is to be produced from saturated water at 200 kPa, what amount of heat must be supplied per kilogram?

The dryness fraction of wet steam can be used to calculate the actual enthalpy that the steam contains, using the formula:

$$h = h_f + qh_{fg}$$

Where q = dryness fraction (expressed as a decimal; e.g. 90% = 0.90)

h = total enthalpy at the stated condition

h_{fg} = enthalpy of evaporation at the given pressure

h_f = enthalpy of the saturated liquid

Note: When $q = 1$, the steam quality is 100%. For 100% dry and saturated steam, $h_g = h_f + qh_{fg}$, but $q = 1$ and is often omitted.

Solution 5

A dryness fraction of 90% (or 0.9) means that only 90% of the saturated water has been converted to saturated steam. The remaining 10% is called the wetness fraction. Consider only the h_{fg} in this example:

Let q = Dryness fraction of the steam = 0.9

Heat (h) to convert water to steam = 0.9 × 2201.9 kJ/kg

= **1981.71 kJ/kg (Ans.)**

Thus, 1981.7 kJ/kg of heat is required to convert saturated water at 200 kPa into wet steam with a dryness fraction of 90%.

Example 6

How much heat must be supplied to water at 0°C to make 1 kg of wet steam at 200 kPa, having a dryness fraction of 90%?

Solution 6

Since the water is raised from 0°C to saturation temperature, one kilogram of water receives its full sensible heat (h). However, since only 90% of the saturated water is converted to saturated steam, the latent heat received is only 90% of h_{fg}.

$$h = h_f + qh_{fg}$$

$$= 504.70 \text{ kJ/kg} + (0.9 \times 2201.9 \text{ kJ/kg})$$

$$= 504.70 \text{ kJ/kg} + 1981.7 \text{ kJ/kg}$$

$$= \mathbf{2486.41 \text{ kJ/kg (Ans.)}}$$

Therefore, 2486.41 kJ/kg of heat is required to convert water at 0°C into wet steam at 200 kPa, having a dryness fraction of 90%.

Self-Test 2

How much heat must be supplied to water at 180°C to make 1 kg of wet steam at 9000 kPa, having a dryness fraction of 80%?

1703.16 kJ/kg (Ans.)

Temperature-Enthalpy Chart

The process of changing water into wet, saturated steam can be shown with a temperature-enthalpy chart as shown in Figure 1. The following example illustrates this.

Example 7

Using information from the steam tables, plot the values of heat required to produce dry saturated steam from feedwater at 0°C at a pressure of 100 kPa.

Solution 7

At 100 kPa:

Saturation temperature = 99.63°C

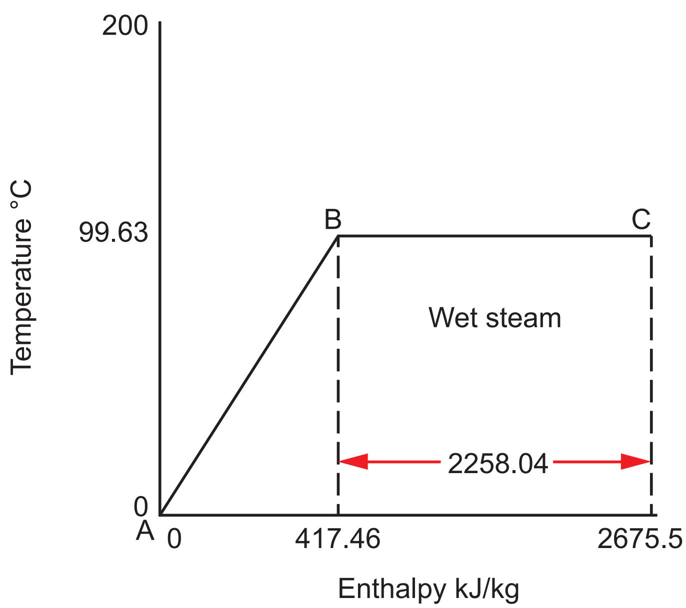
h_f = 417.46 kJ/kg

h_{fg} = 2258 kJ/kg

h_g = 2675.5 kJ/kg

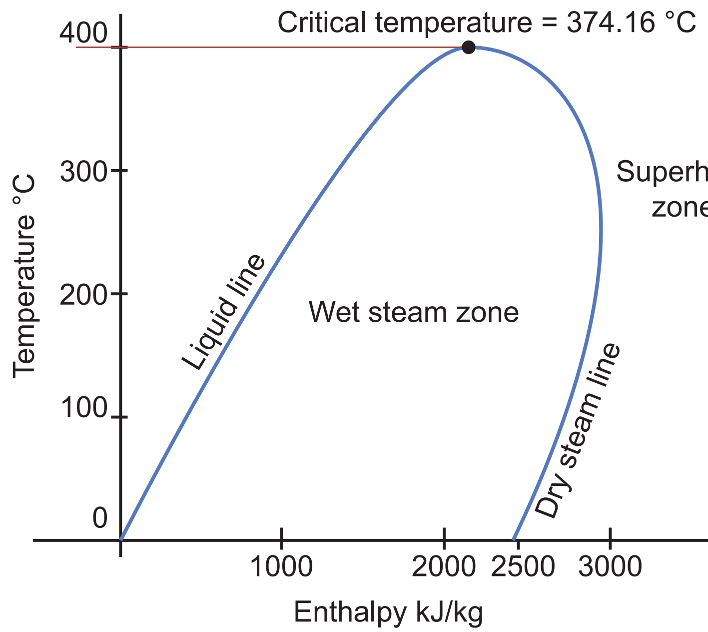
Plotting these values gives a graph similar to the one shown in Figure 1.

Figure 1 – Temperature - Enthalpy Values



If all the various pressures were plotted in the same manner and the points joined, a temperature-enthalpy chart would be produced as in Figure 2. Temperature-enthalpy charts have the advantage that the properties of steam at any saturation temperature can be determined; whereas the steam tables are limited to the temperatures listed.

Figure 2 – Temperature-Enthalpy Chart



Boiler Efficiency

The efficiency of a steam boiler is the ratio of the heat energy required to make steam to the heat energy supplied by the combustion of the fuel.

$$\text{Boiler efficiency} = \frac{\text{Heat given to the steam}}{\text{Heat supplied by the fuel}}$$

The "heat given to the steam" is the total heat that must be absorbed by the feedwater to convert it into steam. This involves knowing the total mass (kg) of steam produced, the initial enthalpy of the feedwater (kJ/kg), and the final enthalpy of the steam (kJ/kg). The "heat given to the steam," then, is the product of the total mass of steam and the heat added to each kg. The heat added to each kg is the difference between the final and initial enthalpies.

The "heat supplied by the fuel" is the total heat created in the boiler furnace by combustion of the fuel. This involves knowing the total mass (kg) of fuel burned and the heating value (kJ/kg) of the fuel. The "heat supplied by the fuel" is then the product of the mass and the heating value.

A more detailed equation, expressed as a percentage is as follows:

$$\text{Boiler efficiency} = \frac{\dot{m}_s\,(h_1 - h_2)}{\dot{m}_f \times \text{ heating value of fuel}}$$

Where

$\dot{m}_s$ = mass flow rate of steam (kg/h)

h_1 = enthalpy of steam produced in boiler (kJ/kg)

h_2 = enthalpy of feedwater to boiler (kJ/kg)

$\dot{m}_f$ = mass flow rate of fuel (kg/h)

Heating value of the fuel = kJ/kg of fuel

Example 8

A boiler generates 7 kg of dry saturated steam per kg of fuel oil burned. The heating value of the oil is 30 000 kJ/kg. The feedwater is supplied at 60°C and the boiler pressure is 200 kPa. Calculate the boiler efficiency.

Solution 8

h_1 = Enthalpy of dry saturated steam (Saturated Vapour, h_g at 200 kPa)
= 2706.7 kJ/kg

h_2 = Enthalpy of the feedwater (Saturated Liquid, h_f at 60°C)
= 251.13 kJ/kg

$\dot{m}_s = 7$ kg
$\dot{m}_f = 1$ kg

$$\text{Boiler efficiency} = \frac{\dot{m}_s\,(h_1 - h_2)}{\dot{m}_f \times \text{Heating value of the fuel}}$$

$$= \frac{7\text{ kg} \times (2706.7\text{ kJ/kg} - 251.13\text{ kJ/kg})}{1\text{ kg} \times 30\,000\text{ kJ/kg fuel}}$$

$$= \frac{7\text{ kg }(2455.57\text{ kJ/kg})}{30\,000\text{ kJ}}$$

$$= \frac{17\,188.99\text{ kJ}}{30\,000\text{ kJ}}$$

= 0.573 × 100%

= 57.3% (Ans.)

This means that 57.3% of the heat available in the fuel was effectively used in the production of steam. The remaining 42.7% of the heat is referred to as the boiler losses. These losses include such items as:

- sensible heat in dry gaseous products of combustion
- incomplete combustion
- moisture in fuel

To attain maximum efficiency in the daily operation of boiler equipment, **boiler losses** need to be kept to a minimum.

Self-Test 3

A boiler generates 10 kg of dry saturated steam per kg of fuel oil burned. The heating value of the fuel oil is 28 000 kJ/kg. The feedwater is supplied at 70°C and the boiler pressure is 300 kPa. Calculate the boiler efficiency.

86.9% (Ans.)

Chapter Summary

This chapter covered the inter-relationships between the main thermodynamic properties of water. It followed the natural sequence from:

- understanding the state of working medium
- using steam tables to define the thermodynamics properties of working mediums, and finally
- practical application of these relationships on determining boiler efficiency

Mastering the contents of this chapter will be helpful to new Power Engineers.

Unit Summary

This unit familiarized future Power Engineers with the structure of molecules and atoms. It explained why energy is released through combustion reactions. It described how chemical reactions apply to energy plant water treatment.

This unit followed a logical sequence to help new Power Engineers understand thermodynamic principles, including heat transfer. The First and Second Laws of Thermodynamics were introduced to help reinforce concepts of heat transfer. Next, these laws were applied to the three major modes of heat transfer: conduction, convection, and radiation. Finally, the basic operation of typical heat exchangers was covered.

The unit ended with discussion of the thermodynamic properties of water. Steam tables were used to determine the thermodynamic properties of the working fluid, which helped in understanding the state of the working media. One practical application that was covered was boiler efficiency calculation.

A self-assessment tool is available on MyPower LMS. Login using the unique user ID and password found on the inside front cover of Unit 1.

Notes

Notes

Notes

UNIT A-2

Knowledge Exercises and Unit Glossary

Chapter 1	Introduction to Matter and Chemistry	U2-9
Chapter 2	Introduction to Thermodynamics	U2-15
Chapter 3	Introduction to Heat Transfer and Heat Exchangers	U2-19
Chapter 4	Thermodynamics of Steam	U2-23
Unit A-2	Unit Glossary	U2-27

Knowledge Exercises – Chapter 1

Name: ______________________________ Date: ________________________________

Instructor: ___________________________ Course: ______________________________

Objective 1

1. State the phase the following are found at room temperature and pressure:
   a) Steam

   ____

   b) Nitrogen

   ____

   c) Copper

   ____

   d) Lemonade

   ____

   e) Cast iron

   ____

Objective 2

2. If pepper and salt are mixed together, do their chemical and physical properties change?

   ____

   ____

3. What is it called when a solid turns directly into a gas or vapour without becoming a liquid at any point?

   ____

4. What is it called when a gas turns into a liquid?

   ____

Objective 3

5. What type of mixture would salt water be?

   ____

Chapter 1 (Cont.)

6. What type of mixture is concrete?

7. Is rust a mixture, an element, or a compound? Explain.

Objective 4

8. What is the atomic number and the atomic mass of sodium (Na)?

9. How many protons does a Zinc (Zn) atom have?

10. What are the molecular masses of the following substances?

    a) O_2

    b) CH_4

    c) $Mg(HCO_3)_2$

Chapter 1 (Cont.)

11. How many kmoles of methane are in 4 kg (assume the molecular mass of methane is 16)?

12. How much mass does 2 kmoles of nitrogen have (assume its molecular mass is 28)?

13. In an atom which of protons, neutrons, and electrons have the least mass?

14. In an atom, what is positively charged?

Objective 5

15. What is an atom called if it has more electrons than protons?

16. What type of bond results in a compound that is likely to be highly soluble in water?

Objective 6

17. In the following chemical equation:

    $CaSO_4 + Ba(OH)_2 \rightarrow BaSO_4 + Ca(OH)_2$

    a) What are the reactants?

    b) What are the products?

    c) Is it a reversible (i.e. equilibrium) reaction?

    d) How many molecules of $Ca(OH)_2$ will be produced for every molecule of $CaSO_4$ used?

Chapter 1 (Cont.)

Objective 7

18. Balance the following equation:

$$C_2H_5SH + O_2 \rightarrow CO_2 + H_2O + SO_2$$

Chapter 1 (Cont.)

19. Given the following equation:

$$N_2H_4 + O_2 \leftrightarrow 2\ H_2O + N_2 \uparrow$$

How much hydrazine is needed to remove 1 kg of oxygen? Assume the reaction goes to completion (i.e. it can be considered a non-equilibrium reaction). What happens to the products?

Objective 8

20. Why are phosphates added to a boiler?

Knowledge Exercises – Chapter 2

Name: ______________________________ Date: ________________________________

Instructor: ___________________________ Course: ______________________________

Objective 1

1. Explain the First Law of Thermodynamics.

2. Explain the Second Law of Thermodynamics.

3. What is temperature?

4. With a simple drawing, compare four temperature scales.

Chapter 2 (Cont.)

5. Convert:
   a) 100°C to K

   b) –50°C to K

   c) 150 K to °C

6. Describe four common instruments used for to measure temperature.

Objective 2

7. Define heat.

8. Define specific heat.

Chapter 2 (Cont.)

9. Calculate the amount of heat required to decrease the temperature of 0.3 kg of copper by 15°C.

10. What is the specific heat for a certain material that has a mass of 5 kg, if it requires 0.150 kJ of heat to change in temperature by 10°C?

Objective 3

11. What is the coefficient of linear expansion?

12. Describe how the volume of water changes with temperature.

13. A steel steam pipe is 7.5 m long when fitted at a temperature of 25°C. Calculate its increase in length when carrying steam at a temperature of 320°C. Take the coefficient of linear expansion of the pipe as 12.0×10^{-6}/°C.

Knowledge Exercises – Chapter 3

Name: ______________________________ Date: ________________________________

Instructor: ___________________________ Course: ______________________________

Objective 1

1. Describe all three heat transfer methods.

2. Describe how these heat transfer methods work together to transfer heat from the furnace to the water within a boiler tube.

Chapter 3 (Cont.)

Objective 2

3. With the aid of a diagram, compare parallel flow heat exchangers and counter flow heat exchangers. Which design is more efficient?

4. The main heat transfer surface in a steam generating unit is called the ______________.

5. Describe the purpose of the economizer in a steam generating unit.

6. Why are plate heat exchangers so effective at transferring heat?

Chapter 3 (Cont.)

Objective 3

7. Identify six important considerations when selecting a heat transfer fluid.

   a) ______________________________

   b) ______________________________

   c) ______________________________

   d) ______________________________

   e) ______________________________

   f) ______________________________

8. What makes water an effective heat transfer fluid?

   ____

   ____

   ____

9. A non-toxic heat transfer fluid that may be used in food industries is ________________ ________________.

10. A common, somewhat toxic compound used as a refrigerant is ________________.

11. Describe the causes of heat exchanger fouling.

    ____

    ____

    ____

12. To assess the operation of a heat exchanger, Power Engineers must observe and record the inlet and outlet ________________ and ________________, and compare them over time.

Objective 4

13. Larger heat exchangers are often pressure vessels, designed to ASME Code Section ___________.

14. Explain why heat exchangers need pressure relief devices.

    ____

    ____

    ____

Chapter 3 (Cont.)

15. Describe a routine heat exchanger inspection, while conducting regular rounds.

16. Circle the correct answer: As a general rule, when placing a heat exchanger in service, it is best to admit the (cooler/hotter) process fluid before admitting the (cooler/hotter) process fluid.

17. List the steps for placing a steam heat exchanger in service.

Knowledge Exercises – Chapter 4

Name: ______________________ Date: ______________________

Instructor: ______________________ Course: ______________________

Objective 1

1. Define latent heat of fusion.

2. Define latent heat of evaporation.

3. Define sensible heat.

4. How much heat is required to convert 5 kg of ice at –5°C to steam at 100°C?

Chapter 4 (Cont.)

Objective 2

5. Using steam tables find:

   a) Saturation temperature at 350 kPa

   b) Enthalpy of water at 350 kPa

   c) Enthalpy of steam at 350 kPa

6. Calculate the required heat that has to be supplied to 5 kg of water at 50°C and 250 kPa to bring it to 75% dry steam.

Chapter 4 (Cont.)

Objective 3

7. A process in an industrial plant requires that 1500 kg of water be heated each hour from 30°C to 70°C. Heating is by a steam coil immersed in the water. The coil is supplied with 95% dry steam at 1250 kPa and the condensate leaving the coil is at a temperature of 80°C. Determine the steam consumption per hour assuming no heat is lost.

Unit A-2 Glossary

Term	Definition
Absolute pressure	The pressure of a fluid measured above a perfect vacuum (which has zero absolute pressure).
Absolute zero	The temperature at which all molecular motion ceases. This occurs at the zero point on an absolute temperature scale, which is zero Kelvin. This is equivalent to minus 273.15 degrees on the Celsius scale.
Air heater	A heat exchanger, located near the flue gas exit of a boiler, which transfers heat from the flue gas to the combustion air entering the boiler. This preheating of the air improves the combustion efficiency.
Alloy	A solid solution of a metal containing two or more metals or non-metals.
American society of mechanical engineers (ASME)	An organization that publishes construction rules for boilers and pressure vessels, to ensure equipment safety over a reasonable service life. Canadian provinces enforce ASME codes as law.
Ammonia	A compound of nitrogen and hydrogen, commonly used as a refrigerant.
Anhydrous ammonia	Ammonia that is free of water.
Anion	An atom with more electrons than protons and, hence, is negatively charged.
Antifreeze	An aqueous solution used to prevent freezing at low temperature.
Ash	The non-combustible product of combustion left from the burning of solid fuel.
ASME	See *American society of mechanical engineers* (ASME).
Atom	The smallest mass particle that exhibits the chemical properties of a particular element. It consists of electrons, protons and neutrons.
Baffle	A partial barrier used in heat exchangers, situated in a fluid flow path that changes the direction of fluid flow, thus maximizing heat transfer.
Boiler	A closed vessel in which water is heated, steam is generated, steam is superheated, or any combination thereof, under pressure or vacuum by the application of heat.
Boiler and pressure vessel code (BPVC)	A collection of codes published by the ASME, used for the safe design and construction of boilers and pressure vessels.
Boiling point	The temperature at which a phase change occurs between liquid and vapour.
BPVC	See *boiler and pressure vessel code* (BPVC).
Cation	An atom with less electrons than protons and, hence, is positively charged.
Coefficient of expansion	The increase in unit length, area, or volume, for each degree rise in temperature.
Coefficient of linear expansion	A unique property of a solid material that describes its change in length, per unit length, per degree change in temperature.
Combustion air	The air provided to ensure complete combustion of a fuel.
Condensate	Fluid formed when steam is cooled to below its saturation temperature.
Conduction	The transmission of heat through and by means of matter unaccompanied by any obvious motion of the matter.
Convection	Transfer of heat by means of movement or flow of a liquid or gas.

Term	Definition
Convection current	The movement of a fluid, due to the action of gravity on a fluid varying in density, and caused by the application of heat.
Convection superheater	A superheater so arranged and located to absorb heat from the products of combustion mainly by convection.
Covalent bond	A type of bond wherein electrons are shared between atoms.
Degrees of superheat	Presents the value of temperature by which the temperature of a superheated vapor exceeds the temperature of the saturated vapor at the same pressure.
Drum	A cylindrical shell closed at both ends designed to withstand internal pressure.
Dryness fraction	Ratio between total amount of mixture (liquid water and vapor) and vapor.
Economizer	A heat recovery device designed to transfer heat from the products of combustion to boiler feedwater.
Electromagnetic waves	Visible and invisible waves that transmit energy, including light waves, x-rays, ultraviolet waves, and infrared heat waves.
Electron	A negatively charged particle with negligible mass that orbits an atom's nucleus.
Element	A pure substance that cannot be separated into simpler substances through chemical means.
Enthalpy	A thermodynamic quantity equal to the total heat content of a system, with reference to a base temperature. Enthalpy is equal to the internal energy of the system plus the product of pressure and volume.
Ethylene	A colourless, flammable hydrocarbon gas, used in the production of ethylene glycol antifreeze.
Expansion joint, heat exchangers	In heat exchangers, a design element that permits the differential expansion of tubesheets and shells, reducing stress.
Feedwater	Water introduced into a boiler during operation. It includes make-up and return condensate.
Flash point	The temperature at which a flammable liquid produces sufficient vapour to momentarily support combustion.
Flue gas	The gaseous products of combustion in the flue to the stack.
Forced convection	The transfer of heat by the forced movement of a liquid or a gas, by means of a fan or pump.
Fouling	The accumulation of solid matter in gas passages or on heat absorbing surfaces which results in undesirable restrictions to the flow of gas or heat.
Freezing point	The temperature at which a liquid will solidify, or freeze, upon removal of heat. The freezing point for water is 0°C.
Furnace	The combustion chamber of a boiler.
Gas	State of matter wherein the molecules are widely spread about with no definite shape nor volume.
Glycol	A hygroscopic, viscous liquid made from ethylene or propylene, mixed with water in various proportions, and used as an antifreeze or heat transfer fluid.
Head	In pressure vessels, the plate that seals the end of a cylindrical shell or drum.

Term	Definition
Heat	A transferable form of energy that acts on substances to raise their temperature; the energy associated with random motion of molecules. The direction of heat transfer is always from a body at higher temperature to a body at lower temperature.
Heat engine	A machine, or assembly of machinery, that converts heat energy to mechanical energy through a series of repetitive thermodynamic operations, such as combustion, compression, expansion, boiling, condensation, and cooling.
Heat transfer coefficient	A number that identifies the characteristic ability of a particular material or mechanism to transfer heat.
Heat transfer surface	A surface area through which heat is conducted.
Internal energy	The sum of the kinetic and potential energies of the particles contained within a system. Internal energy of system depends on its pressure and temperature.
Ionic bond	A type of bond wherein electrons are taken from one atom by another atom creating anions and cations that are attracted to each other.
Latent heat	Heat, that when applied or removed causes matter to undergo a phase change (such as solid to liquid or liquid to gas). Latent heat cannot be observed with sensing instruments, such as thermometers.
Latent heat of evaporation	Energy required to changing from one phase to another: from liquid to vapor.
Latent heat of fusion	Energy required to changing from one phase to another: from solid to liquid.
Linear expansion	The change in length of a solid member due to the application of heat or applied force.
Liquid	A state of matter between that of a gas and a solid, wherein there is a definite volume but no definite shape.
Mandrel	A cylindrical rod around which metal is forged or otherwise shaped.
MAWP	See *maximum allowable working pressure* (MAWP).
Maximum allowable working pressure (MAWP)	The maximum pressure a boiler, pressure vessel, or pressure piping system can be safely operated at, according to its design.
Metallic bond	A type of bond between metal atoms wherein a cloud of delocalized electrons is shared amongst a structure of positively charged metal ions.
Mole	A measure of the number of molecules. One mole contains 6.0221413×10^{23} molecules.
Molecule	The smallest unit of an element or compound composed of one or more atoms.
Natural convection	The circulation of a gas or liquid due to the difference in density, resulting from temperature differences.
Neutron	A neutral particle within an atom's nucleus, with a mass equal to one atomic mass unit.
Non-flow process	A thermodynamic process in which a working fluid performs work, or has work performed on it, only within the system boundary.
Pass	In heat exchangers, a confined passageway through which a fluid, gas, or products of combustion flows in essentially one direction.
Pass partition plate	A plate found in the head of a multi-pass shell and tube heat exchanger, used to direct heat transfer fluid through tubes.

Term	Definition
Propylene	A colourless, flammable gas used as a fuel, or in the manufacture of propylene glycol antifreeze.
Proton	A positively charged particle within an atom’s nucleus, with a mass equal to one atomic mass unit.
Radiant superheater	A superheater so arranged and located to absorb heat by radiation.
Radiation	The emission of energy in the form of electromagnetic waves, or in the form of products of radioactive decay.
Reaction	A chemical process wherein reactant molecules are transformed or rearranged into different product molecules.
Refrigerant	A fluid that absorbs heat at low temperature and pressure, and rejects heat at high temperature and pressure, by undergoing a change of state.
Reheater	A heat transfer apparatus for heating steam after it has given up some of its original heat in doing work in the high-pressure section of a steam turbine.
Sensible heat	Heat, that when applied causes matter to change in temperature. It can be “sensed” by a thermometer.
Shell	The outer cylindrical portion of a pressure vessel.
Solid	State of matter wherein the atoms are arranged such that their overall shape and volume do not change.
Soot	Carbon dust formed by incomplete combustion.
SOP	See *standard operating procedure* (SOP).
Specific heat	The quantity of heat required to change the temperature of a unit mass by one degree.
Specific volume	In thermodynamics, the specific volume of a substance is the ratio of the substance's volume to its mass. It is the reciprocal of density. Specific volume is defined as the number of cubic meters occupied by one kilogram of a particular substance. The standard unit is the m^3/kg
Standard operating procedure (SOP)	A site-specific procedure for conducting routine operations, approved by facility management.
Steady flow process	A thermodynamic process whereby the working fluid enters and exits the system boundaries at the same constant rate.
Steam generator	A unit to which water, fuel, and air or waste heat are supplied and in which steam is generated. It can consist of a boiler furnace, and fuel burning equipment, and may include as component parts water walls, superheater, reheater, economizer, air heater, or any combinations thereof.
Stoichiometry	Based on the law of conservation of mass, where the total mass of the products is equals to the total mass of the reactants of a substance taking part in a chemical reaction.
Strainer	A device such as a screen or filter used to retain solid particles, while permitting liquid to pass through.
Stress	A material's internal resistance to an applied force. Stress is measured in units of pressure.
Superheater	A group of tubes which absorb heat from the products of combustion to raise the temperature of the steam passing through the tubes above its saturation temperature.
Temperature	The measurement of the intensity of heat concentrated in a body.
Temperature gradient	A term that describes the magnitude of temperature difference measured between two points.

Term	Definition
Thermal capacity	The amount of heat a unit mass of substance can absorb and transfer, per degree temperature rise.
Thermal shock	The rapid, stress-inducing differential expansion of a material exposed to sudden temperature change.
Tie rod	A threaded tension member used to hold together sections of heat exchangers (such as cast iron sections, or corrugated metal plates).
Tubesheet	A flat or curved metal plate, found in boilers and other heat exchangers, with holes arranged for the attachment of tubes.
Two-phase	Existing in two phases or states, such as water and steam, or water and ice.
Vapour	A gas-like state that can easily be changed to liquid or solid form with a small change in temperature or pressure.
Viscosity	The measure of the internal friction or the resistance to flow of a liquid (thickness).
Water hammer	A sudden increase in pressure of water due to an instantaneous conversion of momentum to pressure.
Waterside	In a boiler, the side of a heat transfer surface exposed directly to water, steam, or a two-phase mixture of water and steam.
Watertube	A tube in a boiler having the water and steam on the inside and heat applied to the outside.
Work	In mechanics, the product of a force times the distance through which the force acts. The unit for work is the joule (J).
Work done	Work is observed to be energy in transition. It is never contained in a body or possessed by a body.
Zebra mussel	A fast-breeding, invasive fresh-water shellfish, about 3 to 5 cm in length, found in North American bodies of water.

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