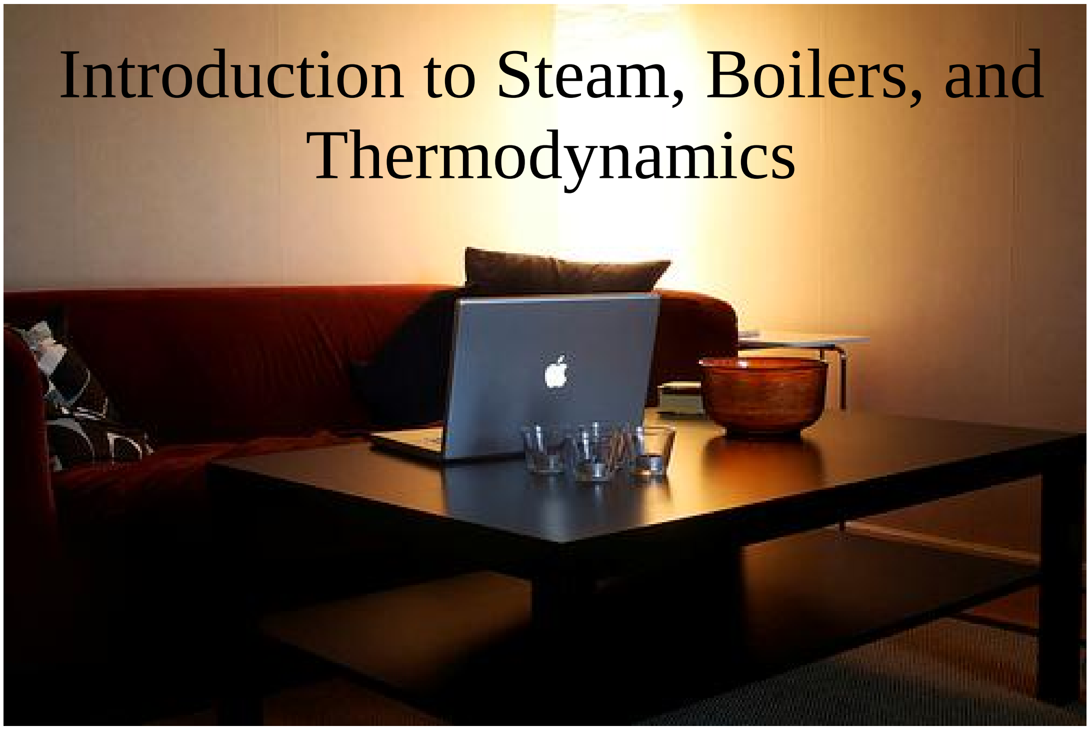

Introduction to Steam, Boilers, and Thermodynamics

By

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PDHLibrary Course No 2020051
4 PDH HOURS

Introduction to Steam, Boilers and Thermodynamics

First Edition, 2020 | saVRee UG | Schluderstrasse 2, Munich, 80634 Germany | www.savree.com | contact@savree.com

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Before Getting Started

This course is distributed globally so units are quoted in both ***imperial*** and ***metric*** wherever possible. A list of common units and conversions (metric to imperial or vice versa.) is given in the ***Appendix***. or ***Resources*** section of this course.

The course is split into ***Chapters*** and ***Lessons***.

ⓘ *Indicates a useful tip that can be used to remember or understand the subject matter.*

Text highlighted like this, indicates fundamental knowledge that should be learnt and understood.

The term '***a.k.a.***' means 'also known as' and is often used within the course.

If you are reading this course in PDF format and have a saVRee account, you may click on images of many of the 3D models to load the associated model.

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Introduction

The ***industrial revolution (circa. 1760-1820)*** may have been fired by coal, but it was powered by steam. Humans have been harnessing the power of steam for thousands of years, but it is only in the past 200 years that we have started to rely on it for countless industrial applications. This course looks at the origins of steam, its theory (thermodynamics), generation and applications.

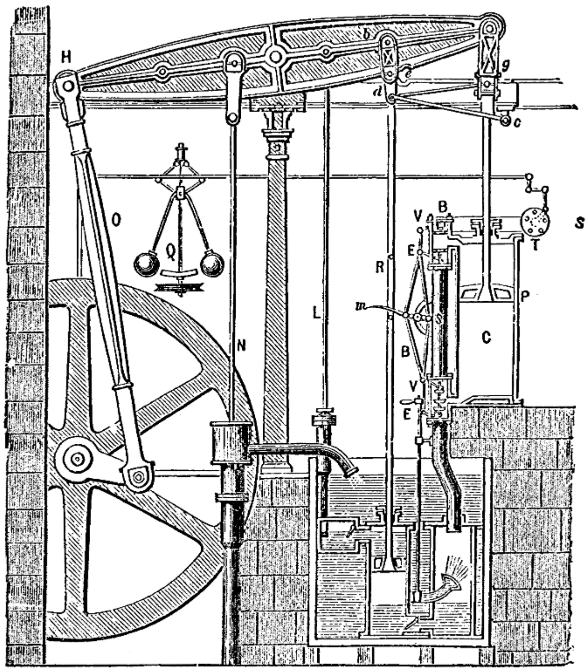
Fire Tube Boilers

History

The first usage of steam was recorded several thousand years ago. ***Hero of Alexandria*** created one of the first steam turbines in the 1st century, but the concept saw little application until much later in the 1800s.

Aeolipile (Hero Engine)

At the start of the industrial revolution, ***James Watt*** designed a reciprocating piston engine that was driven by steam; the design was referred to as a ***steam engine***. The steam engine was widely adopted and became one of the most iconic prime movers of the age.



Boulton and Watt Steam Engine Drawing

But James Watt was not the only person to use the power of steam to complete useful work. Other engineers soon realised that steam engines could be used for a wide range of applications. Some applications included powering railway locomotives, tractors and ships.

Steam Powered Automobile

At about the same time as steam's applications were growing, rapid advances in electrical engineering led to a surge in demand for prime movers that could be used to generate the newest wonder of the age…electricity!

Steam turbines were found to be ideal prime movers for the new power generation industry. Today, over 80% of the world's electricity is provided from steam turbine prime movers.

Almost all industrial revolution prime movers were powered by steam, and it was ***boilers*** that provided that steam. As the applications of steam have grown, so too have the quantity and design variations of steam boilers. Advances in technology and materials have allowed for ever larger prime movers, which has led to a corresponding increase in the size and power of steam boilers.

Steam is used in almost all modern industrial processes, either in the process directly, or for secondary services such as water heating, or space heating. The next lesson discusses the main uses of steam.

Uses of Steam

Steam is used for ***four*** main purposes:

- ***Heating*** – closed loop. Simple design. Low pressures and temperatures.
- ***Power Generation*** – system designs vary from simple to sophisticated. Wide range of pressures and temperatures. May produce medium to very large amounts of steam.
- ***Industrial Processes*** – much like power generation steam systems although much tighter tolerances concerning steam quality may exist. Steam systems are often critical for the plant/factory production process i.e. no steam = no production.
- ***Mechanical Work*** – steam can -and is- used to drive pumps, compressors and other machinery items that may not be well suited for an electrical drive, or other drive type.

It is rare to visit an industrial plant that does not have a boiler on site. Although the uses of steam are numerous, they generally belong to one of the four categories mentioned above.

Why Steam?

Human civilisation requires ***energy*** to function, lots of it. Without energy, it would not be possible to pump water to cities, provide electricity to homes, drive automobiles, or heat buildings. Prior to being used by end consumers, all energy must first be generated and conveyed to the point of use.
Electricity is an example of conveyed energy. Power stations generate electricity by converting heat, pressure, and/or kinetic energy, into electrical current. Converting the original energy source into electrical energy allows it to be conveyed easily across vast distances to the point of use.

Steam can -and is- also used to convey energy, but unlike electricity, steam conveys ***heat energy***, and is a ***fluid***. Because steam is a fluid, and is used to convey energy, it is termed an ***energy fluid***.

*A **fluid** has no fixed shape and yields when external pressure is applied i.e. fluids flow easily. Fluids may be a liquid, or a gas. An **energy fluid** is a fluid used to convey energy, usually in the form of **heat (thermal energy), pressure (pressure energy)** and/or **speed (kinetic energy)**.*

Although other energy fluids are available, steam is considered 'the energy fluid' and is by far the most common energy fluid in use today. The reasons for steam's popularity are closely linked to the properties of the water from which it is made. Water is:

- Plentiful.
- Easy to access (geographical location dependent).
- Cheap compared to other energy fluids.
- Non-toxic.
- Easily conveyed i.e. can be pumped.
- Easily controlled i.e. with valves etc.

After water is converted to steam, it becomes an energy fluid with many advantageous properties:

- A given mass of steam can hold ***five to six times more energy*** than an equivalent mass of water.
- It can be generated efficiently; many boilers operate with ***>80% thermal efficiency***.
- It can be distributed easily by creating a pressure difference in the steam system.
- It is non-toxic and does not damage the environment.
- It will not spark, ignite, or combust (intrinsically safe).
- The amount of energy within the system can be regulated easily by regulating the steam pressure.
- Steam's heat transfer properties are high.

Other energy fluids are usually only used if certain variables make the use of steam undesirable. For example, thermal oils (mineral oil) are used to convey large volumes of heat at very high temperatures for which steam may not be suitable. For safety reasons, buildings are often heated via hot water well below its boiling point; the lower pressures and temperatures also place less stress upon system piping and components, which gives them a longer service life.

The Steam System

The purpose of steam is to transport energy from where it is generated, to where it is required, whilst minimising the energy loses associated with conveying. In order to do this, steam systems consist of ***four*** main parts.

- ***Fuel System*** – provides chemical energy to the boiler (or combustion turbine if a ***heat recovery steam generator (HRSG)*** is used).
- ***Boiler*** – converts the fuel's chemical energy to thermal energy.
- ***Distribution*** – conveys steam to the point of use.
- ***Collection/Recovery*** – recovers ***condensate*** (water) from the steam system and returns it to the boiler.

The systems mentioned above form one basic process cycle:

1. ***Generation***
2. ***Distribution***
3. ***Recovery***
4. ***Repeat***

Energy is transferred to the steam during generation. The steam is then distributed to the point of use where some of the energy is transferred from the steam. The loss of energy causes some of the steam to condense and form condensate, which is then recovered, treated, and returned to the boiler. The entire process is designed based upon energy transfer.

1. ***Generation*** – chemical energy of the fuel transferred to the water. Boiler water ***boils*** then ***evaporates*** to form steam.
2. ***Distribution*** – energy conveyed to the point of use.
3. ***Recovery*** – some of the steam surrenders energy at the point of use and ***condenses*** to form water.
4. ***Repeat*** – remaining energy within the condensate returned to the boiler.

Note that in power stations, a condenser may be used to change a steam turbine's exhaust steam to condensate prior to it being returned to the boiler.

Thermodynamic Fundamentals

This chapter discusses many ***thermodynamic principles*** that every engineer should be aware of when learning about steam. Topics covered include thermodynamic laws, heat, heat transfer, combustion and thermal efficiency.

Pressure

The pressure exerted at sea level is 14.7 pounds per square inch (psi), or 1 bar. Pressure measured at sea level occurs due to the earth's atmosphere, and for this reason is known as ***atmospheric pressure***. Atmospheric pressure decreases as altitude above sea level increases.

Pressure gauges are used to measure pressure. If a pressure gauge is lying on a table at sea level and is open to atmosphere i.e. not connected to a system, the pressure displayed will be 0 psi, or 0 bar. The pressure shown by a gauge is known as ***gauge pressure***, it does not account for atmospheric pressure.

The sum of gauge pressure and atmospheric pressure is ***absolute pressure*** and is given by the equation:

Absolute Pressure = Atmospheric Pressure + Gauge Pressure

Pressures are often given in 'psi' or 'bar', but it is also possible that pressures may be given in 'psi**a**', 'psi**g**', 'bar**a**' or 'bar**g**'. The 'a' and 'g' indicate 'absolute' and 'gauge' pressure readings. Generally, if a pressure reading is given in psi or bar, it is a gauge pressure reading i.e. psig or barg, but the 'g' has not been stated.

Pressure Gauge

It is important to make a distinction between absolute and gauge pressure whenever using gas charts or gas tables, as pressure relates to when a substance changes state and how much energy it carries.

Note that psia, psig, bara and barg, are also sometimes wrote psi(a), psi(g), bar(a), bar(g).

Boiling Point

Steam is produced when water is heated to its ***boiling point***.

*The **boiling point** is the temperature at which a liquid boils and becomes vapour, it is also referred to as the **saturation temperature**.*

At sea level, water boils at ***212°F (100°C)***. If the pressure surrounding the water decreases, the temperature required to boil the water will also decrease. If the pressure surrounding the water increases, the temperature required to boil the water will also increase.

The boiling point of a liquid increases as pressure increases and decreases as pressure decreases.

The below table shows the boiling point of water at various pressures. Note that the temperature required to boil water gradually increases as the pressure increases.

Water Boiling Point			
Imperial Units		**Metric Units**	
Pressure (psia)	**Temperature (°F)**	**Pressure (bara)**	**Temperature (°C)**
14.7	212	1.0	100
30.0	250	2.1	121
45.0	275	3.1	135
60	293	145	4.1

Water Boiling Point Table

Boiling water in an open vessel requires a large amount of energy because it is inefficient. However, if the vessel is fully enclosed with an outlet for steam and inlet for water, the amount of energy required to boil water reduces dramatically.

ⓘ ***Home Experiment:*** *Measure the time it takes to boil a certain amount of water in a pot with the lid off, then repeat the experiment with the lid on. The time needed to boil the water with the lid on will be far less than with the lid-off.*

Thermodynamics Laws

Thermodynamics is the study of thermal energy and how it is transferred to other forms. The 'therm' of thermodynamics relates to 'thermal' whilst 'dynamic' refers to the changing/transferring state of the thermal energy.

There are ***two thermodynamic laws*** of importance when learning about steam.

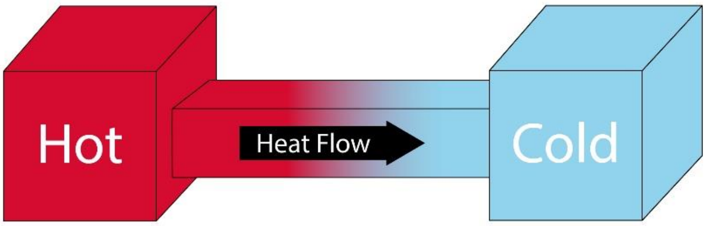
First Law of Thermodynamics – energy cannot be destroyed, or created, it can only change form.
Second Law of Thermodynamics – heat flows from hot to cold.

Example of the First Law of Thermodynamics (energy conversion)

A power station boiler burns fuel thus transferring the chemical energy of the fuel into thermal energy via the process of combustion. This thermal energy is then transferred to a steam system, then to a steam turbine. The steam turbine converts the steam's energy into mechanical energy i.e. steam passing through the turbine causes it to rotate. Finally, the turbine is connected to a generator and the generator converts the mechanical energy supplied by the turbine to electrical energy.

Example of the Second Law of Thermodynamics (hot to cold)

A boiler transfers the heat from combustion to the water in the boiler i.e. the heat travels from hot to cold.



Second Law of Thermodynamics (hot to cold)

Heat

Solids, ***liquids*** and ***gases***, represent three different ***states*** (a.k.a. ***phases***). Solids are *almost totally* incompressible and have a definite shape, whilst liquids are *nearly* incompressible, and gases are compressible. For practical purposes, solids and liquids compress by so little that they are often assumed to be incompressible. Water can exist as a solid (ice), liquid (water), or gas (steam).

Heat is defined as '***thermal energy*** transferred between two systems that are in direct contact with each other, but at different temperatures.' If heat is transferred to a substance, the substance will change temperature, or change state.

Change of State Example

A large amount of heat is transferred to a block of ice, which causes it to melt and become water.

Change of Temperature Example
A small amount of heat is transferred to some water, its temperature increases, but its state does not change.

The important difference in both examples is that energy can be transferred to a substance to change the temperature of the substance, or change the state of the substance. The differences between the two energy forms is clarified in the next section.

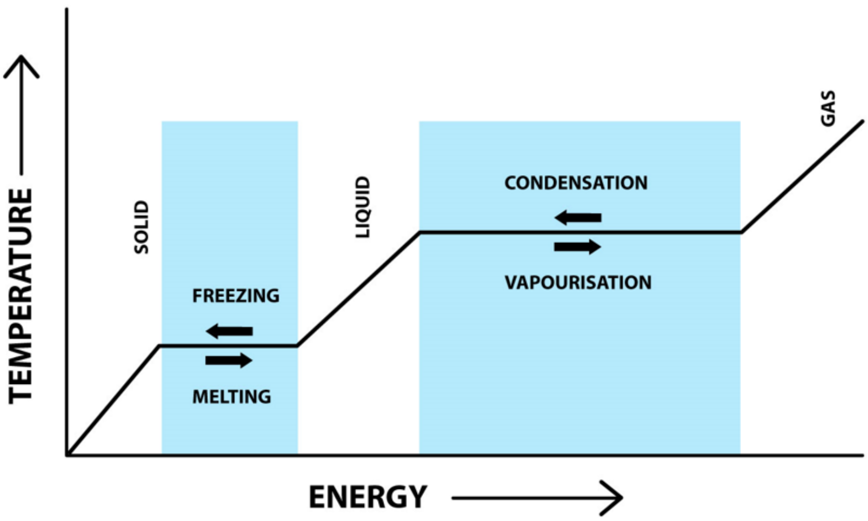
Sensible and Latent Heat

The term ***heat*** (a.k.a. ***heat energy***) describes two types of heat, ***sensible heat*** and ***latent heat***.

Sensible Heat can be measured using a thermometer and sensed by a human ('sense-ible heat'). A change in sensible heat is not accompanied by a change in state.

Latent Heat can be identified by a substance's change in state/phase, but not by a change in temperature. ***Evaporation*** and ***condensation*** are forms of latent heat.

The below graph shows that heat energy added does not always cause a temperature change. Sensible heat is seen whenever heat is added and the temperature changes proportionately (sloped lines on the graph). Latent heat is seen whenever heat is added and no change of temperature occurs (horizontal lines on the graph).



Sensible and Latent Heat Diagram

Adding sensible heat to water will gradually increase its temperature, although it will only boil once it reaches its saturation temperature (boiling point). At saturation temperature, no more sensible heat can be added, but more heat can be added in the form of latent heat.

The additional latent heat causes the water to evaporate and change state to a gas. The resultant steam contains both the sensible and latent heat energy that was transferred into it, however, ***changing water into gas requires far more energy than simply heating the water, thus the steam contains much more latent heat than sensible heat***. The total heat contained by the steam is very important, as this represents the amount of energy that can later be used by the end consumer.

ⓘ *A liquid at saturation temperature (temperature at which it boils), or saturation pressure (pressure at which it boils), is literally saturated with sensible heat i.e. it cannot hold any more heat without beginning to boil.*

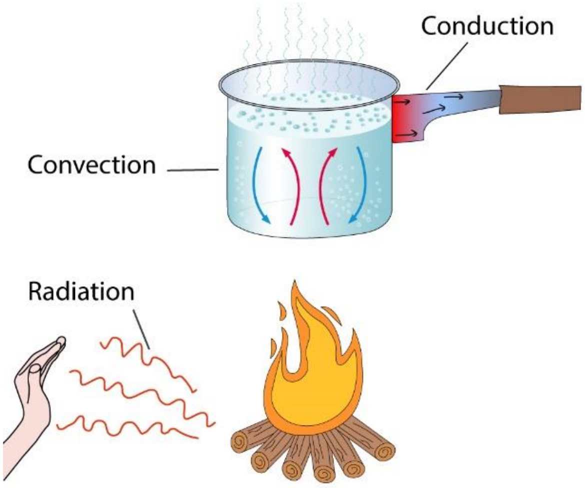
Transferring Heat

As stated in the second law of thermodynamics, heat energy (a.k.a. heat) is transferred from hot to cold. The temperature difference between two substances dictates the heat transfer rate.

Substances with a high temperature difference will have a higher heat transfer rate than substances with a low temperature difference.

Heat is transferred via ***conduction***, ***convection*** or ***radiation***. In most industrial settings, heat is transferred via a mixture of one or more of these heat transfer means, rarely by a single mean.

- ***Conduction*** – heat is transferred directly from one molecule to another. Conduction occurs in solids, liquids and gases.
- ***Convection*** – heat is transferred by molecules in a fluid state. Convection may be forced (using a pump or fan), or, natural, due to temperature and density differences in the fluid. The two types of convection are known as ***forced convection*** and ***natural convection***.
- ***Radiation*** – heat is transferred via radiant energy (***electromagnetic waves***). Radiant energy is only transferred to *opaque* objects i.e. objects that do not allow light to pass through.



Conduction, Convection and Radiation

Conduction

Conduction occurs in solids, liquids and gases. A substance's ability to absorb heat via conduction is referred to as its ***thermal conductivity***. *Generally*, solids have higher thermal conductivity than liquids because the molecules are closer together. Likewise, liquids *generally* have higher thermal conductivity than gases. Air has low thermal conductivity, which is why insulating materials often have large air spaces/pockets.

Note that thermal conductivity is based upon the material, not its state/phase. For example, many types of wood have a lower thermal conductivity rating than water, but wood is a solid and water is a liquid.

Conduction Example

If one end of a metal rod is heated in a fire, whilst the other end is not, the heated metal rod molecules will pass their heat to their neighbouring -cooler- molecules. The process continues allowing heat to be conducted from the hot end of the rod to the cold end.

In the case of boilers, conduction occurs when heat is transferred from the internal heating surfaces of the boiler to the external heating surfaces.

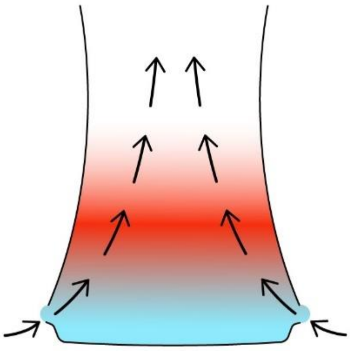
Convection

Convection may be forced or natural. ***Forced convection*** requires a pump or fan etc. ***Natural convection*** occurs due to temperature differences in the fluid (hot molecules are less dense than cold molecules, which is why they have a natural tendency to rise above them).

Convection Example

Heating water in a pot causes the heated molecules to become less dense and thus rise to the top of the pot due to natural convection; cooler more dense molecules then occupy the space where the heated molecules were.

The ***stack effect*** (a.k.a. ***chimney effect***) is an example of natural convection. The below image shows a natural draft cooling tower. The cooling tower allows cooler air to enter through the base, where it is then heated by hot water. The hot -less dense- air then rises to the top of the tower, which causes cooler air to be drawn in through the base of the tower. In this manner, its possible to use very large volumes of air to cool a process without using pumps or fans.



Hot (less dense) Air Rises and is Replaced by Cooler (more dense) Air

In the case of boilers, convection occurs when the water closest to the internal heating surfaces is heated and becomes less dense. The less dense water flows upwards and is replaced by cooler, more dense water; the process is continuous.

Radiation

Radiant energy is only transferred to heat energy when electromagnetic waves impact upon a substance that does not allow light to pass through it i.e. the substance is ***opaque***. For example, the sun transmits radiant energy, but this energy only becomes heat energy once it encounters an opaque object i.e. the earth.

The amount of energy a substance can transfer via radiation depends largely upon its temperature and ***emissivity***. A surface's ability to emit thermal radiation is measured by its ***emissivity***. Generally, rough and dark surfaces have a higher emissivity coefficient than smooth and shiny surfaces.

In the case of boilers, radiant energy is released during combustion and is transmitted onto the opaque internal heating surfaces of the boiler, where it changes to thermal energy. Note that radiant energy is only transferred by ***line of sight***.

Radiation Example

If a boiler operator opens the boiler furnace door, he/she will feel the heat because the electromagnetic waves travel outwards from the furnace to the operator. If the door is then closed, the electromagnetic waves can no longer travel outwards and the heat is no longer felt. Air between the furnace and operator is not heated by the electromagnetic waves because air allows light to travel through it (its not opaque). Only opaque substances with a direct line of sight to the place of combustion will be impacted by the emitted electromagnetic waves.

Heat Felt Due to Radiation

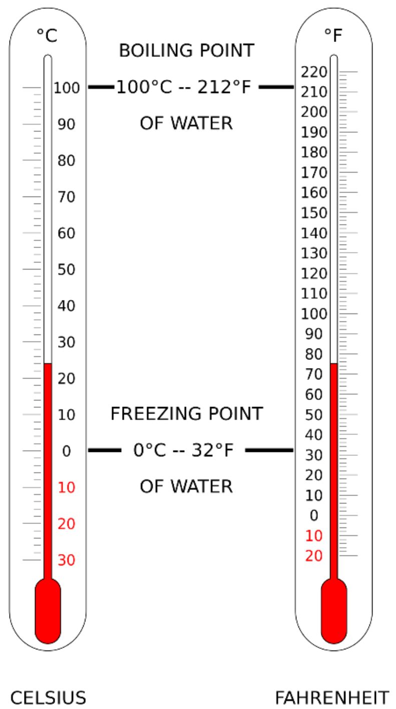
Temperature

Whilst heat can be used to calculate how much internal energy a substance contains, temperature represents the intensity of that energy.

*Temperature is a measure of the average **kinetic energy** that the molecules of a substance contain. Substances with more kinetic energy have a higher temperature than substances with lower kinetic energy.*

In order to compare the temperature of substances, a common measurement scale is required. Common units of measurement for temperature are ***Celsius (°C)***, ***Fahrenheit (°F)*** and ***Kelvin (K)***.

- ***Celsius*** – tends to be favoured in Europe. Fresh water boils at 100°C and freezes at 0°C.
- ***Fahrenheit*** – tends to be favoured in the Americas. Fresh water boils at 212 °F and freezes at 32°F. Saltwater freezes at 0 °F. Fahrenheit is an ***imperial*** form of measurement.
- ***Kelvin*** – one of the seven ***SI units (International System of Units)***. Fresh water boils at 373 K and freezes at 273 K. One Kelvin is equal in magnitude to one Celsius, but the scales used are different. Kelvin is a metric form of measurement.



Celsius and Fahrenheit Thermometer Comparison

Temperature Conversions

Celsius to Fahrenheit

(°C × 9/5) + 32 = °F

Example

(1°C × 9/5) + 32 = 33.8°F

Fahrenheit to Celsius

(°F – 32) × 5/9 = °C

Example

(1°F – 32) × 5/9 = -17.22°C

Heat Units

Heat is a form of energy and is often stated in ***British thermal units (Btus)*** or ***Calories (Cal)***.

- ***Btu*** – the amount of heat required to increase the temperature of one pound of water by one degree Fahrenheit.
- ***Calorie*** – the amount of heat required to increase the temperature of one gram of water by one degree Celsius.

In addition to the units of Btu and Calorie, the unit of ***Joule*** is often used.

Specific Heat

Different substances require different amounts of heat to change temperature. In order to make a comparison between substances possible, substances are given a ***specific heat (S.H.)*** value, these values are then compiled into tables. The values in the compiled tables are approximations only, the true specific heat value of a fuel is determined by sampling and analysing the fuel in a laboratory.

Specific heat is the amount of heat required to change one unit of a substance's mass by one unit in temperature. The units used depend upon if imperial or metric units are favoured. The energy units of ***British thermal units (Btu)*** and ***Joules (J)*** are often used in specific heat calculations.

ⓘ The term ***specific heat capacity*** has the exact same meaning as ***specific heat***, the terms are used interchangeably.

Example 1 (Imperial)

Specific heat may be calculated as the amount of heat required to change one pound of a material by one degree Fahrenheit. Imperial specific heat capacity units are ***Btu/lb°F***.

Example 2 (Metric)

Specific heat may be calculated as the amount of heat energy required to change one kilogram of a material by one degree Kelvin. Metric specific heat capacity units are ***J/kgK***. Note that ***one Celsius is equivalent to one Kelvin in magnitude***, so the unit ***J/kg°C*** yields the same specific heat capacity values as when quoted in ***J/kgK***.

The specific heat values of various substances are given in the below table.

Substance	Imperial Specific Heat (S.H.) Value *(Btu/lb°F)*	Metric Specific Heat (S.H.) Value *(J/kgK)*
Fresh Water	1.0	4,190
Ice	0.49	2,050
Steam	0.48	2,010
Fire Brick	0.21	879
Boiler Scale	0.19	795
Steel	0.12	502
Copper	0.09	377

Specific Heat Values of Various Substances

Combustion

Heat released by the process of combustion is the main source of heat for most boilers. Some boilers heat water using other means, such as electric boilers, but these types of boilers are not as common as fossil fired boilers.

The combustion process involves burning of a fuel's hydrogen atoms in order to release heat. As fossil fired boilers and steam are directly related, a look at the combustion process is necessary to better understand how steam is generated. This chapter covers the combustion process and its relevance to steam generation.

Combustion Chemical Reaction

Combustion is the rapid oxidation of fuel, which results in an energy transfer in the form of heat and light. For this lesson, it is necessary to be aware of some common chemical elements and their symbols.

Chemical Symbol	Element or Substance
C	Carbon
H	Hydrogen
CxHy	Hydrocarbons
O	Oxygen
CO_2	Carbon Dioxide
H_20	Water
N_2	Nitrogen
CO	Carbon Monoxide

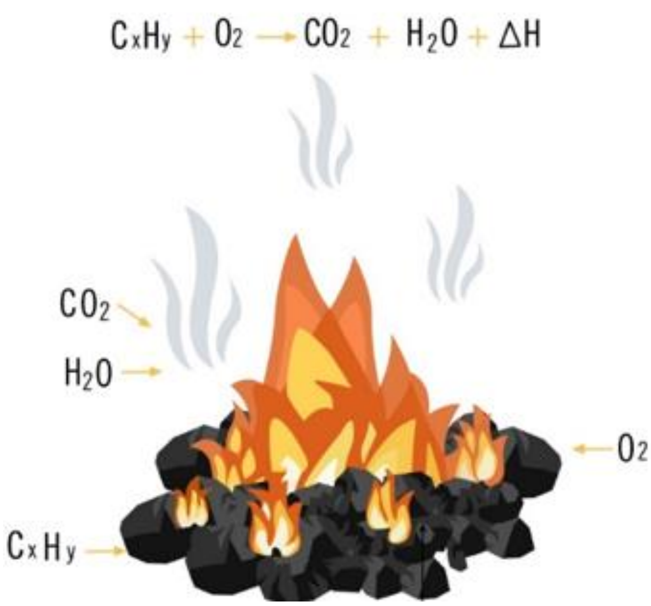
Chemical Symbols Table

Note: Although Oxygen has the chemical symbol 'O', it is most common in its chemical composition of 'O_2' and is often indicated as such.

Fuels are hydrocarbon based and represented by the chemical symbols of CxHy; the values of x and y vary depending upon the fuel. Other substances can be formed when elements bond together, such as when two parts hydrogen (H) bond with one-part oxygen (O) to form water (H_20).

The below image shows the ***chemical reaction*** that occurs when fuel (CxHy) is burnt with oxygen (O). The ***reactants*** of the chemical reaction are fuel (hydrocarbons) and oxygen. The ***products*** of the chemical reaction are carbon dioxide (CO_2), water (H_20) and ΔH.

The symbol 'ΔH' (delta H) is the ***heat of reaction*** (a.k.a. ***enthalpy of reaction***). ΔH represents the amount of energy released/transferred by the chemical reaction. ΔH varies depending upon how complete combustion is.



Combustion Chemical Reaction

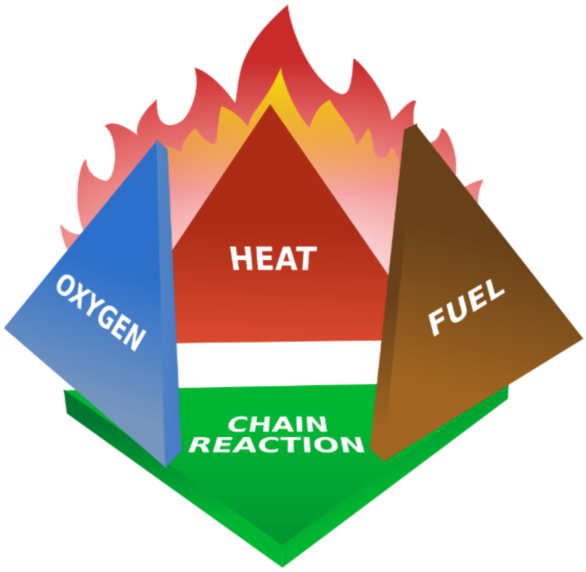
Combustion Requirements

Combustion can only occur if ***three factors*** are present:

- ***Oxygen***
- ***Heat***
- ***Fuel***

In the case of a boiler, oxygen is provided by ambient air, which contains approximately ***21% oxygen***. Predominant boiler fuels are natural gas, fuel oil and coal. Heat can be supplied during ignition, such as when creating an electrical arc to ignite the air/fuel mixture.

A ***fire triangle*** (a.k.a. ***combustion triangle***) indicates the requirements of combustion; a ***fire tetrahedron*** (shown below) performs a similar purpose.



Fire Tetrahedron

The three combustion factors must also be provided in the ***proportionally correct manner***, otherwise combustion cannot occur. Too much air and too little fuel may prevent combustion, as will too much fuel and too little air.

Perfect, Complete and Incomplete

Boiler combustion is termed ***perfect***, ***complete*** or ***incomplete***.

- ***Perfect Combustion*** – the exact amount of air is provided in order to achieve complete combustion of the fuel. Perfect combustion is only achievable in laboratory conditions.
- ***Complete Combustion*** – the minimum amount of air is provided in order to achieve complete combustion. Boiler operators should always try to achieve complete combustion.
- ***Incomplete Combustion*** – too little air is provided and incomplete combustion occurs.

Complete combustion is essential to avoid a reduction in boiler efficiency and potential safety hazards. When fuel combusts completely, common products of combustion include carbon dioxide (CO_2), water vapour (H_2O), Nitrogen (N2), sulphur oxide (SOx) and nitric oxide (NOx). If fuel does not fully combust, products of combustion may include carbon monoxide (CO), soot and smoke.

Carbon monoxide is a toxic flammable gas that is less dense than air. Incomplete combustion may lead to generation of carbon monoxide, which is not desired, as it poses a health and safety risk. Other by-products of incomplete combustion include soot and smoke, both of which can reduce heat transfer within the boiler leading to an overall reduction in efficiency.

Primary, Secondary and Excess Air

The amount of air delivered to a boiler for combustion varies depending upon if combustion is complete or incomplete. Its possible to measure the gases of combustion to determine if combustion was complete or incomplete. Too much oxygen in the gases of combustion indicates that too much air for combustion was provided. High levels of carbon monoxide in the gases of combustion indicates too little air was provided and combustion was incomplete.

If fuel is unburnt during combustion, carbon monoxide levels will be high, and more air will need to be supplied by the boiler burner in order to achieve complete combustion. If too much air is supplied during combustion, the levels of oxygen in the gases of combustion will be high, and the amount of air supplied to the boiler burner will need to be reduced.

The ***total air*** supplied to the boiler is further categorised as either ***primary***, ***secondary*** or ***excess***.

- ***Primary Air*** – is mixed with the fuel ***prior*** to it reaching the combustion space. Primary air controls the *amount* of fuel burnt.
- ***Secondary Air*** – is added to the combustion space **during** combustion. Secondary air controls *how efficiently* fuel is burnt.
- ***Excess Air*** – is air added to the combustion process that was not required for combustion. Excess air is secondary air that was not part of the combustion process.
- ***Total Air*** – the sum of the air supplied for the combustion process i.e. ***primary air + secondary air + excess air = total air***.

*Note: The term **dilution air** describes the air added to the **breeching** (space between the boiler and stack) to aid gases of combustion flow from the boiler to atmosphere.*

Efficiency

Efficiency is a value used to express how much energy is added to a system, and how much of that energy is converted to useful work. Simply stated, it's a comparison of what you put in, compared to what you get out. Efficiency is often represented by the Greek letter ***η (Eta)***.

$$\textbf{Efficiency} = \frac{\textbf{Output}}{\textbf{Input}}$$

Efficiency is a common calculation used throughout the engineering world for measuring waste. High efficiencies represent low waste whereas low efficiencies represent high waste. Waste may be in the form of energy, materials or time etc., all of which are often associated with financial loss. For this reason, high efficiencies are desired.

Combustion Efficiency

Knowing the correct air to fuel ratio that achieves complete combustion, and the expected ratio of the products of combustion, allows boiler operators to calculate how efficiently combustion has occurred.

Combustion efficiency tables contain the information required to calculate ***combustion efficiency***. Information provided in a combustion efficiency table typically includes:

- The % of excess air.
- The % of oxygen in the gases of combustion.
- The % of CO_2 in the gases of combustion.
- The temperature of the air supplied for combustion.
- The temperature of the gases of combustion when measured from the stack.

Notes

*The **gases of combustion** are also referred to as **exhaust gases** or **flue gases**. The term **stack** is used interchangeably with the word **chimney**.*

A typical combustion efficiency table is shown below.

Excess Air %			Net Stack Temperature (°F) (Flue Gas Temperature Minus Combustion Air Temperature)				
% Air	% Oxygen	% CO_2	200	300	400	500	600
9.3	2.0	10.6	85.4	83.1	80.8	78.4	76.0
14.8	3.0	10	85.2	82.8	80.4	77.9	75.4
28.1	5.0	8.8	84.7	82.1	79.5	76.7	74.0
44.2	7.0	7.7	84.1	81.2	78.2	75.2	72.1
81.4	10.0	6.1	82.8	79.3	75.6	71.9	68.2

Natural Gas Combustion Efficiency Table (assuming complete combustion)

Rather than explaining the intricacies of the table, two examples are provided.

Example 1

A boiler has a stack temperature of 500°F. The boiler room temperature is 100°F. The air for combustion in the boiler is taken directly from the space surrounding the boiler, so we know the temperature of air supplied for combustion is the same as the boiler room temperature (100°F). The % of carbon dioxide (CO_2) in the gases of combustion is measured at the stack and has a value of 10.6%.

- Net stack temperature is 500°F – 100°F = 400°F.
- % CO_2 is 10.6%.

Checking the results with the combustion efficiency table indicates that the boiler is operating at 80.8% efficiency.

Excess Air %			Net Stack Temperature °F (Flue Gas Temperature Minus Combustion Air Temperature)				
% Air	% Oxygen	% CO2	200	300	400	500	600
9.3	2.0	10.6	85.4	83.1	80.8	78.4	76.0
14.8	3.0	10	85.2	82.8	80.4	77.9	75.4
28.1	5.0	8.8	84.7	82.1	79.5	76.7	74.0
44.2	7.0	7.7	84.1	81.2	78.2	75.2	72.1
81.4	10.0	6.1	82.8	79.3	75.6	71.9	68.2

Example 2

A boiler has a stack temperature of 420°F and a boiler room temperature of 80°F. The % of oxygen in the gases of combustion is 7.2%.

- Net stack temperature is 420°F – 80°F = 340°F.
- % Oxygen is 7.2%.

Checking the results with the combustion efficiency table indicates that the boiler is operating at *approximately* 81.2% efficiency.

Excess Air %			Net Stack Temperature °F (Flue Gas Temperature Minus Combustion Air Temperature)				
% Air	% Oxygen	% CO2	200	300	400	500	600
9.3	2.0	10.6	85.4	83.1	80.8	78.4	76.0
14.8	3.0	10	85.2	82.8	80.4	77.9	75.4
28.1	5.0	8.8	84.7	82.1	79.5	76.7	74.0
44.2	7.0	7.7	84.1	81.2	78.2	75.2	72.1
81.4	10.0	6.1	82.8	79.3	75.6	71.9	68.2

If we round the net stack temperature to 350°F, we can estimate the efficiency value using the table. The actual efficiency is likely to be between 81.2% and 78.2% because these are the two values given between 300°F and 400°F.

Excess Air %			Net Stack Temperature °F (Flue Gas Temperature Minus Combustion Air Temperature)				
% Air	% Oxygen	% CO2	200	300	400	500	600
9.3	2.0	10.6	85.4	83.1	80.8	78.4	76.0
14.8	3.0	10	85.2	82.8	80.4	77.9	75.4
28.1	5.0	8.8	84.7	82.1	79.5	76.7	74.0
44.2	7.0	7.7	84.1	81.2	78.2	75.2	72.1
81.4	10.0	6.1	82.8	79.3	75.6	71.9	68.2

For example:

1. Combustion efficiency value at 300°F and 7% oxygen is 81.2%
2. Combustion efficiency value at 400°F and 7% oxygen is 78.2%
3. 81.2% - 78.2% = 3%
4. So, there is a 3% reduction in efficiency if the net stack temperature changes from 300°F to 400°F.
5. Knowing there is a 3% reduction in combustion efficiency for a 100°F change on the net stack temperature, we also know that a 50°F change will correspond to a 1.5% reduction in combustion efficiency (because 50°F is half of 100°F and correspondingly 1.5% is half of 3%).
6. The final combustion efficiency is thus calculated as 82.2% - 1.5% = 79.7%.

Notice that ***combustion efficiency reduces as the net stack temperature increases***. A high net stack temperature indicates that less of the heat generated by combustion was transferred to the water, whereas a low net stack temperature indicates more heat was transferred to the water. High exhaust gas temperatures represent a waste of energy and money.

Example 3

An exhaust gas temperature of 600°F with a combustion air temperature of 100°F, gives a net stack temperature of 500°F.

- 600°F -100°F = 500°F

An exhaust gas temperature of 400°F with a combustion air temperature of 100°F, gives a net stack temperature of 300°F.

- 400°F -100°F = 300°F

Notice in our example that all combustion efficiency values relating to a low net stack temperature, are higher than those possible for a high net stack temperature.

Excess Air %			Net Stack Temperature °F (Flue Gas Temperature Minus Combustion Air Temperature)				
% Air	% Oxygen	% CO2	200	300	400	500	600
9.3	2.0	10.6	85.4	83.1	80.8	78.4	76.0
14.8	3.0	10	85.2	82.8	80.4	77.9	75.4
28.1	5.0	8.8	84.7	82.1	79.5	76.7	74.0
44.2	7.0	7.7	84.1	81.2	78.2	75.2	72.1
81.4	10.0	6.1	82.8	79.3	75.6	71.9	68.2

Thermal Efficiency

A boiler's ***thermal efficiency*** is calculated using the below equation. Multiplying the output of the equation by 100 gives the thermal efficiency value in percentage (%).

$$\textbf{Thermal Efficiency} = \frac{\textbf{Heat Absorbed by Boiler Water}}{\textbf{Heat Generated by Combustion}}$$

Thermal efficiency ***is not*** calculated as: (energy out / energy in). Thermal efficiency indicates how much of the heat generated by combustion is transferred to the water; it does not indicate how much of a boiler fuel's chemical energy was transferred to the water. Low thermal efficiency values often indicate heat transfer problems such as dirt or scale on the heat transfer surfaces.

A boiler with high thermal efficiency is desired because it consumes less fuel and thus saves money, this can be better understood when reading the below examples.

Example 1

A boiler thermal efficiency of 50% indicates that half of the thermal energy (heat) generated by the combustion process was not transferred to the water.

Example 2

A boiler thermal efficiency of 100% indicates that all of the thermal energy (heat) generated by the combustion process was transferred to the water.

Most industrial boilers should achieve a thermal efficiency of 80% or more, but this depends heavily upon the boiler's design, type of fuel burnt, age of the boiler and its condition.

Heat Value / Calorific Value

Different fuels contain different amounts of chemical energy. When a fuel is burnt, its chemical energy is transferred to other forms of energy. The ***heat value*** (a.k.a. ***calorific value***) of a substance is used to indicate how much heat will be released by the process of combustion.

In a laboratory, the heat value is measured by burning a known amount of fuel at a constant pressure and temperature. The amount of heat transferred to a known amount of water (placed above the area of combustion) can be calculated by measuring the water's change in temperature.

Heat values are usually given as either ***Higher Heat Values (HHV)*** or ***Lower Heat Values (LHV)***. LHV does not include the water's latent heat energy due to vaporisation, HHV does, thus HHV is always equal to, or higher than, LHV.

The table below shows some common fuels and their associated heat values.

	Imperial Units			***Metric Units***		
Fuel	***Approx.* Heat Value (Btu/cu ft)**	***Approx.* Heat Value (Btu/gallon)**	***Approx.* Heat Value (Btu/lb)**	***Approx.* Heat Value (MJ/m^3)**	***Approx.* Heat Value (MJ/litre)**	***Approx.* Heat Value (MJ/kg)**
Natural Gas	1,000		22,000	37.0		50
Heavy Fuel Oil (HFO)		147,000	18,000		38.0	41.0
Light Fuel Oil (LFO)		151,000	19,000		39.0	42
Anthracite Coal			14,000			31.0
Bituminous Coal			13,000			29

Fuel Heat Values Table

Boiler Fuel Oils

Boiler fuel oils are rated #1 to #6. ***The higher the fuel number, the higher the heat value***.

Example

- Kerosene is a grade #1 fuel oil with a heat value of approximately 134,000 Btu/gallon.
- Heavy fuel oil is a grade #4, #5 or #6 fuel oil, with a heat value of approximately 150,000 Btu/gallon.

A substance's viscosity describes how easily a fluid flows under its own weight. For example, at 10°C, honey has a higher viscosity than water. Fuels with a higher viscosity ('thicker' fuels*) tend to* have a higher heat value than lower viscosity fuels ('thinner' fuels).

The below table is based upon information in the book '*Handbook of Energy Engineering'* and provides further heat values of common fuels. Metric unit calculations were provided by the Cleave Books Unit Conversion Calculator, which can be found at the below link:

http://www.cleavebooks.co.uk/scol/index.htm

Steam Properties

Contrary to popular belief, steam is a colourless and odourless gas. The steam that most people visualise when they think of steam, is actually termed ***wet steam***. The 'steam' that a viewer sees is actually water molecules suspended in air, not steam.

This chapter of the course explains some of the properties of steam and their importance.

Ideal Gas Law

Pressure, volume and temperature, are all related.

The ***combined gas law*** is an equation based upon the ***ideal gas law equation***. The combined gas law states:

$$\boldsymbol{k} = \left(\frac{\boldsymbol{P} \times \boldsymbol{V}}{\boldsymbol{T}}\right)$$

Fuel Oil	**Average Heating Value (imperial unites)**	**Average Heating Value (metric units)**
No. 1 Kerosene	134,000 Btu/gal	37.34 MJ/l
No. 2 Burner Fuel Oil	140,000 Btu/gal	39.02 MJ/l
No. 4 Heavy Fuel Oil	144,000 Btu/gal	40.13 MJ/l
No. 5 Heavy Fuel Oil	150,000 Btu/gal	41.80 MJ/l
No. 6 Heavy Fuel Oil (2.7% sulphur)	152,000 Btu/gal	42.36 MJ/l
No. 6 Heavy Fuel Oil (0.3% sulphur)	143,800 Btu/gal	40.07 MJ/l
Coal	**Average Heating Value (imperial unites)**	**Average Heating Value (metric units)**
Anthracite	13,900 Btu/lb	32.3 MJ/kg
Bituminous	14,000 Btu/lb	32.6 MJ/kg
Sub-bituminous	12,600 Btu/lb	29.3 MJ/kg
Lignite	11,000 Btu/lb	25.6 MJ/kg
Gas	**Average Heating Value (imperial unites)**	**Average Heating Value (metric units)**
Natural	1,000 Btu/cu ft	37.3 MJ/m^3
Liquefied Butane	103,300 Btu/gal	28.79 MJ/l
Liquefied Propane	91,600 Btu/gal	25.53 MJ/l

Fuel Heat Value Table

Where:

P = Pressure

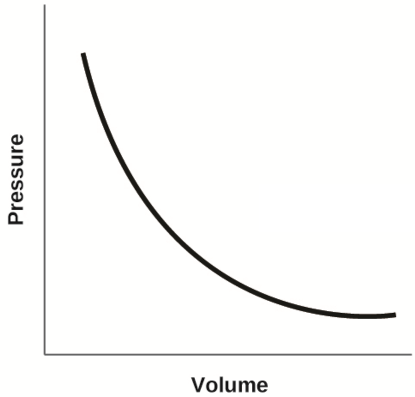
V = Volume

T = Temperature

k = Constant for a fixed amount of gas.

P, V and T, are termed ***variables***, because they vary (vary-able) depending upon real world factors that are then entered as values into the equation. The ratio of PV to T is constant. This means that as P increases, V decreases, and as V increases, P decreases. The relationship between pressure and volume at constant temperature is inversely proportional.

If temperature is held constant, an increase in pressure will be accompanied by a decrease in volume.
If temperature is held constant, a decrease in pressure will be accompanied by an increase in volume.



If P is held at the same value, then V and T are directly related i.e. if V increases then T increases, and vice versa. The same situation occurs if V is held constant i.e. P and T are related, and an increase in P will cause an increase in T, and vice versa. The relationship between temperature and pressure at constant volume is linear, as is the relationship between temperature and volume at constant pressure.

A few examples without units can be used to clarify the equation further.

Example 1

A steam system has a pressure of 10, volume of 3 and temperature of 100.

$$\mathrm{P} = 10$$
$$\mathrm{V} = 3$$
$$\mathrm{T} = 100$$
$$\mathrm{PV} / \mathrm{T} = \mathrm{k}$$
$$\mathbf{(10 \times 3) / 100 = 0.3}$$

A steam system's volume is fixed, as it is a closed system. Increasing the system pressure to 15 must also proportionally increase the temperature because the constant value (k) must be maintained in order for the equation to be valid. It is possible to calculate T, by inputting the new higher-pressure value of 15 then solving the equation.

P = 15
V = 3

K = 0.3

T = ?

PV / T = k

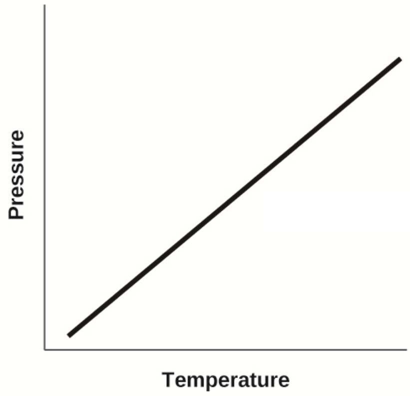
(15 x 3) / T = 0.3

(15 x 3) / 0.3 = T

(15 x 3) / 0.3 = 150

Similarly, a reduction in pressure will lead to a reduction in temperature because the volume is held constant.

If volume is held constant, an increase in pressure will be accompanied by a proportional increase in temperature.
If volume is held constant, a decrease in pressure will be accompanied by a proportional decrease in temperature.



The ideal gas law is used to calculate pressures, volumes and temperatures of a gas across various ranges. Once these values are known, its possible to calculate things such as:

- The amount of energy the system contains and how much can be transferred to the point of use e.g. to a steam turbine.
- The size and thickness of system piping required.
- The size of boilers required.
- Gas velocity within the system.

Some of this data is then tabulated in a ***gas table***, or when used for steam, a ***steam table***. Steam tables are essential when designing and operating a steam system.

Saturated and Superheated Steam

Saturated water contains enough heat that if the temperature remains constant, and the pressure decreases, it will boil.

Saturated steam (a.k.a. dry saturated steam) has just enough heat to remain in a gaseous state. If saturated steam has some heat removed, or, is placed under pressure, it will condense proportionately.

Simply put:

- ***Saturated water*** contains the ***maximum*** amount of heat it can hold at a given pressure without beginning to change state to a gas.
- ***Saturated steam*** contains the ***minimum*** amount of heat it can hold at a given pressure without beginning to change state to a liquid.

If more heat is added to steam after it reaches its saturation temperature (boiling point), the steam is said to be a ***superheated steam***. Power generation industry turbines requires super-heated steam.

ⓘ *The term **supersaturated steam** refers to steam that has values (temperature, pressure etc.) greater than those indicated in steam tables.*

Dry and Wet Steam

Steam is classified as ***wet*** or ***dry***.

Wet steam contains water droplets suspended in the steam.

Dry steam contains no suspended water droplets in the steam.

As previously mentioned, ***saturated steam*** has just enough heat to remain in a gaseous state. If saturated steam has some heat removed, or, the system pressure increases, it will condense proportionately.

Steam that contains water molecules, is referred to as ***wet steam***, or ***wet unsaturated steam***. Steam that contains no water molecules, is referred to as ***dry steam***, or ***dry saturated steam***. Steam tables usually list data based on dry saturated steam values, but dry saturated steam is difficult to produce in a boiler because some water droplets are almost always present.

A typical high-pressure boiler may contain 2-3% water to 97-98% steam, based upon mass. A typical low-pressure boiler may contain 4-6% water to 94-96% steam, based upon mass. Wet steam is sometimes defined as any steam that contains more than 3% water based upon mass, although to be completely correct, wet steam is any steam that contains water, irrespective of how little. Only after removing all moisture within a steam system, can the system be declared truly dry.

Dryness Fraction

Steam containing 5% moisture by mass, also contains 95% steam; the steam is described as having a ***dryness fraction*** of 0.95. Likewise, steam containing 1% moisture has a dryness fraction of 0.99. The equation to calculate a steam's dryness fraction is:

$$\textbf{Dryness Fraction} = \frac{\textbf{Mass of Dry Saturated Steam}}{\textbf{Mass of Dry Saturated Steam} + \textbf{Mass of Water in the Steam}}$$

A steam's dryness fraction is an important consideration when determining how much heat is held by the steam. For example, wet steam always contains less energy than drier steam, thus drier steam makes the system process more efficient and is consequently desired.

The inverse of the dryness fraction is the ***wetness fraction***, although this is less commonly quoted in steam tables than the dryness fraction.

$$\textbf{Wetness Fraction} = \frac{\textbf{Mass of Water in the Steam}}{\textbf{Mass of Water in the Steam} + \textbf{Mass of Dry Saturated Steam}}$$

Clean Steam

Steam is sometimes classified as ***clean*** or ***pure***, with both words having the same meaning. Any contaminants within a steam system will reduce the steam's purity/cleanliness. Contaminants include water treatment chemicals, suspended solids and dissolved solids.

Reducing the amount of moisture within the steam is the most reliable method of reducing the number of contaminants present in the steam system. Steam with a high dryness fraction, contains less contaminants than steam with a low dryness fraction.

Most industrial processes do not require ultra-pure steam, but some industries -such as the pharmaceutical industry- do. Electric boilers, stainless steel boilers, and deaerators, are steam system components that can be used to improve water purity and thus steam purity. Feeding ultra-pure water to the boiler will also increase steam purity.

Enthalpy

If a system is fully closed and the system pressure held constant, the amount of heat released or absorbed, is termed ***enthalpy***. Enthalpy can be thought of as the amount of heat (sensible and latent) a substance contains.

ⓘ *Removing the word 'enthalpy' and replacing it with 'energy' sometimes helps with understanding the meaning of enthalpy.*

Example 1

The amount of sensible heat required to raise a given mass of liquid from its freezing point to its boiling point (saturation temperature) is termed the ***enthalpy of a liquid at saturation temperature***. Replacing the word 'enthalpy' with 'energy' gives 'energy of a liquid at saturation temperature'. This term describes the total amount of ***sensible heat*** required to raise a given mass of liquid from its freezing point to its boiling point i.e. the total amount of *energy* required to raise a given mass of liquid from its freezing point to its boiling point.

Example 2

The amount of latent heat required to turn a given mass of saturated water (water at its boiling point) into dry saturated steam, is termed ***enthalpy of vaporisation***. Replacing the word 'enthalpy' gives '*energy* of vaporisation' (the amount of energy required to evaporate the saturated water). This term describes the total amount of ***latent heat*** required to turn a given mass of saturated water into dry saturated steam i.e. the total amount of *energy* required to turn a given mass of saturated water into dry saturated steam.

Steam Tables

Steam tables indicate properties of steam at various pressures and temperatures (depending upon how the table is designed). The properties listed are usually:

- Pressure.
- Temperature.
- Specific volume of dry saturated steam (V_g).
- Enthalpy of water at saturation temperature (h_f).
- Enthalpy of vaporisation (h_{fg}).
- Enthalpy of dry saturated steam (h_g).

A simplified steam table is shown below.

Gauge Pressure (psig)	Temperature (ºF)	V_g Specific Volume (cu ft/lb)	Enthalpy		
			h_f Saturated Water (Btu/lb)	h_{fg} Latent Heat of Vaporisation (Btu/lb)	h_g Dry Saturated Steam (Btu/lb)
0	212	26.7	180	970	1150
10	239	16.6	208	953	1160
20	259	11.8	227	938	1166
30	274	9.46	243	929	1174
40	287	7.82	256	919	1176
50	298	6.68	267	912	1179
60	307	5.84	277	906	1183
70	316	5.18	286	898	1184
80	324	4.67	294	894	1185
90	332	4.25	302	886	1189
100	339	3.89	309	879	1189

Example Steam Table

The table columns can be read as:

- ***Pressure*** – the gauge pressure at which the steam table values occur i.e. the pressure at which the experiment to measure the other corresponding values was made.
- ***Temperature*** – the temperature at which the water's saturation point is reached i.e. the boiling point.
- ***Specific volume of dry saturated steam (V_g)*** – the volume occupied by 1 lb (imperial) or 1 kg (metric) of dry saturated steam.
- ***Enthalpy of water at saturation temperature (h_f)*** – the amount of sensible heat required to raise 1 lb or 1 kg of water from its freezing point to its saturation temperature (boiling point).
- ***Latent heat of vaporisation (h_{fg})*** – the amount of latent heat required to turn 1 lb or 1 kg of water at saturation temperature into 1 lb or 1 kg of dry saturated steam.
- ***Enthalpy of dry saturated steam (h_g)*** – the total amount of heat required to turn 1 lb or 1 kg of water at its freezing point into 1 kg of dry saturated steam.

Or, to take a ***simplistic*** view:

- ***Pressure*** – pressure at which the experiment was conducted.
- ***Temperature*** – boiling point at the given pressure.
- ***Specific volume of dry saturated steam (V_g)*** – volume of dry saturated steam at the given pressure.
- ***Enthalpy of water at saturation temperature (h_f)*** – energy required to heat the water from its freezing point to its boiling point.
- ***Latent heat of vaporisation (h_{fg})*** – energy required to evaporate the saturated water into dry steam.
- ***Enthalpy of dry saturated steam (h_g)*** – energy required to heat-up and evaporate the water into dry steam.

Example

Sensible heat is applied to water to raise its temperature from its freezing point to its boiling point, this is the value h_f. Latent heat is then added to change the state of the saturated water into dry saturated steam, this is the value h_{fg}.

Adding the values of h_f and h_{fg}, gives the total amount of heat required to take a given mass of water from its freezing point to its boiling point, then to convert that saturated water into dry saturated steam. The equation for this entire process is:

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

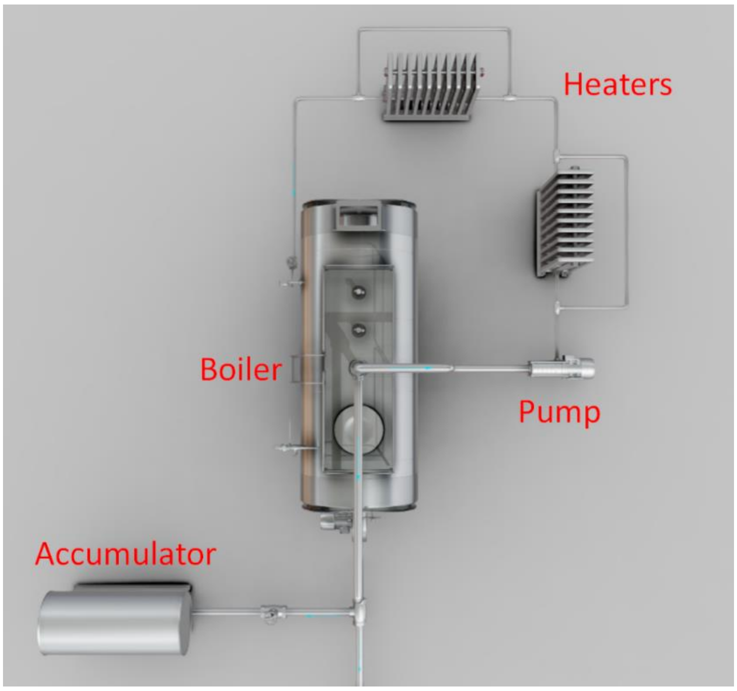
Boilers

This chapter introduces boilers. Common boiler designs are discussed, along with how they work and their applications.

Purpose of a Boiler

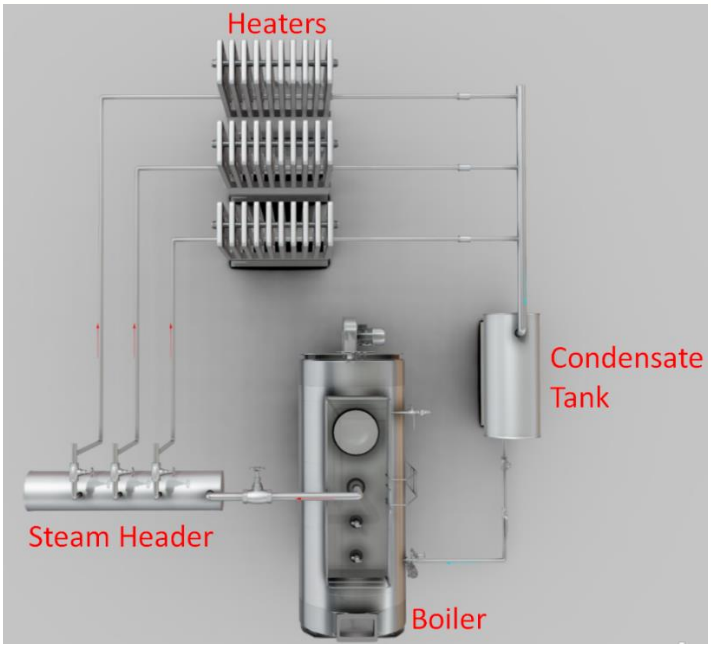
Boilers are used to supply hot water, or steam. A boiler supplying hot water is technically not a boiler, as the water is below its boiling point. Despite this, hot water heaters are colloquially referred to as boilers.

Irrespective of if a boiler is providing hot water or steam, ***the purpose of a boiler is to supply heat that can be used to complete a desired purpose***. Providing the heat required to heat a building or room (a.k.a. space heating) is a common boiler task. A typical system setup for space heating using hot water is shown below.



Typical Hot Water System

A typical system setup for space heating using steam is shown below.



Typical Steam System

Fired and Un-Fired

Open boiler vessels are not used due to their inefficiency, closed vessels are used instead. Closed vessels with an internal furnace are the most common industrial boiler design. A closed vessel under pressure is referred to as an ***un-fired pressure vessel***.

Compressed Air System Un-Fired Pressure Vessel

A closed vessel that uses a means of combustion to generate pressure within the vessel, is referred to as a ***fired pressure vessel***. Combustion usually occurs within the pressure vessel i.e. an ***internal fired pressure vessel***, or outside of the pressure vessel i.e. an ***external fired pressure vessel***.

Fire Tube Boilers (Internal Fired Pressure Vessel)

Fire Tube and Water Tube

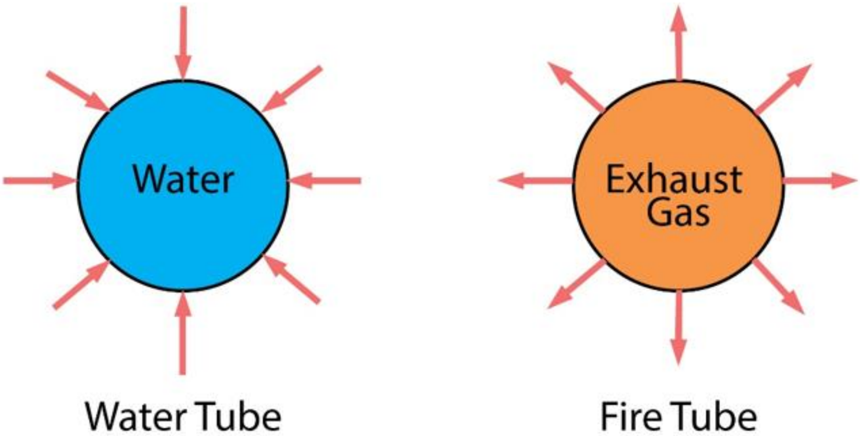
There are ***two*** main types of boiler used in the industrial engineering world, these are the ***fire tube boiler*** and ***water tube boiler***. As the name implies, the difference between the two boilers is where the gases of combustion and water are relative to the boiler tubes.

Water tube boilers have water in the tubes and gases of combustion outside of the tubes.

Fire tube boilers have gases of combustion within the tubes and water outside of the tubes.

Water tube boiler furnaces are surrounded by tubes (pipes) full of water, which allows a large amount of heat from combustion to be transferred to the tubes very quickly.

Fire tube boiler furnaces are usually inside the pressure vessel, but may also be external to the pressure vessel. Exhaust gases of combustion travel through tubes surrounded by water.



Direction of Heat Transfer

Almost all large industrial plants will have a boiler on site. Most industrial plant boilers are of the fire tube design whilst water tube boilers are more favoured in the power generation industry. Large and very large steam capacity boilers are always water tube boilers.

Water Tube Boiler Tubes

Water and Fire Tube Boilers Compared

A detailed overview of water tube and fire tube boilers is not possible within the confines of this course, but the below table highlights some of the main differences between the two designs.

Water Tube	Fire Tube
Water in the tubes.	Combustion gases in the tubes.
Combustion gases surrounding the tubes.	Water surrounding the tubes.
Maximum allowable working pressures (MAWP) in excess of 2,900 psi (200 bar).	Maximum allowable working pressure (MAWP) up to 362 psi (25 bar).
Very high steam generation rate.	Comparatively low steam generation rate.
More efficient than a fire tube boiler (typically greater than 90%).	Less efficient than a water tube boiler (typically 80-85%).
Explosion risk is higher due to higher MAWP.	Explosion risk lower due to lower MAWP.
Suitable for the power generation industry.	Not suitable for the power generation industry.

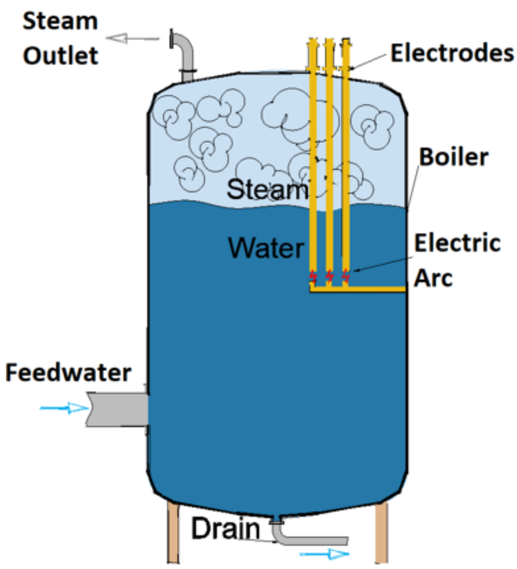
Water Tube and Fire Tube Comparison

For a detailed look at fire tube and water tube boilers, please see the associated saVRee courses.

Electric Boilers

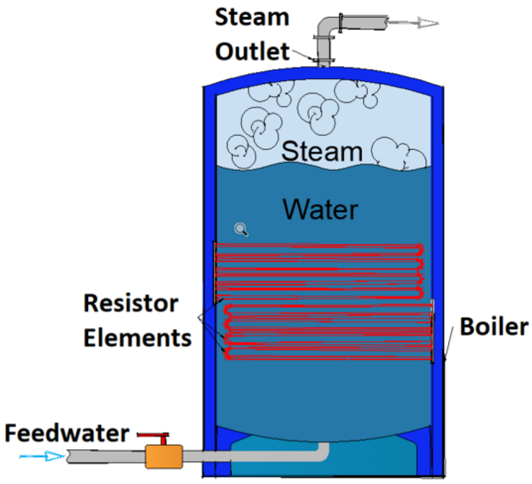
There are ***two common types of electric boiler***, these are the ***electrode boiler*** and ***resistance boiler***. Both boiler designs are relatively simple as they do not require a combustion system.

Electrode boilers generate electrical arcs which heat the water until steam is formed. The number of electrodes per boiler, MAWP and their steam generation rates, varies depending upon the boiler design.



Electrode Boiler

Resistance boilers pass electrical current through submerged resistive elements in order to generate heat. Heat from the elements is transferred to the surrounding water, which gradually turns to steam. Resistance boilers are often used for hot water heating applications.



Resistance Boilers

Electric boilers are emission free (no gases of combustion) and comparatively small compared to combustion type boilers. The largest disadvantage associated with electric boilers is the cost compared to combustion type boilers.

Boiler Resistor Elements

Package and Field Erected Boilers

Package boilers are sold as ***turn-key*** boilers, they are delivered to the site completely assembled and only need to be connected to the various systems they require to operate (feedwater, steam, fuel, exhaust gas etc.).

A large advantage associated with package boilers is that they can be tested completely by the original equipment manufacturer (OEM) at the factory before shipping, and can be replaced by the same (or similar) model quite quickly.

Field erected boilers are too large to ship as a single product and must be assembled on-site. Water tube boilers used in the power generation industry are examples of field erected boilers.

Final Thoughts

This course has introduced the history, theory and applications of steam. Many thermodynamic topics have been covered, along with their real-world significance.

If you would like to learn more about steam, please check for the ***Introduction to Fire Tube Boilers*** and ***Introduction to Water Tube Boilers*** courses.

Appendix.

Units of Measurement

Depending upon your geographical location, you may be more accustomed to either imperial or metric units. For convenience, a list of handy conversion formulas is given below. The list is based on the most common imperial and metric units (SI units).

Celsius to Fahrenheit

(°C × 9/5) + 32 = °F

Example

(1°C × 9/5) + 32 = 33.8°F

Fahrenheit to Celsius

(°F − 32) × 5/9 = °C

Example

(1°F − 32) × 5/9 = -17,22°C

Celsius to Kelvin

°C + 273.15 = K

Fahrenheit to Kelvin

(°F − 32) × 5/9 + 273.15 = K

Bar to PSI

Bar x 14.5038 = psi

PSI to Bar

psi / 14.5038 = Bar

British Thermal Unit

The amount of energy required to increase the temperature of 1 lb of water by 1°F.

British Thermal Unit to Joules

Btu x 1055 = Joule

Calorie

The amount of energy required to increase the temperature of 1 gram of water by 1°C.

Cubic Feet to Metres cubed

35 cu ft = 1 m^3

Unit Conversion Calculator

A useful tool for many boiler conversions is provided by Cleave Books at the following link:
http://www.cleavebooks.co.uk/scol/index.htm

Introduction to Steam, Boilers, and Thermodynamics – Quiz

Updated 2-12-2020

Chapter 2 Introduction

1) Within the context of engineering, what does the term ‘energy fluid’ mean?
   a) Energy fluids are drinks that provide an energy boost, for example Red Bull.
   b) The term ‘energy fluid’ refers to either electricity or steam.
   c) An energy fluid is a fluid used to convey energy, usually in the form of heat (thermal energy), pressure (pressure energy) and/or speed (kinetic energy).

2) A steam system requires several smaller systems in order to function. Select the systems required by a steam system.
   a) Fuel system – provides chemical energy to the boiler.
   b) Boiler – converts the fuel’s chemical energy to thermal energy.
   c) All these options.
   d) Distribution – conveys steam to the point of use.

Chapter 3 Thermodynamics

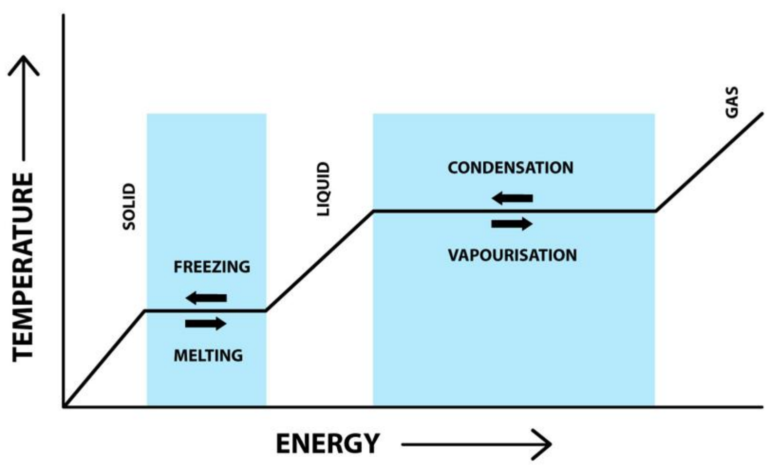
3) Pressure is often given in ‘psi’ or ‘bar’, but it is also possible that pressure may be given in ‘psia’, ‘psig’, ‘bara’ or ‘barg’. The ‘a’ and ‘g’ indicate ‘absolute’ and ‘gauge’ pressure readings.

   a) True
   b) False

4) Heat is defined as '*thermal energy transferred between two systems that are in direct contact with each other, but at different temperatures*.' If heat is transferred to a substance, the substance will change temperature, or change state.
   a) True
   b) False

5) The boiling point is the temperature at which a liquid boils and becomes vapour, it is also referred to as the saturation temperature. How will the boiling point be affected if the pressure surrounding the liquid changes?
   a) The boiling point of a liquid decreases as pressure increases and increases as pressure decreases.
   b) The boiling point of a liquid increases as pressure increases and decreases as pressure decreases.
   c) The boiling point of a liquid does not change with varying pressure.

6) With reference to the graph shown, which of the shown statements is **NOT** correct?



   a) The graph shows that heat added does not always cause a temperature change.
   b) Sensible heat is seen whenever heat is added and the temperature changes proportionately (sloped lines on the graph).
   c) Latent heat is seen whenever heat is added and no change of temperature occurs (horizontal lines on the graph).
   d) The graph shows that heat energy added always causes a temperature change.

7) Regarding sensible and latent heat, which of the given statements is **NOT** true?
   a) Adding sensible heat to water will gradually increase its temperature.
   b) Steam contains both the sensible and latent heat that was transferred into it.
   c) Changing water into gas requires almost no latent heat and a lot of sensible heat.
   d) A liquid at saturation temperature (temperature at which it boils), is literally saturated with sensible heat.

8) Which of the following statements describes heat transfer by conduction?
   a) Heat is transferred directly from one molecule to another. Conduction occurs in solids, liquids and gases.
   b) Heat is transferred by molecules in a fluid state. Conduction may be forced (using a pump or fan), or, natural, due to temperature and density differences in the fluid.
   c) Heat is transferred via radiant energy (electromagnetic waves).

9) Which of the following statements describes heat transfer by radiation?
   a) Heat is transferred directly from one molecule to another. Radiation occurs in solids, liquids and gases.
   b) Heat is transferred by molecules in a fluid state. Radiation may be forced (using a pump or fan), or, natural, due to temperature and density differences in the fluid.
   c) Heat is transferred via radiant energy (electromagnetic waves).

10) Which of the listed is NOT a unit of measurement for temperature?
   a) Degree Celsius (°C) – tends to be favoured in Europe. Fresh water boils at 100°C and freezes at 0°C.
   b) Degree Fahrenheit (°F) – tends to be favoured in the Americas. Fresh water boils at 212 °F and freezes at 32°F. Saltwater freezes at 0 °F.
   c) Kelvin (K). One of the seven SI units (International System of Units). Fresh water boils at 373 K and freezes at 273 K.
   d) All options are units of measurement for temperature.

11) What does the term *specific heat*, also known as *specific heat capacity* refer to?
   a) Specific heat is a measure of the average kinetic energy that the molecules of a substance contain.
   b) Specific heat is the amount of heat required to change one unit of a substance’s mass by one unit in temperature.

Chapter 4 Combustion

12) Choose the true statement:
    a) Efficiency is represented by the Greek letter η and the equation *Efficiency = Output / Input*.
    b) Efficiency is represented by the Greek letter η and the equation *Efficiency = Input / Output*.

13) Concerning boiler thermal efficiency, which of the following equations is true?
    a) Thermal Efficiency = Heat Absorbed by Boiler Water / Heat Generated by Combustion
    b) Thermal Efficiency = Energy Output / Energy Input
    c) Thermal Efficiency = Chemical Energy of the Fuel / Heat Absorbed by Boiler Water

14) It's possible to measure the gases of combustion to determine if combustion was complete or incomplete. Select the correct statement:
    a) Too much oxygen in the gases of combustion indicates that too much air for combustion was provided.
    b) Too much oxygen in the gases of combustion indicates that combustion was incomplete.
    c) High levels of carbon monoxide in the gases of combustion indicates combustion was complete.

Chapter 5 Steam Properties

15) The 'steam' that a viewer sees is actually water molecules suspended in the steam, not steam.
    a) True
    b) False

16) Pressure, volume and temperature, are all related, and the combined gas law (k = P x V / T) describes the relationship between them. Which of the given statements is correct?
    a) If temperature is held constant, a decrease in pressure will be accompanied by a decrease in volume.
    b) If temperature is held constant, an increase in pressure will be accompanied by a decrease in volume.

17) Which of the following statements is correct regarding saturated water?

a) Saturated water contains enough heat that if the temperature remains constant, and the pressure decreases, it will boil.

b) Saturated water contains the maximum amount of heat it can hold at a given pressure without beginning to change state to a vapour.

c) Both of these answers**.**

18) Steam is classified as either *wet* or *dry*. Which of the given statements best describes wet and dry steam?

a) Wet steam contains water droplets suspended in the steam. Dry steam contains no suspended water droplets in the steam.

b) Dry steam contains water droplets suspended in the steam. Wet steam contains no suspended water droplets in the steam.

19) Which of the given statements is true? Select all the correct answers.

a) Wet steam always contains less energy than drier steam, thus drier steam makes the system process more efficient and is consequently desired.

b) The inverse of the dryness fraction is the wetness fraction, although it is less commonly quoted in steam tables.

c) Steam containing 5% moisture by mass, also contains 95% steam; the steam is described as having a dryness fraction of 0.95.

d) All these statements are true.

20) Concerning enthalpy, which of the given statements is **NOT** true?

a) Enthalpy can be thought of as the amount of heat (sensible and latent) a substance contains.

b) The amount of sensible heat required to raise a given mass of liquid from its freezing point to its boiling point (saturation temperature) is termed the enthalpy of a liquid at saturation temperature.

c) Enthalpy is the amount of heat required to change one unit of a substance's mass by one unit in temperature.

d) The amount of latent heat required to turn a given mass of saturated water (water at its boiling point) into dry saturated steam, is termed enthalpy of vaporisation.

21) Properties of steam at various pressures and temperatures (i.e. specific volume, enthalpy etc.) are listed in:
  a) Steam tables.
  b) Steam checklists.
  c) Steam papers.
  d) Steam notebooks.

Chapter 6 Boilers

22) There are two main types of boiler used in the industrial engineering world, these are the *fire tube boiler* and *water tube boiler*. Which statement is true?
  a) Water tube boilers have water outside the tubes and gases of combustion inside the tubes.
  b) Fire tube boilers have gases of combustion outside the tubes and water within the tubes.
  c) Water tube boilers have water in the tubes and gases of combustion outside of the tubes.

23) Concerning water tube boilers, which statement is **NOT** correct?
  a) Combustion gases surround the tubes.
  b) Very high steam generation rate compared to fire tube boilers.
  c) Maximum allowable working pressure (MAWP) up to 362 psi (25 bar).

24) Concerning fire tube boilers, which statement is **NOT** correct?
  a) Combustion gases in the tubes, water surrounding the tubes.
  b) Very high steam generation rate compared to water tube boilers.
  c) Maximum allowable working pressure (MAWP) up to 362 psi (25 bar).