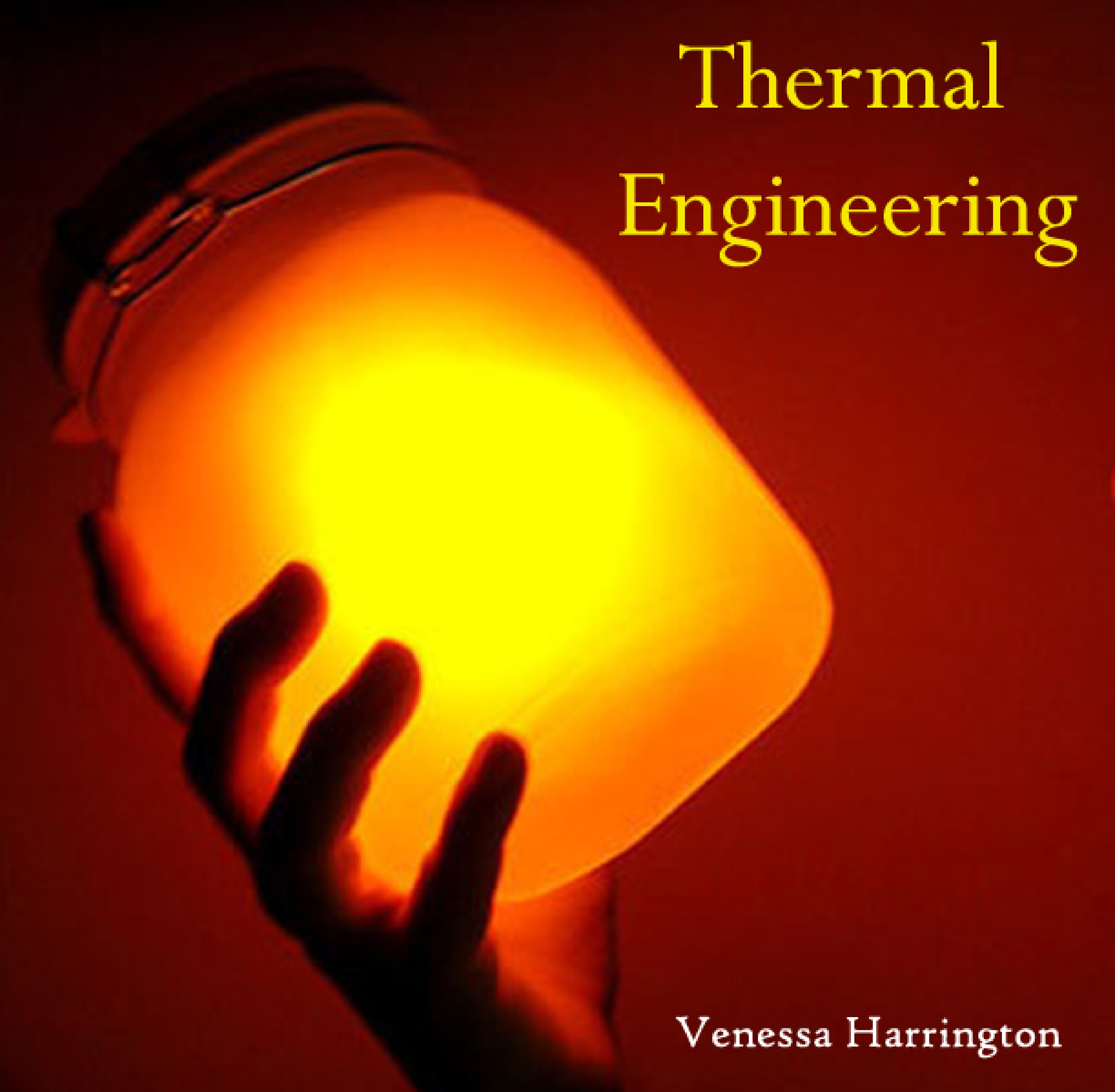
Thermal Engineering



Venessa Harrington

First Edition, 2012

ISBN 978-81-323-2430-0

Published by:
Library Press
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

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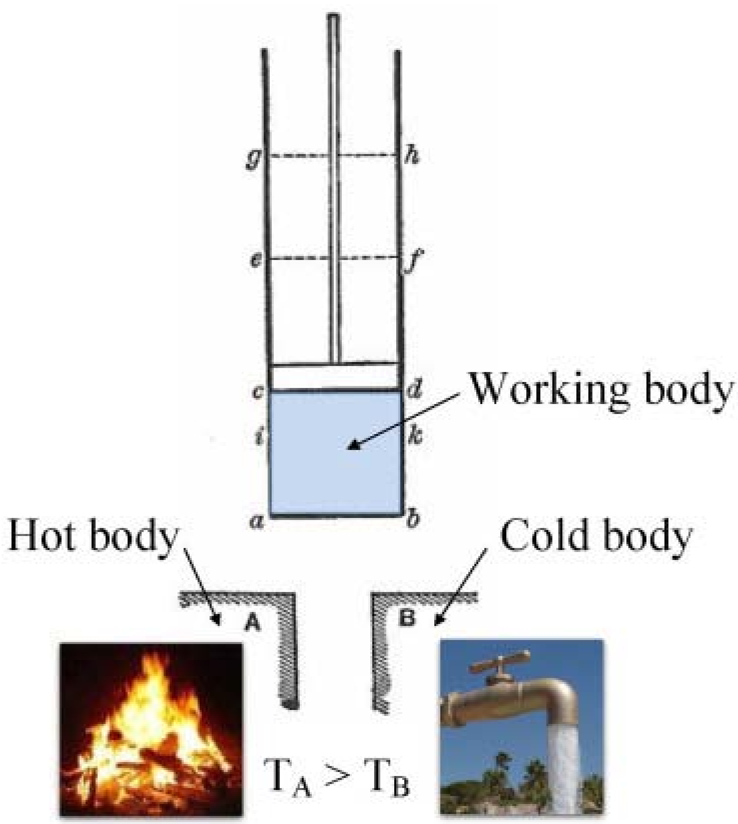
Thermodynamics



Annotated color version of the original 1824 Carnot heat engine showing the hot body (boiler), working body (system, steam), and cold body (water), the letters labeled according to the stopping points in Carnot cycle.

Thermodynamics is the science of energy conversion involving heat and other forms of energy, most notably mechanical work. It studies and interrelates the macroscopic variables, such as temperature, volume and pressure, which describe physical, thermodynamic systems.

Historically, thermodynamics developed out of a desire to increase the efficiency of early steam engines, particularly through the work of French physicist Nicolas Léonard Sadi

Carnot (1824) who believed that engine efficiency was the key that could help France win the Napoleonic Wars. Scottish physicist Lord Kelvin was the first to formulate a concise definition of thermodynamics when he stated in 1854:

Thermo-dynamics is the subject of the relation of heat to forces acting between contiguous parts of bodies, and the relation of heat to electrical agency.

Two fields of thermodynamics emerged in the following decades. Statistical thermodynamics, or statistical mechanics, (1860) concerned itself with statistical predictions of the collective motion of particles from their microscopic behavior, while chemical thermodynamics (1873) studies the nature of the role of entropy in the process of chemical reaction.

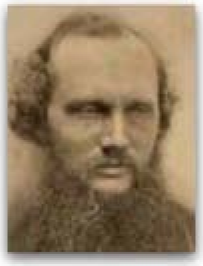
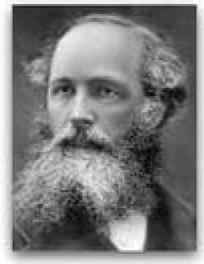
Introduction

The starting point for most thermodynamic considerations are the laws of thermodynamics, which postulate that energy can be exchanged between physical systems as heat or work. They also postulate the existence of a quantity named entropy, which can be defined for any isolated system that is in thermodynamic equilibrium.

In thermodynamics, interactions between large ensembles of objects are studied and categorized. Central to this are the concepts of *system* and *surroundings*. A system is composed of particles, whose average motions define its properties, which in turn are related to one another through equations of state. Properties can be combined to express internal energy and thermodynamic potentials, which are useful for determining conditions for equilibrium and spontaneous processes.

With these tools, thermodynamics can be used to describe how systems respond to changes in their environment. This can be applied to a wide variety of topics in science and engineering, such as engines, phase transitions, chemical reactions, transport phenomena, and even black holes. The results of thermodynamics are essential for other fields of physics and for chemistry, chemical engineering, aerospace engineering, mechanical engineering, cell biology, biomedical engineering, materials science, and economics, to name a few.

The present article is focused mainly on classical thermodynamics, which is concerned with systems in thermodynamic equilibrium. It is wise to distinguish classical thermodynamics from non-equilibrium thermodynamics, which is concerned with systems that are not in thermodynamic equilibrium.

École Polytechnique	Glasgow school	Berlin school	Edinburgh school
			
Sadi Carnot (1796-1832)	William Thomson (1824-1907)	Rudolf Clausius (1822-1888)	James Maxwell (1831-1879)
Vienna school	Gibbsian school	Dresden school	Dutch school
			
Ludwig Boltzmann (1844-1906)	Willard Gibbs (1839-1903)	Gustav Zeuner (1828-1907)	Johannes der Waals (1837-1923)

The thermodynamicists representative of the original eight founding schools of thermodynamics. The schools with the most-lasting effect in founding the modern versions of thermodynamics are the Berlin school, particularly as established in Rudolf Clausius's 1865 textbook *The Mechanical Theory of Heat*, the Vienna school, with the statistical mechanics of Ludwig Boltzmann, and the Gibbsian school at Yale University, American engineer Willard Gibbs' 1876 *On the Equilibrium of Heterogeneous Substances* launching chemical thermodynamics.

History

The history of thermodynamics as a scientific discipline generally begins with Otto von Guericke who, in 1650, built and designed the world's first vacuum pump and demonstrated a vacuum using his Magdeburg hemispheres. Guericke was driven to make a vacuum in order to disprove Aristotle's long-held supposition that 'nature abhors a vacuum'. Shortly after Guericke, the English physicist and chemist Robert Boyle had learned of Guericke's designs and, in 1656, in coordination with English scientist Robert Hooke, built an air pump. Using this pump, Boyle and Hooke noticed a correlation between pressure, temperature, and volume. In time, Boyle's Law was formulated, which states that pressure and volume are inversely proportional. Then, in 1679, based on these concepts, an associate of Boyle's named Denis Papin built a steam digester, which was a closed vessel with a tightly fitting lid that confined steam until a high pressure was generated.

Later designs implemented a steam release valve that kept the machine from exploding. By watching the valve rhythmically move up and down, Papin conceived of the idea of a piston and a cylinder engine. He did not, however, follow through with his design. Nevertheless, in 1697, based on Papin's designs, engineer Thomas Savery built the first engine, followed by Thomas Newcomen in 1712. Although these early engines were crude and inefficient, they attracted the attention of the leading scientists of the time.

The fundamental concepts of heat capacity and latent heat, which were necessary for the development of thermodynamics, were developed by Professor Joseph Black at the University of Glasgow, where James Watt was employed as an instrument maker. Black and Watt performed experiments together, but it was Watt who conceived the idea of the external condenser which resulted in a large increase in steam engine efficiency. Drawing on all the previous work led Sadi Carnot, the "father of thermodynamics", to publish *Reflections on the Motive Power of Fire* (1824), a discourse on heat, power, energy and engine efficiency. The paper outlined the basic energetic relations between the Carnot engine, the Carnot cycle, and motive power. It marked the start of thermodynamics as a modern science.

The first thermodynamic textbook was written in 1859 by William Rankine, originally trained as a physicist and a civil and mechanical engineering professor at the University of Glasgow. The first and second laws of thermodynamics emerged simultaneously in the 1850s, primarily out of the works of William Rankine, Rudolf Clausius, and William Thomson (Lord Kelvin).

The foundations of statistical thermodynamics were set out by physicists such as James Clerk Maxwell, Ludwig Boltzmann, Max Planck, Rudolf Clausius and J. Willard Gibbs.

During the years 1873-76 the American mathematical physicist Josiah Willard Gibbs published a series of three papers, the most famous being *On the Equilibrium of Heterogeneous Substances*, in which he showed how thermodynamic processes could be graphically analyzed, by studying the energy, entropy, volume, temperature and pressure of the thermodynamic system in such a manner, one can determine if a process would occur spontaneously. During the early 20th century, chemists such as Gilbert N. Lewis, Merle Randall, and E. A. Guggenheim began to apply the mathematical methods of Gibbs to the analysis of chemical processes.

Etymology

The etymology of *thermodynamics* has an intricate history.It was first spelled in a hyphenated form as an adjective (*thermo-dynamic*) and from 1854 to 1868 as the noun *thermo-dynamics* to represent the science of generalized heat engines.

American biophysisist Donald Haynie claims that *thermodynamics* was coined in 1840 from the Greek root θέρμη *therme,* meaning heat and δύναμις,*dynamis,* meaning power. However, this etymology has been cited as unlikely.

Pierre Perrot claims that the term *thermodynamics* was coined by James Joule in 1858 to designate the science of relations between heat and power., however, Joule never used that term, but used instead the term *perfect thermo-dynamic engine* in reference to Thomson's 1849 phraseology.

By 1858, *thermo-dynamics*, as a functional term, was used in William Thomson's paper *An Account of Carnot's Theory of the Motive Power of Heat.*

Interpretations

Thermodynamics has developed into several related branches of science, each with a different focus.

Classical thermodynamics

Classical thermodynamics is the description of the states of thermodynamical systems at near-equilibrium, using macroscopic, empirical properties directly measurable in the laboratory. It is used to model exchanges of energy, work and heat based on the laws of thermodynamics. The qualifier *classical* reflects the fact that it represents the level of knowledge in the early 19th century. An atomic interpretation of these principles was provided later by the development of statistical mechanics.

Statistical mechanics

Statistical mechanics (or statistical thermodynamics) emerged only with the development of atomic and molecular theories in the late 19th century and early 20th century, giving thermodynamics a molecular interpretation. This field relates the microscopic properties of individual atoms and molecules to the macroscopic or bulk properties of materials that can be observed in everyday life, thereby explaining thermodynamics as a natural result of statistics and mechanics (classical and quantum) at the microscopic level. This statistical approach is in contrast to classical thermodynamics, which is a more phenomenological approach.

Chemical thermodynamics

Chemical thermodynamics is the study of the interrelation of energy with chemical reactions or with a physical change of state within the confines of the laws of thermodynamics.

Treatment of equilibrium

Equilibrium thermodynamics is the systematic study of transformations of matter and energy in systems as they approach equilibrium. The word equilibrium implies a state of balance. In an equilibrium state there are no unbalanced potentials, or driving forces, within the system. A central aim in equilibrium thermodynamics is: given a system in a well-defined initial state, subject to accurately specified constraints, to calculate what the state of the system will be once it has reached equilibrium.

Non-equilibrium thermodynamics is a branch of thermodynamics that deals with systems that are not in thermodynamic equilibrium. Most systems found in nature are not in thermodynamic equilibrium because they are not in stationary states, and are continuously and discontinuously subject to flux of matter and energy to and from other systems. The thermodynamic study of non-equilibrium systems requires more general concepts than are dealt with by equilibrium thermodynamics. Many natural systems still today remain beyond the scope of currently known macroscopic thermodynamic methods.

Laws of thermodynamics

Thermodynamics defines four laws which do not depend on the details of the systems under study or how they interact. Hence these laws are generally valid and can be applied to systems about which one knows nothing other than the balance of energy and matter transfer. Examples of such systems include Einstein's prediction of spontaneous emission, and ongoing research into the thermodynamics of black holes.

These four laws are:

- Zeroth law of thermodynamics: *If two systems are in thermal equilibrium with a third, they are also in thermal equilibrium with each other.*

This statement implies that thermal equilibrium is an equivalence relation on the set of thermodynamic systems under consideration. Systems are said to be in equilibrium if the small, random exchanges between them (eg. Brownian motion) do not lead to a net change in energy. This law is tacitly assumed in every measurement of temperature. Thus, if one seeks to decide if two bodies are at the same temperature, it is not necessary to bring them into contact and measure any changes of their observable properties in time. The law provides a fundamental definition of temperature and justification for the construction of practical thermometers.

It is interesting to note that the zeroth law was not initially recognized as a law. The need to for the zeroth law was not initially realized, so the first, second, and third laws were explicitly stated and found common acceptance in the physics community first. Once the importance of the zeroth law was realized, it was impracticable to renumber the other laws, hence the *zeroth.*

- First law of thermodynamics: *The internal energy of an isolated system is constant.*

The first law of thermodynamics is an expression of the principle of conservation of energy. It states that energy can be transformed (changed from one form to another), but cannot be created or destroyed.

The first law is usually formulated by saying that the change in the internal energy of a closed thermodynamic system is equal to the difference between the of heat supplied to the system and the amount of work done by the system on its surroundings. It is important to note that internal energy is a state of the system whereas heat and work modify the state of the system. In other words, a specific internal energy of a system may be achieved by any combination of heat and work; the manner by which a system achieves a specific internal energy is path independent.

- Second law of thermodynamics: *Heat cannot spontaneously flow from a colder location to a hotter location.*

The second law of thermodynamics is an expression of the universal principle of decay observable in nature. The second law is an observation of the fact that over time, differences in temperature, pressure, and chemical potential tend to even out in a physical system that is isolated from the outside world. Entropy is a measure of how much this evening-out process has progressed. The entropy of an isolated system which is not in equilibrium will tend to increase over time, approaching a maximum value at equilibrium.

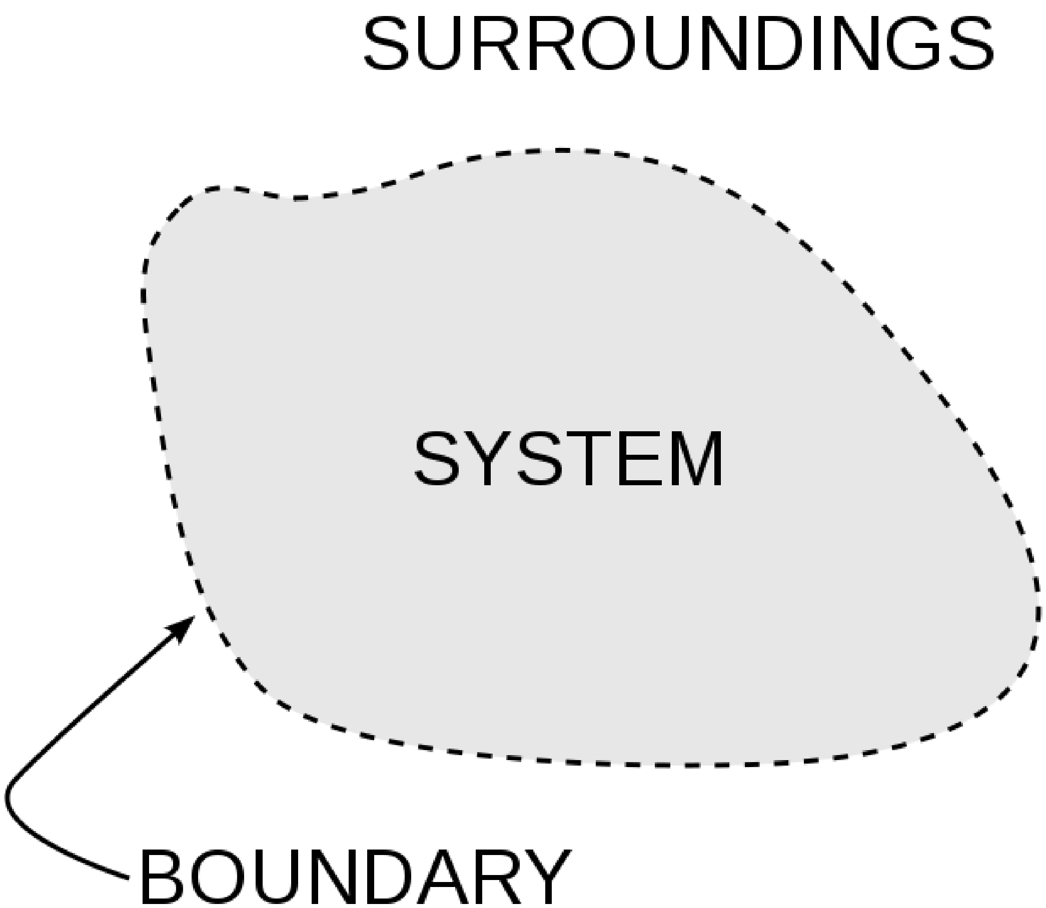
In classical thermodynamics, the second law is a basic postulate applicable to any system involving heat energy transfer; in statistical thermodynamics, the second law is a consequence of the assumed randomness of molecular chaos. There are many versions of the second law, but they all have the same effect, which is to explain the phenomenon of irreversibility in nature.

- Third law of thermodynamics: *As a system approaches absolute zero, all processes cease and the entropy of the system approaches a minimum value.*

The third law of thermodynamics is a statistical law of nature regarding entropy and the impossibility of reaching absolute zero of temperature. This law provides an absolute reference point for the determination of entropy. The entropy determined relative to this point is the absolute entropy. Alternate definitions are, "the entropy of all systems and of all states of a system is smallest at absolute zero," or equivalently "it is impossible to reach the absolute zero of temperature by any finite number of processes".

Absolute zero, at which all activity would stop if it were possible to happen, is −273.15 °C (degrees Celsius), or −459.67 °F (degrees Fahrenheit) or 0 K (kelvin).

System models



A diagram of a generic thermodynamic system

An important concept in thermodynamics is the thermodynamic system, a precisely defined region of the universe under study. Everything in the universe except the system is known as the *surroundings*. A system is separated from the remainder of the universe by a *boundary* which may be notional or not, but which by convention delimits a finite volume. Exchanges of work, heat, or matter between the system and the surroundings take place across this boundary.

In practice, the boundary is simply an imaginary dotted line drawn around a volume when there is going to be a change in the internal energy of that volume. Anything that passes across the boundary that effects a change in the internal energy needs to be accounted for in the energy balance equation. The volume can be the region surrounding a single atom resonating energy, such as Max Planck defined in 1900; it can be a body of steam or air in a steam engine, such as Sadi Carnot defined in 1824; it can be the body of a tropical cyclone, such as Kerry Emanuel theorized in 1986 in the field of atmospheric thermodynamics; it could also be just one nuclide (i.e. a system of quarks) as hypothesized in quantum thermodynamics.

Boundaries are of four types: fixed, moveable, real, and imaginary. For example, in an engine, a fixed boundary means the piston is locked at its position; as such, a constant volume process occurs. In that same engine, a moveable boundary allows the piston to move in and out. For closed systems, boundaries are real while for open system boundaries are often imaginary.

Generally, thermodynamics distinguishes three classes of systems, defined in terms of what is allowed to cross their boundaries:

Interactions of thermodynamic systems

Type of system	**Mass flow**	**Work**	**Heat**
Open	✓	✓	✓
Closed	✗	✓	✓
Isolated	✗	✗	✗

As time passes in an isolated system, internal differences in the system tend to even out and pressures and temperatures tend to equalize, as do density differences. A system in which all equalizing processes have gone to completion is considered to be in a state of thermodynamic equilibrium.

In thermodynamic equilibrium, a system's properties are, by definition, unchanging in time. Systems in equilibrium are much simpler and easier to understand than systems which are not in equilibrium. Often, when analysing a thermodynamic process, it can be assumed that each intermediate state in the process is at equilibrium. This will also considerably simplify the situation. Thermodynamic processes which develop so slowly as to allow each intermediate step to be an equilibrium state are said to be reversible processes.

States and processes

When a system is at equilibrium under a given set of conditions, it is said to be in a definite thermodynamic state. The state of the system can be described by a number of intensive variables and extensive variables. The properties of the system can be described by an equation of state which specifies the relationship between these variables. State may be thought of as the instantaneous quantitative description of a system with a set number of variables held constant.

A thermodynamic process may be defined as the energetic evolution of a thermodynamic system proceeding from an initial state to a final state. Typically, each thermodynamic process is distinguished from other processes in energetic character according to what parameters, such as temperature, pressure, or volume, etc., are held fixed. Furthermore, it is useful to group these processes into pairs, in which each variable held constant is one member of a conjugate pair.

Several commonly studied thermodynamic processes are:

- Isobaric process: occurs at constant pressure
- Isochoric process: occurs at constant volume (also called isometric/isovolumetric)
- Isothermal process: occurs at a constant temperature
- Adiabatic process: occurs without loss or gain of energy by heat
- Isentropic process: a reversible adiabatic process, occurs at a constant entropy
- Isenthalpic process: occurs at a constant enthalpy
- Steady state process: occurs without a change in the internal energy

Instrumentation

There are two types of thermodynamic instruments, the **meter** and the **reservoir**. A thermodynamic meter is any device which measures any parameter of a thermodynamic system. In some cases, the thermodynamic parameter is actually defined in terms of an idealized measuring instrument. For example, the zeroth law states that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other. This principle, as noted by James Maxwell in 1872, asserts that it is possible to measure temperature. An idealized thermometer is a sample of an ideal gas at constant pressure. From the ideal gas law $pV=nRT$, the volume of such a sample can be used as an indicator of temperature; in this manner it defines temperature. Although pressure is defined mechanically, a pressure-measuring device, called a barometer may also be constructed from a sample of an ideal gas held at a constant temperature. A calorimeter is a device which is used to measure and define the internal energy of a system.

A thermodynamic reservoir is a system which is so large that it does not appreciably alter its state parameters when brought into contact with the test system. It is used to impose a particular value of a state parameter upon the system. For example, a pressure reservoir is a system at a particular pressure, which imposes that pressure upon any test system that it is mechanically connected to. The Earth's atmosphere is often used as a pressure reservoir.

Conjugate variables

The central concept of thermodynamics is that of energy, the ability to do work. By the First Law, the total energy of a system and its surroundings is conserved. Energy may be transferred into a system by heating, compression, or addition of matter, and extracted from a system by cooling, expansion, or extraction of matter. In mechanics, for example, energy transfer equals the product of the force applied to a body and the resulting displacement.

Conjugate variables are pairs of thermodynamic concepts, with the first being akin to a "force" applied to some thermodynamic system, the second being akin to the resulting "displacement," and the product of the two equalling the amount of energy transferred. The common conjugate variables are:

- Pressure-volume (the mechanical parameters);
- Temperature-entropy (thermal parameters);
- Chemical potential-particle number (material parameters).

Potentials

Thermodynamic potentials are different quantitative measures of the stored energy in a system. Potentials are used to measure energy changes in systems as they evolve from an initial state to a final state. The potential used depends on the constraints of the system, such as constant temperature or pressure. For example, the Helmholtz and Gibbs energies are the energies available in a system to do useful work when the temperature and volume or the pressure and temperature are fixed, respectively.

The five most well known potentials are:

Name	Symbol	Formula	Natural variables
Internal energy	U	$\int (TdS - pdV + \sum_i \mu_i dN_i)$	$S, V, \{N_i\}$
Helmholtz free energy	F, A	$U - TS$	$T, V, \{N_i\}$
Enthalpy	H	$U + pV$	$S, p, \{N_i\}$
Gibbs free energy	G	$U + pV - TS$	$T, p, \{N_i\}$
Landau Potential (Grand potential)	Ω, Φ_G	$U - TS - \sum_i \mu_i N_i$	$T, V, \{\mu_i\}$

where T is the temperature, S the entropy, p the pressure, V the volume, μ the chemical potential, N the number of particles in the system, and i is the count of particles types in the system.

Thermodynamic potentials can be derived from the energy balance equation applied to a thermodynamic system. Other thermodynamic potentials can also be obtained through Legendre transformation.

Applied fields

- Atmospheric thermodynamics
- Biological thermodynamics
- Black hole thermodynamics
- Chemical thermodynamics

- Classical thermodynamics
- Equilibrium thermodynamics
- Industrial ecology (re: Exergy)
- Quantum thermodynamics
- Statistical thermodynamics
- Thermoeconomics

Chapter- 2

Laws of Thermodynamics

The **laws of thermodynamics** form an axiomatic basis of thermodynamics. They define fundamental physical quantities, such as temperature, energy, and entropy, to describe thermodynamic systems and describe the transport and conversion of heat and work in thermodynamic processes.

Classical thermodynamics describes the thermal interaction of systems individually in thermodynamic equilibrium. Non-equilibrium thermodynamics may be considered separately as an extension to classical theory using the tools of statistical thermodynamics which describes all systems as ensembles of microscopic states.

The four principles, or laws, of thermodynamics are:

> The zeroth law of thermodynamics provides a basic definition of empirical temperature based on the principle of thermal equilibrium.
> The first law of thermodynamics mandates conservation of energy and states in particular that the flow of heat is a form of energy transfer.
> The second law of thermodynamics states that the entropy of an isolated macroscopic system never decreases, or, equivalently, that perpetual motion machines are impossible.
> The third law of thermodynamics concerns the entropy of a perfect crystal at absolute zero temperature, and implies that it is impossible to cool a system to exactly absolute zero.

There have been suggestions of additional laws, but none of them achieve the generality of the accepted laws, and they are not mentioned in standard textbooks.

The laws of thermodynamics have become some of the most important fundamental laws in physics and other sciences.

Zeroth law

The zeroth law of thermodynamics may be stated as follows:

If two thermodynamic systems are each in thermal equilibrium with a third system, then they are in thermal equilibrium with each other.

When two systems, each internally in thermodynamic equilibrium at a different temperature, are brought in diathermic contact with each other they exchange heat to establish a thermal equilibrium between each other.

The zeroth law implies that thermal equilibrium, viewed as a binary relation, is a transitive relation. Thermal equilibrium is furthermore an equivalence relation between any number of system. The law is also a statement about measurability. To this effect the law establishes an empirical parameter, the temperature, as a property of a system so that systems in equilibrium with each other have the same temperature. The notion of transitivity permits a system, for example a gas thermometer, to be used as a device to measure the temperature of another system.

Although the concept of thermodynamic equilibrium is fundamental to thermodynamics, the need to state it explicitly as a law was not widely perceived until Fowler and Planck stated it in the 1930s, long after the first, second, and third law were already widely understood and recognized. Hence it was numbered the zeroth law. The importance of the law as a foundation to the earlier laws is that it defines temperature in a non-circular logistics without reference to entropy, its conjugate variable.

The zeroth law of thermodynamics is a generalization principle of thermal equilibrium among bodies, or thermodynamic systems, in contact.

The zeroth law states that if two systems are in thermal equilibrium with a third system, they are also in thermal equilibrium with each other.

Systems are in thermal equilibrium if they do not exchange heat. The law implies that thermal equilibrium between systems is a transitive relation, which affords the definition of an empirical physical parameter, called temperature. The temperatures are equal for all systems in thermal equilibrium. The law permits the construction of a thermometer to measure this property.

Zeroth law as equivalence relation

A system is said to be in thermal equilibrium when it experiences no net change in thermal energy. If A, B, and C are distinct thermodynamic systems, the zeroth law of thermodynamics can be expressed as:

"If A and C are each in thermodynamic equilibrium with B, A is also in equilibrium with C."

This statement asserts that thermal equilibrium is a Euclidean relation between thermodynamic systems. If we also grant that all thermodynamic systems are in thermal equilibrium with themselves, then thermal equilibrium is also a reflexive relation. Relations that are both reflexive and Euclidean are equivalence relations. One consequence of this reasoning is that thermal equilibrium has a transitive relationship between the temperature T of A, B, and C:

If $T(A) = T(B)$
and $T(B) = T(C)$
then $T(A) = T(C)$.

Thermal equilibrium between many systems

Many systems are said to be in equilibrium if the small, random exchanges (due to Brownian motion, for example) between them do not lead to a net change in the total energy summed over all systems. A simple example illustrates why the zeroth law is necessary to complete the equilibrium description.

Consider N systems in adiabatic isolation from the rest of the universe, i.e. no heat exchange is possible outside of these N systems, all of which have a constant volume and composition, and which can only exchange heat with one another.

The combined First and Second Laws relate the fluctuations in total energy, δU, to the temperature of the ith system, T_i, and the entropy fluctuation in the ith system, δS_i, as follows:

$$\delta U = \sum_i^N T_i \delta S_i.$$

The adiabatic isolation of the system from the remaining universe requires that the total sum of the entropy fluctuations vanishes, or:

$$\sum_i^N \delta S_i = 0.$$

That is, entropy can only be exchanged between the N systems. This constraint can be used to rearrange the expression for the total energy fluctuation and obtain:

$$\delta U = \sum_i^N (T_i - T_j)\delta S_i,$$

where T_j is the temperature of any system j we may choose to single out among the N systems. Finally, equilibrium requires the total fluctuation in energy to vanish, in which case:

$$\sum_i^N (T_i - T_j)\delta S_i = 0,$$

which can be thought of as the vanishing of the product of an antisymmetric matrix $T_i - T_j$ and a vector of entropy fluctuations δS_i. In order for a non-trivial solution to exist,

$$\delta S_i \neq 0.$$

That is, the determinant of the matrix formed by $T_i - T_j$ must vanish for all choices of *N*. However, according to Jacobi's theorem, the determinant of a *N*x*N* antisymmetric matrix is always zero if *N* is odd, although for *N* even we find that all of the entries must vanish, $T_i - T_j = 0$, in order to obtain a vanishing determinant. Hence $T_i = T_j$ at equilibrium. This non-intuitive result means that an odd number of systems are always in equilibrium regardless of their temperatures and entropy fluctuations, while equality of temperatures is only required between an even number of systems to achieve equilibrium in the presence of entropy fluctuations.

The zeroth law solves this odd vs. even paradox, because it can readily be used to reduce an odd-numbered system to an even number by considering any three of the *N* systems and eliminating one by application of its principle, and hence reduce the problem to even *N* which subsequently leads to the same equilibrium condition that we expect in every case, i.e., $T_i = T_j$. The same result applies to fluctuations in any extensive quantity, such as volume (yielding the equal pressure condition), or fluctuations in mass (leading to equality of chemical potentials). Hence the zeroth law has implications for a great deal more than temperature alone. In general, we see that the zeroth law breaks a certain kind of asymmetry present in the First and Second Laws.

Foundation of temperature

Max Planck and others have stated that the zeroth law implies the definition of a temperature function or more informally, that one can construct a thermometer.

In the space of thermodynamic parameters, zones of constant temperature form a surface, that provides a natural order of nearby surfaces. One may therefore construct a global temperature function that provides a continuous ordering of states. The dimensionality of a surface of constant temperature is one less than the number of thermodynamic parameters, thus, for an ideal gas described with three thermodynamic parameters *P*, *V* and *n*, it is a two-dimensional surface.

For example, if two systems of ideal gases are in equilibrium, then $P_1V_1/N_1 = P_2V_2/N_2$ where P_i is the pressure in the *i*th system, V_i is the volume, and N_i is the amount (in moles, or simply the number of atoms) of gas.

The surface *PV*/*N* = *const* defines surfaces of equal temperature, and one may label defining *T* so that *PV*/*N* = *RT*, where *R* is some constant. These systems can now be used as a thermometer to calibrate other systems.

History

The zeroth law of thermodynamics was first stated and named by Ralph H. Fowler in 1931. This law is arguably the most fundamental of the four numbered laws of thermodynamics. It was called the zeroth law because the need to state it explicitly was not understood until after the first, second, and third laws had been named and found common acceptance in the physics community.

First law

The **first law of thermodynamics** is an expression of the principle of conservation of energy.

The law expresses that energy can be transformed, i.e. changed from one form to another, but cannot be created nor destroyed. It is usually formulated by stating that the change in the internal energy of a system is equal to the amount of heat supplied to the system, minus the amount of work performed by the system on its surroundings.

Classical statement

The first explicit statement of the first law of thermodynamics was given by Rudolf Clausius in 1850:

> "*There is a state function E, called 'energy', whose differential equals the work exchanged with the surroundings during an adiabatic process.*"

Description

The first law of thermodynamics says that energy is conserved in any process involving a thermodynamic system and its surroundings. Frequently it is convenient to focus on changes in the assumed internal energy (U) and to regard them as due to a combination of heat (Q) added to the system and work done by the system (W). Taking dU as an infinitesimal (differential) change in internal energy, one writes

$$dU = \delta Q - \delta W$$

where δQ and δW are infinitesimal amounts of heat supplied to the system and work done by the system, respectively. Note that the minus sign in front of δW indicates that a positive amount of work done by the system leads to energy being lost from the system.

When a system expands in a quasistatic process, the work done on the environment is the product of pressure (P) and volume (V) change, i.e. PdV, whereas the work done on the system is $-PdV$. The change in internal energy of the system is:

$$dU = \delta Q - PdV.$$

Work and heat are due to processes which add or subtract energy, while *U* is a particular form of energy associated with the system. Thus the term heat for δ*Q* means that amount of energy added as the result of heating, rather than referring to a particular form of energy. Likewise, work energy for δ*w* means "that amount of energy lost as the result of work". Internal energy is a property of the system whereas work done and heat supplied are not. A significant result of this distinction is that a given internal energy change (dU) can be achieved by, in principle, many combinations of heat and work.

Informally, the law was first formulated by Germain Hess via Hess's Law, and later by Julius Robert von Mayer

Adiabatic processes

The classical statement of the first law of thermodynamics is induced from empirical evidence. It can be observed that given a system in an initial state, if work is exerted on the system in an adiabatic (i.e. thermally insulated) way, the final state is the same for a given amount of work, irrespective of how this work is performed.

For instance, in Joule's experiment, the initial system is a tank of water with a paddle wheel inside. If we isolate thermally the tank and move the paddle wheel with a pulley and a weight we can relate the increase in temperature with the height descended by the mass. Now the system is returned to its initial state, isolated again, and the same amount of work is done on the tank using different devices (an electric motor, a chemical battery, a spring,...). In every case, the amount of work can be measured independently. The evidence shows that the final state of the water (in particular, its temperature) is the same in every case. It's irrelevant if the work is electrical, mechanical, chemical,... or if done suddenly or slowly, as long as it is performed in an adiabatic way.

This evidence leads to the classical statement of the first law of thermodynamics

> *For all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process.*

This affirmation of path independence allows to define a state function, named *internal energy*, *U*, as the adiabatic work necessary to go from a reference state to a given one

$$U(A) = U(O) + \tilde{W}^{\mathrm{ad}}_{O\to A}$$

where, following IUPAC convention we take as positive the work done on the system.

To go from a state A to a state B we can take a path that goes through the reference state, since the adiabatic work is independent of the path

$$\tilde{W}^{\mathrm{ad}}_{A\to B} = \tilde{W}^{\mathrm{ad}}_{A\to O} + \tilde{W}^{\mathrm{ad}}_{O\to B} = -\tilde{W}^{\mathrm{ad}}_{O\to A} + \tilde{W}^{\mathrm{ad}}_{O\to B} = -U(A) + U(B) = \Delta U$$

In particular, if no work is exerted on a thermally isolated system we have

$$\Delta U = 0$$

or, in words,

The internal energy of an isolated system remains constant.

This is the law of conservation of energy.

Diabatic processes

When the system does not evolve adiabatically, it is observed that the work exerted on the system does not coincide with the increase in its internal energy, which, being a state function, can be used for both adiabatic and non-adiabatic processes.

$$\tilde{W} \neq \Delta U$$

The difference is interpreted in terms of the heat that enters the system, so the inequality can be transformed in an equality as

$$\tilde{W} + Q = \Delta U$$

This is the usual expression the first law of thermodynamics. The inclusion of an unknown term (heat) does not transform it in a tautology, since its real physical content lies in the fact that there exists a state function that can be calculated independently of heat and work.

State functional formulation

The infinitesimal heat and work in the equations above are denoted by δ, rather than exact differentials denoted by *d*, because they do not describe the *state* of any system. The integral of an inexact differential depends upon the particular path taken through the space of thermodynamic parameters while the integral of an exact differential depends only upon the initial and final states. If the initial and final states are the same, then the integral of an inexact differential may or may not be zero, but the integral of an exact differential will always be zero. The path taken by a thermodynamic system through a chemical or physical change is known as a thermodynamic process.

An expression of the first law can be written in terms of exact differentials by realizing that the work that a system does is, in case of a reversible process, equal to its pressure times the infinitesimal change in its volume. In other words $\delta w = PdV$ where P is pressure and V is volume. Also, for a reversible process, the total amount of heat added to a system can be expressed as $\delta Q = TdS$ where T is temperature and S is entropy. Therefore, for a reversible process:

$$dU = TdS - PdV.$$

Since U, S and V are thermodynamic functions of state, the above relation holds also for non-reversible changes. The above equation is known as the fundamental thermodynamic relation.

In the case where the number of particles in the system is not necessarily constant and may be of different types, the first law is written:

$$dU = \delta Q - \delta W + \sum_i \mu_i dN_i$$

where dN_i is the (small) number of type-i particles added to the system, and μ_i is the amount of energy added to the system when one type-i particle is added, where the energy of that particle is such that the volume and entropy of the system remains unchanged. μ_i is known as the chemical potential of the type-i particles in the system. The statement of the first law, using exact differentials is now:

$$dU = TdS - PdV + \sum_i \mu_i dN_i.$$

If the system has more external variables than just the volume that can change, the fundamental thermodynamic relation generalizes to:

$$dU = TdS - \sum_i X_i dx_i + \sum_j \mu_j dN_j.$$

Here the X_i are the generalized forces corresponding to the external variables x_i.

A useful idea from mechanics is that the energy gained by a particle is equal to the force applied to the particle multiplied by the displacement of the particle while that force is applied. Now consider the first law without the heating term: $dU = -PdV$. The pressure P can be viewed as a force (and in fact has units of force per unit area) while dV is the displacement (with units of distance times area). We may say, with respect to this work term, that a pressure difference forces a transfer of volume, and that the product of the two (work) is the amount of energy transferred as a result of the process.

It is useful to view the TdS term in the same light: With respect to this heat term, a temperature difference forces a transfer of entropy and the product of the two (heat) is the amount of energy transferred as a result of the process. Here, the temperature is known as a "generalized" force (rather than an actual mechanical force) and the entropy is a generalized displacement.

Similarly, a difference in chemical potential between groups of particles in the system forces a transfer of particles, and the corresponding product is the amount of energy transferred as a result of the process. For example, consider a system consisting of two phases: liquid water and water vapor. There is a generalized "force" of evaporation which drives water molecules out of the liquid. There is a generalized "force" of condensation which drives vapor molecules out of the vapor. Only when these two "forces" (or chemical potentials) are equal will there be equilibrium, and the net transfer will be zero.

The two thermodynamic parameters which form a generalized force-displacement pair are termed "conjugate variables". The two most familiar pairs are, of course, pressure-volume, and temperature-entropy.

Second law

The second law of thermodynamics may be summarized as follows:

When two isolated systems in separate but nearby regions of space, each in thermodynamic equilibrium in itself, but not in equilibrium with each other at first, are at some time allowed to interact, breaking the isolation that separates the two systems, and they exchange matter or energy, they will eventually reach a mutual thermodynamic equilibrium. The sum of the entropies of the initial, isolated systems is less than or equal to the entropy of the final exchanging systems. In the process of reaching a new thermodynamic equilibrium, entropy has increased, or at least has not decreased.

The second law states that spontaneous natural processes increase entropy overall, or in another formulation that heat can spontaneously flow only from a higher-temperature region to a lower-temperature region, but not the other way around. Entropy is increased also by processes of mixing without transfer of heat.

The second law defines entropy, which may be described as a measure of ignorance or uncertainty of the microscopic details of the motion and configuration of the system given only predictable reproducibility of bulk or macroscopic behavior. For example, one has less knowledge about the separate fragments of a broken cup than about an intact cup, because when the fragments are separated, one does not know exactly whether they will fit together again, or whether perhaps there is a missing shard. Crystals, the most regularly structured form of matter, with considerable predictability of microscopic configuration, as well as predictability of bulk behavior, have small values of entropy; and gases, which behave predictably in bulk even when their microscopic motions are unknown, have high entropy.

The entropy of an isolated macroscopic system never decreases. However, a microscopic system may exhibit fluctuations of entropy opposite to that stated by the second law.

Third law

The third law of thermodynamics is usually stated as follows:

As temperature approaches absolute zero, the entropy of a system approaches a minimum.

The third law of thermodynamics is a statistical law of nature regarding entropy:

> The entropy of a perfect crystal approaches zero as the absolute temperature approaches zero.

For other materials, the residual entropy is not necessarily zero,

History

The third law was developed by the chemist Walther Nernst during the years 1906-1912, and is therefore often referred to as **Nernst's theorem** or **Nernst's postulate**. The third law of thermodynamics states that the entropy of a system at absolute zero is a well-defined constant. This is because a system at zero temperature exists in its ground state, so that its entropy is determined only by the degeneracy of the ground state. It means that "*it is impossible by any procedure, no matter how idealised, to reduce any system to the absolute zero of temperature in a finite number of operations*".

An alternative version of the third law of thermodynamics as stated by Gilbert N. Lewis and Merle Randall in 1923:

> *If the entropy of each element in some (perfect) crystalline state be taken as zero at the absolute zero of temperature, every substance has a finite positive entropy; but at the absolute zero of temperature the entropy may become zero, and does so become in the case of perfect crystalline substances.*

This version states not only ΔS will reach zero at 0 kelvins, but S itself will also reach zero as long as the crystal has a ground state with only one configuration. Some crystals form defects which causes a residual entropy. This residual entropy disappears when the kinetic barriers to transitioning to one ground state are overcome.

With the development of statistical mechanics, the third law of thermodynamics (like the other laws) changed from a *fundamental* law (justified by experiments) to a *derived* law (derived from even more basic laws). The basic law from which it is primarily derived is the statistical-mechanics definition of entropy for a large system:

$$S = k_B \log \Omega$$

where S is entropy, k_B is the Boltzmann constant, and Ω is the number of microstates consistent with the macroscopic configuration.

Overview

In simple terms, the third law states that the entropy of a perfect crystal approaches zero as the absolute temperature approaches zero. This law provides an absolute reference point for the determination of entropy. The entropy determined relative to this point is the absolute entropy.

The entropy of a *perfect* crystal lattice as defined by Nernst's theorem is zero (provided that its ground state is unique, whereby ln(1)k = 0).

An example of a system which does not have a unique ground state is one containing half-integer spins, for which time-reversal symmetry gives two degenerate ground states (an entropy of ln(2) k, which is negligible on a macroscopic scale). Some crystalline systems exhibit geometrical frustration, where the structure of the crystal lattice prevents the emergence of a unique ground state. Ground-state helium (unless under pressure) remains liquid.

In addition, glasses and solid solutions retain large entropy at 0K, because they are large collections of nearly degenerate states, in which they become trapped out of equilibrium. Another example of a solid with many nearly-degenerate ground states, trapped out of equilibrium, is ice Ih, which has "proton disorder".

For the third law to apply strictly, the magnetic moments of a perfectly ordered crystal must themselves be perfectly ordered; indeed, from an entropic perspective, this can be considered to be part of the definition of "perfect crystal". Only ferromagnetic, antiferromagnetic, and diamagnetic materials can satisfy this condition. Materials that remain paramagnetic at 0K, by contrast, may have many nearly-degenerate ground states (for example, in a spin glass), or may retain dynamic disorder (a spin liquid).

History

Philosophers of science have argued that the concept of energy and its transformation were expressed already by Aristotle. In the modern era, the historically first established thermodynamic principle which eventually became the second law of thermodynamics was formulated by Sadi Carnot during 1824. By 1860, as formalized in the works of those such as Rudolf Clausius and William Thomson, two established principles of thermodynamics had evolved, the first principle and the second principle, later restated as thermodynamic laws. By 1873, for example, thermodynamicist Josiah Willard Gibbs, in his memoir *Graphical Methods in the Thermodynamics of Fluids*, clearly stated the first two absolute laws of thermodynamics. Some textbooks throughout the 20th century have numbered the laws differently. In some fields removed from chemistry, the second law was considered to deal with the efficiency of heat engines only, whereas what was called the third law dealt with entropy increases. Directly defining zero points for entropy calculations was not considered to be a law. Gradually, this separation was combined into the second law and the modern third law was widely adopted.

Chapter- 3

Fluid Mechanics

Fluid mechanics is the study of fluids and the forces on them. (Fluids include liquids, gases, and plasmas.) Fluid mechanics can be divided into fluid kinematics, the study of fluid motion, and fluid dynamics, the study of the effect of forces on fluid motion, which can further be divided into fluid statics, the study of fluids at rest, and fluid kinetics, the study of fluids in motion. It is a branch of continuum mechanics, a subject which models matter without using the information that it is made out of atoms, that is, it models matter from a macroscopic viewpoint rather than from a microscopic viewpoint. Fluid mechanics, especially fluid dynamics, is an active field of research with many unsolved or partly solved problems. Fluid mechanics can be mathematically complex. Sometimes it can best be solved by numerical methods, typically using computers. A modern discipline, called computational fluid dynamics (CFD), is devoted to this approach to solving fluid mechanics problems. Also taking advantage of the highly visual nature of fluid flow is particle image velocimetry, an experimental method for visualizing and analyzing fluid flow.

Brief history

The study of fluid mechanics goes back at least to the days of ancient Greece, when Archimedes investigated fluid statics and buoyancy and formulated his famous law known now as the Archimedes Principle. Rapid advancement in fluid mechanics began with Leonardo da Vinci (observation and experiment), Evangelista Torricelli (barometer), Isaac Newton (viscosity) and Blaise Pascal (hydrostatics), and was continued by Daniel Bernoulli with the introduction of mathematical fluid dynamics in *Hydrodynamica* (1738). Inviscid flow was further analyzed by various mathematicians (Leonhard Euler, d'Alembert, Lagrange, Laplace, Poisson) and viscous flow was explored by a multitude of engineers including Poiseuille and Gotthilf Heinrich Ludwig Hagen. Further mathematical justification was provided by Claude-Louis Navier and George Gabriel Stokes in the Navier–Stokes equations, and boundary layers were investigated (Ludwig Prandtl), while various scientists (Osborne Reynolds, Andrey Kolmogorov, Geoffrey Ingram Taylor) advanced the understanding of fluid viscosity and turbulence.

Relationship to continuum mechanics

Fluid mechanics is a subdiscipline of continuum mechanics, as illustrated in the following table.

<table>
<tr><td rowspan="4">Continuum mechanics
The study of the physics of continuous materials</td><td rowspan="2">Solid mechanics
The study of the physics of continuous materials with a defined rest shape.</td><td colspan="2">Elasticity
Describes materials that return to their rest shape after an applied stress.</td></tr>
<tr><td>Plasticity
Describes materials that permanently deform after a sufficient applied stress.</td><td rowspan="2">Rheology
The study of materials with both solid and fluid characteristics.</td></tr>
<tr><td rowspan="2">Fluid mechanics
The study of the physics of continuous materials which take the shape of their container.</td><td>Non-Newtonian fluids</td></tr>
<tr><td colspan="2">Newtonian fluids</td></tr>
</table>

In a mechanical view, a fluid is a substance that does not support shear stress; that is why a fluid at rest has the shape of its containing vessel. A fluid at rest has no shear stress.

Assumptions

Like any mathematical model of the real world, fluid mechanics makes some basic assumptions about the materials being studied. These assumptions are turned into equations that must be satisfied if the assumptions are to be held true. For example, consider an incompressible fluid in three dimensions. The assumption that mass is conserved means that for any fixed closed surface (such as a sphere) the rate of mass passing from *outside* to *inside* the surface must be the same as rate of mass passing the other way. (Alternatively, the mass *inside* remains constant, as does the mass *outside*). This can be turned into an integral equation over the surface.

Fluid mechanics assumes that every fluid obeys the following:

- Conservation of mass
- Conservation of energy
- Conservation of momentum
- The *continuum hypothesis*, detailed below.

Further, it is often useful (at subsonic conditions) to assume a fluid is incompressible – that is, the density of the fluid does not change. Liquids can often be modelled as incompressible fluids, whereas gases cannot.

Similarly, it can sometimes be assumed that the viscosity of the fluid is zero (the fluid is *inviscid*). Gases can often be assumed to be inviscid. If a fluid is viscous, and its flow contained in some way (e.g. in a pipe), then the flow at the boundary must have zero velocity. For a viscous fluid, if the boundary is not porous, the shear forces between the fluid and the boundary results also in a zero velocity for the fluid at the boundary. This is called the no-slip condition. For a porous media otherwise, in the frontier of the containing vessel, the slip condition is not zero velocity, and the fluid has a discontinuous velocity field between the free fluid and the fluid in the porous media (this is related to the Beavers and Joseph condition).

The continuum hypothesis

Fluids are composed of molecules that collide with one another and solid objects. The continuum assumption, however, considers fluids to be continuous. That is, properties such as density, pressure, temperature, and velocity are taken to be well-defined at "infinitely" small points, defining a REV (Reference Element of Volume), at the geometric order of the distance between two adjacent molecules of fluid. Properties are assumed to vary continuously from one point to another, and are averaged values in the REV. The fact that the fluid is made up of discrete molecules is ignored.

The continuum hypothesis is basically an approximation, in the same way planets are approximated by point particles when dealing with celestial mechanics, and therefore results in approximate solutions. Consequently, assumption of the continuum hypothesis can lead to results which are not of desired accuracy. That said, under the right circumstances, the continuum hypothesis produces extremely accurate results.

Those problems for which the continuum hypothesis does not allow solutions of desired accuracy are solved using statistical mechanics. To determine whether or not to use conventional fluid dynamics or statistical mechanics, the Knudsen number is evaluated for the problem. The Knudsen number is defined as the ratio of the molecular mean free path length to a certain representative physical length scale. This length scale could be, for example, the radius of a body in a fluid. (More simply, the Knudsen number is how many times its own diameter a particle will travel on average before hitting another particle). Problems with Knudsen numbers at or above unity are best evaluated using statistical mechanics for reliable solutions.

Navier–Stokes equations

The **Navier–Stokes equations** (named after Claude-Louis Navier and George Gabriel Stokes) are the set of equations that describe the motion of fluid substances such as liquids and gases. These equations state that changes in momentum (force) of fluid particles depend only on the external pressure and internal viscous forces (similar to friction) acting on the fluid. Thus, the Navier–Stokes equations describe the balance of forces acting at any given region of the fluid.

The Navier–Stokes equations are differential equations which describe the motion of a fluid. Such equations establish relations among the rates of change of the variables of interest. For example, the Navier–Stokes equations for an ideal fluid with zero viscosity states that acceleration (the rate of change of velocity) is proportional to the derivative of internal pressure.

This means that solutions of the Navier–Stokes equations for a given physical problem must be sought with the help of calculus. In practical terms only the simplest cases can be solved exactly in this way. These cases generally involve non-turbulent, steady flow (flow does not change with time) in which the Reynolds number is small.

For more complex situations, such as global weather systems like El Niño or lift in a wing, solutions of the Navier–Stokes equations can currently only be found with the help of computers. This is a field of sciences by its own called computational fluid dynamics.

General form of the equation

The general form of the Navier–Stokes equations for the conservation of momentum is:

$$\rho\frac{D\mathbf{v}}{Dt} = \nabla\cdot\mathbb{P} + \rho\mathbf{f}$$

where

- ρ is the fluid density,
- $\frac{D}{Dt}$ is the substantive derivative (also called the material derivative),
- $\mathbf{v}$ is the velocity vector,
- $\mathbf{f}$ is the body force vector, and
- $\mathbb{P}$ is a tensor that represents the surface forces applied on a fluid particle (the stress tensor).

Unless the fluid is made up of spinning degrees of freedom like vortices, $\mathbb{P}$ is a symmetric tensor. In general, (in three dimensions) $\mathbb{P}$ has the form:

$$\mathbb{P} = \begin{pmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{pmatrix}$$

where

- σ are normal stresses,
- τ are tangential stresses (shear stresses).

The above is actually a set of three equations, one per dimension. By themselves, these aren't sufficient to produce a solution. However, adding conservation of mass and appropriate boundary conditions to the system of equations produces a solvable set of equations.

Newtonian versus non-Newtonian fluids

A **Newtonian fluid** (named after Isaac Newton) is defined to be a fluid whose shear stress is linearly proportional to the velocity gradient in the direction perpendicular to the plane of shear. This definition means regardless of the forces acting on a fluid, it *continues to flow*. For example, water is a Newtonian fluid, because it continues to display fluid properties no matter how much it is stirred or mixed. A slightly less rigorous definition is that the drag of a small object being moved slowly through the fluid is proportional to the force applied to the object. (Compare friction). Important fluids, like water as well as most gases, behave — to good approximation — as a Newtonian fluid under normal conditions on Earth.

By contrast, stirring a non-Newtonian fluid can leave a "hole" behind. This will gradually fill up over time – this behaviour is seen in materials such as pudding, oobleck, or sand (although sand isn't strictly a fluid). Alternatively, stirring a non-Newtonian fluid can cause the viscosity to decrease, so the fluid appears "thinner" (this is seen in non-drip paints). There are many types of non-Newtonian fluids, as they are defined to be something that fails to obey a particular property — for example, most fluids with long molecular chains can react in a non-Newtonian manner.

Equations for a Newtonian fluid

The constant of proportionality between the shear stress and the velocity gradient is known as the viscosity. A simple equation to describe Newtonian fluid behaviour is

$$\tau = -\mu \frac{dv}{dy}$$

where

τ is the shear stress exerted by the fluid ("drag")
μ is the fluid viscosity – a constant of proportionality
$\frac{dv}{dy}$ is the velocity gradient perpendicular to the direction of shear.

For a Newtonian fluid, the viscosity, by definition, depends only on temperature and pressure, not on the forces acting upon it. If the fluid is incompressible and viscosity is constant across the fluid, the equation governing the shear stress (in Cartesian coordinates) is

$$\tau_{ij} = \mu \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right)$$

where

τ_{ij} is the shear stress on the i^{th} face of a fluid element in the j^{th} direction
v_i is the velocity in the i^{th} direction
x_j is the j^{th} direction coordinate.

If a fluid does not obey this relation, it is termed a non-Newtonian fluid, of which there are several types.

Among fluids, two rough broad divisions can be made: ideal and non-ideal fluids. An ideal fluid really does not exist, but in some calculations, the assumption is justifiable. An Ideal fluid is non viscous- offers no resistance whatsoever to a shearing force.

One can group real fluids into Newtonian and non-Newtonian. Newtonian fluids agree with Newton's law of viscosity. Non-Newtonian fluids can be either plastic, bingham plastic, pseudoplastic, dilatant, thixotropic, rheopectic, viscoelatic.

Chapter- 4

Navier–Stokes Equations

In physics the **Navier–Stokes equations**, named after Claude-Louis Navier and George Gabriel Stokes, describe the motion of fluid substances. These equations arise from applying Newton's second law to fluid motion, together with the assumption that the fluid stress is the sum of a diffusing viscous term (proportional to the gradient of velocity), plus a pressure term.

The equations are useful because they describe the physics of many things of academic and economic interest. They may be used to model the weather, ocean currents, water flow in a pipe and air flow around a wing. The Navier–Stokes equations in their full and simplified forms help with the design of aircraft and cars, the study of blood flow, the design of power stations, the analysis of pollution, and many other things. Coupled with Maxwell's equations they can be used to model and study magnetohydrodynamics.

The Navier–Stokes equations are also of great interest in a purely mathematical sense. Somewhat surprisingly, given their wide range of practical uses, mathematicians have not yet proven that in three dimensions solutions always exist (existence), or that if they do exist, then they do not contain any singularity (smoothness). These are called the Navier–Stokes existence and smoothness problems. The Clay Mathematics Institute has called this one of the seven most important open problems in mathematics and has offered a US$1,000,000 prize for a solution or a counter-example.

The Navier–Stokes equations dictate not position but rather velocity. A solution of the Navier–Stokes equations is called a velocity field or flow field, which is a description of the velocity of the fluid at a given point in space and time. Once the velocity field is solved for, other quantities of interest (such as flow rate or drag force) may be found. This is different from what one normally sees in classical mechanics, where solutions are typically trajectories of position of a particle or deflection of a continuum. Studying velocity instead of position makes more sense for a fluid; however for visualization purposes one can compute various trajectories.

Properties

Nonlinearity

The Navier–Stokes equations are nonlinear partial differential equations in almost every real situation. In some cases, such as one-dimensional flow and Stokes flow (or creeping flow), the equations can be simplified to linear equations. The nonlinearity makes most problems difficult or impossible to solve and is the main contributor to the turbulence that the equations model.

The nonlinearity is due to convective acceleration, which is an acceleration associated with the change in velocity over position. Hence, any convective flow, whether turbulent or not, will involve nonlinearity. An example of convective but laminar (nonturbulent) flow would be the passage of a viscous fluid (for example, oil) through a small converging nozzle. Such flows, whether exactly solvable or not, can often be thoroughly studied and understood.

Turbulence

Turbulence is the time dependent chaotic behavior seen in many fluid flows. It is generally believed that it is due to the inertia of the fluid as a whole: the culmination of time dependent and convective acceleration; hence flows where inertial effects are small tend to be laminar (the Reynolds number quantifies how much the flow is affected by inertia). It is believed, though not known with certainty, that the Navier–Stokes equations describe turbulence properly.

The numerical solution of the Navier–Stokes equations for turbulent flow is extremely difficult, and due to the significantly different mixing-length scales that are involved in turbulent flow, the stable solution of this requires such a fine mesh resolution that the computational time becomes significantly infeasible for calculation. Attempts to solve turbulent flow using a laminar solver typically result in a time-unsteady solution, which fails to converge appropriately. To counter this, time-averaged equations such as the Reynolds-averaged Navier-Stokes equations (RANS), supplemented with turbulence models (such as the k-ε model), are used in practical computational fluid dynamics (CFD) applications when modeling turbulent flows. Another technique for solving numerically the Navier–Stokes equation is the Large eddy simulation (LES). This approach is computationally more expensive than the RANS method (in time and computer memory), but produces better results since the larger turbulent scales are explicitly resolved.

Applicability

Together with supplemental equations (for example, conservation of mass) and well formulated boundary conditions, the Navier–Stokes equations seem to model fluid motion accurately; even turbulent flows seem (on average) to agree with real world observations.

The Navier–Stokes equations assume that the fluid being studied is a continuum not moving at relativistic velocities. At very small scales or under extreme conditions, real fluids made out of discrete molecules will produce results different from the continuous fluids modeled by the Navier–Stokes equations. Depending on the Knudsen number of the problem, statistical mechanics or possibly even molecular dynamics may be a more appropriate approach.

Another limitation is very simply the complicated nature of the equations. Time tested formulations exist for common fluid families, but the application of the Navier–Stokes equations to less common families tends to result in very complicated formulations which are an area of current research. For this reason, these equations are usually written for Newtonian fluids. Studying such fluids is "simple" because the viscosity model ends up being linear; truly general models for the flow of other kinds of fluids (such as blood) do not, as of 2011, exist.

Derivation and description

The derivation of the Navier–Stokes equations begins with an application of Newton's second law: conservation of momentum (often alongside mass and energy conservation) being written for an arbitrary portion of the fluid. In an inertial frame of reference, the general form of the equations of fluid motion is:

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p + \nabla \cdot \mathbb{T} + \mathbf{f},$$

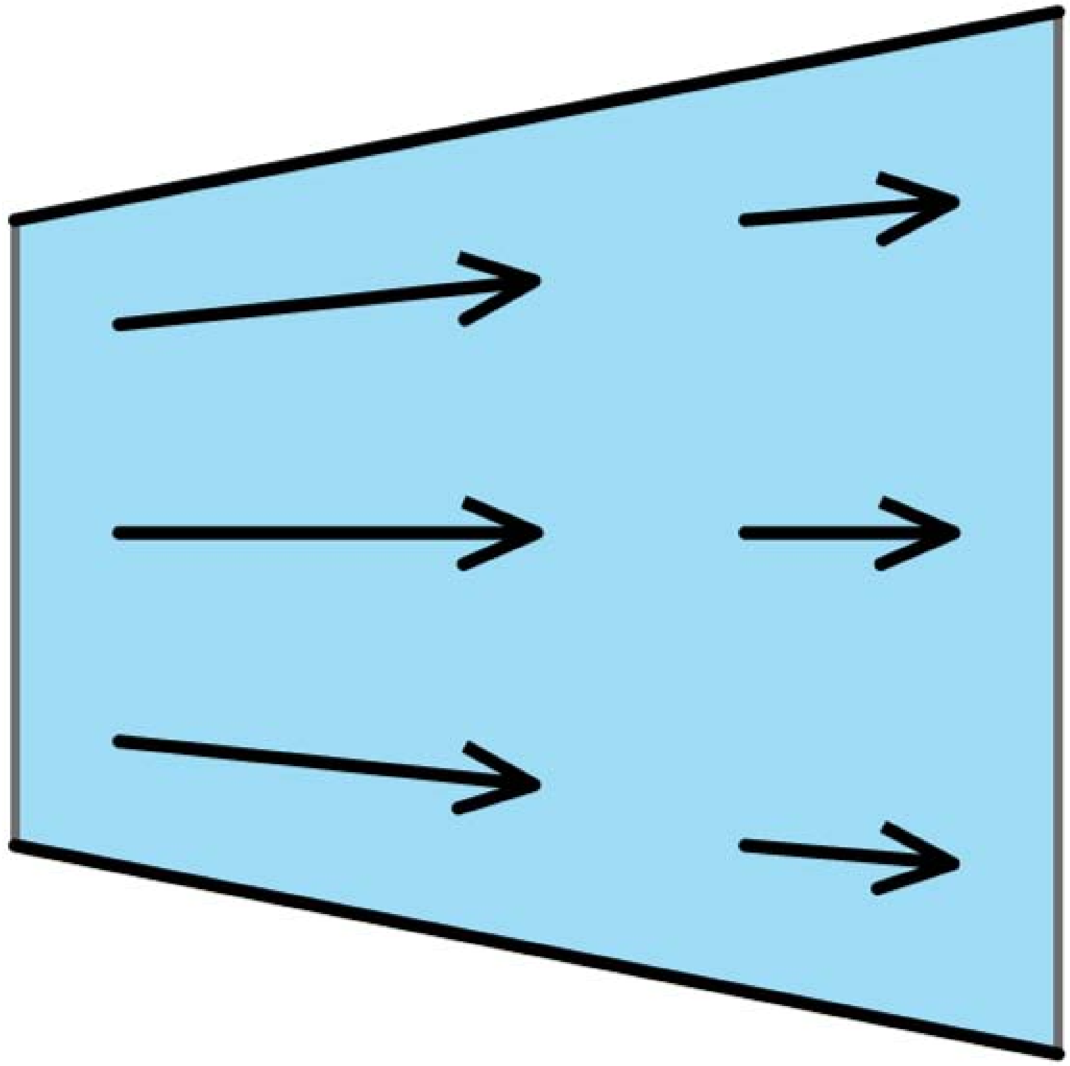
where $\mathbf{v}$ is the flow velocity, ρ is the fluid density, *p* is the pressure, $\mathbb{T}$ is the (deviatoric) stress tensor, and $\mathbf{f}$ represents body forces (per unit volume) acting on the fluid and ∇ is the del operator. This is a statement of the conservation of momentum in a fluid and it is an application of Newton's second law to a continuum; in fact this equation is applicable to any non-relativistic continuum and is known as the Cauchy momentum equation.

This equation is often written using the substantive derivative $D\mathbf{v}/Dt$, making it more apparent that this is a statement of Newton's second law:

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \nabla \cdot \mathbb{T} + \mathbf{f}.$$

The left side of the equation describes acceleration, and may be composed of time dependent or convective effects (also the effects of non-inertial coordinates if present). The right side of the equation is in effect a summation of body forces (such as gravity) and divergence of stress (pressure and shear stress).

Convective acceleration



An example of convection. Though the flow may be steady (time independent), the fluid decelerates as it moves down the diverging duct (assuming incompressible flow), hence there is an acceleration happening over position.

A very significant feature of the Navier–Stokes equations is the presence of convective acceleration: the effect of time independent acceleration of a fluid with respect to space. While individual fluid particles are indeed experiencing time dependent acceleration, the convective acceleration of the flow field is a spatial effect, one example being fluid speeding up in a nozzle. Convective acceleration is represented by the nonlinear quantity:

$$\mathbf{v} \cdot \nabla \mathbf{v},$$

which may be interpreted either as $(\mathbf{v} \cdot \nabla) \mathbf{v}$ or as $\mathbf{v} \cdot (\nabla \mathbf{v})$, with $\nabla \mathbf{v}$ the tensor derivative of the velocity vector $\mathbf{v}$. Both interpretations give the same result, independent of the coordinate system — provided ∇ is interpreted as the covariant derivative.

Interpretation as (v·∇)v

The convection term is often written as

$$(\mathbf{v} \cdot \nabla)\mathbf{v},$$

where the advection operator $\mathbf{v} \cdot \nabla$ is used. Usually this representation is preferred because it is simpler than the one in terms of the tensor derivative $\nabla \mathbf{v}$.

Interpretation as v·(∇v)

Here $\nabla \mathbf{v}$ is the tensor derivative of the velocity vector, equal in Cartesian coordinates to the component by component gradient. The convection term may, by a vector calculus identity, be expressed without a tensor derivative:

$$\mathbf{v} \cdot \nabla \mathbf{v} = \nabla \left(\frac{\|\mathbf{v}\|^2}{2} \right) + (\nabla \times \mathbf{v}) \times \mathbf{v}.$$

The form has use in irrotational flow, where the curl of the velocity (called vorticity) $\omega = \nabla \times \mathbf{v}$ is equal to zero.

Regardless of what kind of fluid is being dealt with, convective acceleration is a nonlinear effect. Convective acceleration is present in most flows (exceptions include one-dimensional incompressible flow), but its dynamic effect is disregarded in creeping flow (also called Stokes flow).

Stresses

The effect of stress in the fluid is represented by the ∇p and $\nabla \cdot \mathbb{T}$ terms; these are gradients of surface forces, analogous to stresses in a solid. ∇p is called the pressure gradient and arises from the isotropic part of the stress tensor. This part is given by normal stresses that turn up in almost all situations, dynamic or not. The anisotropic part of the stress tensor gives rise to $\nabla \cdot \mathbb{T}$, which conventionally describes viscous forces; for incompressible flow, this is only a shear effect. Thus, $\mathbb{T}$ is the deviatoric stress tensor, and the stress tensor is equal to:

$$\sigma = -p\mathbb{I} + \mathbb{T}$$

where $\mathbb{I}$ is the 3×3 identity matrix. Interestingly, only the *gradient* of pressure matters, not the pressure itself. The effect of the pressure gradient is that fluid flows from high pressure to low pressure.

The stress terms *p* and $\mathbb{T}$ are yet unknown, so the general form of the equations of motion is not usable to solve problems. Besides the equations of motion—Newton's second law—a force model is needed relating the stresses to the fluid motion. For this reason, assumptions on the specific behavior of a fluid are made (based on natural observations) and applied in order to specify the stresses in terms of the other flow variables, such as velocity and density.

The Navier–Stokes equations result from the following assumptions on the deviatoric stress tensor $\mathbb{T}$:

- the deviatoric stress vanishes for a fluid at rest, and – by Galilean invariance – also does not depend directly on the flow velocity itself, but only on spatial derivatives of the flow velocity
- in the Navier–Stokes equations, the deviatoric stress is expressed as the product of the tensor gradient $\nabla\mathbf{v}$ of the flow velocity with a viscosity tensor $\mathbb{A}$, i.e.: $\mathbb{T} = \mathbb{A}\left(\nabla\mathbf{v}\right)$
- the fluid is assumed to be isotropic, as valid for gases and simple liquids, and consequently $\mathbb{A}$ is an isotropic tensor; furthermore, since the deviatoric stress tensor is symmetric, it turns out that it can be expressed in terms of two scalar dynamic viscosities μ and μ”: $\mathbb{T} = 2\mu\mathbb{E} + \mu''\Delta\mathbb{I}$, where $\mathbb{E} = \frac{1}{2}\left(\nabla\mathbf{v}\right) + \frac{1}{2}\left(\nabla\mathbf{v}\right)^{\mathrm{T}}$ is the rate-of-strain tensor and $\Delta = \nabla\cdot\mathbf{v}$ is the rate of expansion of the flow
- the deviatoric stress tensor has zero trace, so for a three-dimensional flow $2\mu + 3\mu'' = 0$

As a result, in the Navier–Stokes equations the deviatoric stress tensor has the following form:

$$\mathbb{T} = 2\mu\left(\mathbb{E} - \tfrac{1}{3}\Delta\mathbb{I}\right),$$

with the quantity between brackets the non-isotropic part of the rate-of-strain tensor $\mathbb{E}$. The dynamic viscosity μ does not need to be constant – in general it depends on conditions like temperature and pressure, and in turbulence modelling the concept of eddy viscosity is used to approximate the average deviatoric stress.

The pressure *p* is modelled by use of an equation of state. For the special case of an incompressible flow, the pressure constrains the flow in such a way that the volume of fluid elements is constant: isochoric flow resulting in a solenoidal velocity field with $\nabla\cdot\mathbf{v}=0$.

Other forces

The vector field $\mathbf{f}$ represents body forces. Typically these consist of only gravity forces, but may include other types (such as electromagnetic forces). In a non-inertial coordinate system, other "forces" such as that associated with rotating coordinates may be inserted.

Often, these forces may be represented as the gradient of some scalar quantity. Gravity in the z direction, for example, is the gradient of $-\rho g z$. Since pressure shows up only as a gradient, this implies that solving a problem without any such body force can be mended to include the body force by modifying pressure.

Other equations

The Navier–Stokes equations are strictly a statement of the conservation of momentum. In order to fully describe fluid flow, more information is needed (how much depends on the assumptions made), this may include boundary data (no-slip, capillary surface, etc.), the conservation of mass, the conservation of energy, and/or an equation of state.

Regardless of the flow assumptions, a statement of the conservation of mass is generally necessary. This is achieved through the mass continuity equation, given in its most general form as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

or, using the substantive derivative:

$$\frac{D\rho}{Dt} + \rho(\nabla \cdot \mathbf{v}) = 0.$$

Incompressible flow of Newtonian fluids

A simplification of the resulting flow equations is obtained when considering an incompressible flow of a Newtonian fluid. The assumption of incompressibility rules out the possibility of sound or shock waves to occur; so this simplification is invalid if these phenomena are important. The incompressible flow assumption typically holds well even when dealing with a "compressible" fluid — such as air at room temperature — at low Mach numbers (even when flowing up to about Mach 0.3). Taking the incompressible flow assumption into account and assuming constant viscosity, the Navier–Stokes equations will read, in vector form:

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p + \mu \nabla^2 \mathbf{v} + \mathbf{f}.$$

Here **f** represents "other" body forces (forces per unit volume), such as gravity or centrifugal force. The shear stress term $\nabla\mathbb{T}$becomes the useful quantity $\mu\nabla^2\mathbf{v}$(∇^2 is the vector Laplacian) when the fluid is assumed incompressible, homogeneous and Newtonian, where $\mu$is the (constant) dynamic viscosity.

It's well worth observing the meaning of each term (compare to the Cauchy momentum equation):

$$\overbrace{\rho\Big(\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{\substack{\text{Unsteady}\\ \text{acceleration}}} + \underbrace{\mathbf{v}\cdot\nabla\mathbf{v}}_{\substack{\text{Convective}\\ \text{acceleration}}}\Big)}^{\text{Inertia (per volume)}} = \overbrace{\underbrace{-\nabla p}_{\substack{\text{Pressure}\\ \text{gradient}}} + \underbrace{\mu\nabla^2\mathbf{v}}_{\text{Viscosity}}}^{\text{Divergence of stress}} + \underbrace{\mathbf{f}}_{\substack{\text{Other}\\ \text{body}\\ \text{forces}}}.$$

Note that only the convective terms are nonlinear for incompressible Newtonian flow. The convective acceleration is an acceleration caused by a (possibly steady) change in velocity over *position*, for example the speeding up of fluid entering a converging nozzle. Though individual fluid particles are being accelerated and thus are under unsteady motion, the flow field (a velocity distribution) will not necessarily be time dependent.

Another important observation is that the viscosity is represented by the vector Laplacian of the velocity field (interpreted here as the difference between the velocity at a point and the mean velocity in a small volume around). This implies that Newtonian viscosity is **diffusion of momentum**, this works in much the same way as the diffusion of heat seen in the heat equation (which also involves the Laplacian).

If temperature effects are also neglected, the only "other" equation (apart from initial/boundary conditions) needed is the mass continuity equation. Under the incompressible assumption, density is a constant and it follows that the equation will simplify to:

$$\nabla\cdot\mathbf{v} = 0.$$

This is more specifically a statement of the conservation of volume.

These equations are commonly used in 3 coordinates systems: Cartesian, cylindrical, and spherical. While the Cartesian equations seem to follow directly from the vector equation above, the vector form of the Navier–Stokes equation involves some tensor calculus which means that writing it in other coordinate systems is not as simple as doing so for scalar equations (such as the heat equation).

Cartesian coordinates

Writing the vector equation explicitly,

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+\rho g_x$$
$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\rho g_y$$
$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g_z.$$

Note that gravity has been accounted for as a body force, and the values of g_x,g_y,g_z will depend on the orientation of gravity with respect to the chosen set of coordinates.

The continuity equation reads:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0.$$

When the flow is at steady-state, ρ does not change with respect to time. The continuity equation is reduced to:

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0.$$

When the flow is incompressible, ρ is constant and does not change with respect to space. The continuity equation is reduced to:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0.$$

The velocity components (the dependent variables to be solved for) are typically named *u*, *v*, *w*. This system of four equations comprises the most commonly used and studied form. Though comparatively more compact than other representations, this is still a nonlinear system of partial differential equations for which solutions are difficult to obtain.

Cylindrical coordinates

A change of variables on the Cartesian equations will yield the following momentum equations for *r*, φ, and *z*:

$$r:\ \rho\left(\frac{\partial u_r}{\partial t}+u_r\frac{\partial u_r}{\partial r}+\frac{u_\phi}{r}\frac{\partial u_r}{\partial \phi}+u_z\frac{\partial u_r}{\partial z}-\frac{u_\phi^2}{r}\right)=-\frac{\partial p}{\partial r}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_r}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 u_r}{\partial \phi^2}+\frac{\partial^2 u_r}{\partial z^2}-\frac{u_r}{r^2}-\frac{2}{r^2}\frac{\partial u_\phi}{\partial \phi}\right]+\rho g_r$$

$$\phi: \ \rho\left(\frac{\partial u_\phi}{\partial t}+u_r\frac{\partial u_\phi}{\partial r}+\frac{u_\phi}{r}\frac{\partial u_\phi}{\partial \phi}+u_z\frac{\partial u_\phi}{\partial z}+\frac{u_r u_\phi}{r}\right)=-\frac{1}{r}\frac{\partial p}{\partial \phi}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_\phi}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 u_\phi}{\partial \phi^2}+\frac{\partial^2 u_\phi}{\partial z^2}+\frac{2}{r^2}\frac{\partial u_r}{\partial \phi}-\frac{u_\phi}{r^2}\right]+\rho g_\phi$$

$$z: \ \rho\left(\frac{\partial u_z}{\partial t}+u_r\frac{\partial u_z}{\partial r}+\frac{u_\phi}{r}\frac{\partial u_z}{\partial \phi}+u_z\frac{\partial u_z}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 u_z}{\partial \phi^2}+\frac{\partial^2 u_z}{\partial z^2}\right]+\rho g_z.$$

The gravity components will generally not be constants, however for most applications either the coordinates are chosen so that the gravity components are constant or else it is assumed that gravity is counteracted by a pressure field (for example, flow in horizontal pipe is treated normally without gravity and without a vertical pressure gradient). The continuity equation is:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r u_r\right)+\frac{1}{r}\frac{\partial u_\phi}{\partial \phi}+\frac{\partial u_z}{\partial z}=0.$$

This cylindrical representation of the incompressible Navier–Stokes equations is the second most commonly seen (the first being Cartesian above). Cylindrical coordinates are chosen to take advantage of symmetry, so that a velocity component can disappear. A very common case is axisymmetric flow with the assumption of no tangential velocity ($u_\varphi = 0$), and the remaining quantities are independent of φ:

$$\rho\left(\frac{\partial u_r}{\partial t}+u_r\frac{\partial u_r}{\partial r}+u_z\frac{\partial u_r}{\partial z}\right)=-\frac{\partial p}{\partial r}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_r}{\partial r}\right)+\frac{\partial^2 u_r}{\partial z^2}-\frac{u_r}{r^2}\right]+\rho g_r$$

$$\rho\left(\frac{\partial u_z}{\partial t}+u_r\frac{\partial u_z}{\partial r}+u_z\frac{\partial u_z}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)+\frac{\partial^2 u_z}{\partial z^2}\right]+\rho g_z$$

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r u_r\right)+\frac{\partial u_z}{\partial z}=0.$$

Spherical coordinates

In spherical coordinates, the *r*, φ, and θ momentum equations are (note the convention used: θ is colatitude):

$$\rho\left(\frac{\partial u_r}{\partial t}+u_r\frac{\partial u_r}{\partial r}+\frac{u_\phi}{r\sin(\theta)}\frac{\partial u_r}{\partial \phi}+\frac{u_\theta}{r}\frac{\partial u_r}{\partial \theta}-\frac{u_\phi^2+u_\theta^2}{r}\right)=-\frac{\partial p}{\partial r}+\rho g_r+$$

$$\mu\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial u_r}{\partial r}\right)+\frac{1}{r^2\sin(\theta)^2}\frac{\partial^2 u_r}{\partial \phi^2}+\frac{1}{r^2\sin(\theta)}\frac{\partial}{\partial \theta}\left(\sin(\theta)\frac{\partial u_r}{\partial \theta}\right)-2\frac{u_r+\frac{\partial u_\theta}{\partial \theta}+u_\theta\cot(\theta)}{r^2}+\frac{2}{r^2\sin(\theta)}\frac{\partial u_\phi}{\partial \phi}\right]$$

$$\rho\left(\frac{\partial u_\phi}{\partial t}+u_r\frac{\partial u_\phi}{\partial r}+\frac{u_\phi}{r\sin(\theta)}\frac{\partial u_\phi}{\partial \phi}+\frac{u_\theta}{r}\frac{\partial u_\phi}{\partial \theta}+\frac{u_r u_\phi+u_\phi u_\theta\cot(\theta)}{r}\right)=-\frac{1}{r\sin(\theta)}\frac{\partial p}{\partial \phi}+\rho g_\phi+$$

$$\mu\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial u_\phi}{\partial r}\right)+\frac{1}{r^2\sin(\theta)^2}\frac{\partial^2 u_\phi}{\partial \phi^2}+\frac{1}{r^2\sin(\theta)}\frac{\partial}{\partial \theta}\left(\sin(\theta)\frac{\partial u_\phi}{\partial \theta}\right)+\frac{2\frac{\partial u_r}{\partial \phi}+2\cos(\theta)\frac{\partial u_\theta}{\partial \phi}-u_\phi}{r^2\sin(\theta)^2}\right]$$
$$\rho\left(\frac{\partial u_\theta}{\partial t}+u_r\frac{\partial u_\theta}{\partial r}+\frac{u_\phi}{r\sin(\theta)}\frac{\partial u_\theta}{\partial \phi}+\frac{u_\theta}{r}\frac{\partial u_\theta}{\partial \theta}+\frac{u_r u_\theta-u_\phi^2\cot(\theta)}{r}\right)=-\frac{1}{r}\frac{\partial p}{\partial \theta}+\rho g_\theta+$$
$$\mu\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial u_\theta}{\partial r}\right)+\frac{1}{r^2\sin(\theta)^2}\frac{\partial^2 u_\theta}{\partial \phi^2}+\frac{1}{r^2\sin(\theta)}\frac{\partial}{\partial \theta}\left(\sin(\theta)\frac{\partial u_\theta}{\partial \theta}\right)+\frac{2}{r^2}\frac{\partial u_r}{\partial \theta}-\frac{u_\theta+2\cos(\theta)\frac{\partial u_\phi}{\partial \phi}}{r^2\sin(\theta)^2}\right].$$

Mass continuity will read:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 u_r\right)+\frac{1}{r\sin(\theta)}\frac{\partial u_\phi}{\partial \phi}+\frac{1}{r\sin(\theta)}\frac{\partial}{\partial \theta}\left(\sin(\theta)u_\theta\right)=0.$$

These equations could be (slightly) compacted by, for example, factoring $1 / r^2$ from the viscous terms. However, doing so would undesirably alter the structure of the Laplacian and other quantities.

Stream function formulation

Taking the curl of the Navier–Stokes equation results in the elimination of pressure. This is especially easy to see if 2D Cartesian flow is assumed ($w = 0$ and no dependence of anything on z), where the equations reduce to:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+\rho g_x,$$
$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\rho g_y.$$

Differentiating the first with respect to y, the second with respect to x and subtracting the resulting equations will eliminate pressure and any conservative force. Defining the stream function ψ through

$$u=\frac{\partial \psi}{\partial y} \quad ; \quad v=-\frac{\partial \psi}{\partial x}$$

results in mass continuity being unconditionally satisfied (given the stream function is continuous), and then incompressible Newtonian 2D momentum and mass conservation degrade into one equation:

$$\frac{\partial}{\partial t}\left(\nabla^2\psi\right)+\frac{\partial \psi}{\partial y}\frac{\partial}{\partial x}\left(\nabla^2\psi\right)-\frac{\partial \psi}{\partial x}\frac{\partial}{\partial y}\left(\nabla^2\psi\right)=\nu\nabla^4\psi,$$

where ∇^4 is the (2D) biharmonic operator and ν is the kinematic viscosity, $\nu = \frac{\mu}{\rho}$. We can also express this compactly using the Jacobian determinant:

$$\frac{\partial}{\partial t}\left(\nabla^2\psi\right) + \frac{\partial\left(\psi, \nabla^2\psi\right)}{\partial\left(y, x\right)} = \nu\nabla^4\psi.$$

This single equation together with appropriate boundary conditions describes 2D fluid flow, taking only kinematic viscosity as a parameter. Note that the equation for creeping flow results when the left side is assumed zero.

In axisymmetric flow another stream function formulation, called the Stokes stream function, can be used to describe the velocity components of an incompressible flow with one scalar function.

Compressible flow of Newtonian fluids

There are some phenomena that are closely linked with fluid compressibility. One of the obvious examples is sound. Description of such phenomena requires more general presentation of the Navier–Stokes equation that takes into account fluid compressibility. If viscosity is assumed a constant, one additional term appears, as shown here:

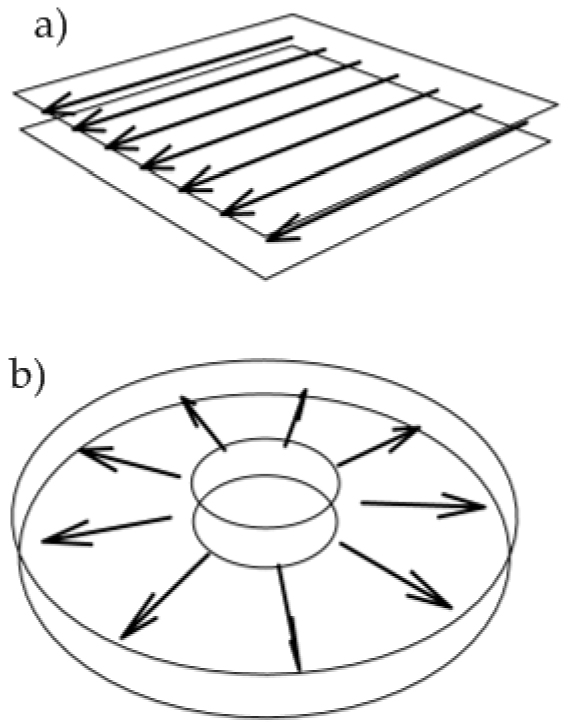
$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \mu\nabla^2\mathbf{v} + \left(\tfrac{1}{3}\mu + \mu^v\right)\nabla(\nabla\cdot\mathbf{v}) + \mathbf{f}$$

where μ^v is the volume viscosity coefficient, also known as *second viscosity coefficient* or *bulk viscosity*. This additional term disappears for an *incompressible fluid*, when the divergence of the flow equals zero.

Application to specific problems

The Navier–Stokes equations, even when written explicitly for specific fluids, are rather generic in nature and their proper application to specific problems can be very diverse. This is partly because there is an enormous variety of problems that may be modeled, ranging from as simple as the distribution of static pressure to as complicated as multiphase flow driven by surface tension.

Generally, application to specific problems begins with some flow assumptions and initial/boundary condition formulation, this may be followed by scale analysis to further simplify the problem. For example, after assuming steady, parallel, one dimensional, nonconvective pressure driven flow between parallel plates, the resulting scaled (dimensionless) boundary value problem is:



Visualization of a) parallel flow and b) radial flow

$$\frac{d^2u}{dy^2} = -1 \quad ; \quad u(0) = u(1) = 0.$$

The boundary condition is the no slip condition. This problem is easily solved for the flow field:

$$u(y) = \frac{y - y^2}{2}.$$

From this point onward more quantities of interest can be easily obtained, such as viscous drag force or net flow rate.

Difficulties may arise when the problem becomes slightly more complicated. A seemingly modest twist on the parallel flow above would be the *radial* flow between parallel plates; this involves convection and thus nonlinearity. The velocity field may be represented by a function *f*(*z*) that must satisfy:

$$\frac{d^2f}{dz^2} + Rf^2 = -1 \quad ; \quad f(-1) = f(1) = 0.$$

This ordinary differential equation is what is obtained when the Navier–Stokes equations are written and the flow assumptions applied (additionally, the pressure gradient is solved for). The nonlinear term makes this a very difficult problem to solve analytically (a lengthy implicit solution may be found which involves elliptic integrals and roots of cubic polynomials). Issues with the actual existence of solutions arise for $R > 1.41$ (approximately. This is not the square root of two), the parameter R being the Reynolds number with appropriately chosen scales. This is an example of flow assumptions losing their applicability, and an example of the difficulty in "high" Reynolds number flows.

Exact solutions of the Navier–Stokes equations

Some exact solutions to the Navier–Stokes equations exist. Examples of degenerate cases — with the non-linear terms in the Navier–Stokes equations equal to zero — are Poiseuille flow, Couette flow and the oscillatory Stokes boundary layer. But also more interesting examples, solutions to the full non-linear equations, exist; for example the Taylor–Green vortex. Note that the existence of these exact solutions does not imply they are stable: turbulence may develop at higher Reynolds numbers.

Wyld diagrams

Wyld diagrams are bookkeeping graphs that correspond to the Navier–Stokes equations via a perturbation expansion of the fundamental continuum mechanics. Similar to the Feynman diagrams in quantum field theory, these diagrams are an extension of Keldysh's technique for nonequilibrium processes in fluid dynamics. In other words, these diagrams assign graphs to the (often) turbulent phenomena in turbulent fluids by allowing correlated and interacting fluid particles to obey stochastic processes associated to pseudo-random functions in probability distributions.

Chapter- 5

Heat Transfer

Heat transfer is a discipline of thermal engineering that concerns the transfer of thermal energy from one physical system to another. Heat transfer is classified into various mechanisms, such as heat conduction, convection, thermal radiation, and phase-change transfer. Engineers also consider the transfer of mass of differing chemical species, either cold or hot, to achieve heat transfer.

Conduction, also called diffusion, is the direct microscopic exchange of kinetic energy of particles through the boundary between two systems. When an object is at a different temperature from another body or its surroundings, heat flows so that the body and the surroundings reach the same temperature at thermal equilibrium. Such spontaneous heat transfer always occurs from a region of high temperature to another region of lower temperature, as required by the second law of thermodynamics.

Transfer by thermal radiation is the transfer of energy by transmission of electromagnetic radiation described by black body theory.

Overview

Heat is defined in physics as the transfer of thermal energy across a well-defined boundary around a thermodynamic system. It is a characteristics of a process and is not statically contained in matter. In engineering contexts, however, the term *heat transfer* has acquired a specific usage, despite its literal redundancy of the characterization of transfer. In these contexts, *heat* is taken as synonymous to thermal energy. This usage has its origin in the historical interpretation of heat as a fluid (*caloric*) that can be transferred by various causes, and that is also common in the language of laymen and everyday life.

Fundamental methods of heat transfer in engineering include conduction, convection, and radiation. Physical laws describe the behavior and characteristics of each of these methods. Real systems often exhibit a complicated combination of them. Heat transfer methods are used in numerous disciplines, such as automotive engineering, thermal management of electronic devices and systems, climate control, Insulation, materials processing, and power plant engineering.

Various mathematical methods have been developed to solve or approximate the results of heat transfer in systems. Heat transfer is a path function (or process quantity), as opposed to a state quantity; therefore, the amount of heat transferred in a thermodynamic process that changes the state of a system depends on how that process occurs, not only the net difference between the initial and final states of the process. Heat flux is a quantitative, vectorial representation of the heat flow through a surface.

Heat transfer is typically studied as part of a general chemical engineering or mechanical engineering curriculum. Typically, thermodynamics is a prerequisite for heat transfer courses, as the laws of thermodynamics are essential to the mechanism of heat transfer. Other courses related to heat transfer include energy conversion, thermofluids, and mass transfer.

The transport equations for thermal energy (Fourier's law), mechanical momentum (Newton's law for fluids), and mass transfer (Fick's laws of diffusion) are similar and analogies among these three transport processes have been developed to facilitate prediction of conversion from any one to the others.

Mechanisms

The fundamental modes of heat transfer are:

Conduction or diffusion
: The transfer of energy between objects that are in physical contact

Convection
: The transfer of energy between an object and its environment, due to fluid motion

Radiation
: The transfer of energy to or from a body by means of the emission or absorption of electromagnetic radiation

Mass transfer
: The transfer of energy from one location to another as a side effect of physically moving an object containing that energy

Conduction

On a microscopic scale, heat conduction occurs as hot, rapidly moving or vibrating atoms and molecules interact with neighboring atoms and molecules, transferring some of their energy (heat) to these neighboring particles. In other words, heat is transferred by conduction when adjacent atoms vibrate against one another, or as electrons move from one atom to another. Conduction is the most significant means of heat transfer within a solid or between solid objects in thermal contact. Fluids—especially gases—are less conductive. Thermal contact conductance is the study of heat conduction between solid bodies in contact.

Steady state conduction is a form of conduction that happens when the temperature difference driving the conduction is constant, so that after an equilibration time, the spatial distribution of temperatures in the conducting object does not change any further.

In steady state conduction, the amount of heat entering a section is equal to amount of heat coming out.

Transient conduction occurs when the temperature within an object changes as a function of time. Analysis of transient systems is more complex and often calls for the application of approximation theories or numerical analysis by computer.

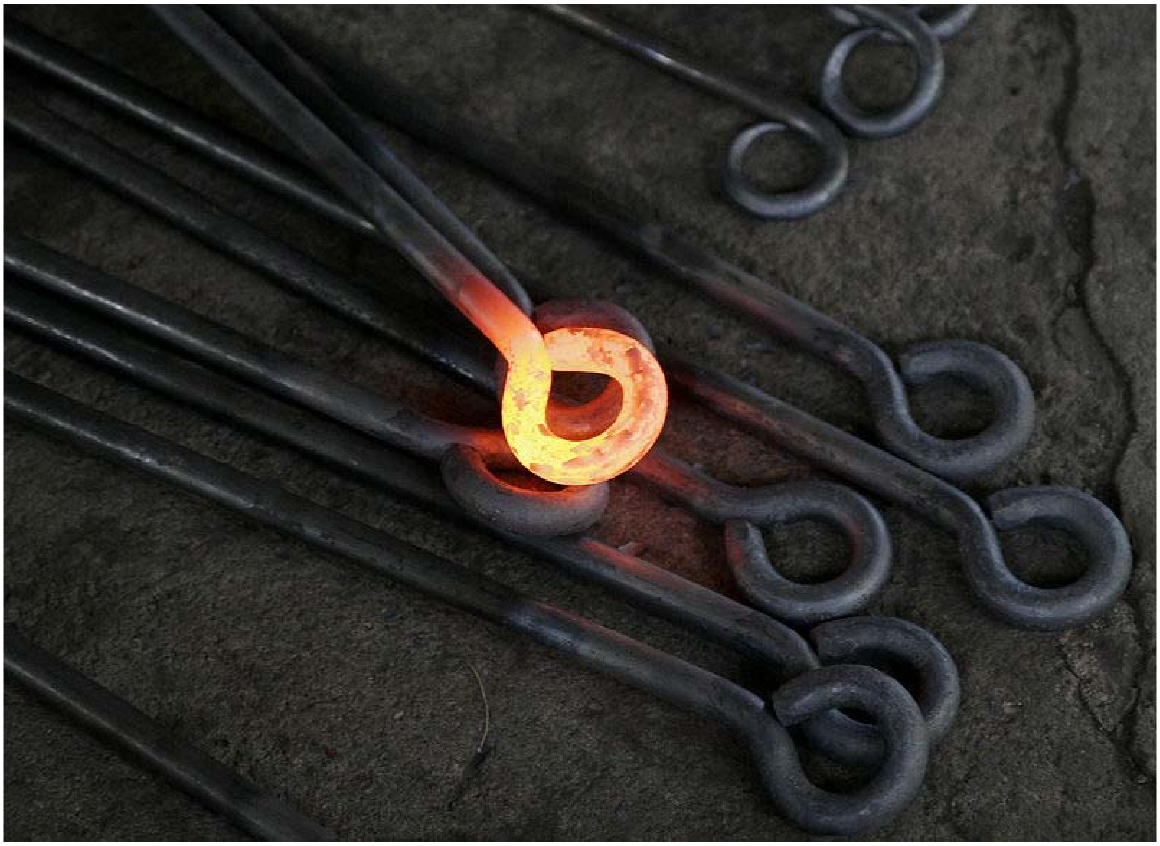
Convection

Convective heat transfer, or convection, is the transfer of heat from one place to another by the movement of fluids. (In physics, the term *fluid* means any substance that deforms under shear stress; it includes liquids, gases, plasmas, and some plastic solids.) Bulk motion of the fluid enhances the heat transfer between the solid surface and the fluid. Convection is usually the dominant form of heat transfer in liquids and gases. Although often discussed as a third method of heat transfer, convection actually describes the combined effects of conduction and fluid flow.

Free, or natural, convection occurs when the fluid motion is caused by buoyancy forces that result from density variations due to variations of temperature in the fluid. *Forced* convection is when the fluid is forced to flow over the surface by external means—such as fans, stirrers, and pumps—creating an artificially induced convection current.

Convection is described by Newton's law of cooling: "The rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings."

Radiation



A red-hot iron object, transferring heat to the surrounding environment primarily through thermal radiation.

Thermal radiation is energy emitted by matter as electromagnetic waves due to the pool of thermal energy that all matter possesses that has a temperature above absolute zero. Thermal radiation propagates without the presence of matter through the vacuum of space.

Thermal radiation is a direct result of the random movements of atoms and molecules in matter. Since these atoms and molecules are composed of charged particles (protons and electrons), their movement results in the emission of electromagnetic radiation, which carries energy away from the surface.

Unlike conductive and convective forms of heat transfer, thermal radiation can be concentrated in a small spot by using reflecting mirrors, which is exploited in concentrating solar power generation. For example, the sunlight reflected from mirrors heats the PS10 solar power tower and during the day it can heat water to 285 °C (545 °F).

Mass Transfer

In mass transfer, energy—including thermal energy—is moved by the physical transfer of a hot or cold object from one place to another. This can be as simple as placing hot water in a bottle and heating a bed, or the movement of an iceberg in changing ocean currents. A practical example is thermal hydraulics.

Convection vs. conduction

In a body of fluid that is heated from underneath its container, conduction and convection can be considered to compete for dominance. If heat conduction is too great, fluid moving down by convection is heated by conduction so fast that its downward movement will be stopped due to its buoyancy, while fluid moving up by convection is cooled by conduction so fast that its driving buoyancy will diminish. On the other hand, if heat conduction is very low, a large temperature gradient may be formed and convection might be very strong.

The Rayleigh number (*Ra*) is a measure determining the result of this competition.

$$Ra = \frac{g\Delta\rho L^3}{\mu\alpha} = \frac{g\beta\Delta T L^3}{\nu\alpha}$$

where

- g is acceleration due to gravity
- ρ is the density with $\Delta\rho$ being the density difference between the lower and upper ends
- μ is the dynamic viscosity
- α is the Thermal diffusivity
- β is the volume thermal expansivity (sometimes denoted α elsewhere)
- T is the temperature and
- ν is the kinematic viscosity.

The Rayleigh number can be understood as the ratio between the rate of heat transfer by convection to the rate of heat transfer by conduction; or, equivalently, the ratio between the corresponding timescales (i.e. conduction timescale divided by convection timescale), up to a numerical factor. This can be seen as follows, where all calculations are up to numerical factors depending on the geometry of the system.

The buoyancy force driving the convection is roughly $g\Delta\rho L^3$, so the corresponding pressure is roughly $g\Delta\rho L$. In steady state, this is canceled by the shear stress due to viscosity, and therefore roughly equals $\mu V / L = \mu / T_{conv}$, where V is the typical fluid velocity due to convection and T_{conv} the order of its timescale. The conduction timescale, on the other hand, is of the order of $T_{cond} = L^2 / \alpha$.

Convection occurs when the Rayleigh number is above 1,000–2,000. For example, the Earth's mantle, exhibiting non-stable convection, has Rayleigh number of the order of 1,000, and T_{conv} as calculated above is around 100 million years.

Phase changes

Transfer of heat through a phase transition in the medium—such as water-to-ice, water-to-steam, steam-to-water, or ice-to-water—involves significant energy and is exploited in many ways: steam engines, refrigerators, etc. For example, the Mason equation is an approximate analytical expression for the growth of a water droplet based on the effects of heat transport on evaporation and condensation.

Boiling

Heat transfer in boiling fluids is complex, but of considerable technical importance. It is characterized by an *S*-shaped curve relating heat flux to surface temperature difference.

At low driving temperatures, no boiling occurs and the heat transfer rate is controlled by the usual single-phase mechanisms. As the surface temperature is increased, local boiling occurs and vapor bubbles nucleate, grow into the surrounding cooler fluid, and collapse. This is *sub-cooled nucleate boiling*, and is a very efficient heat transfer mechanism. At high bubble generation rates, the bubbles begin to interfere and the heat flux no longer increases rapidly with surface temperature (this is the departure from nucleate boiling, or DNB). At higher temperatures still, a maximum in the heat flux is reached (the critical heat flux, or CHF). The regime of falling heat transfer that follows is not easy to study, but is believed to be characterized by alternate periods of nucleate and film boiling. Nucleate boiling slows the heat transfer due to gas bubbles on the heater's surface; as mentioned, gas-phase thermal conductivity is much lower than liquid-phase thermal conductivity, so the outcome is a kind of "gas thermal barrier".

At higher temperatures still, the hydrodynamically-quieter regime of film boiling is reached. Heat fluxes across the stable vapor layers are low, but rise slowly with temperature. Any contact between fluid and the surface that may be seen probably leads to the extremely rapid nucleation of a fresh vapor layer ("spontaneous nucleation").

Condensation

Condensation occurs when a vapor is cooled and changes its phase to a liquid. Condensation heat transfer, like boiling, is of great significance in industry. During condensation, the latent heat of vaporization must be released. The amount of the heat is the same as that absorbed during vaporization at the same fluid pressure.

There are several types of condensation:

- Homogeneous condensation, as during a formation of fog.
- Condensation in direct contact with subcooled liquid.

- Condensation on direct contact with a cooling wall of a heat exchanger: This is the most common mode used in industry:
    - Filmwise condensation is when a liquid film is formed on the subcooled surface, and usually occurs when the liquid wets the surface.
    - Dropwise condensation is when liquid drops are formed on the subcooled surface, and usually occurs when the liquid does not wet the surface.

  Dropwise condensation is difficult to sustain reliably; therefore, industrial equipment is normally designed to operate in filmwise condensation mode.

Modeling approaches

Complex heat transfer phenomena can be modeled in different ways.

Heat equation

The heat equation is an important partial differential equation that describes the distribution of heat (or variation in temperature) in a given region over time. In some cases, exact solutions of the equation are available; in other cases the equation must be solved numerically using computational methods. For example, simplified climate models may use Newtonian cooling, instead of a full (and computationally expensive) radiation code, to maintain atmospheric temperatures.

Lumped system analysis

System analysis by the lumped capacitance model is a common approximation in transient conduction that may be used whenever heat conduction within an object is much faster than heat conduction across the boundary of the object.

This is a method of approximation that reduces one aspect of the transient conduction system—that within the object—to an equivalent steady state system. That is, the method assumes that the temperature within the object is completely uniform, although its value may be changing in time.

In this method, the ratio of the conductive heat resistance within the object to the convective heat transfer resistance across the object's boundary, known as the *Biot number*, is calculated. For small Biot numbers, the approximation of *spatially uniform temperature within the object* can be used: it can be presumed that heat transferred into the object has time to uniformly distribute itself, due to the lower resistance to doing so, as compared with the resistance to heat entering the object.

Applications and techniques

Heat transfer has broad application to the functioning of numerous devices and systems. Heat-transfer principles may be used to preserve, increase, or decrease temperature in a wide variety of circumstances.

Insulation and radiant barriers

Heat exposure as part of a fire test for firestop products

Thermal insulators are materials specifically designed to reduce the flow of heat by limiting conduction, convection, or both. Radiant barriers are materials that reflect radiation, and therefore reduce the flow of heat from radiation sources. Good insulators are not necessarily good radiant barriers, and vice versa. Metal, for instance, is an excellent reflector and a poor insulator.

The effectiveness of an insulator is indicated by its **R-value**, or resistance value. The R-value of a material is the inverse of the conduction coefficient (*k*) multiplied by the thickness (*d*) of the insulator. In most of the world, R-values are measured in SI units: square-meter kelvins per watt ($m^2 \cdot K/W$). In the United States, R-values are customarily given in units of British thermal units per hour per square-foot degrees Fahrenheit ($Btu/h \cdot ft^2 \cdot °F$).

$$R = \frac{d}{k}$$

$$C = \frac{Q}{m\Delta T}$$

Rigid fiberglass, a common insulation material, has an R-value of four per inch, while poured concrete, a poor insulator, has an R-value of 0.08 per inch.

The tog is a measure of thermal resistance, commonly used in the textile industry, and often seen quoted on, for example, duvets and carpet underlay.

The effectiveness of a radiant barrier is indicated by its **reflectivity**, which is the fraction of radiation reflected. A material with a high reflectivity (at a given wavelength) has a low emissivity (at that same wavelength), and vice versa. At any specific wavelength, reflectivity = 1 - emissivity. An ideal radiant barrier would have a reflectivity of 1, and would therefore reflect 100 percent of incoming radiation. Vacuum flasks, or Dewars, are silvered to approach this ideal. In the vacuum of space, satellites use multi-layer insulation, which consists of many layers of aluminized (shiny) Mylar to greatly reduce radiation heat transfer and control satellite temperature.

Critical insulation thickness

Low thermal conductivity (*k*) materials reduce heat fluxes. The smaller the *k* value, the larger the corresponding thermal resistance (*R*) value. Thermal conductivity is measured in watts-per-meter per kelvin ($W \cdot m^{-1} \cdot K^{-1}$), represented as *k*. As the thickness of insulating material increases, the thermal resistance—or R-value—also increases.

However, adding layers of insulation has the potential of increasing the surface area, and hence the thermal convection area.

For example, as thicker insulation is added to a cylindrical pipe, the outer radius of the pipe-and-insulation system increases, and therefore surface area increases. The point where the added resistance of increasing insulation thickness becomes overshadowed by the effect of increased surface area is called the critical insulation thickness. In simple cylindrical pipes, this is calculated as a radius:

$$R_{critical} = \frac{k}{h}$$

Heat exchangers

A heat exchanger is a tool built for efficient heat transfer from one fluid to another, whether the fluids are separated by a solid wall so that they never mix, or the fluids are in direct contact. Heat exchangers are widely used in refrigeration, air conditioning, space heating, power generation, and chemical processing. One common example of a heat exchanger is a car's radiator, in which the hot coolant fluid is cooled by the flow of air over the radiator's surface.

Common types of heat exchanger flows include parallel flow, counter flow, and cross flow. In parallel flow, both fluids move in the same direction while transferring heat; in counter flow, the fluids move in opposite directions; and in cross flow, the fluids move at right angles to each other. Common constructions for heat exchanger include shell and tube, double pipe, extruded finned pipe, spiral fin pipe, u-tube, and stacked plate.

When engineers calculate the theoretical heat transfer in a heat exchanger, they must contend with the fact that the driving temperature difference between the two fluids varies with position. To account for this in simple systems, the log mean temperature difference (LMTD) is often used as an "average" temperature. In more complex systems, direct knowledge of the LMTD is not available, and the number of transfer units (NTU) method can be used instead.

Heat dissipation

A heat sink is a component that transfers heat generated within a solid material to a fluid medium, such as air or a liquid. Examples of heat sinks are the heat exchangers used in refrigeration and air conditioning systems, and the radiator in a car (which is also a heat exchanger). Heat sinks also help to cool electronic and optoelectronic devices such as CPUs, higher-power lasers, and light-emitting diodes (LEDs). A heat sink uses its extended surfaces to increase the surface area in contact with the cooling fluid.

Buildings

In cold climates, houses with their heating systems form dissipative systems. In spite of efforts to insulate houses to reduce heat losses via their exteriors, considerable heat is lost, which can make their interiors uncomfortably cool or cold. For the comfort of the inhabitants, the interiors must be maintained out of thermal equilibrium with the external surroundings. In effect, these domestic residences are oases of warmth in a sea of cold, and the thermal gradient between the inside and outside is often quite steep. This can lead to problems such as condensation and uncomfortable air currents, which—if left unaddressed—can cause cosmetic or structural damage to the property. Such issues can be prevented by use of insulation techniques for reducing heat loss.

Thermal transmittance is the rate of transfer of heat through a structure divided by the difference in temperature across the structure. It is expressed in watts per square meter per kelvin, or W/m^2K. Well-insulated parts of a building have a low thermal transmittance, whereas poorly-insulated parts of a building have a high thermal transmittance.

A thermostat is a device capable of starting the heating system when the house's interior falls below a set temperature, and of stopping that same system when another (higher) set temperature has been achieved. Thus, the thermostat controls the flow of energy into the house, that energy eventually being dissipated to the exterior.

Thermal energy storage

Thermal energy storage refers to technologies that store energy in a thermal reservoir for later use. They can be employed to balance energy demand between daytime and nighttime. The thermal reservoir may be maintained at a temperature above (hotter) or below (colder) than that of the ambient environment. Applications include later use in space heating, domestic or process hot water, or to generate electricity. Most practical active solar heating systems have storage for a few hours to a day's worth of heat collected.

Evaporative cooling

Evaporative cooling is a physical phenomenon in which evaporation of a liquid, typically into surrounding air, cools an object or a liquid in contact with it. Latent heat describes the amount of heat that is needed to evaporate the liquid; this heat comes from the liquid itself and the surrounding gas and surfaces. The greater the difference between the two temperatures, the greater the evaporative cooling effect. When the temperatures are the same, no net evaporation of water in air occurs; thus, there is no cooling effect. A simple example of natural evaporative cooling is perspiration, or sweat, which the body secretes in order to cool itself. An evaporative cooler is a device that cools air through the simple evaporation of water.

Radiative cooling

Radiative cooling is the process by which a body loses heat by radiation. It is an important effect in the Earth's atmosphere. In the case of the Earth-atmosphere system, it refers to the process by which long-wave (infrared) radiation is emitted to balance the absorption of short-wave (visible) energy from the Sun. Convective transport of heat and evaporative transport of latent heat both remove heat from the surface and redistribute it in the atmosphere, making it available for radiative transport at higher altitudes.

Laser cooling

Laser cooling refers to techniques in which atomic and molecular samples are cooled through the interaction with one or more laser light fields. The most common method of laser cooling is Doppler cooling. In Doppler cooling, the frequency of the laser light is tuned slightly below an electronic transition in the atom. Thus, the atoms would absorb more photons if they moved towards the light source, due to the Doppler effect. If an excited atom then emits a photon spontaneously, it will be accelerated. The result of the absorption and emission process is to reduce the speed of the atom. Eventually the mean velocity, and therefore the kinetic energy of the atoms, will be reduced. Since the temperature of an ensemble of atoms is a measure of the random internal kinetic energy, this is equivalent to cooling the atoms.

Sympathetic cooling is a process in which particles of one type cool particles of another type. Typically, atomic ions that can be directly laser-cooled are used to cool nearby ions or atoms. This technique allows cooling of ions and atoms that cannot be laser cooled directly.

Magnetic cooling

Magnetic evaporative cooling is a technique for lowering the temperature of a group of atoms. The process confines atoms using a magnetic field. Over time, individual atoms will become much more energetic than the others due to random collisions, and will escape—removing energy from the system and reducing the temperature of the remaining group. This process is similar to the familiar process by which standing water becomes water vapor.

Other

A heat pipe is a passive device constructed in such a way that it acts as though it has extremely high thermal conductivity. Heat pipes use latent heat and capillary action to move heat, and can carry many times as much heat as a similar-sized copper rod. Originally invented for use in satellites, they have applications in personal computers.

A thermocouple is a junction between two different metals that produces a voltage related to a temperature difference. Thermocouples are a widely used type of temperature sensor for measurement and control, and can also be used to convert heat into electric power.

A thermopile is an electronic device that converts thermal energy into electrical energy. It is composed of thermocouples. Thermopiles do not measure the absolute temperature, but generate an output voltage proportional to a temperature difference. Thermopiles are widely used, e.g., they are the key component of infrared thermometers, such as those used to measure body temperature via the ear.

A thermal diode or thermal rectifier is a device that preferentially passes heat in one direction: a "one-way valve" for heat.

Chapter- 6

Mass Transfer

Mass transfer is the net movement of mass from one location to another. Mass transfer is used by different scientific disciplines for different processes and mechanisms. The phrase is commonly used in engineering for physical processes that involve molecular and convective transport of atoms and molecules within physical systems.

Some common examples of mass transfer processes are the evaporation of water from a pond to the atmosphere; the diffusion of chemical impurities in lakes, rivers, and oceans from natural or artificial point sources; separation of chemical components in distillation columns. In Cooling towers, hot water flows down over the fill material as air flows up and contact between water and air evaporates some of the water. Evaporation requires heat; the heat is removed from the remaining water lowering its temperature.

Astrophysics

In astrophysics, mass transfer is the process by which matter gravitationally bound to a body, usually a star, fills its Roche lobe and becomes gravitationally bound to a second body, usually a compact object (white dwarf, neutron star or black hole), and is eventually accreted onto it. It is a common phenomenon in binary systems, and may play an important role in some types of supernovae and pulsars.

Chemical Engineering

Mass transfer finds extensive application in chemical engineering problems. Often, chemical species transfer between two phases through an interface or diffusion through a phase. The driving force for mass transfer is a difference in concentration; the random motion of molecules causes a net transfer of mass from an area of high concentration to an area of low concentration. For separation processes, thermodynamics determines the extent of separation, while mass transfer determines the rate at which the separation will occur. The amount of mass transfer rate can be quantified through the calculation and application of mass transfer coefficients.

Analogies between heat, mass, and momentum transfer

There are some notable similarities in equations for momentum, heat, and mass transfer. The molecular transfer equations of Newton's law for fluid momentum, Fourier's law for heat, and Fick's law for mass are very similar. A great deal of effort has been devoted to developing analogies among these three transport processes so as to allow prediction of one from any of the others.

Transport phenomena

In engineering and physics, the study of **transport phenomena** concerns the exchange of mass, energy, or momentum between observed and studied engineering systems. This subject is a fundamental component of disciplines involved with fluid mechanics, heat transfer, and mass transfer. It is now considered to be a part of the engineering discipline as much as thermodynamics, mechanics, and electromagnetism. Momentum, heat (energy), and mass transport share a similar mathematical framework, and a similar analytical mechanism that carries out the exchange process.

Transport phenomena actually encompasses all agents of physical change in the universe. Moreover, it is considered to be fundamental building block which developed the universe, and which is responsible for the success of all life on earth. However, the scope here limits the transport phenomena to its relationship to artificial engineered systems.

Overview

In physics, **transport phenomena** are all irreversible processes of statistical nature stemming from the random continuous motion of molecules, mostly observed in fluids. They involve a net macroscopic transfer of matter, energy or momentum in thermodynamic systems that are not in statistical equilibrium.

Examples of transport processes include heat conduction (energy transfer), viscosity (momentum transfer), molecular diffusion (mass transfer), radiation and electric charge transfer in semiconductors.

Transport phenomena have wide application. For example, in solid state physics, the motion and interaction of electrons, holes and phonons are studied under "transport phenomena". Another example is in biomedical engineering, where some transport phenomena of interest are thermoregulation, perfusion, and microfluidics. In chemical engineering, transport phenomena are studied in reactor design, analysis of molecular or diffusive transport mechanisms, and metallurgy.

The transport of mass, energy, and momentum can be affected by the presence of external sources:

- An odour dissipates more slowly when the source of the odor remains present.

- The rate of cooling of a solid that is conducting heat depends on whether a heat source is applied.
- The gravitational force acting on a rain drop counteracts the drag imparted by the surrounding air.

Commonalities among phenomena

An important principle in the study of transport phenomena is analogy between phenomena.

Diffusion

There are some notable similarities in equations for momentum, energy, and mass transfer which can all be transported by diffusion, as illustrated by the following examples:

- Mass: the spreading and dissipation of odours in air is an example of mass diffusion.
- Energy: the conduction of heat in a solid material is an example of heat diffusion.
- Momentum: the drag experienced by a rain drop as it falls in the atmosphere is an example of momentum diffusion (the rain drop loses momentum to the surrounding air through viscous stresses and decelerates).

The molecular transfer equations of Newton's law for fluid momentum, Fourier's law for heat, and Fick's law for mass are very similar. One can convert from one transfer coefficient to another in order to compare all three different transport phenomena.

Comparison of diffusion phenomena

Transported quantity	Physical phenomenon	Equation
Momentum	Viscosity (Newtonian fluid)	$\tau = -\nu \frac{\partial \rho v}{\partial x}$
Energy	Heat conduction (Fourier's law)	$\frac{q}{A} = -k \frac{dT}{dx}$
Mass	Molecular diffusion (Fick's law)	$J = -D \frac{\partial C}{\partial x}$

(Definitions of these formulas are given below).

A great deal of effort has been devoted in the literature to developing analogies among these three transport processes for turbulent transfer so as to allow prediction of one from any of the others. The Reynolds analogy assumes that the turbulent diffusivities are all equal and that the molecular diffusivities of momentum (μ/ρ) and mass (D_{AB}) are negligible compared to the turbulent diffusivities. When liquids are present and/or drag is present, the analogy is not valid. Other analogies, such as von Karman's and Prandtl's, usually result in poor relations.

The most successful and most widely used analogy is the Chilton and Colburn J-factor analogy. This analogy is based on experimental data for gases and liquids in both the laminar and turbulent regimes. Although it is based on experimental data, it can be shown to satisfy the exact solution derived from laminar flow over a flat plate. All of this information is used to predict transfer of mass.

Onsager reciprocal relations

In fluid systems described in terms of temperature, matter density, and pressure, it is known that temperature differences lead to heat flows from the warmer to the colder parts of the system; similarly, pressure differences will lead to matter flow from high-pressure to low-pressure regions (a "reciprocal relation"). What is remarkable is the observation that, when both pressure and temperature vary, temperature differences at constant pressure can cause matter flow (as in convection) and pressure differences at constant temperature can cause heat flow. Perhaps surprisingly, the heat flow per unit of pressure difference and the density (matter) flow per unit of temperature difference are equal.

This equality was shown to be necessary by Lars Onsager using statistical mechanics as a consequence of the time reversibility of microscopic dynamics. The theory developed by Onsager is much more general than this example and capable of treating more than two thermodynamic forces at once.

Momentum transfer

In momentum transfer, the fluid is treated as a continuous distribution of matter. The study of momemtum transfer, or fluid mechanics can be divided into two branches: fluid statics (fluids at rest), and fluid dynamics (fluids in motion). When a fluid is flowing in the x direction parallel to a solid surface, the fluid has x-directed momentum, and its concentration is $\upsilon_x\rho$. By random diffusion of molecules there is an exchange of molecules in the *z* direction. Hence the x-directed momentum has been transferred in the z-direction from the faster- to the slower-moving layer. The equation for momentum transport is Newton's Law of Viscosity written as follows:

$$\tau_{zx} = -\nu \frac{\partial \rho v_x}{\partial z}$$

where τ_{zx} is the flux of x-directed momentum in the z direction, ν is μ/ρ, the momentum diffusivitym z is the distance of transport or diffusion, ρ is the density, and μ is the viscosity. Newtons Law is the simplest relationship between the flux of momentum and the velocity gradient.

Mass transfer

When a system contains two or more components whose concentration vary from point to point, there is a natural tendency for mass to be transferred, minimizing any concentration difference within the system. Mass Transfer in a system is governed by Fick's First Law: 'Diffusion flux from higher concentration to lower concentration is proportional to the gradient of the concentration of the substance and the diffusivity of the substance in the medium.' Mass transfer can take place due to different driving forces. Some of them are:

- Mass can be transferred by the action of a pressure gradient(pressure diffusion)
- Forced diffusion occurs because of the action of some external force
- Diffusion is caused by temperature gradients (thermal diffusion)

This can be compared to Fourier's Law for conduction of heat:

$$J_{Ay} = -D_{AB}\frac{\partial Ca}{\partial y}$$

where D is the diffusivity constant.

Energy transfer

All process in engineering involve the transfer of energy. Some examples are the heating and cooling of process streams, phase changes, distillations, etc. The basic principle is the law of thermodynamic which is expressed as follows for a static system:

$$\frac{q}{A} = -k\frac{dT}{dx}$$

For other systems that involve either turbulent flow, complex geometries or difficult boundary conditions another equation would be easier to use:

$$q = h \cdot (A) \cdot \Delta T$$

where A is the surface area: ΔT is the temperature driving force, q is the heat flow per unit time, and h is the heat transfer coefficient.

Within heat transfer, two types of convection can occur:

Forced convection can occur in both laminar and turbulent flow. In the situation of laminar flow in circular tubes, several dimensionless numbers are used such as Nusselt number, Reynolds number, and Prandlt. The commonly used equation is:

$$Nu_a = \frac{h_a D}{k}$$

Natural or free convection is a function of Grashof and Prandlt numbers. The complexities of free convection heat transfer make it necessary to mainly use empirical relations from experimental data.

Heat transfer is analyzed in packed beds, reactors and heat exchangers.

Chapter- 7

Thermal Energy

Thermal energy is the part of the total, internal energy of a thermodynamic system or sample of matter that results in the system's temperature. The internal energy, also often called the thermodynamic energy, includes other forms of energy in a thermodynamic system in addition to thermal energy, namely forms of potential energy, such as the chemical energy stored in its molecular structure and electronic configuration, intermolecular interactions, and the nuclear energy that binds the sub-atomic particles of matter.

Microscopically, the thermal energy is the kinetic energy of a system's constituent particles, which may be atoms, molecules, electrons, or particles in plasmas. It originates from the individually random, or disordered, motion of particles in a large ensemble. The thermal energy is equally partitioned between all available quadratic degrees of freedom of the particles. These degrees of freedom may include pure translational motion in fluids, normal modes of vibrations, such as intermolecular vibrations or crystal lattice vibrations, or rotational states. In general, the availability of any such degrees of freedom is a function of the energy in the system, and therefore depends on the temperature.

When two thermodynamic systems with different temperatures are brought into diathermic contact, they exchange energy in form of heat, which is a conversion of thermal energy from the system of higher temperature to the colder system. This heat may cause work to be performed on each system, for example, in form of volume or pressure changes. This work may be used in heat engines to convert thermal energy into mechanical energy. When two systems have reached a thermodynamic equilibrium, they have attained the same temperature and the net exchange of thermal energy seizes.

Thermal energy is distinct from heat. In the strict use in physics, heat is a characteristic only of a process, i.e. it is absorbed or produced as an energy exchange, but it is not a static property of matter. Matter does not contain heat, but thermal energy. Heat is thermal energy in the process of transfer or conversion across a boundary of one region of matter to another.

Definitions

Thermal energy is the portion of internal energy that is responsible for a system's temperature. Microscopically, the thermal energy is identified with mechanical kinetic energy of the constituent particles or other forms of kinetic energy associated with quantum-mechanical microstates. The distinguishing difference between the terms *kinetic energy* and *thermal energy* is that thermal energy is the mean energy of disordered, i.e. random, motion of the particles or the oscillations in the system. The conversion of energy of ordered motion to thermal energy results from collisions.

All kinetic energy is partitioned into the degrees of freedom of the system. The average energy of a single particle with f quadratic degrees of freedom in a thermal bath of temperature T is a statistical mean energy given by the equipartition theorem as

$$E_{thermal} = f \cdot \frac{1}{2}kT$$

where k is the Boltzmann constant. The total thermal energy of a sample of matter or a thermodynamic system is consequently the average sum of the kinetic energies of all particles in the system. Thus, for a system of N particles its thermal energy is

$$U_{thermal} = N \cdot f \cdot \frac{1}{2}kT.$$

In general, however, $U_{thermal}$ is not the total energy of a system. Physical systems also contains static potential energy, such as chemical energy, or the particle's rest energy due to the equivalence of energy and mass.

Historical context

In a 1847 lecture entitled *On Matter, Living Force, and Heat*, James Prescott Joule characterized the terms latent heat and sensible heat as components of heat each effecting distinct physical phenomena, namely the potential and kinetic energy of particles, respectively. He describes latent energy as the energy of interaction in a given configuration of particles, i.e. a form of potential energy, and the sensible heat as an energy affecting the thermal energy, which he called the *living force*.

Thermal energy in an ideal gas

Thermal energy is most easily defined in the context of the ideal gas, which is well approximated by a monatomic gas at low pressure. The ideal gas is a gas of particles considered as point objects of perfect spherical symmetry that interact only by elastic collisions and fill a volume such that their free mean path between collisions is much larger than their diameter.

The mechanical kinetic energy of a single particle is

$$E_{kinetic} = \frac{1}{2}mv^2$$

where *m* is the particle's mass and *v* is its velocity. The thermal energy of the gas sample consisting of *N* atoms is given by the sum of these energies, assuming no losses to the container or the environment:

$$U_{thermal} = \frac{1}{2}Nm\overline{v^2} = \frac{3}{2}NkT.$$

where the line over the velocity term indicates that the average value is calculated over the entire ensemble. The total thermal energy of the sample is proportional to the macroscopic temperature by a constant factor accounting for the three translational degrees of freedom of each particle and the Boltzmann constant, converting units between the microscopic model and the macroscopic temperature. This formalism is the basic assumption that directly yields the ideal gas law, and it shows that for the ideal gas, the internal energy consists only of its thermal energy:

$$U = U_{thermal}$$

Distinction of thermal energy and heat

In engineering and technology, and particularly in fields that deal with civil energy use and conservation in building construction, heating systems, and power generation, *heat* and *thermal energy* are often indiscriminately used interchangeably.

In thermodynamics, heat must always be defined as energy in exchange between two systems, or a single system and its surroundings. According to the zeroth law of thermodynamics, heat is exchanged *between* thermodynamic systems in thermal contact only if their temperatures are different. For the purpose of distinction, a system is defined to be enclosed by a well-characterized boundary. If heat traverses the boundary in direction *into* the system, the internal energy change is considered to be a positive quantity, while *exiting* the system, it is negative. Heat is never a property of the system, nor is it *contained* within the boundary of the system.

In contrast to heat, thermal energy exists on both sides of a boundary. It is the statistical mean of the microscopic fluctuations of the kinetic energy of the systems' particles, and it is the source and the effect of the transfer of heat across a system boundary. Statistically, thermal energy is always exchanged between systems, even when the temperatures on both sides is the same, i.e. the systems are in thermal equilibrium. However, at equilibrium, the *net* exchange of thermal energy is zero, and therefore there is no heat.

Thermal energy may be increased in a system by other means than heat, for example when mechanical or electrical work is performed on the system. No qualitative difference exists between the thermal energy added by other means. There is also no need in classical thermodynamics to characterize the thermal energy in terms of atomic or molecular behavior. A change in thermal energy induced in a system is the product of the change in entropy and the temperature of the system.

Heat exchanged with a system may cause changes other than a change in thermal energy. For example, it may cause phase transitions, such as melting or evaporation, which are changes in the configuration of a material. Since such an energy exchange is not observable by a change in temperature, it is called a latent heat and represents a change in the potential energy of the system.

Rather than being itself the thermal energy involved in a transfer, heat is sometimes also understood as the process of transfer, i.e. it has the functioning as a verb.

Thermal energy of individual particles

Thermal energy is also often used as a property of single particles to designate the kinetic energy of the particles. An example is the description of thermal neutrons having a certain thermal energy, which is meant as the kinetic energy of the particle that is equivalent to the temperature of its surroundings.

Chapter- 8

Mechanical Engineering

Mechanical engineers design and build engines and power plants...

structures and vehicles of all sizes.

Mechanical engineering is a discipline of engineering that applies the principles of physics and materials science for analysis, design, manufacturing, and maintenance of mechanical systems. It is the branch of engineering that involves the production and usage of heat and mechanical power for the design, production, and operation of machines and tools. It is one of the oldest and broadest engineering disciplines.

The engineering field requires a vast understanding of core concepts including mechanics, kinematics, thermodynamics, materials science, and structural analysis. Mechanical engineers use these core principles along with tools like computer-aided engineering and product lifecycle management to design and analyze manufacturing plants, industrial equipment and machinery, heating and cooling systems, motorized vehicles, aircraft, watercraft, robotics, medical devices and more.

Mechanical engineering emerged as a field during the industrial revolution in Europe in the 19th century; however, its development can be traced back several thousand years around the world. The field has continually evolved to incorporate advancements in technology, and mechanical engineers today are pursuing developments in such fields as composites, mechatronics, and nanotechnology. Mechanical engineering overlaps with aerospace engineering, civil engineering, electrical engineering, and petroleum engineering to varying amounts.

Development

Applications of mechanical engineering are found in the records of many ancient and medieval societies throughout the globe. In ancient Greece, the works of Archimedes (287 BC–212 BC) deeply influenced mechanics in the Western tradition and Heron of Alexandria (c. 10–70 AD) created the first steam engine. In China, Zhang Heng (78–139 AD) improved a water clock and invented a seismometer, and Ma Jun (200–265 AD) invented a chariot with differential gears. The medieval Chinese horologist and engineer Su Song (1020–1101 AD) incorporated an escapement mechanism into his astronomical clock tower two centuries before any escapement can be found in clocks of medieval Europe, as well as the world's first known endless power-transmitting chain drive.

During the years from 7th to 15th century, the era called the Islamic Golden Age, there have been remarkable contributions from Muslim inventors in the field of mechanical technology. Al-Jazari, who was one of them, wrote his famous *Book of Knowledge of Ingenious Mechanical Devices* in 1206, and presented many mechanical designs. He is also considered to be the inventor of such mechanical devices which now form the very basic of mechanisms, such as the crankshaft and camshaft.

Important breakthroughs in the foundations of mechanical engineering occurred in England during the 17th century when Sir Isaac Newton both formulated the three Newton's Laws of Motion and developed calculus. Newton was reluctant to publish his methods and laws for years, but he was finally persuaded to do so by his colleagues, such as Sir Edmund Halley, much to the benefit of all mankind.

During the early 19th century in England, Germany and Scotland, the development of machine tools led mechanical engineering to develop as a separate field within engineering, providing manufacturing machines and the engines to power them. The first British professional society of mechanical engineers was formed in 1847 Institution of Mechanical Engineers, thirty years after the civil engineers formed the first such professional society Institution of Civil Engineers. On the European continent, Johann Von Zimmermann (1820–1901) founded the first factory for grinding machines in Chemnitz (Germany) in 1848.

In the United States, the American Society of Mechanical Engineers (ASME) was formed in 1880, becoming the third such professional engineering society, after the American Society of Civil Engineers (1852) and the American Institute of Mining Engineers (1871). The first schools in the United States to offer an engineering education were the United States Military Academy in 1817, an institution now known as Norwich University in 1819, and Rensselaer Polytechnic Institute in 1825. Education in mechanical engineering has historically been based on a strong foundation in mathematics and science.

Education

Degrees in mechanical engineering are offered at universities worldwide. In Bangladesh, China, India, Nepal, North America, and Pakistan, mechanical engineering programs typically take four to five years of study and result in a Bachelor of Science (B.Sc), Bachelor of Technology (B.Tech), Bachelor of Engineering (B.Eng), or Bachelor of Applied Science (B.A.Sc) degree, in or with emphasis in mechanical engineering. In Spain, Portugal and most of South America, where neither BSc nor BTech programs have been adopted, the formal name for the degree is "Mechanical Engineer", and the course work is based on five or six years of training. In Italy the course work is based on five years of training; but in order to qualify as an Engineer you have to pass a state exam at the end of the course.

In Australia, mechanical engineering degrees are awarded as Bachelor of Engineering (Mechanical). The degree takes four years of full time study to achieve. To ensure quality in engineering degrees, the Australian Institution of Engineers accredits engineering degrees awarded by Australian universities. Before the degree can be awarded, the student must complete at least 3 months of on the job work experience in an engineering firm.

In the United States, most undergraduate mechanical engineering programs are accredited by the Accreditation Board for Engineering and Technology (ABET) to ensure similar course requirements and standards among universities. The ABET web site lists 276 accredited mechanical engineering programs as of June 19, 2006. Mechanical engineering programs in Canada are accredited by the Canadian Engineering Accreditation Board (CEAB), and most other countries offering engineering degrees have similar accreditation societies.

Some mechanical engineers go on to pursue a postgraduate degree such as a Master of Engineering, Master of Technology, Master of Science, Master of Engineering Management (MEng.Mgt or MEM), a Doctor of Philosophy in engineering (EngD, PhD) or an engineer's degree. The master's and engineer's degrees may or may not include research. The Doctor of Philosophy includes a significant research component and is often viewed as the entry point to academia. The Engineer's degree exists at a few institutions at an intermediate level between the master's degree and the doctorate.

Coursework

Standards set by each country's accreditation society are intended to provide uniformity in fundamental subject material, promote competence among graduating engineers, and to maintain confidence in the engineering profession as a whole. Engineering programs in the U.S., for example, are required by ABET to show that their students can "work professionally in both thermal and mechanical systems areas." The specific courses required to graduate, however, may differ from program to program. Universities and Institutes of technology will often combine multiple subjects into a single class or split a subject into multiple classes, depending on the faculty available and the university's major area(s) of research.

The fundamental subjects of mechanical engineering usually include:

- Statics and dynamics
- Strength of materials and solid mechanics
- Instrumentation and measurement
- Electrotechnology
- Thermodynamics, heat transfer, energy conversion, and HVAC
- Fluid mechanics and fluid dynamics
- Mechanism design (including kinematics and dynamics)
- Manufacturing engineering, technology, or processes
- Hydraulics and pneumatics
- Mathematics - in particular, calculus, differential equations, and linear algebra.
- Engineering design

- Mechatronics and control theory
- Material Engineering
- Design engineering, Drafting, computer-aided design (CAD) (including solid modeling), and computer-aided manufacturing (CAM)

Mechanical engineers are also expected to understand and be able to apply basic concepts from chemistry, physics, chemical engineering, civil engineering, and electrical engineering. Most mechanical engineering programs include multiple semesters of calculus, as well as advanced mathematical concepts including differential equations, partial differential equations, linear algebra, abstract algebra, and differential geometry, among others.

In addition to the core mechanical engineering curriculum, many mechanical engineering programs offer more specialized programs and classes, such as robotics, transport and logistics, cryogenics, fuel technology, automotive engineering, biomechanics, vibration, optics and others, if a separate department does not exist for these subjects.

Most mechanical engineering programs also require varying amounts of research or community projects to gain practical problem-solving experience. In the United States it is common for mechanical engineering students to complete one or more internships while studying, though this is not typically mandated by the university. Cooperative education is another option.

License

Engineers may seek license by a state, provincial, or national government. The purpose of this process is to ensure that engineers possess the necessary technical knowledge, real-world experience, and knowledge of the local legal system to practice engineering at a professional level. Once certified, the engineer is given the title of Professional Engineer (in the United States, Canada, Japan, South Korea, Bangladesh and South Africa), Chartered Engineer (in the United Kingdom, Ireland, India and Zimbabwe), *Chartered Professional Engineer* (in Australia and New Zealand) or *European Engineer* (much of the European Union). Not all mechanical engineers choose to become licensed; those that do can be distinguished as Chartered or Professional Engineers by the post-nominal title P.E., P.Eng., or C.Eng., as in: Mike Thompson, P.Eng.

In the U.S., to become a licensed Professional Engineer, an engineer must pass the comprehensive FE (Fundamentals of Engineering) exam, work a given number of years as an *Engineering Intern (EI)* or *Engineer-in-Training (EIT)*, and finally pass the "Principles and Practice" or PE (Practicing Engineer or Professional Engineer) exams.

In the United States, the requirements and steps of this process are set forth by the National Council of Examiners for Engineering and Surveying (NCEES), a national non-profit representing all states. In the UK, current graduates require a BEng plus an appropriate masters degree or an integrated MEng degree, a minimum of 4 years post graduate on the job competency development, and a peer reviewed project report in the candidates specialty area in order to become chartered through the Institution of Mechanical Engineers.

In most modern countries, certain engineering tasks, such as the design of bridges, electric power plants, and chemical plants, must be approved by a Professional Engineer or a Chartered Engineer. "Only a licensed engineer, for instance, may prepare, sign, seal and submit engineering plans and drawings to a public authority for approval, or to seal engineering work for public and private clients." This requirement can be written into state and provincial legislation, such as in the Canadian provinces, for example the Ontario or Quebec's Engineer Act.

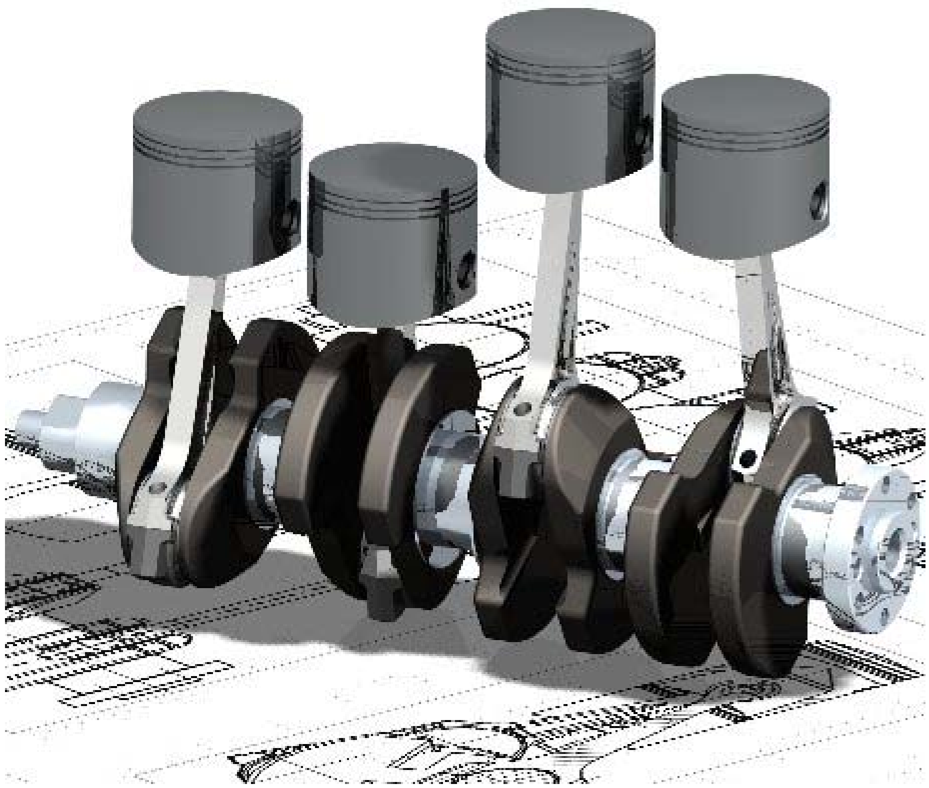
In other countries, such as Australia, no such legislation exists; however, practically all certifying bodies maintain a code of ethics independent of legislation that they expect all members to abide by or risk expulsion.

Salaries and workforce statistics

The total number of engineers employed in the U.S. in 2009 was roughly 1.6 million. Of these, 239,000 were mechanical engineers (14.9%), the second largest discipline by size behind civil (278,000). The total number of mechanical engineering jobs in 2009 was projected to grow 6% over the next decade, with average starting salaries being $58,800 with a bachelor's degree. The median annual income of mechanical engineers in the U.S. workforce was roughly $74,900. This number was highest when working for the government ($86,250), and lowest in education ($63,050).

In 2007, Canadian engineers made an average of CAD$29.83 per hour with 4% unemployed. The average for all occupations was $18.07 per hour with 7% unemployed. Twelve percent of these engineers were self-employed, and since 1997 the proportion of female engineers had risen to 6%.

Modern tools



An oblique view of a four-cylinder inline crankshaft with pistons

Many mechanical engineering companies, especially those in industrialized nations, have begun to incorporate computer-aided engineering (CAE) programs into their existing design and analysis processes, including 2D and 3D solid modeling computer-aided design (CAD). This method has many benefits, including easier and more exhaustive visualization of products, the ability to create virtual assemblies of parts, and the ease of use in designing mating interfaces and tolerances.

Other CAE programs commonly used by mechanical engineers include product lifecycle management (PLM) tools and analysis tools used to perform complex simulations. Analysis tools may be used to predict product response to expected loads, including fatigue life and manufacturability. These tools include finite element analysis (FEA), computational fluid dynamics (CFD), and computer-aided manufacturing (CAM).

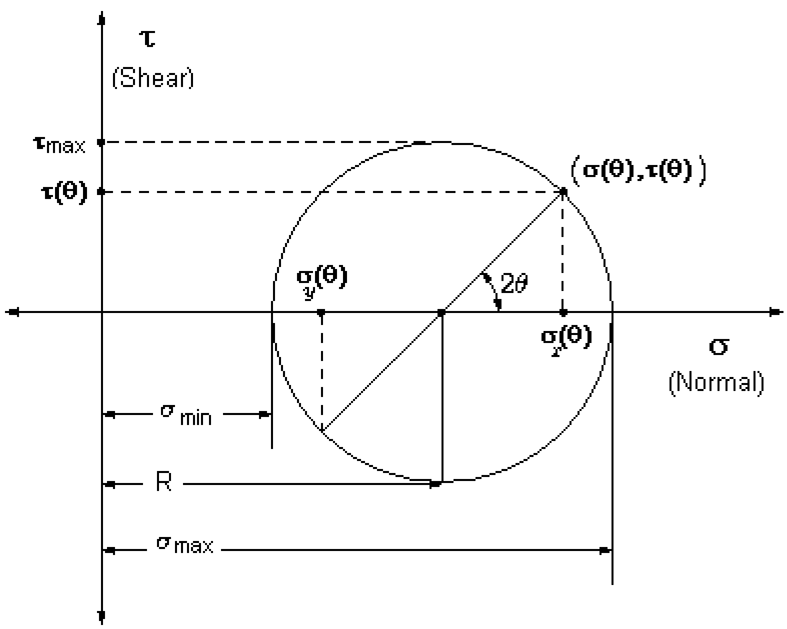
Using CAE programs, a mechanical design team can quickly and cheaply iterate the design process to develop a product that better meets cost, performance, and other constraints. No physical prototype need be created until the design nears completion, allowing hundreds or thousands of designs to be evaluated, instead of a relative few. In addition, CAE analysis programs can model complicated physical phenomena which cannot be solved by hand, such as viscoelasticity, complex contact between mating parts, or non-Newtonian flows

As mechanical engineering begins to merge with other disciplines, as seen in mechatronics, multidisciplinary design optimization (MDO) is being used with other CAE programs to automate and improve the iterative design process. MDO tools wrap around existing CAE processes, allowing product evaluation to continue even after the analyst goes home for the day. They also utilize sophisticated optimization algorithms to more intelligently explore possible designs, often finding better, innovative solutions to difficult multidisciplinary design problems.

Subdisciplines

The field of mechanical engineering can be thought of as a collection of many mechanical disciplines. Several of these subdisciplines which are typically taught at the undergraduate level are listed below, with a brief explanation and the most common application of each. Some of these subdisciplines are unique to mechanical engineering, while others are a combination of mechanical engineering and one or more other disciplines. Most work that a mechanical engineer does uses skills and techniques from several of these subdisciplines, as well as specialized subdisciplines. Specialized subdisciplines, as used here, are more likely to be the subject of graduate studies or on-the-job training than undergraduate research. Several specialized subdisciplines are discussed in this section.

Mechanics



Mohr's circle, a common tool to study stresses in a mechanical element

Mechanics is, in the most general sense, the study of forces and their effect upon matter. Typically, engineering mechanics is used to analyze and predict the acceleration and deformation (both elastic and plastic) of objects under known forces (also called loads) or stresses. Subdisciplines of mechanics include

- Statics, the study of non-moving bodies under known loads, how forces affect static bodies
- Dynamics (or kinetics), the study of how forces affect moving bodies
- Mechanics of materials, the study of how different materials deform under various types of stress
- Fluid mechanics, the study of how fluids react to forces
- Continuum mechanics, a method of applying mechanics that assumes that objects are continuous (rather than discrete)

Mechanical engineers typically use mechanics in the design or analysis phases of engineering. If the engineering project were the design of a vehicle, statics might be employed to design the frame of the vehicle, in order to evaluate where the stresses will be most intense. Dynamics might be used when designing the car's engine, to evaluate the forces in the pistons and cams as the engine cycles. Mechanics of materials might be used to choose appropriate materials for the frame and engine. Fluid mechanics might be used to design a ventilation system for the vehicle, or to design the intake system for the engine.

Kinematics

Kinematics is the study of the motion of bodies (objects) and systems (groups of objects), while ignoring the forces that cause the motion. The movement of a crane and the oscillations of a piston in an engine are both simple kinematic systems. The crane is a type of open kinematic chain, while the piston is part of a closed four-bar linkage.

Mechanical engineers typically use kinematics in the design and analysis of mechanisms. Kinematics can be used to find the possible range of motion for a given mechanism, or, working in reverse, can be used to design a mechanism that has a desired range of motion.

Mechatronics and robotics

Training FMS with learning robot SCORBOT-ER 4u, workbench CNC Mill and CNC Lathe

Mechatronics is an interdisciplinary branch of mechanical engineering, electrical engineering and software engineering that is concerned with integrating electrical and mechanical engineering to create hybrid systems. In this way, machines can be automated through the use of electric motors, servo-mechanisms, and other electrical systems in conjunction with special software. A common example of a mechatronics system is a CD-ROM drive. Mechanical systems open and close the drive, spin the CD and move the laser, while an optical system reads the data on the CD and converts it to bits. Integrated software controls the process and communicates the contents of the CD to the computer.

Robotics is the application of mechatronics to create robots, which are often used in industry to perform tasks that are dangerous, unpleasant, or repetitive. These robots may be of any shape and size, but all are preprogrammed and interact physically with the world. To create a robot, an engineer typically employs kinematics (to determine the robot's range of motion) and mechanics (to determine the stresses within the robot).

Robots are used extensively in industrial engineering. They allow businesses to save money on labor, perform tasks that are either too dangerous or too precise for humans to perform them economically, and to insure better quality. Many companies employ assembly lines of robots,especially in Automotive Industries and some factories are so robotized that they can run by themselves. Outside the factory, robots have been employed in bomb disposal, space exploration, and many other fields. Robots are also sold for various residential applications.

Structural analysis

Structural analysis is the branch of mechanical engineering (and also civil engineering) devoted to examining why and how objects fail and to fix the objects and their performance. Structural failures occur in two general modes: static failure, and fatigue failure. *Static structural failure* occurs when, upon being loaded (having a force applied) the object being analyzed either breaks or is deformed plastically, depending on the criterion for failure. *Fatigue failure* occurs when an object fails after a number of repeated loading and unloading cycles. Fatigue failure occurs because of imperfections in the object: a microscopic crack on the surface of the object, for instance, will grow slightly with each cycle (propagation) until the crack is large enough to cause ultimate failure.

Failure is not simply defined as when a part breaks, however; it is defined as when a part does not operate as intended. Some systems, such as the perforated top sections of some plastic bags, are designed to break. If these systems do not break, failure analysis might be employed to determine the cause.

Structural analysis is often used by mechanical engineers after a failure has occurred, or when designing to prevent failure. Engineers often use online documents and books such as those published by ASM to aid them in determining the type of failure and possible causes.

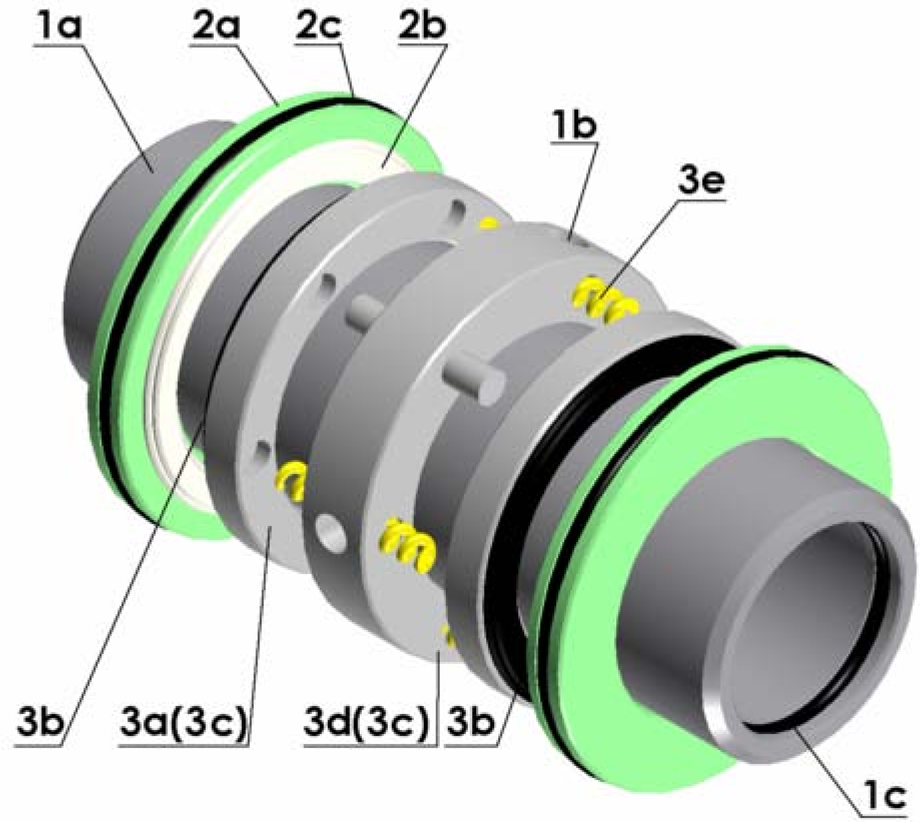
Structural analysis may be used in the office when designing parts, in the field to analyze failed parts, or in laboratories where parts might undergo controlled failure tests.

Thermodynamics and thermo-science

Thermodynamics is an applied science used in several branches of engineering, including mechanical and chemical engineering. At its simplest, thermodynamics is the study of energy, its use and transformation through a system. Typically, engineering thermodynamics is concerned with changing energy from one form to another. As an example, automotive engines convert chemical energy (enthalpy) from the fuel into heat, and then into mechanical work that eventually turns the wheels.

Thermodynamics principles are used by mechanical engineers in the fields of heat transfer, thermofluids, and energy conversion. Mechanical engineers use thermo-science to design engines and power plants, heating, ventilation, and air-conditioning (HVAC) systems, heat exchangers, heat sinks, radiators, refrigeration, insulation, and others.

Drafting



A CAD model of a mechanical double seal

Drafting or technical drawing is the means by which mechanical engineers create instructions for manufacturing parts. A technical drawing can be a computer model or hand-drawn schematic showing all the dimensions necessary to manufacture a part, as well as assembly notes, a list of required materials, and other pertinent information. A U.S. mechanical engineer or skilled worker who creates technical drawings may be referred to as a drafter or draftsman. Drafting has historically been a two-dimensional process, but computer-aided design (CAD) programs now allow the designer to create in three dimensions.

Instructions for manufacturing a part must be fed to the necessary machinery, either manually, through programmed instructions, or through the use of a computer-aided manufacturing (CAM) or combined CAD/CAM program. Optionally, an engineer may also manually manufacture a part using the technical drawings, but this is becoming an increasing rarity, with the advent of computer numerically controlled (CNC) manufacturing. Engineers primarily manually manufacture parts in the areas of applied spray coatings, finishes, and other processes that cannot economically or practically be done by a machine.

Drafting is used in nearly every subdiscipline of mechanical engineering, and by many other branches of engineering and architecture. Three-dimensional models created using CAD software are also commonly used in finite element analysis (FEA) and computational fluid dynamics (CFD).

Frontiers of research

Mechanical engineers are constantly pushing the boundaries of what is physically possible in order to produce safer, cheaper, and more efficient machines and mechanical systems. Some technologies at the cutting edge of mechanical engineering are listed below.

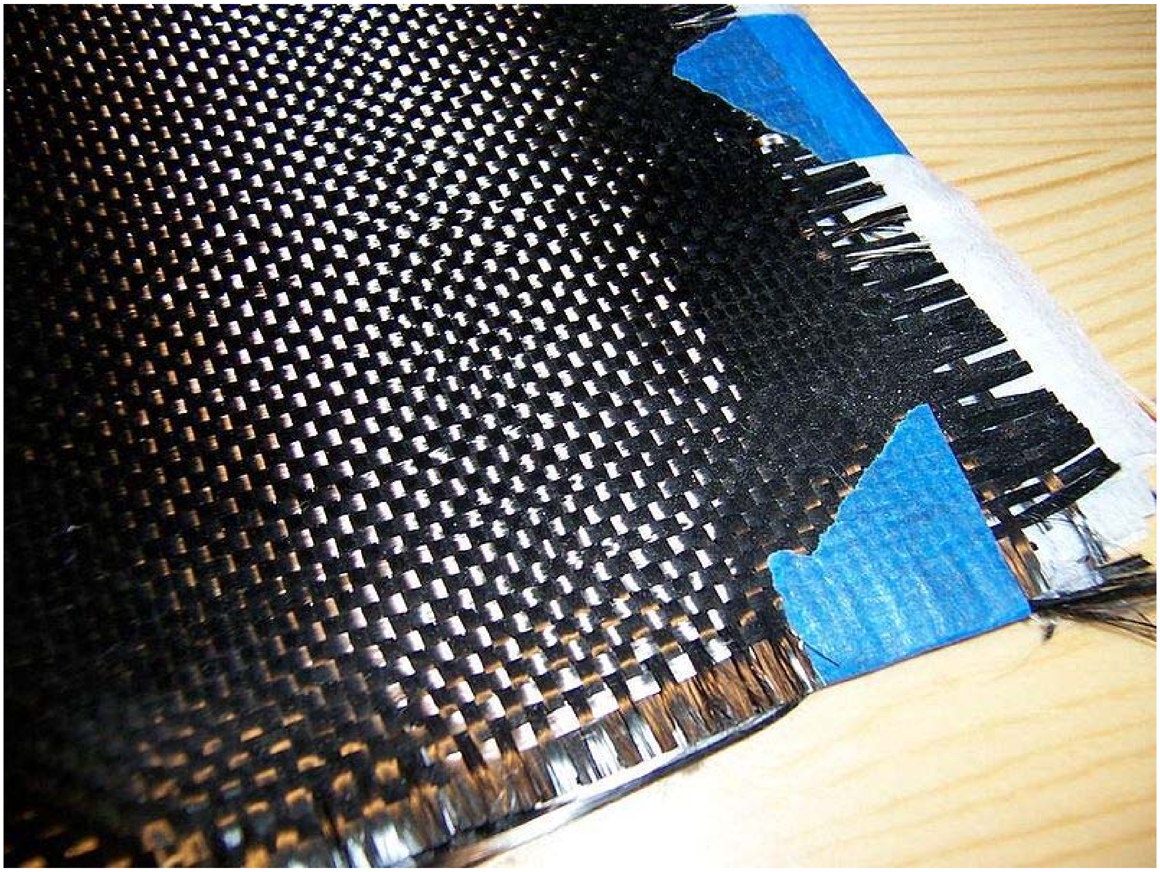
Micro electro-mechanical systems (MEMS)

Micron-scale mechanical components such as springs, gears, fluidic and heat transfer devices are fabricated from a variety of substrate materials such as silicon, glass and polymers like SU8. Examples of MEMS components will be the accelerometers that are used as car airbag sensors, modern cell phones, gyroscopes for precise positioning and microfluidic devices used in biomedical applications.

Friction stir welding (FSW)

Friction stir welding, a new type of welding, was discovered in 1991 by The Welding Institute (TWI). This innovative steady state (non-fusion) welding technique joins materials previously un-weldable, including several aluminum alloys. It may play an important role in the future construction of airplanes, potentially replacing rivets. Current uses of this technology to date include welding the seams of the aluminum main Space Shuttle external tank, Orion Crew Vehicle test article, Boeing Delta II and Delta IV Expendable Launch Vehicles and the SpaceX Falcon 1 rocket, armor plating for amphibious assault ships, and welding the wings and fuselage panels of the new Eclipse 500 aircraft from Eclipse Aviation among an increasingly growing pool of uses.

Composites



Composite cloth consisting of woven carbon fiber

Composites or composite materials are a combination of materials which provide different physical characteristics than either material separately. Composite material research within mechanical engineering typically focuses on designing (and, subsequently, finding applications for) stronger or more rigid materials while attempting to reduce weight, susceptibility to corrosion, and other undesirable factors. Carbon fiber reinforced composites, for instance, have been used in such diverse applications as spacecraft and fishing rods.

Mechatronics

Mechatronics is the synergistic combination of mechanical engineering, Electronic Engineering, and software engineering. The purpose of this interdisciplinary engineering field is the study of automation from an engineering perspective and serves the purposes of controlling advanced hybrid systems.

Nanotechnology

At the smallest scales, mechanical engineering becomes nanotechnology —one speculative goal of which is to create a molecular assembler to build molecules and materials via mechanosynthesis. For now that goal remains within exploratory engineering.

Finite element analysis

This field is not new, as the basis of Finite Element Analysis (FEA) or Finite Element Method (FEM) dates back to 1941. But evolution of computers has made FEM a viable option for analysis of structural problems. Many commercial codes such as ANSYS, Nastran and ABAQUS are widely used in industry for research and design of components.

Other techniques such as finite difference method (FDM) and finite-volume method (FVM) are employed to solve problems relating heat and mass transfer, fluid flows, fluid surface interaction etc.

Chapter- 9

Thermal Power Station

Republika Power Plant, a thermal power station in Pernik, Bulgaria

Mohave Generating Station, a 1,580 MW thermal power station near Laughlin, Nevada fuelled by coal

Geothermal power station in Iceland

A **thermal power station** is a power plant in which the prime mover is steam driven. Water is heated, turns into steam and spins a steam turbine which drives an electrical generator. After it passes through the turbine, the steam is condensed in a condenser and recycled to where it was heated; this is known as a Rankine cycle. The greatest variation in the design of thermal power stations is due to the different fuel sources. Some prefer to use the term *energy center* because such facilities convert forms of heat energy into electrical energy. Some thermal power plants also deliver heat energy for industrial purposes, for district heating, or for desalination of water as well as delivering electrical power. A large proportion of CO_2 is produced by the worlds fossil fired thermal power plants; efforts to reduce these outputs are various and widespread.

Introductory overview

Almost all coal, nuclear, geothermal, solar thermal electric, and waste incineration plants, as well as many natural gas power plants are thermal. Natural gas is frequently combusted in gas turbines as well as boilers. The waste heat from a gas turbine can be used to raise steam, in a combined cycle plant that improves overall efficiency. Power plants burning coal, oil, or natural gas are often referred to collectively as *fossil-fuel power plants*. Some biomass-fueled thermal power plants have appeared also. Non-nuclear thermal power plants, particularly fossil-fueled plants, which do not use co-generation are sometimes referred to as *conventional power plants*.

Commercial electric utility power stations are most usually constructed on a very large scale and designed for continuous operation. Electric power plants typically use three-phase or individual-phase electrical generators to produce alternating current (AC) electric power at a frequency of 50 Hz or 60 Hz (hertz, which is an AC sine wave per second) depending on its location in the world. Other large companies or institutions may have their own usually smaller power plants to supply heating or electricity to their facilities, especially if heat or steam is created anyway for other purposes. Shipboard steam-driven power plants have been used in various large ships in the past, but these days are used most often in large naval ships. Such shipboard power plants are general lower power capacity than full-size electric company plants, but otherwise have many similarities except that typically the main steam turbines mechanically turn the propulsion propellers, either through reduction gears or directly by the same shaft. The steam power plants in such ships also provide steam to separate smaller turbines driving electric generators to supply electricity in the ship. Shipboard steam power plants can be either conventional or nuclear; shipboard nuclear plants are with very few exceptions only in naval vessels. There have been perhaps about a dozen turbo-electric ships in which a steam-driven turbine drives an electric generator which powers an electric motor for propulsion.

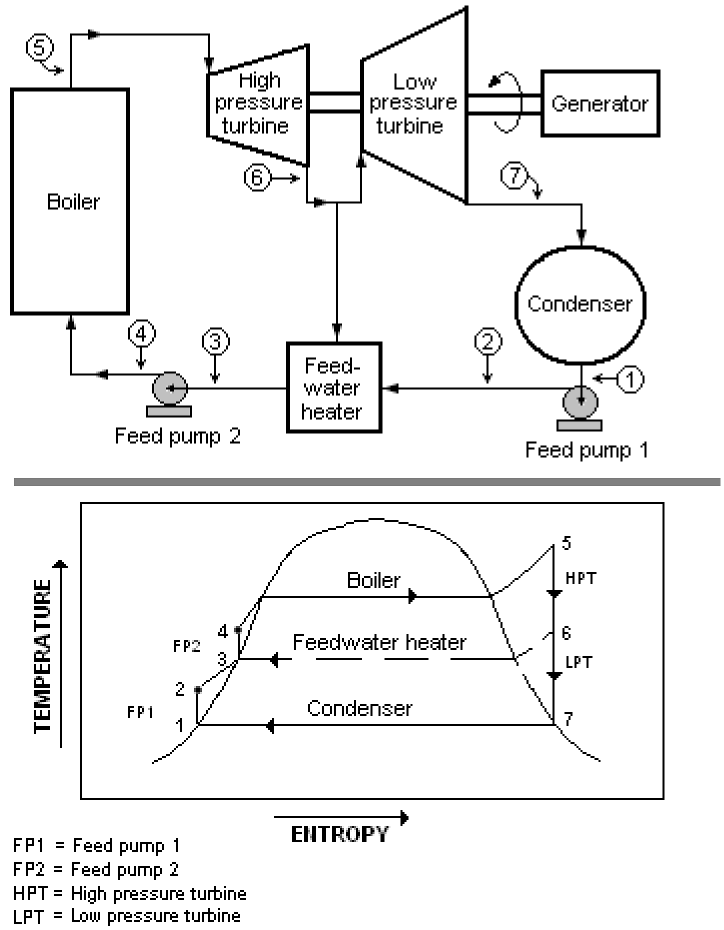
In some industrial, large institutional facilities, or other populated areas, there are *combined heat and power* (CH&P) plants, often called *co-generation plants*, which produce both power and heat for facility or district heating or industrial applications. AC electrical power can be stepped up to very high voltages for long distance transmission with minimal loss of power. Steam and hot water lose energy when piped over substantial distance, so carrying heat energy by steam or hot water is often only worthwhile within a local area or facility, such as steam distribution for a ship or industrial facility or hot water distribution in a local municipality.

History

Reciprocating steam engines have been used for mechanical power sources since the 18th Century, with notable improvements being made by James Watt. The very first commercial central electrical generating stations in the Pearl Street Station, New York and the Holborn Viaduct power station, London, in 1882, also used reciprocating steam engines. The development of the steam turbine allowed larger and more efficient central generating stations to be built. By 1892 it was considered as an alternative to reciprocating engines. Turbines offered higher speeds, more compact machinery, and stable speed regulation allowing for parallel synchronous operation of generators on a common bus. Turbines entirely replaced reciprocating engines in large central stations after about 1905. The largest reciprocating engine-generator sets ever built were completed in 1901 for the Manhattan Elevated Railway. Each of seventeen units weighed about 500 tons and was rated 6000 kilowatts; a contemporary turbine-set of similar rating would have weighed about 20% as much.

Efficiency

The energy efficiency of a conventional thermal power station, considered as salable energy (in MW) produced at the plant busbars as a percent of the heating value of the fuel consumed, is typically 33% to 48% efficient. This efficiency is limited as all heat engines are governed by the laws of thermodynamics. The rest of the energy must leave the plant in the form of heat. This waste heat can go through a condenser and be disposed of with cooling water or in cooling towers. If the waste heat is instead utilized for district heating, it is called co-generation. An important class of thermal power station are associated with desalination facilities; these are typically found in desert countries with large supplies of natural gas and in these plants, freshwater production and electricity are equally important co-products.



A Rankine cycle with a two-stage steam turbine and a single feed water heater

Since the efficiency of the plant is fundamentally limited by the ratio of the absolute temperatures of the steam at turbine input and output, efficiency improvements require use of higher temperature, and therefore higher pressure, steam. Historically, other working fluids such as mercury have been experimentally used in a mercury vapor turbine power plant, since these can attain higher temperatures than water at lower working pressures. However, the obvious hazards of toxicity, and poor heat transfer properties, have ruled out mercury as a working fluid.

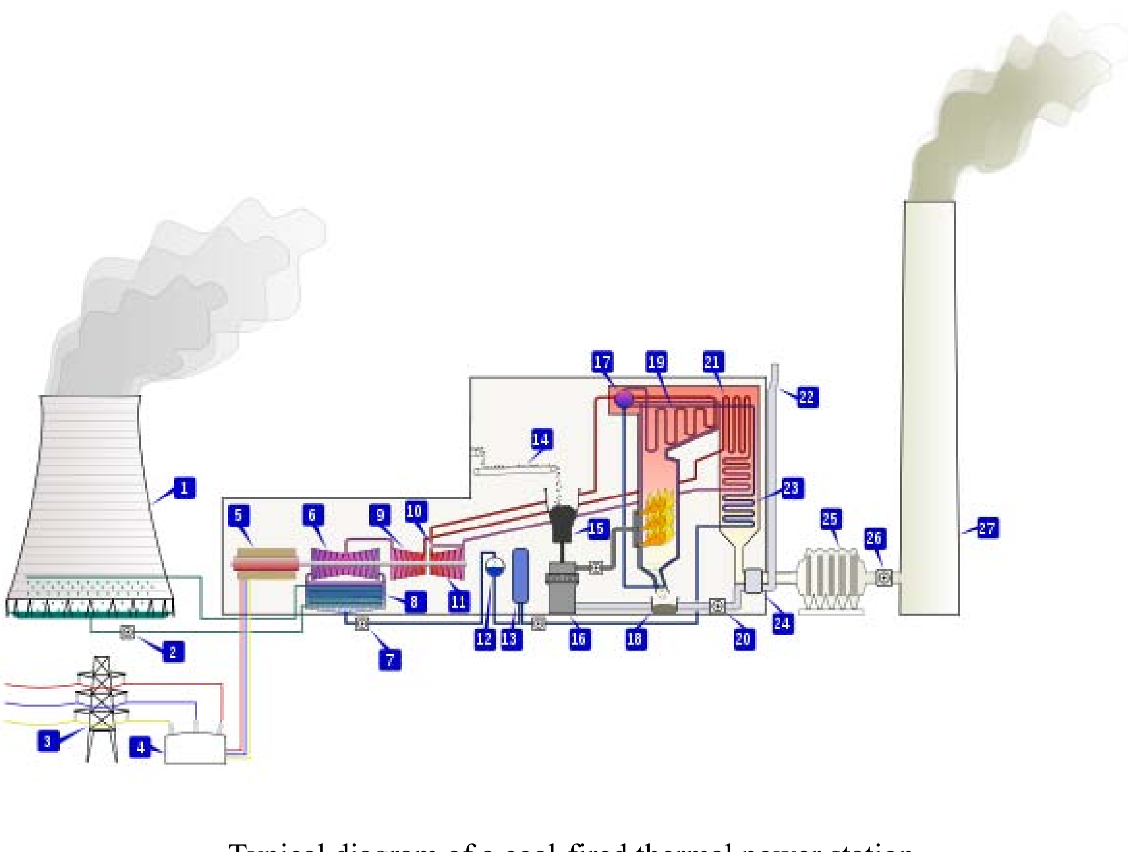
Above the critical point for water of 705 °F (374 °C) and 3,212 psi (Template:Convert/MP), there is no phase transition from water to steam, but only a gradual decrease in density. Boiling does not occur and it is not possible to remove impurities via steam separation. In this case a super critical steam plant is required to utilize the increased thermodynamic efficiency by operating at higher temperatures. These plants, also called *once-through* plants because boiler water does not circulate multiple times, require additional water purification steps to ensure that any impurities picked up during the cycle will be removed. This purification takes the form of high pressure ion exchange units called condensate polishers between the steam condenser and the feed water heaters. Sub-critical fossil fuel power plants can achieve 36–40% efficiency. Super critical designs have efficiencies in the low to mid 40% range, with new "ultra critical" designs using pressures of 4,400 psi (Template:Convert/MP) and dual stage reheat reaching about 48% efficiency.

Current nuclear power plants operate below the temperatures and pressures that coal-fired plants do. This limits their thermodynamic efficiency to on the order of 30–32%. Some advanced reactor designs being studied, such as the Very high temperature reactor, Advanced gas-cooled reactor and Super critical water reactor, would operate at temperatures and pressures similar to current coal plants, producing comparable thermodynamic efficiency.

Cost of electricity

The direct cost of electric energy produced by a thermal power station is the result of cost of fuel, capital cost for the plant, operator labor, maintenance, and such factors as ash handling and disposal. Indirect, social or environmental costs such as the economic value of environmental impacts, or environmental and health effects of the complete fuel cycle and plant decommissioning, are not usually assigned to generation costs for thermal stations in utility practice, but may form part of an environmental impact assessment.

Diagram of a typical coal-fired thermal power station



Typical diagram of a coal-fired thermal power station

1. Cooling tower	10. Steam Control valve	19. Superheater
2. Cooling water pump	11. High pressure steam turbine	20. Forced draught (draft) fan
3. transmission line (3-phase)	12. Deaerator	21. Reheater
4. Step-up transformer (3-phase)	13. Feedwater heater	22. Combustion air intake
5. Electrical generator (3-phase)	14. Coal conveyor	23. Economiser
6. Low pressure steam turbine	15. Coal hopper	24. Air preheater
7. Condensate pump	16. Coal pulverizer	25. Precipitator
8. Surface condenser	17. Boiler steam drum	26. Induced draught (draft) fan
9. Intermediate pressure steam turbine	18. Bottom ash hopper	27. Flue gas stack

For units over about 200 MW capacity, redundancy of key components is provided by installing duplicates of the forced and induced draft fans, air preheaters, and fly ash collectors. On some units of about 60 MW, two boilers per unit may instead be provided.

Boiler and steam cycle

In fossil-fueled power plants, *steam generator* refers to a furnace that burns the fossil fuel to boil water to generate steam.

In the nuclear plant field, *steam generator* refers to a specific type of large heat exchanger used in a pressurized water reactor (PWR) to thermally connect the primary (reactor plant) and secondary (steam plant) systems, which generates steam. In a nuclear reactor called a boiling water reactor (BWR), water is boiled to generate steam directly in the reactor itself and there are no units called steam generators.

In some industrial settings, there can also be steam-producing heat exchangers called *heat recovery steam generators* (HRSG) which utilize heat from some industrial process. The steam generating boiler has to produce steam at the high purity, pressure and temperature required for the steam turbine that drives the electrical generator.

Geothermal plants need no boiler since they use naturally occurring steam sources. Heat exchangers may be used where the geothermal steam is very corrosive or contains excessive suspended solids.

A fossil fuel steam generator includes an economizer, a steam drum, and the furnace with its steam generating tubes and super heater coils. Necessary safety valves are located at suitable points to avoid excessive boiler pressure. The air and flue gas path equipment include: forced draft (FD) fan, Air Preheater (AP), boiler furnace, induced draft (ID) fan, fly ash collectors (electrostatic precipitator or baghouse) and the flue gas stack.

Feed water heating and deaeration

The feed water used in the steam boiler is a means of transferring heat energy from the burning fuel to the mechanical energy of the spinning steam turbine. The total feed water consists of recirculated *condensate* water and purified *makeup water*. Because the metallic materials it contacts are subject to corrosion at high temperatures and pressures, the makeup water is highly purified before use. A system of water softeners and ion exchange demineralizers produces water so pure that it coincidentally becomes an electrical insulator, with conductivity in the range of 0.3–1.0 microsiemens per centimeter. The makeup water in a 500 MWe plant amounts to perhaps 20 US gallons per minute (1.25 L/s) to offset the small losses from steam leaks in the system.

The feed water cycle begins with condensate water being pumped out of the condenser after traveling through the steam turbines. The condensate flow rate at full load in a 500 MW plant is about 6,000 US gallons per minute (400 L/s).

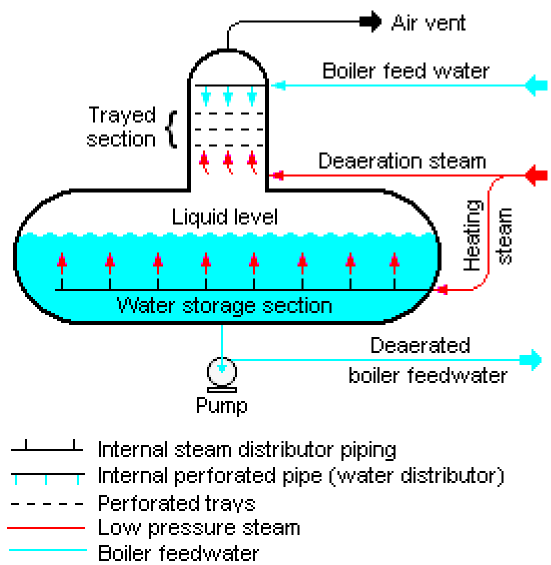


Diagram of boiler feed water deaerator (with vertical, domed aeration section and horizontal water storage section

The water flows through a series of six or seven intermediate feed water heaters, heated up at each point with steam extracted from an appropriate duct on the turbines and gaining temperature at each stage. Typically, the condensate plus the makeup water then flows through a deaerator that removes dissolved air from the water, further purifying and reducing its corrosivity. The water may be dosed following this point with hydrazine, a chemical that removes the remaining oxygen in the water to below 5 parts per billion (ppb). It is also dosed with pH control agents such as ammonia or morpholine to keep the residual acidity low and thus non-corrosive.

Boiler operation

The boiler is a rectangular furnace about 50 feet (15 m) on a side and 130 feet (40 m) tall. Its walls are made of a web of high pressure steel tubes about 2.3 inches (58 mm) in diameter.

Pulverized coal is air-blown into the furnace from fuel nozzles at the four corners and it rapidly burns, forming a large fireball at the center. The thermal radiation of the fireball heats the water that circulates through the boiler tubes near the boiler perimeter. The water circulation rate in the boiler is three to four times the throughput and is typically driven by pumps. As the water in the boiler circulates it absorbs heat and changes into steam at 700 °F (371 °C) and 3,200 psi (Template:Convert/MP). It is separated from the water inside a drum at the top of the furnace. The saturated steam is introduced into superheat pendant tubes that hang in the hottest part of the combustion gases as they exit the furnace. Here the steam is superheated to 1,000 °F (500 °C) to prepare it for the turbine.

Plants designed for lignite (brown coal) are increasingly used in locations as varied as Germany, Victoria, and North Dakota. Lignite is a much younger form of coal than black coal. It has a lower energy density than black coal and requires a much larger furnace for equivalent heat output. Such coals may contain up to 70% water and ash, yielding lower furnace temperatures and requiring larger induced-draft fans. The firing systems also differ from black coal and typically draw hot gas from the furnace-exit level and mix it with the incoming coal in fan-type mills that inject the pulverized coal and hot gas mixture into the boiler.

Plants that use gas turbines to heat the water for conversion into steam use boilers known as heat recovery steam generators (HRSG). The exhaust heat from the gas turbines is used to make superheated steam that is then used in a conventional water-steam generation cycle, as described in gas turbine combined-cycle plants section below.

Boiler furnace and steam drum

Once water inside the boiler or steam generator, the process of adding the latent heat of vaporization or enthalpy is underway. The boiler transfers energy to the water by the chemical reaction of burning some type of fuel.

The water enters the boiler through a section in the convection pass called the economizer. From the economizer it passes to the steam drum. Once the water enters the steam drum it goes down the down comers to the lower inlet water wall headers. From the inlet headers the water rises through the water walls and is eventually turned into steam due to the heat being generated by the burners located on the front and rear water walls (typically). As the water is turned into steam/vapor in the water walls, the steam/vapor once again enters the steam drum. The steam/vapor is passed through a series of steam and water separators and then dryers inside the steam drum. The steam separators and dryers remove water droplets from the steam and the cycle through the water walls is repeated. This process is known as natural circulation.

The boiler furnace auxiliary equipment includes coal feed nozzles and igniter guns, soot blowers, water lancing and observation ports (in the furnace walls) for observation of the furnace interior. Furnace explosions due to any accumulation of combustible gases after a trip-out are avoided by flushing out such gases from the combustion zone before igniting the coal.

The steam drum (as well as the super heater coils and headers) have air vents and drains needed for initial start up. The steam drum has internal devices that removes moisture from the wet steam entering the drum from the steam generating tubes. The dry steam then flows into the super heater coils.

Super heater

Fossil fuel power plants can have a super heater and/or re-heater section in the steam generating furnace. In a fossil fuel plant, after the steam is conditioned by the drying equipment inside the steam drum, it is piped from the upper drum area into tubes inside an area of the furnace known as the super heater, which has an elaborate set up of tubing where the steam vapor picks up more energy from hot flue gases outside the tubing and its temperature is now superheated above the saturation temperature. The superheated steam is then piped through the main steam lines to the valves before the high pressure turbine.

Nuclear-powered steam plants do not have such sections but produce steam at essentially saturated conditions. Experimental nuclear plants were equipped with fossil-fired super heaters in an attempt to improve overall plant operating cost.

Steam condensing

The condenser condenses the steam from the exhaust of the turbine into liquid to allow it to be pumped. If the condenser can be made cooler, the pressure of the exhaust steam is reduced and efficiency of the cycle increases.

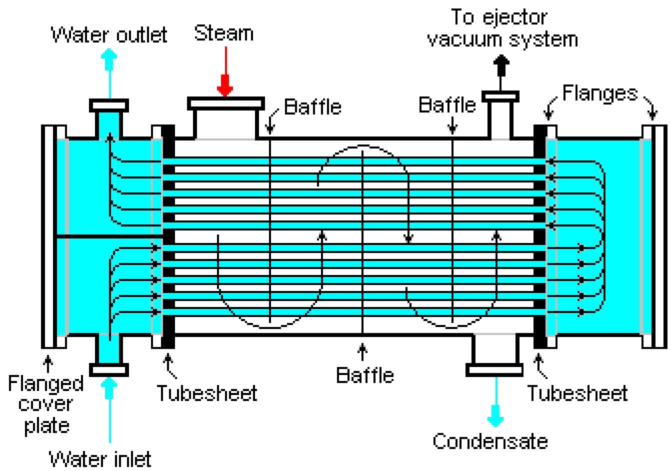


Diagram of a typical water-cooled surface condenser

The surface condenser is a shell and tube heat exchanger in which cooling water is circulated through the tubes. The exhaust steam from the low pressure turbine enters the shell where it is cooled and converted to condensate (water) by flowing over the tubes as shown in the adjacent diagram. Such condensers use steam ejectors or rotary motor-driven exhausters for continuous removal of air and gases from the steam side to maintain vacuum.

For best efficiency, the temperature in the condenser must be kept as low as practical in order to achieve the lowest possible pressure in the condensing steam. Since the condenser temperature can almost always be kept significantly below 100 °C where the vapor pressure of water is much less than atmospheric pressure, the condenser generally works under vacuum. Thus leaks of non-condensible air into the closed loop must be prevented.

Typically the cooling water causes the steam to condense at a temperature of about 35 °C (95 °F) and that creates an absolute pressure in the condenser of about 2–7 Pa (Template:Convert/in Hg), i.e. a vacuum of about -95 Pa (Template:Convert/in Hg) relative to atmospheric pressure. The large decrease in volume that occurs when water vapor condenses to liquid creates the low vacuum that helps pull steam through and increase the efficiency of the turbines.

The limiting factor is the temperature of the cooling water and that, in turn, is limited by the prevailing average climatic conditions at the power plant's location (it may be possible to lower the temperature beyond the turbine limits during winter, causing excessive condensation in the turbine). Plants operating in hot climates may have to reduce output if their source of condenser cooling water becomes warmer; unfortunately this usually coincides with periods of high electrical demand for air conditioning.

The condenser generally uses either circulating cooling water from a cooling tower to reject waste heat to the atmosphere, or once-through water from a river, lake or ocean.

A Marley mechanical induced draft cooling tower

The heat absorbed by the circulating cooling water in the condenser tubes must also be removed to maintain the ability of the water to cool as it circulates. This is done by pumping the warm water from the condenser through either natural draft, forced draft or induced draft cooling towers (as seen in the image to the right) that reduce the temperature of the water by evaporation, by about 11 to 17 °C (20 to 30 °F)—expelling waste heat to the atmosphere. The circulation flow rate of the cooling water in a 500 MW unit is about 14.2 m^3/s (500 ft^3/s or 225,000 US gal/min) at full load.

The condenser tubes are made of brass or stainless steel to resist corrosion from either side. Nevertheless they may become internally fouled during operation by bacteria or algae in the cooling water or by mineral scaling, all of which inhibit heat transfer and reduce thermodynamic efficiency. Many plants include an automatic cleaning system that circulates sponge rubber balls through the tubes to scrub them clean without the need to take the system off-line.

The cooling water used to condense the steam in the condenser returns to its source without having been changed other than having been warmed. If the water returns to a local water body (rather than a circulating cooling tower), it is tempered with cool 'raw' water to prevent thermal shock when discharged into that body of water.

Another form of condensing system is the air-cooled condenser. The process is similar to that of a radiator and fan. Exhaust heat from the low pressure section of a steam turbine runs through the condensing tubes, the tubes are usually finned and ambient air is pushed through the fins with the help of a large fan. The steam condenses to water to be reused in the water-steam cycle. Air-cooled condensers typically operate at a higher temperature than water cooled versions. While saving water, the efficiency of the cycle is reduced (resulting in more carbon dioxide per megawatt of electricity).

From the bottom of the condenser, powerful condensate pumps recycle the condensed steam (water) back to the water/steam cycle.

Re heater

Power plant furnaces may have a re heater section containing tubes heated by hot flue gases outside the tubes. Exhaust steam from the high pressure turbine is rerouted to go inside the re heater tubes to pickup more energy to go drive intermediate or lower pressure turbines.

Air path

External fans are provided to give sufficient air for combustion. The forced draft fan takes air from the atmosphere and, first warming it in the air preheater for better combustion, injects it via the air nozzles on the furnace wall.

The induced draft fan assists the FD fan by drawing out combustible gases from the furnace, maintaining a slightly negative pressure in the furnace to avoid backfiring through any opening.

Steam turbine generator

Rotor of a modern steam turbine, used in a power station

The turbine generator consists of a series of steam turbines interconnected to each other and a generator on a common shaft. There is a high pressure turbine at one end, followed by an intermediate pressure turbine, two low pressure turbines, and the generator. As steam moves through the system and loses pressure and thermal energy it expands in volume, requiring increasing diameter and longer blades at each succeeding stage to extract the remaining energy. The entire rotating mass may be over 200 metric tons and 100 feet (30 m) long. It is so heavy that it must be kept turning slowly even when shut down (at 3 rpm) so that the shaft will not bow even slightly and become unbalanced. This is so important that it is one of only five functions of blackout emergency power batteries on site. Other functions are emergency lighting, communication, station alarms and turbogenerator lube oil.

Superheated steam from the boiler is delivered through 14–16-inch (360–410 mm) diameter piping to the high pressure turbine where it falls in pressure to 600 psi (4.1 MPa) and to 600 °F (320 °C) in temperature through the stage. It exits via 24–26-inch (610–660 mm) diameter cold reheat lines and passes back into the boiler where the steam is reheated in special reheat pendant tubes back to 1,000 °F (500 °C). The hot reheat steam is conducted to the intermediate pressure turbine where it falls in both temperature and pressure and exits directly to the long-bladed low pressure turbines and finally exits to the condenser.

The generator, 30 feet (9 m) long and 12 feet (3.7 m) in diameter, contains a stationary stator and a spinning rotor, each containing miles of heavy copper conductor—no permanent magnets here. In operation it generates up to 21,000 amperes at 24,000 volts AC (504 MWe) as it spins at either 3,000 or 3,600 rpm, synchronized to the power grid. The rotor spins in a sealed chamber cooled with hydrogen gas, selected because it has the highest known heat transfer coefficient of any gas and for its low viscosity which reduces windage losses. This system requires special handling during startup, with air in the chamber first displaced by carbon dioxide before filling with hydrogen. This ensures that the highly explosive hydrogen–oxygen environment is not created.

The power grid frequency is 60 Hz across North America and 50 Hz in Europe, Oceania, Asia (Korea and parts of Japan are notable exceptions) and parts of Africa.

The electricity flows to a distribution yard where transformers step the voltage up to 115, 230, 500 or 765 kV AC as needed for transmission to its destination.

The steam turbine-driven generators have auxiliary systems enabling them to work satisfactorily and safely. The steam turbine generator being rotating equipment generally has a heavy, large diameter shaft. The shaft therefore requires not only supports but also has to be kept in position while running. To minimize the frictional resistance to the rotation, the shaft has a number of bearings. The bearing shells, in which the shaft rotates, are lined with a low friction material like Babbitt metal. Oil lubrication is provided to further reduce the friction between shaft and bearing surface and to limit the heat generated.

Stack gas path and cleanup

As the combustion flue gas exits the boiler it is routed through a rotating flat basket of metal mesh which picks up heat and returns it to incoming fresh air as the basket rotates, This is called the air preheater. The gas exiting the boiler is laden with fly ash, which are tiny spherical ash particles. The flue gas contains nitrogen along with combustion products carbon dioxide, sulfur dioxide, and nitrogen oxides. The fly ash is removed by fabric bag filters or electrostatic precipitators. Once removed, the fly ash byproduct can sometimes be used in the manufacturing of concrete. This cleaning up of flue gases, however, only occurs in plants that are fitted with the appropriate technology. Still, the majority of coal fired power plants in the world do not have these facilities. Legislation in Europe has been efficient to reduce flue gas pollution. Japan has been using flue gas cleaning technology for over 30 years and the US has been doing the same for over 25 years. China is now beginning to grapple with the pollution caused by coal fired power plants.

Where required by law, the sulfur and nitrogen oxide pollutants are removed by stack gas scrubbers which use a pulverized limestone or other alkaline wet slurry to remove those pollutants from the exit stack gas. Other devices use catalysts to remove Nitrous Oxide compounds from the flue gas stream. The gas travelling up the flue gas stack may by this time have dropped to about 50 °C (120 °F). A typical flue gas stack may be 150–180 metres (490–590 ft) tall to disperse the remaining flue gas components in the atmosphere. The tallest flue gas stack in the world is 419.7 metres (1,377 ft) tall at the GRES-2 power plant in Ekibastuz, Kazakhstan.

In the United States and a number of other countries, atmospheric dispersion modeling studies are required to determine the flue gas stack height needed to comply with the local air pollution regulations. The United States also requires the height of a flue gas stack to comply with what is known as the "Good Engineering Practice (GEP)" stack height. In the case of existing flue gas stacks that exceed the GEP stack height, any air pollution dispersion modeling studies for such stacks must use the GEP stack height rather than the actual stack height.

Fly ash collection

Fly ash is captured and removed from the flue gas by electrostatic precipitators or fabric bag filters (or sometimes both) located at the outlet of the furnace and before the induced draft fan. The fly ash is periodically removed from the collection hoppers below the precipitators or bag filters. Generally, the fly ash is pneumatically transported to storage silos for subsequent transport by trucks or railroad cars.

Bottom ash collection and disposal

At the bottom of the furnace, there is a hopper for collection of bottom ash. This hopper is always filled with water to quench the ash and clinkers falling down from the furnace.

Some arrangement is included to crush the clinkers and for conveying the crushed clinkers and bottom ash to a storage site.

Auxiliary systems

Boiler make-up water treatment plant and storage

Since there is continuous withdrawal of steam and continuous return of condensate to the boiler, losses due to blowdown and leakages have to be made up to maintain a desired water level in the boiler steam drum. For this, continuous make-up water is added to the boiler water system. Impurities in the raw water input to the plant generally consist of calcium and magnesium salts which impart hardness to the water. Hardness in the make-up water to the boiler will form deposits on the tube water surfaces which will lead to overheating and failure of the tubes. Thus, the salts have to be removed from the water, and that is done by a water demineralising treatment plant (DM). A DM plant generally consists of cation, anion, and mixed bed exchangers. Any ions in the final water from this process consist essentially of hydrogen ions and hydroxide ions, which recombine to form pure water. Very pure DM water becomes highly corrosive once it absorbs oxygen from the atmosphere because of its very high affinity for oxygen.

The capacity of the DM plant is dictated by the type and quantity of salts in the raw water input. However, some storage is essential as the DM plant may be down for maintenance. For this purpose, a storage tank is installed from which DM water is continuously withdrawn for boiler make-up. The storage tank for DM water is made from materials not affected by corrosive water, such as PVC. The piping and valves are generally of stainless steel. Sometimes, a steam blanketing arrangement or stainless steel doughnut float is provided on top of the water in the tank to avoid contact with air. DM water make-up is generally added at the steam space of the surface condenser (i.e., the vacuum side). This arrangement not only sprays the water but also DM water gets deaerated, with the dissolved gases being removed by an air ejector attached to the condenser.

Fuel preparation system

In coal-fired power stations, the raw feed coal from the coal storage area is first crushed into small pieces and then conveyed to the coal feed hoppers at the boilers. The coal is next pulverized into a very fine powder. The pulverizers may be ball mills, rotating drum grinders, or other types of grinders.

Some power stations burn fuel oil rather than coal. The oil must kept warm (above its pour point) in the fuel oil storage tanks to prevent the oil from congealing and becoming unpumpable. The oil is usually heated to about 100 °C before being pumped through the furnace fuel oil spray nozzles.

Boilers in some power stations use processed natural gas as their main fuel. Other power stations may use processed natural gas as auxiliary fuel in the event that their main fuel supply (coal or oil) is interrupted. In such cases, separate gas burners are provided on the boiler furnaces.

Barring gear

Barring gear (or "turning gear") is the mechanism provided to rotate the turbine generator shaft at a very low speed after unit stoppages. Once the unit is "tripped" (i.e., the steam inlet valve is closed), the turbine coasts down towards standstill. When it stops completely, there is a tendency for the turbine shaft to deflect or bend if allowed to remain in one position too long. This is because the heat inside the turbine casing tends to concentrate in the top half of the casing, making the top half portion of the shaft hotter than the bottom half. The shaft therefore could warp or bend by millionths of inches.

This small shaft deflection, only detectable by eccentricity meters, would be enough to cause damaging vibrations to the entire steam turbine generator unit when it is restarted. The shaft is therefore automatically turned at low speed (about one percent rated speed) by the barring gear until it has cooled sufficiently to permit a complete stop.

Oil system

An auxiliary oil system pump is used to supply oil at the start-up of the steam turbine generator. It supplies the hydraulic oil system required for steam turbine's main inlet steam stop valve, the governing control valves, the bearing and seal oil systems, the relevant hydraulic relays and other mechanisms.

At a preset speed of the turbine during start-ups, a pump driven by the turbine main shaft takes over the functions of the auxiliary system.

Generator cooling

While small generators may be cooled by air drawn through filters at the inlet, larger units generally require special cooling arrangements. Hydrogen gas cooling, in an oil-sealed casing, is used because it has the highest known heat transfer coefficient of any gas and for its low viscosity which reduces windage losses. This system requires special handling during start-up, with air in the generator enclosure first displaced by carbon dioxide before filling with hydrogen. This ensures that the highly flammable hydrogen does not mix with oxygen in the air.

The hydrogen pressure inside the casing is maintained slightly higher than atmospheric pressure to avoid outside air ingress. The hydrogen must be sealed against outward leakage where the shaft emerges from the casing. Mechanical seals around the shaft are installed with a very small annular gap to avoid rubbing between the shaft and the seals. Seal oil is used to prevent the hydrogen gas leakage to atmosphere.

The generator also uses water cooling. Since the generator coils are at a potential of about 22 kV and water is conductive, an insulating barrier such as Teflon is used to interconnect the water line and the generator high voltage windings. Demineralized water of low conductivity is used.

Generator high voltage system

The generator voltage for modern utility-connected generators ranges from 11 kV in smaller units to 22 kV in larger units. The generator high voltage leads are normally large aluminum channels because of their high current as compared to the cables used in smaller machines. They are enclosed in well-grounded aluminum bus ducts and are supported on suitable insulators. The generator high voltage leads are connected to step-up transformers for connecting to a high voltage electrical substation (of the order of 115 kV to 520 kV) for further transmission by the local power grid.

The necessary protection and metering devices are included for the high voltage leads. Thus, the steam turbine generator and the transformer form one unit. Smaller units,may share a common generator step-up transformer with individual circuit breakers to connect the generators to a common bus.

Monitoring and alarm system

Most of the power plant operational controls are automatic. However, at times, manual intervention may be required. Thus, the plant is provided with monitors and alarm systems that alert the plant operators when certain operating parameters are seriously deviating from their normal range.

Battery supplied emergency lighting and communication

A central battery system consisting of lead acid cell units is provided to supply emergency electric power, when needed, to essential items such as the power plant's control systems, communication systems, turbine lube oil pumps, and emergency lighting. This is essential for a safe, damage-free shutdown of the units in an emergency situation.

Transport of coal fuel to site and to storage

Most thermal stations use coal as the main fuel. Raw coal is transported from coal mines to a power station site by trucks, barges, bulk cargo ships or railway cars. Generally, when shipped by railways, the coal cars are sent as a full train of cars. The coal received at site may be of different sizes. The railway cars are unloaded at site by rotary dumpers or side tilt dumpers to tip over onto conveyor belts below. The coal is generally conveyed to crushers which crush the coal to about ¾ inch (6 mm) size. The crushed coal is then sent by belt conveyors to a storage pile. Normally, the crushed coal is compacted by bulldozers, as compacting of highly volatile coal avoids spontaneous ignition.

The crushed coal is conveyed from the storage pile to silos or hoppers at the boilers by another belt conveyor system.