BASIC MECHANICAL ENGINEERING

SECOND EDITION

Pearson

Pravin Kumar

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Basic Mechanical Engineering

Second Edition

Pravin Kumar
Assistant Professor
Department of Mechanical Engineering
Delhi Technological University (DTU)

Pearson

Dedicated to

My Wife and Sons

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Head Office: 15th Floor, Tower-B, World Trade Tower, Plot No. 1, Block-C, Sector-16, Noida 201 301, Uttar Pradesh, India.
Registered Office: 4th Floor, Software Block, Elnet Software City, TS-140,
Block 2 & 9, Rajiv Gandhi Salai, Taramani, Chennai 600 113, Tamil Nadu, India.
Fax: 080-30461003, Phone: 080-30461060
Website: in.pearson.com, Email: companysecretary.india@pearson.com

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Preface to the Second Edition

It is my great pleasure to present the second edition of the Basic Mechanical Engineering textbook after the much praised first edition of the book. Due to continuous change in the curriculum of the engineering education, it becomes necessary to modify the contents of the book as per the requirements of the universities. After the first edition, it has been observed that few topics of the book are not much relevant for the first year engineering students, for example, Chapter 13—Lifting Machines and Chapter 23—Unconventional Machining Processes and therefore, these two chapters are removed from the second edition of the book.

Also, in the second edition, several topics have been added. Global warming and biofuels are now discussed in detail in Chapter 2. Due to fast change in the technology, some advanced technologies such as Multi-point Fuel Injection Engine (MPFI), Common Rail Direct Injection (CRDI), Hybrid Engines have been introduced in Chapter 6. Chapter 13 has been upgraded by removing the Lifting Machines and adding spring, CAM and followers, and bushing and bearing. In Chapter 19, grinding and surface finishing processes have been included. Smithy works have been added in Chapter 21. Introduction to Automation and Robotics have been included in Chapter 22.

In addition to the above changes, some minor improvements have been done in the entire book and the questions asked in various university examinations have also been included. These questions are indicated by an asterisk (*) symbol.

Chapter Structure and Coverage

This book provides a basic knowledge of the various aspects of mechanical engineering. The chapter structure and coverage are discussed below:

Chapter 1 covers the laws of thermodynamics and properties of gases. Under the laws of thermodynamics, we first discuss, second and third laws of thermodynamics, concepts of specific heat, enthalpy, entropy, etc., followed by the discussion on properties of gases such as Boyle's Law, Charles's Law, Gay Lusssac's Law, combined gas law and gas constant, etc.

Chapter 2 deals with fuels and their combustion. The various types of fuels such as solid, liquid, and gaseous fuels are introduced and their applications for power generation have been discussed. Again to measure the calorific value of fuel, a basic idea about calorimeters and their working procedure has been given.

Chapter 3 describes power plant engineering. In this chapter, the methods of conversion of various forms of energy into mechanical energy and electrical energy along with an introduction to the basic concepts of thermal power plant, hydroelectric power plant, and nuclear power plant with some of the non-conventional energy sources has been discussed.

Chapter 4 covers steam properties and its generation. Various properties of steam such as internal energy, enthalpy, and entropy at different ambient conditions are discussed. The steam table and the Mollier diagram that are helpful in showing the methods to find the properties of steam at the given condition are also introduced. In addition to this, the working of steam generators (boilers) and the functions of various mountings and accessories used in boilers are also discussed.

Chapter 5 deals with the conversion of heat energy into mechanical energy or shaft power followed by discussion on the working of steam engines, steam turbines, and gas turbines in detail. These are the devices used to convert heat energy carried by steam or gases into shaft power. The shaft power is further converted into electrical energy using an electricity generator.

Chapter 6 describes internal combustion engines and their working. There is a wide scope to discuss various mechanisms and developments in I.C. engines, we have however focused our discussion only to the basic concepts of working on I.C. engines such as petrol (Gasoline) engines, diesel engines, two-stroke engines, four-stroke engines, thermodynamic cycles, and performance measurement of an I.C. engine.

Chapter 7 deals with the various modes of heat transfer. It gives a basic idea about the thermal conductivity and the overall heat transfer coefficient.

Chapter 8 covers refrigeration and air conditioning. Refrigeration deals with the various types of processes such as vapor compression refrigeration, air refrigeration, absorption type refrigeration, and the properties of some of the refrigerants. Air conditioning deals with psychrometric properties of air and the processes to control these properties.

Chapter 9 covers fluid mechanics and hydraulic machines. Fluid mechanics provides an introduction to fluid statics and fluid dynamics. Hydraulic machines deal with the working of water turbines, water pumps, hydraulic coupling, and torque converters.

Chapter 10 describes air compression systems. Single-stage and multistage compressors, as well as rotary compressors, are discussed in detail and vane type compressors, centrifugal compressors, and axial flow compressors are discussed at an introductory level.

Chapter 11 describes centroid, the center of gravity and moment of inertia for various sections. Parallel and perpendicular axis theorems are used to find the moment of inertia for the different cross sections. This chapter is very useful to analyze the dynamics of a machine element.

Chapter 12 describes stress and strain, that is, the properties of materials under various types of loading. It also demonstrates relationships among different types of elastic constants.

Chapter 13 deals with springs, different types of CAMs and followers, bushing and bearing.

Chapter 14 describes the working of flywheel and governor. Flywheel works just like an energy reservoir while governor controls the speed by controlling the fuel supply.

Chapter 15 deals with power transmission devices such as belt drive, chain drive, and gear drive. In belt drive, we discuss open and cross belt drives and their applications; in the chain drive, we provide a basic idea about the power transmission mechanisms; and in gear drive, we discuss different types of gears and working on gear trains.

Chapter 16 covers other types of power transmission devices such as coupling and clutch. It also discusses the mechanisms of various types of braking systems. Clutch provides a flexibility to engage or disengage the engine from the load.

Chapter 17 covers some of the important engineering materials and their mechanical properties such as tensile strength, hardness, toughness, ductility, malleability, etc. Some practical methods to measure the tensile strength, hardness, and toughness are also discussed.

Chapter 18 demonstrates various types of measurements such as the measurement of pressure, velocity, flow, force, torque, etc. Also, some of the devices used in metrology have been introduced such as vernier caliper, screw gauge, sine bar, dial gauge and slip gauge.

Chapter 19 deals with the mechanism of machining and working of various machine tools such as lathe, shaper and planer, drilling and boring, and milling operations.

Chapter 20 describes the primary shaping (casting) and joining (welding) processes such as welding. In this chapter, sand casting and other casting processes with casting defects are discussed. Different conventional and non-conventional welding and allied processes with welding defects are also explained.

Chapter 21 covers various forging operations, sheet metal processes, and powder metallurgy. These are the basic processes frequently used in mechanical workshops.

Chapter 22 provides a basic idea of the numerical control machine, computer numerical control machine, and direct numerical control machines. Also, the basic concepts of automation and robotics have been discussed. These are the machines used in metal cutting with improved productivity and accuracy.

Chapter 23 deals with heat treatment processes. In this chapter, the mechanism of controlling the mechanical properties by heating and cooling with different rates is discussed.

Preface to the First Edition

In many institutions and universities, Basic Mechanical Engineering is a compulsory paper for the first year engineering students. This book covers a basic overview of several areas of mechanical engineering. The main purpose to teach Basic Mechanical Engineering to the non-mechanical students is to provide the knowledge of the basic mechanical operations and familiarize the students with the commonly used mechanical machines/instruments. It is broadly divided into three parts—thermal engineering, mechanical design, and manufacturing engineering.

In thermal engineering, we discuss various forms of energy transfer, laws of thermodynamics, steam properties and steam generators, fluid mechanics, turbines, internal combustion engines, heat transfer, refrigeration and air conditioning, compressors, etc. In mechanical design, we discuss the mechanism of working of machine elements such as belt drive, chain drive, gear drive, springs, CAM and follower, bushing and bearing, couplings, etc. Also, some basic concepts of centroid and moment of inertia, stress and strain, power transmission, etc have been discussed. In manufacturing engineering, we discuss basic manufacturing processes such as casting, welding, machining, machine tools (Lathe, Drilling, Boring, Slotting, Shaper, Planer, Milling, and Grinding Machines), powder metallurgy, sheet metal working, smithy and metrology and provide a basic idea of automation (NC, CNC, DNC) and robotics. Thus, the basic concepts of mechanical engineering are covered completely and hence this book will be useful to both mechanical as well as other engineering students. In this book, the author has tried to cover the maximum syllabi of all the major institutions/universities in India.

Pravin Kumar

About the Author

Pravin Kumar obtained his Ph.D. from IIT Delhi and M.Tech. from Institute of Technology (BHU), Varanasi. Presently, he is working as a faculty in the Department of Mechanical Engineering, Delhi Technological University (Formerly Delhi College of Engineering). He has more than 16 years of teaching and research experience. He has been teaching Basic Mechanical Engineering for several years. He has also authored two more books—Industrial Engineering and Management, published by Pearson Education, and Fundamentals of Engineering Economics, published by Wiley India Pvt. Ltd. He has published more than 50 research papers in the National and International Journals and Conferences.

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I am grateful to my elder brothers Arun Kumar Singh and Pramod Kumar for their moral support and motivation to pursue my research and publish this work. I would like to thank my wife Dr Prerna Sinha and my sons Harshit and Arpit for their support, patience, and wholehearted participation in accomplishing this work. I am also grateful to all the well-wishers, whose names could not be mentioned here, for their direct and indirect support. I would also like to express my gratitude to my parents, father-in-law and mother-in-law, who remain a continuous source of inspiration.

Last but not least, I am immensely grateful to the Pearson Education, especially Harsha Singh and G. Sharmilee, for their continuous support during writing and editing process of the book. This book could not have attained its present form both in content and presentation without their active interest and direction.

Pravin Kumar

CHAPTER 1

Concepts of Thermodynamics and Properties of Gases

Learning Objectives

By the end of this chapter, the student will be able:

- To describe the basic concepts of thermodynamics
- To state the laws of thermodynamics
- To apply the laws of thermodynamics for different engineering applications
- To state the gas laws and solve the related problems

1.1 ► Introduction

There are different forms of energy; all the energy cannot be used as a work. The convertibility of energy into work depends on its availability, i.e., how much energy can be converted into useful work. Thermodynamics is a branch of science and engineering that deals with interaction of energy mainly in the forms of heat and work. Thermodynamics is concerned with the thermal behavior of a matter and its interaction with other physical and chemical behavior of the matter. Broadly, thermodynamics is studied into two forms—Classical and Statistical. Classical thermodynamics is concerned with the macrostructure of matter. It addresses the gross characteristics of large aggregations of molecules and not the behavior of individual molecules. The microstructure of matter is studied in kinetic theory and statistical mechanics. Statistical thermodynamics is concerned with the microstructure of the matter and addresses behavior of individual molecules of the matter. In this chapter, only classical approach to thermodynamics has been discussed. Gases are very important part of engineering thermodynamics; therefore, to know the behavior of an ideal gas at standard temperature and pressure is very important. In this chapter, we have also discussed about the different gas laws and universal gas constants.

Macroscopic Vs Microscopic Viewpoint of Thermodynamics

Macroscopic and Microscopic views are used to study the behavior of the matter. If the matter is studied about its behavior on the basis of certain amount or volume without consideration of its properties at the molecular level, it is known as macroscopic thermodynamics. If the matter is studied at its molecular level for its properties, it is known as microscopic thermodynamics. Both, macroscopic and microscopic thermodynamics are discussed in the following sections in detail.

Macroscopic (Classical Thermodynamics)

- In this approach, a certain quantity or volume of the matter is considered, without taking into account the events occurring at the molecular level.
- This approach to the study of thermodynamic properties does not require knowledge of the behavior of individual particles.
- It is only concerned with the effects of the action of many combined molecules, and these effects can be perceived by human senses.
- The macroscopic observations are completely independent of the assumptions regarding the nature of matter.

Microscopic (Statistical Thermodynamics)

- From the microscopic viewpoint, it is assumed that matter is composed of a large number of small molecules and atoms.
- This approach to the study of thermodynamics requires knowledge of the behavior of individual particles.
- It is concerned with the effects of the action of many molecules, and these effects cannot be perceived by human senses.
- The microscopic observations are completely dependent on the assumptions regarding the nature of matter.

1.2 ► Important Terminologies Used in Thermodynamics

Thermodynamics: It is the field of thermal engineering that studies the properties of systems that have a temperature and involve the laws that govern the conversion of energy from one form to another, the direction in which heat will flow, and the availability of energy to do the work.

Mass and Force: Mass is one of the fundamental dimensions, like time, it cannot be defined in terms of other dimensions. Much of our intuition of what mass is followed from its role in Newton's second law of motion

$$F = M \cdot f$$

In this relationship, the force F required to produce a certain acceleration f of a particular body is proportional to its mass M.

Volume: The familiar property, volume, is formally defined as the amount of space occupied in three-dimensional space. The *SI* unit of volume is cubic meters (m^3).

Pressure: For a fluid system, the pressure is defined as the normal force exerted by the fluid on a solid surface or a neighboring fluid element, per unit area. From a molecular point of view, the pressure exerted by a gas on the walls of its container is a measure of the rate at which the momentum of the molecules colliding with the wall is changed.

The SI unit for pressure is a Pascal,

$$1\ Pa = 1\ N/m^2$$

Also commonly used unit is bar, which is defined as

$$1 \text{ bar} = 10^5\ Pa = 10^5\ N/m^2$$

As a result of some practical devices measuring pressures relative to the local atmospheric pressure, we distinguish between gauge pressure and absolute pressure. Gage pressure is defined as

$$\boldsymbol{P_{\text{gauge}} = P_{\text{abs}} + P_{\text{atm}}}$$

System: System is the fixed quantity of matter and/or the region that can be separated from everything else by a well-defined boundary/surface. Thermodynamic system is the system on which thermodynamic investigation is done. The surface separating the system and surroundings is known as the *control surface* or *system boundary*. The control surface may be movable or fixed. Everything beyond the system is the *surroundings*. A system of fixed mass is referred to as a closed system. When there is flow of mass through the control surface, the system is called an *open system*. An *isolated system* is a closed system that does not interact in any way with its surroundings.

Properties of a System

Any characteristic of a system by which its physical condition is defined called as property. Pressure, temperature, volume, mass, viscosity, thermal conductivity, modulus of elasticity, thermal expansion coefficient, electrical resistivity, velocity, elevation, etc.

are the examples of the properties of a system. Properties may be either *intensive* or *extensive*.

- Intensive properties are those that are independent of the mass of a system, such as temperature, pressure, and density.
- Extensive properties are those whose values depend on the size or extent of the system. Total mass, total volume, and total momentum are some examples of extensive properties.
- Extensive properties per unit mass are called specific properties.

State: At any instant of time, the condition of a system is called a *state*. The state at a given instant of time is defined by the properties of the system such as pressure, volume, temperature, etc. A *property* is any quantity whose numerical value depends on the state but not on the history of the system. There are two types of properties—extensive and intensive. Extensive properties depend on the size or extent of the system. Volume, mass, energy, and entropy are examples of extensive properties. An extensive property is additive in the sense that its value for the whole system equals the sum of the values for its molecules. Intensive properties are independent of the size or extent of the system. Pressure and temperature are examples of intensive properties.

State and Equilibrium

When no change occurs in the system properties, at this point, all the properties can be measured or calculated throughout the entire system. The properties at this static condition describe the state of the system. At a given state, all the properties of a system have fixed values. If the value of even one property changes, the state will change to a different one. The word equilibrium implies a state of balance. In an equilibrium state, there are no unbalanced potentials/forces within the system. When a system is isolated from its surroundings, the system experiences no change in it. There are mainly three types of equilibrium, and a system is not in thermodynamic equilibrium unless the conditions of all the three relevant types of equilibrium are satisfied:

(a) Thermal equilibrium: Temperature should be same throughout the system.
(b) Mechanical equilibrium: Unbalanced forces should be absent, e.g., change in pressure.
(c) Chemical equilibrium: No chemical reaction and mass transfer occur.

Change in State: Thermodynamic system undergoes changes due to flow of mass and energy. The mode in which the changes in the state of a system take place is known as process such as isobaric (constant pressure) process, isochoric (constant volume) process, isothermal (constant temperature) process, adiabatic (constant entropy) process, etc. The path is the loci of series of state changes from initial state to final state during a process. The changes in state and path of a process are shown in Figure 1.1. The thermodynamic cycle refers to the sequence of processes in which initial and final states of the system are same. For example, Otto cycle, Diesel cycle, Duel cycle, Joule cycle, Rankine cycle, Carnot cycle, etc. have identical initial and final states.

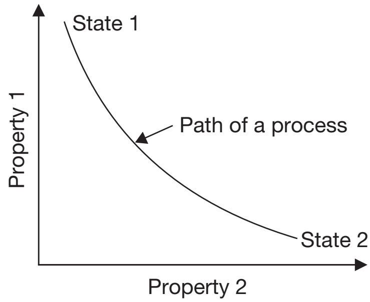

FIGURE 1.1

Change in State with a Process

Process: Two states are identical if, and only if, the properties of the two states are same. When any property of a system changes its value, there is a change in the state, and the system is said to undergo a *process*. When a system from a given initial state goes into a sequence of processes and finally returns to its initial state, it is said to have undergone a *cycle*.

Phase: Phase refers to a quantity of matter that is homogeneous throughout in its chemical composition and physical structure. A system can contain one or more phases. A mixture of water and water vapor has two phases. A pure substance is one that is uniform and invariable in chemical composition. A pure substance can exist in more than one phase, but its chemical composition must be the same in each phase. For example, if liquid water and water vapor form a system with two phases, the system can be regarded as a pure substance because each phase has the same composition.

Equilibrium: In thermodynamics the concept of equilibrium includes not only a balance of forces, but also a balance of other influencing factors, such as thermal equilibrium, pressure equilibrium, phase equilibrium, etc. To observe a thermodynamic equilibrium in a system, one may test it by isolation of the system from its surroundings and watch for changes in its observable properties. If no change takes place, it may be said that the system is in equilibrium. The system can be in an equilibrium state. When a system is isolated, it cannot interact with its surroundings; however, its state can change as a consequence of spontaneous changes occurring internally as its intensive properties, such as temperature and pressure, tend toward uniform values. When all such changes cease, the system is in equilibrium. At equilibrium, temperature and pressure are uniform throughout. If gravity is significant, a pressure variation with height can exist, as in a vertical column of liquid.

Systems and Control Volumes

A system is defined as a *quantity of matter or a region in space considered for study. The mass or region outside the system is called the surroundings.* The real or imaginary surface that separates the system from its surroundings is called the boundary. The boundary of a system can be *fixed or movable. The boundary is the* contact surface shared by both the systems and the surroundings. The boundary has zero thickness, and thus it can neither contain any mass nor occupy any volume in space.

Open and Closed Systems

Systems may be considered as closed, open, and isolated depending on the flow of mass and energy. A closed system consists of a fixed amount of mass, and no mass can cross its boundary. But energy, in the form of heat or work, can cross the boundary; and the volume of a closed system is not to be fixed necessarily. When the energy is also not allowed to cross the boundary, that system is called an isolated system. In an open system or a control volume, both mass and energy can cross the boundary of a control volume. In general, any arbitrary region in space can be selected as a control volume. The boundaries of a control volume are called a control surface, and they can be real or imaginary.

Zeroth Law of Thermodynamics

It is law of thermal equilibrium, which states that if a system A is in thermal equilibrium with systems B and C, then systems B and C will be in thermal equilibrium.

Zeroth law of thermodynamics is the basis of temperature measurement. To measure the temperature, a reference body is used, and a certain physical characteristic of this body, which changes with temperature is selected. The change in the selected characteristic may be taken as an indication of change in temperature. The selected characteristic is called the thermometric property, and the reference body, which is used in the determination of temperature is called the thermometer. A commonly used thermometer consists of a small amount of mercury in an evacuated capillary tube. In this case, the extension of the mercury in the tube is used as the thermometric property.

Quasi-static Process: When a process proceeds in such a way that the system remains infinitesimally close to an equilibrium state at all times, it is called a quasi static process. A quasi-static process can be understood as a sufficiently slow process that allows the system to adjust internally so that properties in one part of the system do not change any faster than those at other parts.

Temperature: Temperature is a property of a substance by which it can be differentiated from other substance in terms of degree of hot or cold. A scale of temperature independent of the thermometric substance is called a thermodynamic temperature scale. The Celsius temperature scale (centigrade scale) uses the degree Celsius (°C), which has the same magnitude as the Kelvin. Thus, temperature differences are identical on both scales. However, the zero point on the Celsius scale is shifted to 273.15 K, as shown by the following relationship between the Celsius temperature and the Kelvin temperature:

$$^{0}C = K - 273.15$$

Two other temperature scales are commonly used are the Rankine and Fahrenheit scale, the various relationships between temperature scales are as shown below:

$$R = 1.8\,K$$

$$F = R - 459.67$$

$$F = 1.8\,^{0}C + 32$$

Internal Energy: The Internal Energy (U) of a system is the total energy content of the system. It is the sum of the kinetic, potential, chemical, electrical, and all other forms of energy possessed by the atoms and molecules of the system. U is path independent and depends only on temperature for an ideal gas. Internal energy may be stored in the system in the following forms:

- Kinetic energy of molecules.
- Molecular vibrations and rotations.
- Chemical bonds that can be released during a chemical reaction.
- Potential energy of the constituents of the system.

Work: Work in thermodynamics may be defined as any quantity of energy that flows across the boundary between the system and surroundings which can be used to change the height of a mass in the surroundings.

Heat: Heat is defined as the quantity of energy that flows across the boundary between the system and surroundings because of a temperature difference between system and surroundings. There are following characteristics of heat:

- Heat is transitory and appears during a change in state of the system and surroundings. It is not a point function.
- The net effect of heat is to change the internal energy of the system and surroundings in accordance to first law.
- If heat is transferred to the system, it is positive and if it is transferred from the system it is negative.

Enthalpy: Enthalpy, h, of a substance is defined as $\boldsymbol{h = u + PV}$. It is intensive properties of a substance and measured in terms of kJ/kg.

1.3 ► Specific Heat Capacity

1.3.1 Specific Heat at Constant Volume (C_v)

The rate of change of internal energy with respect to absolute temperature at constant volume is known as specific heat at constant volume (C_v).

$C_v = \left(\frac{\partial u}{\partial T}\right)_v$; Where u is internal energy and T is absolute temperature.

$$\mathbf{Q = \Delta u + W = \Delta u + PdV = \Delta u = \int_{T_1}^{T_2} C_v dT}$$

Enthalpy is sum of internal energy and product of pressure and volume, i.e., $h = u + PV$. But,

$$Q = \partial u + PdV = \partial u + \partial(PV) = \partial(u + PV) = \partial h$$

since $dP = 0$ at constant pressure

1.3.2 Specific Heat at Constant Pressure (C_P)

The rate of change of enthalpy with respect to absolute temperature when pressure is constant is known specific heat at constant pressure (C_P).

$$C_P = \left(\frac{\partial h}{\partial T}\right)_P ;\ \text{for a constant pressure process.}$$

$$\mathbf{\partial h = \partial Q = \int_{T_1}^{T_2} C_P dT}$$

EXAMPLE 1.1

The property of a substance is given as

$$u = 186 + 0.718t$$
$$pv = 0.287(t + 273)$$

where u is the specific internal energy (kJ/kg), t is the temperature in °C, p is pressure in kN/m^2, and v is specific volume (m^3/k). Find the Cv and Cp of the substance.

SOLUTION

$$C_v = \frac{\delta u}{\delta t} = \mathbf{0.718\ kJ/kg}$$

$$C_p = \frac{\delta h}{\delta t} = \frac{\delta(u + pv)}{\delta t} = \frac{\delta u}{\delta t} + \frac{\delta(pv)}{\delta t} = 0.718\,kJ/kgK + 0.287\,kJ/kgK = \mathbf{1.005\ kJ/kgK}$$

1.3.3 Relationship Between C_p and C_v

The specific heat capacity of a gas is the amount of heat required to raise the temperature by one degree Celsius of unit mass of the gas. We will use here specific values of the state variables (of the variable divided by the mass of the substance). The value of the constant is different for different materials and depends on the process. It is not a state variable.

If we are considering a gas, it is most convenient to use forms of the thermodynamic equations based on the enthalpy of the gas. From the definition of enthalpy:

$$h = u + pv$$

where h in the specific enthalpy, p is the pressure, v is the specific volume, and u is the specific internal energy. During a process, the values of these variables change. Let's denote the change by Δ. For a constant pressure process the enthalpy equation becomes:

$$\Delta h = \Delta u + p\Delta v$$

The enthalpy, internal energy, and volume are all changed, but the pressure remains the same. From our derivation of the enthalpy equation, the change of specific enthalpy is equal to the heat transfer for a constant pressure process:

$$\Delta h = c_p . \Delta T$$

where ΔT is the change of temperature of the gas during the process, and c is the specific heat capacity. We have added a subscript p to the specific heat capacity at a constant pressure process.

The equation of state of a gas relates the temperature, pressure, and volume through a gas constant R. The gas constant is derived from the universal gas constant, but has a unique value for every gas.

$$pv = RT$$

For a constant pressure process:

$$p\Delta v = R\Delta T$$

Now let us consider a constant volume process with a gas that produces exactly the same temperature change as the constant pressure process that we have been discussing. Then the first law of thermodynamics tells us:

$$\Delta u = \Delta q - \Delta w$$

where q is the specific heat transfer and w is the work done by the gas. For a constant volume process, the work is equal to zero. And we can express the heat transfer as a constant times the change in temperature. This gives:

$$\Delta u = c_v \Delta T$$