Thermodynamics and Energy

Thermodynamics is the science of energy, including energy storage and energy in transit. The Conservation of Energy Principle states that energy cannot be created or destroyed, but can only change its form. The three forms of energy storage of greatest interest to us are Potential Energy (PE), Kinetic Energy (KE), and Internal Energy (U), which we introduce below. The two forms of energy in transit that we consider are Work (W) and Heat (Q), and the interactions between these various forms of energy are defined in terms of the First Law of Thermodynamics, which we introduce in Chapter 3.

A Word on Units

In this course we use the International System (SI) units exclusively, with occasional lapses. In the US this is an ongoing battle causing much confusion in the global technical environment (refer to wikipedia on this subject). Even the National Council of Examiners for Engineering and Surveying (NCEES) seems to be confused at this point - the Fundamentals of Engineering (FE) Reference Handbook and exam contain exclusively SI units and then, when you reach maturity and are ready to take the Professional Engineering (PE) exam, you find that the English system of units (USCS) is acceptable, and in some cases used exclusively. This confusion reached a new climax when in the Fall of 1999, NASA's $125 million Mars Climate Orbiter broke up in the Martian atmosphere, because scientists in one of NASA's subcontractors failed to convert critical data from the English system to the SI system of units.

Force and Work

We begin with Newton's Second Law, as follows:

$$\boxed{F\,[N] = m.a\;\left[kg.\frac{m}{s^2}\right]}$$

where: F is the force in Newtons [N]

m is the mass in kilograms [kg]

a is the acceleration in $meters/second^2$ $\left[\frac{m}{s^2}\right]$

The Weight of a body is the force acting on that body due to the acceleration due to gravity (g = 9.807 [m/s^2]), in accordance with the Universal Theory of Gravitation developed by Isaac Newton. Legend has it that Newton was inspired by an apple falling on his head, as is shown in a delightful website by Mike Guidry of the University of Tennessee on Sir Isaac Newton, in which we see a cartoon showing the apple falling on Newton's head.

Well, this legend is extremely relevant, since the weight of a small apple is approximately one Newton. Furthermore, the mass of a plastic bottle containing one liter of water is approximately one kilogram.
Quick Quiz - can you estimate how many Newtons (or apples) a liter of water weighs?

At this point we note that the major confusion of the English system of units came about because of the decision to define mass and force independently as 1 lb (pound), when in fact they are related through Newton's Second Law. In order to justify this one has to separately define a pound mass (lbm) and a pound force (lbf), thus since the acceleration due to gravity g = 32.2 [ft/s^2] we have:

$$1\ \text{lbf} = \left[\frac{32.2\ \text{lbm ft}}{\text{s}^2}\right]$$

One attempt to solve this paradox has been the introduction of a new unit of mass, the "slug", thus:

1 slug = 32.2 lbm

however I challenge anyone to go to the grocery store and request a slug of potatos.

We now consider the work done (W), the energy in transit requiring both the applied force (F) and movement (x). If the force (F) is constant over the distance moved (x) then the work done is given by:

$$\boxed{W\ [J] = F.x\ [Nm]}$$

where: W is the work done in Joules [J]
F is the force in Newtons [N]
x is the distance moved in meters [m]

However, in general the force (F) is not constant over the distance x, thus we need to sum all the incremental work processes taking into consideration the variation of the force (F). This leads to the equivalent integral form for determining work done (W) as follows:

$$\boxed{W\,[J] = \int F\,dx}$$

where: W is the work done in Joules [J]

F is the force in Newtons [N]

x is the distance moved in meters [m]

A Units Survival Kit for US Students

Over the years we have developed a basic Units Survival Kit (for the SI challenged) in order to help convert between the USCS (English) system and the SI (International) system of units, as well as to develop a feel for the magnitudes of the various units.

Distance, Velocity, Acceleration

$$g \approx 9.81\left[\frac{m}{s^2}\right] \approx 32.2\left[\frac{ft}{s^2}\right] \Rightarrow 1[m] = 3.28[ft]$$

$$4\left[\frac{m}{s}\right] \approx 9\left[\frac{miles}{hour}\right] \Leftrightarrow 80\left[\frac{km}{hour}\right] \approx 50\left[\frac{miles}{hour}\right]$$

Mass, Volume

$1[kg] \approx 2.2[lbm]$

$1[m^3]$ water $\approx 1000[kg] \Rightarrow$
1 Liter water $\approx 1[kg]$

$1[m^3]$ air $\approx 1.2[kg]$

Energy, Power

1 [kJ] (kiloJoule) $\approx$ 1 [BTU] (British Thermal Unit)

$^3/_4$ [kW] (kiloWatt) $\approx$ 1 [hp] (Horse Power)

more correctly:

1 [kJ] = 1.055 [BTU]

0.746 [kW] = 1 [hp]

Force, Pressure, Area

Weight of one small apple $\approx$ 1 [N] (Newton)

Area of a SI standard card table $\approx$ 1 $[m^2]$

Pressure due to apple sauce made from a single apple spread evenly accross the card table $\approx$ 1 [Pa] (Pascal)

Pressure due to the atmosphere $\approx$ 1[bar] (=1.0132 [bar])

$$1[bar] = 100[kPa] \approx 14.5\left[\frac{lbf}{in^2}\right] \text{ (psi)}$$

Quick Quiz - we all know (from reading our speedometers) that 50 mph is equivalent to 80 km/hr.

1. What is the accuracy of this conversion?
2. Use this information to show that 9 mph is equivalent to 4 m/s.

We find that with the above survival kit we can determine many unit conversions between SI & English units, typically as demonstrated in the following block:

Unit Conversions (SI $\Leftrightarrow$ English)

$$1\ m^3\left[\left(\frac{32.2\ ft}{9.81\ m}\right)^3\right] = 35.36\ ft^3$$

$$1\ lbf\left[\frac{32.2\ lbm\ ft}{s^2} \Big/ lbf\right]\left[\frac{kg}{2.2\ lbm}\right]\left[\frac{9.81\ m}{32.2\ ft}\right]\left[N \Big/ \frac{kg\ m}{s^2}\right] = 4.46\ N$$

As we progress and learn new concepts we will add to this Survival Kit.

Forms of Energy

We introduce the various forms of energy of interest to us in terms of a solid body having a mass m [kg]. These include potential, kinetic and internal energy. Potential energy (PE) is associated with the elevation of the body, and can be evaluated in terms of the work done to lift the body from one datum level to another under a constant acceleration due to gravity g [m/s^2], as follows:

$$W = \int_{h1}^{h2} F\,\mathbf{dx} = \int_{h1}^{h2} m.g\,\mathbf{dx} = m.g(h_2 - h_1) = m.\Delta pe = \Delta PE$$

Kinetic energy (KE) of a body is associated with its velocity $\vec{V}$[m/s] and can be evaluated in terms of the work required to change the velocity of the body, as follows:

$$W = \int F\,\mathbf{dx} = \int m.a\,\mathbf{dx} = \int m.\frac{\mathbf{d}\vec{V}}{\mathbf{dt}}\mathbf{dx}$$

however, velocity $\vec{V} = \dfrac{\mathbf{dx}}{\mathbf{dt}}$, thus integrating from $\vec{V}_1$ to $\vec{V}_2$:

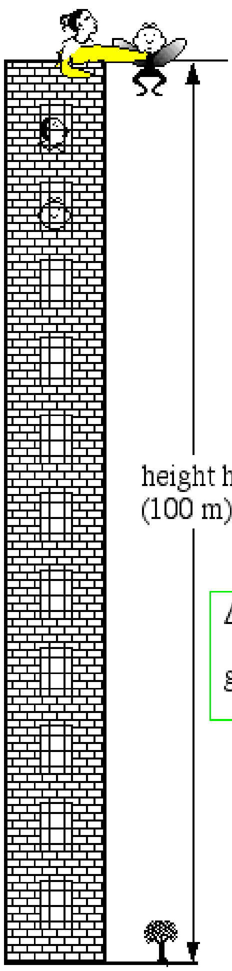
$$W = \int_{\vec{V}_1}^{\vec{V}_2} m.\vec{V}\,\mathbf{d}\vec{V} = m.\left(\frac{\vec{V}_2^{\,2} - \vec{V}_1^{\,2}}{2}\right) = m.\Delta ke = \Delta KE$$

Internal energy (U) of a body is that associated with the molecular activity of the body as indicated by its temperature T [°C], and can be evaluated in terms of the heat required to change the temperature of the body having a specific heat capacity C [J/kg.°C], as follows:

$$Q = m.C.\Delta T = m.\Delta u = \Delta U$$

Cooking with Potential Energy

In order to gain an intuitive appreciation for the relative magnitudes of the different forms of energy we consider the (tongue-in-cheek) example of an attempt to cook a turkey by potential energy. The turkey is brought to the top of a 100 m building (about 30 stories) and then dropped from the ledge. The potential energy is thus converted into kinetic energy, and finally on impact the kinetic energy is converted into internal energy. The increase in internal energy is represented by an increase in temperature, and hopefully, if this experiment is repeated enough times the temperature increase will allow the turkey to cook. This remarkable experiment was first reported by R.C.Gimmi and Gloria J Browne - "Cooking with Potential Energy", published in the Journal of Irreproducible Results (Vol 33, 1987, pp 21-22).



Potential Energy:

$$W = \int_0^h F\,dx = \int_0^h m\,g\,dx$$

$$\boxed{W = m.g.h = \Delta PE}$$

Kinetic Energy:

$$W = \int F\,dx = \int m\,g\,dx = \int m\frac{d\vec{V}}{dt}\,dx$$

$$= m\int \frac{dx}{dt}\,d\vec{V} = m\int_0^{\vec{V}} \vec{V}\,d\vec{V}$$

$$\boxed{W = \frac{m.\vec{V}^2}{2} = \Delta KE}$$

Internal Energy:

$$\boxed{Q = m.C.\Delta T = \Delta U}$$

Equating all three energy forms:

$$\Delta PE = \Delta KE = \Delta U \quad [J]$$

$$m.g.h = \frac{m.\vec{V}^2}{2} = m.C.\Delta T$$

Since mass m is common, evaluate specific energy (h = 100 m):

$$\Delta pe = \Delta ke = \Delta u \quad [J/kg]$$

$$g.h = \frac{\vec{V}^2}{2} = C.\Delta T \approx 1000 \; [J/kg]$$

$$\left(g = 9.81\left[\frac{m}{s^2}\right],\; g.h \approx 1000\left[\frac{m^2}{s^2}\right]\right)$$

$$\frac{\vec{V}^2}{2}\left[\frac{m^2}{s^2}\right] = 1000\left[\frac{J}{kg}.\frac{N.m}{J}.\frac{kg.m}{s^2}.\frac{1}{N}\right] \quad \text{(Units check)}$$

$$\vec{V}_{impact} = \sqrt{2000} = 44.7\left[{}^{m}\!/_{s}\right] \; (\approx 100\text{ mph!})$$

We estimate the specific heat of a turkey: $C = 3000\;[J/kg\,^\circ C]$

Thus $C\,\Delta T = 3000\,\Delta T = 1000\;[J/kg] \Rightarrow \boxed{\Delta T = 0.33^\circ C}$

What a disappointment! At 0.33°C per fall it will require repeating the experiment 600 times just to reach the cooking temperature of 200°C.

Source: http://www.ohio.edu/mechanical/thermo/Intro/Chapt.1_6/Chapter1.html