First Law of Thermodynamics

Dr. Manoj Ranaweera
Senior Lecturer
Department of Mechanical Engineering

Learning Outcomes

- This lecture facilitates students to achieve some parts of the intended learning outcome LO1
  - ✓ LO1:
    - state the First Law of Thermodynamics and define heat, work, thermal efficiency and the difference between various forms of energy.

Introduction

- The first law stipulates the concept of conservation of energy by its nature.
- The first law is an expression of the behavior of the nature. Thus, it cannot be mathematically proven.
- However, any violation of the first law is a violation of natural law. Thus, such a process does not exist.

Introduction

- The first law was first defined for closed systems undergoing thermodynamic cycles. However, this does not impose any constraints on the application of 1st law into processes as well as other systems.

The First Law

"When a system (closed) undergoes a thermodynamic cycle, sum of the net heat supplied to the system from its surroundings and the net work input to the system from its surroundings must equal zero"

$$\sum Q + \sum W = 0$$

In a simplified statement:
"Energy cannot be created nor be destroyed, it can only change from one form to another"

Example:

A turbine of a steam power plant develops 1 MW. The heat supplied to the steam in the boiler is 2800 kJ/kg, the heat rejected by the turbine to the cooling water is 2100 kJ/kg and the feed-pump power required to pump the condensate back into the boiler is 5 kW. Calculate the steam flow rate in kg/s.

Source: Eastop, T.D. and McConkey, A., Applied Thermodynamics for Engineering Technologist, 5th Edition, Pearson, pp. 38

Sign Convention

- Because heat and work transfer can happen in both directions between system and surrounding, a sign convention is needed.
- There are different sign conventions, stick to one.
- This lecture series considers the following sign convention

Heat supplied to the system - POSITIVE
Work done by the system - POSITIVE

Heat rejected by the system - NEGATIVE
Work done on the system - NEGATIVE

Corollary 1:

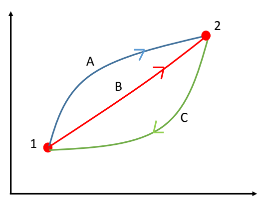
"There exists a property of a closed system such that a change in its value is equal to the sum of the net heat and work transfer during any change of state"

$$\sum(Q+W) = \Delta U$$

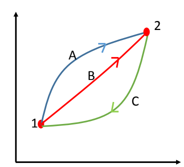
This can be proven by method of contradiction while accepting the validity of the 1st law.

Corollary 1: Proof

Consider two independent thermodynamic processes (process A and B) which transform a closed system from state 1 to state 2. The third process (process C) brings the state 2 back to state 1 making a complete thermodynamic cycle.



Corollary 1: Proof



Let the property in consideration is U.

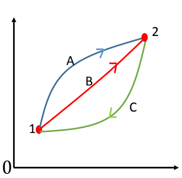
$$\sum(Q+W)_A = \Delta U \rightarrow (1)$$

$$\sum(Q+W)_B = \Delta U \rightarrow (2)$$

Assume the converse of the proposition of the corollary 1 is true.

$$\sum(Q+W)_A \neq \sum(Q+W)_B \rightarrow (3)$$

Corollary 1: Proof



Consider the cycles AC and BC and apply the 1st law.

$$\oint(Q+W)_{AC} = \oint(Q+W)_{BC} = 0$$

$$\sum(Q+W)_A + \sum(Q+W)_C = \sum(Q+W)_B + \sum(Q+W)_C$$

$$\sum(Q+W)_A = \sum(Q+W)_B$$

This invalidates the assumption made in Equation 3. Thus, the assumption is wrong. Consequently, the converse of the proposition is wrong. Therefore, the corollary is true.

Corollary 2:

"The internal energy of a closed system remain unchanged if the system is isolated from its surrounding"

$$\sum(Q+W) = \Delta U$$

$$If\ Q = 0\ and\ W = 0\ then, \Delta U = 0$$

Corollary 3:

"Perpetual motion machine of first kind is impossible"

Perpetual motion machine of first kind is a machine which continuously produce work without any heat input

Non-flow energy equation

- The first law is not only for cycles. It can be applied to any thermodynamic process.
- The generic application of the 1st law for a closed system undergoing a thermodynamic process is known as the non-flow energy equation.

$$\begin{pmatrix}\text{Net energy transferred to (or from)}\\ \text{the system as heat and work}\end{pmatrix}=\begin{pmatrix}\text{Net increase (or decrease) in}\\ \text{the total energy of the system}\end{pmatrix}$$

$$Q - W = \Delta E$$

Non-flow energy equation

$$\begin{pmatrix}\text{Net energy transferred to (or from)}\\ \text{the system as heat and work}\end{pmatrix}=\begin{pmatrix}\text{Net increase (or decrease) in}\\ \text{the total energy of the system}\end{pmatrix}$$

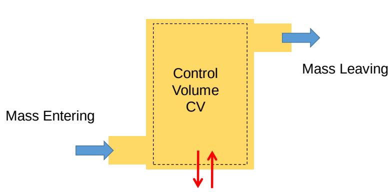
$$Q - W = \Delta E$$

$$Q - W = \Delta U + \Delta KE + \Delta PE$$

First law for flow / open systems

- Thermodynamic analysis of flow processes are generally done using control volumes.
- A control volume is an arbitrary shaped volume where both mass and heat can cross the system boundary.
- When a flow process, energy can cross the system boundary not only as heat and work.
- Mas entering and leaving the system is also associated with energy transfer.

Control Volume (Open Systems)



First Law for Open Systems

$$\begin{pmatrix}\text{Total Energy}\\ \text{crossing CV}\\ \text{boundary as}\\ \text{heat and work}\end{pmatrix}+\begin{pmatrix}\text{Total Energy}\\ \text{of the mass}\\ \text{entering the CV}\end{pmatrix}-\begin{pmatrix}\text{Total energy}\\ \text{of the mass}\\ \text{leaving the CV}\end{pmatrix}=\begin{pmatrix}\text{Net change}\\ \text{in energy of}\\ \text{the CV}\end{pmatrix}$$

$$Q - W + \Sigma E_{in} - \Sigma E_{out} = \Delta E_{CV}$$

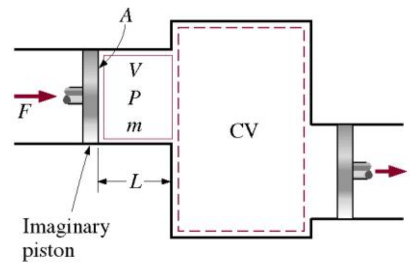
Flow work

- It is the energy required to push fluid mass into and out of the control volume
- It is considered to be part of the energy transported during the process under consideration

$$w_{flow} = Pv$$

Flow work is generally referred to as flow energy too.

Flow Work



Total energy of a flowing fluid (θ)

$$\begin{pmatrix}\text{Total energy of a}\\ \text{non flow system (e)}\end{pmatrix} = u + \frac{V^2}{2} + gz$$

$$\begin{pmatrix}\text{Total energy of a}\\ \text{flow system }(\theta)\end{pmatrix} = e + \textit{flow energy}\,(Pv)$$

$$\theta = u + Pv + \frac{V^2}{2} + gz$$

$$\theta = h + \frac{V^2}{2} + gz$$

Steady flow processes

- Steady
  - ✓ Properties does not change with time
- Steady Flow Process
  - ✓ Fluid properties may change from one point to the other point within the control volume, but at any fixed point they remain the same during the entire process

Characteristics of steady flow

- Properties within the control volume do not change with time
- Properties at the boundaries do not change with time
- Heat and work interaction between system and surrounding do not change with time

First law for steady flow process

$$\begin{pmatrix}\text{Total Energy}\\ \text{crossing CV}\\ \text{boundary as}\\ \text{heat and work}\end{pmatrix} + \begin{pmatrix}\text{Total Energy}\\ \text{of the mass}\\ \text{entering the CV}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{of the mass}\\ \text{leaving the CV}\end{pmatrix} = \underbrace{\begin{pmatrix}\text{Net change}\\ \text{in energy of}\\ \text{the CV}\end{pmatrix}}_{0}$$

$$\begin{pmatrix}\text{Total Energy}\\ \text{crossing CV}\\ \text{boundary as}\\ \text{heat and work}\end{pmatrix} = \begin{pmatrix}\text{Total Energy}\\ \text{of the mass}\\ \text{leaving the CV}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{of the mass}\\ \text{entering the CV}\end{pmatrix}$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_e\,\theta_e - \sum \dot{m}_i\theta_i$$

First law for steady flow process

- General form of the first law for steady flow process

$$\dot{Q} - \dot{W} = \sum \dot{m}_e \left(h_e + \frac{C_e^2}{2} + gz_e \right) - \sum \dot{m}_i \left(h_i + \frac{C_i^2}{2} + gz_i \right) \quad kW$$

- Special Cases
  - ✓ For a single stream steady flow process

$$\dot{Q} - \dot{W} = \dot{m} \left(h_e - h_i + \frac{C_e^2 - C_i^2}{2} + g(z_e - Z_i) \right) \quad kW$$

To prevent confusions between volume and velocity, letter C is generally used to represent velocity.

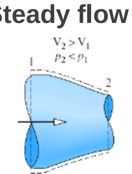
Steady flow energy equation (SFEE)

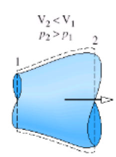
- Usually, thermodynamic analysis of devices are done on per unit mas basis to simplify the scalability of analysis.

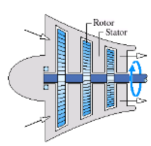
- The SFEE on unit mass basis can be expressed as:

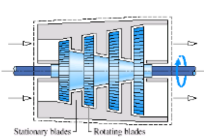
$$\boxed{q - w = \left(h_e - h_i + \frac{C_e^2 - V_i^2}{2} + g(z_e - Z_i) \right) \quad kJ/kg}$$

Steady flow devices









Examples

1. During a working stroke, an engine rejects 200 kJ/kg of heat of the working substance. The total energy of the working substance also decreases by 350 kJ/kg. Determine the work done by the engine

Examples

2. A steam turbine in a power plant develops 2000 kW. The heat supplied to the steam in the boiler is 3500 kJ/kg, the heat rejected by the steam to the cooling water in the condenser is 1800 kJ/kg. The feed-pump work required to pump the condensate back into the condenser is 7.5 kW. Calculate the mass flow rate of the steam.

Examples

3. A fluid flows through a steady flow open system at the rate of 3 kg/s. At the inlet, the pressure, velocity, and internal energy are 5atm, 150 m/s, and 2000kJ/kg, respectively, and the specific volume is 0.4 m^3/kg. The fluid leaves the system with 1.2atm, 80 m/s, an internal energy of 1300 kJ/kg and specific volume of 1.1 m^3/kg. The fluid loses 25kJ/kg through heat transfer during the process. Determine the power output of the system, neglect the changes in potential energy.

Examples

4. In the turbine of a gas turbine plant, the gases flow through the turbine at 17 kg/s and the power developed by the turbine is 14 MW. The specific enthalpies of the gases at the inlet and the outlet are 1,200 kJ/kg and 360 kJ/kg, respectively and the velocities of the gases at the inlet and the outlet are 60 m/s and 150 m/s, respectively Calculate the rate at which heat is rejected from the turbine. Find the area of the inlet pipe given that the specific volume of the gases at the inlet is 0.5 m^3/kg

Wrap up