

ME 266 THERMODYNAMICS 1

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THE FIRST LAW OF THERMODYNAMICS

An Energy Conservation Principle

- **First Law for a Cycle:**

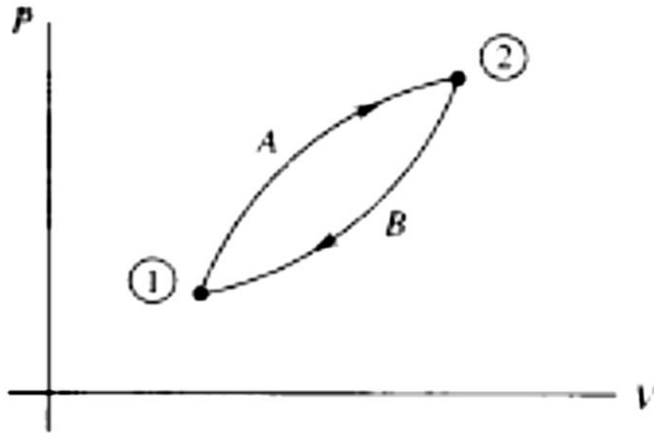
$$\sum W = \sum Q \quad \text{or} \quad \oint \delta W = \oint \delta Q$$

– the net heat transfer is equal to the net work done for a system undergoing a cycle.

THE FIRST LAW OF THERMODYNAMICS

An Energy Conservation Principle

- First Law for a Cycle:



$$\int_1^2 \delta Q_A + \int_2^1 \delta Q_B = \int_1^2 \delta W_A + \int_2^1 \delta W_B$$

$$\int_1^2 \delta(Q - W)_A = \int_1^2 (Q - W)_B$$

The change in the quantity **$Q - W$** from state 1 to state 2 is the same along **path A** as along **path B**. Since this change is **independent of the path** between states 1 and 2 we may write:

$$dQ - dW = dE$$

THE FIRST LAW OF THERMODYNAMICS

An Energy Conservation Principle

- First Law for a Cycle:

$$dQ - dW = dE$$

The quantity **E is an extensive property** of the system and represents the energy of the system at a particular state. Integration yields:

$$Q_{1-2} - W_{1-2} = E_2 - E_1$$

Q_{1-2} is the heat transferred to the system during the process from state 1 to state 2, W_{1-2} is the work done by the system on the surroundings during the process, and E_2 and E_1 are the values of the property **E**.

THE FIRST LAW OF THERMODYNAMICS

An Energy Conservation Principle

The property **E** represents all of the energy: **kinetic energy KE**, **potential energy PE**, and **internal energy U**.

The first law of then takes the form:

$$Q_{1-2} - W_{1-2} = KE_2 - KE_1 + PE_2 - PE_1 + U_2 - U_1$$
$$= \frac{1}{2} m(V_2^2 - V_1^2) + mg(z_2 - z_1) + U_2 - U_1$$

E is an extensive property with associated intensive property **e**.

THE FIRST LAW OF THERMODYNAMICS

An Energy Conservation Principle

Enthalpy:

- In the solution of problems involving systems, certain products or sums of properties occur with regularity.
- One such combination of properties is the **Enthalpy**, defined as:
- **$H = U + PV$** or **$h = u + Pv$** on a unit mass basis.
- For a constant-pressure equilibrium process, heat transferred is may be found as:

$$Q_{1-2} = H_2 - H_1$$

THE FIRST LAW OF THERMODYNAMICS

An Energy Conservation Principle

SPECIFIC HEAT:

The heat required to raise the temperature of a unit mass of a substance by 1 °C.

$$Q_{1-2} = \int_1^2 m C_n dT$$

where C_n is the specific heat.

For a **constant pressure** process:

$$Q_{1-2} = \int_1^2 m C_p dT$$

For a constant volume process:

$$Q_{1-2} = \int_1^2 m C_v dT$$

THE FIRST LAW OF THERMODYNAMICS

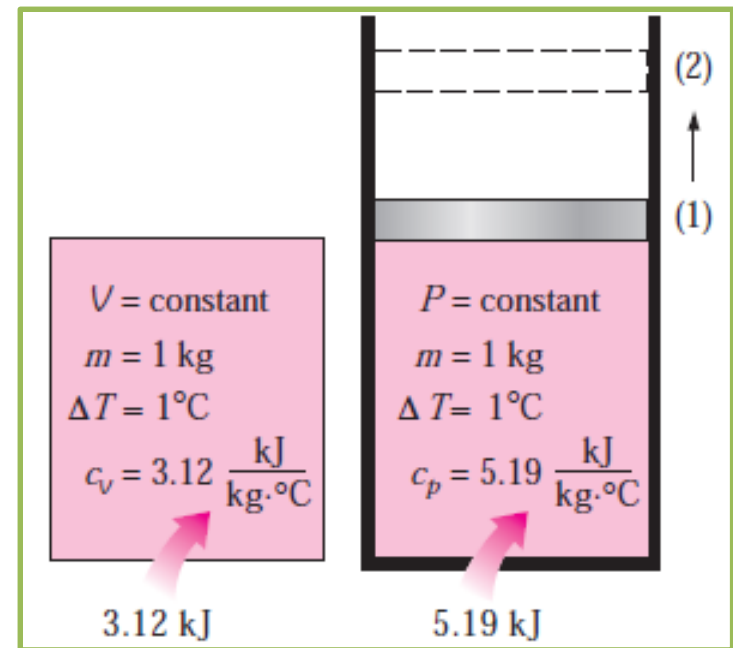
Specific Heats

- Specific Heat: the energy required to raise the temperature of a unit mass of a substance by one degree.
- In general, this energy depends on how the process is executed.
- In thermodynamics, we are interested in two kinds of specific heats:
 1. Specific heat at constant volume C_v
 2. Specific heat at constant pressure C_p

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Specific Heats

- Physically, the **specific heat at constant volume C_v** can be viewed as the energy required to raise the temperature of the unit mass of a substance by one degree as the volume is maintained constant.
- The energy required to do the same as the pressure is maintained constant is the **specific heat at constant pressure C_p** .



THE FIRST LAW OF THERMODYNAMICS

Specific Heats

- In a **constant-volume process**, the amount of energy added may be expressed as:

$$\delta e_{\text{in}} - \delta e_{\text{out}} = du$$

$$c_v dT = du$$

$$c_v = \left(\frac{\partial u}{\partial T} \right)_v$$

- an expression for the specific heat at constant pressure c_p can be obtained by considering a constant-pressure expansion or compression process.

$$c_p = \left(\frac{\partial h}{\partial T} \right)_p$$

- Units:**

$$\text{kJ/kg} \cdot ^\circ\text{C} \text{ or } \text{kJ/kg} \cdot \text{K}$$

$$\text{kJ/kmol} \cdot ^\circ\text{C} \text{ or } \text{kJ/kmol} \cdot \text{K}$$

$$c_v = \left(\frac{\partial u}{\partial T} \right)_v$$

= the change in internal energy with temperature at constant volume

$$c_p = \left(\frac{\partial h}{\partial T} \right)_p$$

= the change in enthalpy with temperature at constant pressure

THE FIRST LAW OF THERMODYNAMICS

Internal Energy, Enthalpy, and Specific Heats of Ideal Gases

- Ideal gases by definition obey the equation:

$$Pv = RT$$

- It has been demonstrated (mathematically and experimentally) that for an ideal gas the internal energy is a function of the temperature only. That is:

$$u = u(T)$$

- From the definitions above:
$$\left. \begin{array}{l} h = u + Pv \\ Pv = RT \end{array} \right\} h = u + RT$$

- Since **R** is constant and **u = u(T)**, it follows that enthalpy is a function of temperature only: $h = h(T)$

THE FIRST LAW OF THERMODYNAMICS

Internal Energy, Enthalpy, and Specific Heats of Ideal Gases

- For ideal gases u , h , C_v , and C_p are functions of temperature alone:

$$\Delta u = u_2 - u_1 = \int_1^2 c_v(T) dT \cong c_{v,\text{avg}}(T_2 - T_1)$$
$$\Delta h = h_2 - h_1 = \int_1^2 c_p(T) dT \cong c_{p,\text{avg}}(T_2 - T_1)$$

**Ratio of specific heats:
1.667 for mono-
atomic gases and 1.4
for diatomic gases**

- For ideal gases, C_v and C_p are related by:

$$c_p = c_v + R \quad (\text{kJ/kg} \cdot \text{K})$$

$$k = \frac{c_p}{c_v}$$

- For incompressible substances (liquids and solids), both the constant-pressure and constant-volume specific heats are identical and denoted by c :

$$c_p = c_v = c \quad (\text{kJ/kg} \cdot \text{K})$$

THE FIRST LAW OF THERMODYNAMICS

Constant-Temperature Process

$$Q - W = \Delta U$$

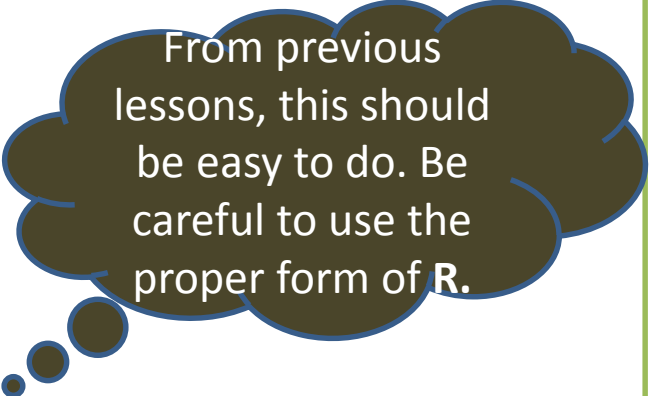
- the internal energy depends only on the temperature and thus $\Delta U = 0$ for an isothermal process; for such a process:

$$Q = W$$

$$W = \int_{V_1}^{V_2} P dV$$

$$= mRT \int_{V_1}^{V_2} \frac{dV}{V} = mRT \ln \frac{V_2}{V_1} = mRT \ln \frac{P_1}{P_2}$$

$$P_1 V_1 = P_2 V_2$$



From previous lessons, this should be easy to do. Be careful to use the proper form of **R**.

THE FIRST LAW OF THERMODYNAMICS

Constant-Volume Process

- Since dV is zero, work PdV is zero and the first law becomes: $Q = \Delta U$

- For an ideal gas with constant C_v :

$$Q = mC_v(T_2 - T_1) \quad \text{or} \quad q = c_v(T_2 - T_1)$$

THE FIRST LAW OF THERMODYNAMICS

Constant-Pressure Process

- For a constant pressure process:

$$Q = \Delta H$$

$$Q = m \int_{T_1}^{T_2} C_p dT$$

$$Q = mC_p(T_2 - T_1)$$

THE FIRST LAW OF THERMODYNAMICS

Adiabatic Process

- For an adiabatic process:
- $Q=0$
- $-\delta W = du$
- $du + Pdv = 0$
- For an ideal gas: $C_v dT + \frac{RT}{v} dv = 0$

Rearrange and integrate between states 1 and 2, assuming constant C_v

$$\frac{C_v}{R} \ln \frac{T_2}{T_1} = -\ln \frac{v_2}{v_1}$$

- this can be put in several forms:

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2}\right)^{\frac{k}{C_v}} = \left(\frac{v_1}{v_2}\right)^{k-1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} \quad \text{and} \quad \frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^k$$

FIRST LAW APPLIED TO CONTROL VOLUMES

Conservation of Mass - Continuity

- In a steady flow mode, the amount of mass that enters a control volume can be expressed

as:
$$\begin{aligned}\Delta m_1 &= \text{volume} \times \text{density} = \text{area} \times \text{length} \times \text{density} \\ &= \text{area} \times (\text{velocity} \times \text{time}) \times \text{density} \\ &= A_1 V_1 \Delta t \rho_1\end{aligned}$$

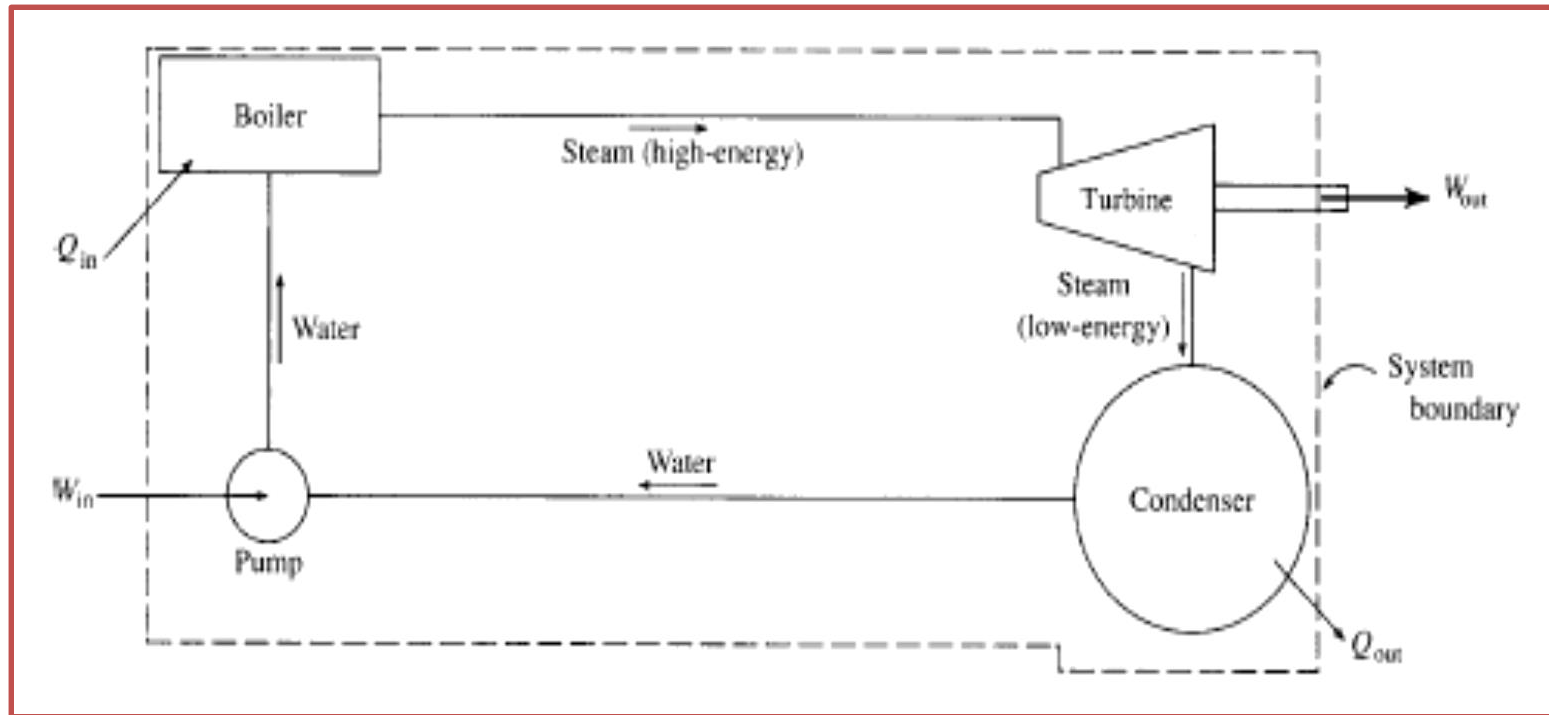
- Similarly, the mass leaving the control volume can be expressed as: $\Delta m_2 = A_2 V_2 \Delta t \rho_2$

- For steady flow, $\Delta m_1 = \Delta m_2$

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2$$

Also note that Volumetric Flow, $Q \text{ (m}^3\text{/s)} = A * V$

Schematic of a Power Plant



For an analysis of this system, we must relate W_{in} , Q_{in} , W_{out} , and Q_{out} to the pressure and temperature changes for the pump, boiler, turbine, and condenser, respectively.

The Energy Equation

- The first law for a steady-state device can be stated as:

$$Q - W = E_{sys}(t + \Delta t) - E_{sys}(t)$$

$$Q - W = \rho_2 A_2 V_2 \Delta t \left(u_2 + \frac{1}{2} V_2^2 + g z_2 \right) - \rho_1 A_1 V_1 \Delta t \left(u_1 + \frac{1}{2} V_1^2 + g z_1 \right)$$

The Energy Equation

- The **work W** is composed of two parts:
 1. the work, sometimes called **flow work**, due to the pressure needed to move the fluid into and from the device.
 2. and the work that results from a shaft that is usually rotating, called shaft work **W_s** , that operates inside the device.

$$W = P_2 A_2 V_2 \Delta t - P_1 A_1 V_1 \Delta t + W_s$$

The Energy Equation

- Substitute the expression for work W :

$$W = P_2 A_2 V_2 \Delta t - P_1 A_1 V_1 \Delta t + W_s$$

into

$$Q - W = \rho_2 A_2 V_2 \Delta t \left(u_2 + \frac{1}{2} V_2^2 + g z_2 \right) - \rho_1 A_1 V_1 \Delta t \left(u_1 + \frac{1}{2} V_1^2 + g z_1 \right)$$

- and express the **flow work** term as

$\rho A V (P/\rho) \Delta t$. The first law is then arranged as

$$Q - W_s = \rho_2 A_2 V_2 \left(\frac{V_2^2}{2} + g z_2 + u_2 + \frac{P_2}{\rho_2} \right) \Delta t - \rho_1 A_1 V_1 \left(\frac{V_1^2}{2} + g z_1 + u_1 + \frac{P_1}{\rho_1} \right) \Delta t$$

The Energy Equation

- Dividing through by Δt , we obtain:

$$\dot{Q} - \dot{W}_s = \dot{m} \left(\frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) + u_2 - u_1 + \frac{P_2}{\rho_2} - \frac{P_1}{\rho_1} \right)$$

- Where:

$$\dot{m} = \dot{m}_1 = \dot{m}_2$$

- And:

$$\dot{Q} = \frac{Q}{\Delta t}, \dot{W}_s = \frac{W_s}{\Delta t}, \dot{m} = \rho AV$$

- For many devices in Thermodynamics, KE and PE changes are negligible, hence we may write:

$$\dot{Q} - \dot{W}_s = \dot{m}(h_2 - h_1)$$

The Energy Equation

$$\dot{Q} - \dot{W}_s = \dot{m}(h_2 - h_1)$$

$$\text{since } h = u + Pv = u + P/\rho$$

- On a unit mass basis:

$$q - w_s = h_2 - h_1$$

For a steady flow with $\rho_2 = \rho_1 = \rho$, neglecting heat transfer and changes in internal energy, the energy equation takes the form:

$$\dot{W}_s = \dot{m} \left[\frac{P_2 - P_1}{\rho} + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) \right]$$

This form of the Energy Equation is useful for the analysis on pumps and hydro turbines.

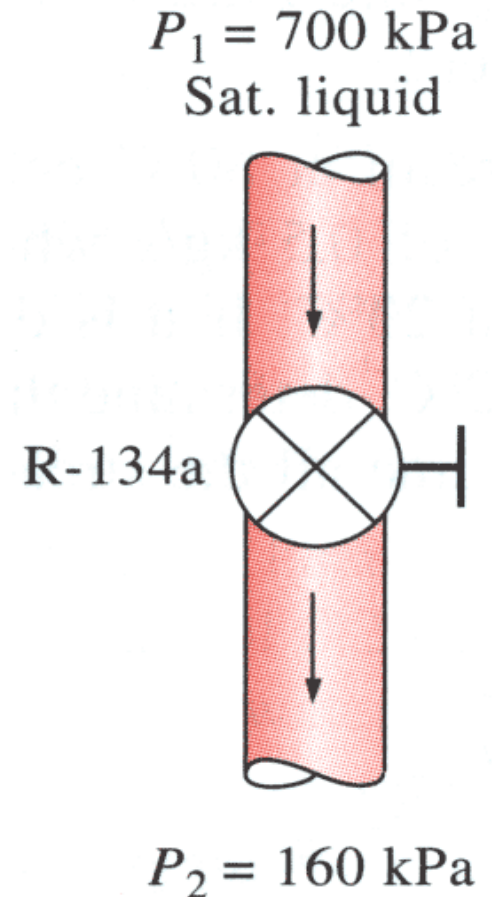
APPLICATIONS OF THE ENERGY EQUATION

Throttling Devices

A throttling device involves a steady-flow adiabatic process that provides a pressure drop with no significant potential energy changes, kinetic energy changes, heat transfer, or work.

The Energy Equation then becomes:

$$h_2 = h_1$$



Throttling valves find major application in refrigeration and air-conditioning

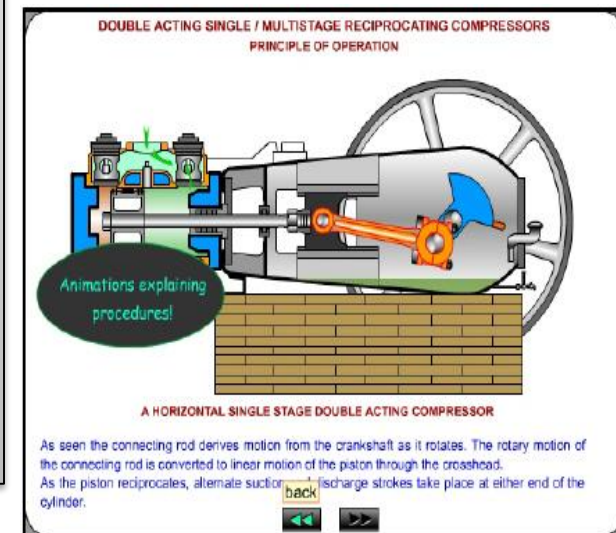
APPLICATIONS OF THE ENERGY EQUATION

COMPRESSORS, PUMPS, AND TURBINES

Pumps are devices that transfer energy to a **liquid** (incompressible fluid), result in **pressure increase**.

A compressor is a machine for raising a **gas** - a compressible fluid - to a **higher level of pressure**.

A turbine, on the other hand, is a device in which **work is done by the fluid** on a set of rotating blades.



APPLICATIONS OF THE ENERGY EQUATION

COMPRESSORS, PUMPS, AND TURBINES

ANALYSIS

- Heat transfer is usually negligible
- Kinetic and Potential Energy changes are also usually very small and are often ignored

Therefore at steady-state the energy equation for these devices becomes:

$$-\dot{W}_s = \dot{m}(h_2 - h_1) \quad \text{or} \quad -w_s = h_2 - h_1$$

For liquids, such as water, the energy equation neglecting kinetic and potential energy changes, becomes:

$$-\dot{W}_s = \dot{m} \frac{P_2 - P_1}{\rho}$$



Please note the direction of Work done in all these devices

APPLICATIONS OF THE ENERGY EQUATION

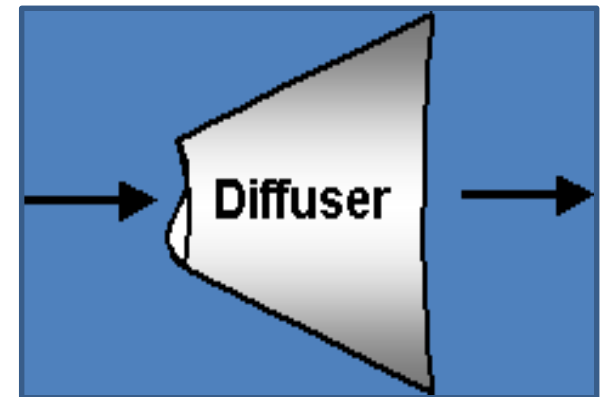
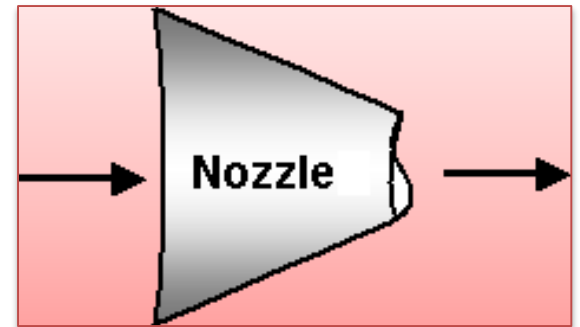
Nozzles and Diffusers

A nozzle is a device that increases the velocity of a fluid at the expense of pressure.

The chief use of nozzle is to produce a jet of steam (or gas) of high velocity to produce thrust for the propulsion of rocket motors and jet engines and to drive steam or gas turbines

A diffuser is a device that slows down a fluid by increasing the pressure.

Diffusers are used in compressors, combustion chambers etc.



APPLICATIONS OF THE ENERGY EQUATION

Nozzles and Diffusers

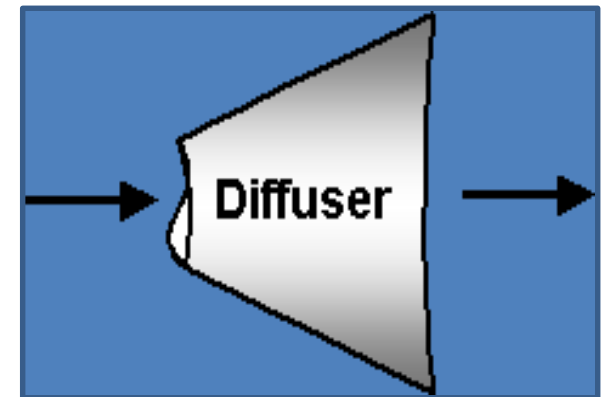
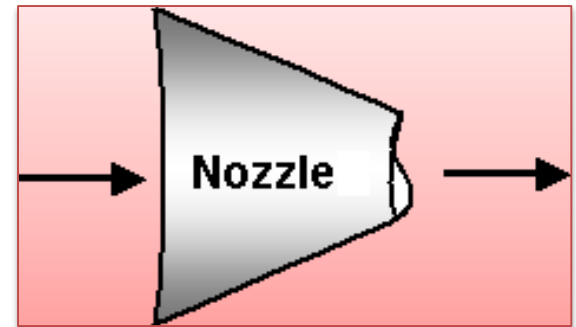
ANALYSIS

There is no work input and heat transfer is usually negligible.

With additional assumptions of negligible internal energy and potential energy changes, the energy equation takes the form:

$$0 = \frac{V_2^2 - V_1^2}{2} + h_2 - h_1$$

Three equations may be used for nozzle and diffuser flow: **energy**, **continuity**, and a **process equation**, such as for an adiabatic quasi-equilibrium flow



$$\dot{Q} - \dot{W}_s = \dot{m} \left(\frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1) + u_2 - u_1 + \frac{P_2}{\rho_2} - \frac{P_1}{\rho_1} \right)$$

Worked Example

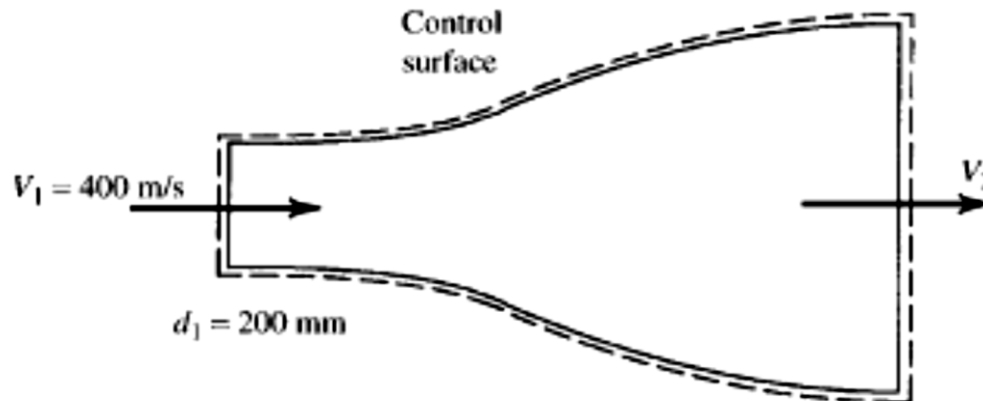
Air flows through the supersonic nozzle shown. The inlet conditions are **7 kPa** and **420 °C**. The nozzle exit diameter is adjusted such that the exiting velocity is **700 m/s**.

Calculate (a) the exit temperature,

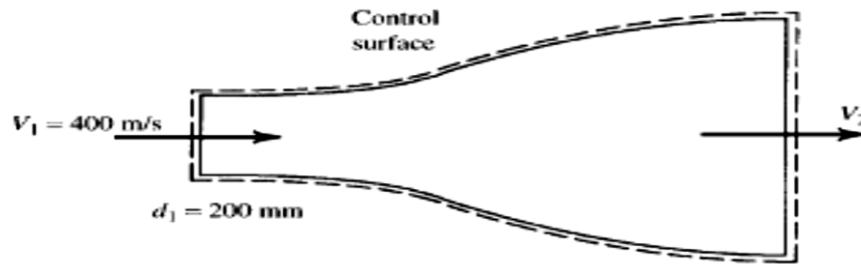
(b) the mass flow rate, and

(c) the exit diameter.

Assume an adiabatic quasi-equilibrium flow.



Second Law of Thermodynamics



Solution

(a) To find the exit temperature the energy equation is used. Noting that:

$$\Delta h = C_p \Delta T$$

The energy equation becomes:

$$\frac{V_1^2}{2} + C_p T_1 = \frac{V_2^2}{2} + C_p T_2$$

using $C_p = 1000 \text{ J/kg.K}$

$$T_2 = \frac{V_1^2 - V_2^2}{2C_p} + T_1 = \frac{400^2 - 700^2}{2 \times 1000} + 420 = 255 \text{ }^\circ\text{C}$$

(b) To find the mass flow rate we must find the density at the entrance