

Introduction

to

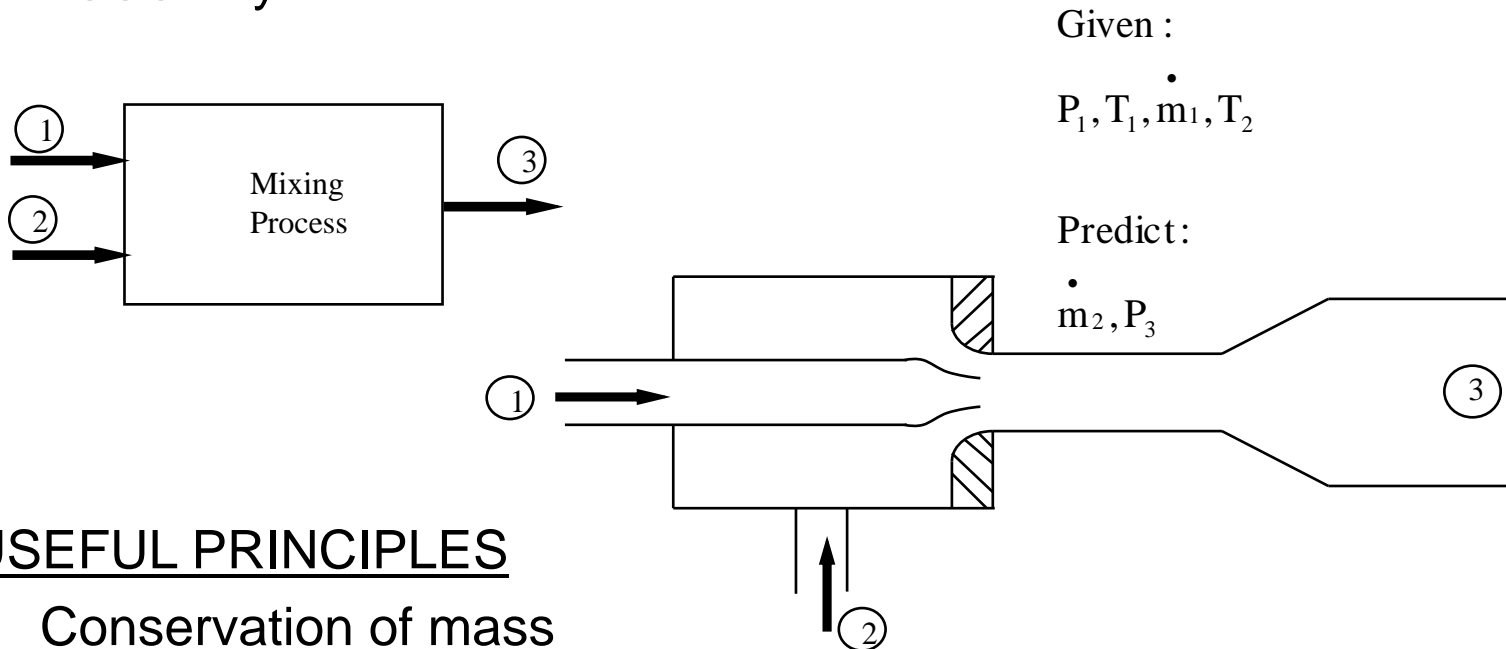
Thermodynamics Concepts

<http://www.drshokuhi.com>

INTRODUCTION

A jet entrainment thermal mixer

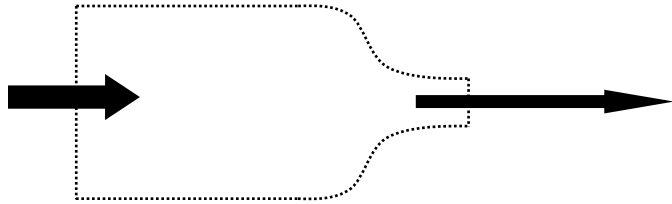
- An example of thermodynamic concepts applied to a SSSF system



USEFUL PRINCIPLES

- Conservation of mass
- Conservation of linear momentum
- Conservation of Energy
- 2nd Law of Thermodynamics
- Bernoulli Equation (in some places)

Flow through the nozzle:



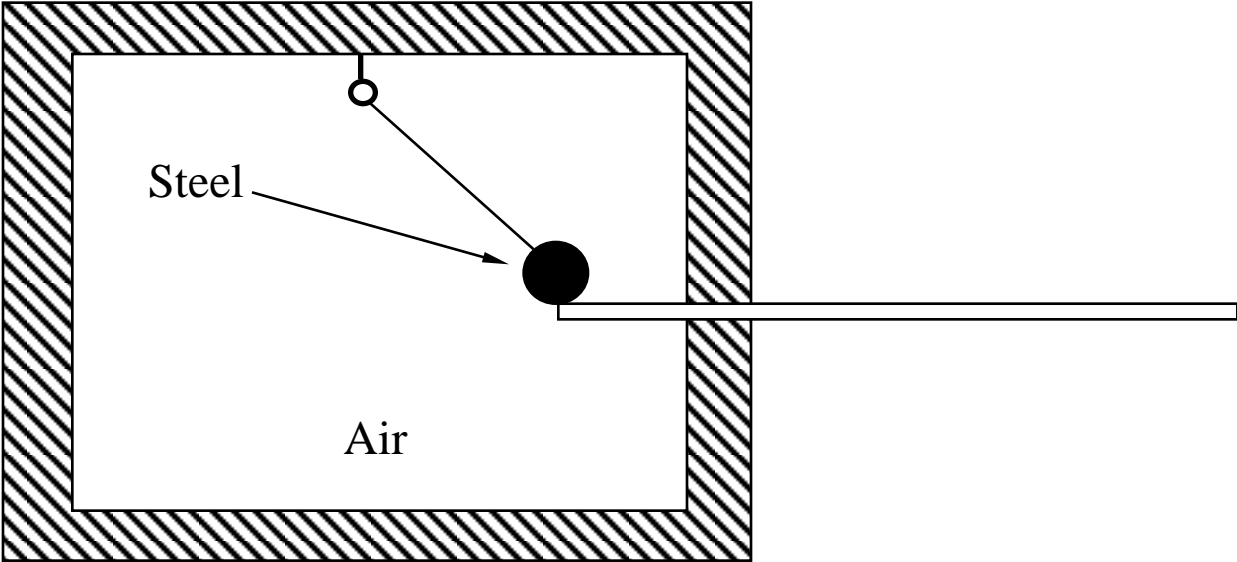
- Is it inviscid / irrotational? => Bernoulli
- Is it isentropic (reversible + adiabatic?)
 - for ideal gas - constant C_p / C_v :
- What would make it irreversible?
 - friction
 - separation

$$P + \frac{1}{2}\rho V^2 = \text{constant}$$

$$\left(\frac{T_2}{T_1}\right) = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

- The thermodynamic analysis applies equally to the large (global) control volume and the small, differential control volume
- The thermodynamic analysis allows us to perform a 1-D thermo-fluid analysis which is quite powerful in its own right
- All the principles are for classical, equilibrium thermodynamics

An example of a closed system



AME 530 / Advanced Thermodynamics

OBJECTIVE: Review basic Concepts necessary for execution of a thermodynamic analysis

System, surroundings, state, property, equilibrium, first law, reversible & irreversible processes, second law, equation of state

System - A region of constituent parts that can be separated from everything else by a well-defined surface
A collection of constituents that have an amount

Surroundings or Environment - Everything that is not the system

State - The “condition” of a system at any instant in time

Property - An attribute of the system that can be evaluated at any given instant in time by a set of measurements

A quantity whose numerical value depends on the state, but not the history of a system

Example properties: E - energy
 S - entropy
 $H = U + PV$ - enthalpy

- Properties may be:
 - independent or
 - interdependent

Example of interdependent property:

P_{SAT} , T_{SAT} : cannot change one without changing the other

Property

- Intensive - independent of size or extent
- Extensive - dependent on size or extent

Equilibrium State

A state that does not change with time while the system is isolated from all other systems

Non-Equilibrium State

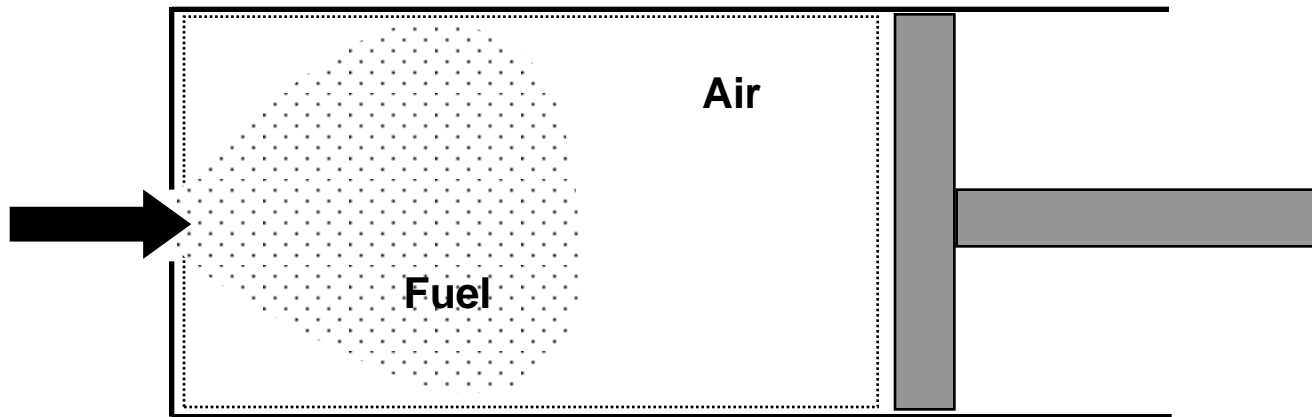
A state that changes spontaneously with time, without any effects on or interactions with any systems in the environment. Starting from a non-equilibrium state a system can be made to lift a weight without leaving any other net change in the state of the environment

Examples:

- residual stress state in a metal (will it relax by itself?)

Example:

- injection of a fuel-air mixture into a chamber



- what causes this system to be in equilibrium?

- temperature gradients
- concentration gradients

Equilibrium States

of a

System

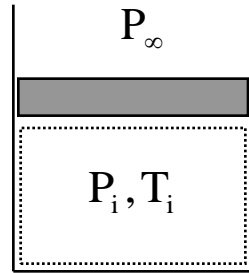
Ref: Zemansky, 4th Ed. Heat & Thermodynamics, Ch.2 p.24

Mechanical Equilibrium - there are no unbalanced forces in the interior of a system, and also between system and surroundings

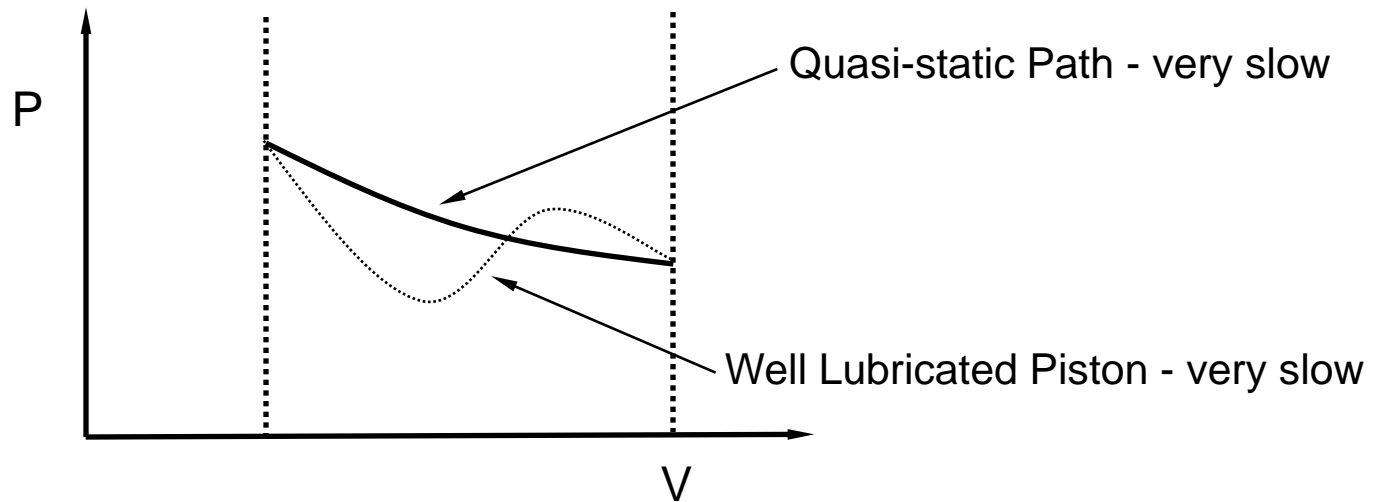
Chemical Equilibrium - there is no spontaneous change of the internal structure or a transfer of matter from one part of the system to another due to chemical rxn

Thermal equilibrium - there is no spontaneous change in the system when it is separated from its surroundings by a diathermal wall. All parts of the system are at the same temperature, and this temperature is the same as the surroundings.

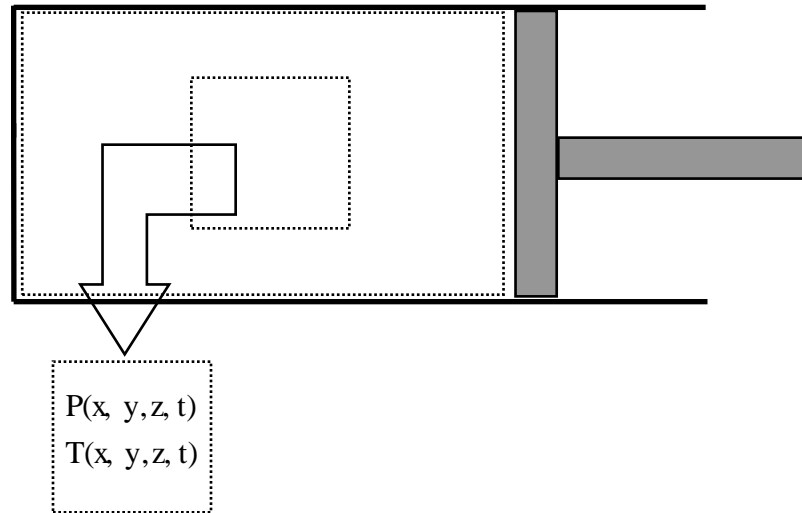
Example: (see Modell & Reid, p.17)



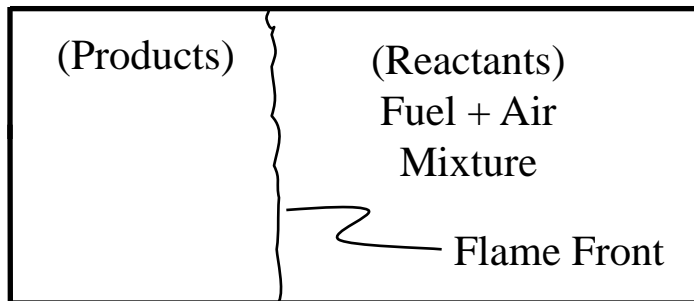
If $P_i = 2P_\infty$ initially



- the path is certainly rate dependent, but there is only one quasi-static path
- the intermediate states in the well-lubricated cylinder are not in equilibrium



- when would we be interested in mapping $P(x, y, z, t)$, $T(x, y, z, t)$
- when we want to know the rate at which work can be performed
- what *limits* the rate at which the process occurs?



- Diffusion of heat
- Diffusion of species
- Hydrostatic mechanisms (grouped together in what we call “mixing”)

- If we assume global equilibrium, we will badly compute the rate of work extraction because...

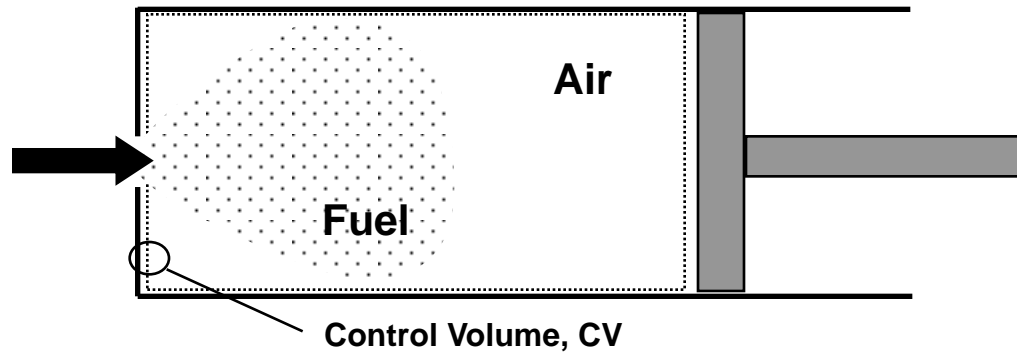
The rate is limited by transport

- Paths for which all intermediate states are equilibrium states are called “quasi-static” paths (see Modell & Reid, p.17)
 - Quasi-static paths are closely related to reversible processes but are not necessarily the same

Summary Comments

- Classical Thermodynamics, as we study it, is related to thermo-static processes, processes that instantaneously may be assumed to occupy an equilibrium state
- Also note that the relationship between state properties, the state equation, is developed for systems in equilibrium

Example: an illustration of mixing assumptions injection of a fuel-air mixture into a chamber:



- what causes the system to be in dis-equilibrium?
 - temperature gradients
 - concentration gradients
 - pressure gradients

- can we use $P=P(v,T)$?

A generalized equation of state?

- But we shall find that the state principle relates to properties that are in equilibrium

- Thus, how can we evaluate even the most basic thing, such as:

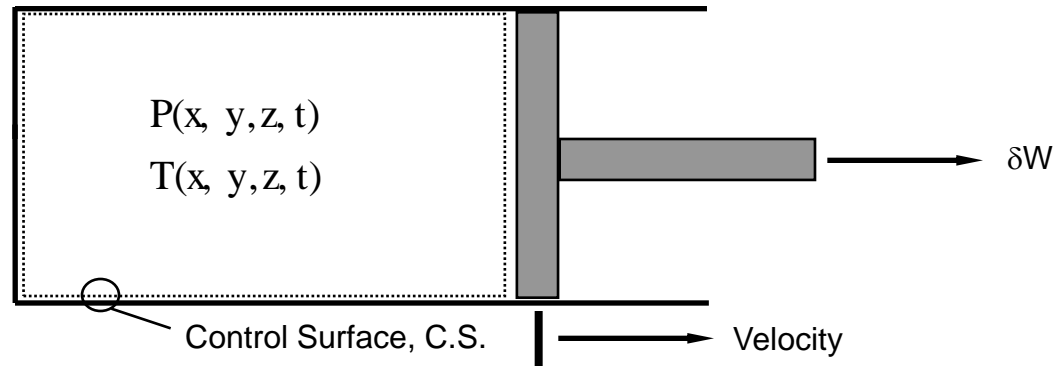
$$W_{1-2} = \int_{V_1}^{V_2} P dV \quad ?$$

Answer: (a) assume system is in equilibrium

or

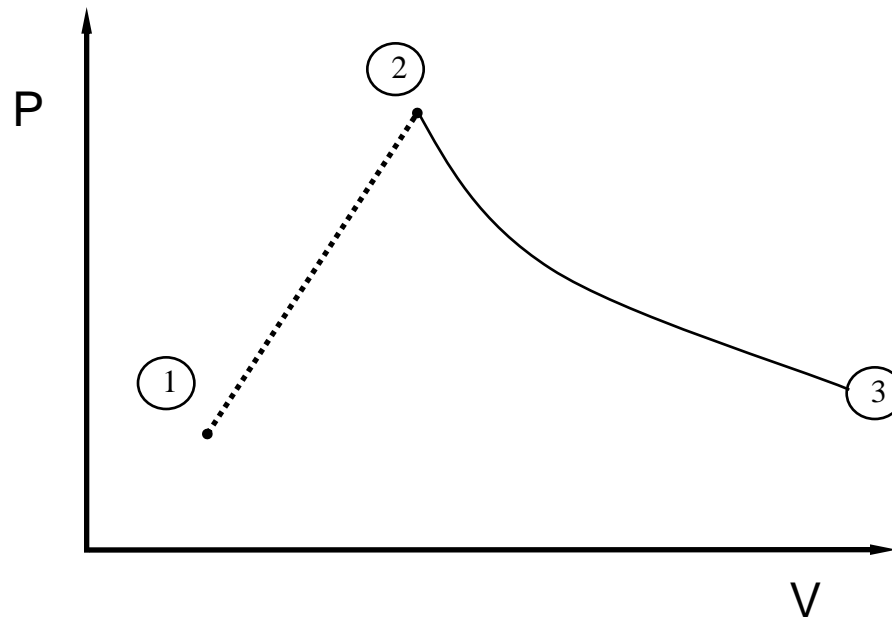
(b) choose a smaller system that can be assumed to be in equilibrium

If we assume the system is in equilibrium, does that mean instantaneously?



- Entire system is assumed to be in equilibrium, instantaneously
- What is required to justify this assumption?
 - instantaneous mixing
 - no temperature gradients
 - no species gradients
 - no pressure gradients (no shocks)
- The system undergoes a change in state with interaction with environment, assuming quasi-static processes

- Path is the trajectory in state space (P,V) taken by the process during the state change



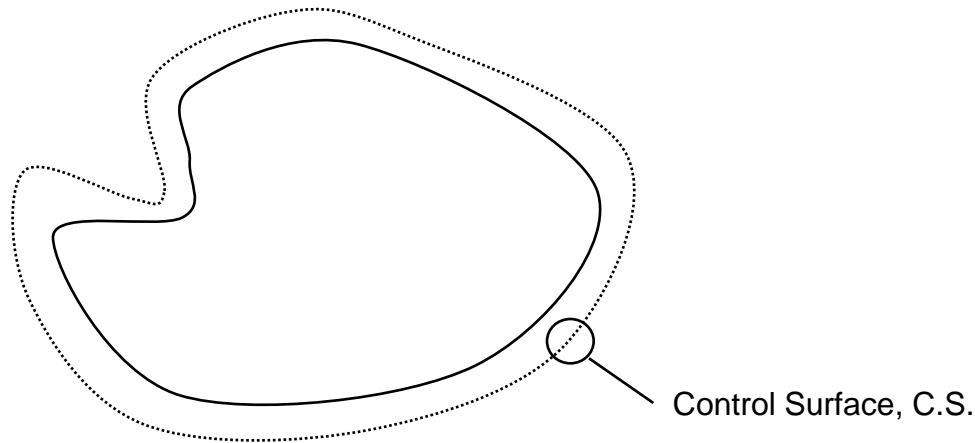
- Question: Is the path independent of the rate?

Control Surfaces

and

Control Volumes

Control Surfaces & Control Volumes



- The boundary or control surface separates the environment from its surroundings
- The value of a property measured at the boundary must be shared by both system and surroundings

The system control volume may be:

- stationary or moving (accelerating)
- any size or shape
- may deform

• The CV is a useful tool because every approach to the interior is intercepted by a C.S. There is no way in which matter, momentum, or energy can enter the CV in which crossing through one of the control surfaces.

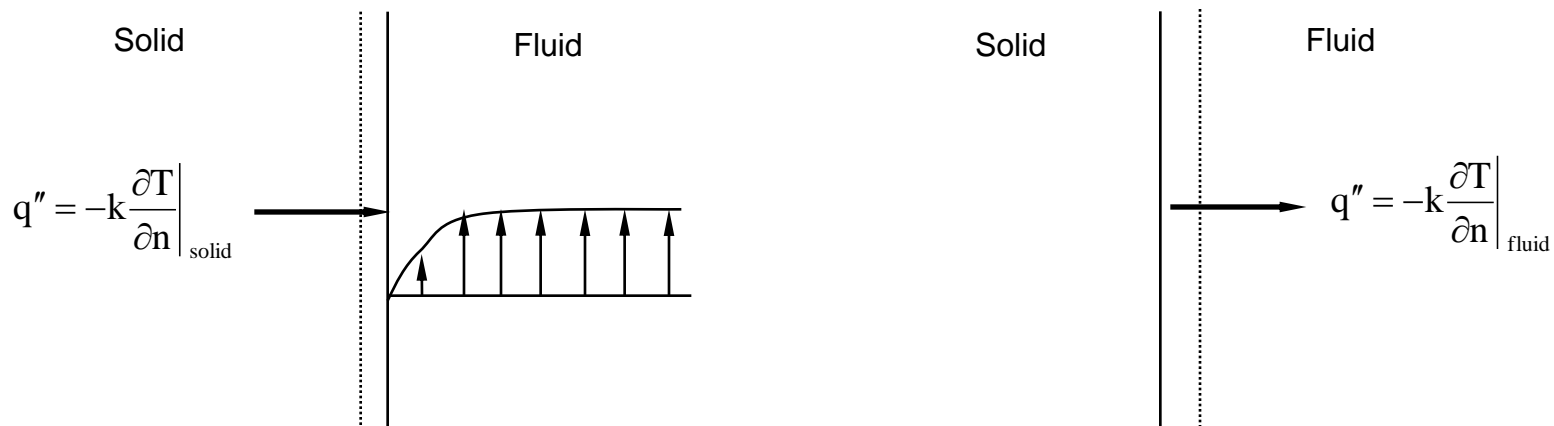
• All statements about the behavior of the system inside the CV are deduced from the observed flows and forces (interactions) acting on or through the CS. One cannot deduce the distribution within a CV with thermodynamics alone.

The control surface must be UNIQUE

Uniqueness:

- It is necessary to place the C.S. so that at all places in is unambiguously located.
- A C.S. should never be placed at the interface between two surfaces, an interface is a discontinuity

An example

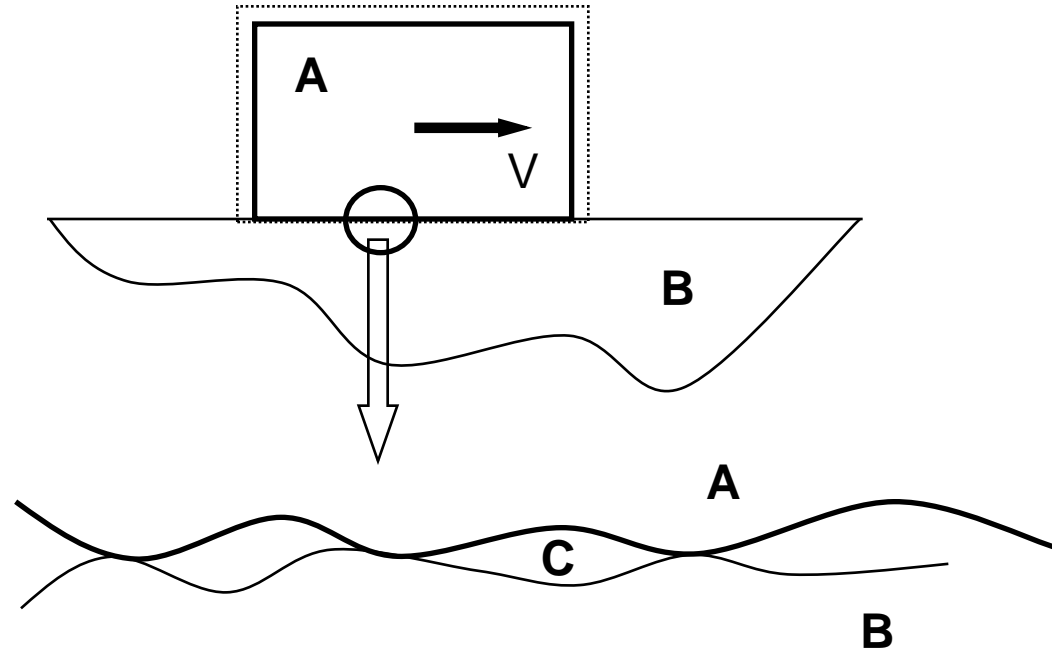


Questions to check for uniqueness:

- what is the thermal conductivity of the interface?
- what is the temperature of the interface?
- what are k , T of the C.S.?

Example:

Ambiguity in the Location of a Sliding Interface



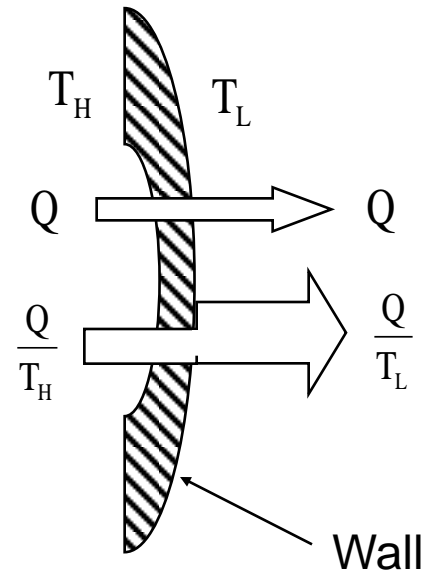
- where is the C.S.?
 - Does it include all of A, B or C?
- Can we simplify the location of the C.S. by putting it all in A or all in B?

Observations from Bejan

- The Boundary or C.S. separates the environment from its surroundings
- The value of a property measured at the boundary must be shared by both systems and surroundings

Example of Sources of Confusion

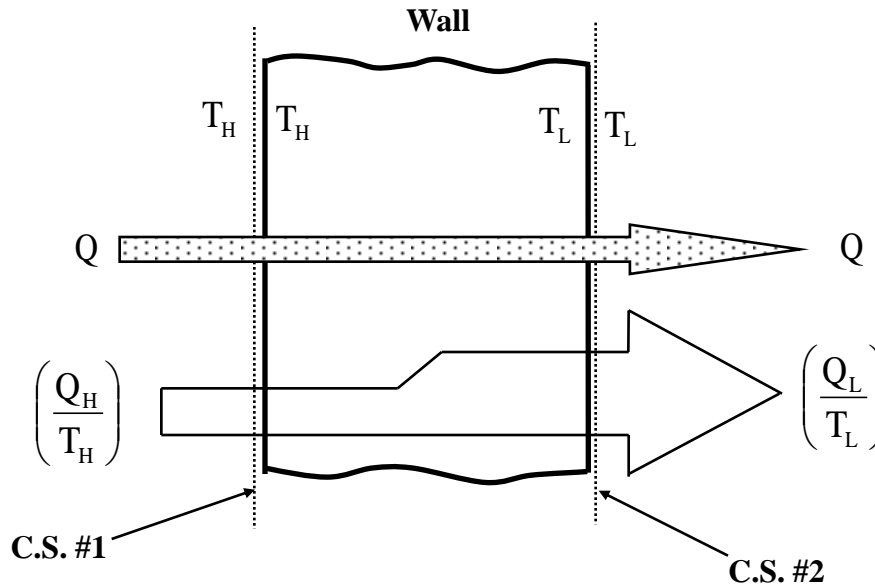
Entropy Transfer with Heat



- If $T_H > T_L$, is entropy transfer conserved?
- In evaluating $\left(\frac{Q}{T}\right)$, should you use T_H or T_L ?

Entropy generated with heat transfer

Discontinuity Occurs

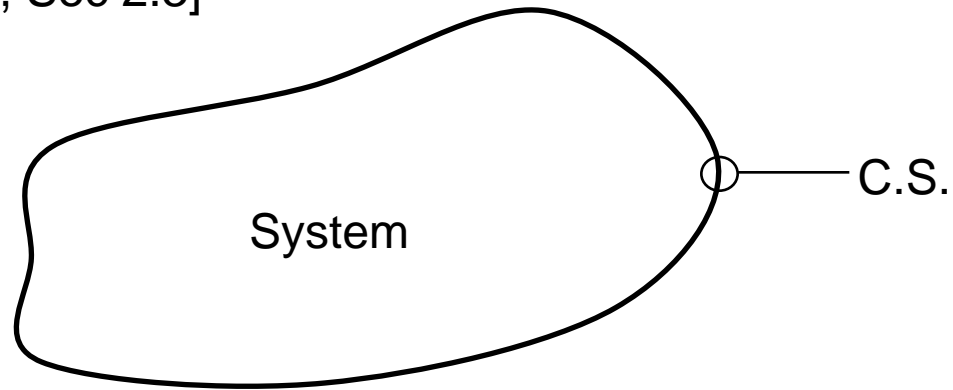


- if the CS #1 is used $(\frac{Q_H}{T_H})$ is the entropy flow
- if the CS #2 is used $(\frac{Q_L}{T_L})$ is the entropy flow
- Q is not dependent on choice of C.S.
- But, $(\frac{Q}{T})$ is dependent on choice of C.S.

Question: Why does $(\frac{Q}{T})$ increase? What does it mean?

Answer: Entropy is produced by heat transfer

Classification of Boundaries:
[see Modell & Ried, Sec 2.3]



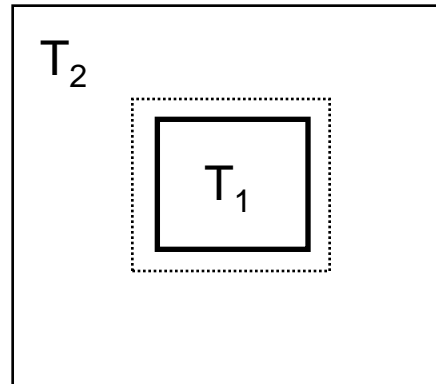
- Closed System - boundary impermeable to mass flow
- Open System - allows mass flux of at least one component of the system at one point, at least

Boundaries may be: rigid or movable
 permeable or impermeable to mass
 adiabatic or diathermal

Isolated system: impermeable, rigid, adiabatic surfaces, resulting in
no interactions with environment

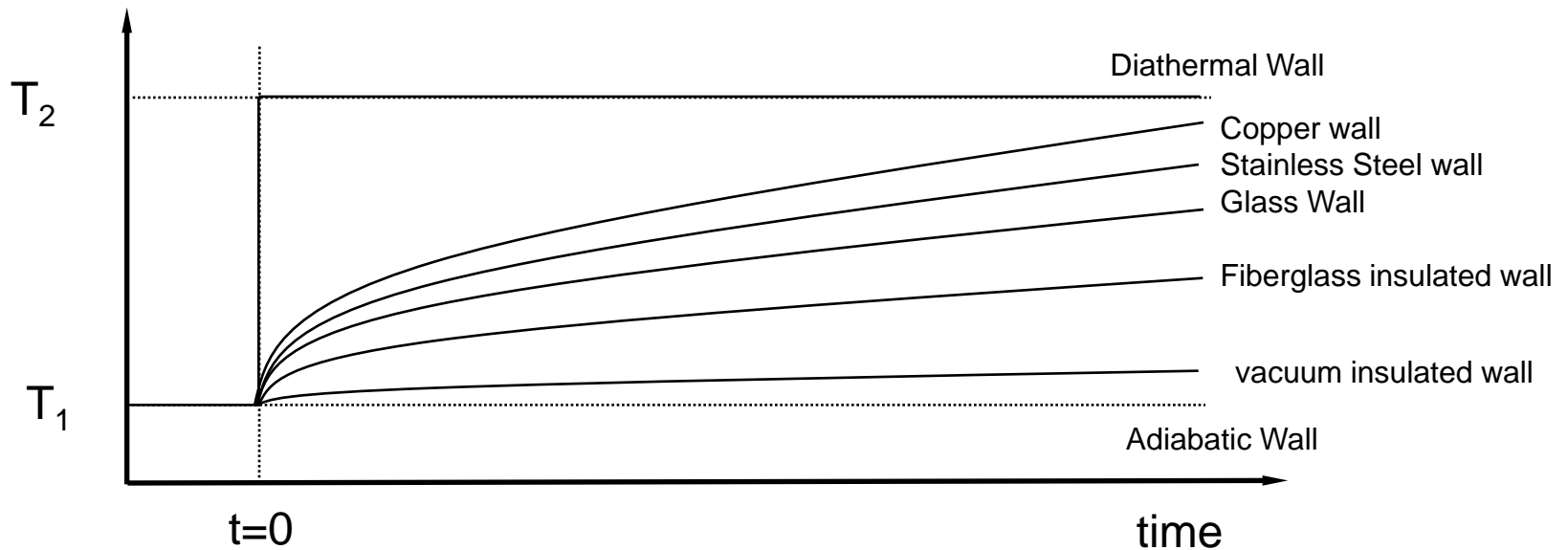
Adiabatic Wall - We have not defined heat yet so we cannot use it in the definition (otherwise the definition is circular)

Consider the System in an Environment



See Modell / Reid Fig. 2.1

For $T_2 > T_1$



Adiabatic Wall - leads to no change in system temperature

Diathermal Wall - leads to instantaneous change in system temperature, to surrounding temperature (perfectly conductive)

Conservation Statements

Conservation statements:

Basic principles for a control mass; or closed system

Reynolds Bookkeeping Approach:

In general for a system:

$$P \equiv \text{production} = \text{outflow} - \text{inflow} + \underline{\text{increase}} \text{ in storage}$$

or

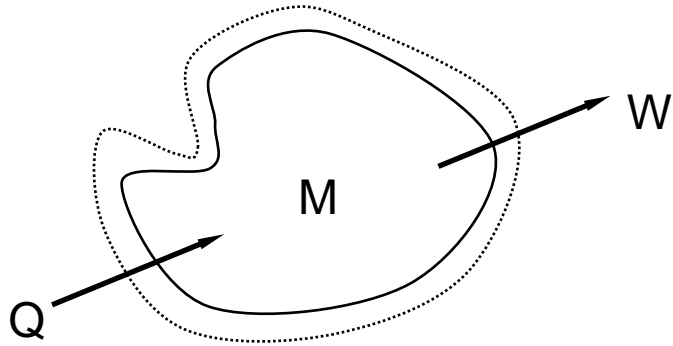
$$P + \text{Inflow} = \text{Storage} + \text{outflow} \text{ (PISO)}$$

On a rate basis:

$$\dot{P} = \text{rate of production} = \text{rate of outflow} - \text{rate of inflows} \\ + \text{rate of increase in storage}$$

Sometimes \dot{P} is called ROC, Rate Of Creation

Specifically for a closed system:



Conservation of Mass:

Differential Basis:

$$\begin{array}{ccc} \delta P_{\text{mass}} & = & dM \\ \textit{Bookkeeping} & & \textit{Physics} \\ & & = 0 \end{array}$$

Rate Basis:

$$\dot{P}_{\text{mass}} = \frac{dM}{dt} = 0$$

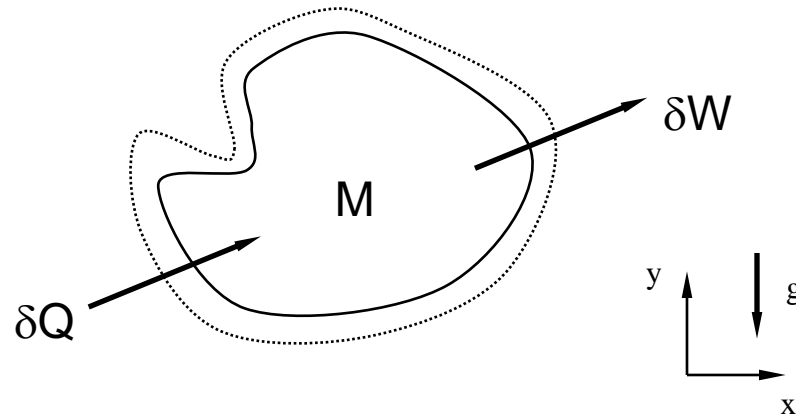
Total Change Basis:

$$\int_i^f \delta P_{\text{mass}} = \int_i^f dM = 0$$

$$P_{\text{mass}} = M_f - M_i = 0$$

$$M_f = M_i$$

First Law for Closed System



Differential:

$$dP_E = \sum (\delta Q + \delta W)_{\text{out}} - \sum (\delta Q + \delta W)_{\text{in}} + dE = 0$$

E = total energy of M (J)

e = specific total energy (E/M) (J/kg)

$$e = \left(u + \frac{1}{2} V^2 + gz \right)$$

u - specific internal energy

$\frac{1}{2} V^2$ - specific K.E. (energy on mass motion)

gz - specific P.E. (energy of mass position)

Q = energy transfer as heat

W = energy transfer as mechanical heat

Notes:

- Internal frame of reference needed (why)?
- u represents energy associated with configuration and motions of constituent particles

What is the meaning of the symbol

δQ or δW

Compared to dE ?

$\delta()$ - a small amount of
 $d()$ - a small change in

Work Transfer Interactions

Conservation of Energy - Closed System

Heat Engine Sign Convention:

$$\delta Q - \delta W = dE$$

Inflow outflow

For a Change in State

$$E_2 - E_1 = \int_1^2 \delta Q - \int_1^2 \delta W$$

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

energy change (property) energy interactions (non-property)

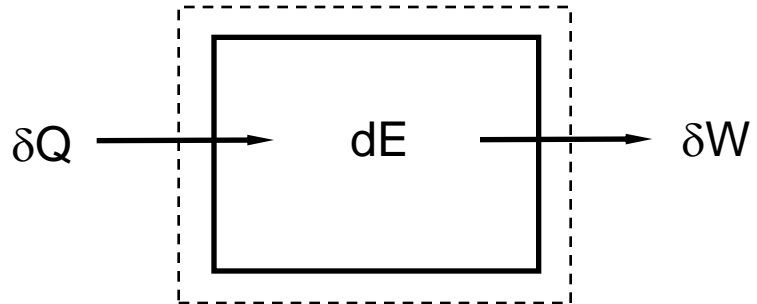
On a rate basis:

$$\frac{\delta Q}{dt} - \frac{\delta W}{dt} = \frac{dE}{dt}$$

$$\dot{Q} - \dot{W} = \frac{dE}{dt}$$

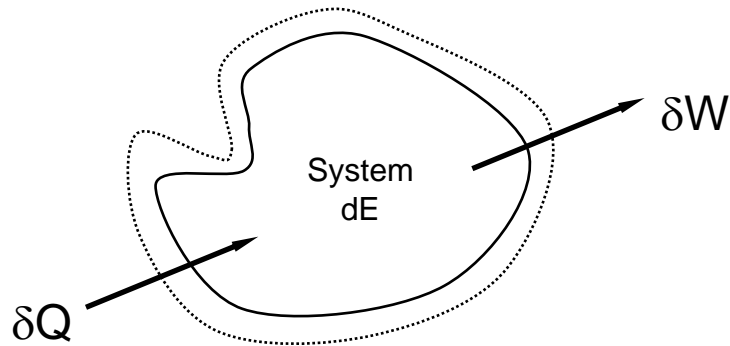
For a Cycle

$$\oint \delta Q - \oint \delta W = 0$$



Work Transfer Interactions

(see Bejan 8-9)



Heat Engine Sign Convention:

- Work is positive when the system does work on its surroundings.
- Heat is positive when the surroundings transfer heat to the system.

Thus:

$$dE + \delta W - \delta Q = 0$$

or

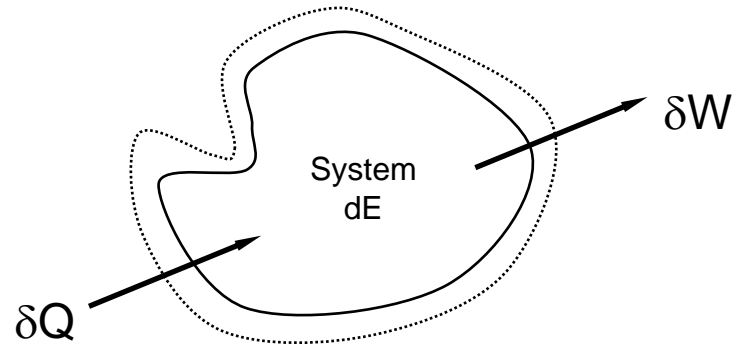
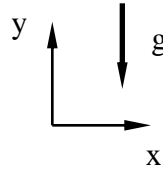
$$\delta Q - \delta W = dE$$

- where δQ , δW are infinitesimal increments in work or heat transfer.

- dE , exact differential of E

Summary:

Mechanical Work Interaction



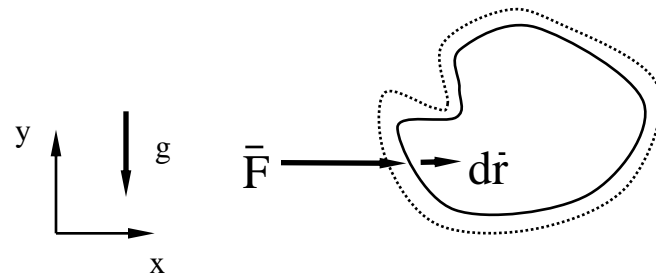
Heat Engine Sign Convention

$$\delta Q - \delta W = dE$$

Diagram illustrating the sign convention for the first law of thermodynamics:

- δQ is labeled as inflow.
- δW is labeled as outflow.
- dE is labeled as increase in stored energy.

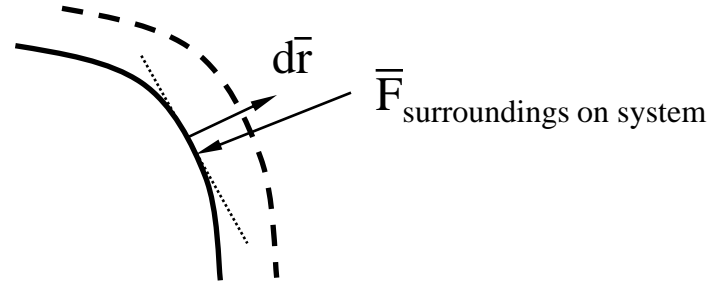
Work of a Moving Boundary



\bar{F} = force of surroundings on system

$d\bar{r}$ = infinitesimal displacement relative to an inertial reference frame

Work associated with displacement of a system boundary - Boundary Work



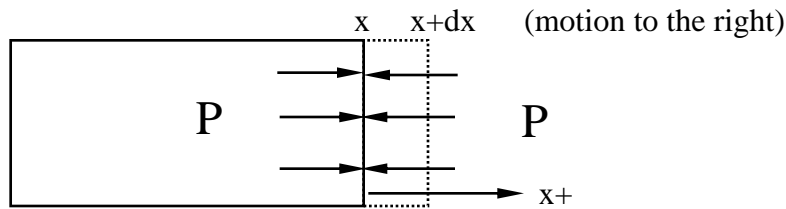
If F is a force of surroundings on system, and dr is the infinitesimal displacement taken as positive outward, then

$$\delta W = -\bar{F} \cdot d\bar{r}$$

└ remember, work of system on surroundings

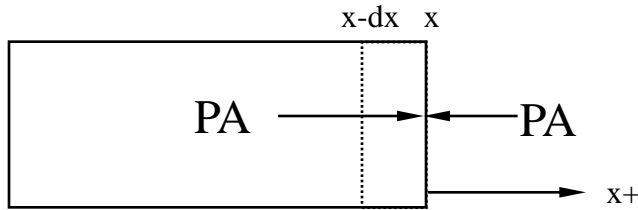
- For there to be work
 - 1) a force must be present on the boundary
 - 2) the “point of application” of the force must move

Example: Reversible Work



$$\delta W_{\text{rev, system on surroundings}} = (-) (-P A) (+dr) = \boxed{+ P dV}$$

- consider the case: (motion to left)

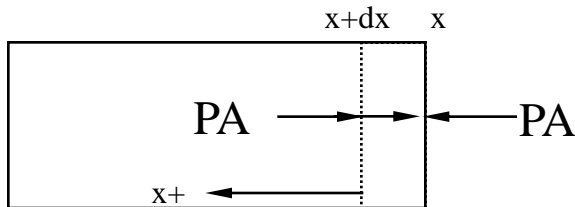


$$\delta W_{\text{rev, system on surroundings}} = (-) \overbrace{(-P A)}^{\text{work of surroundings on system}} \underbrace{(-dr)}_{\text{Displacement in (-) r direction}}$$

$$= - P dV$$

- What does it mean to have “negative work”?
(surroundings do work on system)
- Does the displacement vector have to have a sign convention also?
- The outward pointing normal is assumed to be positive, but doesn't have to be.

Example:



$$\delta W_{\text{rev, system on surroundings}} = (-) (-P A) (-dr)$$

$$= - P dV$$

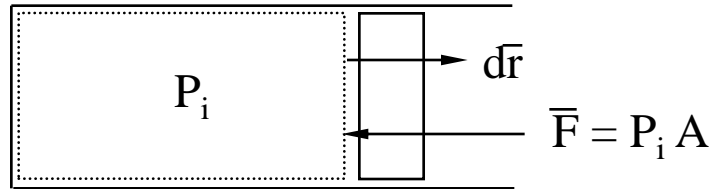
- What does this negative work mean?
- net work is surrounding on system!

Then:

$$\delta W = -\bar{F} \cdot d\bar{r}$$

└── force of surroundings on system
└── work of system on surroundings

Work of an Expanding Volume

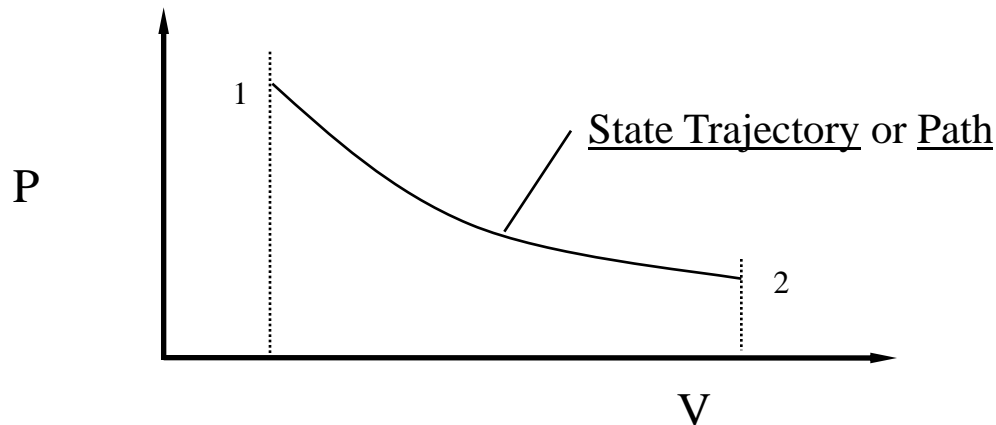


$$\delta W = - (P_i A dx) = P_i dV$$

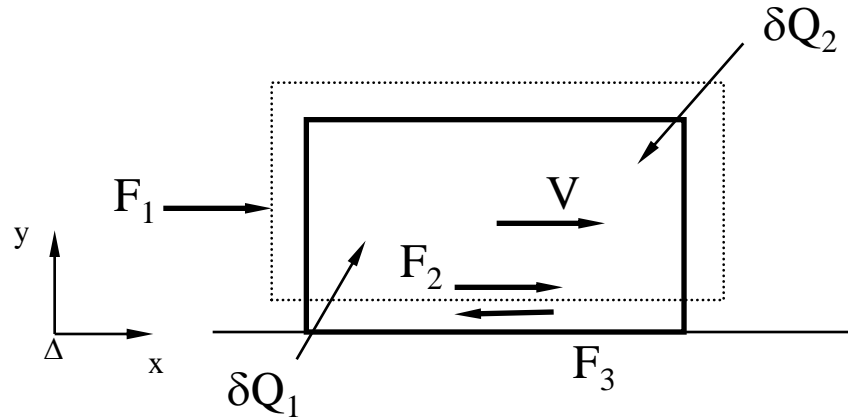
$$W = \int_{V_1}^{V_2} P_i dV \quad (\text{work of system on surroundings})$$

Assumptions:

- 1) P_i is uniform over A (in fact over entire volume)
- 2) Process is sufficiently slow to allow equilibrium at any instant in time.



The Sliding Block Problem



E.B. Heat Engine Sign Convention:

$$\delta Q - \delta W = dE$$

in out, system on surroundings

$$(\delta Q_1 - \delta Q_2) - [-(F_1)(+dx) - (-F_3)(+dx)] = dE$$

or:
$$\delta Q_1 - \delta Q_2 + F_1 dx - F_3 dx = dE$$

If $V = \text{constant}$, steady state: $dE \Rightarrow 0$

Then:
$$\delta Q_1 - \delta Q_2 = (F_3 - F_1) dx$$

But: $F_1 = F_3$ from Newton's 2nd Law

Then:
$$\delta Q_1 = \delta Q_2$$

Question, in the E.B.

- What did it mean that the sign of the friction work term is:

$$- (-F_3 dx) ? = +F_3 dx$$

- In fact the “system” does work on surroundings, In fact F₂ does work, not F₃ !

- What does it mean that sign of F₁ work was:

$$- (+F_1)(+dx) = -F_1 dx$$

(does negative work mean anything?)

Then the “surrounding perform work on the system!”

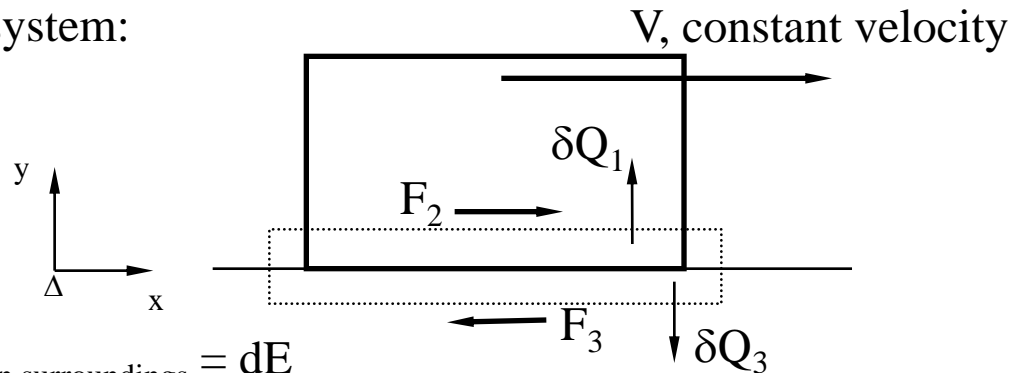
- Why did we work in terms of F₃ instead of F₂ ?

Because F₃ is the force of surroundings !

F₂ is force of system.

But we want to express quantities based on what we observe at the surface,
without regard to what is inside the CV !

Consider the following system:



$$(-\delta Q_1 - \delta Q_3) - \delta W_{\text{system on surroundings}} = dE$$

• F_2 does work on the system:

$$\delta W_{\text{system on surroundings}} = - (+F_2 dx) - (-F_3 \cdot 0)$$

└─ table has no displacement relative to reference frame

$$\delta W_{\text{system on surroundings}} = - F_2 dx$$

Therefore:
$$-\delta Q_1 - \delta Q_3 - (- F_2 dx) = dE$$

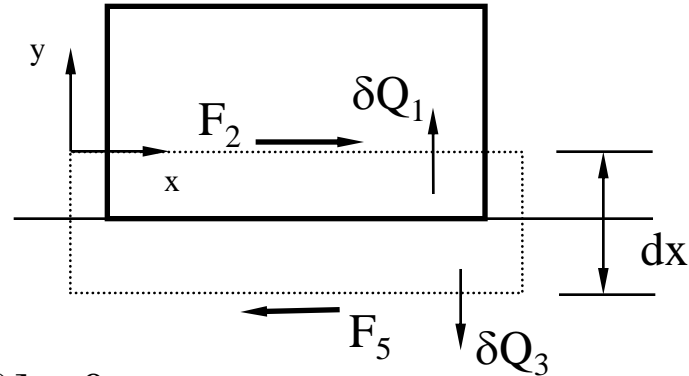
or: $F_2 dx = \delta Q_1 + \delta Q_3$ No Storage

Work of surroundings on system

Heat dissipated by:

- 1) plastic deformation (irreversible conversion of mechanical work)
- 2) creation of new surfaces may also be possible
- 3) elastic deformation (10^{-3}) [energy stored !]

- What if the coordinate system is attached to the block?



$$(-\delta Q_1 - \delta Q_3) - [- (-F_5)(-dx)] = 0$$

Then: $\boxed{\delta Q_1 + \delta Q_3 = F_5 dx}$!

- What assumptions were made here?

- It appears in this reference frame that table performs work on block.