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Critical analysis of expansion of an ideal gas as a classroom example of reversible and irreversible process

Dr. Vinay Chandra Jha[1*], Mr. Gaurav Tamrakar[2]
[1*]Professor Kalinga University, Naya Raipur
[2] Assistant Professor of Mechanical Engineering, Kalinga University, Naya Raipur
[*]Emai:vinaychandrajha@rediffmail.com

ABSTRACT

The difference between reversible and irreversible expansion of an ideal gas in a cylinder having frictionless piston is analyzed on the basis of quantity. Reversible expansion is achieved by removing infinitely small masses properly distributed vertically from the piston as it ascends and expansion of the gas takes place. In the past, this example has been used pedagogically in qualitative form only. Reversibility is demonstrated in several ways, most notably by showing the equality of the work done by the system and the work done on the surroundings.

INTRODUCTION

In the past, various researchers and authors dealing with engineering thermodynamics have treated this topic qualitatively. They have made the basis on the background of common sources of irreversibility (friction , unrestricted gas expansion, heat transfer over a non-zero temperature difference etc.). The criteria of reversibility are noted as:

1. Infinitely slow speed of limitation at which a process takes place. Change must be infinitely slow so that the system maintains internal thermodynamic equilibrium at all times.

2. Returning the system from its final state to its initial state by the same path must leave both the system and surroundings unchanged.

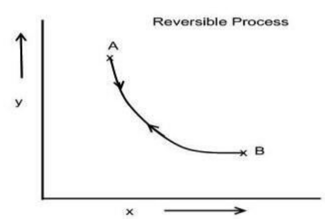
3. Work done by (or on) the system must be equal to the work done on (or by) the surroundings.

4. There must be no friction at all.

REVERSIBLE PROCESS:

The process in which without producing any changes in the thermodynamics properties of the universe, the system and surroundings can be restored to the initial state from the final state is called a reversible process. We suppose that the system has undergone a change from state A to state B shown in the diagram.

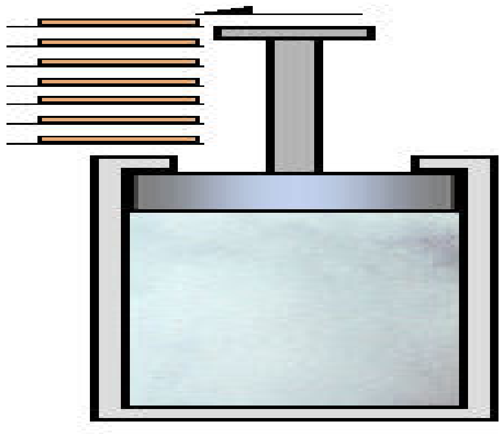
The process is said to be a reversible process If the system can be restored from state B to state A, and there is no change in the universe. The concept of reversible process is that it can be reversed completely and there is no trace left to show that the system had undergone thermodynamic change.



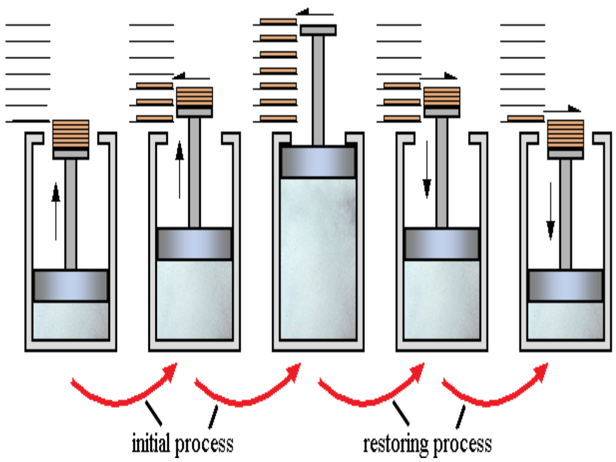
IRREVERSIBLE PROCESS:

All the real processes are irreversible processes are also called the natural processes. All the natural processes occur due to the finite gradient between the two states of the system. Heat flow between two systems occurs due to the temperature gradient between the two systems. This is in fact the natural flow of heat. Similarly, water flows from high level to low level, current moves from high potential to low potential, etc.

Isothermal expansion of an ideal gas :



Reversible Process:



Reversible Expansion:

Removing a small mass from the pedestal causes the piston to vary and slightly expand the gas in the cylinder. Each removal of a small mass approximates an infinitesimal equilibrium stage so that the overall process is quassistatic i.e. reversible. At all points in the expansion process, the conditions of external equilibrium, namely

$T = T_{surr}$ and $P = P_{surr} - Kmg/A$------------(1) are satisfied.

In equation (1) T_{surr} and P_{surr} are respectively the constant temperature and constant pressure of the surroundings. The number of small masses removed from the piston is denoted by k ($0 \leq k \leq N$), g is the acceleration due to gravity, m is the mass of one individual molecule and A is the cross sectional area of the piston.

The P-V work done by the ideal gas during the reversible, isothermal expansion from initial and final volumes V_i and V_f is

W_{rev} = ------------------ (2)

The work done by the surroundings due to constant temperature process maintained

W_{surr} -------------------------- (3)

From equation 2 and equation 3 shows that

W_{rev} = so a criterion of reversibility is satisfied for this process. In addition, the process can be reversed by sequentially the small masses put on the pedestal of their original elevations when the initial state is recovered exactly the same amount of heat that was added during expansion process will have been removed during the compression process. Both system and surroundings will have been restored to their original state.

IRREVERSIBLE EXPANSION:

When the entire mass "M" is removed from the piston as shown in fig 1, the system is not in equilibrium with the surroundings. The piston rapidly ascends, oscillates as the gas acts as a spring and eventually settles to the final elevation .In this case the potential energy gain ΔEp is easily determined from the elevation change of the large mass, which is directly related to the volume change of gas by $\Delta h = (V_f - V_i)/A$.

The work done by the surroundings in this irreversible process is

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$W_{irr} = P_{surr}\ (V_f - V_i) - Mg(V_f - V_i)/A$

The final results are a reasonable representation of the work done to the extent that $P_f < p_{surr}$. At the final equilibrium state, the force balance of the piston gives $p_{surr} - P_f = Mg/A$,combining these two equations and using the ideal gas law yields.

$$W_{irr} = (P_f + Mg/A)(V_f - V_i) - Mg(V_f - V_i)/A$$

$$= (V_f - V_i)(P_f + Mg/A - Mg/A)$$

$$= P_f V_f (1 - V_i/V_f)$$

$$= nRT(1 - V_i/V_f) \text{ ------------------------(4)}$$

Comparing this equation with equation (2) for $V_f/V_i = 3$

(as an example) shows that the ratio of reversible work of

the expansion to the irreversible work is

$$W_{rev}/W_{irr} = nRT\ln(V_f/V_i)/nRT(1-(V_i/V_f))$$

$$= \ln 3/(1-(1/3))$$

$$=1.5 \ln 3$$

$$= 1.65$$

That is work done in reversible process is 1.65 times work

Done in irreversible process.

CONCLUSIONS :

Reversible expansion of an ideal gas in a piston-cylinder apparatus by the distributed weight method has been analyzed quantitatively .the objective was to add an analytical structure to this often used pedagogical tool to aid students in thermodynamics course to better grasp the concepts of reversible and irreversible process.

For the reversible expansion process, the equality of work done by the system with that done on the surroundings is demonstrated by the ratio of the reversible and irreversible work requirements for the isothermal version of the process is determined as a function of the expansion ratio.

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