ESO201A

Lecture#32

(Class Lecture)

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By

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Reversible and Irreversible Processes

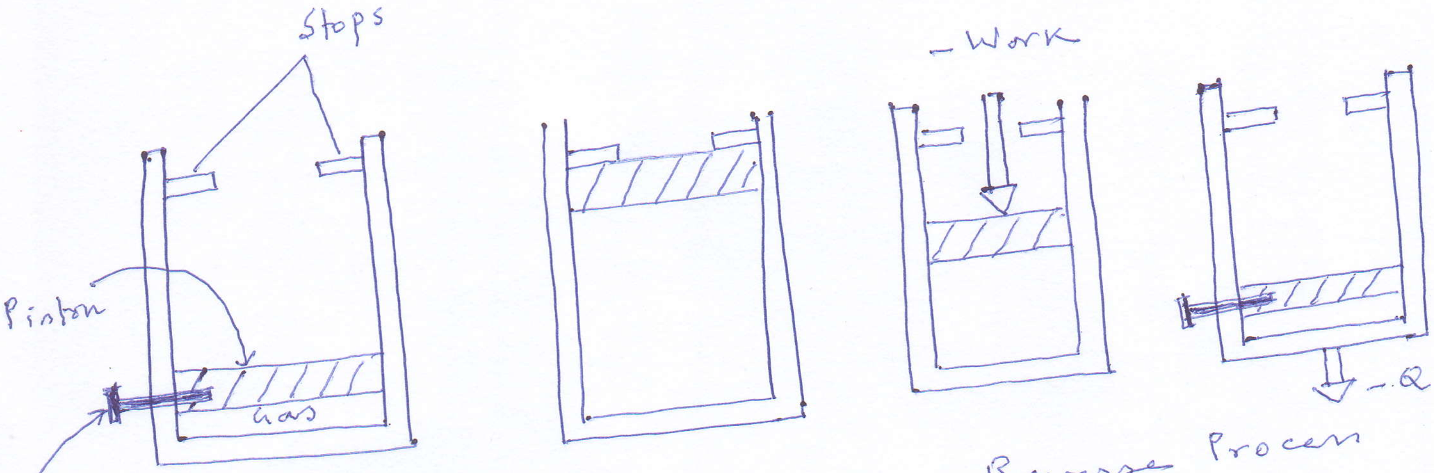
The Reversible Process

The question that can now logically be posed is this: If it is impossible to have a heat engine of 100% efficiency, what is the maximum efficiency one can have? The first step in the answer to this question is to define an ideal process, which is called a reversible process.

A reversible process for a system is defined as a process that, once having taken place, can be reversed and in so doing leave no change in either system or surroundings.

Let us illustrate the significance of this definition for a gas contained in a cylinder that is fitted with a piston. Consider first Fig. 1, in which a gas, which we define as the system, is restrained at high pressure by a piston that is secured by a pin. When the pin is removed, the piston is raised and forced abruptly against the stops. Some work is done by the system, since the piston has been raised by a certain amount.

Suppose we wish to restore the system to its initial state. One way of doing this would be to exert a force on the piston and thus compress the gas until the pin can be reinserted in the piston. Since the pressure on the face of the piston is greater on the return stroke than on the initial stroke, the work done on the gas in this reverse process is greater than the work done by the gas in the initial process. An amount of heat must be transferred from the gas during the reverse stroke so that the system has same internal energy as it had originally. Thus, the system is restored to its initial state, but the surroundings have changed by virtue of the fact that work was required to force the piston down and heat was transferred to the surroundings. The initial process is therefore an <u>irreversible</u> process because it could not be reversed without leaving a change in the surroundings.



Initial Process

Reverse Process

Fig. 1 An example of an irreversible Process

In Fig. 2, let the gas in the cylinder comprise the system, and let the piston be loaded with a number of weights. Let the weights be slid off horizontally, one at a time, allowing the gas to expand and do work in raising the weights that remain on the piston. As the size of the weights is made smaller and their number is increased, we approach a process that can be reversed, for at each level of the piston during the reverse process there will be a small weight that is exactly at the level of the platform and thus can be placed on the platform without requiring work. In the limit, therefore, as the weights become small, the reverse process can be accomplished in such a manner that both the system and its surroundings are in exactly the same state they were initially. Such a process is a reversible process.

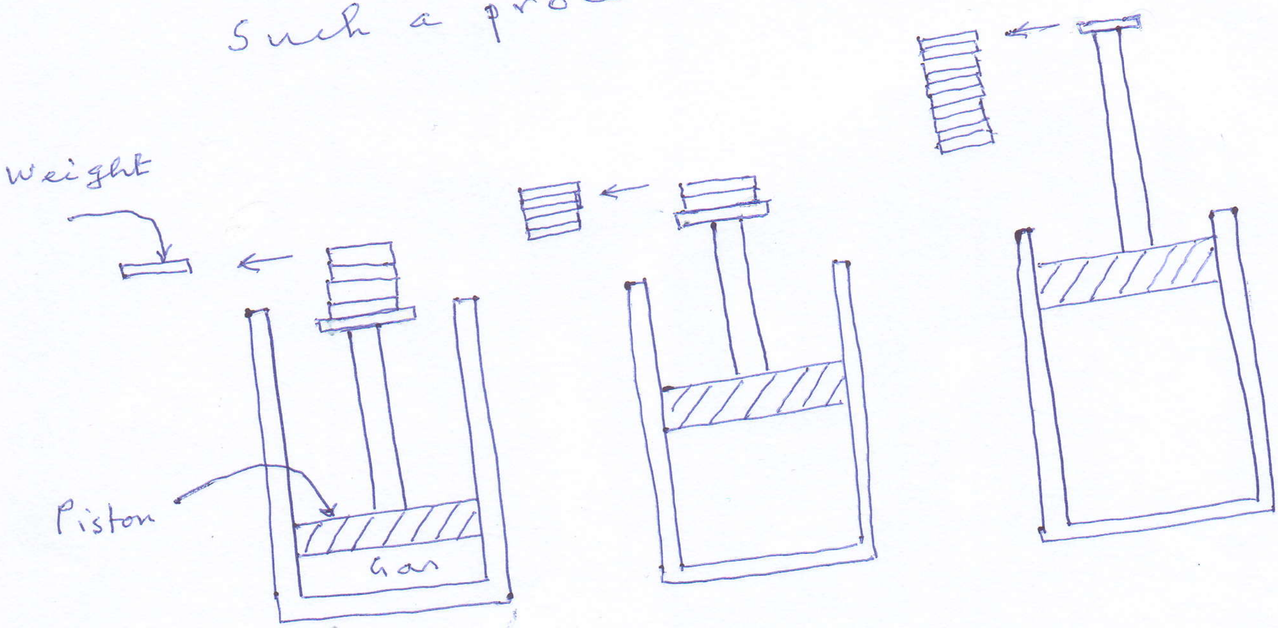


Fig. 2 An example of a process that approaches reversibility

Factors That Render Processes Irreversible

There are many factors that make processes irreversible. Four of those factors — friction, unrestrained expansion, heat transfer through a finite temperature difference, and mixing of two different substances — are considered in this section.

Friction

Let a block and an inclined plane make up a system as shown in Fig. 3, and let the block be pulled up the inclined plane by weights that are lowered. A certain amount of work is needed to do this. Some of this work is required to overcome the friction between the block and the plane, and some is required to increase the potential energy of the block. The block can be restored to its initial position by removing some of the weights and thus allowing the block to slide back down the plane. Some heat transfer from the system to the surroundings will no doubt be required to restore the block to its initial temperature. Since the surroundings are not restored to their initial state at the conclusion of the reverse process, we conclude that the friction has rendered the process irreversible. Another type of frictional effect is that associated with the flow of viscous fluids in pipes and passages and in the movement of bodies through viscous fluids.

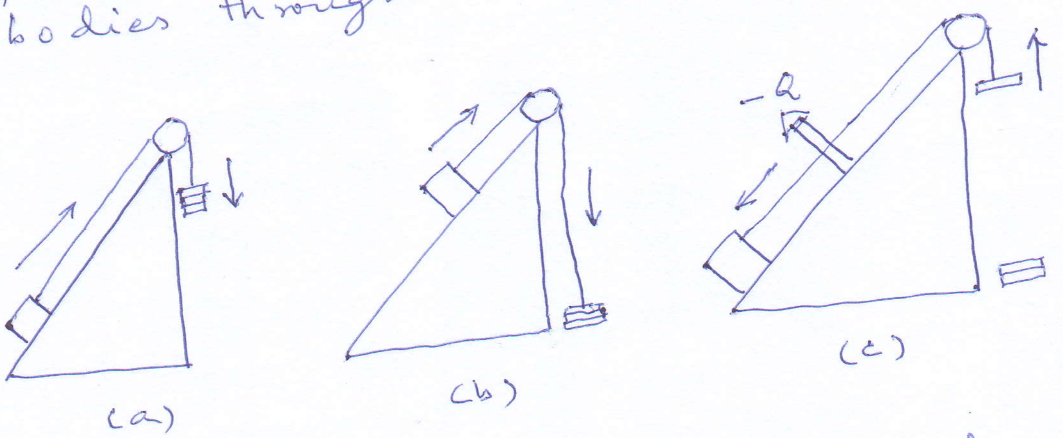


Fig. 3 Demonstration of the fact that friction makes processes irreversible.

Unrestrained Expansion

The classic example of an unrestrained expansion (Fig. 4), is a gas separated by a membrane. When the membrane is punctured the gas fills the entire vessel. The gas would have to be compressed and heat transferred from the gas until its initial state is reached. Since the work and heat transfer involve a change in the surroundings, the surroundings are not restored to their initial state, indicating that the unrestrained expansion was an irreversible process. The process described in Fig. 1 is also an example of an unrestrained expansion.

In the reversible expansion of a gas, there must be only an infinitesimal difference between the force exerted by the gas and the restraining force, so that the rate at which the boundary moves will be infinitesimal. In accordance with our previous definition, this is a quasi-equilibrium process. However, actual systems have a finite difference in forces, which causes a finite rate of movement of the boundary, and thus the processes are irreversible in some degree.

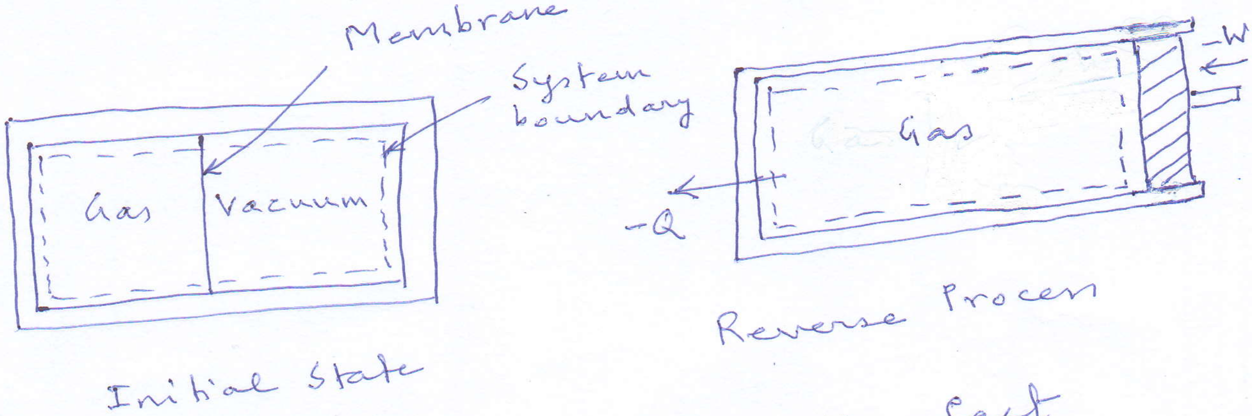


Fig. 4 Demonstration of the fact that unrestrained expansion makes processes irreversible.

Heat Transfer Through a Finite Temperature Difference

Consider a can of cold drink left in a warm room. Heat is transferred from the warmer room air to the cooler drink. The only way this process can be reversed and the soda restored to its original temperature is to provide refrigeration, which requires work from the surroundings and some heat transfer to the surroundings will also be necessary. Because of the heat transfer and the work, the surroundings are not restored to their original state, indicating that the process was irreversible.

A heat-transfer process approaches a reversible process as the temperature difference between the two bodies approaches zero. Therefore, we define a reversible heat-transfer process as one in which the heat is transferred through an infinitesimal temperature difference. We realize, of course, that to transfer a finite amount of heat through an infinitesimal temperature difference would require an infinite amount of time or infinite heat-transfer area. Therefore, all actual heat transfers are through a finite temperature difference and hence are irreversible, and the greater the temperature difference, the greater the irreversibility. We will find, however, that the concept of reversible heat transfer is very useful in describing ideal processes.

Mixing of Two Different Substances

Figure 5 illustrates the process of mixing two different gases separated by a membrane. When the membrane is broken, a homogeneous mixture of oxygen and nitrogen fills the entire volume. We can say here that this may be considered a special case of an unrestrained expansion, for each gas undergoes an unrestrained expansion as it fills the entire volume. A certain amount of work is necessary to separate these gases. Thus, an air separation plant requires an input work to accomplish the separation.

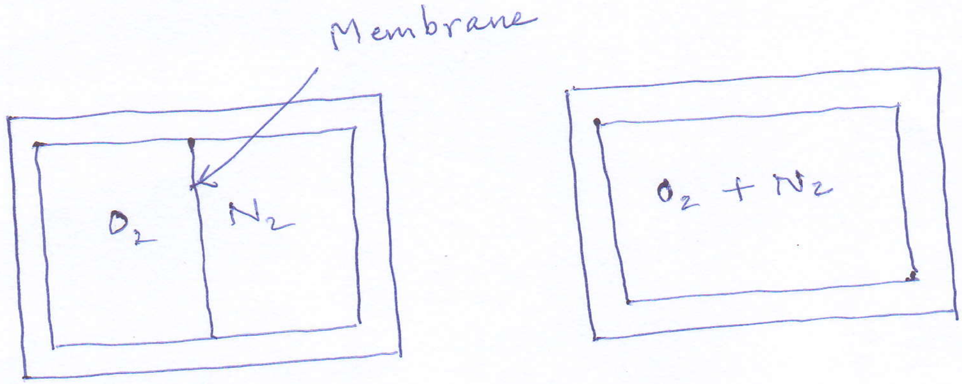


Fig. 5 Demonstration of the fact that the mixing of two different substances is an irreversible process.

Internal and External Irreversibility

It is frequently advantageous to distinguish between internal and external irreversibility. Figure 6 shows two identical systems to which heat is transferred. Assuming each system to be a pure substance, the temperature remains constant during the heat-transfer process. In one system the heat is transferred from a reservoir at a temperature $T + dT$, and in the other the reservoir is at a much higher temperature, $T + \Delta T$, than the system. The first is a reversible heat-transfer process, and the second is an irreversible heat-transfer process. However, as far as the system itself is concerned, it passes through exactly the same states in both processes, which we assume are reversible. Thus, we can say for the second system that the process is internally reversible but externally irreversible because the irreversibility occurs outside the system.

We should also note that the general interrelation of reversibility, equilibrium, and time. In a reversible process, the deviation from equilibrium is infinitesimal, and therefore it occurs at an infinitesimal rate. Since it is desirable that actual processes proceed at a finite rate, the deviation from equilibrium must be finite, and therefore the actual process is irreversible in some degree. The greater the deviation from equilibrium, the greater the irreversibility and the more rapidly the process will occur.

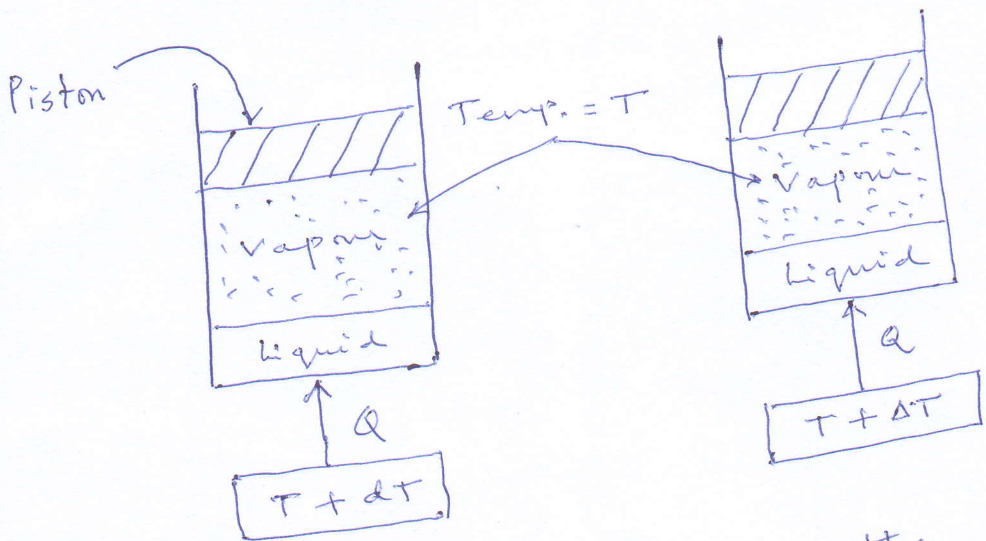


Fig. 6 Illustration of the difference between an internally reversible and an externally reversible process.

The Carnot Cycle

Having defined the reversible process and considered some factors that make processes irreversible, let us now pose the following question: If the efficiency of all heat engines is less than 100%, what is the most efficient cycle we can have?

Let us assume that a heat engine, which operates between the given high-temperature and low-temperature reservoirs, does so in a cycle in which every process is reversible. If every process is reversible, the cycle is also reversible; and if the cycle is reversed, the heat engine becomes a refrigerator. It can be shown that this is the most efficient cycle that can operate between two constant-temperature reservoirs. It is called the carnot cycle and is named after a French engineer, Sadi Carnot (1796–1832), who built the foundations of the second law of thermodynamics in 1824.

The important point to be made here is that the Carnot cycle, regardless of what the working substance may be, always has the same four basic processes. These processes are:

1. A reversible isothermal process in which heat is transferred to or from the high-temperature reservoir. (Boiler in steam turbine, condenser in refrigerator)
2. A reversible adiabatic process in which the temperature of the working fluid decreases from the high temperature to the low temperature. (Turbine in steam plant, Expander in refrigerator)
3. A reversible isothermal process in which heat is transferred to or from the low temperature reservoir. (Condenser in steam plant, evaporator in refrigerator)
4. A reversible adiabatic process in which the temperature of the working fluid increases from the low temperature to high temperature. (Pump in steam plant, compressor in refrigerator)

It may be noted that a Carnot cycle can be devised that takes place entirely within a cylinder, using a gas as the working substance.

Two Propositions Regarding the Efficiency of a Carnot Cycle

There are two important propositions regarding the efficiency of a carnot cycle.

First Proposition

It is impossible to construct an engine that operates between two given reservoirs and is more efficient than a reversible engine operating between the same two reservoirs.

Proof

Let us assume that there is an irreversible engine operating between two given reservoirs that has a greater efficiency than a reversible engine operating between the same two reservoirs.

Let the heat transfer to the irreversible engine be Q_H, the heat rejected be Q_L', and the work be W_{IE} (which equals $Q_H - Q_L'$), as shown in Fig. 1. Let the reversible engine operate as a refrigerator (this is possible since it is reversible). Finally, let the heat transfer with the low-temperature reservoir be Q_L, the heat transfer with the high-temperature reservoir be Q_H, and the work required be W_{RE} (which equals $Q_H - Q_L$).

Since the initial assumption was that the irreversible engine is more efficient, it follows (because Q_H is the same for both engines) that $Q_L' < Q_L$ and $W_{IE} > W_{RE}$. Now the irreversible engine can drive the reversible engine and still deliver the net work W_{net}, which equals $W_{IE} - W_{RE} = Q_L - Q_L'$.

If we consider the two engines and the high-temperature reservoir as a system (Fig. 1), we have a system that operates in a cycle, exchanges heat with a single reservoir, and does a certain amount of work. However, this would constitute a violation of the second law, and we conclude that our initial assumption (that the irreversible engine is more efficient than a reversible engine) is incorrect. Therefore, we cannot have an irreversible engine that is more efficient than a reversible engine operating between the same two reservoirs.

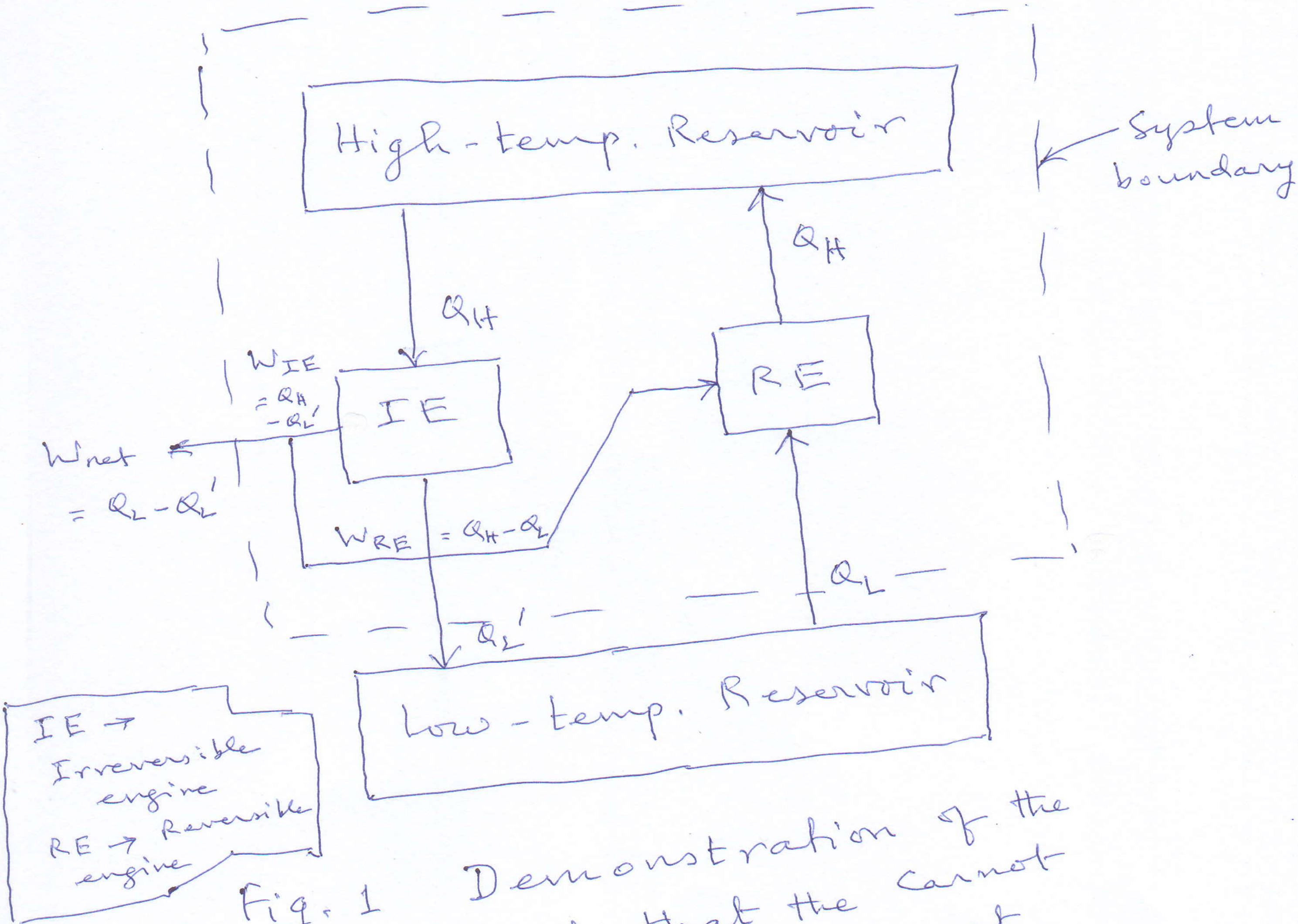


Fig. 1 Demonstration of the fact that the Carnot cycle is the most efficient cycle operating between two fixed-temperature reservoirs

Second Proposition

All engines that operate on the Carnot cycle between two given constant-temperature reservoirs have the same efficiency.

Proof

Let the carnot cycle with the higher efficiency replace the irreversible cycle of the previous argument, and let the carnot cycle with the lower efficiency operate as a refrigerator. The proof proceeds in the same line of reasoning as in the first proposition. See Fig. 2. We end up having an engine that produces a net amount of work while exchanging heat with a single reservoir, which is a violation of the second law. Therefore, we conclude that no reversible engine can be more efficient than a reversible engine operating between the same two reservoirs, regardless of how the cycle is completed or the kind of working fluid used.

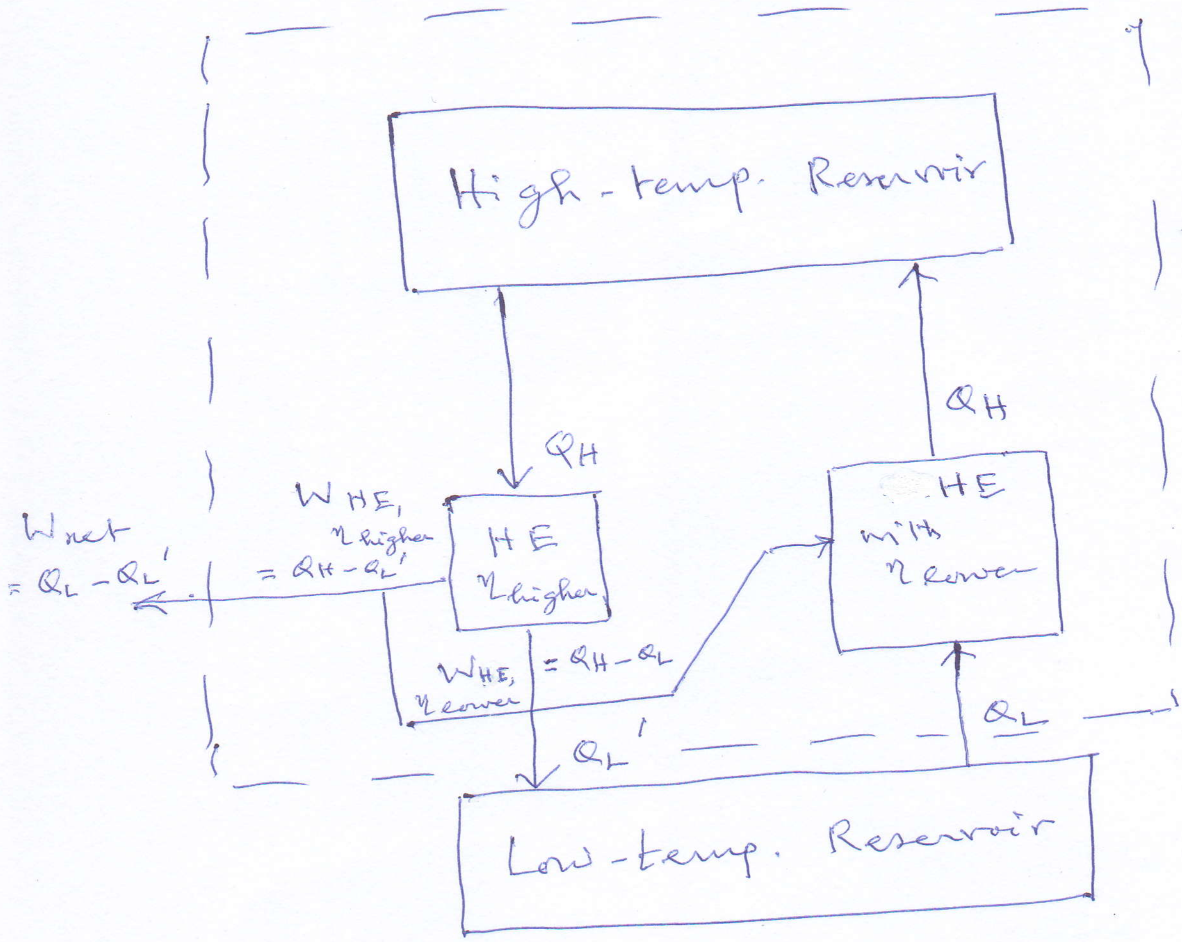


Fig. 2 Proof of the second proposition