Thermodynamics
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Lecture 58
Quasi-static Process Revisited: Work Against an External Force

Let’s revisit the concept of a quasi-static process.

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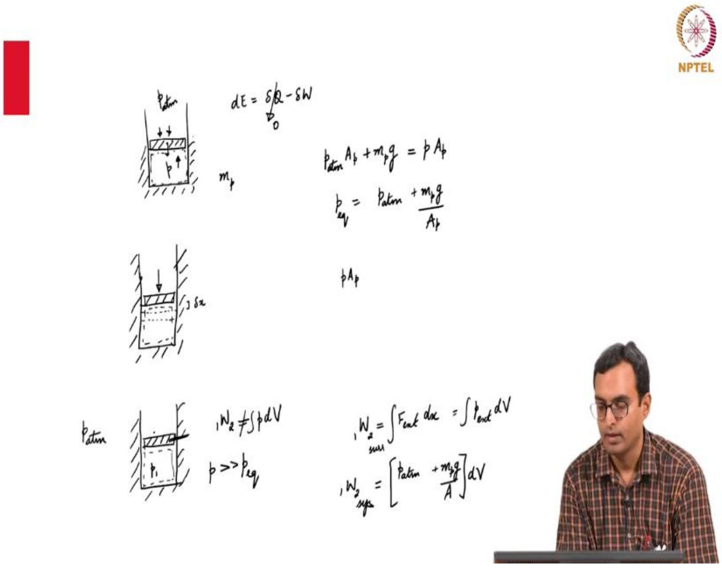

Figure 1.

Consider an insulated piston-cylinder arrangement as shown in Fig. 1 in the top left corner. The first law for such a system is $dE = -\delta W$ as $\delta Q = 0$. The pressure outside is the atmospheric pressure, p_{atm}, the pressure inside the arrangement is p, the mass of the piston is m_p and the area of the piston facing the gas inside the arrangement is A_p. If the system is in equilibrium, the force balance gives,

$$p_{atm}A_p + m_p g = pA_p \quad \rightarrow \quad p = p_{atm} + \frac{m_p g}{A_p} \ldots\ldots(1)$$

In such a case, the piston will not move. Hence, there is no work interaction. If we want to move this piston, for example, in a downward direction, we need to apply external force on the piston in the downward direction. This force must be slightly higher than the force (pA_p) given by the equation (1) so that the piston moves small distance δx. In this process, the pressure p also increases. If we want to move the piston again by δx (compress more), we need to increase the force slightly as the pressure p inside has increased. Hence, this external force needs to keep increasing slowly if we want to compress more and more. In a similar fashion, if we want to move the piston upwards, the external force needed keeps on increasing because the pressure inside decreases as the piston moves up. Note that the process is adiabatic and quasi-static in both the cases considered above.

Consider a similar piston-cylinder arrangement. Equation (1) is valid for this arrangement. Now, move the piston down by external force and pin it to the new location. Here, the pressure p_1 inside is greater than p from (1). Here, the extra force to hold the piston in its position is provided by the pin. As soon as the pin is released, the piston shoots up. However, this sudden upward movement of the piston is not slow. The process is not quasi-static. For such a process, we cannot calculate $\int pdV$.

Now assume that the upward movement of the piston is quasi-static or slow (after the release of the pin). In such a process (movement of the piston from the moment the pin is released till the achievement of the equilibrium), we can assume that the atmospheric pressure is constant throughout the process because the piston is moving very slowly. If the piston were moving very fast, the pressure close to the piston surface wouldn't be atmospheric (it would be higher than the atmospheric pressure). The mass of the piston is anyways constant. Here, we don't know the pressure inside, but we know the pressure outside (p_{atm}) and the force due to the mass of the piston on the gas inside the system. Hence, work done in this process is $W = \int F_{ext} dx = \int pdV = \int \left(p_{atm} + \frac{m_p g}{A_p}\right) dV$. Here, dV is the change in volume of the surroundings which also equals the change in volume of the system. For the system, dV is positive as it is expanding, while dV is negative for the surroundings.

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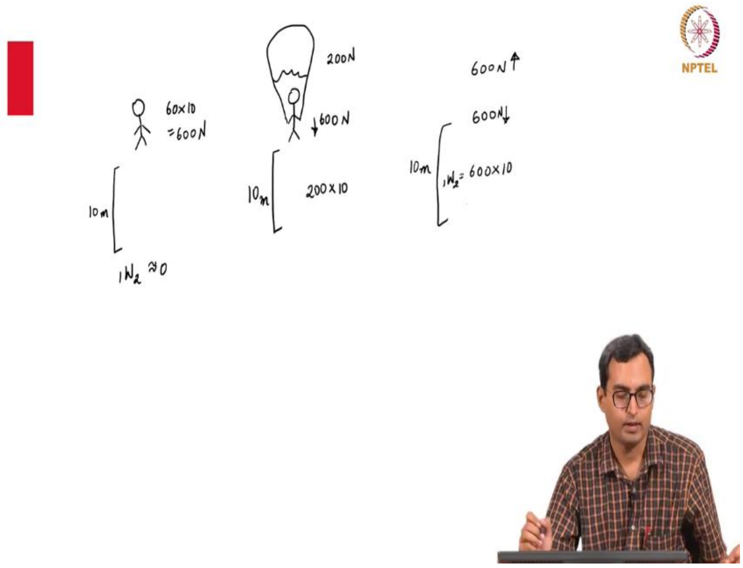

Figure 2.

We had looked at an example of a paratrooper jumping from a plane while discussing work interaction. Initially, the paratrooper does not deploy the parachute (he/she falls freely). Assuming negligible air resistance, the work interaction for the paratrooper is 0. Assume that the weight of the paratrooper is 600 N. Now, the paratrooper deploys the parachute, decelerates and falls through 10 m vertically. Suppose the air resistance during this fall is 200 N because of the parachute. The work interaction here is because of the air resistance, which is $200\ N \times 10\ m = 2000\ J$. After the parachute is completely deployed and the person is no more accelerating/decelerating, the air resistance is 600 N. Here, the work interaction is 600 N$\times\ 10\ m = 6000\ J$.

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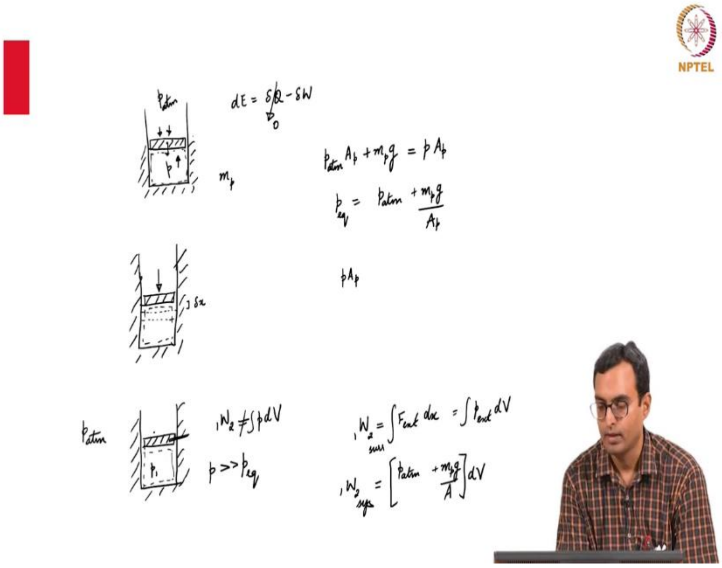

Similarly in the case of the piston-cylinder arrangement considered above, after the release of the pin, the movement of the piston is resisted by the weight of the piston and the atmospheric pressure. During the quasi-static process, the movement of the piston is fully-resisted and it is resisted by the pressure $p_{atm} + \frac{m_p g}{A_p}$.

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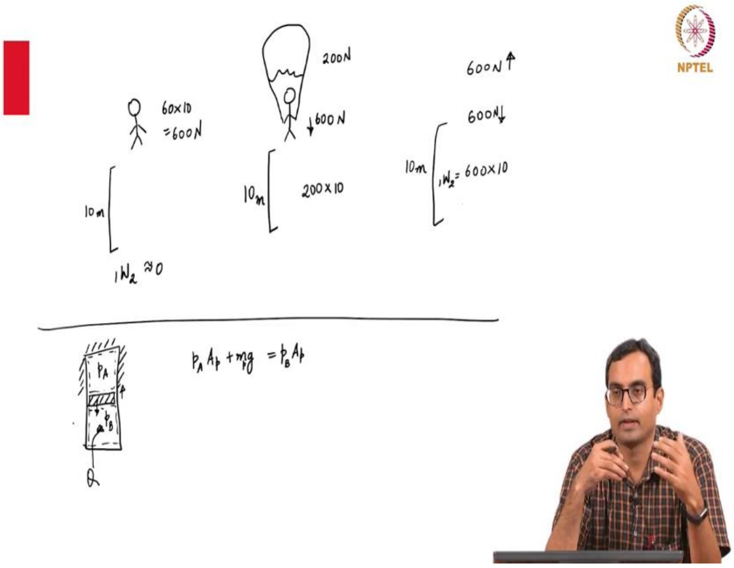

Figure 2.

Consider a piston-cylinder arrangement system as shown in Fig. 2. One half is insulated. The piston is also insulated. At equilibrium, $p_A A_p + m_p g = p_B A_p$. Heat is now transferred slowly to the section B. p_B increases. The piston moves up resulting in the increase of p_A. Here, the piston movement is fully-resisted. We can calculate the work interaction for both A and B. For A it is negative, whereas for B, it is positive. The work interactions are equal.

So, we can calculate work in quasi-static (near-equilibrium, slow) processes only. During the process, the work interaction is only due to the resistance by the external force. In non-quasi-static processes, we can’t measure the properties as the process is very fast and we have multiple values of a single property inside or outside the system. Hence, we can’t calculate the work interaction.