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Article

The duality of internal energy of ideal gas

Tian Zhao · Zengyuan Guo

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Abstract This contribution starts with the discussion on the classification of energy, and then the behaviors of various thermodynamic processes are analyzed, accompanying with the comparison of the adiabatic compression process of an ideal gas and an elastic rod. All these analyses show that the internal energy of ideal gases exhibits the duality of thermal energy–mechanical energy, that is, the internal energy acts as the thermal energy during the isochoric process, while the internal energy acts as the mechanical energy during the isentropic process. Such behavior of the internal energy is quite different from other types of energy during the energy conversion process because the internal energy of ideal gases exhibits the duality of thermal energy–mechanical energy. Because of this duality, the internal energy of ideal gas is proposed to be refered to as thermodynamic energy rather than thermal energy as indicated in some literature, although it consists of kinetics of the microscopic random motion of particles and can be expressed as the function of temperature only.

Keywords Internal energy · Mechanical energy · Ideal gas · Duality

1 The classification of energy

It is well known that all types of energy can be classified based on the forms of motion of matter, such as mechanical energy, electromagnetic energy, chemical energy, nuclear energy and thermal (heat) energy [1], where thermal energy is referred to as the energy associated with the microscopic random motion of particles [2]. Furthermore, energy types can also be classified as being either extrinsic (external) or intrinsic (internal) energy [3]. The internal energy usually contains nuclear energy, chemical energy, thermal energy and so on, while the mechanical energy is often not regarded as a part of internal energy. In thermodynamics, the internal energy is one of the two cardinal state functions of the state variables of a thermodynamic system and it refers to the stored microscopic energy on the atomic and molecular scale in two aspects. One is the microscopic kinetic energy due to the microscopic motion of the system's particles (translations, rotations, vibrations). The other is the potential energy associated with the electrical/magnetic/nuclear forces, including the chemical bonds, between the particles [4]. Solids sustain their thermal energy by the vibration of atoms about their mean lattice positions, while atoms in a liquid translate, rotate (albeit more sluggishly than gases) and vibrate [2]. For the internal energy of the ideal gas, however, the random translational kinetic energy of molecules is only left, and at this time, the temperature of the gas is proportional to the average kinetic energy of molecules. As a result, the internal energy of an ideal gas is regarded as an equivalence of thermal energy in some literature, for instance in Refs. [4–6]. However, the internal energy behaves quite different from electrical energy, mechanical energy or thermal energy during its transformation into other type energy. Therefore, in this paper, various thermodynamic processes of ideal gas have been analyzed to explore the characteristics of the internal energy and the relation between the internal energy and thermal energy of ideal gas.

T. Zhao · Z. Guo (✉)
Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China
e-mail: demgzy@tsinghua.edu.cn

2 The isochoric process of ideal gas

Figure 1 presents a rigid container filled up with unit mass of ideal gas at the temperature T, pressure p, specific volume v and isochoric specific heat capacity c_v. As an infinitesimal heat δq is transported reversibly into the container, the first law of thermodynamics yields [6]

$$\delta q = \mathrm{d}u. \quad (1)$$

The differential of internal energy u of the ideal gas is [7]

$$\mathrm{d}u = c_v \mathrm{d}T, \quad (2)$$

where c_v is the function of temperature only for ideal gas and named as the thermal coefficient, because it is related to thermal process only and the temperature T acts as the system potential during heat transfer from the heat sources to the ideal gas.

It can be found in Eq. (2) that the increment in internal energy can be expressed in terms of the variation of c_v and T only. Therefore, we may say that the internal energy acts as the thermal energy during an isochoric process, where there is heat interaction alone between the ideal gas and environment.

3 The adiabatic process of ideal gas

For the ideal gas in an elastic container, as shown in Fig. 2, its pressure and specific volume satisfy the following relation during a reversible adiabatic process [8]

$$p^{\frac{1}{\gamma}} v = c_0, \quad (3)$$

where γ stands for ratio of specific heat capacities and c_0 may be regarded as a mechanical coefficient, because it is related to mechanical parameters only. It should be noted that unlike c_v which is the temperature function only during any thermodynamic process for ideal gases, c_0 is a function of the pressure and specific volume in general processes and remains constant only during reversible adiabatic process, which is also isentropic process.

The first law of thermodynamics offers that for a reversible adiabatic process [9]

$$\mathrm{d}u = \delta q - \delta w = -\delta w = -p\mathrm{d}v. \quad (4)$$

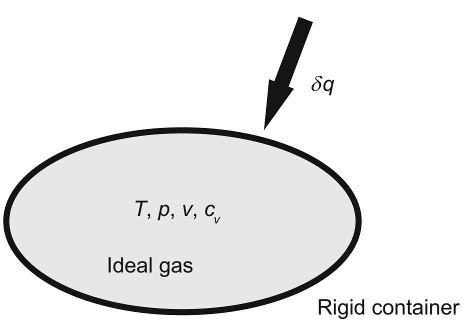

Fig. 1 Ideal gas in a rigid container

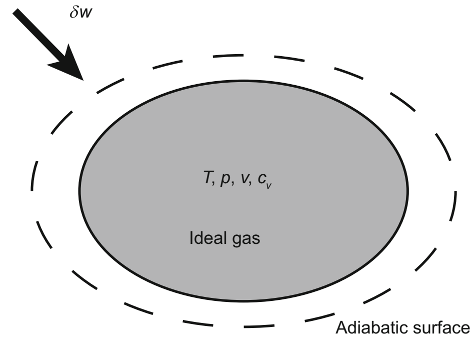

Fig. 2 Ideal gas in an elastic container

The differential of Eq. (3) yields

$$\frac{\mathrm{d}p}{p} + \gamma \frac{\mathrm{d}v}{v} = 0. \quad (5)$$

Substituting Eq. (5) into (4) gives

$$\mathrm{d}u = \frac{v}{\gamma} \mathrm{d}p. \quad (6)$$

Combining Eqs. (6) and (3) leads to

$$\mathrm{d}u = \frac{c_0}{\gamma} p^{-\frac{1}{\gamma}} \mathrm{d}p = \frac{c_0}{\gamma - 1} \mathrm{d}\left(p^{1-\frac{1}{\gamma}}\right) = c_a \mathrm{d}\left(p^{1-\frac{1}{\gamma}}\right). \quad (7)$$

Noticing that the pressure p acts as the system potential during work transfer from the environment to the ideal gas, it can be seen that the physical meaning of c_a is the amount of work done by the environment for increasing a unit $p^{1-1/\gamma}$ of system. Equation (7) gives the differential expression of internal energy of ideal gas, which consists of merely mechanical parameters in a reversible adiabatic process. Hence, we may say in this case that the internal energy acts as the mechanical energy during an isentropic process, where there is work interaction alone between the ideal gas and environment.

In order to explain further that the adiabatic process of ideal gas can be regarded as a kind of mechanical motion, we take an elastic rod as an example. The elastic rod can be both compressed and stretched, and once the rod is deformed, there would be elastic force in the rod [10]. The elastic force is a function of elastic deformation, which is described through Hooke's law. Moreover, when the rod is compressed or stretched, the rod would store elastic potential energy. Figure 3 shows an elastic rod with compress force N, and the rod is compressed in a quasi-static process. Thus, at every moment, the compress force is equal to the elastic force in the rod:

$$F = N = k(x)\Delta x = k(x)(x_0 - x), \quad (8)$$

where $\Delta x = (x_0 – x)$ and k is the elastic coefficient. During an infinitesimal deformation process of the elastic rod, the work exerted on the compressed rod, that is, the elastic potential energy stored in the rod, is [11]