Application of stable flow energy equation in steam turbine and other power machines

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Abstract. The stable flow energy equation reflects the general law of energy conversion in the process of stable flow of working fluid, which is widely used in various thermal equipment. This paper mainly introduces application of stable flow energy equation in steam turbine and other power machines. Through the example calculation, it is verified that in the practical application process, the energy equation can be reasonably simplified according to the specific situation, and the calculation can be completed in a simpler and clearer form.

1. Introduction

1.1 Characteristics of steady flow
In production practice, a large number of engineering devices, such as turbines, nozzles, heat exchangers and compressors operate for long periods of time under the same conditions once the transient start-up periods complete and steady operations are established. The thermal state and flow state of each point in the flow do not change with time. That is the fluid properties at any point remain constant during the entire process. This flow state of fluid is called steady flow. However, the fluid properties can change from point to point in the process of flow. For example, the flow process of a steam turbine with constant load is a stable flow process.

1.2 Stable flow energy equation
The energy equation of steady flow can be obtained by applying the principle of energy conservation to steady flow.

The energy equation applicable to various stable flows can be expressed as

\[ Q = m(h_2 - h_1) + \frac{1}{2}m(c_2^2 - c_1^2) + mg(z_2 - z_1) + mw_s \]  \hspace{1cm} (1)

On a unit mass basis, it becomes

\[ q = (h_2 - h_1) + \frac{1}{2}(c_2^2 - c_1^2) + g(z_2 - z_1) + w_s \]  \hspace{1cm} (2)

in which \( \frac{1}{2}(c_2^2 - c_1^2) \) is kinetic energy, \( g(z_2 - z_1) \) is gravitational potential energy, \( w_s \) is shaft work. They belong to mechanical energy and can be used directly in technique. Therefore, this part of energy carried by flowing fluid is also called technical work, denoted as \( w_t \).

\[ w_t = \frac{1}{2}(c_2 - c_1) + (z_2 - z_1) + w_s \]  \hspace{1cm} (3)
2. Application of stable flow energy equation

In engineering practice, the stable flow energy equation is widely used. According to the operation characteristics of the actual equipment, the stable flow energy equation can be properly simplified, which is more convenient for application. Based on the teaching requirements of higher vocational colleges, this paper mainly analyses the application of stable flow energy equation in steam turbine and other thermal equipment. There are many power machines, such as steam turbine, steam engine, internal combustion engine, gas turbine, etc. The steam turbine would be an example in the paper.

2.1 Application of steady flow energy equation in steam turbine

When the steam turbine is in stable working state, the flow process of steam is steady flow. The pressure of steam flowing through the turbine drops and works with expansion. Steam parameters at the inlet and outlet of steam turbine are shown in Figure 1.

![Figure 1. Turbine diagram](image)

In actual operation, the velocity of steam flow at the inlet and outlet of steam turbine has little difference. Therefore, the kinetic energy difference between inlet and outlet can be negligible. In addition, the difference of gravitational potential energy can also be disregarded. The heat transfer from turbines passing through the boundary is also small compared with the output power, which can also be ignored. The expansion process of steam turbine is adiabatic. That is

\[ \frac{1}{2}(c_2^2 - c_1^2) \approx 0, \quad g(z_2 - z_1) \approx 0, \quad q \approx 0 \] (4)

Therefore, when the turbine is in stable operation, the energy equation can be simplified as follows

\[ w_t = w_s = h_1 - h_2 \] (5)

So, the shaft work output from the turbine per unit mass of steam is equal to its enthalpy decrease. And then, the output power of the turbine is

\[ P = m \cdot w_t = m \cdot w_s = m \cdot (h_1 - h_2) \] (6)

where \( m \) is the mass flow, its unit is \( \text{kg/s} \).

2.2 An example

In a steam power plant, the boiler supplies steam to the turbine at a mass flow rate of 40000kg/h. The turbine inlet pressure gauge reads 8.9 MPa, the enthalpy of the steam is 3441 kJ/kg. The reading of turbine outlet vacuum gauge is 730.6 mmHg, the enthalpy of the outlet steam is 2248 kJ/kg. The turbine radiates heat to the environment as 6.81 × 10^5 kJ/h. If the local atmospheric pressure is 760 mmHg. Determine (1) the absolute pressure of inlet and outlet steam, (2) the power of the turbine regardless of the kinetic energy difference and potential energy difference between the inlet and outlet, (3) the power of the turbine at turbine inlet and outlet speeds of 70 m/s and 140 m/s respectively, (4) the impact on turbine power, if the height difference of turbine inlet and outlet is 1.6m[2].

2.3 Solution

(1) The inlet absolute pressure
$$p_1 = p_{g1} + p_b = 8.9 + 760 \times 133.3 \times 10^{-6} = 9.01 \text{ MPa}$$

The outlet absolute pressure

$$p_2 = p_b - p_{v2} = (760 - 730.6) \times 133.3 \times 10^{-6} = 0.39 \times 10^{-2} \text{ MPa}$$

(2) The power of the turbine

$$w_s = h_1 - h_2 = 3441 - 2248 = 1193 \text{ kJ/kg}$$

$$P = \frac{ mw_s}{3600} \times 1193 = 1.33 \times 10^4 \text{ kW}$$

$$P' = P - \frac{Q}{\tau} = 1.33 \times 10^4 - \frac{6.81 \times 10^5}{3600} = 1.31 \times 10^4 \text{ kW}$$

$$\Delta P_1 = P' - P = \frac{Q}{\tau} = \frac{6.81 \times 10^5}{3600} = 0.02 \times 10^4 \text{ kW}$$

(3) If the turbine inlet and outlet speeds are considered, the change of power is

$$\Delta P_2 = \frac{1}{2} \frac{m}{\tau} (c_2^2 - c_1^2) = \frac{1}{2} \frac{40000}{3600} \times (140^2 - 70^2) \times 10^{-3} = 81.67 \text{ kW}$$

(4) If the height difference between the inlet and outlet is considered, the change of power is

$$\Delta P_3 = m g \Delta z = \frac{40000}{3600} \times 9.81 \times 1.6 \times 10^{-3} = 0.17 \text{ kW}$$

The influence of heat loss, inlet and outlet speed and inlet and outlet height on turbine power is shown in Table 1.

| $P$  | $\Delta P_1 / P$ | $\Delta P_2 / P$ | $\Delta P_3 / P$ |
|------|------------------|------------------|------------------|
| $1.33 \times 10^4$ | 1.50%         | 0.61%           | 0.001%          |

It can be seen from the table that the heat dissipation, energy difference between the inlet and outlet, and height difference between the inlet and outlet are not significant for the turbine power, which can be ignored in the actual calculation.

2.4 Analysis

Generally, in the thermal calculation, the work or power is calculated further according to the temperature and pressure of steam in and out of the turbine. For example, in the above example, it is known that the inlet steam pressure of the turbine is 9 MPa, the temperature is 570 °C, the exhaust steam pressure is 0.0039 MPa, the exhaust steam dryness is 0.87. Determine (1) the Steam turbine work. (2) the turbine power at 40 t/h steam flow.

Solution From the $h - s$ diagram[3], the following properties can be obtained, as shown in Figure 2.

$$\Delta P_2 = \frac{1}{2} \frac{m}{\tau} (c_2^2 - c_1^2) = \frac{1}{2} \frac{40000}{3600} \times (140^2 - 70^2) \times 10^{-3} = 81.67 \text{ kW}$$

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Figure 2. The $h - s$ diagram
Point 1: \( h_1 = 3441 \text{ kJ/kg} \), Point 2: \( h_2 = 2248 \text{ kJ/kg} \)

On a unit mass basis, the steam turbine work is

\[ w_s = h_1 - h_2 = 3441 - 2248 = 1193 \text{ kJ/kg} \]

If the steam flow is 40 t/h, the turbine power is

\[ P = \dot{m}w_s = \frac{40 \times 10^3}{3600} \times 1193 = 1.33 \times 10^4 \text{ kW} \]

3. Conclusion

The stable flow energy equation is widely used. Students majoring in thermal power in vocational and technical colleges should not only understand its form, but also master its specific application in thermal equipment. Besides, the ability of using the h-s diagram of steam to determine the state parameters is necessary for students. On the one hand, the parameters of steam can be checked by h-s diagram. On the other hand, they can be checked through steam tables. Steam tables are divided into a thermodynamic properties table for saturated liquid and vapor and for unsaturated liquid and superheated vapor. It's easier to use h-s diagram, although it is more likely to cause errors.

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