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Analysis of the adiabatic process by using the thermodynamic property diagram of water vapor

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Abstract. In the steam power plant, the working medium used for energy transformation is water vapor. The thermodynamic properties of water vapor are usually obtained by using water vapor tables and charts. Adiabatic process of water vapor is widespread in engineering applications. The adiabatic process is realized without heat addition or rejection and the entropy of the working medium during a reversible adiabatic process remains constant. During an adiabatic expansion process, superheated steam turns into saturated vapor , and further into wet vapor, the pressure and the temperature of the steam decreases. The entropy during a irreversible adiabatic process increases. In general, when analyzing the thermodynamic process of water vapor, we first determine the state parameters by using charts and tables, and then make relevant calculations according to the first law of thermodynamics.

1 Introduction

The adiabatic process is a process in the steam power plant cycle, such as the expansion process of steam in the steam turbine and the pressure rise process of water in the water pump. If the irreversible loss such as friction is not considered in the adiabatic process, the entropy of the working medium remains constant. The water vapor thermodynamic analysis is based on the first and the second laws of thermodynamics. In general, steam tables and h-s diagrams are used.

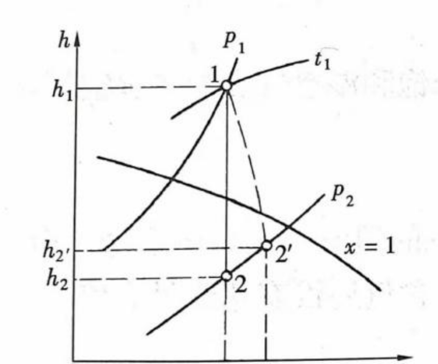

Fig. 1. Reversible and Irreversible Adiabatic Process

For an adiabatic process of water vapor, if the initial parameters are pressure p_1 and temperature t_1, and the final parameter is p_2, the initial and final state points and process lines of the process can be determined on the h-s diagram, as shown by a straight line 1-2 in Figure 1[1].The T-s diagram of the process is shown in Figure 2[2].

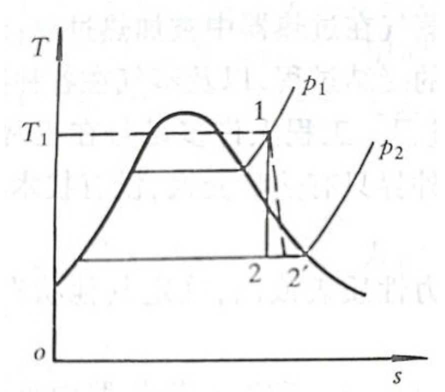

Fig. 2. T-s diagram of water vapor adiabatic process.

2 Analysis of the adiabatic process of water vapor

Let us analyze the adiabatic process of water vapor through an example.
Example:

The inlet parameters of a steam turbine are p_1=9.0MPa, t_1=500℃. The outlet steam pressure is p_2=0.004MPa.

Determine:

(1) the superheat of inlet steam;

(2) the work output per unit mass of steam when it can reverse flow through the turbine;

(3) if the enthalpy per kilogram of steam at the outlet is increased by 200 kJ due to the viscous friction of steam, determine the work output and the loss of adequate energy when the unit mass steam flows through

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the turbine irreversibly. The ambient temperature is t_0=17℃[3].
The process of calculation and analysis is as follows:

2.1 Analysis by h-s diagram

From the h-s diagram, we can get to know the steam is superheated vapor at state 1. The other properties of this state are

$$h_1 = 3390 \quad kJ/kg$$

$$s_1 = 6.66 \quad kJ/(kg \cdot K)$$

The final properties at p_2=0.004 MPa are

$$h_2 = 2005 \quad kJ/kg$$

$$s_2 = s_1 = 6.66 \quad kJ/(kg \cdot K)$$

According to the steady flow energy equation

$$\begin{aligned} q &= (u_2 - u_1) + (p_2 v_2 - p_1 v_1) \\ &\quad + \frac{1}{2}(c_2^2 - c_1^2) + g(Z_2 - Z_1) + w_s \\ &= (h_2 - h_1) + w_t \end{aligned} \tag{1}$$

The technical work output available is

$$\begin{aligned} w_t &= h_1 - h_2 \\ &= 3390 - 2005 \\ &= 1385 \quad kJ/kg \end{aligned} \tag{2}$$

In engineering, the adiabatic expansion process of steam in the steam turbine and the adiabatic compression process of water in the water pump are not entropy processes, but entropy increase process due to the existence of irreversible factors such as friction. It is shown by line 1-2′in Figure 1 and 2. The other properties at state 2′are

$$s_{2'} = 7.32 \quad kJ/(kg \cdot K)$$

According to the meaning of the example, there is

$$\begin{aligned} h_{2'} &= 2005 + 200 \\ &= 2205 \quad kJ/kg \end{aligned} \tag{3}$$

Then the technical work output available is

$$\begin{aligned} w_t' &= h_1 - h_{2'} \\ &= 3390 - 2205 \\ &= 1185 \quad kJ/kg \end{aligned} \tag{4}$$

the loss of effective energy is

$$\begin{aligned} i &= T_0(s_2' - s_2) \\ &= (17 + 273) \times (7.32 - 6.66) \\ &= 191.4 \quad kJ/kg \end{aligned} \tag{5}$$

In order to reflect the irreversibility of the adiabatic process, the efficiency of the steam turbine is defined in engineering.

$$\begin{aligned} \eta_t &= \frac{w_t'}{w_t} \\ &= \frac{1185}{1385} \times 100\% \\ &= 85.56\% \end{aligned} \tag{6}$$

2.2 Analysis by water vapor thermodynamic property tables

According to the thermodynamic property table of water vapor, the state parameters of water vapor in different states can also be determined, so as to further calculate the physical quantities such as the work exchanged between the system and the outside world in the thermodynamic process.

For the example above, we can get to know the enthalpy and entropy of the superheated vapor at 9.0MPa, 500℃ from the water vapor table. Some of the data are shown in Table 1. The data in Table 1 are taken from the table of thermodynamic properties of unsaturated water and superheated vapor in reference [4].

Table 1. Properties of unsaturated water and superheated vapor (by pressure and temperature)

p	9.0MPa		
Sat properties	ts= 303.385℃ v′= 0.0014177 v″ =0.020500 h′= 1363.1 v″ =2741.9 s′= 3.2854 s″ =5.6771		
t (℃)	*v* (m^3/kg)	*h* (kJ/kg)	*s* (kJ/kg.K)
0	0.0009957	9.08	0.0004
...	...	...	...
450	0.033474	3256.0	6.4835
500	0.036733	3385.0	6.6560
600	0.042789	3630.8	6.9552

The properties of state 1 and 2 are

$$h_1 = 3385 \quad kJ/kg$$

$$s_1 = 6.656 \quad kJ/(kg \cdot K)$$

Since entropy remains constant during the process, so

$$s_2 = s_1 = 6.656 \quad kJ/(kg \cdot K)$$

Then, we use the entropy of state 2 point to calculate its dryness. The entropy of saturated water and the entropy of dry saturated steam are checked out from table 2. The data in Table 2 are taken from the table of thermodynamic properties of saturated water and vapor (by pressure) in reference [4].

Table 2. Properties of saturated water and vapor (by pressure)

Press.	Temp.	Specific volume		Enthalpy		Entropy	
		Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor	Sat. liquid	Sat. vapor
P MPa	t °C	v' m³/kg	v'' m³/kg	h' kJ/kg	h'' kJ/kg	s' kJ/kg.K	s'' kJ/kg.K
0.001	6.9491	0.0010001	129.185	29.21	2513.29	0.1056	8.9735
...							
0.003	24.1142	0.0010028	45.666	101.07	2544.68	0.3546	8.5758
0.004	28.9553	0.0010041	34.796	121.30	2553.45	0.4221	8.4725
0.005	32.8793	0.0010053	28.191	137.72	2560.55	0.4761	8.3930
...							
22.064	373.99	0.003106	0.003106	2085.9	2085.9	4.4092	4.4092

Entropy of wet vapor is

$$s = xs'' + (1-x)s' \tag{7}$$

Thus, the calculation method of dryness can be obtained

$$x_2 = \frac{s - s'}{s'' - s'} \tag{8}$$

Therefore the dryness at state 2 is

$$\begin{aligned} x_2 &= \frac{s_2 - s_2'}{s_2'' - s_2'} \\ &= \frac{6.656 - 0.4221}{8.4725 - 0.4221} \\ &= 0.774 \end{aligned} \tag{9}$$

So, the enthalpy at state 2 is

$$\begin{aligned} h_2 &= x_2 h'' + (1-x_2)h' \\ &= 0.774 \times 2553.45 + (1-0.774) \times 121.30 \\ &= 2003.78 \quad kJ/kg \end{aligned} \tag{10}$$

then

$$\begin{aligned} w_t &= h_1 - h_2 \\ &= 3385 - 2003.78 \\ &= 1381.22 \quad kJ/kg \end{aligned} \tag{11}$$

According to the theme

$$\begin{aligned} h_{2'} &= 2003.78 + 200 \\ &= 2203.78 \quad kJ/kg \end{aligned} \tag{12}$$

the technical work output available is

$$\begin{aligned} w_t' &= h_1 - h_{2'} \\ &= 3385 - 2203.78 \\ &= 1181.22 \quad kJ/kg \end{aligned} \tag{13}$$

The dryness at state 2′ is

$$\begin{aligned} x_{2'} &= \frac{h_{2'} - h_{2'}'}{h_{2'}'' - h_{2'}'} \\ &= \frac{2203.78 - 121.30}{2553.45 - 121.30} \\ &= 0.856 \end{aligned} \tag{14}$$

The entropy at state 2′ is

$$\begin{aligned} s_{2'} &= x_{2'} s_{2'}'' + (1 - x_{2'}) s_{2'}' \\ &= 0.856 \times 8.4725 + (1-0.856) \times 0.4221 \\ &= 7.313 \quad kJ/(kg \cdot K) \end{aligned} \tag{15}$$

the loss of effective energy is

$$\begin{aligned} i &= T_0 (s_2' - s_2) \\ &= (17+273) \times (7.313 - 6.656) \\ &= 190.53 \quad kJ/kg \end{aligned} \tag{16}$$

the turbine efficiency is

$$\begin{aligned} \eta_t &= \frac{w_t'}{w_t} \\ &= \frac{1181.22}{1381.22} \times 100\% \\ &= 85.52\% \end{aligned} \tag{17}$$

We compare the calculation results of two different methods, as shown in Table 3.

It can be seen from the table that there is a certain deviation in the calculation results with two different methods.

Table 3. Calculation results of two different methods

	by h-s diagram	by water vapor thermodynamic property tables
h_1 (kJ/kg)	3390	3385
s_1 (kJ/kg.K)	6.66	6.656
h_2 (kJ/kg)	2005	2003.78
s_2 (kJ/kg.K)	6.66	6.656
w_t (kJ/kg)	1385	1381.22
$s_{2'}$ (kJ/kg.K)	7.32	7.313
$h_{2'}$ (kJ/kg)	2205	2203.78
$w_t^{'}$ (kJ/kg)	1185	1181.22
i (kJ/kg)	191.4	190.53
η_t (%)	85.56	85.52

Using an h-s diagram to determine the state parameters of water vapor is straight forward, but the reading is not accurate due to human error. It is more accurate to determine the state parameters of water vapor by using the thermodynamic property table of water vapor, but sometimes it needs interpolation calculation, so the calculation is troublesome.

3 Conclusion

From the analysis process of the whole example, we can see that there is only work exchange in the adiabatic process, but no heat exchange between the working medium and the outside world.

The expansion process of steam in turbine, the compression process of water in pump and the compression process of refrigerant in compressor can be regarded as adiabatic process. When the loss is not considered, they are entropy processes.In engineering, the actual adiabatic expansion process and compression process inevitably exist irreversible factors such as friction, so the actual process is irreversible adiabatic process.

Through the analysis of the whole example, we have a general understanding of the analysis steps of steam adiabatic process. And we have a direct perceptual understanding of the calculation results and the comparison between the two methods. Especially for the students in our vocational and technical colleges, it is helpful to understand the basic knowledge.

To sum up, the general steps to analyze and solve the thermodynamic process of water vapor are as follows:

(1) Based on the two independent properties of the known initial state, determine the initial state and its other state properties using steam thermodynamic property table or h-s diagram.

(2) Based on the given condition and the characteristics of the process, determine the initial state and its properties.

(3) Depict the process on an h-s diagram to directly represent the characteristics of the thermal process.

(4) According to the first law of thermodynamics, calculate the work exchange.

(5) If it is an irreversible process, the effective energy loss is further analyzed.

In engineering applications, the adiabatic process of steam is widespread. The water vapor commonly used in thermodynamic systems cannot be treated as an ideal gas. Water vapor does not follow the ideal gas equation of state. To analyze the thermodynamic process of water vapor, its charts and tables are mainly used.

References

1. Jing, Z.H. (2009) Thermal Engineering, China Electric Power Press, Beijing.
2. He, Y.L. (2001) Essential analysis of engineering thermodynamics and solutions to typical problems, Xi'an Jiaotong University Press, Xi'an
3. Zhao, L, Engineering Thermodynamics (A Bilingual Textbook) (2012), China Building Industry Press, Beijing.
4. Xu, Y.P., Ke, X.Y. (2012) Thermal Engineering. ChinaElectricPowerPress, Beijing.
5. Shang, Y.Q. (2007) Engineering Thermodynamics. China Electric Power Press, Beijing.
6. Tong, J.G., Wang, P.Y., Su, Y.K.(2008) Thermal engineering. Shanghai Jiaotong University Press.
7. Zhu, M.S., Liu, Y., Lin, Z.Z., Peng, X.F. (2011) Engineering Thermodynamics. Tsinghua university press, Beijing.
8. Cheng, G.T., Wang, Y.Z. (2007) Engineering Thermodynamics (Second Edition). Beijing University of Technology Press, Beijing.
9. Chen, Z.H. (2009) Basic Thermal Engineering, China Electric Power Press, Beijing .
10. Shen,W.D., Geng,T.J. (2007) Engineering Thermodynamics, Higher Education Press, Beijing.
11. Han, S.F., Ren, J.Y. (2014) Foundation and application of thermal engineering. Beijing University of Technology Press, Beijing.