Analysis of thermodynamic process of water vapor in boiler

YarongWang[1*] and PeirongWang[2]

[1] Baoding Electric Power VOC.&TECH. College, Baoding, Hebei, 071051, China
[2] Hebei Software Institute, Baoding, Hebei, 071000, China

Abstract. In steam power plant, the working medium used for energy transformation is water vapor. The generation process of water vapor has experienced three stages: pre-heat, vaporization and superheat stage. There are five states in the process. They are sub-cooled liquid, saturated water, saturated liquid-vapour mixture, saturated vapor and superheated vapor. The thermodynamic properties of each state are usually obtained by using water vapor tables and charts. The constant pressure process of water vapor is very common in engineering application. In general, 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

In steam power plant, the working medium used for energy transformation is water vapor. Water vapor has good expansibility and fluidity. It also has other characteristics, such as stable thermal performance, non-toxic, non corrosive, low price and easy to obtain. In a actual thermodynamic process, the phase state of water vapor will change. And water vapor is not far away from the liquid state, so it can not be treated as an ideal gas. Industrial water vapor is usually produced by heating in a boiler. This is a constant pressure process.

2 Analysis on thermodynamic process of water vapor in boiler

2.1 The three stages and five kinds of states in the process of water vapor generation

The simple device shown in Figure 1[1] can be used to simulate the constant pressure process of water vapor generation in a boiler. We can use this simple device to observe the state changes in the process.

The generation of water vapor has experienced three stages. The first stage is the pre-heat stage: sub-cooled liquid to saturated liquid. A sub-cooled liquid is also called a compressed liquid. It is unsaturated water. At this stage, the temperature is lower than the saturation temperature of the corresponding pressure. Until the saturated water state is reached, the saturation temperature is reached. The second is the vaporization stage: saturated liquid to saturated vapor. In this stage, the temperature of the working medium is always saturated temperature and remains unchanged if the pressure is held constant. During the entire phase-change process, the liquid and vapour phases coexistence in equilibrium, which is called saturated liquid-vapour mixture. The third is the superheat stage: saturated vapor to superheated vapor. At this stage, further transfer of heat results in an increase in temperature. The temperature is higher than the saturation temperature corresponding to the pressure.

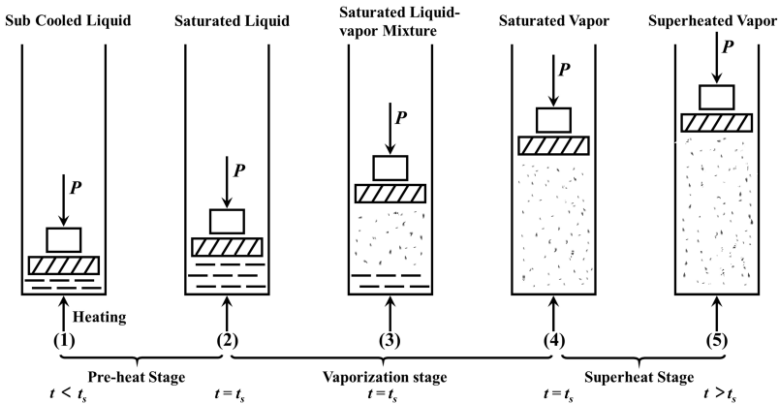

Figure 1. Phase Change Process of Water at Constant Pressure

*Corresponding author's e-mail: bjoycg2008@163.com, wangpeirong@hbsi.edu.cn

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).

The p-v diagram and T-s diagram of the phase change process of water at a constant pressure can be drawn, as shown in Figure 2[1]. In the figure, a-b is the pre-heat stage, b-c-d is the vaporization stage, d-e is the superheat stage.

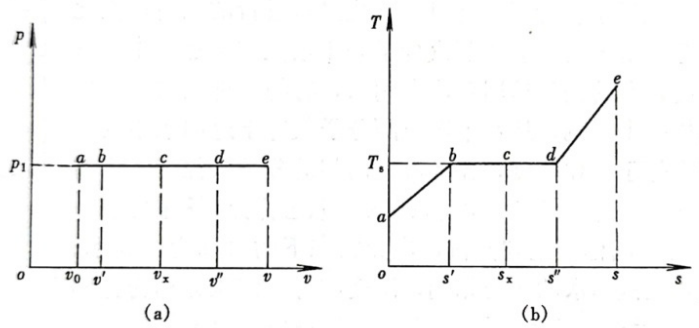

Figure 2. p-v diagram and T-s diagram of water vapor at a constant pressure

2.2 Water vapor tables and the enthalpy-entropy diagram (h-s diagram) for water vapor

We can see the variation law of p, v, T and s in the process of water vapor generation from Figure 2. But it is far from meeting the needs of engineering calculation. Tables and h-s diagram for water vapor are used to determine the state parameters of each state of water vapor. Water vapor tables are divided into a thermodynamic properties table for saturated liquid and saturated vapor and a thermodynamic properties table for unsaturated liquid and superheated vapor, which is used to check the state parameters of corresponding state. The parameters of saturated liquid-vapour mixture are calculated by the parameters of saturated liquid and saturated vapor under the same pressure and the quality.

The h-s diagram for water vapor is used to check the state parameters of water vapor, including the state of saturated liquid- vapour mixture, which is simple and intuitive. The h-s diagram structure of water vapor is shown in Figure 3[2].

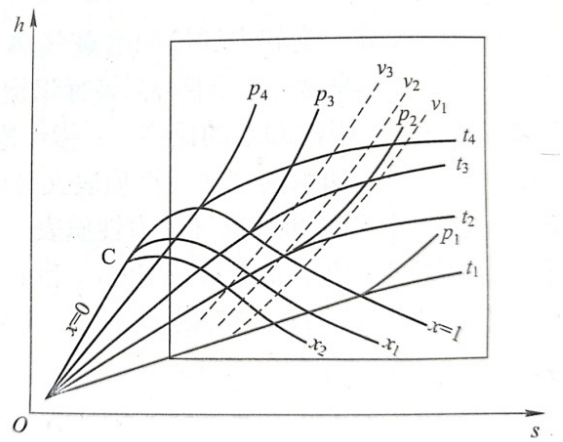

Figure 3. h-s diagram for water vapor

2.3 The constant pressure process in boiler

Constant pressure process is a common process in steam power plant. The heat absorption process in each heat exchanger of a boiler, the heating process of feed water in a regenerative heater, and the heat release process of exhaust steam in a condenser can be regarded as constant pressure process. We analyze the constant pressure process in a boiler with the following examples.

Example

A schematic diagram of a boiler is shown in Figure 4[3]. It produces 15t superheated vapor of 1MPa, 350℃ per hour. The feed water temperature is known to be 20 ℃. The efficiency of boiler is 0.75. The calorific value of coal is 29400 kJ/kg, The quality of the wet vapor entering the superheater is 0.95. Determine: (1) The coal consumption. (2) The heat absorption capacity of wet vapor in Superheater[3].

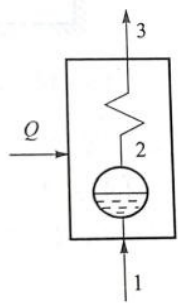

Figure4. A schematic diagram of a boiler

Solution

From the water vapor table,we can get to know the enthalpy of the superheated vapor at 1MPa, 350℃, and the enthalpy of the feed water at 1MPa, 20℃.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. Thermodynamic properties of unsaturated water and superheated vapor

p	1.0MPa		
Sat properties	ts= 179.916℃ v′= 0.0011272 v″ =0.19440 h′= 762.84 v″ =2777.7 s′= 2.1388 s″ =6.5859		
t (℃)	V (m^3/ kg)	h (kJ/kg)	s (kJ/(kg•K)
20	0.0010014	84.80	0.2961
...	...	...	...
350	0.28247	3157.0	7.2999

The amount of the heat absorption by the feed water in the boiler per hour can be determined by

$$Q = m \cdot (h - h_0) = 15 \times 10^3 \times (3157.0 - 84.80) = 4.6083 \times 10^7 \quad kJ/h$$

From

$$\eta = \frac{Q}{Q'} \times 100\%$$

get

$$Q' = \frac{Q}{\eta} = \frac{4.6083 \times 10^7}{0.75} = 6.1444 \times 10^7 \quad kJ/h$$

The coal consumption is

$$M = \frac{Q'}{q'} = \frac{6.1444 \times 10^7}{29400} = 2.09 \times 10^3 \quad kg/h$$

That is, the coal consumption per hour is 2.09×10^3t.

Calculate the enthalpy of wet vapor by the following formula:

$$h_x = xh'' + (1-x)h' = 0.95 \times 2777.7 + (1-0.95) \times 762.84 = 2676.957 \quad kJ/kg$$

The amount of the heat absorption by the wet vapor in superheater is

$$Q_g = m(h - h_x) = 15 \times 10^3 \times (3157.0 - 2676.95) = 7.20 \times 10^6 \quad kJ/h$$

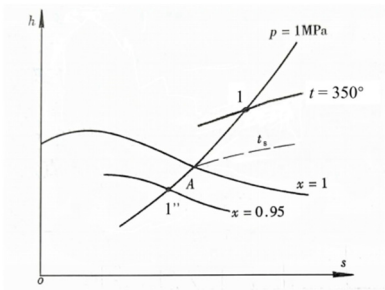

Figure5. The constant pressure process of wet vapor in superheater

In addition, the parameters of wet vapor and superheated steam can also be obtained on h-s diagram. On h-s diagram, the heat absorption process of wet vapor in superheater is depicted by the curve 1 " -1 in Figure 5.

The enthalpy of the saturated liquid-vapor mixture at 1MPa and the quality x=0.95 is

$$h_x = 2675 \quad kJ/kg$$

The enthalpy of the superheated vapor at 1MPa and 350℃ is

$$h = 3160 \quad kJ/kg$$

The amount of the heat absorption is

$$Q_g = m(h - h_x) = 15 \times 10^3 \times (3160 - 2675) = 7.275 \times 10^6 \quad kJ/h$$

Although there is human error in reading data on h-s diagram, it is more convenient to use h-s diagram to determine the properties of water vapor. In practice, the combination of two methods is adopted, which not only simplifies the calculation but also ensures the accuracy.

3 Conclusion

From the analysis process of the whole example, we can see that in the process of constant pressure, there is only heat exchange between working medium and the outside world, but no work exchange. The solution steps are generally 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 h-s diagram.

(4) According to the first law of thermodynamics, calculate the heat exchange between working medium and the outside world.

In engineering application, the constant pressure process of steam is very common. The water vapor commonly used in thermodynamic systems can not be treated as an ideal gas, because it is usually not far away form liquid and often experiences phase changes during working processes.

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. (2014) Thermal Theory and Application (Third Edition). China Electric Power Press, Beijing.
2. Zhao, L, Engineering Thermodynamics (A Bilingual Textbook) (2012), China Building Industry Press, Beijing.
3. Cheng, G.T., Wang, Y.Z. (2007) Engineering Thermodynamics (Second Edition). Beijing University of Technology Press, Beijing.
4. Xu, Y.P., Ke, X.Y. (2012) Thermal Engineering. China Electric Power Press, Beijing.