Steam compression with inner evaporative spray cooling: a case study

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Abstract: An adiabatic dry saturated steam compression process with inner evaporative spray cooling in screw compressors for steam heat pump systems is studied. Thermodynamic model and simulation of this variable-mass compression process are devised. Differential equations are formulated and used to calculate the amount of liquid injected and the work to drive the compressor on the basis of simplification, taking into consideration the factors such as the isentropic efficiency of the compressor and the degree of superheating. Compared with the ordinary adiabatic compression, an example of steam compression with water injection is illustrated. The results show that the compression work is reduced and the discharge temperature decreases.

Keywords: inner evaporative spray cooling; compression; screw compressor.

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1 INTRODUCTION

Adiabatic compression process is commonly encountered in industrial applications such as in screw and scroll compressors. The single-stage pressure ratio of the compression is restricted by factors such as the discharge temperature. When the air at the temperature of 20°C is compressed from 0.1 to 0.8 MPa in one compression stage, the discharge temperature is roughly 250°C. Thus, methods such as an interstage cooling in heat exchangers for the multi-stage compression, are applied to lower the discharge temperature. But this configuration is relatively complex. In recent years, spray oil cooling for screw compressors [1–4] was studied and successfully applied to lower the discharge temperature. The evaporative spray cooling [5–9] was also discussed and experimented in various applications. Currently, the application of inner evaporative spray cooling on compressors is getting much attention for improving compressor performances.

In refrigeration/heat pump systems, a dry saturated steam compression is often encountered. For example, saturated steam compression of high pressure-ratio in low-pressure range is applied in a new heat pump system [10,11]. The discharge temperature would be too high if the process is carried out without cooling. To solve the problem, a compression process with inner evaporative cooling, which can be applied in screw compressors, was introduced in this paper. In this compression process, steam is compressed with inner water injection and to keep the discharge temperature low. In contrast to the case of air compressors with inner evaporative cooling, where an extra work is needed to compress the evaporated steam and the liquid steam needs to be separated from the compressed air subsequently. However, this is not the case for steam compression with water injection as the injected water will evaporate to constitute part of the steam in the compression chamber. Hence, the simulation process is also different from that for air compressors with evaporative cooling. It is believed that the process introduced here will help in improving cycle efficiency and hence system's performance.

Differential equations are derived to calculate the amount of liquid injected and the compression work to drive the compressor. With the aid of a digital computer, an example is shown and the results show that this variable-mass compression process reduces compression work and lowers the discharge temperature significantly.

2 PRINCIPLE OF INNER EVAPORATIVE SPRAY COOLING AND ITS IMPLEMENTATION

The implementation of the spray evaporative cooling is the same as that in the oil-injected screw compressors.

Injection holes are drilled isometrically into the wall along the direction of the screw rotor, similar to that of screw compressor with oil injection cooling. An auxiliary pump ensures that the liquid can be injected through the injection holes into the compression volume.

For applications of air compression with water injection, air is compressed with a modest temperature rise while the injected water evaporates continuously in the compression volume. The latent heat of the evaporating liquid water is large and thus limits the temperature rise due to compression, remarkably. The evaporated steam consumes a small portion of compression work and usually needs to be separated from the air.

For steam compression with water injection, evaporative spray cooling helps to lower the discharge temperature, similar to that in the air compression with water injection. However, in the case of steam heat pump system [10,11], the evaporated steam forms part of the useful working fluid. Therefore, the liquid separation device is not required and I addition to that, the process helps to reduce the energy consumption. The process is, however, applicable only when the working condition is below the critical conditions of H_2O. Since the critical temperature of H_2O is 374°C high and the discharging temperature limit is about 140°C in common applications, the discharging temperature still restrains single stage pressure ratio and the discharging pressure. In another word, the water injection cooling for steam compression is applicable only for compressors operating at low-pressure range.

3 PROCESS DESCRIPTION

The compression process of dry saturated steam with evaporative spray cooling is discussed below. The work to drive the auxiliary pump for liquid injection is much less than the steam compression work and thus is negligible. The injected liquid, which is homogeneous to the compressed steam, evaporates in the compression volume, and thus lowers the compressed steam temperature. That is, the steam in the compression volume is compressed with a modest temperature rise while the injected liquid evaporates continuously to limit the temperature rise. If the injected liquid is enough and if the process proceeds slowly, the compressed steam can be kept in the state of dry saturated during the whole compression process, in which case, the discharge temperature is the lowest. This ideal situation is shown as 1-2*T* in Figure 1. If the amount of injected liquid is not enough or the liquid does not fully evaporate in time, the actual path is 1-2. The path 1-2*s* denotes the adiabatic compression process. Points 2*T*, 2 and 2*s* are under the same pressure.

4 THERMODYNAMIC MODEL AND SIMULATION

As shown in Figure 2, the pressure at the inlet of the screw compressor is p_1, and the outgoing steam pressure is p_2. Changes of the potential and kinetic energies of fluids are negligible in this process. The actual state of the steam changes along the curve 1-2. Points 2, 2*s* and 2*T* are at the same pressure, p_2. Point 2*T*, the dry saturated steam, and point 2*s*, the entropy of which equals to that of point 1, are given for comparison.

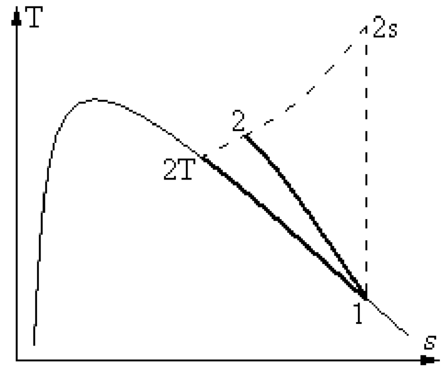

Figure 1 *States of the compressed steam in T–s diagram*

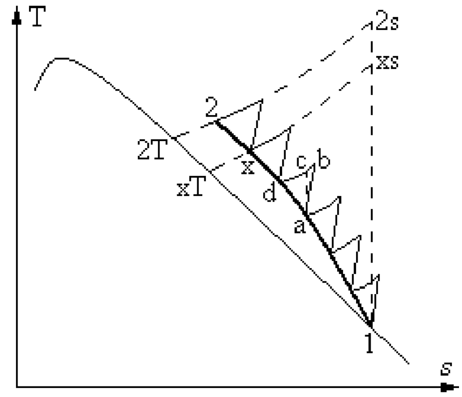

Figure 2 *T–s diagram of the simulated compression process*

In order to calculate the work and the amount of liquid injected for the compression process 1-2, the degree of superheating, D_{sh}, is defined as

$$D_{sh} = \frac{T_x - T_{xT}}{T_{xs} - T_{xT}} \tag{1}$$

where, suffix x denotes an arbitrary point on curve 1-2, excluding point 1, thus T_x is the temperature at point x, pressures at point xT and xs equal to the pressure at point x; point xT is in a state of dry saturated steam, and the entropy at point xs equals to that at point 1. We assume that D_{sh} is constant so that the state of every point on the curve 1-2 can be identified.

According to the equation (1), the temperature at point d, T_d, can be expressed as

$$T_d = T_{dT} + D_{sh}(T_{ds} - T_{dT}) \tag{2}$$

where, T_{ds} and T_{dT} are calculated according to the equation of state and the thermodynamic relations. Assuming that the compression process can be divided into infinitesimal processes, and each infinitesimal process consists of an ordinary adiabatic compression process and the complex evaporating and blending process. Path *a*-*b*-*d* indicates the change of the steam state in Figure 2. In this infinitesimal process, the pressure of the steam increases from p at point a to $p + dp$. The injected liquid flow is assumed to be dm and the steam mass on curve 1-2 is m. It is obvious that the infinitesimal process approximates the curve 1-2 when dp approximates the infinitesimal.

For the adiabatic compression process *a*-*b*, the work to drive the compressor is the enthalpy difference associated with the compression process.

$$dw = h_b - h_a = \frac{h_c - h_a}{\eta_{\text{comp}}} = \frac{h(s(p,T), p+dp) - h(p,T)}{\eta_{\text{comp}}} \tag{3}$$

where, w is the work to compress 1 kg of steam at point a, η_{comp} is the isentropic efficiency of the infinitesimal compression process, p is the pressure at point a, T is the temperature at point a, $h(p, T)$ denotes the steam enthalpy at pressure p and at temperature T. The symbol $s(p, T)$ denotes the entropy at pressure p and temperature T. The symbol $h(s(p, T), p + dp)$ denotes the enthalpy which is a function of the entropy $s(p, T)$ and the pressure $p + dp$.

For the whole infinitesimal process, as shown in Figure 3, the energy balance can be established as

$$h_{\text{liquid}} dm + mh(p,T) + mdw = (m+dm)h(p+dp, T_d) \tag{4}$$

where, h_{liquid} is the enthalpy of the injected liquid.

From equations (3) and (4), the following differential equation can be obtained.

$$\frac{dm}{m} = \frac{h(p,T) - h(p+dp,T_d) + \frac{h(s(p,T),p+dp)-h(p,T)}{\eta_{\text{comp}}}}{h(p+dp,T_d) - h_{\text{liquid}}} \tag{5}$$

And the total work in the infinitesimal process dw_{comp} is expressed as

$$dw_{\text{comp}} = mdw = \frac{m[h(s(p,T), p+dp) - h(p,T)]}{\eta_{\text{comp}}} \tag{6}$$

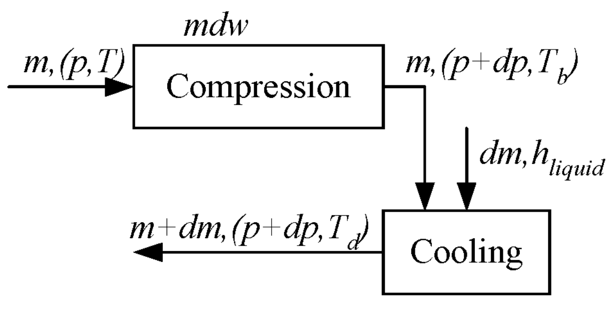

Figure 3 *Flow diagram of the infinitesimal process*

Equations (5) and (6) are integrated with the integrating range from m_{in} to m_{out}, where m_{in} is taken as 1 kg. Hence, when 1 kg steam flows into the compressor, the steam mass at the outlet of the compressor, m_{out} and the total work, w_{comp} can be calculated by numerical integration.

The injected liquid ratio R_{inj} is defined as

$$R_{\text{inj}} = \frac{m_{\text{out}} - m_{\text{in}}}{m_{\text{in}}} \tag{7}$$

Equations (5) and (6) can be solved using numerical integration technique.

5 EXAMPLE AND ANALYSIS

The analysis on an example of steam compression with evaporative water-spray cooling is conducted. The properties of water and steam are calculated using 'The IFC – 1967 formulation for industrial use for thermodynamic properties of water and steam' [12], and the simulation method mentioned above was applied. Initial data of the example are given in Table 1.

Simulation results are shown below.

$R_{\text{inj}} = 13.81\%$

$w_{\text{comp}} = 455.2$ kJ

$T_2 = 381$ K

For the purpose of the comparison, assuming that the whole compression process is the ordinary adiabatic process, the high temperature at the end of the compression process steam is then mixed with water, which evaporates and becomes part of the steam. In this process, the work to drive the compressor for 1 kg intake steam, w_{comp}, is 514.3 kJ and the mass of evaporated liquid steam is about 16% that of the intake steam. Compared with the compression process with inner evaporative cooling, the former process consumes more energy and with a higher discharge temperature. Results indicated that the compression process with inner evaporative cooling reduces energy consumption and remarkably lowers the discharge temperature.

Figure 4 shows that if D_{sh} increases, w_{comp} increases linearly. Thus, ways to improve compression efficiency are preferred and the amount of injected water should be sufficient.

From Figure 5, both R_{inj} and w_{comp} decrease when η_{comp} increases.

Table 1 *Initial parameters of the example*

Parameters	*Value*
Pressure at the inlet of the compressor, p_1, Pa	12,000
Pressure at the outlet of the compressor, p_2, Pa	100,000
Pressure of the injected water, p_{liquid}, Pa	500,000
Temperature of the injected water, T_{liquid}, K	303.15
Isentropic efficiency of the infinitesimal compression process, η_{comp}	0.80
Degree of superheating, D_{sh}	0.05

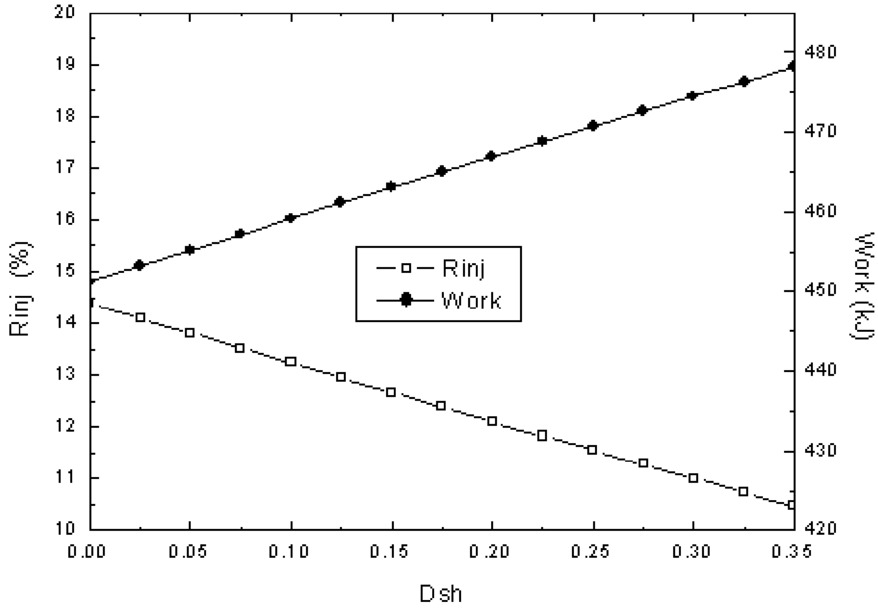

Figure 4 *Influence of the* D_{sh}

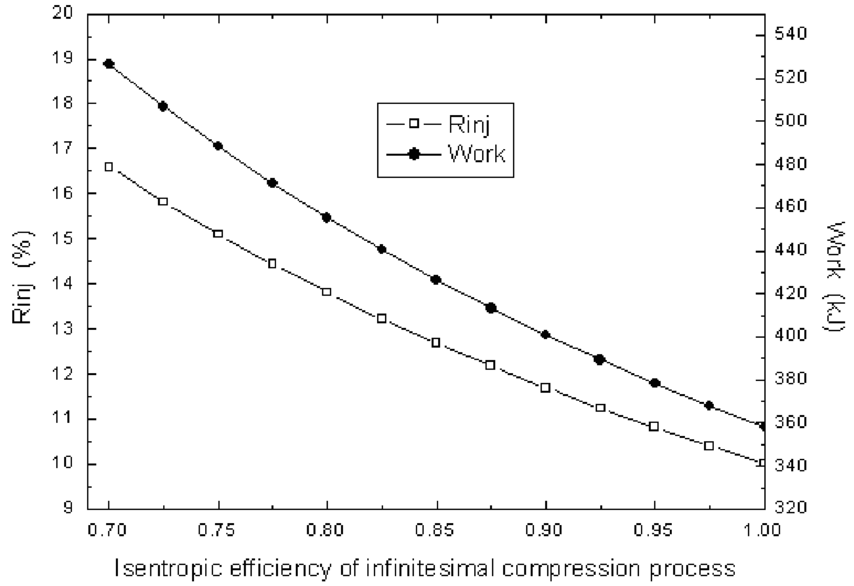

Figure 5 *Influence of* η_{comp}

6 CONCLUSION

In order to evaluate the adiabatic dry saturated steam compression with water injection for screw compressors in steam heat pump applications, thermodynamic model and simulation of this variable-mass compression process with inner evaporative cooling are discussed. Differential equations are formulated to calculate the amount of liquid injected and the work to drive the compressor. Factors such as the isentropic efficiency of compressor and the degree of superheating are taken into consideration in the model. From the simulation results, in the example of steam compression with water-injection, the process results in significant energy saving and lowers the discharge temperature remarkably.

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BIOGRAPHICAL NOTES

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