THE CHARACTERISTIC ANALYSIS OF WATER SPRAY COOLING COMPRESSED AIR

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Abstract. With the extensive development of compressed air systems, the problem of reducing energy consumption in the compression system is popular. And water spray cooling compressed air is one of the effective methods, the compression process is close to the isothermal compression after water spray cooling and the compression power is reduced. In this experiment, the effect of water cooling was verified, and the influence of water spray flow on cooling effect was studied. And the experiment proves that the water spray pressure has little effect on the performance of water spray cooling. This experimental study provides a reference for the energy saving of the compression system.

Keywords: Compressed air/ Compression power/ Air temperature/ Spray pressure/ Water spay cooling

INTRODUCTION

Air compression system is widely used in metallurgy, machinery, mining, electricity, textile, petrochemical and other industries. Air compressor power consumption occupies a large proportion of energy consumption in the device, compressed air requires a high cost, it accounts for 10% to 20% of the power consumption in large industrial equipment, and some even up to 30% [1]. Therefore, saving air compressor energy consumption is an important way to reduce the overall energy consumption and product cost [2].

Spray water cooling is one of the important ways to save energy and reduce consumption in piston air compressor [3]. Spray water cooling is spray water into compressed air in the inlet or compression process. Water spray as a refrigerant direct contact with compressed air and absorbs heat, cooling efficiency is significantly higher than the external cooling method [4-5]. Effective cooling of the compressed air can make the compression process close to isothermal compression [6-7], thereby reducing the power of compression [8-9].

The air cooling method can be sorted by contact and non-contact [10]. Contact cooling mixes compressed air and coolant, the coolant directly absorbs the heat of the compressed air and then filters the coolant in the separator [11]. The non-contact cooling method cools the internal compressed air outside the compression chamber, compressed air and coolant are isolated during heat exchange.

Water spray cooling is to mix the water spray and compress the air, they exchange heat directly in the tank. This cooling method greatly increases the heat transfer area between the compressed air and the spray droplets, which reduces the heat transfer resistance between the hot and cold fluids, and the cooling effect is remarkable. A. J. White and A. J. Meacock used water spray cooling to enhance the performance of gas turbines [12]. R. K. Bhargava and his partner discussed the problem with droplet dynamics, and the factors influencing the droplet size were analyzed by experiment [13]. Sepehr Sanaye and Mojtaba Tahani studied the effect of evaporative cooling on the performance of gas turbines, and proposed the prediction equation of net power [14]. M. W. Coney et al. used a large amount of water to enter the compressor through the nozzle to achieve a quasi-isothermal compression process [15].

In this study, the water-cooling process of the compressor was studied, and the parameters such as water spray pressure, water flow rate and droplet diameter were considered, and the influence of these factors was verified by experiments.

ANALYSIS OF SPRAY COOLING COMPRESSED AIR

The water spray is injected into the compressed air, which produces heat and mass exchange between high temperature and low temperature. The surface between droplet and compressed air will form a saturated air boundary layer, where temperature is between compressed air and water [16].

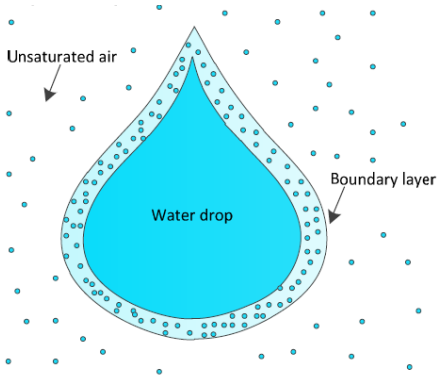

FIGURE 1. Heat and mass transfer of compressed air and water droplets.

Calculate the heat transfer between compressed air and surface of water spray droplets :

$$dQ_x = \alpha(t - t_b)dF \tag{1}$$

α- sensible heat coefficient between surface of water spray droplets and compressed air, $W/(m^2 \cdot K)$;
t- ambient air temperature, K;
t_b- the air temperature of the boundary layer, K;
dF- Contact surface area, m^2;

Calculate the heat dissipation of the compressed air in the tank:

$$G_r = \frac{g\beta\,(T_s - T_\infty)L^3}{\nu^2} \tag{2}$$

g- gravity acceleration, $N \bullet kg^{-1}$;
β- Thermal expansion coefficient (ideal gas equal to about 1 / T), K^{-1};
Ts - the surface temperature, K;
$T\infty$ - the bulk temperature, K;
L- characteristic length, m;
v- Kinematic viscosity, $W / (m \cdot K^{-1})$;

Calculate the convective heat transfer coefficient h of the gas tank:

$$h = \frac{\lambda \cdot C(G_r P_r)^a}{L} \tag{3}$$

λ- Thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$;
C- Constant of convective heat transfer;
Gr- Grashof number;
Pr- Prandtl number;
α - Flow index, α is 1/4 in laminar flow; α is 1/3 in turbulence;
L- Length, m;

In addition, the heat loss needs to be calculated:

$$q = hA(T_s - T_\infty) \tag{4}$$

A - Contact area of spray droplets and compressed air, m^2 ;
T_s and T_∞ have the same meaning as above.

Calculate the energy consumption of the compressor (assuming the compression process is adiabatic reversible process):

$$W_{CS} = \frac{k}{k\text{-}1} R_g T_g \left[\left(\frac{V_1}{V_2} \right)^{k-1} - 1 \right] \tag{5}$$

k- Isentropic index;
R_g-The molar mass of the air, $kg \cdot mol^{-1}$;
T_g-The temperature of the entrance, K;
V_1-Initial volume of air, m^3 ;
V_2-The volume of compressed air, m^3 ;

Calculate the power loss for water compression into the spray:

$$\Delta W_{a-c} = \frac{k}{k\text{-}1} R_g \left(T_{adiabatic} \text{-} T_{spray} \right) \left[\left(\frac{V_1}{V_2} \right)^{k-1} - 1 \right] \tag{6}$$

$T_{adiabatic}$-The inlet temperature without spray cooling, K;
T_{spray}-The inlet temperature with spray cooling, K;
Calculate the energy saving rate using the compressed power:

$$\varepsilon = \frac{\Delta W_{a-c}}{W_{adiabatic}} \tag{7}$$

$W_{adiabatic}$-Adiabatic compression power, W;
W_{spray}- Compression power of the spray cooling, W.

EXPERIMENTAL SETUP

Figures 2 and 3 show a schematic of a compressed air water spray cooling system, which comprising a high pressure atomization system, an air compression system and a data acquisition system.
Compressed air systems produce compressed air with ATLAS screw compressors. Adjust the compressed air outlet pressure with a pressure valve and adjust the outlet flow with the flow valve. Monitor the data with flow meters and pressure gauges. The experiment was established by SMC FLOW SWITCH PF2A751-04-27 and SMC AR60-10G.
Components of the high-pressure water atomization system include: a water tank, a water filter, a low and a high pressure water pump, pressure gauges, a water pressure regulator, and nozzles. The nozzle diameter can be adjusted from 0.1mm to 0.5mm. They produce water spray is very tiny. Use the ball valve and pressure valve to control the spray flow rate. They are installed between high pressure pumps and different nozzles.
The high-speed data acquisition system is set up on the experimental platform, which includes a 6120 USB board, it can have up to eight input channels. The data acquisition process is programmed with LABVIEW software. 6210 USB board transform temperature of the inlet and outlet water, temperature of the compressed air, pressure of gas tank, pressure of water spray to digital signals.
The gas tank is made of the 304 # stainless steel, which has a diameter of 200 millimeters and a long 500 millimeters. The heat and mass transfer between compressed air and water spray is carried out in this critical device.

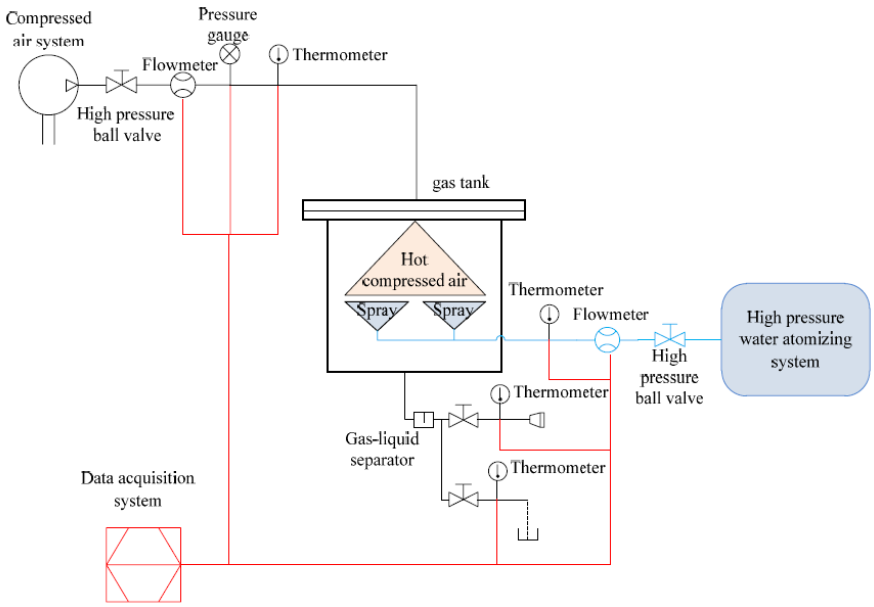

FIGURE 2. A schematic diagram of an experimental setup system.

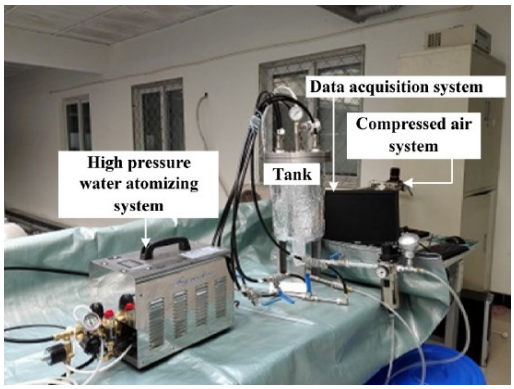

FIGURE 3. The actual diagram of the experimental system.

RESULTS

Measurement of Water Flow Rate

The spray nozzle flow is measured by weighing. The specific method is as follows:
First, collecting water in the tank. Second, start the timer and detecting the total weight of the spray on the electronic balance. Then, stop the timer. At last, the total weight of the water spray divided by total time is flow rate of water spray.

The seven nozzles produce spray with pressure of 3,4,5 MPa and the spray from nozzle to gas tank with pressure of 0.2 MPa. Figure 4 shows a schematic representation of the nozzle structure. Figure 5 show the flow characteristics of the nozzle. It can be found that the increase in nozzle diameter and inlet pressure leads to a gradual increase in flow rate.

FIGURE 4. Structure of nozzle

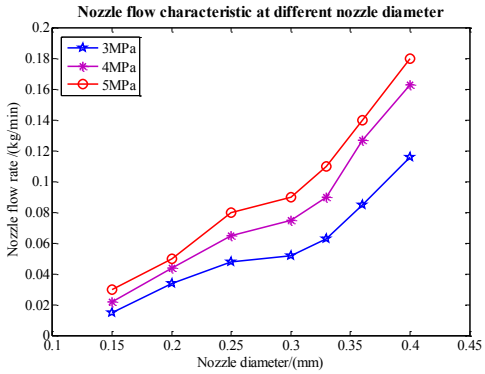

FIGURE 5. The nozzle flow rate with different diameters.

Comparison of Experimental Results

Experiments with no water spray are compared with experiments with water spray. The experimental conditions were as follows: the ambient temperature was 19 ° C and the low humidity was 24%. Set the temperature of the compressed air to 91.1 ℃, 92.7℃, 93.9℃. The time of the environment and facility to reach the thermal equilibrium takes approximately half an hour. Table 1 shows the temperature difference between the inlet and the outlet and heat transfer surface area, which can calculate the heat transfer coefficient.

TABLE 1. The measured temperature without water spray under the inlet pressure 0.2 MPa.

Inlet temperature ℃	Outlet temperature ℃	Different between inlet and outlet ℃	Heat transfer coefficient $w/(m^2 \cdot °C)$
93.9	51.1	42.9	256.3
92.7	48.3	44.4	256.6
91.1	47.4	43.4	259.8

The experimental conditions for water spray are the same as those without water spray above. The temperature of ambient is 19-20 ° C, relative humidity is about 20% -30%, The effluent water temperature of high pressure water atomization system is 24 ° C. Adjust the pressure of the water with the ball valve. The data acquisition system collects pressure and temperature signals. The water spray flow has a direction which opposite from compressed air. This opposite flow direction enhances the heat transfer between the water spray and the compressed air.

As shown in Fig.6, at a given inlet temperature and compressed air flow rate, the outlet temperature of compressed air is reduced gradually with the increase in water spray flow rate. The outlet temperature curves overlapping each other reveal that generated pressure of water spray has little influence on the outlet temperature.

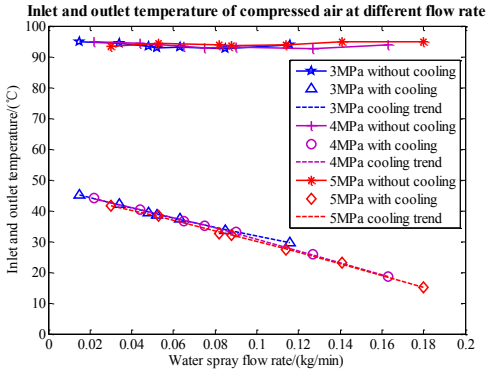

FIGURE 6. Inlet and outlet temperature of compressed air at different water spray flow rate

It is proved that the increase of the flow rate leads to the increase of the temperature difference. Therefore, increasing the water flow rate to improve the cooling efficiency is an effective way.

DISCUSSION ON COMPRESSION POWER

Figure 7 shows a schematic diagram of a two-stage compression system and a water atomization system. Water spray injection system is a water injection between two stages. Air into the compression chamber is compressed, and then into the gas tank to cool, and finally into the compressor.

The experimental steps are as follows:

First, assuming that the compression process is adiabatic compression, the pressure of the compressed air in the first-stage compressor becomes 0.2 MPa and the temperature becomes 90 ° C. And then the compressed air will enter the tank, compressed air and water spray contact for heat transfer, water spray will affect the temperature of compressed air. The inlet temperature of the compressed air varies with the water spray in the second stage compressor. Therefore, the compression power becomes smaller due to the effect of water cooling in the second stage of compression. As shown in Figure 8. And as the water pressure increases the compression power will gradually decrease.

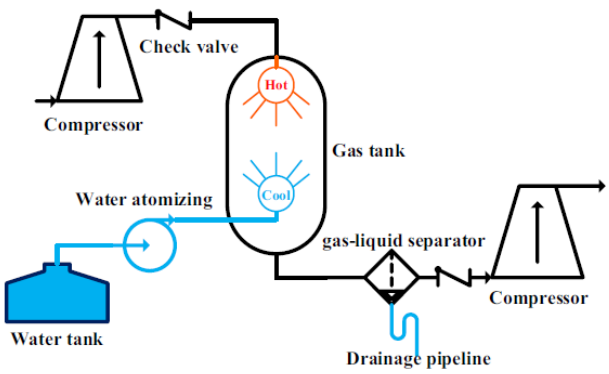

FIGURE 7. Two-stage compression system.

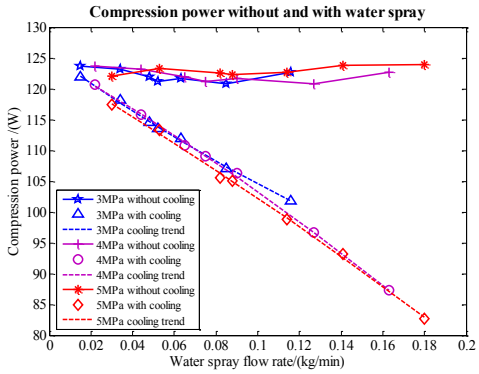

FIGURE 8. Compression power without and with water spray.

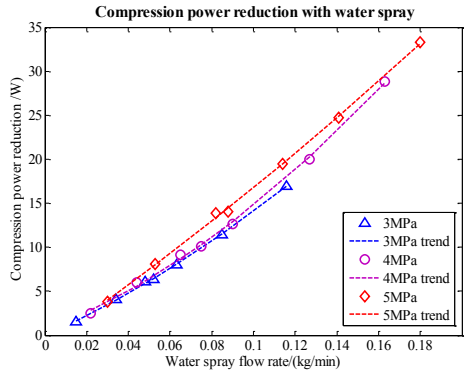

FIGURE 9. Compression power reduction with water spray.

As shown in Fig. 9, the power used to compress the air is reduced with the flow rate of water spray increases, due to the cooling effect of the water spray. But as shown in Figure 13 is the system power is not always reduced when the water flow is increased. Because the system power includes two parts, water atomization power and compressed air power. When the power of the water atomization is greater than the power saved by the water spray cooling, the power saving rate will be below the reference value. In the case of a nozzle diameter of 0.4 mm and a water spray pressure of 5 MPa, the compression power is reduced by 23%.

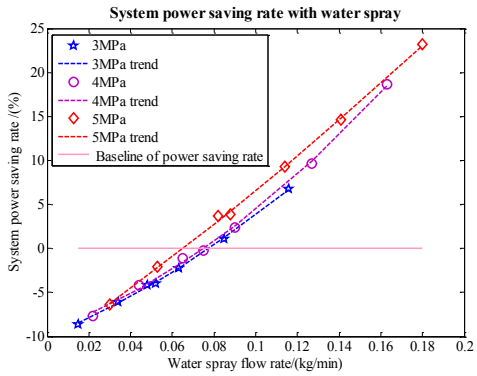

FIGURE 10. System power saving rate with water spray.

The equations (5) and (7) are linearly transformed (assuming W_{spray} is a constant), the power savings rate ε can be obtained from the power reduction $\Delta W_{a\text{-}c}$. When the water atomization pressure changes from 3 MPa to 5 MPa, its power W_{spray} is about 12.5±1W. The linear transformation changes only the amplitude of the curve, but does not change the shape of the curve. Thus, Figures 9 and 10 appear to be essentially the same.

It is seen from equation (6) that the cooling temperature of compressed air affects the power saving rate. While the temperature of the compressed air is high or low by the effect of the water spray flow rate, but the effect of pressure changes on the temperature of the compressed air is not significant. The conclusion is that the spray flow determines the power saving rate.

CONCLUSIONS

Experiments show the characteristic of water spray cooling compressed air, and the following conclusions are obtained:

(1) An increase in nozzle diameter leads to an increase in water flow;

(2) The increase in water inlet pressure can lead to an increase in water flow;

(3) The water inlet pressure does not have a significant effect on cooling the compressed air.

(4) Experimental use of the nozzle with water pressure of 5MPa and diameter of 0.4mm, compression power reduced by 23%.

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