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The experimental analysis of the water spray cooling compressed air

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Abstract – Air compressor costs approximate 10%–40% of total power in manufacturing industries. And its efficiency is less than 50%. Methods for reducing compression power have been explored extensively. Most of the methods focus on cooling compressed air to achieve isothermal compression. Recently, water spray cooling has become increasingly popular for its high specific heat, small spray diameter and large evaporation heat. In this study, compression system with water spray is compared with that without water spray. The experimental results show that increasing flow rate of water spray can enhance cooling effect and the generated pressure of water spray has little influence on cooling effect. Water spray method has a potential in reducing compression power by 23%. This study provides guidance for the compressor design and basic experiment data for further research.

Key words: Compressed air / Water spray / Cooling / Heat and mass transfer

1 Introduction

Compressed air has been widely used in engineering, such as automobile manufacturing, electronics, semiconductor manufacturing, manufacturing automation, packaging automation, etc. Air compressor is the primary energy-consuming equipment which costs approximate 10%–40% of total power in manufacturing industries [1]. And its efficiency is very low (<50%). The efficient method of compression is explored extensively under the trends of conserving energy, reducing emissions and protecting the environment.

Isothermal compression is an effective method. The theoretical calculation results show that the adiabatic compression power is 10%–30% more than that of isothermal compression when the compression ratio is 2–8 [2]. The key technology to achieve isothermal compression is to reduce the temperature of the compressed air by cooling.

Compressed air cooling methods can be divided into the non-contact and contact [3]. Non-contact cooling: coolant and compressed air are isolated by a wall, through which the heat is exchanged between coolant and compressed air. Contact cooling: coolant is mixed with compressed air. Compression heat released by compressed air is absorbed directly by the coolant, and then coolant is filtered in separator.

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For the non-contact cooling, with the isothermal container [4–7] it approximates isothermal in air charging and discharging experiments. The heat transfer material is filled in container to absorb or release heat. This method has been applied successfully in generating unsteady air flow to verify performance of unsteady flow meter. However, as a heat transfer material, copper wire with the diameter generally 20 to 50 microns is not suitable for compressed air cooling. The copper wire is too slender and easy to break off. And the broken cooper wire will move with air flow into motion parts of compressors. The motion parts wear will be accelerated by the cooper wire and so as the failure of the compressors.

For contact cooling, liquid spray has been increasingly applied to attain the isothermal compression due to its high heat transfer rate, large contact surface, small installation space, easy handling. Cooling liquid is injected to the compressed gas directly and absorbs the compression heat to keep the temperature at a low level, due to its high specific heat and evaporation heat.

Generally, oil is a common medium for cooling and lubrication, whereas, the effect of cooling is not perfect. The temperature difference between inlet and outlet of the compressor is just 10 °C at the rotating speed 2000 rpm under 0.1 MPa [8]. The viscosity of oil is so high that the diameter of oil spray is very large (hundred microns), and the specific heat of oil droplets is small and not sufficient to absorb the compression heat [9, 10].

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Nomenclature

Notion	Units	Description
dQ_x	W	Heat transferred between air and liquid droplets
α	$w.(m^2)^{-1}.K^{-1}$	Heat coefficient between compressed air and the droplet
t	K	Compressed air temperature around droplet
t_b	k	Compressed air temperature in the boundary layer
dF	m^2	Surface contact area between compressed air and droplets
g	$N.kg^{-1}$	Acceleration due to Earth's gravity
β	K^{-1}	Coefficient of thermal expansion (equal to approximately 1/T, for ideal gases)
T_s	K	Surface temperature
T_∞	K	Bulk temperature
L	m	Characteristic length
ν	$W.m^{-1}.K^{-1}$	Kinematic viscosity
λ	$W.m^{-1}.K^{-1}$	Thermal conductivity of the fluid
C		Natural convection heat transfer of constant according to the geometric shape
G_r		Grashof number
P_r		Prandtl number
α		Flow index, for laminar flow, α is 1/4; For turbulence α is 1/3
A	m^2	Total surface contact area between compressed air and droplets
n		Polytropic exponent
R_g	$kg.mole^{-1}$	Molar mass of air
T_g	K	Inlet temperature
p_1	Pa	Inlet pressure
p_2	Pa	Outlet pressure
$W_{adiabatic}$	W	Adiabatic compression power
$W_{cooling}$	W	Water spray cooled compression power
W_{spray}	W	Water spray system's power

Water spray cooling has become increasingly popular for its higher specific heat (Relative to the oil), smaller spray diameter (micron), and larger evaporation heat. Bagnoli et al. [11] applied the water spray cooling to the compression process in order to increase the output power of a gas turbine. Bhargava and Meher - Homji [12] comparatively analyzed the variation of the inlet and outlet temperature with and without water spray. Blagojević et al. [13] studied the heat transfer between water spray and air, and got the distributive characters of temperature and humidity along the air flow direction by simulation. The simulation results agreed with experiment data. Sureshkumar et al. [14,15] studied the process of the cooling air with water spray through experiments and discussed the various factors that affect compression power.

In this study, an experimental analysis was conducted on water spray cooling process, and the factors such as water pressure, nozzle flow rate and diameter that effect the cooling is discussed.

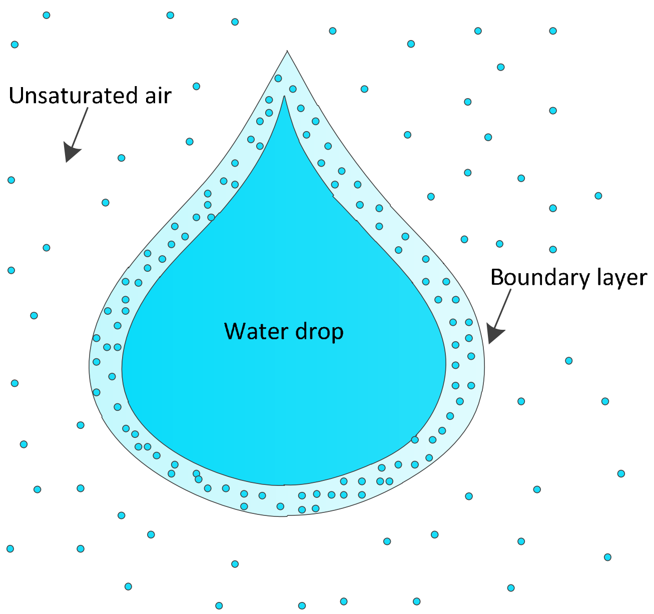

Fig. 1. Heat and mass transfer of water spray and compressed air.

2 Calculation heat transfer of spray and compressed air

The heat and mass transfer begins when low temperature of water sprays flow into the high temperature of compressed air. A thin layer is formed between compressed air and water spray surface, called saturated air boundary layer, where the temperature is between that of water spray and compressed air (as shown in Fig. 1 [16]). And it shows that the thin layer of compressed air is in saturated state.

The tiny contact superficial area dF (m^2) of water spray and compressed air for the quantity the heat is [17]:

$$dQ_x = \alpha(t - t_b)dF \quad (1)$$

Here, dQ_x the heat transferred between air and liquid droplets, W; α heat coefficient between compressed air and the droplet, w.m^{-1}.K^{-1}; t compressed air temperature around droplet, K; t_b compressed air temperature in the boundary layer, K; dF the surface contact area between compressed air and droplets, m^2.

In natural convection condition, heat of compressed air is transferred through a tank and the Grashof number of the heat dissipation of tank is:

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

Here, g acceleration due to Earth's gravity, N.kg^{-1}; β the coefficient of thermal expansion (equal to approximately 1/T, for ideal gases), K^{-1}; T_s the surface temperature, K; T_∞ the bulk temperature, K; L characteristic length, m; ν kinematic viscosity, w/(m.K^{-1}).

Further, the convective heat transfer coefficient h between tank and environment is obtained.

$$h = \frac{\lambda \cdot C(G_r\,\mathrm{Pr})^a}{L} \quad (3)$$

Here, λ thermal conductivity of the fluid w.m^{-1}.K^{-1}; C natural convection heat transfer of constant according to the geometric shape; G_r Grashof number; Pr Prandtl number; L characteristic length, m; α flow index, for laminar flow α is 1/4; For turbulence α is 1/3.

The loss of thermal q is,

$$q = hA\left(T_s - T_\infty\right) \quad (4)$$

Here, A the total surface contact area between compressed air and droplets, m^2. T_s surface temperature, K; T_∞ bulk temperature, K.

3 Calculation of compression work

In the process of reversible adiabatic compression, the power consumption of compressor is

$$W_{CS} = \frac{k}{k-1}R_gT_g\left[\left(\frac{V_1}{V_2}\right)^{k-1} - 1\right] \quad (5)$$

where, k isentropic index; R_g molar mass of air, kg.mole^{-1}; T_g inlet temperature, K; V_1 initial volume, m^3; V_2 volume of compressed air, m^3; $V_1/V_2 = 2$ in this study.

Applying Equation (5) to the compression with spray, compression power reduction with water spray is obtained as follows,

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

where, $T_{\text{adiabatic}}$ inlet temperature without water spray, K; T_{cooling} inlet temperature with water spray, K.

To compare efficiency of adiabatic compression with water spray cooled compression, power saving rate is defined as:

$$\varepsilon = \frac{\Delta W_{a-c} - W_{\text{spray}}}{W_{\text{adiabatic}}} \quad (7)$$

where, $W_{\text{adiabatic}}$ Adiabatic compression power; W_{cooling} water spray cooled compression power; W_{spray} Water spray system's power.

4 Experimental facility

A facility was built for testing the important features of the heat transfer between the compressed air and the water spray. The schematic of cooling facility and experimental station are demonstrated in Figures 2 and 3 including the compressed air system, the high pressure atomizing system and the data acquisition system.

4.1 Compressed air system

The Compressed air system employs a screw compressor of ATLAS to produce compressed air. The outlet pressure and flow rate of compressed air is regulated with the pressure valve and the flow rate valve. With the flow meter and pressure gauge, experiment condition can be set by a SMC FLOW SWITCH PF2A751-04-27 and a SMC AR60-10G.

4.2 High pressure water atomizing system

The high pressure water atomizing system mainly consists of a water tank, a low and a high pressure water pump, a water filter, a water pressure regulator, pressure gauges, and nozzles. The diameter of the nozzle is from 0.1 mm to 0.5 mm. They can produce micro water spray. The spray flow rate was controlled with a ball valve and a pressure valve. They are located between different nozzle and high pressure water pump.

4.3 Data acquisition system

The experiment platform is configured with a high-speed data acquisition system including a 6120 USB board with up to 8 input channels. LABVIEW software is employed for programming the data acquisition process. The 6210 USB board transfers pressure of the water, pressure of the gas tank, temperature of inlet and outlet water, temperature of compressed air into digital signal.

4.4 Tank for heat and mass transfer

The tank with a diameter of 200 mm and 500 mm long is made of 304# stainless steel. It is a pivotal device for heat and mass transfer between spray water and compressed air.

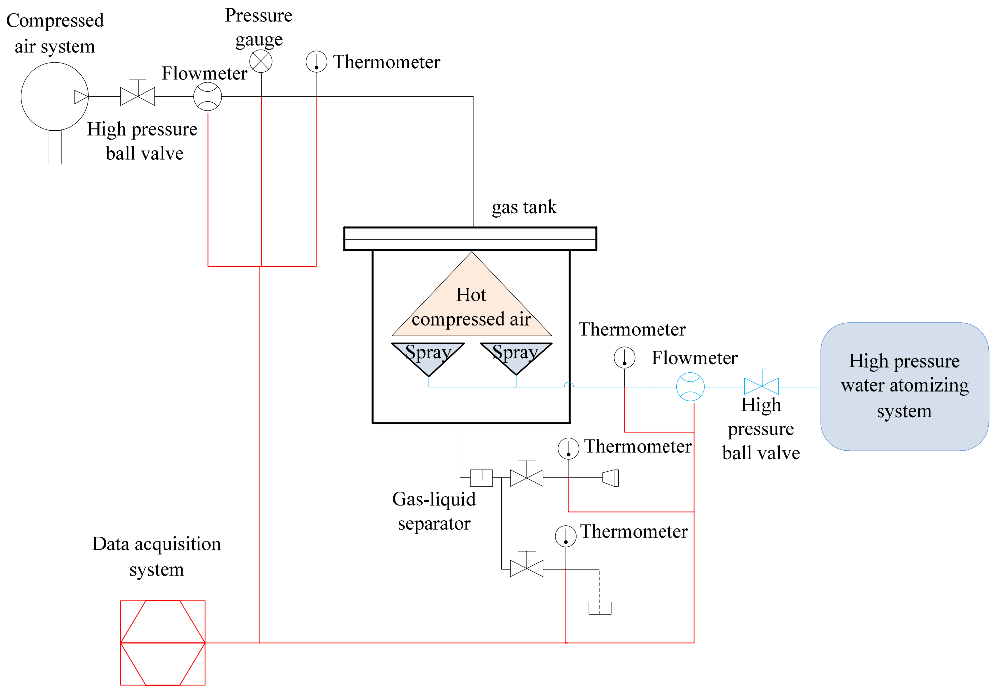

Fig. 2. Schematic of compressed air and water spray cooling system.

Table 1. Flow rate of the nozzle at different pressure.

Pressure / Diameter(mm)	3 MPa	4 MPa	5 MPa
0.15	0.015	0.022	0.03
0.2	0.034	0.044	0.05
0.25	0.048	0.065	0.08
0.3	0.052	0.075	0.09
0.33	0.063	0.09	0.11
0.36	0.085	0.127	0.14
0.4	0.116	0.163	0.18

5 Experimental results

5.1 Flow characteristic of the nozzles

The weighing method is adopted for measuring the spray nozzle flow rate. The concrete method:

(a) The water spray is collected by in the tank;
(b) Start timer;
(c) Electronic balance is used to measure total weight of water spray;
(d) Stop timer;
(e) The flow rate of water spray is total weight of water spray divided by the total time.

Water spray is generated at pressure of 3, 4, 5 MPa from seven nozzles and injected into the gas tank at the pressure of 0.2 MPa. The structure of nozzle is demonstrated in Figure 4. Flow characteristic of the nozzles are shown in Table 1 and Figure 5. It shows that the flow rate is increased gradually with the increase in inlet pressure and nozzle diameter.

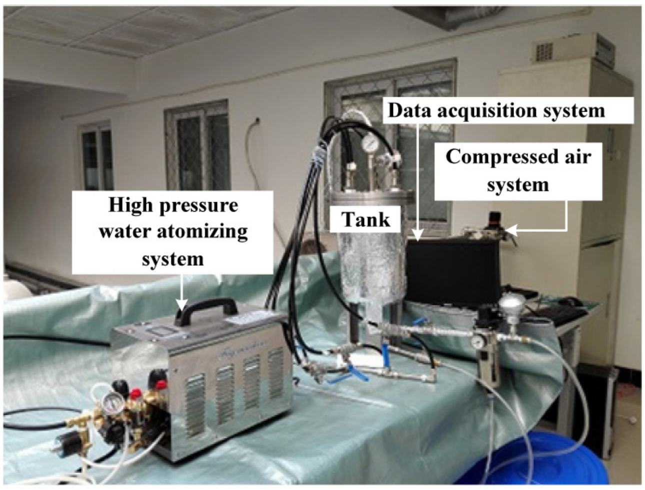

Fig. 3. Experimental station of compressed air and water spray cooling system.

5.2 Experiments without water spray

Experiments were run without water spray for comparing with experiments with water spray. The experiment is run at the ambient temperature of 19 °C and low humidity of 24%. The temperature of the compressed air is set to 93.9, 92.7, and 91.1 °C. It takes about half an hour to attain thermal equilibrium between facility and the ambient. The heat transfer coefficient could be calculated with the temperature difference of compressed air between inlet and outlet and the surface area of heat transfer, which is shown in Table 2.

Table 2. Properties without water spray under the inlet pressure 0.2 MPa.

Inlet temperature °C	Outlet temperature °C	Different between inlet and outlet °C	heat transfer coefficient w/(m^2 °C)
93.9	51.1	42.9	256.3
92.7	48.3	44.4	265.6
91.1	47.4	43.4	259.8

Fig. 4. Structure of nozzle.

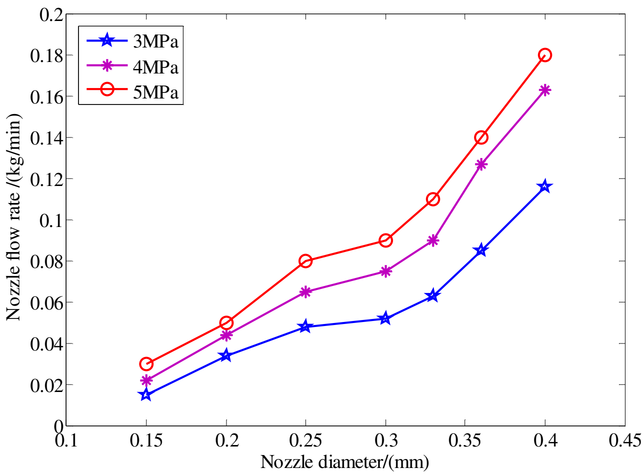

Fig. 5. Flow characteristic.

5.3 Experiments with water spray

Experiments with water spray were carried out at the same conditions as the experiments without water spray. The ambient temperature is 19–20 °C, relative humidity is 20%–30%, and water temperature in the outlet of the high pressure water atomizing system is 24 °C. The water pressure was adjusted with a ball valve. Pressure and temperature signal is collected by the data acquisition system. The flow direction of water spray is opposite from that of the compressed air. This opposite setting is able to enhance heat transfer comparing with identical direction setting.

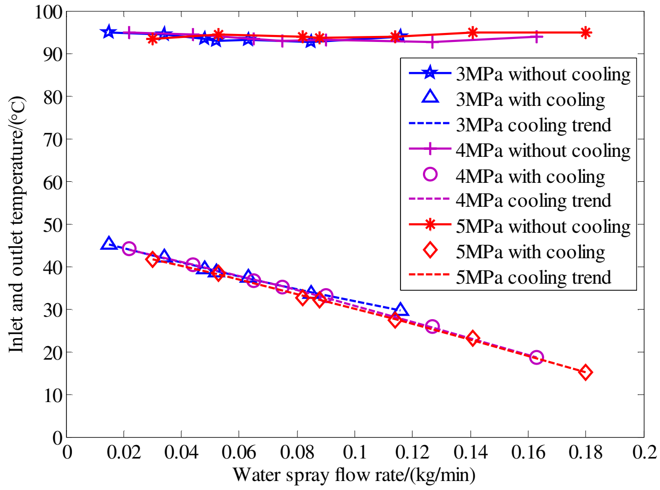

Fig. 6. Inlet and outlet temperature of compressed air at different water spray flow rate.

As shown in Figure 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 is to show the relationship between water spray flow rate and outlet temperature of the compressed air. The outlet temperature is reduced gradually with the increase in water spray flow rate. However, at a same water spray flow rate, the water pressure variation from 3 MPa to 5 MPa has little influence on the outlet temperature. To explain this, we should use the flow rate Equation (8) of water as following,

$$Q = CA\sqrt{\frac{2P_0}{\rho}} \tag{8}$$

where Q is the flow rate of water spray (m^3/s), C is flow coefficient of water, A is sectional area of a nozzle (m^2), p_0 is supply pressure of water spry (MPa), ρ is density of water (kg.m^{-3}). And with the conservation of mass, the flow velocity u is obtained as Equation (9). From Equations (8) and (9), the higher water pressure p_0 causes greater velocity u. Figure 6–1 shows the velocity from the experiment. Generally, greater velocity u will enhance heat transfer, and the temperature air should be lower.

$$u = \frac{Q}{A} \tag{9}$$

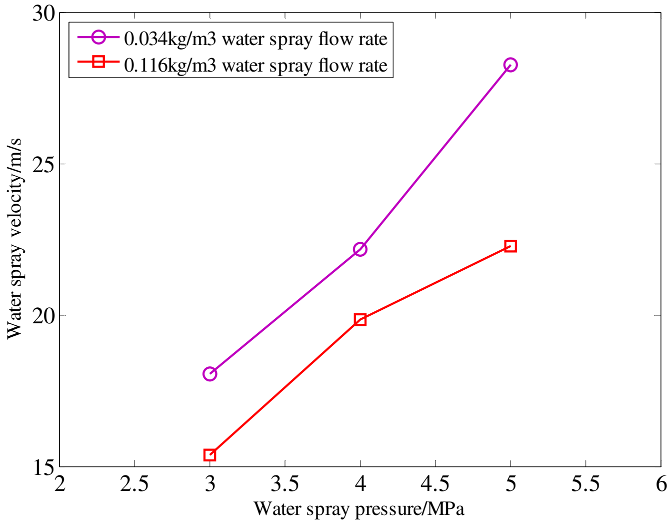

Fig. 6. Water spray pressure and velocity.

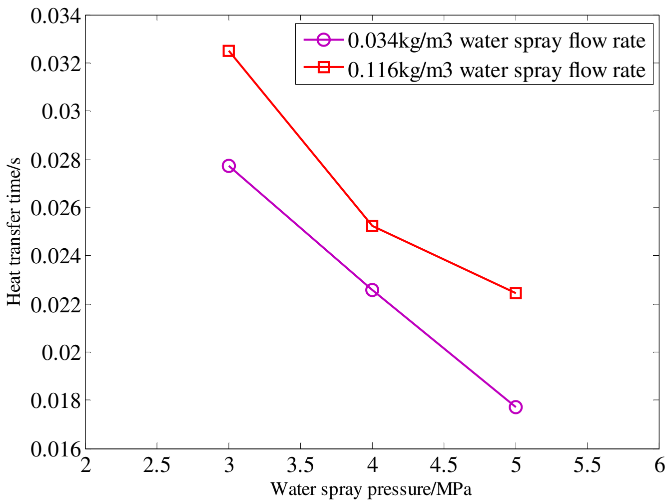

Fig. 6. Water spray pressure and heat transfer time.

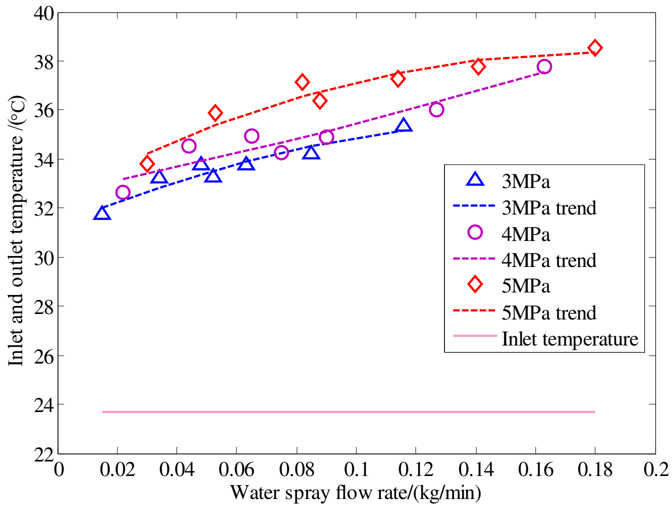

Fig. 7. Inlet and outlet temperature of water spray at different water spray flow rate.

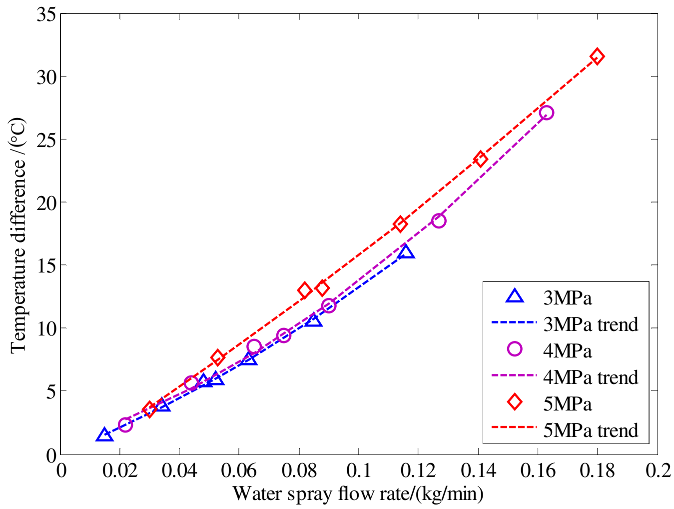

Fig. 8. Temperature difference between inlet and outlet compressed air.

However, the heat transfer time ($t = L/u$) is shorter when the flow velocity u becomes greater. The air-water contact time depends on the height L of the gas tank and the velocity of water spray. In the experiment, the spray flies up so fast from the bottom of the tank that it gets stick on the top. As a result, the spray flying stroke equals to the height of the tank. Figure 6–2 shows heat transfer time from the experiment. Therefore, the heat taken by the water spray from the compressed air is not changed too much when the water pressure vary in the range 3 MPa to 5 MPa, and so as the outlet temperature.

As shown in Figure 7, the outlet temperature of water spray grows gradually with the increase in water spray flow rate.

Figures 8 and 9, respectively, demonstrates temperature difference of inlet and outlet of water spray and compressed air in the counter flow. It's demonstrated that increasing flow rate results in the increase in temperature difference. This trend reveals that the cooling effect is enhanced by increasing the water spray flow rate. The temperature difference of the compressed air increases from 1.42 to 31.6 °C with the increase in the water spray flow rate from 0.015 to 0.18 kg.min^{-1}.

6 Compression power comparison

The compression power of the system without and with water spray is compared. For simplicity, the comparison is based on a two stage compression system in Figure 10. The water atomizing system is set between two compressors. Air is compressed in first stage compressor then flows to the gas tank for cooling (without or with water spray) at constant pressure, finally flows to the second compressor.

Suppose compression in the two compressors was adiabatic. Through the first stage compressor, the pressure of the air increases to 0.2 MPa and the temperature increases to 90 °C. In the gas tank, the compressed air

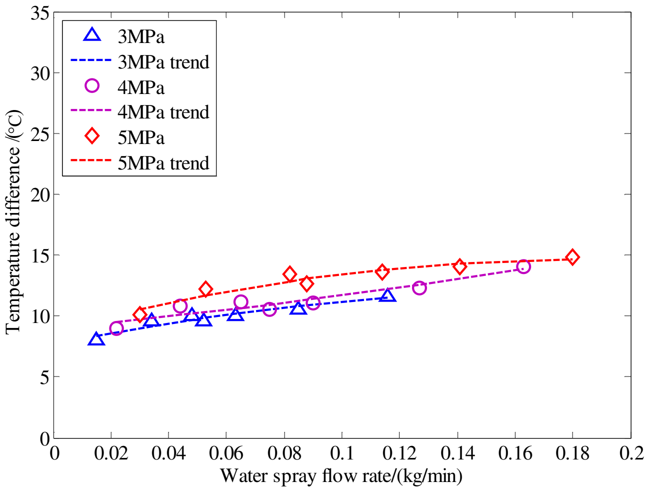

Fig. 9. Temperature difference between inlet and outlet water spray.

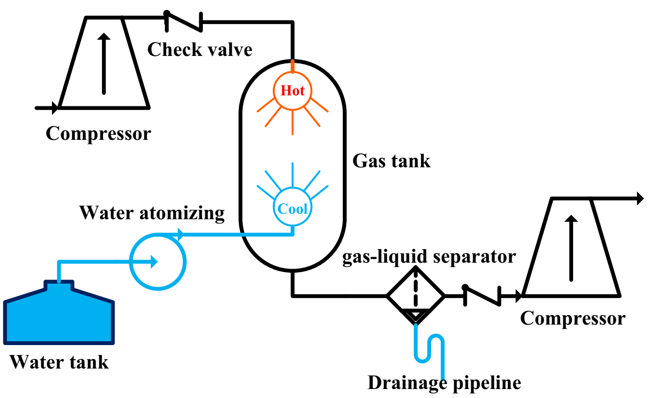

Fig. 10. Two stage compression system.

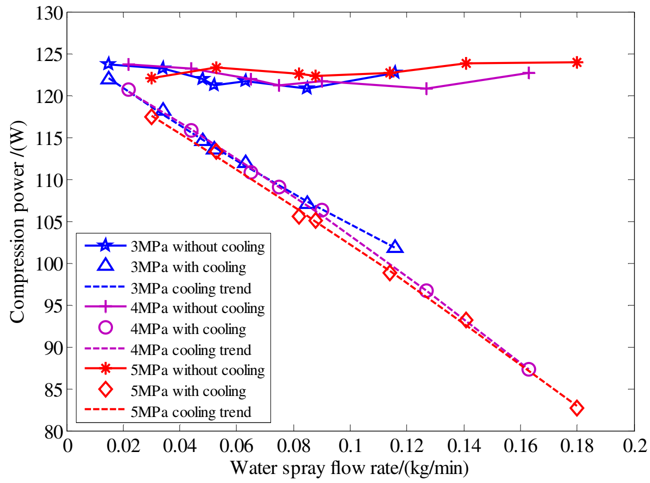

Fig. 11. Compression power without and with water spray.

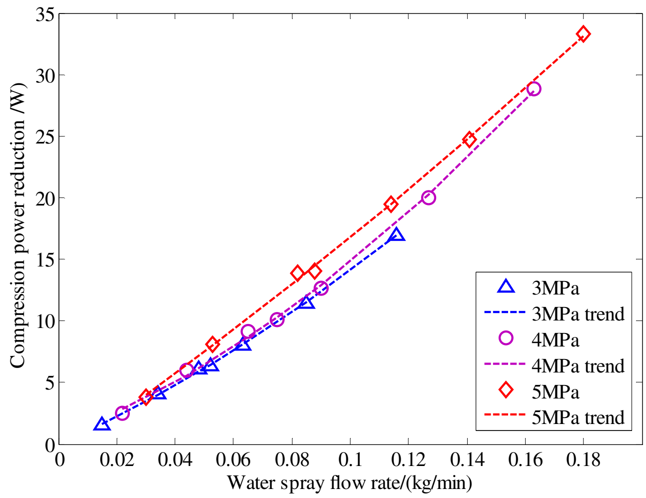

Fig. 12. Compression power reduction with water spray.

transfers heat with water spray. The output temperature (gas tank) of the air changes with the water spray condition. Accordingly, the input temperature of the second compressor changes with the water spray condition. This difference results in variation of compression power in the second compressor. Figure 11 shows that in the conditions with water spray, the compression power is less. The compression power is reduced with the increase in the water spray generated pressure.

In the compression system with water spray, the system power is consist of the compression power and the atomizing power. Figure 12 shows the water spray can reduce the temperature of compressed gas, and the compression power is reduced accordingly. Figure 13 shows system power is not always reduced with water spray. If the power saving ratio is below the baseline (zero), it means the power consumption of the atomizer is more than the power saved with water spray. Applying water spray could reduce compression power by 23% at water pressure 5 MPa and nozzle diameter 0.4 mm.

From results of the calculation, Figures 12 and 13 are uniform in shape. Comparing Equations (5) and (7), the power saving rate ε is obtained from power reduction ΔW_{a-c} by a linear transform (W_{spray} is regarded as constant). In the experiment, the power of the water atomizing system W_{spray} equals 12.5 ± 1 W when its output pressure varies from 3 MPa to 5 MPa. Linear transform just changes the amplitude of the curve rather than its shape. As a result, Figures 12 and 13 looks the same.

The power saving rate depends on the temperature of cooled compressed air, according to Equation (6). And the temperature is greatly influenced by the water spray flow rate, but is little affected by pressure variation (3 MPa to 5 MPa). As a result, the power saving rate depends on spray flow rate.

7 Conclusions

The experiments were set up to test the heat transfer process and effect of cooling by the water spray in the counter flow. The major results of the experiments are summarized below:

(a) The flow rate of the water spray increases gradually as the inlet pressure or the nozzle diameter increasing.

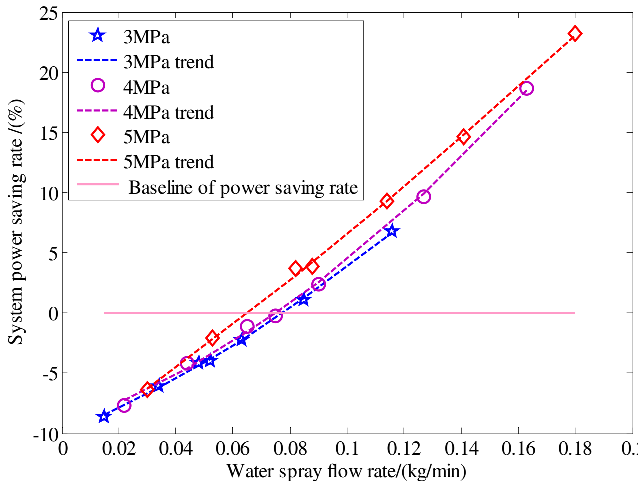

Fig. 13. System power saving rate with water spray.

(b) Increasing flow rate of water spray can enhance cooling effect and the generated pressure of water spray has little influence on cooling effect.

(c) Water spray method has a potential in reducing compression power by 23% at water pressure 5 MPa and nozzle diameter of 0.4 mm.

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