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INTERNAL WATER-SPRAY COOLING IN THE RECIPROCATING COMPRESSOR

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ABSTRACT

This paper discussed some method for further improving the effectiveness of the internal water-spray cooling in the reciprocating compressor. Starting with the mechanisms of the water-spray atomization and the droplet evaporation, the effects of the factors such as the construction and position of the atomizer, the characteristics of the gasflow, the surface tension of the water on the atomizing quality were studied. It was indicated that the tinier the diameter of the droplet formed by water-spray, and the longer the suspending period of the droplet, the better the cooling effectiveness. Experimental relationship between the above -mentioned factors and the cooling effectiveness was given. By using the internal water-spray, a decrease in temperature was about 28°C, and in specific power about 7.8% for an air compressor (ⅡZA-1.5/8) with external water cooling.

INTRODUCTION

Internal water-spray cooling is an effective energe-saving way for the compressor. For the internal water-spray, water is sprayed into the suction pipe in the form of droplet, where the droplet and the suction gas are fully mixed, then the mixture enters into the cylinder. The water-droplets directly absorb the heat of the compressed gas in cylider. The heat transfer and the mass transfer between the water- droplets and the gas is conducted simultaneously. There are both the visible heat exchange between droplet and gas, and latent heat exchange of the droplet evaporation. In this case, cooling of the gas is enhanced duing the compressing process. Then the process tends to an isothermal one, so as to decrease the discharge temperature, and the work in the compressing process.

Research results on the internal liquid-spray cooling have been reviewed(1-7). Some workers(6,7) have indicated that there exists the problem of the water deposition in the suction pipe, plenum chamber, and crankshaft box, so that the industrial application of the internal water-spray is limited. Starting with the mechanisms of the water-spray atomization and the droplet evaporation, in this work the viable methods have been proposed to decrease the water deposition, and further improve the effectiveness of the water-spray cooling in the reciprocating compressor. At the same time, the feasibility of the method was witnessed by experiments.

THEORETICAL CONSIDERATION

It is characteristics of water with high evaporative latent heat that are used for the internal water-spray cooling in the compressor. During compression, the droplets are continuously evaporated, and absorb the heat of the compressed gas. Therefore, index of the compressing process is decreased, and the discharge temperature and the indicative work is decreased. It is clear that the effectiveness of the cooling is dependent upon the evaporative degree of the droplets. The optimal cooling effectiveness can be reached only when the droplets sprayed into the cylinder are fully evaporated.

Mathematical Expression of Droplet Evaporation

The completeness x of droplet evaporation can be used to evaluate whether the droplets entered into the cylinder are fully evaporated. The x value is defined as a ratio of a droplet volume at the moment of τ to that of starting evaporation.

The relation can be expressed as follows

$$x = 1 - (1 - \tau/\tau_0)^{3/2} \qquad (1)$$

where τ is the time(hr) required by the patial evaporation of the droplet, τ_0 the time (hr) required by the complete evaporation of the droplet, that is, x=1. Moreover, there is

$$\tau_0 = d^2/K \qquad (2)$$

where d is the droplet diameter(m), k the factor(m^2/hr), and

$$K = 0.8 D_p p_s/\rho_w \qquad (3)$$

where ρ_w is the density of the atomized medium, D_p the diffuse factor of steam(m/h), and p_s the saturated steam pressure near the droplet surface(N/m^2). The D_p and P_s are indicated as follows:

$$D_p = 0.0754 (1.01\times10^5/p)(1+t_r/273)^{1.75}/(R(t_r+273)] \qquad (4)$$

$$p_s = \exp[11.7 - 3816/(t_r+227)] \exp[4v\sigma/dR(t_r+273)] \qquad (5)$$

where p is the gas pressure in cylinder(N/m^2), v the specific volume of the atomized medium(m^3/kg), σ the surface tension of the atomized medium(N/m), R the gas constant of the steam of the evaporative droplet(J/kg.K), and t_r the temperature of the evaporative droplet(°C).

Based on the thermal equilibrium equation of the droplet evaporation, it is found that

$$t_r = t_g - D_p p_s r/\lambda \qquad (6)$$

where λ is the heat conductivity of the humid gas(J/m.hr.°C), and $\lambda = f(t_r)$, t_g the temperature of the compressed gas (°C), and r the evaporative latent heat of the atomized medium(J/kg). If the time τ is known, the evaporative completeness x can be obtained from Eq.(1). The larger the x value, the more complete the evaporation, and the better the cooling effectiveness. In addition, the tinier the droplet diameter, the shorter the time required by the complete evaporation of the droplet. It means that the complete evaporation becomes easy to conduct. As concerns effects of the factor K on the x value, K is a constant when the temperature t_r of the evaporative droplet obtained from Eq.(6) is stationary. Therefore, fining the droplet is an effective means for improving the cooling.

Mechanism of Liquid-Spray Atomization

Theory of atomization is that the liquid is broken into the droplets in a certain range of size by using an atomizer. Due to the addition of energy, the specific surface area of the liquid increases continuously till it becomes instable, then a large quantity of small droplets are formed. The process is called as atomization. The energy required by the liquid atomization may be expressed as

$$E = A\sigma \qquad (7)$$

where A is the average of the surface area of the droplet formed per minute. It is indicated that the liquid with smaller surface tension is easily brocken. For a gasflow atomizer, the atomization is carried on by a supersonic gasflow which lashes at the low-speed liquid flow. The energy required by breaking into the liquid is

$$E = 0.402 G_g T\{0.5 M_a^2 + 2.5[1 - (p_1/p_2)^{0.286}]\} \qquad (8)$$

where G_g is the mass flow of the gas-spray, T the temperature of the gas-spray, Ma the Mach number of the gas-spray, and p_1/p_2 the ratio of the initial pressure to the final one of the gas-spray. From the Eq.(8), energy of the liquid atomization is relevant with the type and geometry of the atomizer, and the dynamic characteristics of the gas-spray. In order to fine the droplet, it is necessary to improve the atomizer design, physical properties of liquid-spray and dynamic characteristics of the gas-spray.

Reason of Droplet Diposition

Under the action of forces, suspended time of the droplet in some gasflow is very short. The droplet may not mix with gasflow in full, and partial droplets are deposited in the suction pipe and plenum chamber. If the droplets entered into cylinder can not completely evaporate, the patial droplets may also deposit in the cylinder. The deposition of the droplet not only weakens the cooling effectiveness, but also damages the working reliability of the compressor. For the researching on the motion law of droplet, the deposition has been found(7). In this work, the deposition of droplet during the suction process is caused by three reasons. There are turbulent deposition, gravitational deposition, and inertial deposition.

Turbulent deposition: The droplets atomized by a atomizer has a sufficient kinetic energy. However, the droplets move in different conditions. The droplets located in the boundary layer of the turbulence may have mass exchange with the gasflow in the suction pipe. Then, the turbulent boundary layer of the droplet expands continuously with the forward motion of the droplets and gasflow. When the expansion of the thickness of boundary layer reaches the wall of the pipe, some droplets surmount the boundary and deposit on the wall. Clearly, the more the droplets in the state of turbulence, the larger the turbulent deposition. The quantity of the turbulent deposition will increase with the distance S between the atomizer and the inlet of the plenum chamber.

Gravitational deposition: Under the gravitation, trace of the horizontal moved droplet becomes parabola. When the diameter of the suction pipe is smaller than the vertical fall of the droplet, the droplets deposit on the pipe wall. Clearly, the quantity of the gravitational deposition will increase with the size of the droplet, and the distance S.

Inertial deposition: When the droplets in motion meet obstacle in the suction pipe, the droplet may bump into the obstacle then deposit due to it inertia. The shape of the suction pipe should fit the atomizing angle of the droplet, and the sufficient atomizing space is needed for the mixture of the droplet and the gasflow, so as to decrease the inertial deposition. If the distance S is so short that the droplet with high kinetic energy may bump into the wall of the plenum chamber, and deposit. That is, the longer the distance S, the smaller the inertial deposition.

From the above, the droplet deposition is not avoidable. Fining the droplet is an effective way to decrease the deposition. Thus, the atomizer has an optimal installational position.

METHOD AND EXPERIMENT

Atomizer

A gasflow atomizer designed in this work is shown in Fig.1(a). The jet of water was behind the critical cross-section, and 4 jets uniformly distributed along the cycle of the sprayer. In this case, the energy of the gas-spray was utilized fully, and there was no gas oblique blow to the liquid. Therefore, comparied with the atomizer shown in Fig.1(b), the distribution of the droplet spectrum was uniform, and the diameter of the droplet was small. Fig.2 gives the comparison of the droplet diameters between the two atomizers. It is obvious that the smaller the diameter d_w of the sprayer jet of the atomizer, the finer the droplet. However, the impurity in water may stop up the sprayer jet, thus in this work, d_w=0.5mm. Fig.2(a) shows the spectrum distribution of the droplets measured, when G_g=4.2kg/hr, G_w=5.5kg/hr, and S=0.45m. The average of the droplets diameter d=59μm.

Surface Tension of Water

To fine the droplet, it is necessary to decrease the surface tension of water. In this work, a minute quantity of unionized surface activator was added in the water. The experiment indicated that the minimum (σ=0.0458N/m) of the surface tension of water was obtained when the concertration of the additive was equal to 0.01wt% of water. Fig.3 shows the spectrum distribution of droplets containing the additive. The average of the droplets diameter d=42μm (the G_g,G_w,S values are the same as above), and the d value decreases by 15-20μm compared with that using pure water.

Characteristics of Gasflow

It is evident that the average of the droplet diameter d will decrease with the increase of the gas-spray speed, as shown in Fig.4. Moreover, the experiment shows that the d value will decrease with the increase of the ratio of the gas-spray quantity to the water-spray quantity, G_g/G_w, and the trend towards an hyperbola in shape, as shown in Fig.5. In order to analyse the relation easily, we difind $(G_g/G_w)_c$ as ratio of the gas to liquid. When $G_g/G_w<(G_g/G_w)_c$, the d value rapidly decreases with the increase of the G_g/G_w. However, when $G_g/G_w>(G_g/G_w)_c$, the d value slow decreases with the increase of the G_g/G_w, and the quantity of the expended gas increases. That is, the energy expense increases. Clearly, there is an optimal value of G_g/G_w for the total effectiveness of the internal water-spray.

Installational Position of the Atomizer

Theoretical analysis indicated that there exists an optimal installational position S of the atomizer for decreasing the droplets deposition. The authors found the optimal position by experiments on the basis of improving the construction of plenum chamber and the suction pipe shape. Fig.6 gives the measured curves between the droplet deposition m_d and S value. The deposition is the smallest, when S=0.45m.

The methods, as mentioned above, were combined and used in an air compressor with external cooling (Type ⅡZA-1.5/8). In the exprreriments, the atomizer used was shown in Fig.1(a), the concentration of the additive was 0.01wt%, the quantity of gas-spray G_g=4.2kg/hr, the quantity of water-spray G_w=5.5kg/hr, the position of the atomizer S=0.45m. The operational parameters of the compressor were as follows: the environmental temperature t_s=20°C, the suction pressure P_s=98000P_a, the pressure ratio ε=8, the relative humidity ψ=76%, the rotational speed n=520 rpm, the quantity of external cooling water m_w=240kg/hr. In the above condition, the discharge temperature t_d was descreased by 28°C, and specific power by 7.8%. Table 1 gives the comparison of the performances between the compressor with only external cooling and one with both external and internal cooling.

Table 1 Comparison of the Performances

	External Cooling	External Cooling with Water-Spray	
		Pure Water	Additive,wt%
Suction Temperature,t_s,°C	18.0	14.0	13.5
Discharge Temperature,t_d,°C	154	135	126
Power,N,kw	9.01	8.60	8.36
Capacity,Q,m^3/min	1.382	1.390	1.392
Specific Power,N_s,kw/(m^3/min)			

CONCLUSIONS

1. Internal water-spray cooling is an effective method for save of energy in the reciprocating compressor.
2. All the methods such as rational construction and installational position of the atomizer, changing the surface tension of water, and appropriate gas-liquid ratio are essential to improve the effectiveness of the water-spray cooling.

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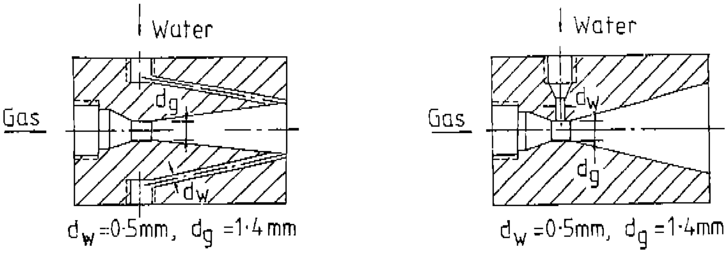
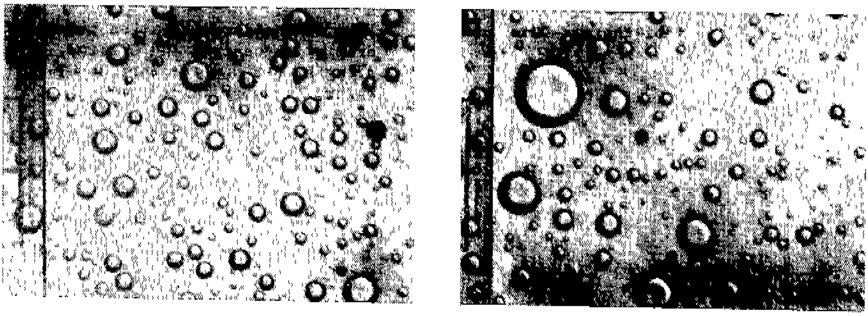


(a) Type A

(b) Type B

Fig. 1. Atomizer



(a) Atomizer Type A

(b) Atomizer Type B

Fig. 2. Spectrum distribution of droplets measured.

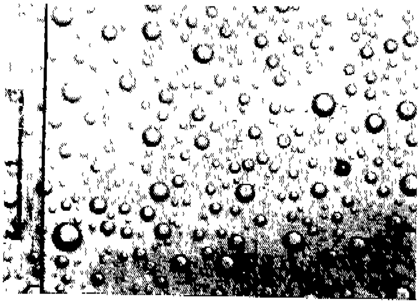


Fig. 3. Spectrum distribution of droplets containing additive.

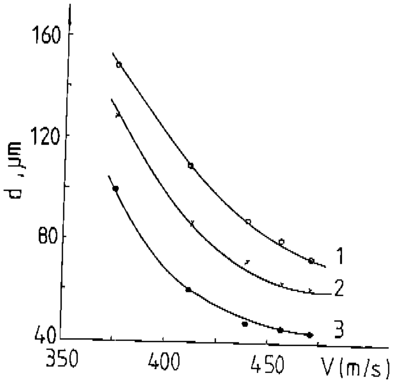


Fig. 4. Relation of the gas-spray speed versus the droplet diameter (1: G_w=9.21 kg/hr; 2: G_w=7.37kg/hr; 3: G_w=5.53kg/hr).

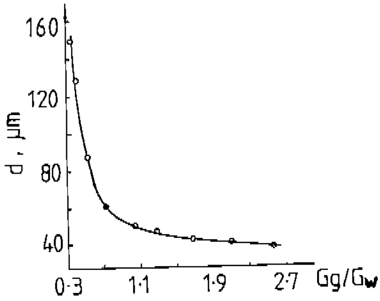


Fig. 5. Effect of the gas-water ratio on the d value.

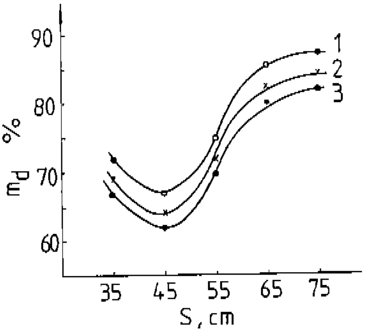


Fig. 6. Measured relation between the droplet deposition and S value, G_g = 4.2kg/hr (1: G_w=7.4kg/hr; 2: G_w=5.5 kg/hr; 3: G_w=3.7kg/hr).