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Calculations of the Heat and Mass Transfer in Reciprocating Compressor with Spraying Water Into Cylinders

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ABSTRACT

The air compressor with spraying water into cylinders can make its power consumption and discharge temperature decrease but the effect of spraying water to power consumption and discharge temperature is difficult to be quantitatively showed with different starting condition. This paper establishs a formula to calculate the polytropic exponent in ideal compressing processes of spraying water because the polytropic exponent can clearly show the contribution to power consumption and discharge temperature. In the formula, each parameter appears evidently its meaning and its effect to the polytropic exponent, and the result points out that the best way to decrease the polytropic exponent is to increase the atomization effect in cylinders. Through analysing the formula, a spraying water parameter is found to show the spraying water result.

SYMBOLS

- Q heat transfer
- σ moisture-transfer coefficient
- C_p constant-pressure specific heat
- T temperature
- X latent heat of water per unit mass
- B thermal conductivity of air
- D containing water vapour in per unit mass of pure dry air
- F total surface area of drops
- t time
- α heat transfer coefficient of air
- U total internal energy
- P pressure
- V volume
- K specific heat ratio of air
- n plytropic exponent
- M number of drops
- L average diameter of drops
- W mass of water
- γ density
- Nu Nusselt number
- G mass of air
- C containing water in per unit mass of air
- R air constant
- V_o cylinder volume
- E angle
- Y clearance ratio
- Z ratio between connecting rod and crank radius
- N turning speed per minute
- A spraying water parameter
- S overall parameter of speed and spraying water

SUBSCRIPTS

- g air
- b saturation point on drop surface
- o starting condition
- c saturation point of air in iso-temperature
- w water

INTRODUCTION

The air compressor with spraying water into cylinders make its power consumption and discharge temperature decrease, that can save energy 8-15% and increase the compression ratio, but circumstances in a real process is very complex. Using the polytropic exponent in the ideal process of spraying water, which can remove various effect in real process, the relation between the result of spraying water and saving energy and decreasing discharge temperature can be known because the polytropic exponent is clear to evaluate the power consumption and the change of the discharge temperature. And it removes the starting condition of compressors. This paper establishs the formula to calculate the polytropic exponent in the ideal process of spraying water and gives out the effect of spraying water parameter to the polytropic exponent.

INFERENCE OF THE FORMULA

The heat and mass transfer of the adiabatic compression in cylinders with spraying water is

$$dQ = \sigma\left[Cpg(Tg-Tb) + X(Dg-Db)\right]\cdot F\cdot dt$$

The vaporization process in cylinders is iso-enthalpy because the heat of water vaporization is from the air in cylinders, that makes the temperature decrease and the containing vapour in air increase, then the heat of air in vaporization is constant, or dQ=0, but the heat inhaled by pure dry air is

$$dQ_1 = -\alpha(Tg-Tb)\cdot F\cdot dt \qquad (1)$$

According to the first law of thermodynamics, when compressing, the energy equation of pure dry air in cylinders is

$$dQ_2 = dUg + Pg\cdot dV$$

$$= \frac{K-n}{K-1}\cdot Pg\cdot dV \qquad (2)$$

Because $dQ_1=dQ_2$, then

$$\frac{K-1}{K-n} = \frac{-Pg}{\alpha(Tg-Tb)\cdot F}\;\frac{dV}{dt} \qquad (3)$$

In cylinders, the total surface of water can be replaced by the quantity of water and the average diameter of drops

$$F = M\cdot\pi\cdot L^2 = \frac{6W}{L\cdot\gamma_w} \qquad (4)$$

$$\alpha = Nu\cdot\frac{B}{L} \qquad (5)$$

Substituting (4) and (5) into (3), we obtain

$$\frac{K-1}{K-n} = \frac{-Pg\cdot L^2\cdot\gamma_w}{6\cdot W\cdot Nu\cdot B\cdot(Tg-Tb)}\cdot\frac{dV}{dt} \qquad (6)$$

where $W = G\cdot C$

then the formula (6) is changed into

$$\frac{K-1}{K-n} = \frac{L^2\cdot Tg\cdot R\cdot\gamma_w}{6\cdot C\cdot Nu\cdot B\cdot(Tg-Tb)}\cdot\frac{-dV}{V\cdot dt} \qquad (7)$$

For reciprocating compressors, their volume change is

$$V = V_o\left[Y + \frac{1}{2}\left[(1-\cos(E)) + \frac{Z}{4}(1-\cos(2\cdot E))\right]\right] \quad (8)$$

then

$$\frac{1}{V}\cdot\frac{dV}{dt} = \frac{N\cdot\pi\cdot\left[\sin(E) + \frac{Z}{2}\cdot\sin(2E)\right]}{60\cdot\left[Y + \frac{1}{2}\left((1-\cos(E)) + \frac{Z}{4}\cdot(1-\cos(2E))\right)\right]} \quad (9)$$

and

$$M = \frac{6W_o}{\gamma_w\cdot\pi\cdot L_o^3} = \frac{6W}{\gamma_w\cdot\pi\cdot L^3}$$

$$L = L_o\left(\frac{W}{W_o}\right)^{\frac{1}{3}} = L_o\left(\frac{C}{C_o}\right)^{\frac{1}{3}} \quad (10)$$

Putting (9) and (10) into (7), we obtain

$$n = K + \frac{360(K-1)}{\pi\cdot R\cdot\gamma_w}\cdot\frac{Nu\cdot Co^{\frac{2}{3}}}{N\cdot L_o^2}\cdot C^{\frac{1}{3}}\cdot B\left(1-\frac{Tb}{Tg}\right)\cdot\frac{Y + \frac{1}{2}\left[(1-\cos(E)) + \frac{Z}{4}(1-\cos(2E))\right]}{\sin(E) + \frac{Z}{2}\cdot\sin(2E)} \quad (11)$$

From the formula (11), which shows polytropic exponent change with turning angle of compressors at any moment, it is clearly known that the first one is specific heat ratio Cp/Cv, the second is constant, the third is the starting condition of compressors which dependent on the quantity and method of spraying water and the turning speed of compressors, the fourth is the quantity of water in per unit mass of air, the fifth is the air condition in cylinders and the final one is the structure characteristic of compressors. And the formula is dimensionless.

The containing water is far larger than the spraying water in cylinders because of the flowing inertia of water. For example, if the Y=0.01 and the piston of a compressor is on top of cylinder when the cylinder volume is 0.001m^3 and the cylinder gap is full of water, the maximum containing water can reach 0.0083Kg, or Co can reach 8.3 in cylinders. Because the vaporising water is far less than the containing water in cylinders, the change of C is small, then

$$A = \frac{Co^{\frac{2}{3}}\cdot C^{\frac{1}{3}}}{L_o^2} \approx \frac{Co}{L_o^2}$$

The spraying water parameter, A, shows evidently its contribution to the polytropic exponent. For any compressor the formula (11) becomes

$$n = K + \frac{6(K-1)}{R\cdot\gamma_w}\cdot Nu\cdot A\cdot B\left(1-\frac{Tb}{Tg}\right)\cdot\left(\frac{1}{V}\cdot\frac{dV}{dt}\right) \quad (12)$$

From the formula above, the only method to decrease power consumption and discharge temperature is to increase A, or enhance the result of atomization, because the Nu is not easy to increase, which dependent on the velocity difference between air and drops in cylinders.

CALCULATION PROCESS

Though the formula for calculating the polytropic exponent is established, the containing water in air, C, and the air condition, X(1-Tb/Tg), are necessary to be determined in calculating process. The calculating step is

$$n_i = K + \frac{6(K-1)}{R\cdot\gamma_w}\cdot\frac{Nu\cdot Co^{\frac{2}{3}}}{L_0^2}\cdot C^{\frac{1}{3}}\cdot B_i\left(1-\frac{T_{bi}}{T_{gi}}\right)\cdot\left(\frac{1}{V}\cdot\frac{dV}{dt}\right)_i$$

$$T_{gi+1} = T_{gi}(V_i/V_{i+1})^{n_i-1}$$

$$P_{gi+1} = P_{gi}(V_i/V_{i+1})^{n_i}$$

$$Q_i = C_{vg}(T_{gi+1} - T_{gi})\cdot(K-n_i)/(n_i - 1)$$

$$D_{i+1} = D_i + Q_i/X_{gi}$$

$$C_{i+1} = C_i - Q_i/X_{gi}$$

For calculating out T_{bi+1}

$$D_{bi+1} = 0.622\cdot P_{bi+1}/(P_{gi+1} - P_{bi+1})$$

$$C_{pg}T_{gi+1}+X_{gi+1}D_{i+1}+C_{pw}(T_{gi+1}-273)\cdot D_{i+1}$$

$$= C_{pg}T_{bi+1}+X_{bi+1}D_{bi+1}+C_{pw}(T_{bi+1}-273)\cdot D_{bi+1}$$

$B = (2.431+0.00715(T-273))\cdot 10^{-5}$	$273 < T \leq 473$	
$B = (3.861+0.00675(T-473))\cdot 10^{-5}$	$473 < T < 573$	$K_j/(m\cdot s\cdot K)$
$X = 2501-2.438(T-273)$	$273 < T \leq 453$	
$X = 2014-2.06(T-453)$	$453 < T < 543$	K_j/K_g
$P_b = 10^{(9.1513-2317.7/T)}$	$273 < T \leq 313$	
$P_b = 10^{(8.8444-2224.4/T)}$	$313 < T < 400$	mmHg

Using the calculating method above, a reciprocating compressor with spraying water into cylinders is calculated. The containing water in per unit mass of air has a small change and the caculating error is less than 5% as a result of the containing water change by analysing data if a overall parameter is used

$$S = \frac{C_0}{N\cdot L_0^2}$$

In order to simplify a lot of caculating result, the overall parameter is used to show the total result though the containing water is changed in our caculating. The results is on Fig.1 .

CONCLUSION

A formula to calculate the polytropic exponent is established in the ideal process of spraying water. The formula shows evidently the relation between the polytropic exponent and the spraying water parameter, speed and structure of compressors. The result of spraying water is expressed by the Co/L_0^2 , which shows the effect of the spraying water quantity and atomization, and the better method to dcrease the power consumption and discharge temperature is to strengthen the atomization in cylinders.

Another overal parameter is found for reciprocating compressors, $\frac{C_0}{N\cdot L_0^2}$, which includes the result of spraying water quantity, atomization and turning speed for the polytropic exponent. The overall parameter can be changed from 10^4 to $8\cdot10^6$. The polytropic exponent tends to K when it is less than 10^4, because the turning speed is too fast or the total surface of heat transfer is too small to transfer heat. The polytropic exponent tends to 1.12 when the overall parameter is more than $8\cdot10^6$, because the temperature difference of heat transfer is too small, or the active humidity tends to 1.

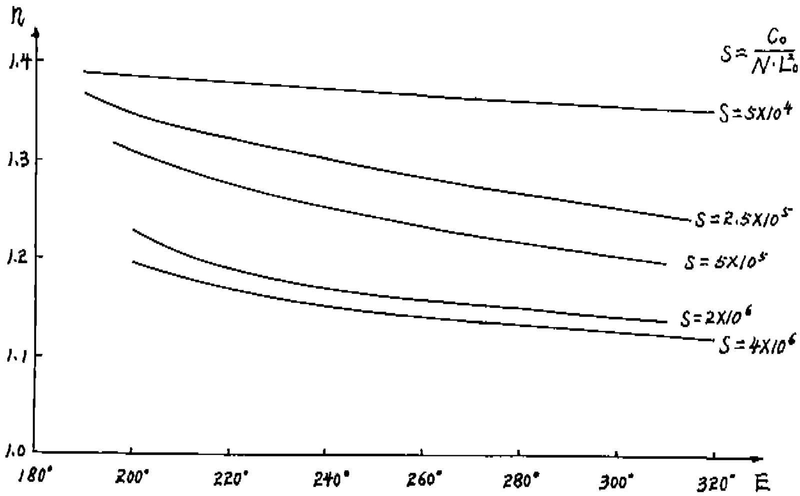

Fig. 1 The changing curves of the polytropic exponent with the turning angle of compressor in different overall parameter.

[illegible]=0.05 Z=0.25