Application and Analysis of water ring vacuum pumps reform Based on Characteristic Curve

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Abstract: The operating efficiency of a vacuum pump is closely related to the characteristic curve and affected by the sealing water temperature of the vacuum pump. Tests have been put on the vacuum pump based on the analysis of the characteristic curve, and the circulating water system is reformed to control the temperature of the sealing water. The energy consumption of the equipment decreases, the operation stability improves, and the cost of the equipment is reduced. Furthermore, the benefits brought by the adjustment are verified through data analysis.

1. Facility Configuration Status
Ningbo cigarette factory power workshop vacuum station is equipped with 5 sets of 2BE1 303-0 water ring vacuum pumps and 1 set of cooling circulation system. The rated power of the vacuum pump is 75kw, the maximum rotating speed is 590r/min, the limited vacuum degree is 3.3kpa, and the maximum suction volume is 3210 m³/h. The vacuum pump participates in controlling the technological requirements of cigarette making machines, packaging machines and Case sealer machine in the cigarette wrapping workshop. It is put into use for more than 16 hours a day and is essential for supporting equipment for cigarette packaging and sealing.

Water ring vacuum pumps, widely used in petroleum, chemical industry, tobacco, machinery, mining, light industry, medicine, and food, is currently the mainstream vacuum pump used in industrial enterprises[1]. Its structure is simple, the pump speed is high, gas compression is close to isothermal compression, suction is uniformed and stable, and the friction resistance between various parts is small[2]. Besides these advantages, the disadvantages of the water ring vacuum pump are also easy to see:

(1) The efficiency is low, generally about 30%, preferably up to 50%.
(2) The vacuum degree is low, which is not only due to structural limitations but also caused by the saturated vapor pressure of the working fluid.

The internal mechanical performance of water ring vacuum pump equipment (such as a crack problem) is greatly affected by cavitation phenomenon, and the equipment maintenance cost is high, which also affects the safe operation of the equipment[3]. This is manifested in the frequent damage of the rotor of the vacuum pump and the increasing maintenance cost[4]. Hence, technical reform has been put on the pump to protect equipment, improve performance, reduce auxiliary power consumption rate, and increase economic income, etc.

2. Theory of Vacuum Pump
The impeller is eccentrically installed in the pump body, and a certain height of the water is injected into the pump before starting (the pump is started after the automatic drain valve discharges water)[5]. When the impeller rotates, the water forms a rotating water ring in the inner wall of the pump body under the
action of centrifugal force, the blades and the distributors at both ends form a sealed cavity.
During the first half rotation (passing through the suction hole at this time), the sealed cavity volume gradually expands, and gas is sucked through the suction hole; During the second half rotation (passing through the exhaust hole at this time), the volume of the sealed cavity gradually reduces, and the gas is discharged from the exhaust hole to complete an air extraction process. In order to maintain the water ring of the Homeostasis, water must be continuously supplied to the pump during operation (Figure 1).

![Figure 1. theory of vacuum pump](image)

1. Water Ring 2. Pump 3. Impeller 4. Suction Cavity 5. Exhaust Cavity

3. Operational Characteristics of Water Ring Vacuum Pumps
The water ring pump performance is related to the state of the pumped gas and the operational water temperature. The characteristic curve is the external expression of the movement rule of liquid in the pump. Different pump characteristic curves are different, therefore, each pump has a specific characteristic curve.

![Capacity vs. Pumping Pressure](image)
Based on the axial efficiency chart and the cigarette production process, the vacuum degree required for production is determined to be less than or equal to -60Kpa, and the equipment is tested with this vacuum degree as the target vacuum degree.

4. Adjustment of Water Ring Vacuum Pumps’ Operating Point

The rated power of 2BE1-303 vacuum pump is 75kw, the maximum rotating speed is 590r/min (curve basis), the limited vacuum degree is 3.3kpa, and the maximum suction volume is 3210 m³/h.

- PABS: Absolute Pressure
  - B: Standard atmosphere, 0.1013Mpa
  - \[PABS = B + Pg\]

  The vacuum degree of the vacuum pump ranges from 3.3 kPa to 101.3 kPa, or from 33 mbar to 1013 mbar;
  
  Vacuum pump demand pressure is less than or equal to -60kpa, actual set pressure is -65kpa, the bottom level of pressure value is -61kpa, the top limit value is -75kpa, converted into vacuum degree (plus 1 atmosphere) and unified unit.
  
  Vacuum pump vacuum degree processing requirements: 413mbar or less, actual set vacuum degree 363mbar.
  
  All curves described in Figure 4 are characteristic curves under absolute pressure.
When the type of vacuum pump is fixed, the pressure ratio of the vacuum pump is determined.

$\nu$: pressure ratio

$\nu_{cr}$: Critical pressure ratio

$\nu_{max}$: Maximum pressure ratio

$\nu < \nu_{cr}$, the pumping efficiency increases while the pressure ratio increases gradually;

$\nu = \nu_{cr}$, the pressure ratio is equal to the critical pressure, the pumping efficiency reaches the highest.

$\nu > \nu_{cr}$, the pumping rate will drop rapidly;

$\nu = \nu_{max}$, the pumping stops;

In fig. 4, point A1 is the set negative pressure value point, and the absolute pressure is 363 mbar. Taking this point as the equipment reference point, a straight line is perpendicular to the x-axis of point A1, intersecting with the 590 r/min curve in the suction rate diagram. The intersection point is point B1, the A1B1 line segment divides fig. 4 into left and right sides. Based on the actual vacuum demand of 363mbar or less, the left side of this line segment is the effective operation area, and point B1 is the bottom point of negative pressure requirement, serving as the efficiency reference point.

Point D1 is the minimum shaft power required at the pumping rate of point B1;

B2 and C1 points are auxiliary points for finding D1 points;

According to the figure, the shaft power of D1 is about 54kw;

The best efficiency point is C2 point with the highest outlet velocity, D2 is the best shaft power point for vacuum pump operation, which is about 67kw.

In conclusion, it can be seen that the optimal axle power range is 54 kW to 67 kW.

$$\frac{P}{P_{max}} = f \frac{f}{f_{max}}$$

Therefore, the best frequency range is from 37Hz to 44.6Hz, and the frequency is set to Floor and
ceiling functions. Also, the vacuum pump equipment depends on the coupling for transmission, the shaft power is less than the power of the equipment motor, so the frequency range is finally set between 38Hz~45Hz.

5. Water System Adjustment in water ring vacuum pumps
The temperature of water ring vacuum pumps sealing water is closely related to energy consumption (Figure 5). When the temperature of sealing water rises leads to the rise of the exhaust temperature and the condenser pressure, and the energy consumption required for the overall operation of the unit rises. Therefore, lower the inlet water temperature of circulating water of the equipment can effectively reduce the energy consumption required for the pump operation. At the same time, under the condition of low water temperature, cavitation can be effectively prevented, the service life of the equipment can be prolonged, and the stability of the equipment can be increased.

The vacuum pump unit of Ningbo Cigarette Factory adopts parallel connection and shares a set of the water system. Sealed water inside the pump body flows into the expansion water tank, lifting to the cooling tower through the circulating water pump, the water has been cooled down by the cooling tower and flows back into the pump body under gravity.

![Figure 4. correlation between 2BE1353-0 water ring vacuum pumps Seal Water Temperature, Condenser Pressure, and Standard coal Consumption](image)

One side of the water inlet pipe is provided with a branch to lead-out part of the circulating water without passing through the inside of the pump body. On the premise that the sealed water quantity in the pump body is fixed, the part of the circulating water that led out and directly flows into the expansion water tank. Through the direct mixing of the low-temperature water and the circulating water in the expansion water tank, which decreases the water temperature in the water tank outlet. The greater the temperature difference between the water temperature and the outdoor atmospheric dew point temperature, the more heat is taken away, thus reducing the temperature of the sealed water and improving the operation efficiency of the vacuum pump.

6. Contrastive Analysis and Verification of Operation Effect
Relevant renovation and optimization were implemented in February 2017 and put into operation in March. The energy consumption of a single box was reduced by 24.3% annually. In order to remove the influence of other interference factors on energy consumption, the author selects the energy consumption data of vacuum pumps for 12 months from September 2016 to August 2017 (in Table 1) to analyze the effect of this retrofit.

The cooling tower is opened according to real-time temperature and humidity regulation, that is, the power consumption of the cooling tower changes with the temperature, that is, the energy consumption of the cooling tower changes seasonally, which may affect the analysis of energy consumption changes before and after the renovation.

Figure 6 shows that the cooling tower consumes a small proportion of the total power consumption of the vacuum pump. By calculation, the cooling tower consumes 3.36% of the total power consumption of the vacuum pump system every month. Therefore, the influence of the change of the cooling tower's energy consumption on the energy consumption of the vacuum pump system can be neglected, that is,
the influence of the change of weather on the energy consumption of the vacuum pump is not considered in this paper.

The optimized vacuum pump will be put into use in March 2017. Therefore, the energy consumption data of the vacuum pump from September 2016 to February 2017 will be used as the pre-transformation data, and the energy consumption data of the vacuum pump from March 2017 to August 2017 will be used as the post-transformation data (in table 2).

**Table 1. Statistical Table of Vacuum Pump Energy Consumption**

| Date    | Power Consumption of Vacuum Pump (Kwh) | Power Consumption of Cooling Tower (Kwh) | Reduced Energy Consumption (Kgce) | Single tank energy consumption (Kgce/tank) |
|---------|----------------------------------------|----------------------------------------|----------------------------------|-------------------------------------------|
| 2016-09 | 54625.1                                 | 1822.8                                 | 6937.45                          | 0.104                                     |
| 2016-10 | 55890.4                                 | 1674.4                                 | 7074.71                          | 0.102                                     |
| 2016-11 | 55582.3                                 | 1519.3                                 | 7017.79                          | 0.108                                     |
| 2016-12 | 69571.3                                 | 1624                                   | 8749.9                           | 0.122                                     |
| 2017-01 | 71386.6                                 | 1343.7                                 | 8938.55                          | 0.160                                     |
| 2017-02 | 62852.1                                 | 1274.9                                 | 7881.21                          | 0.136                                     |
| 2017-03 | 47273.1                                 | 1289.2                                 | 5968.31                          | 0.096                                     |
| 2017-04 | 41751.1                                 | 1279.9                                 | 5288.51                          | 0.087                                     |
| 2017-05 | 49712.3                                 | 1317.3                                 | 6271.54                          | 0.092                                     |
| 2017-06 | 39153.6                                 | 1418.1                                 | 4986.26                          | 0.081                                     |
| 2017-07 | 40156.7                                 | 1702.2                                 | 5144.46                          | 0.076                                     |
| 2017-08 | 42858.4                                 | 1710.5                                 | 5477.52                          | 0.077                                     |

**Figure 5. Power Consumption Diagram of Vacuum Pump and Cooling Tower**

**Table 2. Energy consumption comparison of vacuum pump every tank before and after the reformation**

| No. | before Reformation | after Reformation |
|-----|--------------------|-------------------|
| 1   | 0.104              | 0.096             |
| 2   | 0.102              | 0.087             |
| 3   | 0.108              | 0.092             |
The two sets of data were analyzed by one-way ANOVA and the original hypothesis was put forward.

\[ H_0: \text{There is no difference before and after the transformation.} \]

\[ H_1: \text{There are significant differences before and after the transformation.} \]

| Group                  | Observations | Summation | Average | Variance |
|------------------------|--------------|-----------|---------|----------|
| before Reformation     | 6            | 0.732606  | 0.122101| 0.000509 |
| after Reformation      | 6            | 0.508646  | 0.084774| 6.79E-05 |

|          | SS       | df | MS       | F       | P-value | F crit  |
|----------|----------|----|----------|---------|---------|---------|
| betweenGroup | 0.004179814 | 1  | 0.00418 | 14.48201| 0.003454| 4.964603 |
| Within Groups | 0.002886211 | 10 | 0.000289 |         |         |         |
| Total     | 0.007066025 | 11 |          |         |         |         |

According to the table above, when the confidence is 95%, P-value is 0.0035 < 0.05, so rejecting the original hypothesis H0: there is no difference before and after the transformation, and drawing a conclusion that there is a significant difference before and after the transformation. Therefore, the renovation and optimization of energy consumption have been significantly improved.

7. Conclusion

After adjustment and renovation, the number of vacuum pumps in daily operation has been reduced from the original 3 to 2. The actual energy efficiency has been improved, the gas output of a single device increases, the energy saving effect is obvious, the average monthly power consumption has been saved by more than 12000Kwh, and the total energy consumption of the device has been reduced by more than 25%. The reduction of water temperature avoids cavitation, effectively protects the equipment and improves the unit's performance. At the same time, this optimizing reformation also provides examples for other tobacco enterprises in their technological transformation and adjustment.

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