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Energy-efficient Operation Strategy for Air Compressor and Cooling Tower System

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The compressed air consumption in CSC is about 200,000 Nm^3/hr, and the annual power consumption is about 250 million kWh, accounting for 5% of the company's total consumption. Improving the efficiency of the air compressor systems is an important issue for energy conservation. The Multi-stage centrifugal air compressor is the most common type of air compressor in CSC. Theoretical analysis shows that decreasing outlet air temperature of the inter-cooler can reduce compressor energy consumption. However, the cost is that it increases the energy consumption of the cooling tower. Therefore, the overall system's (air compressor and cooling tower) energy consumption must be considered. First, the relationship between energy consumption of the air compressor and the cooling water temperature of the intercooler was confirmed by the ASPEN simulation. Then, the previous research results showed that the relationship between the energy consumption of the cooling tower and outlet cooling water temperature. The cooling water temperature setting can be calculated from cooling tower and air compressor energy models. Simulation results show that reducing the cooling water temperature by 4°C, the compressor energy consumption is reduced by about 1%. However, considering the energy consumption required reducing the cooling water temperature, the overall system energy consumption can be reduced by 0.8%. The plant test in CSC #2 and #3 compressed air stations show that reducing the cooling water temperature by 5°C, the system energy consumption is reduced by about 1%. Therefore the annual electricity saving is about 300,000 kWh. The test results of the cooling tower system of DSC oxygen plant also show that the low cooling water temperature operation can improve the energy consumption by 1.5% and save about 1 million kWh.

Keywords: Compressed Air, Cooling Tower, Optimal Operation, Energy Conservation

1. INTRODUCTION

Compressed air is one of the most important utilities in large manufacturing industries such as, steel plants, power plants, refineries and petrochemical plants. The compressed air station typically consists of multiple air compressors and supplies compressed air to pneumatic equipment and instrument meters of each process. The compressed air consumption for CSC is about 220 kNm^3/h, and the unit of air to electricity consumption is 0.112 kWh/Nm^3. So, annual electricity consumption for compressed air production is 200 million kWh. There are two strategies to improve the energy efficientancy of a compressed air system. The first strategy is the improvement of equipment, such as preventing leakage and building a heat recovery system, etc. However, the shortcoming is the high investment cost to the slow investment return. The second strategy is the improvement of production management and operation. The advantage is the low investment cost, but requires a high technical threshold. Therefore, This paper focuses on the second strategy.

Usually, the air is compressed by multi-stage centrifugal compressor. After filtering, the air is compressed by the first stage compressor. Then, the air from the first stage is cooled by the intercooler. After cooling, the air is compressed by the next stage compressor. The compressor converts electrical energy into kinetic energy which in turn is used to compress the air. The cost of compressed air production is double that of electricity production and three times that of steam production. Compressed air is the most expansive of all the utilities. There are many scientific literatures about energy saving of compressed air systems, systematic integrated operation technology and energy saving operation of air compressors. Saidur et. al.$^{(1)}$ summarized that compressed-air systems account for about 10% of total industrial-energy use in the EU. The life cycle cost of a compressor shows that the equipment investment and maintenance costs only account for 22% of the compressor's running cost. The remaining 78% of the running cost is the electricity power consumption. The sourcebook of US DOE (2) also shows that a 4°C reduce in the temperature of the inlet air will decrease energy consumption by 1%. It can reduce the energy consumption of a compressor effetely by maintaining a certain cooling effect by intercooler. However, lowering the cooling water temperature increases the cooling tower energy consumption. Lu and Cai(3) mentioned that the system must be considered in the energy saving project. It is necessary to consider not only the energy saving of the unit equipment but also the energy saving of the overall system.

The previous research showed that the energy consumption of an air compressor can be improved by an optimal operation method. Lowering the energy consumption of the air compressor can be achieved by lowering the inlet air temperature. The research about energy saving need to consider that not only the single unit equipment but also the previous and next production process relation. In this paper, we develop the systematic energy saving operation technology of compressor and cooling tower. The optimum cooling water temperature which minimize the energy consumption of the overall air compressor and cooling tower system can be calculated by the proposed method.

2. METHOD

2.1 Energy model for air compressor

The air is compressed by multi-stage centrifugal compressor. After filtering, the air is compressed by the first stage compressor. Then, the air from the first stage is cooled by the intercooler. After cooling, the air is compressed by the next stage compressor. (Fig.1.). The three stage compression process is the most common type of compressor in CSC. The energy model for an air compressor can be described by the enthalpy difference between inlet and outlet air:

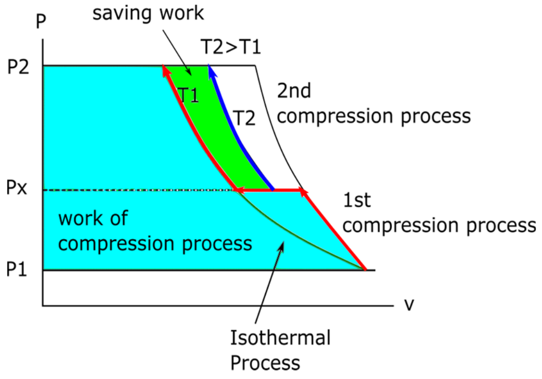

Fig.1. The pressure change trend for the multi-stage compression process.

$$W_c = \dot{m} \times \Delta h \tag{1}$$

Here, $\dot{m}$ is mass flow rate, Δh is the air enthalpy difference between inlet and outlet. The enthalpy change can be calculated as follows.

$$\Delta h = \Delta e + \Delta PV$$

$$= \Delta e + R\Delta T \tag{2}$$

Here, Δe is the difference in value of internal energy, P is the pressure of compressed air, V is the volume of compressed air, T is the temperature of compressed air and R is the gas constant. The different value of internal energy under constant volume can be described as follows.

$$\Delta e = C_v \Delta \mathrm{T} \tag{3}$$

Here, C_v is heat capacity under constant volume. From $C_p - C_v = R$ 、$C_p \,/\, C_v = k'$ C_v 、， is given by :

$$C_v = \frac{R}{k-1} \tag{4}$$

So, equation (2) can be calculated as follows.

$$\Delta \mathrm{h} = \left(\frac{R}{k-1} + \mathrm{R}\right)\Delta \mathrm{T}$$

$$= \frac{k}{k-1} R\Delta T \tag{5}$$

Combining (1) and (5), the energy consumption is show in equation (6).

$$W_c = \dot{m} \times (\frac{k}{k-1}) R\Delta T \tag{6}$$

Assuming the compressed process is polytropic process. Then,

$$\mathrm{P}V^k = constant \tag{7}$$

So,

$$P_{in} V_{in}^k = P_{out} V_{out}^k$$

$$P_{in} \left(\frac{nRT_{in}}{P_{in}}\right)^k = P_{out} \left(\frac{nRT_{out}}{P_{out}}\right)^k$$

$$\frac{T_{out}}{T_{in}} = \left(\frac{P_{out}}{P_{in}}\right)^{\frac{k-1}{k}}$$

$$T_{out} = T_{in} (\frac{P_{out}}{P_{in}})^{\frac{k-1}{k}} \tag{8}$$

Combining (8) and (6)

$$W_c = \dot{m} \times \left(\frac{k}{k-1}\right) \mathrm{R}(T_{out} - T_{in})$$

$$= \dot{m} \times \left(\frac{k}{k-1}\right) \mathrm{R}\left[T_{in}\left(\frac{P_{out}}{P_{in}}\right)^{\frac{k-1}{k}} - T_{in}\right]$$

$$= \dot{m} \times \left(\frac{k}{k-1}\right) \mathrm{R}T_{in}\left[\left(\frac{P_{out}}{P_{in}}\right)^{\frac{k-1}{k}} - T_{in}\right] \text{................ (9)}$$

Equation (9) shows that the energy consumption is highly correlated to the inlet air temperature (Tin) under the constant compression ratio (Pout/Pin). In the multi-stage compression process, the high temperature air from the previous stage is cooled via the intercooler, and then enters the next stage. Inlet air temperature is affected by the performance of the intercooler. Assuming that the current intercooler performance is unchanged, the compressed air temperature is affected by the cooling water temperature of the intercooler. Therefore, the relationship between the water temperature of the cooler and the energy consumption of the air compressor can be obtained.

However, a complex mathematical expression is required to directly determine the relationship between the intercooler water temperature and the air compressor energy consumption. It might take a long time to calculate and the results are not easy to implement. An air compressor model using Aspen simulation software was used to quickly establish the relationship between the cooling water temperature and the energy consumption of the air compressor. Then, the air compressor model based on the current operating data can be established. The energy consumption under different conditions can be found by the air compressor model. Fig.2 illustrates the steps to build an air compressor energy model.

2.2 Energy model for cooling tower

Lowering the energy consumption of the air compressor can be achieved by lowering the inlet water temperature of the intercooler. However, lowering the cooling water temperature increases the cooling tower energy consumption. Therefore, it is necessary to understand the relationship between the power consumption of the cooling tower and the cooling water temperature. If the cost of lowering the cooling water temperature is too high, a balance point must be found to minimize total system energy.

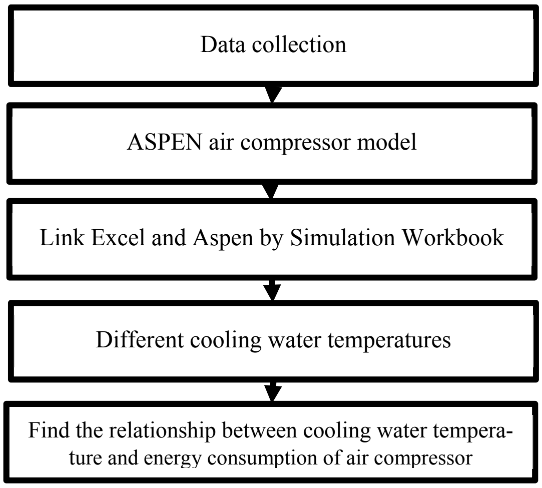

Fig.2. Flowchart of building an air compressor energy model.

In a cooling tower system, heat is removed from the water by sensible heat, temperature differences; and latent heat, via the evaporation of small amounts of water. The evaporation process accounts for 80% of total heat removal. The rate of water evaporation in a cooling tower is determined by relative humidity, ambient air temperature and airflow rate. The thermal performance of the cooling tower depends principally on the wet-bulb temperature of inflowing air. The lowest outlet water temperature is limited by ambient air wet-bulb temperatures. Water temperature decreases along its path through the tower, due to evaporative cooling. The specific enthalpy of the saturated air film and its variation with water temperature is given by the saturation curve on the psychometric chart. The difference between the specific enthalpies of saturated and bulk air is the enthalpy driving force responsible for evaporative cooling. The energy balance is described in equation (10) and Fig.3.

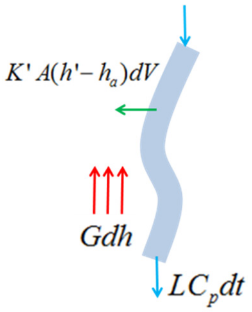

Fig.3. The heat transfer between air and liquid in the cooling tower.

$$\mathrm{L}C_p dT = Gdh = K'A(h' - h_a)dV \text{ ....(10)}$$

Here, L is cooling water mass flow rate; C_p is specific heat of cooling water; dT is the difference in water temperature; G is air mass flow rate; dh is the difference in air enthalpy; K' is mass transfer per unit volume and area; A is contacting area between liquid and air; h' is saturated air enthalpy under water temperature; h_a is saturated air enthalpy under web bulb temperature; dV is controlled volume. The number of transfer units (NTU) is defined by K'AV/L. The relationship between enthalpy difference and temperature change can be described in equation (11).

$$\frac{K'AV}{L} = \int_{T1}^{T2} \frac{C_p}{h'-h_a} dT \qquad (11)$$

Cooling tower efficiency evaluation method from CTI mentioned the following definition. Once the cooling tower size and heat sink form are determined, the heat transfer characteristics will be determined. The empirical formula for cooling towers is shown in equation (12). C_0 and m is the constant from experience. It can be found by measuring the operation parameter from the experiment. Usually, the operational and characteristic curves are provided by cooling tower vender. C_0 is the value between 0.55 and 0.65 or calculated by historical process data. m is usually given by 0.6.

$$\frac{K'AV}{L} = C_0\left(\frac{L}{G}\right)^{-m} \qquad (12)$$

The fan current can be calculated by giving the wet bulb temperature, water flow rate, water inlet temperature and outlet water temperature from equations (11) and (12). The calculation steps are shown in Fig.4.(3)

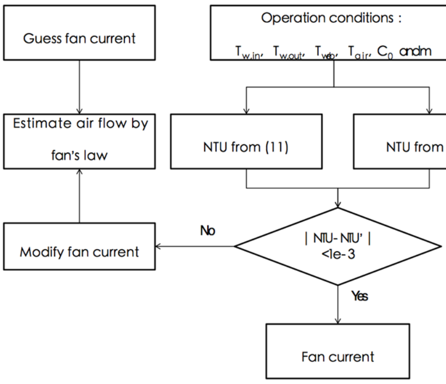

Fig.4. The steps of predicting fan current.

2.3 Energy model for cooling tower

The systematical energy conservation can be obtained by integrating energy models for the air compressor and cooling tower. The concept is to find a cooling water temperature that the air compressor and cooling tower system energy is at their combined lowest. According to the process and environmental conditions, the maximal variation range of cooling water temperature is about 10°C. So, the energy consumption performances in the range of 10°C can be obtained. Therefore, the cooling water temperature with the lowest energy consumption can be found. Fig.5 shows the calculation steps.

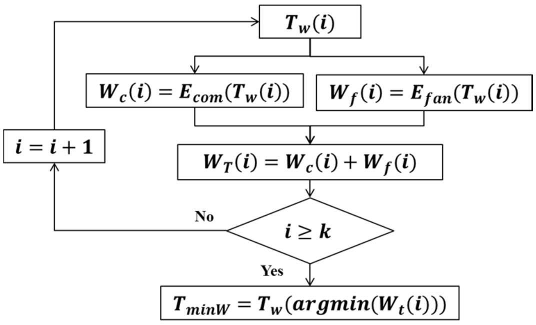

Fig.5. The flowchart of systematical energy conservation technology.

3. RESULTS AND DISCUSSION

The research subject was #2 and #3 compressed air stations and 300C cooling tower. The power consumption simulation results and plant test results are described as follows.

3.1. The energy simulation results for #2 and #3 compressed air stations

There are twelve air compressors in #2 and #3 compressed air stations. The power consumption of each compressor is about 1,200~1,300 kW. The annual electricity consumption is 70 million kWh. The cooling water that supplies the compressed air station is from 300C cooling tower. 300C cooling tower also supplies the blast furnace and continuous casting process. (Fig.6) There is between 25%~30% cooling water suppling the compressed air station.

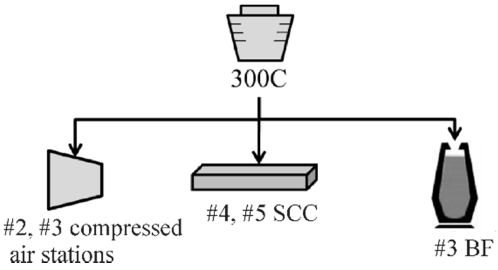

Fig.6. 300C cooling water system.

The three stage compression process can be simulated by ASPEN model. (Fig.7.) The set points of the compressor and intercooler are referred by the process conditions and equipment specification. The simulation results are shown in Table 1. The outlet pressure and temperature of each compressed stage are close to the real process data. The mean error is less than 1%.

Table 1 The simulation results of compressor.

	1st stage outlet		**2nd stage inlet**		**2nd stage outlet**	
	Temperature	Pressure	Temperature	Pressure	Temperature	Pressure
	C	kg/sqcm	C	kg/sqcm	C	kg/sqcm
Simulation	130.81	2.08	41.54	2.08	110.10	3.54
Real	131.42	2.05	41.96	2.11	110.15	3.57
error	-0.5%	1.4%	-1.0%	-1.5%	0.0%	-1.0%

	3rd stage inlet		**3rd stage outlet**		**1st intercooler inlet**	**2nd intercooler outlet**
	Temperature	Pressure	Temperature	Pressure	Temperature	Temperature
	C	kg/sqcm	C	kg/sqcm	C	C
Simulation	43.54	3.54	143.26	6.47	36.34	35.24
Real	43.16	3.54	142.00	6.50	36.01	34.42
error	0.9%	0.0%	0.9%	-0.4%	0.9%	2.4%

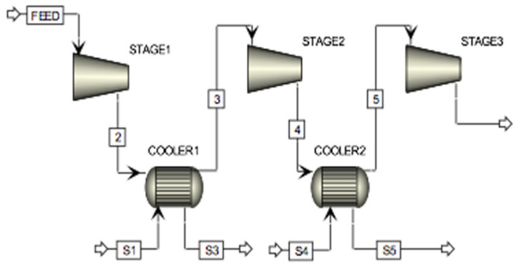

Fig.7. The compressor simulation model in ASPEN.

The following common process condition is used to illustrate the relationship between energy consumption and cooling water temperature. Inlet air temperature is 30°C. Compressed air follow rate is 11,500 Nm^3/hr. Intercooler water temperature is from 32 to 20°C. When the cooling water temperature is changed from 32°C to 28°C. The energy consumption of the compressor reduces from 1344kW to 1326kW. It is an improvement of 1.34%. (Table 2, Fig.8) About 8 air compressors are normally operated in #2 and #3 compressed air stations. When the cooling water temperature is lowered by 4°C, a 144 kW reduction can be gained.

3.2. The energy simulation results for 300C cooling tower

The energy consumption of the cooling tower is mainly determined by the outlet water temperature, atmospheric temperature and humidity at that time. The wet bulb temperature is the physical minimum outlet water temperature. Assume that the atmospheric temperature is 22°C, the humidity is 75%, the cooling water flow rate is 10,000 M^3/hr, and the cooling tower is cooled by 3°C (inlet and outlet water temperature difference), the energy simulation is shown in Fig.9.

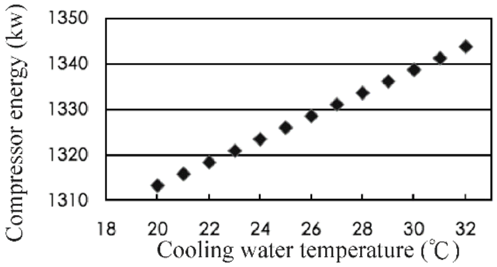

Fig.8. The relation between compressor energy and cooling water temperature.

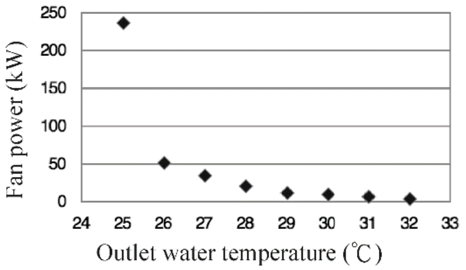

Fig.9. The relation between cooling tower energy and cooling water temperature.

Table 2 The simulation results under different conditions.

	Conditions							Total energy consumption	**1st stage simulation results**			
Scenario	Atmospheric temperature	Atmospheric pressure	Air flow rate	1st stage Compression ratio	2nd stage Compression ratio	3rd stage Compression ratio	Cooling water temperature		Energy consumption	Tout	Pout	
	C	kg/sqcm	cum/hr				C	kW	kW	C	kg/sqcm	
Case1	30	1.03	11500	2.02	1.7	1.83	32	1343.9	500.8	130.8	2.1	
Case2	30	1.03	11500	2.02	1.7	1.83	31	1339.4	500.8	130.8	2.1	
Case3	30	1.03	11500	2.02	1.7	1.83	30	1335.0	500.8	130.8	2.1	
Case4	30	1.03	11500	2.02	1.7	1.83	29	1330.5	500.8	130.8	2.1	
Case5	30	1.03	11500	2.02	1.7	1.83	28	1326.0	500.8	130.8	2.1	
Case6	30	1.03	11500	2.02	1.7	1.83	27	1321.5	500.8	130.8	2.1	
Case7	30	1.03	11500	2.02	1.7	1.83	26	1317.0	500.8	130.8	2.1	
Case8	30	1.03	11500	2.02	1.7	1.83	25	1312.5	500.8	130.8	2.1	
Case9	30	1.03	11500	2.02	1.7	1.83	24	1308.0	500.8	130.8	2.1	
Case10	30	1.03	11500	2.02	1.7	1.83	23	1303.5	500.8	130.8	2.1	
Case11	30	1.03	11500	2.02	1.7	1.83	22	1299.0	500.8	130.8	2.1	
Case12	30	1.03	11500	2.02	1.7	1.83	21	1294.5	500.8	130.8	2.1	
Case13	30	1.03	11500	2.02	1.7	1.83	20	1290.0	500.8	130.8	2.1	

	2nd stage simulation results					**3rd stage simulation results**						
	Tin	Pin	Energy consumption	Tout	Pout	Tin	Pin	Energy consumption	Tout	Pout	1st intercooler T	2nd intercooler T
	C	kg/sqcm	kW	C	kg/sqcm	C	kg/sqcm	kW	C	kg/sqcm	C	C
Case1	43.7	2.1	342.7	112.8	3.5	46.1	3.5	500.5	146.6	6.5	36.6	35.5
Case2	42.8	2.1	341.0	111.7	3.5	45.1	3.5	497.6	145.3	6.5	35.7	34.5
Case3	42.0	2.1	339.4	110.6	3.5	44.1	3.5	494.8	144.0	6.5	34.7	33.5
Case4	41.1	2.1	337.7	109.5	3.5	43.1	3.5	492.0	142.7	6.5	33.8	32.5
Case5	40.2	2.1	336.0	108.5	3.5	42.1	3.5	489.2	141.3	6.5	32.8	31.5
Case6	39.3	2.1	334.3	107.4	3.5	41.1	3.5	486.4	140.0	6.5	31.8	30.5
Case7	38.4	2.1	332.6	106.3	3.5	40.0	3.5	483.6	138.7	6.5	30.9	29.5
Case8	37.5	2.1	331.0	105.3	3.5	39.0	3.5	480.8	137.4	6.5	29.9	28.5
Case9	36.7	2.1	329.3	104.2	3.5	38.0	3.5	478.0	136.0	6.5	29.0	27.5
Case10	35.8	2.1	327.6	103.1	3.5	37.0	3.5	475.1	134.7	6.5	28.0	26.5
Case11	34.9	2.1	325.9	102.1	3.5	36.0	3.5	472.3	133.4	6.5	27.0	25.5
Case12	34.0	2.1	324.2	101.0	3.5	35.0	3.5	469.5	132.1	6.5	26.1	24.5
Case13	33.1	2.1	322.6	99.9	3.5	34.0	3.5	466.7	130.7	6.5	25.1	23.5

3.3. The energy simulation results for the overall system

Assume that the atmospheric temperature is 22°C, the humidity is 75%, the cooling water flow rate is 10,000 M^3/hr, the compressed air flow rate is 11,500 Nm3/hr and six air compressors are running with the temperature range of the cooling water between 25 to 30°C. When the cooling water is 30°C, the overall energy consumption is 8019.6kW. When the cooling water is 26°C, the overall energy is 7953.5 kW. At this time, the power consumption reduction of the air compressor can overcome the increased power consumption of the cooling tower. If the cooling water is 25°C, the energy consumption of cooling water is higher than the power saved by the air compressors. So, the overall power is increased (Fig.10.). Only 30-35% water flow rate is provided to air compressors in the 300C cooling water system. The increased energy of the cooling tower is not only for air compressors therefore the cost of cooling is high. Lower cooling water temperature has no affect on the other users. However, it is hard to quantify the benefits of positive impacts currently.

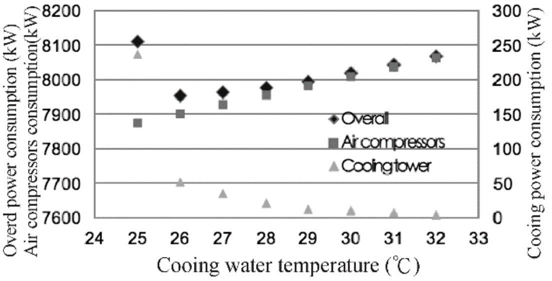

Fig.10. The relation between overall system energy and cooling water temperature.

3.4. The plant test results for the overall system

The simulation results show that the lowest energy consumption is around 26°C cooling water temperature. Therefore, the overall energy consumption under 26.5°C cooling water temperature is compared to that under 32°C cooling water temperature. The test results are shown in Table 3 and Fig.11.. The power consumption of the air compressor is improved by 1.51%. Considering the power increase of the cooling tower, the overall system power is improved by 1%. Assuming that one-third of the year can reduce energy consumption by 1%, the annual electricity saving of #2 and #3 compressed air stations is about 300,000kWh. The similar plant tests are also implied to DSC oxygen plant. The overall system power consumption can be improved by 1.5% under low cooling water temperature operation. The annual electricity saving of the DSC oxygen plant is about 1,000,000 kWh.

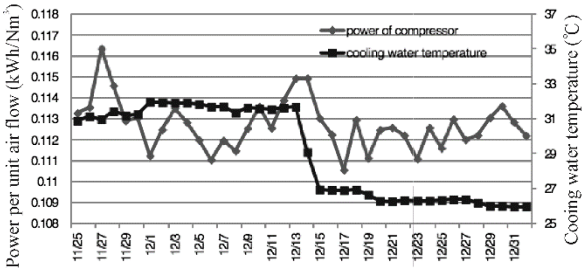

Fig.11. The relation between overall system energy and cooling water temperature.

4. CONCLUSIONS

The research proposed a systematical energy conservation method. The lowest power consumption can be found by integrating the energy model of compressors

Table 3 The plant test results for #2 and #3 compressed air stations.

	Cooling tower outlet water temperature (°C)	Cooling tower inlet water temperature (°C)	Atmospheric temperature (°C)	Power of cooling tower (kW)	Power of air compressors (kW)	Compressed air flow rate (Nm^3/h)	Efficiency of air compressors (kWh/Nm^3)	Efficiency of overall system (kWh/Nm^3)	Air pressure (Kg/cm^2)
11/27-12/14	31.5	33.9	22.0	24.7	7297.8	64763.5	0.1127	0.1131	5.1
12/15-12/31	26.4	28.9	21.2	66.2	7368.6	66382.1	0.1110	0.1120	5.1
Improvement							1.51%	1.0%	

and cooling tower. The simulation results show that there is a best cooling water temperature set point for overall system. The plant tests also confirm the simulation results. The overall power for #2 and #3 compressed air stations and 300C cooling tower is improved by 1% under reducing cooling water temperature by 5°C. The annual electricity saving is about 300,000 kWh. The power consumption also can be improved by 1.5% in the DSC oxygen plant under low cooling water temperature condition and the annual electricity saving is about 1,000,000 kWh.

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