Optimal Operation of Compressed Air Station

CHUN-CHENG CHANG*, MING-WEI LI*, DING-SHUO CHEN* and HSIN-HUNG CHEN**

**Green Energy & System Integration Research & Development Department*
***Utilities Department*
China Steel Corporation

Compressed air is one of the most important utilities in industry. 75~90% of energy is dissipated during the compression process. Only 10%~25% of the energy is used efficiently. The cost of compressed air is double that of electricity and triple that of steam, so compressed air is the most expensive utility. In order to maintain production as normal, the compressed air station produces as much compressed air as possible. However, the pressure of the compressed air header will increase when demand is low and as a result increases production cost. The normal outlet pressure of the compressor is at 5-6 kg/cm^2-g. The energy consumption of the compressor is reduced by 1% for every 0.14 kg / cm^2 (2 psi) outlet pressure reduction. We use an Exponential Weighting Moving Average (EWMA) method to predict the pressure of the compressed air header based on the historical process data. The operators can regulate the compressor operation unit to maintain the stability of the pipe pressure and reduce the use of the compressor units. The online test results show that the electricity can be reduced 7,200 kWh per day, saving 6 million NTD in annual operation cost.

Keywords: Compressed air, Optimal operation, Production management, 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 consists of multiple air compressors and supplies compressed air to pneumatic equipment and instrument meters of each process. Usually, the air is compressed by multi-stage centrifugal compressors. 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 second stage compressor. The compressor converts electrical energy to kinetic energy which is required for a rotating device. Then, the air is compressed by the kinetic energy. Therefore, the cost of compressed air production is double that of electricity production and three times that of steam production. The compressed air is the most expansive utility. A reduction in the energy consumption of the compressor effetely by maintaining a certain cooling effect of intercooler. In general, a 4℃ rise in the temperature of the inlet air will increase energy consumption by 1%. Because of compressed air being one of the utilities in a plant, the compressed air station will produce as much compressed air as possible. The pressure of a pipeline system increases when some processes are unloaded and the compressed air demand is reduced. If the pressure at the discharge exceeds the capability of the compressor, a blow-off valve is automatically opened to avoid a surge condition. When the blow-off valve is opened, some of the compressed air is discharged to the environment not to the production process there by production costs will be increased. The energy consumption of the compressor is reduced by 1% for every 0.14 kg/cm^2 (2 psi) reduction in discharge pressure.

The air compressor stations are connected to the production process by a pipeline system at China Steel (CSC). There are multiple air compressors in each air compressor station to produce compressed air. The operational mode of the air compressor station is that all base load compressors are started up. When the compressed air demand is reduced, the blow-off valve of the air compressor is automatically opened to avoid a surge condition and maintain the balance of the pipeline system pressure. Additionally, one or two compressors are in the standby mode to quickly respond to changes in compressed air demand. However, the standby mode is not an energy efficient operational method. There is still 25% energy needed for the standby mode with no compressed air being produced. In order to avoid compressed air releases and reduce power consumption, we model the pressure of the pipeline system by an Exponential Weighting Moving Average (EWMA) method and process information. We also refer to the production schedule to predict the demand for compressed air and variation in pipeline system pressure. The prediction results can be used as a reference for the operation. Finally, considering the current operating efficiency of each compressor, the proposed method provides the most energy efficiency operational guide for the operator to adjust. Additionally, the cooling efficiency baseline for the intercoolers for each compressor was created from the historical process information. When the cooling efficiency is lower than the control limit, maintenance staff are notified to replace or clear the intercoolers.

2. METHOD

2.1 Production schedule and suggestion for air compressor station

The single compressor capacity in #1 and #2 air compressor stations is 12,000 Nm^3/hr. The current operational status is that all base load compressors are started up. One or two compressors are on standby mode. When the pressure of the pipeline system is lower than the set point pressure, the standby compressor starts up automatically to adjust for demand of compressed air. Because the operators cannot know the future demand of compressed air, they do not shut down the compressor rashly. The only one thing they can do is to blow off the excess compressed air. This operation results in unnecessary energy usage. If the total demand of compressed air is known as D, the start-stop operation of compressors can be described as an integer linear optimization problem：

$$\underset{c}{Min}\sum_{i=1}^{N} c_i \times F_i \times Eff_i$$

$$st.\sum_{i=1}^{N} c_i \times F_i \geq D \quad (1)$$

N is the number of compressors. C is 0 or 1 to indicate the start or stop status of the air compressor. Fi is the air flow rate of each air compressor. Effi is the efficiency which can be described as electricity use per unit air flow. The key question is how to estimate the total compressed air demand, D, for process. In this research, The average pressure per hour of the pipeline system ($\hat{y}_{i+1}$) is predicted by EWMA[(2)]:

$$\hat{y}_{i+1} = \lambda\ y_i + (1-\lambda)\hat{y}_i \quad (2)$$

y_i and $\hat{y}_i$ are respectively the average and predicted pressure one hour ago. λ is the weighting factor to tune the ratio between average pressure and predicted pressure. Normally, the rage of weighting factor is 0.6~0.8. The decision of startup or shut down is based on the predicted pressure. When the predicted pressure is higher than the set point pressure, it is recommended to shut down the running compressors. Otherwise, it is recommended to startup compressors. The test results show that starting one compressor which capacity is 12,000 Nm^3/hr can increase pipeline system pressure by 0.17 kg/cm^2. Otherwise, Stop one compressor can reduce the pressure by 0.12 kg/cm^2. (Table 1)

Figure 1 is the algorithm for compressor operation. First, pipeline system pressure value in one hour will be predicted by the algorithm. The set point of pipeline system pressure is read from the database. The running number of compressors set to 0 which means i=0. Then, the difference between the predicted pressure and the set point (dP) can be calculated. If the difference is larger than 0.12 (dP>0.12), it indicates that one unit can be unload at least. The dP value is decreased by 0.12 for unloading every one unit. Until dP is less than 0, the algorithm compare the current dP value with the previous dP value. If the current absolute dP value is less than the previous dP value (|dP|<dPi-1), it is suggested that i units with large power consumption can be shut down. Otherwise, i-1 units with high power consumption can be shut down. The steps of loading compressors are described as following. If the difference is less

Table 1 The pressure test result of AS2 and AS3

description	Test-1		Test-2		Test-3	
	2/3AS pipeline system pressure (kg/cm^2)	Pressure difference	2/3AS pipeline system pressure (kg/cm^2)	Pressure difference	2/3AS pipeline system pressure (kg/cm^2)	Pressure difference
Starting one compressor (12,000 Nm^3/hr)	4.97	0.21	4.97	0.12	4.99	0.19
Stable period	5.18		5.09		5.18	
Stop one compressor (12,000 Nm^3/hr)	5.22	-0.11	5.11	-0.12	5.19	-0.13
Stable period	5.11		4.99		5.06	

than -0.17(dP<-0.17), it indicates that one unit needs to load at least. The dP value is increased by 0.17 for loading every one unit. Until dP is larger than 0, the algorithm compares the current dP value with the previous dP value. If the previous absolute dP value is less than the current dP value (|dPi-1|<dP), it is suggested that i-1 units with low power consumption can be started up. Otherwise, i units with low power consumption can be started up.

The efficiency which is the guideline of the operation sequence can be described as the power consumption per unit compressed air volume. If there are N compressors, equation (3) shows the efficiency of each compressor.

$$\eta_i = \frac{W_i}{Q_i}, \quad i=1...N \qquad (3)$$

Here, Wi and Qi are respectively power consumption and compressed air volume of the previous day.

2.2 The key efficiency index of the intercooler

The efficiency index of a compressor can be calculated by power consumption, compressed air volume and outlet pressure. The efficiency index of intercooler can also be calculated by temperature and flow rate of cooling water, and temperature and flow rate of compressed air. Then, a baseline for the best operational efficiency can be found by the historical process data after maintenance or design spec. The operational efficiency of equipment can be estimated by comparing current efficiency index to the baseline. The operation efficiency gets better as it gets closer to the baseline. This can be one of the conditions to preferentially start the unit. Additionally, the control limit of operational efficiency can be determined by the operators' experience or historical process data before maintenance. When operational efficiency is over the control limit, we should inform the maintenance department and schedule a maintenance project. Figure 2 is the flow chart for monitoring operational efficiency of the air

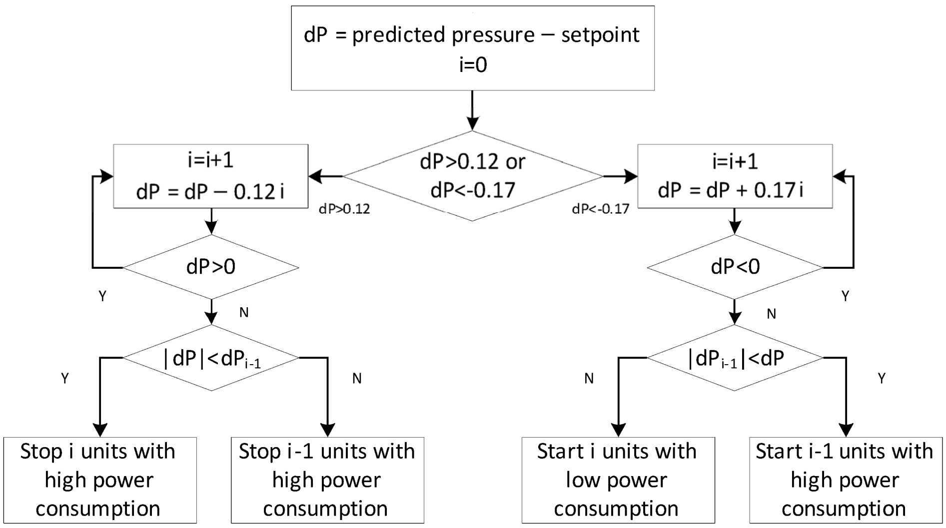

Fig.1. Algorithm of compressor loading and unloading.

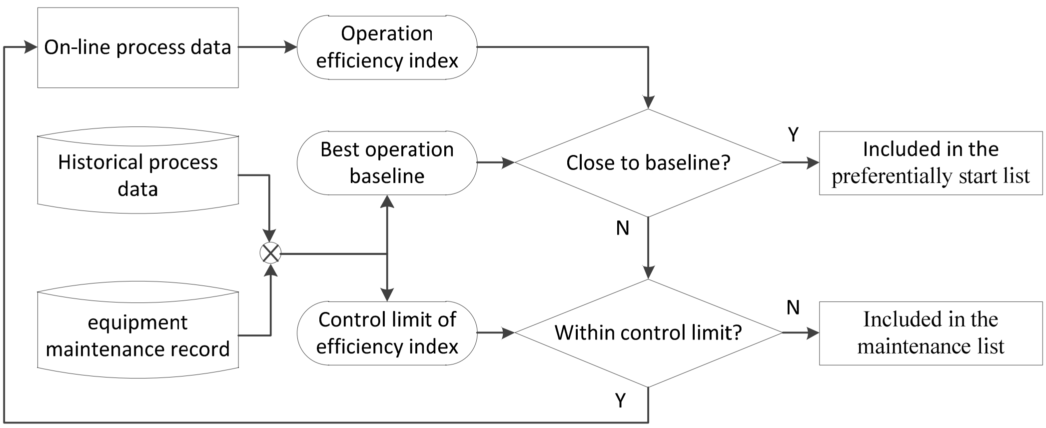

Fig.2. Flow chart of compressor and inter cooler monitoring.

compressor.

Equation (4) shows the energy balance equation of shell and tube heat exchanger.

$$Q = \dot{m} C_p (T_i - T_0) \quad (4)$$

Here $\dot{m}$ is mass flow rate, C_p is heat capacity, T_i and T_0 are respectively inlet and outlet temperature. Equation (5) shows the heat flux equation.

$$Q = UA\Delta T_m \quad (5)$$

Here, *A* is heat transfer area of the surface and *U* overall heat transfer coefficient. ΔT_m is the logarithmic mean temperature difference (LMTD). The LMTD is defined by the logarithmic mean as equation (6):

$$\Delta T_m = \frac{\Delta T_2 - \Delta T_1}{ln(\Delta T_2 / \Delta T_1)} \quad (6)$$

ΔT_1 is the difference value of hot steam ($T_{H,o}$– $T_{C,i}$), ΔT_2 is the difference value of cold steam ($T_{H,i}$– $T_{C,0}$).The dirt in the shell side of the intercooler can be removed by a backwash process but the pipe diameter of the tube side is too small to be clean during operation. The small particles are accumulated gradually and cause clogging, making a smaller heat transfer area. Therefore, the heat transfer flux, Q, of intercooler can be calculated by equation (4) and measured air temperature. Equation (7) shows the product of overall heat transfer coefficient and heat transfer area. It can be obtained by equation (4)-(5) and real-time process data.

$$UA = \frac{\dot{m} C_p (T_i - T_0)}{\Delta T_m} \quad (7)$$

The key performance index (KPI) can be defined by the current UA and design UA.

$$KPI = \frac{UA}{UA_d} \times 100\% \quad (8)$$

The timing of replacing the intercooler can be determined by instantly monitoring the KPI of the intercooler.

3. RESULTS AND DISCUSSION

3.1 The benefit of the compressor operation regulation

The pipeline system pressure is modeled by equation (2) and historical process data. Figure 3 shows the model results. The black dot on Fig.3 is the 8 hours average use of compressed air. The line is the predicted value when λ=0.7 in equation (2). Figure 3 also shows the Relative Error of Prediction (REP).

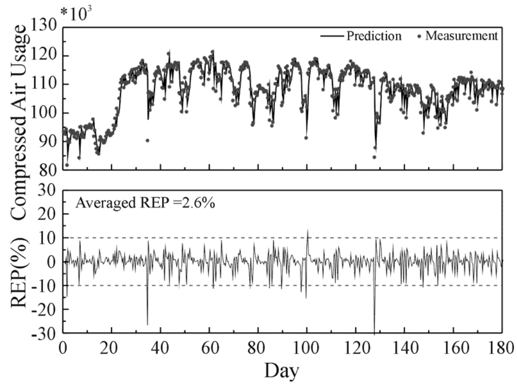

Fig.3. Prediction result of PA consumption.

$$REP = \frac{\left(y_i - \hat{y}_i\right)}{y_i} \times 100\% \quad (9)$$

The REP in Fig.3 is 2.6%. Only 11 shifts in 540 shifts (180 days) have a REP more than ± 10%. In order to reduce the prediction error and avoid frequent air compressor starting and stopping, the predicted value ($\tilde{y}_i$) is corrected in the fourth hour of each shift.

$$\tilde{y}_i = \frac{1}{8}\left(\sum_{j=1}^{4} x_j + 4 \times \hat{x}_5\right)$$

$$\hat{x}_5 = \lambda' x_4 + (1 - \lambda')\ \hat{x}_4 \quad (10)$$

Here, x_j, j=1,⋯4 is the hour average in the first four hours of each shift. $\hat{x}_5$ is the predicted value in the next hour by EWMA and average usage (x_4) in the fourth hour. λ′ in the equation (10) is the weighting factor. The line in Fig.4 is the corrected predicted value. Figure 4 also shows the REP is reduced to 0.8% and there is no REP more than ±5% after correction.

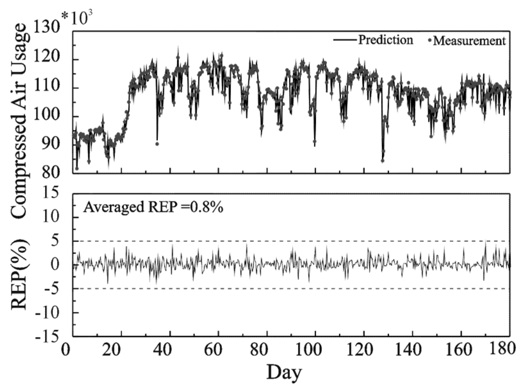

Fig.4. Prediction result of PA consumption after correction.

By integrating the above algorithm, Fig.5 shows the user interface. The trend chart on Fig.5 shows hour average of pipeline system pressure (hollow round), predicted value (diamond) and set point (solid round). The blue bar is the 8 hour average of power consumption. The dark light indicates that the unit is running. The light-colored light indicated that the unit is unloading. When the suggestion status and current status are different, it will remind the operator of the flashing red. The operator also can set the set point value and pressure change value of loading or unloading one compressor.

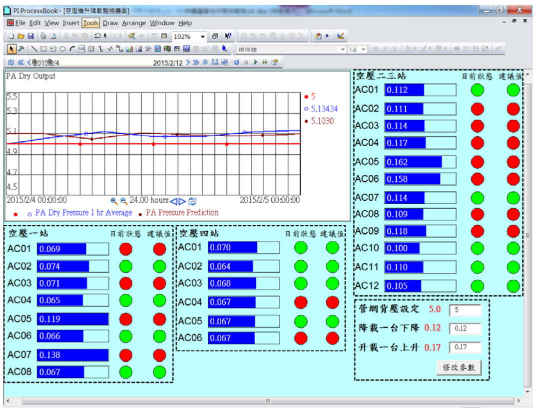

Fig.5. User interface of compressor optimal operation.

When the pipeline system pressure set point is 5kg/cm^2, 3 months test data show that the proposed method can reduce the use of electricity by about 7,200 degrees per day and save 1.6 million NTD in 3 months. (Table 2)

Table 2 Benefit of optimal compressor operation

	Set point = 5 kg/cm^2		Total
Shutdown units	1	2	
Shutdown hours	420	170	
Saving cost	1,125,000	460,000	1,585,000

*power consumption = 0.1 kW・hr/Nm^3, per kilowatt-hour (kW・hr)=NT$2.4

3.2 Monitoring of intercoolers

The cooling efficiency should be stable when all temperature and flow rate meters are in normal conditions. Figure 6 shows a case study of AS3CA11 first intercooler. In the normal condition, the first intercooler KPI of AS3AC11 is stable. However, the air inlet temperature significantly reduction causes the cooling efficiency change (Fig.7).

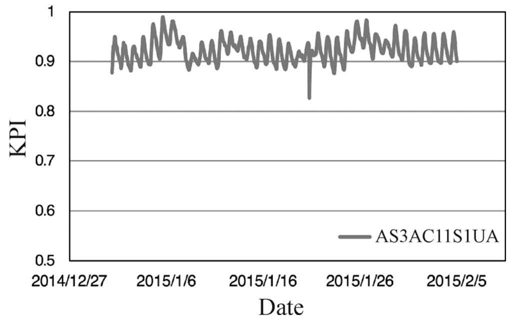

Fig.6. Efficiency of AS3AC11S1 intercooler.

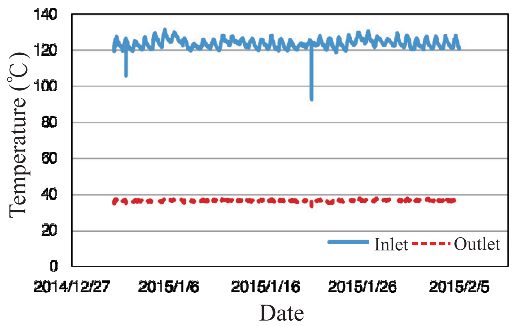

Fig.7. Air inlet and outlet temperature of AS3AC11S1 intercooler.

4. CONCLUSIONS

In this work, we proposed a method of predicting pipeline system pressure and determining the operational schedule of air compressors. Simulations using this method showed that the prediction error was 0.8%.The test results in the compressed air station also showed it can reduce the use of electricity by about 7,200 kWh per day and save about 6 million NTD in annual operational cost. The current method only shows the guidelines to operators. Any change must be adjusted manually by operators. The future work targets will be automatic loading/unloading operation.

REFERENCES

1. R. Saidur, N. A. Rahim and M. Hasanuzzaman, "A Review on Compressed-air Energy Use and Energy Savings", Renewable and Sustainable Energy Reviews, 14.4, pp.1135-1153, 2010.
2. D. C. Montgomery, "Introduction to Statistical Quality Control", 6th Edition, Wiley, 2008. □