

Research on Energy-Saving Operation of Screw Air Compressor

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Abstract: Based on analysis of a screw air compressor volumetric efficiency under different discharge pressure conditions, this study establishes the mathematic model of the adiabatic compression power consumption. Under load/unload conditions, to change the offline pressure with step of 0.01 MPa, the power consumption floats up and down with the change of unloading and loading and then the screw compressor power consumption is simulated in MATLAB. The results shows that the optimal offline pressure exists at the given air consumption and meanwhile power consumption is minimal with the optimal offline pressure. It also reveals that the required optimal offline pressures will vary by air consumptions. Then, based on dynamic mechanical analysis for fluid motion in the pipe, considering that there is a causal relationship between pressure variation and gas flow variation, a method for measuring flow rate of one dimensional unsteady flow dynamically is proposed based on theory of linear approximation. In order to lower the online pressure and further reduce the energy consumption of screw air compressor, we propose a method is to calculate the rate of pressure drop and predict times for the discharge pressure dropping to the online pressure. And the further optimal control method of screw air compressor is given. It is correct and feasible, which proved by experiments.

Keywords: Energy saving, optimal control, optional offline pressure, screw air compressor

INTRODUCTION

Screw air compressor has been widely used due to its safe operation and convenience in the industrial field. In most industrial facilities, compressed air is necessary to manufacturing. Compressed-air generation is energy intensive and for most industrial operations, energy cost fraction of compressed air is significant compared with overall energy costs. Compressed air is different from the primary energy and it is converted from the primary energy or secondary energy by an air compressor. Production of compressed air is one of the major energy-consuming sectors in industrial production. Compressed air accounts for as much as 10% of industrial electricity consumption in the European Union (Radgen, 2006). Figure 1 shows compressed-air energy use in 15 EU countries. Compressed-air systems in China use 9.4% of China's electricity.

Nowadays, with the rising crude oil price, energy issues become increasingly prominent. Many problems including those concerning low efficiency and serious energy wasting in compressed-air system are pressing issues to be addressed and energy saving of compressed-air system has been an urgent task worldwide. Because power consumption of the air compressor accounts for about 96% of the total power consumption in compressed-air system, energy-saving study of the compressed-air system should mainly focus on

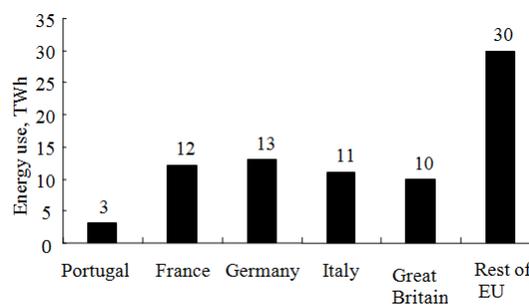


Fig. 1: Compressed-air energy use in 15 EU countries (Radgen, 2006)

compressors (Cai, 2009; Kameya, 2009; Kovacevic, 2007). According to the statistics for published papers in the International Conference on Compressors and their Systems, the authors find Scholars at home and abroad concentrated on how to increase compressor's life and to improve efficiency by optimizing internal structure design of compressors (Ooi, 2007; Pizarro-Recabarren, 2009).

In this study, the authors take the screw air compressor as study object, for the reason that the screw air compressor is widely used in the industrial production and more and more screw air compressors will be used in the future. Although many scholars had studied on the screw air compressor from different angles, such as structure, theoretical operating process and so on, they haven't done depth study on operation

control of a screw air compressor under the load/unload conditions. And the authors believe poor performance of the control method of the screw air compressor will lead to high energy consumption and low resource utilization problems under the load/unload conditions.

Under the load/unload conditions, the authors analyze factors affecting the energy consumption of screw air compressor and then how to set the offline pressure and online offline pressure is proposed to reduce air compressor's operating energy and improve screw air compressor's operating efficiency. With actual operating conditions of screw air compressor, the optimal control method is given to control operation of screw air compressor. By doing this, energy-saving operation will be achieved.

MODELING COMPRESSION POWER OF SCREW AIR COMPRESSOR

Theoretical compression power:

$$P_T = W \cdot Q_s = \sqrt{3}UI \cos \theta = P_s / \eta_m \quad (1)$$

where,

- P_T = Power at fully loaded operation (kW)
- W = The specific power consumption (kW/ (m³/min))
- Q_s = The rated capacity (m³/min)
- I = The current (A)
- U = The voltage (kV)
- $\cos \theta$ = The power factor
- P_s = The shaft power (kW)
- η_m = The motor efficiency

$$P_s = P_g + P_m \quad (2)$$

where,

- P_g = The isentropic compression power (kW)
- P_m = The power loss (kW), caused by bearing friction and air vortex and so on

Compression power of the screw air compressor (P_g) consists of two parts: The power consumption of adiabatically compressing air from inlet atmosphere to terminal pressure (P_i) of compression; the discharge power consumption in state of isopiestic pressure. It can be expressed as:

$$P_g = \frac{n}{n-1} \cdot \frac{P_s q_v}{0.06} \left[\left(\frac{P_d}{P_s} \right)^{\frac{n-1}{n}} - 1 \right] \quad (3)$$

where,

- p_s = The atmosphere absolute pressure at a compressor suction inlet (MPa), $p_s = 0.1$ MPa
- n = The isentropic exponent, $n = 1.35$
- q_v = The capacity of a screw air compressor (m³/min)

Discharge pressure effect on volumetric efficiency:
In the actual operation of a screw air compressor,

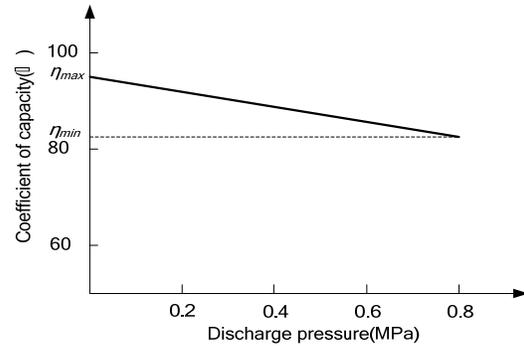


Fig. 2: Typical coefficient of capacity curve of the low-speed screw air compressor

compressed air between the lobes on each rotor will leak through the gap. And leakage will reduce the volumetric efficiency and efficiency of a screw air compressor. This study focuses on the low-speed screw air compressor and leakage is the main factor, which affects the volumetric efficiency of a screw air compressor.

The actual air production of a screw air compressor is the discharge flow converted from the atmosphere at the air inlet suction. Considering the coefficient of capacity η_v , the actual air production q_v can be calculated as:

$$q_v = \eta_v q_{vt} = \eta_v C_\phi C_{nl} n \lambda D_l^3 \quad (4)$$

where,

- q_{vt} = Theoretical capacity
- C_ϕ = The torsion angle coefficient
- C_{nl} = The utilization coefficient of the area
- n = The rotational speed of male screw rotor
- λ = The ratio of length to diameter of the screw rotor
- D_l = The diameter of male screw rotor

The difference between q_{vt} and q_v is mainly caused by the compressed-air leakage for the low-speed screw air compressor and the coefficient of capacity of a screw air compressor η_v is affected by the screw rotor shape, speed of driver, discharge pressure and so on. Because the factors of the screw rotor shape, speed of driver are determined by the design of screw air compressor, so η_v is calculated by mathematical simulation method in the actual operation. In order to facilitate the analysis and calculation, the authors take a smooth curve to replace actual coefficient curve of capacity in the study. A typical coefficient of capacity curve of the low-pressure and low-speed screw air compressor is given as shown in Fig. 2. η_v is only affected by the discharge pressure in the actual operation and the overall pressure ratio is 7.5; the rated discharge pressure is 0.8 MPa. η_{max} is the maximum coefficient of capacity and η_{min} is the minimum.

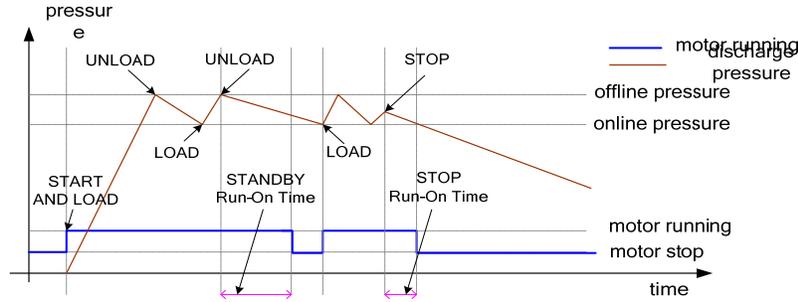


Fig. 3: Screw air compressor under the load/unload conditions

It can be seen from the Fig. 2 that actual coefficient of capacity is inversely proportional to discharge pressure with different discharge pressures, that is, the higher the discharge pressure is, the worse the actual air production will be. Therefore, the coefficient of capacity can be approximately obtained as Eq. (5):

$$\eta_v = \frac{(\eta_{\max} - \eta_{\min})(p_i - p_d)}{p_i} + \eta_{\min} \quad (5)$$

From Eq. (4) and (5), actual air consumption of a screw air compressor can be obtained as Eq. (6):

$$q_v = \eta_v q_{vt} = \left[\frac{(\eta_{\max} - \eta_{\min})(p_i - p_d)}{p_i} + \eta_{\min} \right] q_{vt} \quad (6)$$

Substituting Eq. (4) and (5) into Eq. (3), power consumption of a screw air compressor can be expressed as:

$$P_g = \frac{n}{n-1} \cdot \frac{p_s}{0.06} \left[\left(\frac{p_d}{p_s} \right)^{\frac{n-1}{n}} - 1 \right] \left[\frac{(\eta_{\max} - \eta_{\min})(p_i - p_d)}{p_i} + \eta_{\min} \right] q_{vt} \quad (7)$$

SIMULATION OF POWER CONSUMPTION OF SCREW AIR COMPRESSOR

Screw air compressor under load/unload conditions: In a load/unload control scheme, with the fluctuations of air consumption, the basic adjusting method is to close the inlet valve and unload the compressor, when its discharge pressure reaches a certain pressure point (offline pressure). Then, re-opening the inlet valve and load the compressor, when its discharge pressure reduced to another certain pressure point (online pressure). This reduces the number of start/stop cycles for electric motors over a start/stop control scheme and improves equipment service life with a minimal change in operating cost. This scheme is utilized by nearly all industrial air compressor manufacturers. When a load/unload control scheme is combined with a timer to stop the compressor after a predetermined period of continuously unloaded operation, it is known as load/unload mode. The load/unload mode is shown in Fig. 3. This adjusting method ensures that the discharge pressure of the screw air compressor fluctuate in a

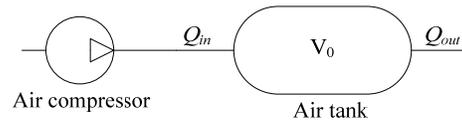


Fig. 4: Compressed-air system model

certain range, which makes it to be not too high (high energy consumption) and not too low (meeting the pressure demand of pneumatic devices).

Currently, the online pressure is fixed, a little higher than the minimum pressure demand of pneumatic devices. The offline pressure is set by operators before operation, which is high enough to ensure that frequency of load/unload is not too high in the case of fluctuations of air consumption. And the set offline pressure isn't changed during operation. According to statistics, each additional 0.1 MPa of the discharge pressure will increase at least 5.8% energy consumption of screw air compressor. That is, the energy consumption will increase with the rising of discharge pressure. Will the offline pressure be better when lower? With the above-mentioned energy consumption model of screw air compressor, this study will simulate the process of screw air consumption to find the advantage of the offline pressure in the following.

Establishment of a compressed-air system model: A typical compressed-air system works as follows: Firstly, the air separation tank is filled with compressed air produced by the screw air compressor host; Secondly, when air is compressed to the required pressure value, the minimum pressure valve will open and exhaust air to the dryer to cool down and to the filter to purify. Finally, the clean compressed air will be transported to pneumatic devices utilization. This study focuses on the screw air compressor's energy consumption in its operation; therefore, the simplified compressed-air system model will be established as shown in Fig. 4. Regardless of dryer and pipe pressure losses, assume that the compressed air generated by the screw air compressor is directly stored in the air tank and air flow out of the air tank will be the real-time air consumption of pneumatic devices.

The compressed-air system model can be equivalent to the process of charge-discharge of the air tank, which

is ideally considered to be an isothermal process. The state of compressed air in the air tank can be described as:

$$pV = mR\theta \quad (8)$$

Because of the isothermal process, Eq. (8) can be differential as:

$$\frac{dp}{dt} = \frac{1}{V_0} \frac{dm}{dt} R\theta_a = \frac{1}{V_0} \rho_a Q R\theta_a = \frac{\rho_a R\theta_a}{V_0} (Q_{int} - Q_{out}) \quad (9)$$

In the actual operation, the screw air compressor should firstly increase the internal pressure when it comes to produce compressed air from the status of stop or unload. To simplify the tow processes, this study takes t_{unl} as the delay times from the status of unload to exhaust compressed air to the air tank and t_{sto} as the delay times from the status of stop to exhaust compressed air to the air tank. In the both processes, energy consumption of the screw air compressor increases linearly with the internal pressure rising.

By Eq. (4), the actual air production of the screw air compressor can be expressed as:

$$Q = \begin{cases} 0 & t < t_{unl} \\ \left[\frac{(\eta_{max} - \eta_{min})(P_i - P_d)}{P_i} + \eta_{min} \right] \times Q_0 & t \geq t_{unl} \\ 0 & t < t_{sto} \\ \left[\frac{(\eta_{max} - \eta_{min})(P_i - P_d)}{P_i} + \eta_{min} \right] \times Q_0 & t \geq t_{sto} \\ 0 & \text{unload/stop} \end{cases} \quad (10)$$

where,

Q = The actual air production (m^3/s)

Q_0 = The rated capacity at full load operating (m^3/s)

The actual shaft power of the screw air compressor can be calculated as:

$$P = \begin{cases} 50\%P_0 & \text{unload} \\ \frac{n}{n-1} \times \frac{P_s}{0.06} \times \left[\left(\frac{P_d}{P_s} \right)^{\frac{n-1}{n}} - 1 \right] \times Q + 30\%P_0 & \text{load} \\ 0 & \text{stop} \end{cases} \quad (11)$$

where,

P = The actual shaft power (kW)

P_0 = The rated shaft power (kW)

Under the load/unload conditions, this study simulated the operation of the screw air compressor in Simulink which is one tool of MATLAB. The screw air compressor GA250-8.5 produced by the Atlas Copco

Group is selected to simulate power consumption, whose market share is the largest. Its performance parameters are as follows:

Rated power (shaft power) $P_0 = 250$ kW

Rated capacity $Q_0 = 0.72$ m^3/s

$\eta_{max} = 0.95$, $\eta_{min} = 0.85$

The power of unload = 125 kW, which is 50% of rated power.

Generally, adiabatic efficiency of the screw air compressor is 0.65~0.85, in this study, it is taken as 0.7. And the power loss during compression process is 30% of P_0 , that is, 75 kW.

The offline pressure was set at 0.58 MPa and the initial pressure of the air tank was set at 0.55 MPa. The initial status of the screw air compressor was stop; air consumption of pneumatic devices was 0.1 m^3/sec with 17% increase for each additional pressure of 0.1 MPa. Simulation time was set at 100 sec and $t_{unl} = 4$ sec and $t_{sto} = 6$ sec.

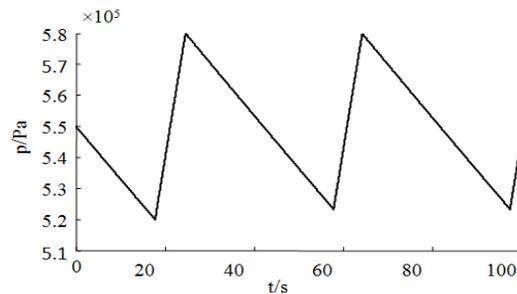


Fig. 5: Pressure curve of the air tank

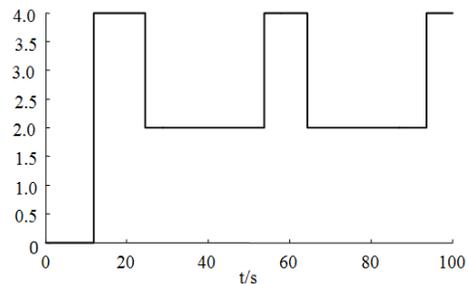


Fig. 6: Status curve of the compressor
0: Stop; 2: Unload; 4: Load

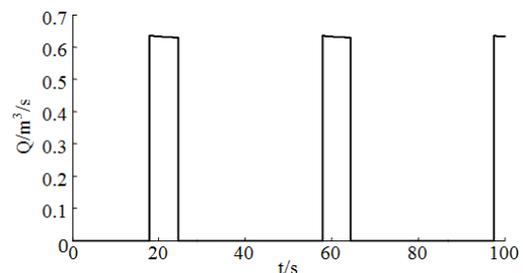


Fig. 7: Actual air production of the compressor

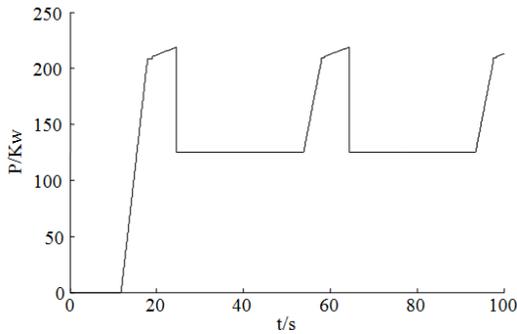


Fig. 8: Power consumption curve of the air compressor

The simulation results obtained are obtained in Fig. 5 to 8. It can be learned from the Fig. 5 to 8, during operation of the screw air compressor, with the pressure rising in the air tank, actual air production of the air compressor is declining, while power consumption is on the rise.

Optimal offline pressure: In order to analyze the power consumption of the screw air compressor under various discharge pressures, the offline pressure was changed in the simulation, elevated by a small pressure-step with 0.01 MPa from the initial offline pressure 0.54 MPa. At the same time, the online pressure was fixed at 0.53 MPa. Air consumption was set at 0.1 m³/sec. With simulation, the average power consumed in 4000 sec by air compressor at the different offline pressures is calculated at the different offline pressures. The result is shown as Fig. 9.

It can be seen from Fig. 9 that the power consumption curve of the screw air compressor is U-curve under different offline pressures and a least value of power consumption exists. When offline pressure was set at 0.55 and 0.66 MPa, respectively, the following part shows the curve of pressure in the air tank and the screw air compressor power consumption in details:

- Offline pressure is set at 0.55 MPa
- Offline pressure is set at 0.66 MPa

It can be seen from Fig. 10 to 12 that frequencies of load/unload are different under different offline pressures. When the power consumption is lower, the frequency of load/unload is higher. Thus the optimal offline pressure value must live up to two requirements, which is used to control the operation of screw air compressor:

- Frequency of load/unload should be higher than an appropriate value. The low frequency will increase the jump current to the power supply grid when the screw air compressor changes status from unload to load and also increase the mechanical shock shorting life of the air compressor.

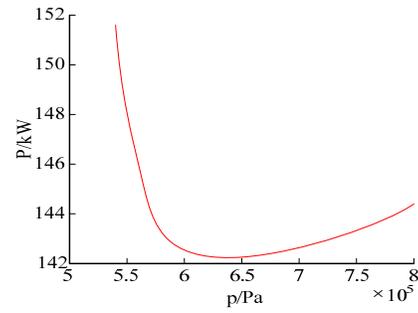


Fig. 9: Power consumption curve at different offline pressures

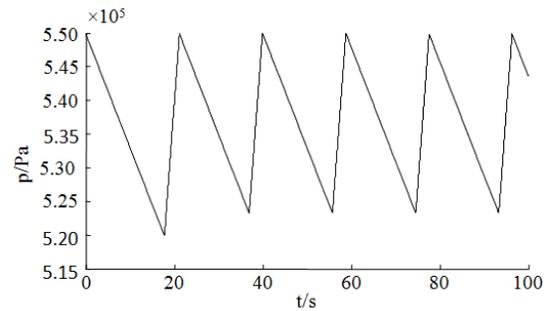


Fig. 10: Pressure curve of the air tank

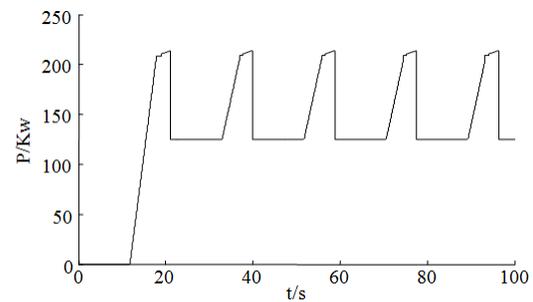


Fig. 11: Power consumption curve of the air compressor

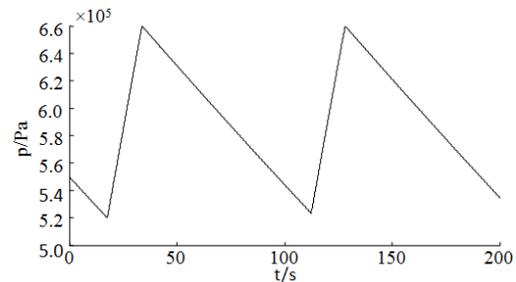


Fig. 12: Pressure curve of the air tank

- The screw air compressor power consumption should be as low as possible.

As a result, as illustrated above, 0.65 MPa is the best of the offline pressure in the load/unload control

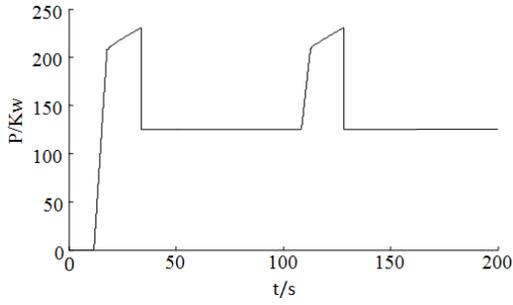


Fig. 13: Power consumption curve of the air compressor

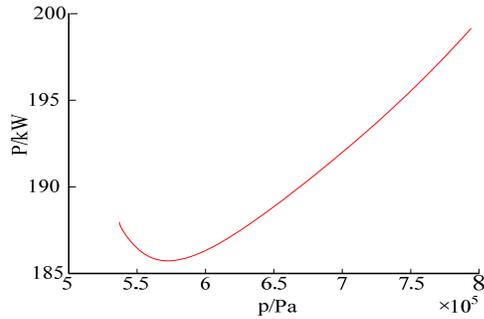


Fig. 14: Power consumption curve at different discharge pressures

scheme. In other words, a lower offline pressure may not always be a better choice.

Another curve shown as follows for screw compressor's average power consumption will be formed if the air consumption is adjusted to 0.4 m³/sec.

The comparison between Fig. 9 to 14 reveals that different air consumption requires different optimal offline pressure of the screw air compressor under the load/unload conditions.

OPTIONAL CONTROL OF SCREW AIR COMPRESSOR

Under the load/unload conditions, the optimal offline pressure of the screw air compressor at given air consumption is proved above. And using the optimal offline pressure can reduce energy consumption. Based on this rule, with the compressed air fluctuations resulting from air consumption in the compressed-air system, the authors propose an algorithm to optimally control the screw air compressor.

Calculation of air consumption: When the optimal offline pressure is used to adjust the air screw compressor's flow rate in accordance with the fluctuation of air consumption, the different air consumption corresponds to the different optimal offline pressures at given performance parameters of the screw compressor. This means the air consumption firstly needs to be known. In this section, based on dynamic mechanical analysis for fluid motion in the pipe,

considering that there is a causal relationship between pressure variation and gas flow variation, the authors propose a method for measuring flow rate of one dimensional unsteady flow dynamically based on theory of linear approximation. The measurement results are compared with that of the traditional method using pressure loss in the pipe and its dynamic error is less. The new method doesn't damage mechanical structure of the pipe, which is its greatest advantage, especially when air flow meter cannot be installed in the pipe and it is also very convenient to use.

The conditions for assumption of linear approximation: Pipe's cross-sectional area is known and remains constant; the convection item is neglected. The parameters of air flow inside the pipe are composed of average parameters and pulse parameters, namely:

$$\begin{cases} p = p_0 + \Delta p \\ \rho = \rho_0 + \Delta \rho \\ u = u_0 + \Delta u \\ T = T_0 + \Delta T \end{cases} \quad (12)$$

Combining with $G = \rho u A$ yields:

$$u_0 = G_0 / \rho_0 A \quad (13)$$

$$\Delta u = \Delta G / \rho_0 A \quad (14)$$

Because the pressure loss, as well as the rate of change of flow velocity along the pipe, is small, the equation $\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = -\frac{1}{\rho} \frac{\partial p}{\partial x} - \frac{\lambda}{2D} u^2$ can be simplified as Eq. (15) by neglecting the convection item:

$$\rho_0 \frac{\partial u}{\partial t} + \frac{\partial p}{\partial x} + \frac{\lambda}{2D} \rho_0 u^2 = 0 \quad (15)$$

Substituting Eq. (12) into (15) yields the following equations:

$$(\rho_0 + \Delta \rho) \frac{\partial}{\partial t} (u_0 + \Delta u) + \frac{\partial}{\partial x} (p_0 + \Delta p) + \frac{\lambda}{2D} (\rho_0 + \Delta \rho) (u_0 + \Delta u)^2 = 0 \quad (16)$$

Neglecting terms that are quadratic small, the above equation is:

$$\rho_0 \frac{\partial u_0}{\partial t} + \Delta \rho \frac{\partial u_0}{\partial t} + \rho_0 \frac{\partial \Delta u}{\partial t} + \frac{\partial p_0}{\partial x} + \frac{\partial \Delta p}{\partial x} + \frac{\lambda}{2D} (\rho_0 u_0^2 + 2\rho_0 u_0 \Delta u + \Delta \rho u_0^2) = 0 \quad (17)$$

Substituting $\rho_0 \frac{\partial u_0}{\partial t} + u_0 \frac{\partial p_0}{\partial x} + \frac{\lambda}{2D} \rho_0 u_0^2 = 0$ and $\Delta \rho \frac{\partial u_0}{\partial t} = 0$ into Eq. (17) yields:

$$\rho_0 \frac{\partial \Delta u}{\partial t} + \frac{\partial \Delta p}{\partial x} + \frac{\lambda}{2D} \rho_0 u_0 \Delta u + \frac{\lambda}{2D} \Delta \rho u_0^2 = 0 \quad (18)$$

Substituting $\Delta u = \Delta G/\rho_0$ into Eq. (18), ignoring $\frac{\lambda}{2D} \Delta \rho u_0^2$ yields:

$$\frac{\partial \Delta G}{\partial t} + A \frac{\partial \Delta p}{\partial x} + \frac{\lambda}{D} u_0 \Delta G = 0 \quad (19)$$

The above equation can be spread out as:

$$\frac{\partial \Delta G}{\partial t} + A \frac{\partial \Delta p}{\partial t} \frac{\partial t}{\partial x} + \frac{\lambda}{D} u_0 \Delta G = 0 \quad (20)$$

Set time step $\Delta t = t_0$, space step $\Delta x = h$ in the simulation, then $\frac{\partial t}{\partial x} = \Delta t / \Delta x = t/h$, the Eq. (20) can be transformed into:

$$\frac{\partial \Delta G}{\partial t} + \frac{\lambda}{D} u_0 \Delta G + A \frac{t_0}{h} \frac{\partial \Delta p}{\partial t} = 0 \quad (21)$$

Solving the first-order linear differential Eq. (21) with condition $\Delta G(t)|_{t=0} = 0$ yields:

$$\Delta G(t) = \frac{AD}{\lambda u_0 h} \cdot \left(\frac{\partial \Delta p}{\partial t} \right) \left(e^{-\frac{\lambda u_0 t}{D}} - 1 \right) \quad (22)$$

From the above Eq. (22), it can be seen that the mass flow rate $G(t)$ as well as $Q(t)$ at time t can be computed through integration if Δp and $G(0)$ are known.

Prediction of drop in pressure: Currently, the online pressure is fixed, which is a little higher than the minimum pressure demand of pneumatic devices. In the operation of screw air compressor, when its discharge pressure drops to offline pressure point, controller of screw air compressor generates the output signal to reopen the inlet valve and load the compressor. Because there is a delay times t_{unl} from unload to exhaust compressed air to the air tank, discharge pressure will drop to another pressure point below the set online pressure. The principle of current operating control of air compressor is as shown in Fig. 15.

Usually, with sufficient margin for the minimum pressure demand of pneumatic devices, the online pressure is set highly. In order to lower the online pressure and reduce the energy consumption of air compressor further, the authors propose a method to calculate the rate of pressure drop and predict times for the discharge pressure dropping to the online pressure. And compressor is loaded in advance to prevent the discharge pressure drop before it drops to the online pressure.

The principle of pre-starting air compressor to prevent pressure drop is as shown in Fig. 16. For a

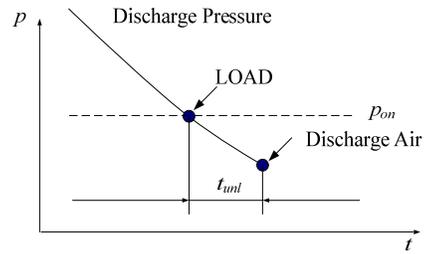


Fig. 15: The principle of current operating control of air compressor

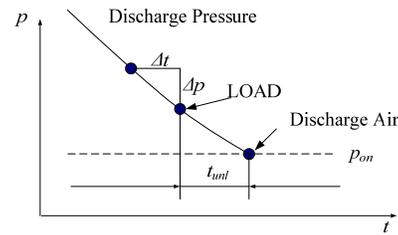


Fig. 16: The principle of pre-starting air compressor

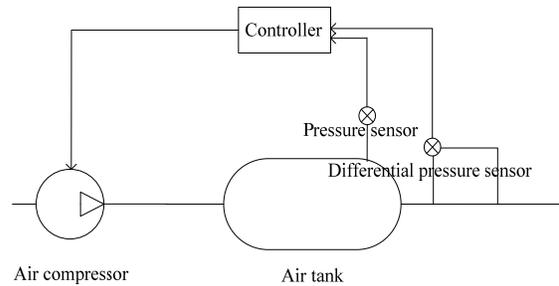


Fig. 17: The control program of air compressor under the load/unload conditions

specific screw air compressor, t_{unl} is a fixed value and assume that the current discharge pressure is p_t . online pressure is set at p_{on} . The time for discharge pressure dropping to p_{on} is calculated by Eq. (23). When the T_{al} is near to t_{unl} , the screw air compressor should be loaded:

$$T_{al} = (p_t - p_{on}) \Delta t / \Delta p \quad (23)$$

Optimal control process: Under the load/unload conditions, the authors build a control system to control the screw air compressor in the optimal offline pressure mode as shown in Fig. 17. The controller real-time collects signals of the pressure in the air tank by pressure sensor and differential pressure in the pipe by differential pressure sensor.

To precisely achieve optimal control of air compressor under the load/unload conditions; the following main steps shown in Fig. 18 must be proceeded. What follows is the detailed explanation of

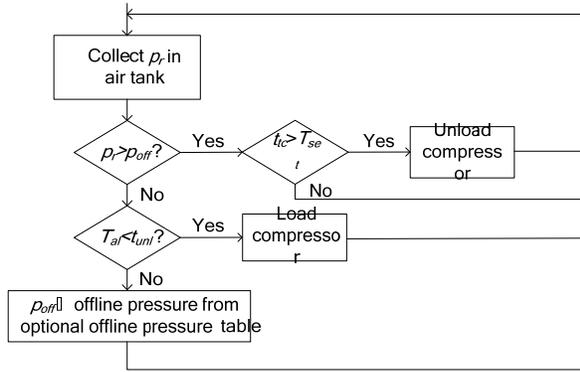


Fig. 18: The process of control algorithm based on the optimal offline pressure

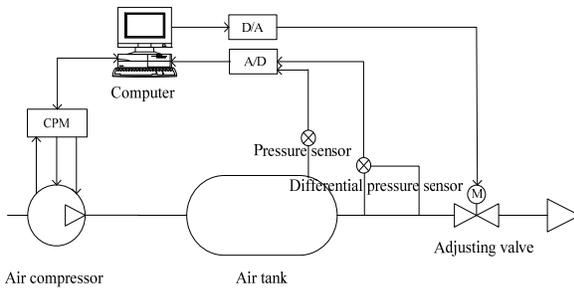


Fig. 19: Measurement and control program

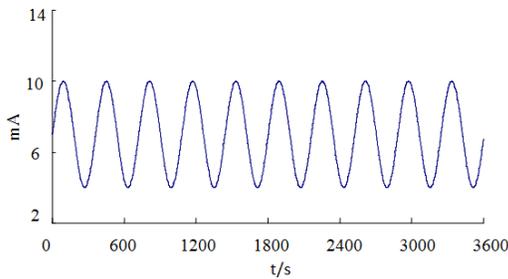


Fig. 20: Control signal of the adjusting valve



Fig. 21: Picture of compressor energy consumption measurement

steps for optimal control of a screw air compressor based on the optimal offline pressure and prediction of drop in pressure.

Table 1: Contrast of experimental value

Offline pressure (MPa)	0.68	0.72	Optimal control
Online pressure (MPa)	0.60	0.60	0.59
Energy consumption (kW)	20.50	21.30	19.70

Step 1: Real-time collect pressure (p_r) in the air tank. If p_r is higher than pre-setting value of the offline pressure (p_{off}) and the operating time t_{ic} (from the last continuously unloaded operation to load) is over the set cycle time (T_{set}) of load/unload, then unload the compressor.

Step 2: If p_r is less than the set offline pressure (p_{off}) and $t_{ic} < T_{set}$, go to step1.

Step 3: If $T_{al} < t_{unl}$, load the screw air compressor.

Step 4: Calculate the current air consumption of the compressed-air system. The process of calculation is mentioned in the above section.

According to air consumption calculated at t time, predict the air consumption at $t+1$ time by change of pressure in the air tank, then locate the offline pressure from the optimal pressure table corresponding to the air consumption, then the optimal offline pressure located is assigned to p_{off} , go to step1.

EXPERIMENTAL RESULTS AND ANALYSIS

In this section, energy consumption of the screw air compressor based on optimal offline pressure is discussed to demonstrate the effectiveness of the proposed optimal control algorithm. The proposed optimal control algorithm is contrasted with current control algorithm using the fixed offline pressure. Measurement and control program is shown in Fig. 18.

Firstly, Using the CPM-50 (Multifunction Power Meter) to meter energy consumption of the compressor (KOBELCO AG390A), this provides high accuracy measurement. The CT ratio of the current is 100/5.

Secondly, using electric adjusting valve to change the air consumption, whose performance parameters are as follow: nominal diameter is 15 mm; an electrical control signal is 4~20 mA. System of air consumption is shown in Fig. 19.

Thirdly, the DI of the data acquisition card (ADVANTECH USB-4711A) can be used to collect operating status signals of the compressor (Stop, Unload, Load) and the DO can be used to control the operation of the compressor (start, stop, unload, load a compressor). Differential pressure signal is collected by the AI, which is used to calculate flow rate. And the AO is used to electric adjusting valve to change the air consumption.

The set of energy consumption test of the compressor as follows:

Energy consumption of the air screw compressor is tested three times in the experiment. Offline pressure is set at 0.68 MPa invariably in the first test; offline pressure is set at 0.72 MPa invariably in the second test;

the optimal offline pressure is used in the third test. In each test, time for testing is 3600 sec (1 h) and control signals of the adjusting valve are the same as shown in Fig. 20, which is a sinusoidal signal. Maximum value of control signals is 10 mA and minimum value is 4 mA. Experimental results are shown in Table 1.

As can be seen from Table 1, energy consumption of the screw air compressor of using optimal control algorithm is less than using the fixed offline pressure, in other words, tests show that this control method of adopting optimal offline pressure is reasonable and feasible. Figure 21 shows the picture of compressor energy consumption measurement.

CONCLUSION

In order to improve the operating efficiency of the air screw compressor, the authors explore corresponding energy-saving theory, technology and algorithm of the air screw compressor' operation and carries out some experiments. The results of the experiments show that the algorithm can improve the operating efficiency and reduce energy consumption of the screw compressor. The main conclusions are as follows:

- Under the load/unload conditions, the optimal offline pressure at given air consumption exists. Using the optimal offline pressure can help to reduce energy consumption of air compressor.
- In the process of controlling the air screw compressors, the influence of the load/unload frequency on the reliability of operation should be considered.
- A method for measuring flow rate of one dimensional unsteady flow dynamically based on theory of linear approximation is proposed.
- Combining the optimal offline pressure and the frequency of load/unload, the optimal control method of the screw air compressor is given, which reduces its energy consumption. Thus, the study

helps us to find out the direction of economic operation of the air screw compressor.

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