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Investigation on wind energy-compressed air power system*

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Abstract: Wind energy is a pollution free and renewable resource widely distributed over China. Aimed at protecting the environment and enlarging application of wind energy, a new approach to application of wind energy by using compressed air power to some extent instead of electricity put forward. This includes: explaining the working principles and characteristics of the wind energy-compressed air power system; discussing the compatibility of wind energy and compressor capacity; presenting the theoretical model and computational simulation of the system. The obtained compressor capacity vs wind power relationship in certain wind velocity range can be helpful in the designing of the wind power-compressed air system. Results of investigations on the application of high-pressure compressed air for pressure reduction led to conclusion that pressure reduction with expander is better than the throttle regulator in energy saving.

Key words: Wind energy, Compressed air power, Pressure reduction, Clean energy
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INTRODUCTION

Wind energy of about 2.53×10^{11} W available everywhere, especially in coastal regions, deserts, grasslands and countryside areas in China, is pollution free and renewable (Xue *et al*., 2001). Use of wind energy can improve the living and working conditions of people. The many electricity generators driven by wind power all over the world efficiently extract wind energy for conversion into electrical energy. Many regions, such as countryside and rural areas have high density of wind power, but the conditions are not good enough for establishing a high electric power grid from wind energy. Compressed air is often referred to as the fourth utility, along with electricity, oil or gas and water (Wagner, 1993), and is labor saving. Compressed air has some advantages over other power producers, once the application scopes of compressed air power are developed and enlarged. So a new approach is put forward to transform wind energy to the compressed air power to some extent instead of electricity, thus enlarging the range of wind energy utilization. In this paper, the efficiency and feasibility of the compressed air power system driven by wind energy are analyzed.

CONFIGURATION OF SYSTEM

The configuration and process of energy transmission of the wind energy-compressed air power system is shown in Fig.1. The wind energy received by the wind turbine is clean and renewable energy resource that can drive the compressor to generate high pressure compressed air stored in a receiving tank serving as power source of the air-powered

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engines and tools. The depressurized control unit is the key part of the system that controls the energy transmission and conversion under the expected conditions. The compressed air powered engines and tools run the machines that do work. The load includes all kinds of work needed to be done and resistance forces that must be overcome by the pneumatic actuators.

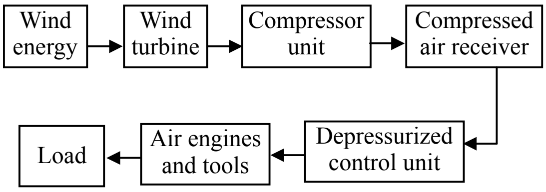

Fig.1 Wind energy-compressed air power system

MODEL OF WIND ENERGY

The energy content of wind is the kinetic energy of an air-stream. The kinetic energy of a unit volume of air depends upon its mass density and wind speed. The wind energy transferred to a unit area of crossing plane normal to the velocity vector is defined as the power density is denoted as (Daoo *et al.*, 1998; Habali *et al.*, 2001)

$$p_e = \frac{1}{2}\rho_w v_w^3 \tag{1}$$

where p_e is the power density (W/m^2); ρ_w is the mass density of the air-stream (kg/m^3); v_w is the wind speed (m/s).

Obviously, not all the kinetic energy of an air-stream can be extracted on a continuous basis, since completely stopping the moving air-stream implies an accumulation of air at that point. The maximum power that may be obtained from the wind using a wind machine is 16/27 of the kinetic energy. The power available in the wind is the flux of kinetic energy crossing the area swept by the rotor of the wind energy converter. Transforming efficiencies differ with different type of wind power turbines (Mitchell, 1983; Desire, 1982; Tchinda *et al.*, 2000). The wind energy that is extracted by the convertor can be estimated by

$$P = \frac{1}{2}K_w A \rho_w v_w^3 \tag{2}$$

where P is the power in watts W available in the wind; A is the crossing area swept by the rotor of the wind energy convertor (m^2); K_w is the extracted wind energy efficiency, K_w = 0.3 to 0.593 (Tchinda *et al.*, 2000).

The total energy obtained from the wind also depends on the local wind characteristics.

ENERGY MODEL OF COMPRESSING AIR

Understanding of compressor control and how to use them are important factors determining how well the air system functions and the amount of energy it consumes. Rotary screw compressors have become the predominant type in use in small to moderate sized compressed air systems. Multi-stage screw compressors are suitable for high pressure compressed air powered system (Van Ormer, 2001). Air can be compressed and stored at high pressure, and then used in the working process of a compressed air expander.

The air compressing processes mainly depend on the adiabatic, isothermal and polytropic process. Compressors include the single-stage unit and the multi-stage unit. A single-stage unit compresses air from inlet to discharge pressure in one stage. A multi-stage unit compresses air from inlet to discharge pressure in two or more stages, generally passing the air through an intercooler to remove some heat of compression between each stage which saves power and keeps the compressor's internal operating temperature lower.

The intercooler cools the high temperature air to lower temperature in order to increase the compressed air density. Then the air quantity of mass into the next stage is increased at the same volumetric flow rate, and the volumetric efficiency is enhanced. So the multi-stage with intercooler compressor is preferable selection in the compressed air generation (Rollins, 1973). Now, we will discuss the energy feature in the compressed process.

The power consumption per unit mass compressed air in single-stage compressing process is used as the reference value according to the energy theory (Brown, 1986). Considering the air compression as a polytropic process, the power consumption can be expressed as

$$w_s = \frac{k}{k-1} R T_1 \left(\left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}} - 1 \right) \tag{3}$$

where w_s is the power consumption per unit mass compressed air (J/kg); R is gas constant (J/kg/K); T_1 is air absolute temperature at inlet of compressor (K); p_1 and p_2 are the air pressure at the inlet and the outlet of the compressor, respectively (MPa); k is the polytropic exponent.

In multi-stage compressor, stage number n, the highest efficiency is at the point of the same compression ratio in every stage, i.e.

$$\frac{p_2}{p_1} = \frac{p_3}{p_2} = \cdots = \frac{p_{n+1}}{p_n} = \left(\frac{p_o}{p_i} \right)^{\frac{1}{n}} = \gamma \tag{4}$$

where p_i and p_o are the input and output air pressure of the multi-stage compressor, respectively (MPa); γ is the compression ratio.

Temperature rise and power consumption value in each stage is the same for the same compression ratio. So the total power consumption is equal to the power consumption of a single-stage multiplied by the stage number n:

$$w_m = \frac{k}{k-1} n R T_1 \left(\left(\frac{p_o}{p_i} \right)^{\frac{k-1}{nk}} - 1 \right) \tag{5}$$

where w_m is the total power consumption of the multi-stage compressor (J/kg).

It is known that the multi-stage compressor can save more energy for generating the high-pressure compressed air than the single stage compressor; but it is not always suitable to increase the stage number for compressed air unlimitedly.

Under conditions: p_i=0.1 MPa; T_1=293 K; R=287 J/kg/K; k=1.3; Fig.2 shows the power consumption of the compressor with different p_o and n. The energy saving ratio of the power consumption is decreased with increased n. Although more stages can save energy, the complicacy of the compressor is increased, while the initial cost and maintenance cost are increased more sharply. When the high-pressure required less than 5.0 MPa, the two-stage compressor can save energy by about 27 percent more than the single-stage compressor; the three-stage compressor by about 34 percent; but the cost increased by about 30 percent; the four-stage compressor by about 38 percent, while the cost increased about 50 percent. So the two-stage compressor is better than the others in the above discharge pressure range.

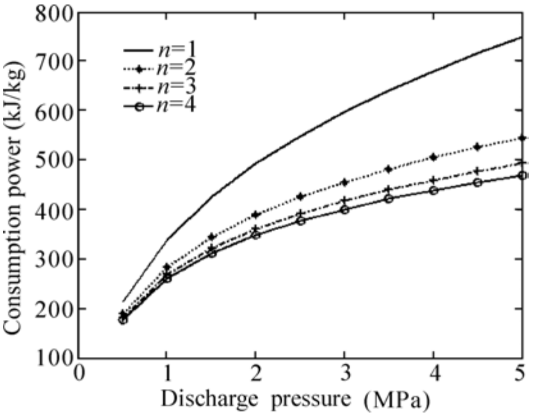

Fig.2 Consumption power of the compressed air at the changed discharge pressure and stage number

MODEL OF WIND POWER TO COMPRESSED AIR

If the compressor is directly driven by wind energy, the relation between the compressed air power and the wind power extracted can be expressed by

$$P = Q_m w_m / \eta_m \eta_w \tag{6}$$

where Q_m is the compressed air mass flow rate generated by the compressor (kg/s); η_m is the mechanical efficiency of the wind energy transforming machine and compressor; η_w is the transforming efficiency of the wind energy. They can be obtained by test.

The proper compressor capacity should be determined match with the local available wind energy. The compressor capacity can be calculated from the compressed air mass and the mass density of the local air as

$$Q_{\mathrm{v}} = Q_{\mathrm{m}} / \rho \tag{7}$$

where Q_{v} is the compressor capacity (m^3/s); ρ is the mass density of the local air ($\mathrm{kg/m}^3$);

Applying Eq.(2), Eqs.(5)−(7), yields the expression for volumetric flow rate Q_{v} in compressed air power system driven by wind energy as

$$Q_{\mathrm{v}} = 0.5K_{\mathrm{w}} A v_{\mathrm{w}}^3 \frac{\rho_{\mathrm{w}}}{\rho} \eta_{\mathrm{w}} \eta_{\mathrm{m}} \frac{1}{nRT_1} \frac{k-1}{k} \left(\left(\frac{p_{\mathrm{o}}}{p_{\mathrm{i}}} \right)^{\frac{k-1}{nk}} - 1 \right)^{-1} \tag{8}$$

Q_{v} will be a reference of the compressor capacity.

Fig.3 shows that the compressor capacity deceases with increase of discharge pressure and decrease of compressor stage number. Fig.4 shows that the compressor capacity increases with increase of wind speed and decrease of discharge pressure. Therefore, the energy extracted by the wind energy-compressed air power system used for generating the compressed air power follows the rule of generating high-pressure compressed air at higher wind speed and generating low pressure compressed air at lower speed will be regular way.

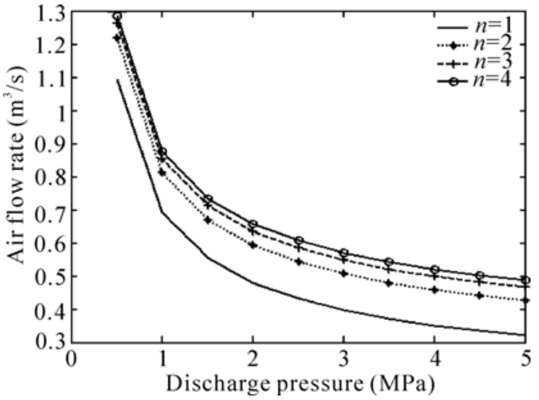

Fig.3 The compressor capacity fitting to the discharge pressure when stage number changed

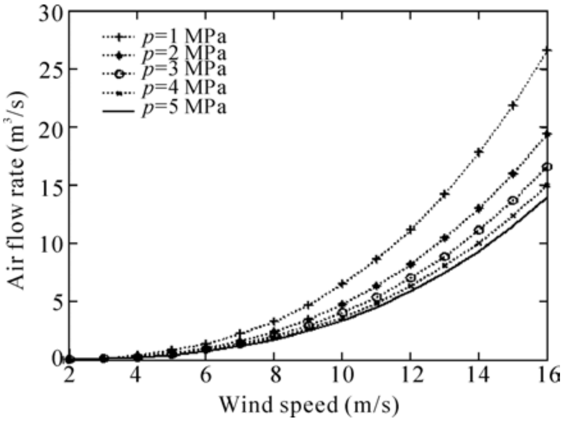

Fig. 4 Compressor capacity fitting to the wind speed under different compressed air discharge pressure

APPLICATION OF COMPRESSED AIR POWER

For preventing the ecological environment in which people live and work from being ruined by emission of vehicles that are mainly powered by petroleum, diesel oil and natural gas, some cleaner powered vehicles or cars are being developed. The compressed air powered vehicle~~s~~ (APV) is being investigated and developed (Chen *et al*., 2002). The nucleus of the APV is the compressed air engine and pressure reduction control system.

Although it is very common that compressed air is used for driving the actuators in pneumatic system, the engine driven by compressed air is very new. Therefore, the energy control system of the compressed air powered car should be analyzed and investigated. The aim is to construct a base for development of the compressed air powered car.

In order to obtain the benefits and advantages of compressed air, pressure control and regulation of the compressed air system are essential.

Standard air engines and air tools are available for operation at pressure of from 0.4 to 0.85 MPa. If the air supply receiver stored compressed air at high-pressure, reducing pressure is necessary to general application.

The depressurized unit is used to control the compressed air from air source at high-pressure level to air supply receiver at lower pressure level in order to energy saving in the air engine. Reducing the pressure of compressed air involves use of a volumetric expander and a throttle regulator.

Pressure reduction by throttle regulator

Depressurization by throttle regulator is a conventional method by which the compressed air at high pressure passes the throat with the friction between air particles and wall, and followed by energy loss. The throttle process is considered to be an adiabatic process, which is a typical irreversible process wherein power loss is inevitable.

The expression for the power loss Δe_1 in the adiabatic throttle process is:

$$\Delta e_1 = T_1 R \ \ln\frac{p_1}{p_2} \tag{9}$$

Pressure reduction by expander

Unlike a throttle regulator restricting flow to control pressure, an expander increases the volume from higher upstream pressure to the downstream control pressure. Because expanders are sized for the expanded flow at the predetermined operating pressure, they require very little supply energy to function properly. Expanders also are very precise control devices normally using a PLC platform-centered, PID control format; control and response sensitivity within thousandths of MPa can be obtained (Foss, 1999).

The free and adiabatic process of expander control of air pressure from original state to end state is also an irreversible process wherein power loss exists. The deducing process is explained as follow.

Enthalpy is a main energy criterion of compressed air in a stream system. The enthalpy exergy is defined as the maximum technical (available) work that can be acquired or converted when the air flows from state (T, p) to ambient state (T_0, p_0). The equations of specific enthalpy exergy at state 1 and state 2 are denoted by,

$$e_{h1} = (h_1 - h_0) - T_0(s_1 - s_0) \tag{10}$$

$$e_{h2} = (h_2 - h_0) - T_0(s_2 - s_0) \tag{11}$$

where e_h is the specific enthalpy exergy (J/kg); h is the specific enthalpy (J/kg); Δs is the specific entropy (J/kg/K); 0, 1 and 2 indicate the ambient environment state, start state and end state, respectively.

The power loss Δe due to the expander's pressure reduction of compressed air in the free and adiabatic process from state with volume V_1, pressure p_1 to state with volume V_2, pressure p_2 is described by

$$\Delta e = e_{h1} - e_{h2} = (h_1 - h_2) - T_0(s_1 - s_2) \tag{12}$$

$$\Delta e = -\Delta h + T_0 \Delta s \tag{13}$$

When air is ideal gas, then

$$\Delta h = c_p \Delta T = c_p (T_2 - T_1) \tag{14}$$

$$\Delta s = c_p \ln\frac{T_2}{T_1} - R \ \ln\frac{p_2}{p_1} \tag{15}$$

so

$$\Delta e = c_p T_1 (1 - \frac{T_2}{T_1}) + c_p T_0 \ln\frac{T_2}{T_1} - T_0 R \ \ln\frac{p_2}{p_1} \tag{16}$$

in the polytropic process

$$\frac{T_2}{T_1} = (\frac{p_2}{p_1})^{\frac{k-1}{k}} \tag{17}$$

Substituting Eq.(17) into Eq.(16) yields :

$$\Delta e = c_p T_1 (1 - (\frac{p_2}{p_1})^{\frac{k-1}{k}}) + c_p T_0 \frac{k-1}{k} \ln\frac{p_2}{p_1} - T_0 R \ln\frac{p_2}{p_1} \tag{18}$$

The power losses of unit mass air at different process of pressure reduction are respectively described by Eq.(9) and Eq.(18). The digital simulation results based on these equations are shown in Fig.5. The results show the energy saving in pressure reduction with expander is about 5%−20% more than with conventional throttle from high-pressure at 5 MPa to control pressures at 0.5−0.8 MPa.

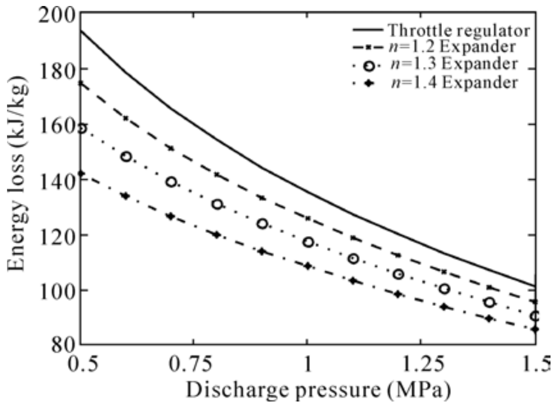

Fig.5 Energy loss of pressure reduction process by expander or regulator

CONCLUSION

Theoretical analysis to a new feasible approach wherein instead of using electricity, wind energy is directly used to generate compressed air power to meet the daily living and working requirements of local people, thus enlarging the utilization range of wind energy.

The potential wind energy and compressor capacity are very important in the wind energy-compressed air power system.

The depressurized application of high pressure compressed air by means of expander is better than throttle regulator in saving energy.

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