

Thermo-Dynamical Analysis on Electricity-Generation Subsystem of CAES Power Plant

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Abstract

Besides pumped hydropower, Compressed Air Energy Storage (CAES) is the other solution for large energy storage capacity. It can balance fluctuations in supply and demand of electricity. CAES is essential part of smart power grids. Linked with the flow structure and dynamic characteristic of electricity generation subsystem and its components, a simulation model is proposed. Thermo-dynamical performance on off-design conditions have been analyzed with constant air mass flux and constant gas combustion temperature. Some simulation diagrams of curve are plotted too. The contrast of varied operation mode thermal performance is made between CAES power plant and simple gas turbine power plant.

Keywords

Electricity Generation Sub-System; CAES Power Plant; Thermal Performance; Simulation Analysis; Off-Design Conditions

1. Introduction

With the development of renewable energy, the grid load regulation problem is becoming more and more serious. Its performance is dependent on energy storage system because of the load fluctuation. Some problems can be solved by electrical energy storage system, for example the peak & off-peak demand of power generation, the improvement of reliability and steadiness of power supply [1] [2].

In CAES technology, air is compressed with a motor/generator using low cost, off-peak electricity and stored underground in caverns or porous media. This is called energy storage subsystem. This pressurized air is released from the ground and then be mixed and burned with gas in a combustor. The hot expanding gases drive a turbo expander and run a motor/generator which, in turn, produces electricity during peak demand periods. This is the other subsystem, electricity generation subsystem. The electricity generation subsystem of CAES includes [3]: isobaric heating process in burner, adiabatic expanding process in turbo expander and isobaric heat release process. Main influence factors of practical thermo-dynamic processes including burning efficiency of burner η_b , expansion efficiency of turbo expander and some performance parameters of flowing loss processes. Combined

with the characteristics of this subsystem and its components, an off-design condition simulation model is proposed based on unit's modeling system. Equipments selection and their off-design condition characteristics are analyzed.

2. Simulation Modeling [4] [5]

Turbo expander is key equipment of electricity generation subsystem for CAES. For the sake of utilizing high pressure air released from air storage dome, the air expander can be added before gas expander. At the same time, the re-heater and recuperator can be used in this subsystem. **Figure 1** is the conceptual diagram of electricity generation subsystem. M/G is motor/generator, Air EXP is air expander, Gas EXP is gas expander, REC is recuperator and AS is air storage dome.

The electricity generation subsystem can be divided to some modeling parts, as **Figure 2**.

Model based on assumptions as follows: 1) air and gas is ideal air, 2) the specific heat of air is constant, 3) the flowing of air and heat transfer between air and wall is steady process, 4) η_b is constant.

The equations of these typical parts can be formulated. They include 6 differential equations. With consideration of practical conditions, the heat content of air and gas can be ignored, the compressibility of air and gas in recuperator can be ignored too.

The equation for metal heat storage is Equation (1):

$$\rho_w \cdot \delta \cdot c_p \frac{dT_m}{d\tau} = \alpha_g (\bar{T}_g - T_m) - \alpha_a (T_m - \bar{T}_a) \tag{1}$$

δ —the thickness of recuperator wall

α_g, α_a —hot end and cold end convection heat transfer coefficients

\bar{T}_a, \bar{T}_g —average temperature of air part and gas part

$\rho_w A_w$ —density of wall and heat transfer area

Based on $Q = KA\Delta t$, $\Delta t = 75 \text{ K}$ and $K_0 = 100 \text{ W}/(\text{m}^2 \cdot \text{K})$ on design condition.

The density of recuperator material is $7800 \text{ kg}/\text{m}^3$, specific heat $c_p = 460 \text{ J}/(\text{kg} \cdot \text{K})$, $\alpha_g = \alpha_a = \alpha$, so the time constant can be derived as Equation (2) on design condition:

$$\frac{\rho_w V_w}{\alpha A_w} c_p = \tau_c = 3588000 \delta / a \tag{2}$$

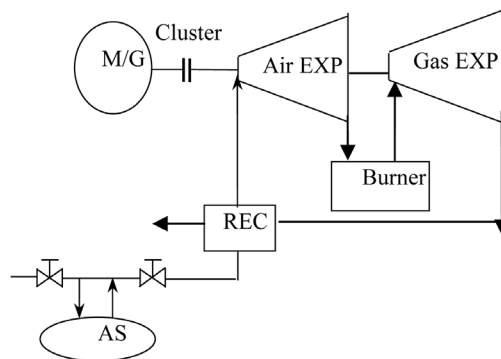


Figure 1. The conceptual diagram of electricity generation subsystem.

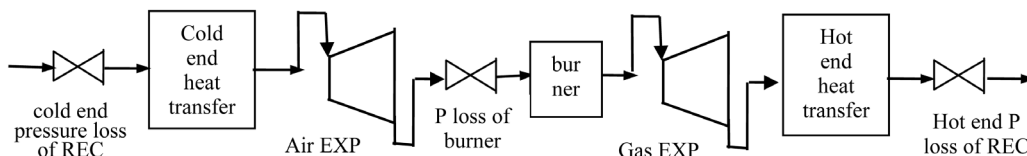


Figure 2. Typical modeling parts of electricity generation subsystem.

The burning efficiency of burner can be expressed as Equation (3).

$$\eta_b = f\left(\frac{P^{1.75} A_{\max} D_{\max} e^{T/300}}{G_a}\right) \quad (3)$$

P, T —inlet pressure and inlet temperature of burner

A_{\max}, D_{\max} —maximum cross-section area and its diameter

The off-design equations of recuperator is Equation (4)

$$\frac{\sigma}{\sigma_0} = 1 / [\sigma_0 + (1 - \sigma_0) \left(\frac{G_a}{G_{a0}}\right) \left(\frac{K_0}{K}\right)] \quad (4)$$

Heat transfer coefficient K is associated with recuperator type and air flux, so the off-design formula can be expressed as Equation (5)

$$\frac{K_0}{K} = \left(\frac{G_{a0}}{G_a}\right)^{0.8} \left(\frac{T_{a0}}{T_a}\right)^{0.06} \left(\frac{T_{g0}}{T_g}\right)^{0.16} \quad (5)$$

3. Off-Design Conditions Operation Simulation [4]

PG9171E (GE) can be taken as simulation object, main parameters as **Table 1**. Some values are as follows: 1) Relative internal efficiency of gas expander is 0.905 ($k = 1.33$) and air expander is 0.88. 2) The pressure losses in burner, cold end of recuperate and hot end of recuperator are 3%, 1% and 3% respectively. LHV of fuel is 41,960 kJ/kg, working consuming for compressing air $P_c = 617.65$ kJ/kg [4], outlet air pressure of air storage dome is 61bar, temperature is 30°C.

The additional formulations are as follows (6)-(9):

$$0 = c_{p1} \cdot G_a \cdot (t_1 - t_2) - c_{p1} \cdot G_a \cdot (t_1 + 273) \left(1 - \pi_1^{\frac{k_1-1}{k_1}}\right) \cdot \eta_a \quad (6)$$

$$0 = \eta_b \cdot LHV \cdot G_f - (G_a + G_f) \cdot c_{p2} \cdot t_3 + c_{p1} \cdot G_a \cdot t_2 \quad (7)$$

$$0 = c_{p2} \cdot (G_a + G_f) \cdot (t_3 - t_4) - c_{p2} \cdot (G_a + G_f) \cdot (t_3 + 273) \left(1 - \pi_2^{\frac{k_2-1}{k_2}}\right) \cdot \eta_t \quad (8)$$

$$0 = \frac{t_1 - 30}{t_4 - 30} - 0.85 \quad (9)$$

t_1, t_2 , —inlet T and outlet T of air expander.

0.85—the heat transfer efficiency of recuperator.

A) Simulation calculations on design air flux, additional equation are as follows (10)-(12) [6] [7]:

$$P_e = [c_{p2} \cdot (G_a + G_f) \cdot (t_3 - t_4) + c_{p1} \cdot G_a \cdot (t_1 - t_2)] \eta_m \cdot \eta_g \quad (10)$$

$$\frac{\eta_a}{\eta_{a0}} = \sqrt{\frac{h_{as0}}{h_{as}}} \left(2 - \sqrt{\frac{h_{as0}}{h_{as}}}\right) \quad (11)$$

$$\frac{\eta_t}{\eta_{t0}} = \sqrt{\frac{h_{ts0}}{h_{ts}}} \left(2 - \sqrt{\frac{h_{ts0}}{h_{ts}}}\right) \quad (12)$$

The calculation results are shown as **Figures 3-5**. Some conclusions can be drawn from figures. With the load lowered, the internal efficiency of air expander and gas expander is lowered obviously, heat rate of generating

Table 1. Main performance parameters of gas turbine.

Type	P_e (kW)	η_e (%)	Pressure ratio	G_a (kg/s)	Initial T/ t_3 (°C)	Leakage T/ t_4 (°C)	Leakage air flux G_4 (kg/s)
PG9171E	123400	33.8	12.3	403.7	1124	538	412.4

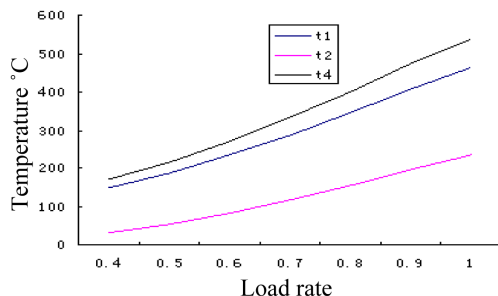


Figure 3. t_1, t_2, t_4 varying with load rate on design air flux.

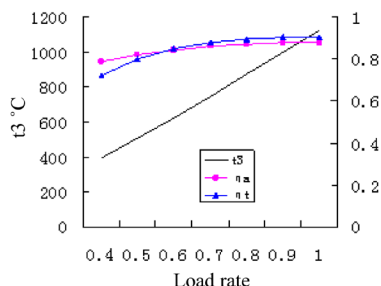


Figure 4. t_3, η_a, η_t varying with load rate on design air flux.

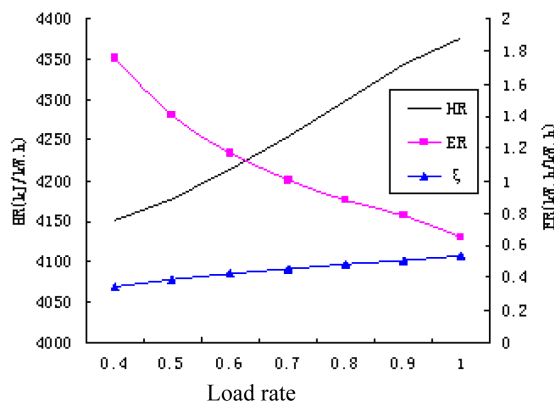


Figure 5. HR, ER, ζ varying with load rate on design air flux.

electricity is lowered, electricity rate of generating electricity is improved obviously, the energy transformation coefficient is lowered obviously too.

B) Simulation calculations on design inlet temperature of gas expander.

Some results are seen as **Figures 6-8**. Some conclusions are: with the load lowered, the internal efficiency of air expander and gas expander is constant approximately, heat rate and electricity rate of generating electricity are improved, the energy transformation coefficient is lowered a little.

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C) Contrast with off-design gas turbine performance.

On the basis of off-design performance of gas turbine, using former selected gas turbine, the performance contrast diagram of gas turbine and electricity generation subsystem is shown in **Figure 9** with the load scope 100% - 40%.

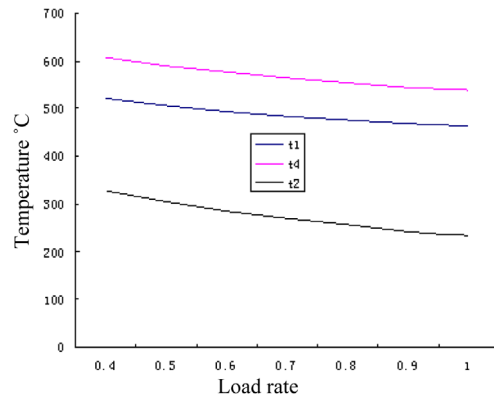


Figure 6. t_1, t_2, t_4 varying design inlet temperature.

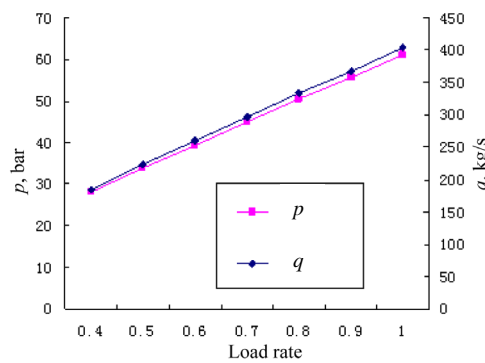


Figure 7. t_3, η_a, η_t varying with load rate on design inlet temperature.

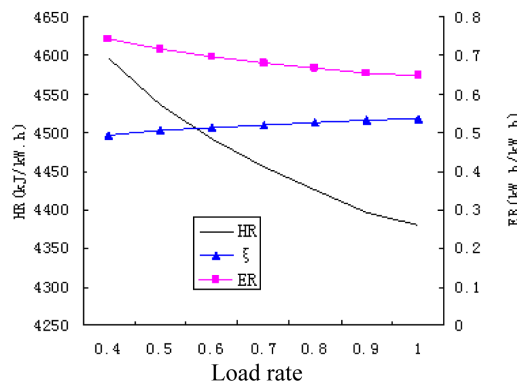


Figure 8. HR, ER, ζ varying with load rate on design inlet temperature.

It is obvious that thermal efficiency is varying from 33.8% to 0% of gas turbine power plant when load rate varying among 100% - 40%. But energy transform coefficient varies from 53.6% to 34.3% on design air flux, from 53.6% to 49.5% on design inlet temperature.

4. Conclusions

1) The electricity generation subsystem of CAES is divided into three processes, the difference between practical process and ideal process is described and analyzed in this paper.

2) Combined with the characteristic of electricity generation subsystem and its components, a subsystem simulation model is proposed based on unit's modeling system.

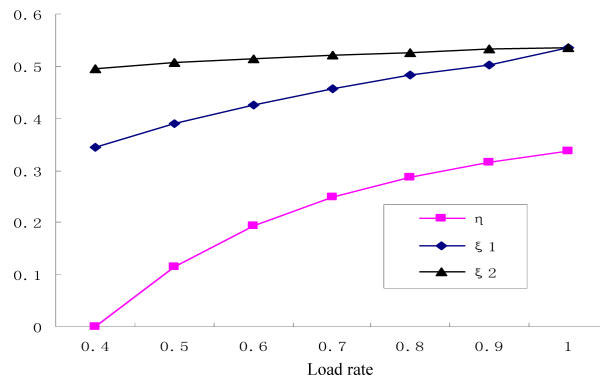


Figure 9. η , ξ_1 , ξ_2 varying with load rate. H —thermal efficiency of gas turbine; ξ_1 —energy transform coefficient on design air flux; ξ_2 —energy transform coefficient on design inlet temperature.

3) The simulation diagrams of off-design condition are plotted. The conclusion is that thermal efficiency is varying from 33.8% to 0% of gas turbine power plant when load rate varying among 100% - 40%. But energy transform coefficient varies from 53.6% to 34.3% on design air flux, from 53.6% to 49.5% on design inlet temperature.

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