

Thermodynamic Analyses of Compressed Air Energy Storage System with Partial Oxidation Gas Turbine Technology

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Abstract—This article presents thermodynamic calculations and initial optimization of the conceptual technological system, connecting an energy storage system in compressed air (CAES) with partial oxidation gas turbine (POGT). Concept of operation of such system and way of calculations is presented. The CAES with POGT system is analyzed with the help of an energy balance. Optimization based on maximization of energy efficiency was performed. The obtained results were compared with other cases.

Index Terms—CAES, POGT, energy storage.

I. INTRODUCTION

In conception of future sustainable energy systems demand the introduction of integrated with energy system, storage technologies. Looking for more and more efficient and flexible energy storage systems are currently in scope of many scientific studies as well as intensive R&D activities worldwide. Energy storage technologies are being developed due to the high demand for energy storage in power systems. For example emergency power supply or energy storage from renewable sources [1]. To accumulate large volume of energy, pumped-storage systems have the biggest share (99%) in installed power compared to other energy storage technologies used worldwide [2]. The advantages of this technology are the possibility of short start-up time, storage for any length of time, cheap and commonly available energy carrier, low cost of energy generation, maturity of technology and long lifetime. The most important disadvantages of this technology are: the dependability on hydro geological conditions, high investment expenditure and changes in the eco system [3]. An important alternative to pumped hydro storage plants are Compressed Air Energy Storage (CAES) systems [4]. The main advantage of this installation include use of a free energy carrier i.e. air. In a classical CAES installation electric energy available outside the peak is used for compressing air which is stored in an underground caverns or ground vessels. If there is a need to generate electricity, compressed air is mixed with natural gas, burnt and decompressed in expander, thus powering the generator. This

paper proposes the concept of incorporation of the partial oxidation gas turbine (POGT) technology into the CAES system to increase the efficiency of energy storage.

II. SYSTEM CONCEPTION

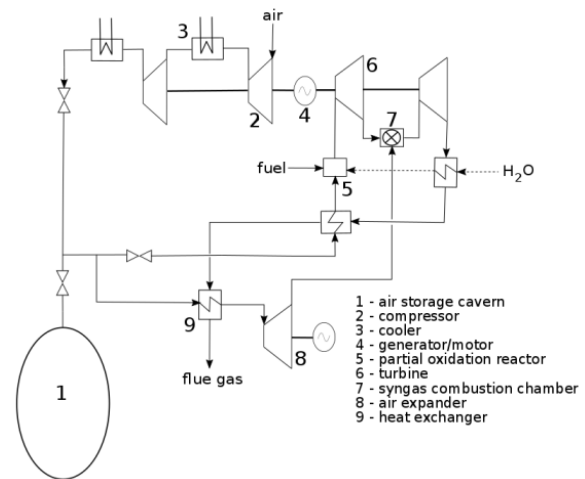


Fig. 1. Diagram of CAES system with POGT.

The conceptual layout includes the connection of the CAES system with the POGT installation. A partial oxidation gas turbine is characterized by the presence of a partial oxidation reactor at the location of the combustion chamber in gas turbine. Partial oxidation is a process where quantity of oxidizer is less than that stoichiometric air ratio requested for the complete combustion of a hydrocarbon fuel. As a result of chemical reactions occurring under substoichiometric conditions, a gas containing combustible parts such as CO or H₂. The resulting gas can be burned or used in other ways (e.g. for the production of hydrogen). The division of the oxidation process of fuel leads to a reduction of demand for the compressed air in the system and thus the driving energy for the compressors. What is more, POGT systems feature low NO_x emissions [5]. Comparing to standard GT system POGT system obtains higher, about 10 percentage points, efficiency of electricity generation [6]. The article presents the proposal of usage of the POGT system in the existing Huntorf CAES installation in Germany. In this installation compressed air is stored in two salt caverns with a capacity of approx. 300 000 m³ [7]. The designed power of the system is 290 MW, using a two-stage gas turbine and two combustion chambers. The total power of two stage compressors is about 60 MW. During compression process, intermediate coolers were also used [8]. Diagram of the conceptual layout of the installation

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is presented in Fig. 1. The figure shows the use of partial oxidation reactor with a water vapour injection technology [9]. Heating air system with recuperators is also applied. Additional element used in this system is expander of the air supplied to the low pressure syngas combustion chamber.

A. Assumptions

Calculations of the original design parameters of the system were preserved such as: the volume of air storage, work pressures of air, streams of compressed and expanded air. Other adopted assumptions are presented in Table I.

TABLE I: ASSUMPTIONS TO SIMULATION MODEL INPUT [7], [8], [10]

Operating condition	Value	Unit
Compressor total power	60	MW
Atmospheric air pressure	0,1013	MPa
Atmospheric air temperature	10	°C
Compressed air flow	108	kg/s
Cavern operating pressure	4,6-6,6	MPa
Compressor outlet temperature	50	°C
Discharge air consumption	417	kg/s
HP turbine inlet pressure	4.2	MPa
Air storage volume	2×150000	m ³
Caverns surface	50000	m ²
Fuel	methane	-
Convective heat transfer coefficient	8	W/m ² K

Other parameters of the system work have been optimized in the further part of this work

B. Calculation model

The calculation would be divided into two parts. In the first dynamic air compression system, modelled in Matlab® software and the other, power generation part, modeled in the EBSILON® Professional program.

The cavern charging is a dynamic process where ordinary differential equations were solved numerically. The Crank-Nicolson predictor-corrector method was used.

The compression cycle and air charging at CAES power plant was modelled using own calculation codes developed in the Matlab® software with CoolProp thermophysical property library [11]. The calculations were based on mass (1), and energy (2) balances of the air cavern:

$$\frac{d\rho}{dt} = \frac{\dot{m}_{in}}{V} \quad (1)$$

$$\frac{dU}{dt} = \dot{m}_{in} \cdot h_{in} - \dot{Q}_{am} \quad (2)$$

ρ : density

t : time

\dot{m}_{in} : input air mass flow

V : cavern volume

U : internal energy

h_{in} : input air specific enthalpy

\dot{Q}_{am} : ambient heat losses

The air volume was assumed to be humid gas treated as perfect mixture instead of real gasses including moisture. Heat flow phenomena in salt caverns has been simplified. It was assumed that the temperature of the cavern's wall is equal to the temperature of the salt massif, and the temperature

inside the cavern is homogeneous. Calculation of heat losses through tank walls has been approximated by the equation. (3).

$$\dot{Q}_{am} = \alpha \cdot A_c (T - T_{cw}) \quad (3)$$

α : heat transfer coefficient

A_c : caverns surface

T : air temperature in cavern

T_{cw} : cavern wall temperature

Calculations of the power generation system were made using the EBSILON® Professional software. Since the operating pressure range in the caverns is between 6,6 – 4,6 MPa, and the air supplied to the POR is throttled to the pressure of 4,2 MPa, it has been assumed that the expansion process can be simplified to a steady state model. An important task was to properly calculate the reactions in the POR, for this purpose the "Gibbs reactor" component model of the EBSILON® Professional was used. This component performs chemical equilibrium calculations through minimization of the Gibbs free enthalpy:

$$\sum_{i=1}^{i=nc} \sum_{j=1}^{j=np} n_{ji} [g_{ji}^0(T, p) + RT \ln(z_{ji})] \rightarrow \min \quad (4)$$

i : component index

j : phase index

nc : number of components

np : number of phases

$g_{ji}^0(T, p)$: specific Gibbs enthalpy of pure component i in phase j

p : pressure

R : universal gas constant (8,314 J/molK)

z_{ji} : molar fraction of component i in phase j

Specific Gibbs free enthalpy of component i is:

$$g_i^0(T, p) = h_i^0(T) - T s_i^0(T, p) \quad (5)$$

h_i^0 : specific enthalpy of pure component i

s_i^0 : specific entropy of pure component i

III. RESULTS

A. Results

The first stage of the calculations was to simulate the section of compression and accumulation of air. Dynamic calculations were made in the Matlab software, and the results are presented in Table II.

TABLE II: RESULTS OF CALCULATIONS

Data	Value	Unit
Input of electricity energy	3576,43	GJ
Charging time	16,833	h
Amount of stored air	6544800	kg

Obtained results, especially the electrical power consumption, were used in calculations and optimization of power generation section.

B. Optimization of Discharge System

Optimization of analysed system was focused on round trip efficiency increasing, defined by the formula (6)

$$\eta = \frac{E_{el.out}}{E_{el.in} + Q_f} \quad (6)$$

$E_{el.out}$: net output electrical energy

$E_{el.in}$: input electrical energy

Q_f : fuel energy input

An important issue is the possibility of solid carbon fraction (soot) occurrence in the partial oxidation plant. It is caused due to the substoichiometric conditions present in the POR. The formation of soot might have a detrimental effect to operation of the installation, causing contamination of equipment. In order to reduce the amount of solid carbon fraction, steam injection into the reactor is used. Injection of steam in this type of systems also serves to reduce the temperature in the reactor due to the limit values. The relationship between mass fraction of solid carbon in the syngas and temperature in partial oxidation reactor as a function of steam to fuel mass ratio for two excess air coefficient are shown in Fig. 2.

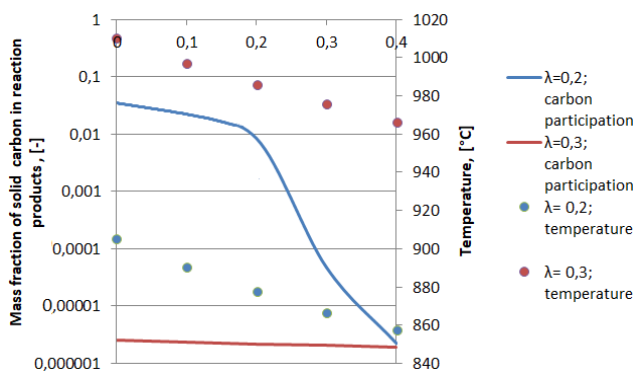


Fig. 2. Graph of mass participation of carbon in syngas and temperature in POR as a functions of steam to fuel mass ratio.

The graph shows that increase of steam - fuel ratio causes a decrease in the share of solid coal fractions in syngas and reduces the temperature in the reactor. It can be observed that for excess air coefficient 0,2 there is a moment of avalanche decrease in the proportion of soot in the gas. In the case of $\lambda=0,3$, the share of the solid carbon fraction is all the case at a low level, even in the absence of water injection (ratio of steam to fuel quantity = 0). This indicates that in the reactor there may be pressure and temperature conditions for which there is no need for steam injection and in the POR large quantities of soot do not occur.

The first optimized parameters were the excess air coefficient (λ) in the POR reactor. The case studies calculations included λ range from 0,2 to 0,5. Compressed air flow from caverns, was constant, while the ratio of air fed to POR to the amount of air fed into the syngas combustion chamber was changing. Importantly, it was assumed that the temperature before the expanders cannot exceed 1100 °C, due to the expander's limitations. The temperature limitation in the POR was controlled by the injection steam flow whereas maintaining the permissible temperature in the syngas combustion chamber was controlled by excess air. In addition, it was assumed that the mass participation of soot in the gas can not exceed $1 \cdot 10^{-5}$. To show the graph, the most efficient system configurations that meet all the assumptions and temperature limits were selected with the given excess air coefficient. The relation between the efficiency of the system and excess air coefficient in POR is presented in the Fig. 3.

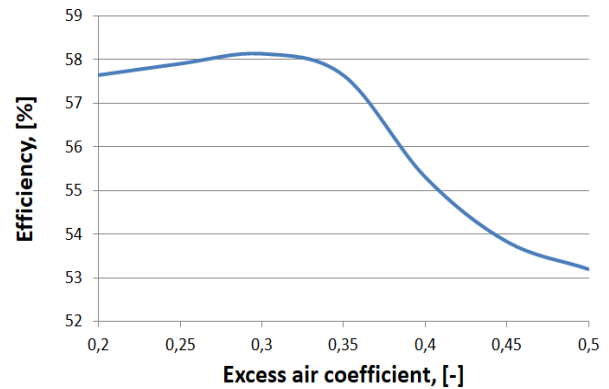


Fig. 3. Graph of efficiency variation as a function of excess air coefficient.

The Fig. 3 shows that the efficiency of the system is the largest in the case of λ about 0,3.

In the next optimization step, for the case of excess air coefficient equal to 0,3, it was decided to analyze the impact of interstage pressure on the system's efficiency. In addition, possible interstage pressure from 1,4 to 4 MPa was analyzed. The previous assumptions have also been retained. The calculation results are shown in Fig. 4.

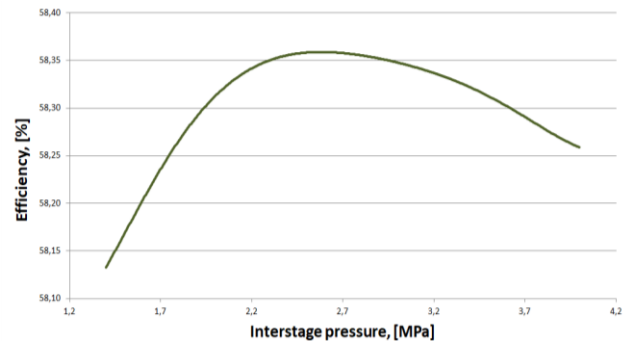


Fig. 4. Graph of efficiency variation as a functions of interstage pressure

TABLE III: ANALYSIS RESULTS

Data	Value	Unit	
Net efficiency	58,36	%	
Fuel stream	8,052	kg/s	
Air stream to POR	41,559	kg/s	
POR temperature	989	°C	
Steam to fuel mass ratio	0	-	
Temperature after the combustion chamber	1100	°C	
POR excess air coefficient	0,3	-	
Combustion chamber excess air coefficient	3,86	-	
Air stream	417	kg/s	
POR supply pressure	4,2	MPa	
Interstage pressure	2,6	MPa	
Total power	368,15	MW	
Net output of electricity	5772,47	GJ	
Discharging time	4,355	h	
Electrical own needs	7,3	MW	
Syngas mass composition	N ₂	0,6322	-
	Ar	0,0108	-
	H ₂ O	0,0432	-
	CO ₂	0,0344	-
	CO	0,2290	-
	H ₂	0,0312	-
	CH ₄	0,0187	-
	C	2,56 · 10 ⁻⁶	-

The graph shows that increasing the pressure rise the

efficiency of the system, reaching a maximum in 2,6 MPa. Further increase of the interstage pressure brings about a decrease in the efficiency of the system. For optimal value of pressure, system achieves efficiency 58,36%.

Obtained results of most important parameters of the optimal system are presented in Table III.

C. Comparison of Solutions

In relation to the reference case a significant efficiency increase was obtained. For comparison, several CAES installations were compared. The set of CAES systems are presented in Table IV.

TABLE IV: COMPARISON OF VARIOUS CAES SYSTEM TECHNOLOGIES [12]

Data	CAES Huntorf	CAES McIntosh	CAES + POGT	Unit
GF	1.56	1.17	1.09	kWh/kWh
η	42	54	58	%

GF: gas consumption to energy production factor

The McIntosh CAES power plant differs from the CAES Huntorf case using heat recuperation, where hot exhaust fumes heat the air supplied to the combustion chamber. The comparative table shows that the installation of an energy storage system in compressed air in combination with a partial oxidation gas turbine shows the best efficiency.

IV. CONCLUSION

For article purposes, thermodynamic analysis of the energy storage system in compressed air with partial oxidation gas turbine was made. During the analysis, the initial optimization of such parameters as: air excess coefficient, steam injection or interstage pressure was performed. The optimization concern to maximize of the energy efficiency of the entire installation. As a result of the optimization, a higher efficiency than the reference system (Huntorf) was obtained, by 16 percentage points. CAES + POGT system was also compared with the CAES system with heat recuperation (McIntosh), where also a higher efficiency value was obtained, by 4 percentage points. The analyzed installation is also characterized by the lowest gas consumption to energy production factor. In addition, the turbine power has been increased from 290 to 368 MW, which is a significant change considering that the outgoing air stream remained unchanged. The results of the analysis indicate that the addition of a partial oxidation to the CAES system results in high energy efficiency indicators.

Additionally, the system's efficiency can be increased by utilization the heat produced in the compressor intercoolers. This heat can be used for example, for district heating purposes, creating a cogeneration system.

An additional advantage of the POGT installation is a wide range of possibilities for using synthesis gas, eg in a fuel cell, or for the production of hydrogen [13].

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projects.

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