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Energy and Exergy analysis of the power station at Huntorf as an
example of Compressed-air energy storage.

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Abstract

The demand in energy sources is highly increasing and the urge for usage of renewable sources of energy is increasing which motivates engineers day after day to develop different ways to store energy as it's the main difficulty that face renewable sources dependency between all the resources and CAES can be used as one of the means of electric energy storage.

In this thesis simulation and modelling of compressed air and energy storage (CAES) Huntorf Power Plant is being discussed. The thesis work begins with the literature review of Compressed air energy storage technologies and goes more specifically about Huntorf Power Plant, collection of information about the plant specifics, layout, and components dynamic. In this thesis, MATLAB-CANTERA software tool is employed to create a simulation model of the Huntorf compressed-air energy storage power plant based on measured steady-state values. The state variable of the actual state of the plant in Huntorf are Reproduced by the model in a realistic manner. The primary task of this thesis is to create a model of the plant with high flexibility to change the plant configuration to study different scenarios which in turn increase the output efficiency of the power plant and optimize the plant losses which can be determined through Energy and Exergy analysis of the power plant which give us the tools to develop different scenarios by adding different components to enhance the plant overall efficiency and the potential of development of the current components which can be optimized to reduce the high losses. Modeling of the entire unit using MATLAB tool has been conducted by importing Cantera thermodynamic module for modelling of power plants. Previously it was conducted by using another software tool STEAG's EBSILON Professional software and applying different scenarios such as increase in the the accumulator pressure from the current maximum pressure of 66 bar in the actual state to 100 bar which lead to an approximate doubling of the possible operating time of the power plant (from 6.7 hours to 12 hours in relation to the discharging operation). Since Huntorf power plant has been established in 1978 it has high potential of development as the technologies used at this time is somehow old-technology in comparison with the current development done for the new power plants. Compressed air energy storage power plants usually works with a dynamic operation conditions since the accumulator pressure varies with time therefore steady-state model is not satisfying the realistic operation conditions and that's why IEVB needed a model based on steady-state operation to develop in the future to suit all the dynamics of the power plant and studying the effect of the cavern accumulator in the air properties.

Keywords : Compressed air and Energy Storage, Huntorf Power Plant, Gas power cycles, Cantera_MATLAB, CAES, Cavern, Simulation, Thermal power plant

Chapter 1. Introduction

This chapter begins with a brief overview about the importance of the renewable energy sources for playing a significant role in the global warming. Also, this chapter discusses in detail the Huntorf compressed air and energy storage power plant which provides an efficient way for energy storage which is the biggest problem of using renewable energy as its availability most of the time is intermittent. The idea of the thesis is to conduct the modelling of the entire power plant using MATLAB tool with Cantera thermodynamic module. The chapter discusses the problem, the scope of thesis, methodologies adopted to solve the problem and finally it summarizes the complete structure of the thesis

1.1. Renewable energy sources impact

In order to slow down global warming, more renewable energy sources has to be used and the use of fossil fuels reduced. Consequently, the Federal Government of Germany has set itself the goal of increasing the share of renewable energies to 80% of electricity consumption by 2050. The energy transition encompasses the three sectors of heat, electricity and mobility and is driven by the potential of wind, solar, marine and biomass energy as well as hydropower (in short: renewable energy). These renewables need to be further developed. In the electricity sector, a share of around 40% renewables was achieved in 2018. It should be noted that the structure of the power supply changes, as wind turbines and photovoltaic systems feed electricity into the grid, but this decentralized and not demand-oriented. In order to cover the electricity demand and the production in order to build an energy storage infrastructure is necessary. It is foreseeable that the demand for short-term and flexibly usable power storage units will increase. For the minute reserve, there are not very many technically mature options available except for pumped storage and compressed air storage. Both are similar in terms of performance and system services. Currently, the operation of power storage in general and compressed air storage in particular is not economical enough to justify the investment in new power storage facilities, therefore, the optimization of these power plants is being researched with the aim of making them more efficient as storage technology.

Worldwide there are only two commercial compressed air storage power plants in Huntorf, Germany, and in McIntosh, USA. Apart from these two power plants, only smaller research facilities in the kW range have been built so far. The power plant in Huntorf is a compressed air storage power plant commissioned in 1978 with a turbine output of 320 MW. In injection mode (compressor power), it consumes about 70 MW. The compressed air storage power plant in McIntosh went into operation in 1990. It has a capacity of 110 MW in storage operation and 60 MW in storage. In contrast to Huntorf, it has a recuperator to preheat the combustion air with the enthalpy of the exhaust gas. It is thus somewhat more efficient in terms of fuel consumption. As the only commercial-sized facilities, Huntorf and McIntosh serve as reference for similar follow-up projects and developments.

The efficiency increase of the Huntorf compressed air storage power plant will be tested in this work on the basis of concept simulations. The simulation is based on a good modeling of the power plant in its present state (actual state). This work is therefore understood as an element for the optimization of compressed air storage power plants.

1.2. Problem statement

The problem description includes understanding the complexities in the Huntorf power plant system followed by modelling of the entire system using Cantera module in MATLAB environment by employing the plant specific data

gathered in literature review and study of the plant. The problem description also includes the optimizing the efficiency of the power plant by modifying the variables which include the throttling of air, increasing the pressure, addition of recuperator and miscellaneous variables which affect the entire power plant efficiency and behavior.

1.3. Scope of thesis

The scope of the thesis is divided into two major phases.

Phase-I

The objectives of this phase are to perform preliminary literature review about the compressed air and energy storage Huntorf power plant which is the type of power plant configuration that is primarily adopted to satisfy load demand in high load times and store the air to produce power when the electricity price is low. During the phase-I of the project, plant specific data of operation of the plant is collected and the theoretical modelling and calculation of the preliminary results for the dynamics of the plant are carried out. During this phase-I that brainstorming is conducted to study the plant dynamics better, consider the system losses, brainstorm the first and second law efficiency concepts also including the exergy point of view. The idea during this phase-I is to prepare everything ready for initiating the modeling and simulation and finally yielding the results.

Phase-II

The aim of the second phase is to perform the modelling of the plant on MATLAB using Cantera thermodynamic module. Optimize the process variables and apply different scenarios to yield the best efficiency scenario. The process includes comparison of multiple contributing energy and exergy factors which play a major role in plant efficiency. Finally, the MATLAB script for the plant is compiled and made user friendly for user to understand and simulate different components of the plants and then the results are tabulated for the report.

1.4. Methodology

After getting command on the power plant basics and the theoretical modelling and calculations, a modeling algorithm was set up to simulate the plant using MATLAB (with Cantera module). The major assistance during the coding came from the theoretical design calculations. The understanding of MATLAB programming and using the specific modules was developed to be able to model the plant in the best possible manner.

- Learning the basics of MATLAB programming
- Learning the Cantera thermodynamic module tools available and understanding the limitations
- Reviewing the theoretical modelling and calculations to be able to develop MATLAB model effectively
- Debugging the algorithm step by step to make sure the effectiveness of the code and errors happen.

1.5 Structure of Thesis

Objective and Procedure

The aim of this work is the development of a model that reflects the operating parameters of the status quo of the compressed air storage power plant Huntorf in stationary operation (actual state) as well as the testing of several operating concepts where improved performance characteristics are to be expected. The simulation is based on the measured quantities supplied by the power plant operator UNIPER as input values. The results of this work should first of all represent the plant in a realistic way, show ways to increase efficiency or performance and finally provide

a basis for further concept studies for optimization as well as eg. B. for the design of energy storage in the context of a required network expansion.

Actions

Preparation of input data

In the first step of the whole process consisting be documented the necessary input data for the simulation of plant components as well as various measurements after a rollover

Simulation

Based on the input data, the power station is mapped with the modeling software "MATLAB using Canterra Thermodynamic Module" and then configured to result in values of the various state points to generate the cycle finally to be evaluated.

Model Validation

The values of the cycle, as a result of the simulation are compared with previously created cycle models as well as other measured values from the plant to determine if the simulation is a good approximation to the actual process

Chapter 1	Introduction	Covers complete introduction of the thesis including the brief overview of the concept, scope, objectives, problem description, methodologies and the overall structure of the thesis.
Chapter 2	Theory of Huntorf power plant	Covers complete literature review of the energy storage systems followed by compressed air and energy storage systems and the description
Chapter 3	Thermodynamic modelling of Huntorf power plant	Explains the modelling and analysis of energy and energy of the Huntorf Power plant and demonstrates the theoretical and practical model
Chapter 4	Results and Discussion	This chapter shows the results of the modelling work and discusses the outcomes critically
Chapter 5	Conclusion	This chapter concludes the overall work that has been carried out
Chapter 6	Future Work	Enlists the future possibilities of the work

Chapter 2 Theory of Huntorf Power Plant

2.1 Introduction of Energy Storage Technologies

Ever since the human started using the various forms of energy for his comfort and necessities one of the widely researched topics till today is energy management. Around the world countries face the transition to a more sustainable and renewable energy system. However, Wind and solar fluctuations lead to a very non-uniform power production rate. Thus, there is a need for a more flexible energy grid that compensates temporary gaps between power demand and supply. Therefore, Research and development aims to find different trustworthy methods to store energy when it's not needed and re-use it when the demand is high. Researches are carried out to study various forms of energy that can be stored effectively without causing high losses and to achieve the economic competitiveness of energy prices.

2.1.1. Classification according to type of energy:

Thermal Energy Storage:

Thermal energy storage (TES) is a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used later for heating and cooling applications and power generation. Both heating and cooling storage have an opposite operating principle, whereby the heat accumulator absorbs heat during storage and the cold accumulator releases energy into heat. If the stored energy temperature is below the ambient temperature, then cold storage is mentioned. Above ambient temperature is heat storage.

Thermal storage is used to couple the energy supply with energy demand, and it can be classified considering temporal change and compatibility between the demand and supply. Then it can be classified as following:

- 1- Energy storage period: long-term & short-term heat storage.
- 2- Thermodynamic storage principle: latent heat, sensitive and thermochemical storage.
- 3- Level of useful temperature: in low, medium and high temperature storage.

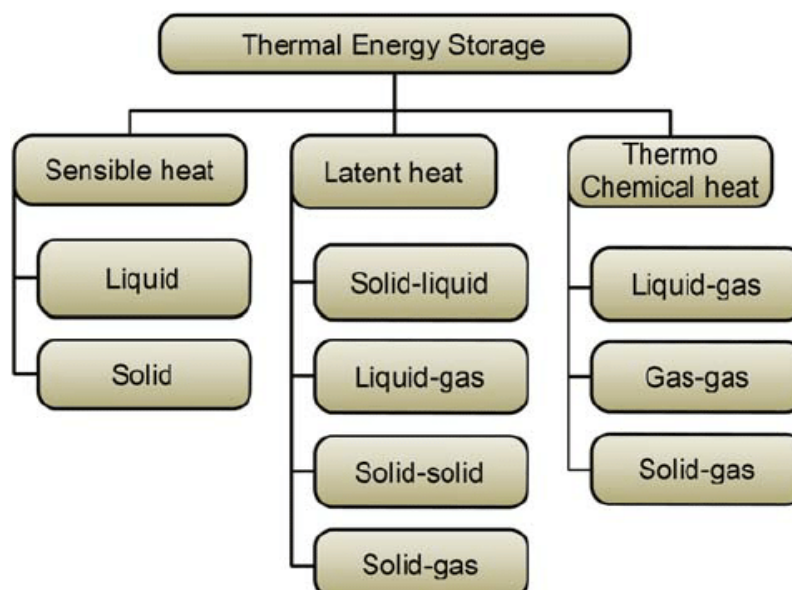
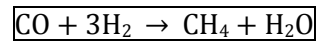
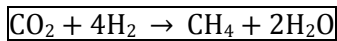


Figure 1 Thermal energy classification

Chemical Energy Storage:

Chemical energy is stored in the bonds that connect atoms with other atoms and molecules with other molecules. Because chemical energy is stored, it is a form of potential energy. When a chemical reaction takes place, the stored chemical energy is released. Under chemical energy storage all fossil fuels could be sorted. However, the term is generally used for storage, where chemical energy is made of other forms of energy. A good example of this technology is the "Power-to-gas", where electrical power-mainly from renewable sources-is used to produce a gas fuel (such. As hydrogen or methane).

Methane is the simplest hydrocarbon with the molecular formula CH₄ which is more practical for storage & Transportation than Hydrogen. In Synthetic natural gas SNG it's produced by different processes as first we obtain H₂ by water electrolysis and then with Sabatier process under temperature of 300-400 C we can obtain the Methane for storage.



In this era, Fossil fuels are the backbone of the conventional energy supply especially for long-term storage of the electricity sector. In 2016 the total world energy supply TPES coming from 80% fossil fuels, 10% biofuels, 5% nuclear and 5% renewable (hydro, wind, solar, geothermal). Only 18% of that total world energy was in the form of electricity. Most of the other 82% was used for heat and transportation.

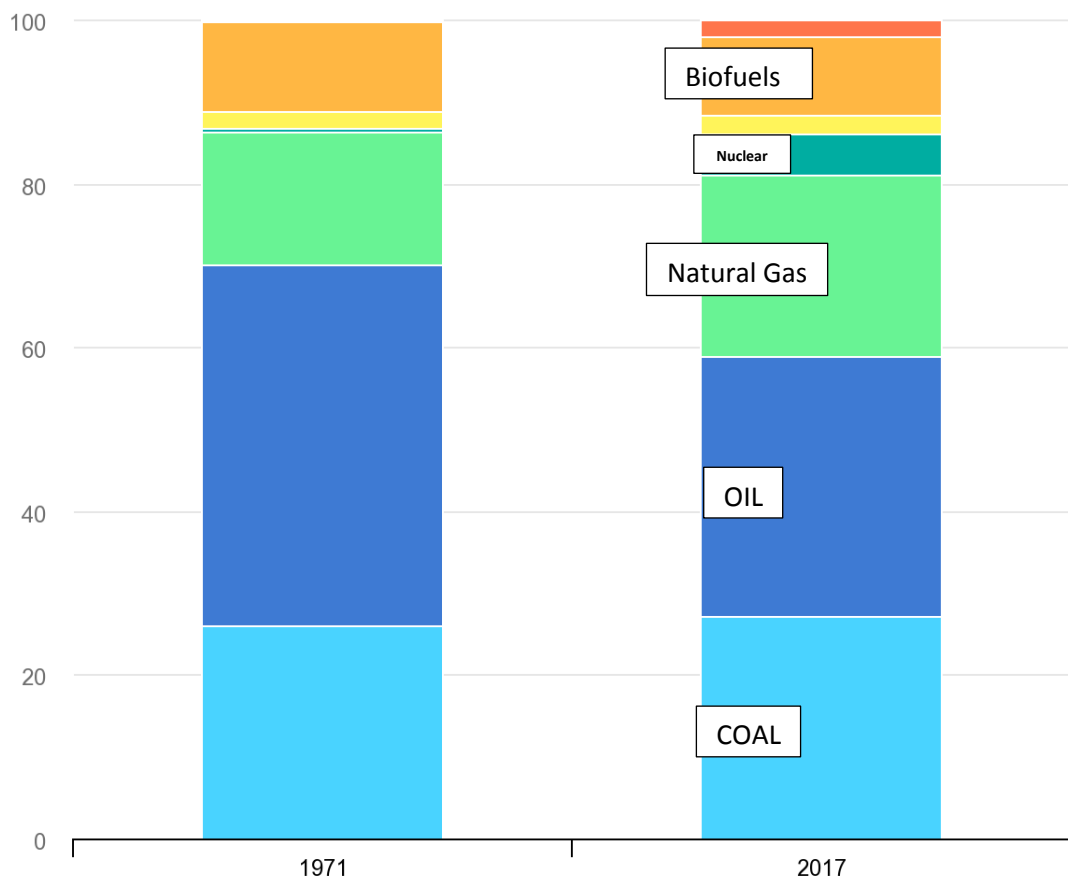
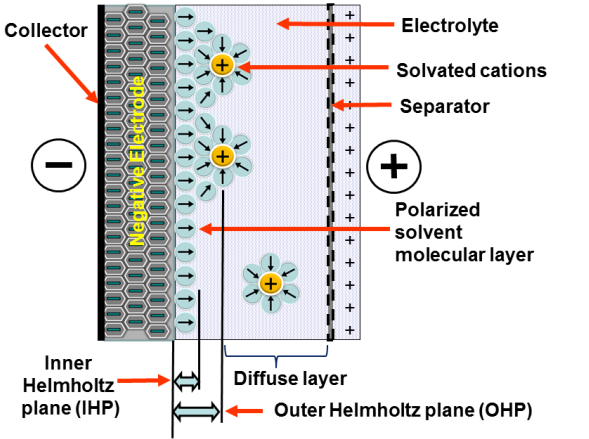
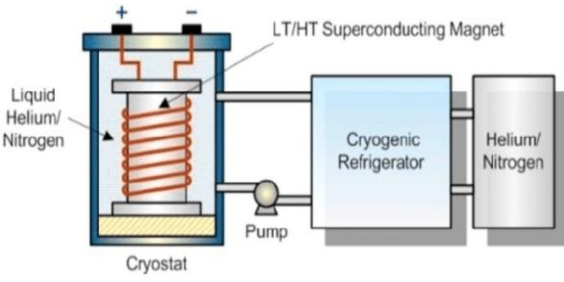


Figure 2 Total primary energy supply by fuel, 1971 and 2017 [IEA]

- Coal
- Oil
- Natural gas
- Nuclear
- Hydro
- Biofuels
- Other renewables

Electrical Energy Storage:

The advantage of electrical energy storage systems that we don't have to lose any conversion energy and this technology was primarily achieved by using a Capacitors which is a passive two terminal electrical components used to store energy electrostatically, Capacitors are mainly used as a temporary battery in most of electronic devices.

<p align="center">Electrochemical Double-Layer Capacitor DLC</p>	<p align="center">Superconducting magnetic energy storage SMES</p>
<p>Known as Supercapacitors and it fill the gap between two classical capacitors which can store energy in an electrostatic field between 2 conducting plates separated by a dielectric insulator as indicated in the graph below.</p>	<p>SMES systems work according to an electrodynamic principle. The energy is stored in the magnetic field created by the flow of direct current in a superconducting coil, which is kept below its superconducting critical temperature by using cryogenic liquified N2/H2</p>
<p align="center">Advantages:</p> <p>1-Extremely high capacitance values, and high specific power density. 2-Possibility of very fast charges and discharges due to extraordinarily low inner resistance. 3-Durability, no maintenance, high reliability, and long lifetime. 4-Environmentally friendly</p>	<p align="center">Advantages:</p> <p>1-Very quick response time while the requested power is available instantaneously. 2-High overall round-trip efficiency 85-90%. 3-Moderate reliability, no-moving parts. 4-Can store Electric Energy for a long time as far as the cooling system is working.</p>
<p align="center">Disadvantage:</p> <p>1-Hight self-discharge rate so it isn't suitable for long time storage. 2-Low energy density & High investment cost. 3-Degredation of Solvent after 5-6 years</p>	<p align="center">Disadvantage:</p> <p>1-High cooling demand. 2-longer storage times are limited by the energy demand of the refrigeration system</p>
 <p>Simplified view of a double layer of negative ions in the electrode and solvated positive ions in the liquid electrolyte, separated by a layer of polarized solvent molecules.</p>	 <p>Superconducting magnetic energy storage SMES schematic</p>

Mechanical Energy Storage:

This method includes different technology such as: Pumped storage, Flywheels, Solid-Mass gravitational, and Compressed air energy storage CAES which is the focus of this thesis.

In mechanical energy storage we take into account the speed, which represent the kinetic energy, and location which indicates the potential energy and thermodynamic properties (pressure, temperature,....etc) of any solid, liquid, or gas used to store energy.

2.2. Compressed air energy storage CAES general concept

This technology known and used since the 19th century for different industrial applications and Specially with air as a storage medium due to its availability. A compressed air energy storage CAES uses electrical energy from grid off-peak low-cost electricity to feed a compression process with/without intercooling to store compressed air in either an underground structure or an above-ground system of vessels or pipes which is then used at later time to produce power through turbines. The stored air thermodynamic properties such as temperature and pressure determined according to the chosen cavern temperature and limits of maximum operational values of pressure.

We can categorize CAES systems mainly to three types:

- 1- Diabatic compressed storage system.
- 2- Adiabatic compressed storage system.
- 3- Isothermal compressed storage system.

2.2.1. Diabatic compressed storage systems [D-CAES].

Intercoolers and aftercoolers are used in order to improve efficiency of the compression stages and minimize the thermal stress on the storage cavern walls. Heat of compression is dissipated to environment by intercoolers between each stage, the compressed air then injected in a storage vessel which can be a cavern created by solution mining or abandoned mines while underground systems need some particular geologic formations (salt domes, aquifers, depleted gas mines, etc.).

This heat waste deteriorates the efficiency of the cycle [around 55%-EASE] as before air expansion in the turbines a certain amount of fuel-natural gas- is needed for combustion to avoid icing risk for the blades of the turbines at the outlet which in turn might lead the material and seals to become brittle. In addition, without combustion the air temperature will be at the wall temperature of the reservoir so to produce the power needed we will have to use much higher air flow to achieve the same output.

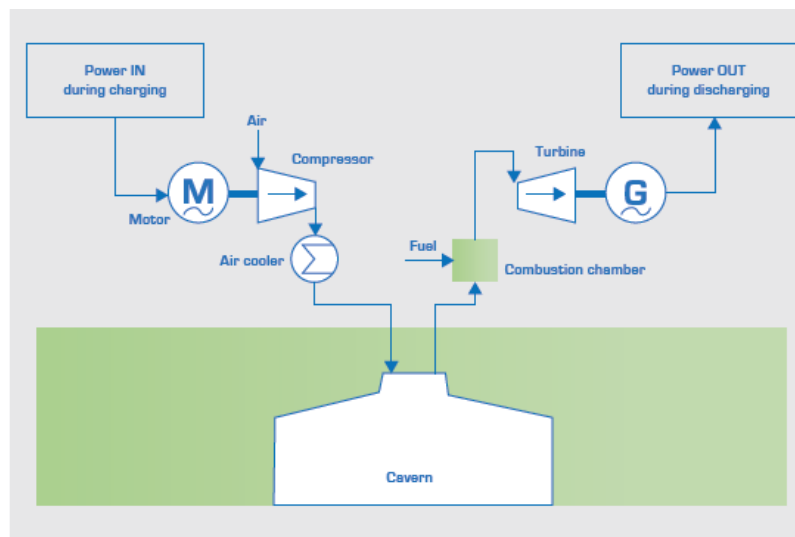


Figure 3 Layout of CAES

2.2.2. Adiabatic compressed storage systems [A-CAES]

It works like diabatic reservoirs with the difference that the heat exchange with the environment is largely avoided. For this purpose, the compression heat is not released into the environment, but stored in a storage for thermal energy. This heat is used to heat the air flow from the cavern before entrance of the turbine to generate electrical energy and eliminates the need to burn fuel in the combustion chambers. Therefore, storage efficiency is higher in this concept [$>70\%$ -EASE]. The below figure is a process diagram of an adiabatic compressed air storage (A-CAES). In contrast to the diabatic compressed air accumulator, the compression is often not multilevel to achieve higher air temperatures and a heat storage needed for the system.

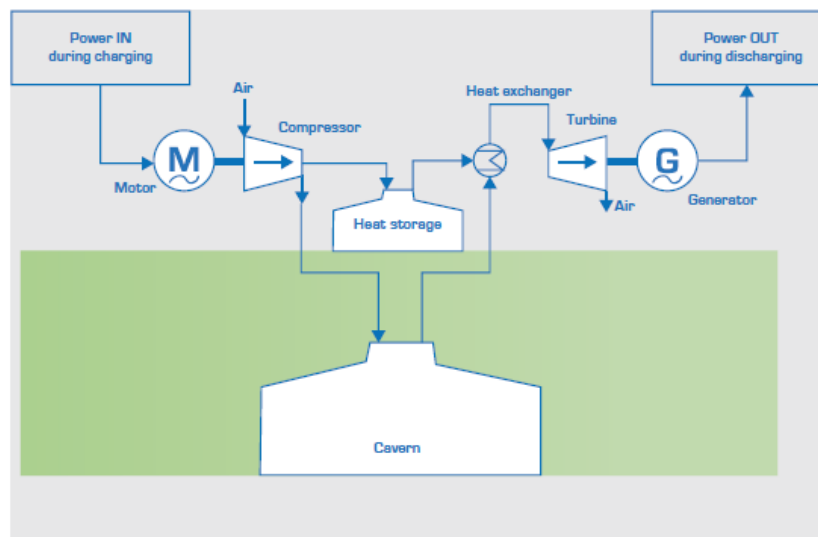


Figure 4 layout of Adiabatic compressed storage systems

2.2.3. Isothermal compressed storage systems [I-CAES]

Isothermal compressed air energy storage (I-CAES) is an emerging technology which tries to overcome some of the limitations of traditional (diabatic or adiabatic) CAES. Instead of using numerous stages for compression, cooling and expansion, Isothermal CAES aims to achieve a real isothermal compression and expansion on spot which increases the efficiency and lowering the capital cost as it negates the need to use a heat storage to keep the heat of compression.

The main challenge of this technology that heat needs to be removed continuously during compression and re-added continuously during expansion to keep the air flow at constant temperature which is practically almost impossible as in principal heat transfer occurs proportionally to temperature gradient and heat transfer surface area so with minimal temperature difference we need very large surface area to transfer this heat.

Currently, no commercial Isothermal CAES implemented, but several solutions are proposed by using reciprocating compressors and turbines. One of the methods is to spray droplets of water inside the piston head during compression which aim to keep the temperature almost constant within the piston due to the high heat capacity of water compared to air. Similarly, can happen during expansion.

2.3. Huntorf power plant Technical structure & Functions

Successful compressed air energy storage implementation originates from the mid of the last century, as in 1949 the Swedish turbine manufacturer *Stal-Laval* acquired the patent to store air underground cavern which was the spark for further CAES applications. Then, In 1978 the first utility-scale CAES plant in the world installed and it belonging to *Nordwestdeutsche Kraftwerke AG (NWK)* and operated by ABB at Huntorf-Germany with the rated power of 290MW. In 1991, a new large-scale CAES plant started operation in McIntosh-USA with the rated power of 110MW which can be continuously delivered for 26 hours.

2.3.1 Huntorf power plant operation conditions and technical design:

Huntorf CAES power plant was engineered by Brown Boveri Co., located in Mannheim, to be consists of mainly this 4-process equipment:

- 1- Compressor Train.
- 2- Motor-Generator unit.
- 3- Gas turbine.
- 4- Underground compressed air storage

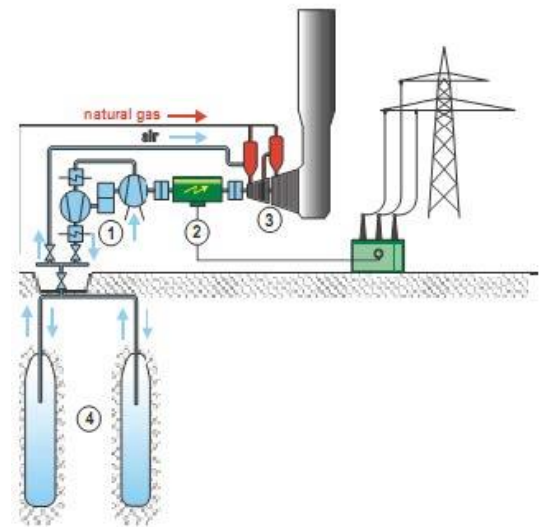


Figure 5 Huntorf power plant layout design

Huntorf-Compressor train

In Huntorf a group of compressors incorporate an axial LP unit and a centrifugal HP unit driven by a gearbox to transfer the power from the motor to them at different speeds. Each unit it consists of 2 stages of compression with intercooler after each stage to cool down the air flow at the entrance of each stage to be 35 °C and it transfer this heat to high mass flow rate 50 kg/s of water flowing in the Intercooler with a pressure of 2 bar. one Aftercooler is needed to cool down the air flow before entering the reservoir to be around 50 °C.

While the compressors charging the reservoirs, the pressure in them rises so in turn the compressors charging pressure increases from 48 bar to 66 bar which can happen during the 8 hours of charging time. Total drive power required to run both compressors is 60 MW and 75% of this power is used to run the high-pressure centrifugal compressor at a speed of 7626 rpm.

Low Pressure Compressor		High Pressure Compressor	
Type	Axial	Type	Centrifugal
Speed	3000 rev/min	Speed	7626 rev/min
Intake Conditions	1.013 bar 283 k	After-Compression Conditions	48-66 bar 323 k
Air Mass flow rate	108 kg/s	Number of Intercoolers.	3
Drive power of both compressors	60 MW	Number of Aftercoolers	1

Motor/ Generator unit

The generator maybe used as a motor to drive compressors so that the Motor/Generator unit is separated from both turbine & compressor shafts by self-engaging clutches. The motor unit needed to provide 60MW power to compressors and the generator unit needed to produce electricity from the 290 MW power supplied by the turbine. The generator apparent power is 341 MVA and operating voltage of 21 kV with power factor of 0.85 and due to electrical losses hydrogen cooling plan is necessary for the unit.

Gas Turbine unit:

We have 2 pressure stages in the single shaft with reheat gas turbine which have a Power capacity of 290 MW at speed 3000 rev/min and air mass flow rate of 417 kg/s. to maintain constant electrical power the air withdrawn from the reservoir throttled by throttling valve to a constant pressure of 46 bar which changes when the pressure goes lower this value.

The air pressure drop from 46 to 11 bar in the HP turbine stage while Compressed air temperature first must be increased from reservoir temperature 50°C to the HP turbine inlet temperature of 550°C in the HP combustor which uses natural gas for combustion process. For the conventional gas turbines, it's driven in partial loads by constant pressure with varying flow temperature while in Huntorf the pressure is varying in partial loads and temperature is kept constant at 550°C for HP stage. After the air expansion in the HP stage its enthalpy is too low at pressure of 11 bar so it must be reheated to a temperature of 825°C in order to increase its exergy. After expansion in LP turbine the exhaust temperature is 400°C

Huntorf-Underground compressed air storage

Huntorf CAES power plant has 2 salt caverns with total volume of 310,000 m³ to store air and the plant has been extended in the meanwhile with an own 300 m³ natural gas cavern to supply the gas turbines with higher economic efficiency. The two-cavern design was planned for different reasons although this total volume could have been easily achieved by just one cavern but with 2 cavern design, we can ensure the following:

- Redundancy during maintenance and cavern shutdown
- Easier cavern refilling after drawing down the pressure in one of the caverns to atmospheric pressure
- Start-up procedures for plant compressor requires minimum pressure in one of the caverns to be at least 13 bar to allow the compressors operate.

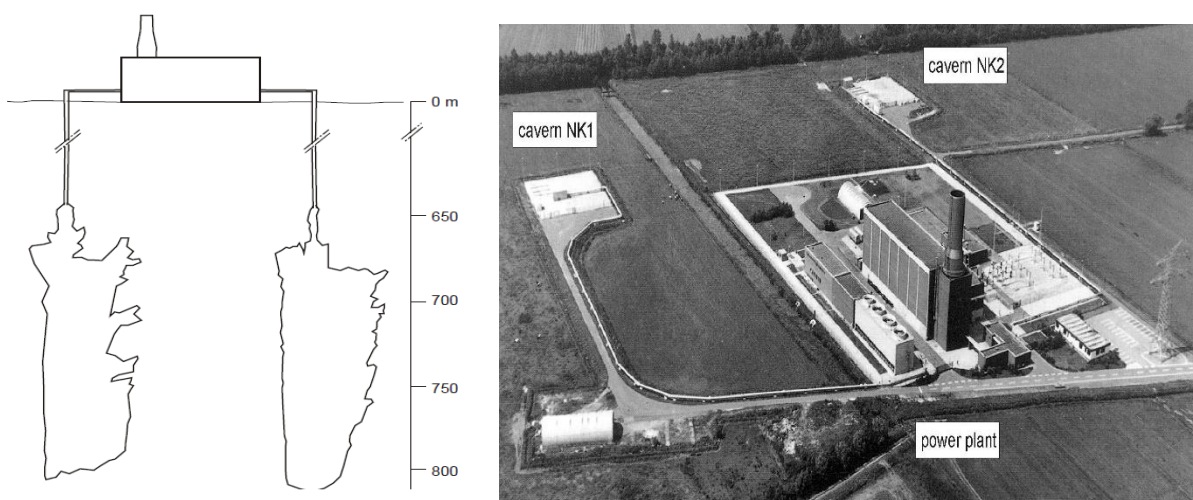


Figure 6 L.H.S. The 2 caverns and plant on the same scale/R.H.S. Aerial photo of Huntorf power plant

In order to design a cavern for CAES we must determine the depth of caverns to guarantee the design maximum pressure of 100 bar and to ensure the stability for several months at atmospheric internal pressure.

Cavern wells playing a crucial role for the design as it must handle the required high flow rate of the air 417 kg/s with minimal pressure loss that's why it's required to have 20"/21" production string and accordingly 24 1/2" final casing. From fig() as can be seen that dry air is injected in the annulus to prevent corrosion by the completely water-saturated compressed air in the cavern which has very corrosive properties knowing that this corrosion prohibition is usually assured by installing a packer between the outer tubing and the inside of the casing.

The air reservoirs in Huntorf can be operated as a sliding-pressure container with pressure ranging from 66 to 46 bar and pressure drop gradient of 10 bar/hr which maintain constant pressure inlet of 46 bar to turbines to produce constant electrical power output for some hours.

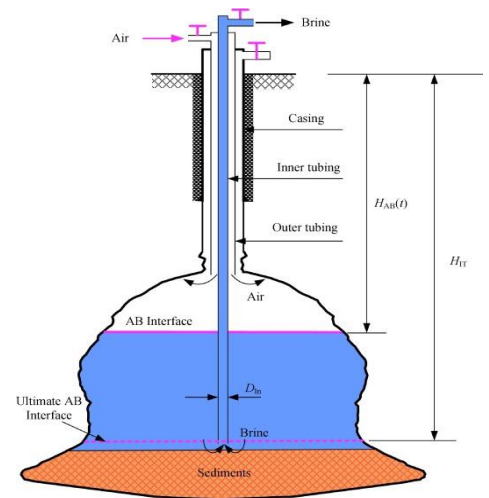


Figure 7 Cavern well design

2.3.2 Comparison between Huntorf & McIntosh power plant

Huntorf and McIntosh CAES power plants has proved the reliability and feasibility of investment in CAES technology as a mean to provide energy during the peak demand and the transition time needed from base load plant to reach the operative point. There's similarities between both plants in many operational aspects as inlet temperatures and pressure, however due to the lower power output of McIntosh plant it can serve for longer time continuously as shown in the below table. Efficiency of McIntosh is much higher than Huntorf due to the installation of recuperator to re-use the high temperature of the flue gases in the turbine outlet and it reduces the fuel consumption by almost 26% at full load output in addition to a dual-fuel combustor to enable the combustion of fuel oil and natural gas.

Location	Huntorf, Germany	McIntosh, USA
Commissioned	1978	1991
Storage volume	Two cylindrical salt caverns of total volume 310000 m ³	Salt cavern 540000m ³
Input energy	Around 60MW over 12 hours	50MW over 41 hours
Output energy	290MW over 3 hours	100MW over 26hrs
Energy required for 1 kWh _{el}	0.8 kWh electricity	0.69 kWh electricity
Pressure tolerance	43-70 bar	45-76 bar
Efficiency	~ 42%	~54%

As shown in the below plant layout of McIntosh power plant consists of series of compressor stages which takes the air from ambient pressure 1.013 bar and then compress it through the 1st stage to reach 4.1 bar then the air is cooled down to the ambient temperature by the 1st intercooler to enter the following 3 stages and increase the pressure to 10.3 bar by 2nd stage, then 26.9 bar in 3rd stage, and finally in the 4th stage can be compressed to the range 62-80 bar. Before the cavern inlet last aftercooler brings the air to temperature 317 K then in can be stored in the cavern which has a wall temperature of almost 325 K. In power production phase the air comes out from the cavern and passes through the throttling valve to reduce the pressure to 50.7 bar then the flow goes through the recuperator which has exhaust temperature of 568 K and then the air enters the high pressure combustion chamber to reach to temperature of 810K and pressure of 43 bar to enter the 1st high pressure expansion stage and exits with pressure around 15 bar which can be used for a 2nd expansion stage after a reheat in the LP combustion chamber to reach a temperature of 1144 K.

Comparison between Huntorf & McIntosh power plants on T-S diagram can give us more clear point of view about the thermodynamics properties similarities and differences.

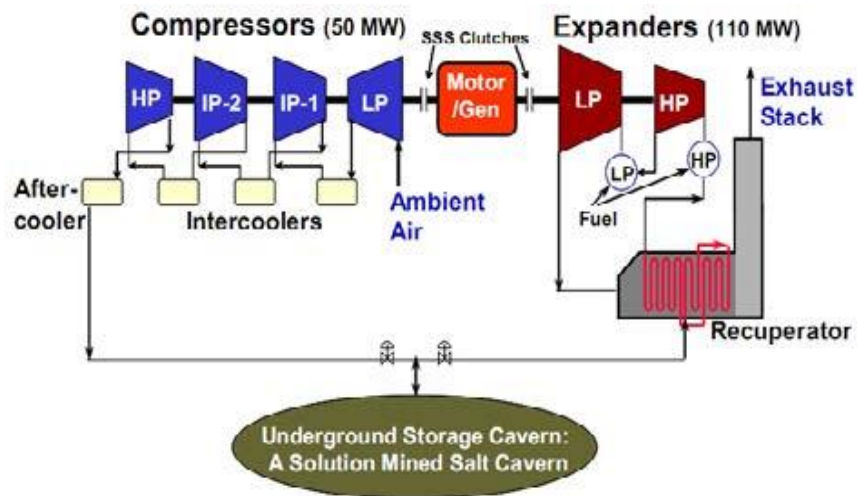


Figure 8 Huntorf power plant schematic

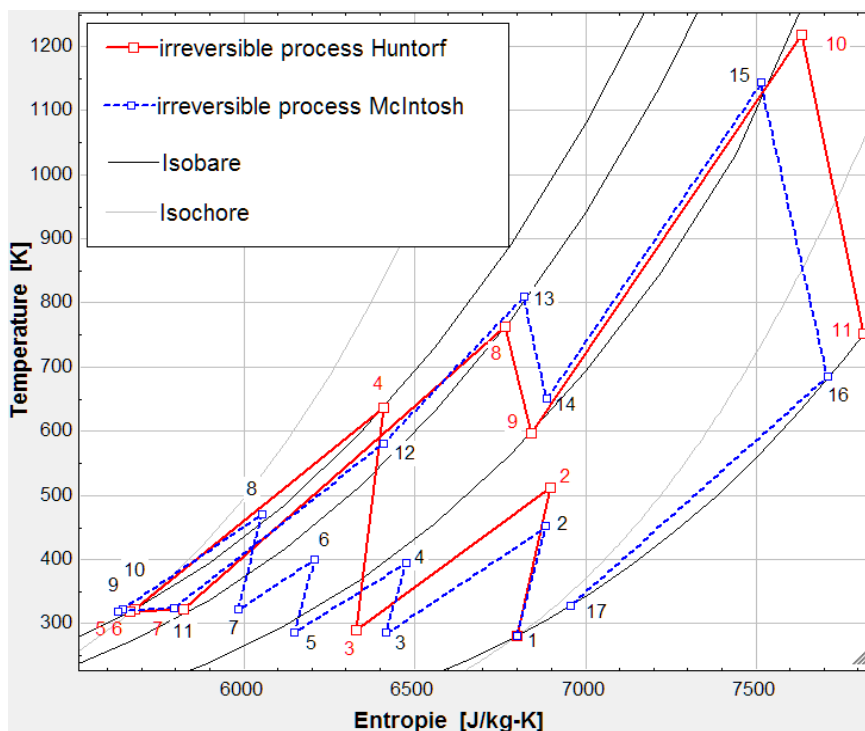


Figure 9 Huntorf power plant typical T-S diagram

Chapter 3 Thermodynamic modelling of Huntorf Power Plant

In this study we have used Cantera 2.4.0. software by integrating with MATLAB R2019b to develop a model similar to the real plant to enable us to study the performance under different scenarios of improvements to the real model.

3.1 Introduction to CANTERA-MATLAB software

Cantera is an open source scientific computing project, that allows users to incorporate and execute fundamentals of thermodynamic, chemical kinetic, and species transport calculations in their work quickly and efficiently. Interfaces to the Cantera package exist for MATLAB, Python, C++ and FORTRAN. In addition, it can be used to:

- Perform kinetics simulations with large reaction mechanisms.
- Calculate thermodynamic & transport properties of mixtures.
- Evaluate chemical equilibrium.
- Perform reaction path analysis and by using networks of stirred reactors it can create process simulators.
- Model non-ideal fluids.

In this simulation of Huntorf power plant we have used CANTERA specifically to provide two main things. Firstly, create *Thermodynamic Property Model* of all the processes of charging/discharging systems by calculating all the thermodynamic properties (enthalpy, entropy, pressure, etc.) for some pure simple, and compressible substances. Secondly, evaluate the chemical combustion process in both high- and low-pressure combustion chambers by creating a set of *Reactors and Reactor Networks* to get the combustion product species molar fractions and evaluate its thermodynamic properties.

3.1.1 Cantera – Thermodynamic Property Models

Cantera uses different models to provide thermodynamic data for each species in a phase. Each model applies different functional form(parameterization) for heat capacity. However, each species in a phase can use the most appropriate parameterization to represent the accurate dependence of heat capacity on temperature. Several types are applied to find species properties suitable for models of ideal gas mixtures, ideal solutions, and pure compounds.

1- The NASA 7-Coefficient Polynomial Parameterization.

It is used to compute the species reference-state thermodynamic properties $\hat{C}^0_p(T)$, $\hat{h}^0(T)$, $\hat{s}^0(T)$

$$\frac{c^0_p(T)}{R} = a_0 + a_1T + a_2T^2 + a_3T^3 + a_4T^4$$

$$\frac{h^0(T)}{RT} = a_0 + \frac{a_1}{2}T + \frac{a_2}{3}T^2 + \frac{a_3}{4}T^3 + \frac{a_4}{5}T^4 + \frac{a_5}{T}$$

$$\frac{s^0(T)}{R} = a_0 \ln T + a_1T + \frac{a_2}{2}T^2 + \frac{a_3}{3}T^3 + \frac{a_4}{4}T^4 + a_6$$

2- The NASA 9-Coefficient Polynomial Parameterization.

It is an extension of the old NASA 7-coefficient polynomial parameterization as it includes two additional terms in each temperature region, also supporting an arbitrary number of temperature regions. The NASA9 parameterization represents the species thermodynamic properties with the following equations:

$$\frac{c^0 p(T)}{R} = a_0 T^{-2} + a_1 T^{-1} + a_2 + a_3 T + a_4 T^2 + a_5 T^3 + a_6 T^4$$

$$\frac{h^0(T)}{RT} = -a_0 T^{-2} + a_1 \frac{\ln T}{T} + a_2 + \frac{a_3}{2} T + \frac{a_4}{3} T^2 + \frac{a_5}{4} T^3 + \frac{a_6}{5} T^4 + \frac{a_7}{T}$$

$$\frac{s^0(T)}{R} = -\frac{a_0}{2} T^{-2} - a_1 T^{-1} + a_2 \ln T + a_3 T + \frac{a_4}{2} T^2 + \frac{a_5}{3} T^3 + \frac{a_6}{4} T^4 + a_8$$

3- The Shomate Parameterization.

The Shomate parameterization uses different variable to represent the temperature where $t=T/1000K$ and it needs 7 coefficients $A, B, C, D, E, F,$ and G to be defined for each species. This parameterization method is used to represent reference-state properties in the NIST Chemistry WebBook knowing that coefficients A to G are unitless values.

$$\widehat{c^0 p}(T) = A + Bt + Ct^2 + Dt^3 + \frac{E}{t^2}$$

$$\widehat{h^0}(T) = At + \frac{Bt^2}{2} + \frac{Ct^3}{3} + \frac{Dt^4}{4} - \frac{E}{t} + F$$

$$\widehat{s^0}(T) = A \ln t + Bt + \frac{Ct^2}{2} + \frac{Dt^3}{3} - \frac{E}{2t^2} + G$$

4- Constant Heat Capacity.

In some cases heat capacity can be assumed constant specially when species properties are required at a single temperature or over a small temperature range so simply we can represent the following:

$$\widehat{c^0 p}(T) = \widehat{c^0 p}(T_0)$$

$$\widehat{h^0}(T) = \widehat{h^0}(T_0) + \widehat{c^0 p} \cdot (T - T_0)$$

$$\widehat{s^0}(T) = \widehat{s^0}(T_0) + \widehat{c^0 p} \cdot \ln(T/T_0)$$

In the previous equations we can find four constants: $T_0, \widehat{C^0 p}(T_0), \widehat{h^0}(T_0), \widehat{s^0}(T_0)$ while $T_0=298.15K$ & the rest of the constant's value are set to be zeros.

3.1.2 Cantera – Reactor and Reactor networks:

Cantera Reactors are the adequate tool for chemically reacting systems as it represents an extensive thermodynamic control volume assuming that all state variables are distributed homogeneously. For chemically reacting system it is frequently unsteady as all the states are function of time and due to the possibility of chemical reactions it works with transient state changes until it reaches the chemical equilibrium. However, we assume that thermodynamic equilibrium is present all over the reactor at all instants of time.

Reactors can interact with surroundings in different ways such as

1. Expansion/Compression work
2. Heat transfer
3. Mass transfer
4. Surface interaction

These interactions can also be a function of time or state as for example in heat transfer interaction with surrounding it's a function of the temperature difference between the reactor and environment which vary with time, Similarly, in expansion/compression work the walls of the reactor moves representing the change of the reactor volume due to work and this movement of the walls can be modelled as a function of pressure difference. Reactors are governed by a variety of equations to ensure balance with the different variables.

Governing Equations for Single Reactors

Mass Conservation: The total mass of the reactor's contents changes as a result of flow through the reactor's inlets and outlets, and production of homogeneous phase species on the reactor walls:

$$\frac{dm}{dt} = \sum_{in} \dot{m}_{in} - \sum_{out} \dot{m}_{out} + \dot{m}_{wall}$$

Species Conservation: The total rate at which species i is generated depends on the rate of generation through homogeneous phase reaction plus migration through the wall as follow:

$$\dot{m}_{i,gen} = V\dot{w}_i W_i + \dot{m}_{i,wall}$$

While the temporal change of the mass of each species is

$$\frac{d(mY_i)}{dt} = \sum_{in} \dot{m}_{in} Y_{i,in} - \sum_{out} \dot{m}_{out} Y_i + \dot{m}_{i,gen}$$

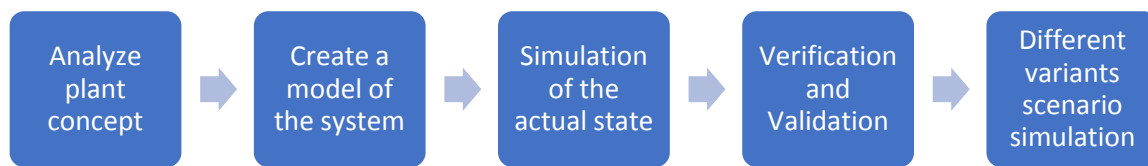
From the mass conservation we got $\frac{dm}{dt}$ and by expanding the derivative on the left hand side we can get the equation for each phase species as:

$$m \frac{d(Y_i)}{dt} = \sum_{in} \dot{m}_{in} (Y_{i,in} - Y_i) + \dot{m}_{i,gen} - Y_i \dot{m}_{wall}$$

3.2 Simulation model of Huntorf Power Plant:

The simulation model of the Huntorf CAES power plant is intended to reflect the system behaviour in stationary operation as close to reality as possible. After creation and validation of the model for the actual state of the plant, various new scenarios concepts of the model are also tested.

The below figure graphically represents the procedure for creating and validating the simulation model. The first step is to create a conceptual model of the plant then it is used for the creation of a computer model and finally verified and validated as a model for the actual plant which enable us testing and simulate different concept variants scenario.



In the previous chapter we have indicated the Huntorf power plant concept and technical design parameters therefore it's necessary to specify the input data that the simulation model will hinge on.

3.2.1 Model and Simulation of the actual state.

The model can be divided into two main parts before & after cavern which is grouped according to the operating cases of charging and discharging from the cavern. Therefore, the necessary input data of the power plant and its general conditions are documented and shown in a table.

Input data for Simulation:

The input data for the model are the following data that we acquired from the power plant operator UNIPER, which are shown from the general to the specific in the following three tables. Table (I) lists general boundary conditions, constants, and geometric values needed to model Huntorf compressed air storage process.

input data	value	unit
ambient pressure	1.01325	bar
Exhaust pressure = ambient pressure	1.01325	bar
Ambient temperature (average)	288	K
Air enthalpy reference value	8,649.34	J / mol
Molecular weight of air	0.0289586	kg / mol
reference air enthalpy	298.6794942	kJ / kg
acceleration of gravity	9.81	N / kg
caverns volume	253414	m ³
depth	650	m
caverns number	2	
Rock temperature in the caverns	322	K
Specific gas constant air	287	J / kgK

Table () shows an overview of the design variables at different points of state of the compressed air storage process Huntorf. It should be noted that the high-pressure compressor is divided into three thermodynamic stages for modelling. Physically, it is a six-stage compressor, which has intermediate cooling of the compressed air after every two stages. Accordingly, we can assume that the plant is operated by 4 compressors -including the low pressure compressor- with intercoolers after each compressor; However, the intermediate pressures of the three stages high pressure are not known as a design data and therefore it can be estimated according to formula () (for state point 4) or formula (4.2) (state point 6) (the state numbers are shown in Figure 8):

$$P_{Comp2,P4} = \sqrt[3]{P_{Comp1,P2}^2 * P_{Comp,P8}}$$

- $P_{Comp2,P4}$: Pressure after compressor 2, state point 4
- $P_{Comp1,P2}$: Pressure after compressor 1, state point 2
- $P_{Comp4,P8}$: Pressure after compressor 4, state point 8

$$P_{Comp3,P6} = \sqrt[3]{P_{Comp1,P2}^2 * P_{Comp,P8} * P_{Comp,P8}}$$

- $P_{Comp3,P6}$: Pressure after compressor 3, state point 6
- $P_{Comp1,P2}$: Pressure after compressor 1, state point 2
- $P_{Comp4,P8}$: Pressure after compressor 4, state point 8

These formulas are in line with the assumption that intermediate pressure in high-pressure compressors that require minimal technical work for compression are derived for Ideal gas from the formula: $P_{Intermediate} =$

$$\sqrt{P_{Inlet\ pressure} * P_{outlet\ pressure}}$$

Table () shows an overview of the layout data and the data of the system that have just been calculated for some state points (the state numbers are shown in Figure 8).

Component		State point	Physical property	Value	Unit
Low pressure Compressor	Comp 1	2	Temperature	510	K
			pressure	6	Bar
High Pressure Compressor	Comp 2	4	Pressure	13.47	Bar
	Comp 3	6	Pressure	30.27	Bar
	Comp 4	8	Pressure	68	Bar
Low pressure turbine	Turb 1	15	Temperature		K
			Pressure		Bar
High pressure turbine	Turb 2	13	Temperature		K
			Pressure		Bar
Cooler		3,5,7,9	Temperature	308	K
Throttle valve		12	Pressure	42	bar

Mass flow rates of air during the charge and discharge mode from the cavern and mass flow rate of natural gas for combustion chamber are listed in the below table ()

Mass flow rate (kg/s)	Value
Air mass flow during the charging process (Constant value)	108
Air mass flow during discharging process (Maximum value)	455
Total Natural gas mass flow rate	11.44
NG mass flow into the low-pressure combustion chamber	4.46
NG mass flow into the high-pressure combustion chamber	6.98

3.2.2 Model component in charging system (Before Cavern)

After the definition of the input data in the previous part, Now it's time to model each component in the charging system to store the air in the cavern. In the below layout we have 4 compressors driven by electric motor via drive shaft to compress the air from atmospheric pressure to 68 bar.

After each compressor a cooling process occur to reduce the specific volume of the compressed air specially in the high pressure stages as it cools down the air to 35°C after each stage until it reaches to the last after-cooler which cool it down to 50°C close to the cavern wall temperature.

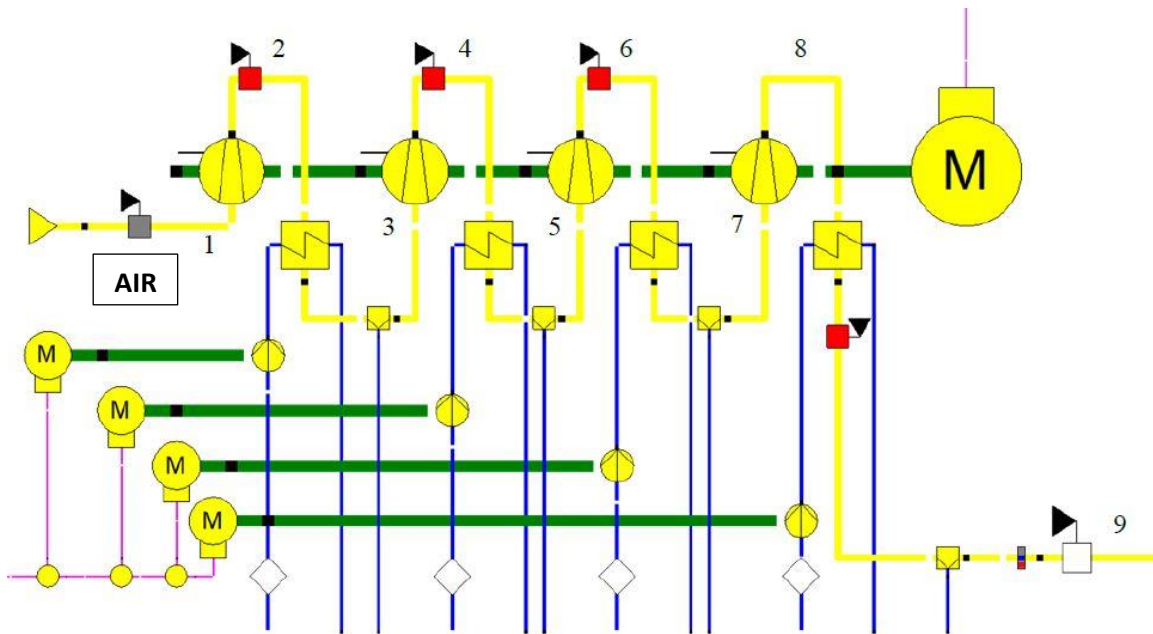


Figure 10 Cavern charging system components

Intercooler pump work is negligible as it's very small compared to the power of the compressor. In order to get the compressor power we shall define the isentropic efficiency of each compressor which is defined as the ratio of the work input to an isentropic process, to the work input to the actual process between the same inlet and exit pressures which should be defined for each compressor

$$\eta_{\text{Compressor isentropic}} = \frac{w_s}{w_{\text{real}}} = \frac{h_{2s} - h_1}{h_2 - h_1}$$

Compressor 1 + Intercooler 1 (points 1-3)

The low pressure compressor has an isentropic efficiency of 84.4% and it takes the air from the ambient conditions to compress it to 6 bar with mass flow rate of 108 kg/s. at the outlet of the compressor temperature reaches to 510 K(237°C) and then it's cooled down through Intercooler 1 to reach temperature 308 K(35°C) before entering to the high pressure compressor. Due to the cooling of the air stream, it loses almost 0.2kg/s of its mass flow rate due to vapor condensation.

In fig () we can see all the streams thermodynamics properties due to compression and cooling processes. The cooling water enter the Intercooler with mass flow rate of 50 kg/s at pressure of almost 2 bars and temperature of 308 K (35°C)and the hot water leaves the intercooler at temperature 392.5 K (119°C)which is considered as a waste of energy from the control volume of the plant.

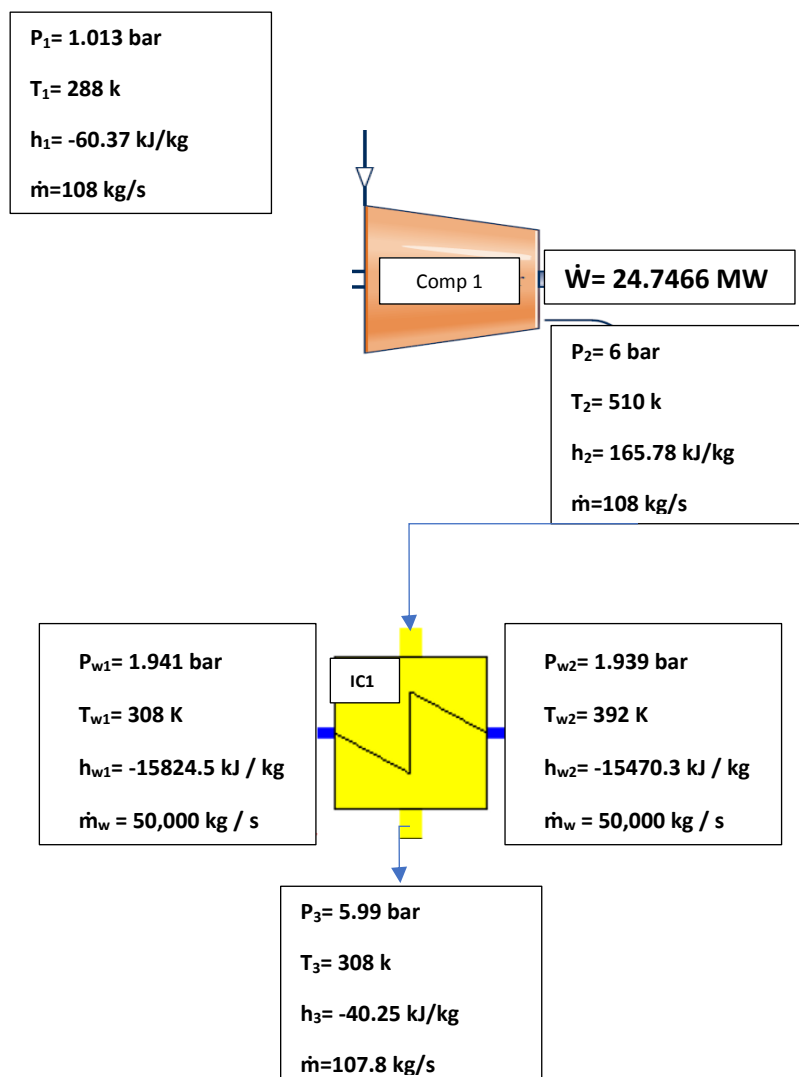


Figure 11 Low-pressure compressor with first intercooler process flow points 1-3

Compressor 2 + Intercooler 2 (Points 3-5)

The high-pressure compressor is a six stages compressor in which we can divide each 2-stages as separate compressor after which air is cooled down to temperature 35°C K in coolers. Compressor 2 has an isentropic efficiency of 73% and the air enters to compressor 2 with pressure of 5.99 bar to be compressed to intermediate pressure of 13.42 bar and it reaches to temperature of 416.64 K (-143.64°C). The compressor consumes shaft power of 12.237 MW to compress a mass flow rate of 107.8 kg/s. After that the air enters to intercooler 2 which is cooled down by a flow of water that enters at 35°C and leaves at 97°C with mass flow rate of 50 kg/s.

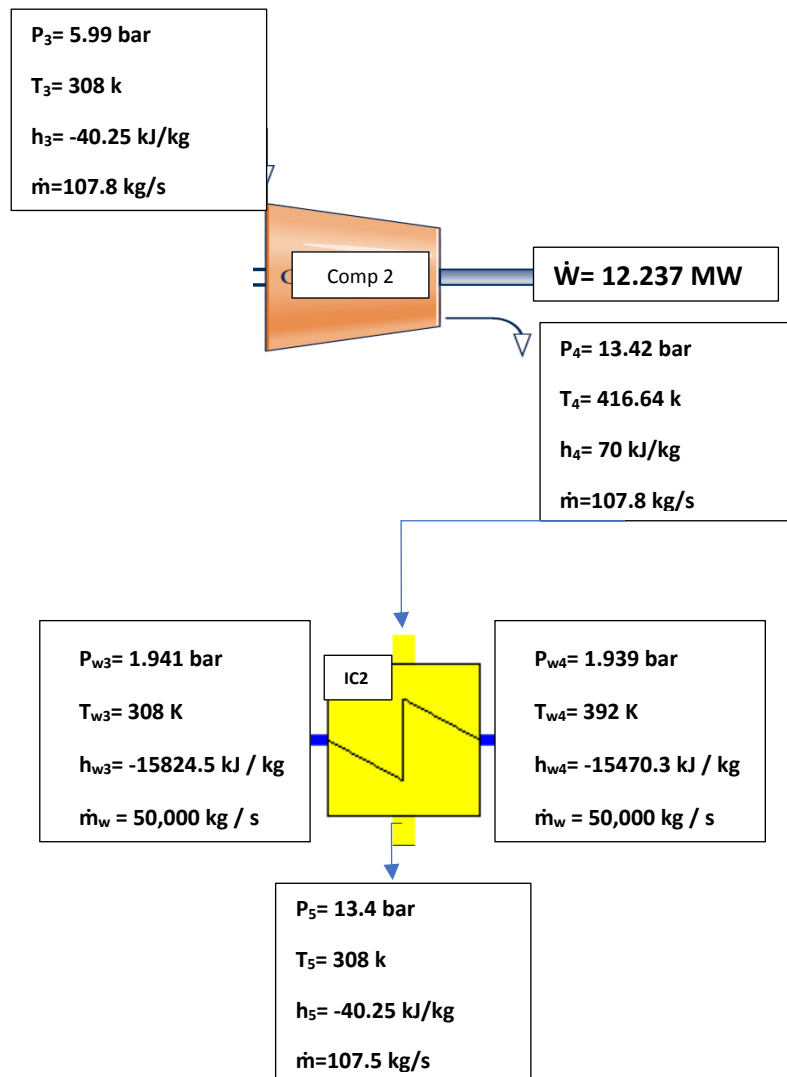


Figure 12 High pressure compressor with 2nd intercooler process flow Points 3-5

Compressor 3 + Intercooler 3 (Points 5-7)

The 3rd & 4th stages in the high-pressure compressor are represented by compressor 3 which receives the air at pressure 13.4 bar to compress it to 30 bar and temperature reaches 412.4 K (139.2°C). Mass flow rate of air in compressor is 107.5 kg/s therefore the consumed shaft power in compressor 3 is 11.72 MW. The air enter the Intercooler to be cooled to 35°C which increase the cooling water to reach 92.7°C at the outlet. Air mass flow rate losses almost 0.2 kg/s due to vapor condensation after cooling.

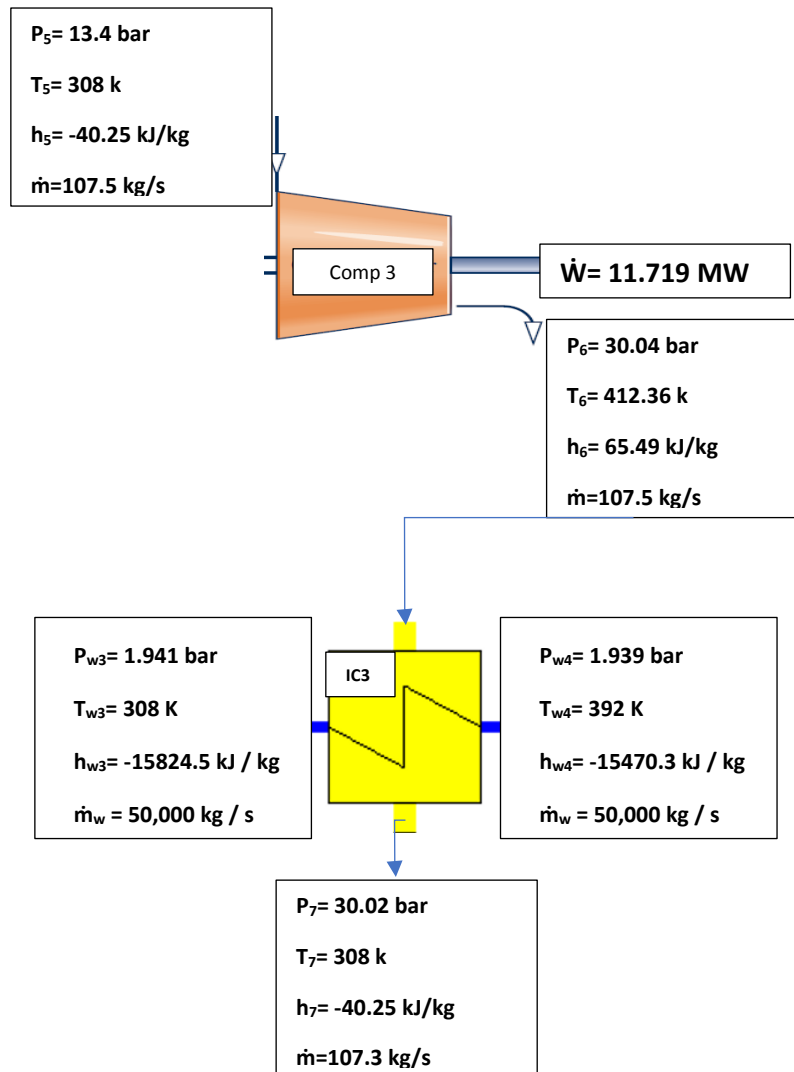


Figure 13 High-pressure (3rd stage) compressor with intercooler 3 points 5-7

Compressor 4 + Aftercooler 4 (Points 7-9)

Last 2 stages in the high-pressure compressor are represented by compressor 4 which takes the air at pressure 30 bar and pressurize it to the cavern pressure of 68 bar to compress mass flow rate of 107.3 kg/s and it consumes shaft power 13.67 MW from the electric motor shaft. After-cooler is important to cool down the air before storage from 157 to 50 °C which is the wall temperature of the cavern.

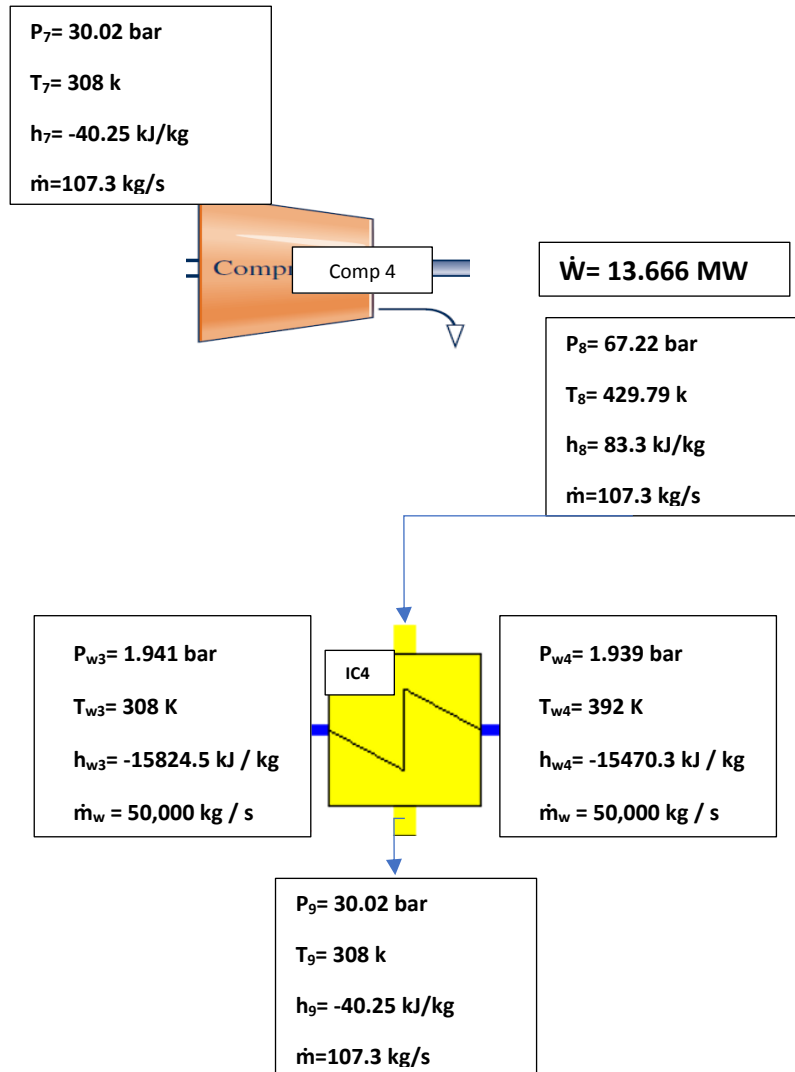
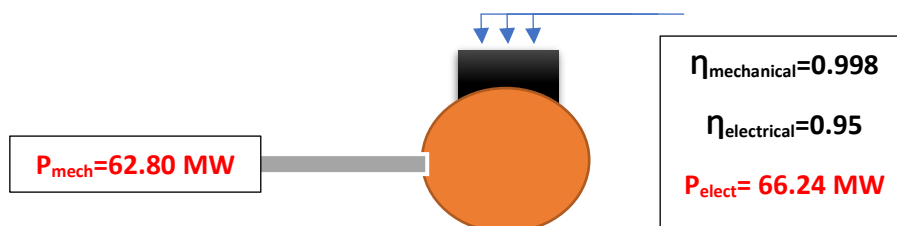


Figure 14 Compressor 4+ Aftercooler 4 process flow (points 7-9)

Compressors drive motor:

the high- and low-pressure compressors are driven by an electric-motor delivers total shaft power of 62.80 MW the electric motor has a mechanical efficiency of 99.8% and electrical efficiency of 95%



3.2.3 Model component in discharging system (After Cavern):

During the discharge system, the air from the cavern is constantly throttled to 42 bar with a throttle valve. Before throttling, the air filtered through an air filter of cavernous dust and other contaminants to protect the blades of the turbines from damage. After throttling, the air passes into the first Silo-type combustor, where the first combustion of natural gas occurs in the high-pressure combustion chamber to raise the temperature of the air and then expand the air-exhaust mixture through the high-pressure turbine.

After the first air expansion, the second combustion takes place in the low-pressure combustion chamber to finally expand the air within the low-pressure turbine to ambient pressure. As the air expands in the turbines, the generator shaft is driven to re-convert the mechanical energy into electrical energy. Figure () is a section of the model system for the power production part whose main components are illustrated below.

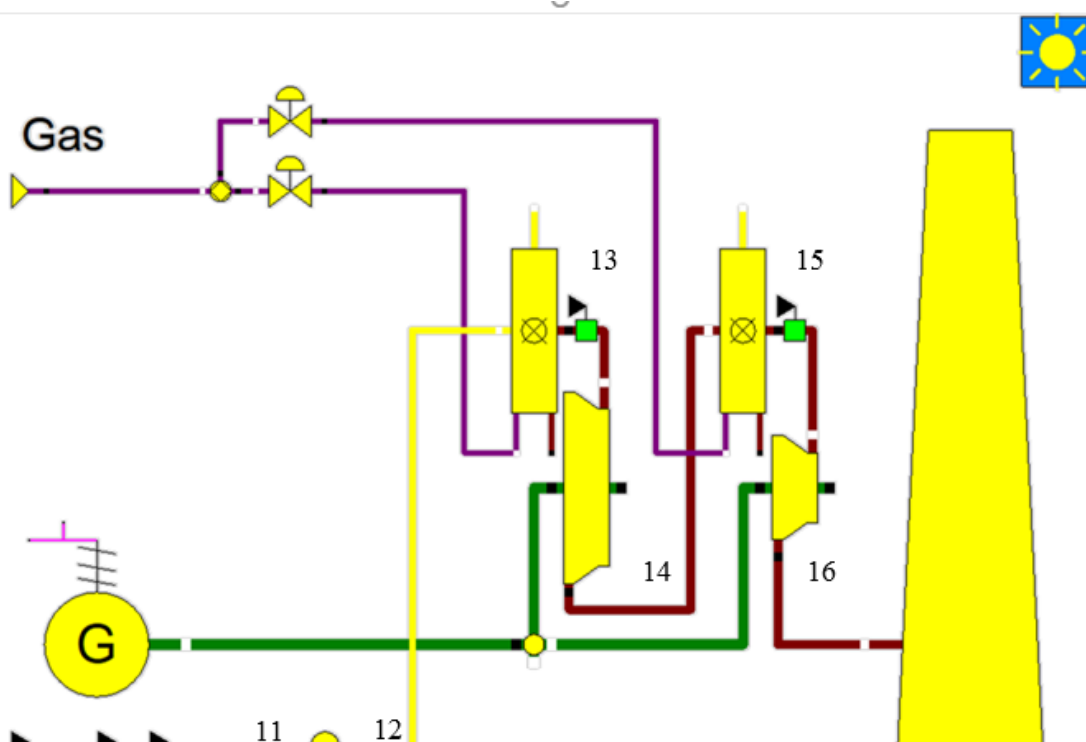


Figure 15 Components of discharging system

Throttle valve (Points 11-12):

First, the air coming out of the cavern is throttled after the air filtration by a throttle valve set from a maximum of 68 bar to constant pressure 42 bar. The throttling is an isenthalpic process in which the so-called Joule-Thomson effect comes into play. The resultant of Joule-Thomson effect cools the air from 41°C to 36.5°C at (-33.767 kJ/kg). Inversion-temperature of air is +450 °C, above this temperature the expansion will warm the air. In the case of Huntorf power plant throttle, no work is done to the outside during expansion and because of the high flow velocity no heat is exchanged with the surroundings (approximately), but only internal work against intermolecular forces.

The Joule-Thomson coefficient μ can be used to describe the direction and strength of the isenthalpic state change, which depends on the gas type, initial temperature, and initial pressure. The coefficient can be calculated by using the following formula:

$$\mu = \left(\frac{\Delta T}{\Delta P} \right)_H$$

The rate of change of temperature ΔT with respect to pressure P in a Joule-Thomson process (at constant enthalpy H) is the Joule–Thomson coefficient μ .

However, in Cantera we can't find the temperature reduction since we are dealing with Ideal gas and the enthalpy is a function only of temperature $h(T)$ not as real gases which is a function of temperature and pressure $h(P,T)$; Therefore, we to get the temperature after expansion we used the data of another study made by using Epsilon STEAG

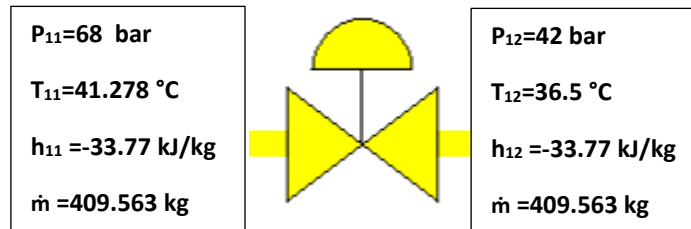


Figure 16 Throttle valve process flow (Points 11-12)

High-pressure combustion chamber(Points 12-13):

After throttling, an (almost) isobaric combustion takes place at 41.998 bar in the high-pressure combustion chamber to raise the temperature of the gas mixture consisting of the compressed air and natural gas from about 36.5°C to 570° C. Without this combustion, the subsequently connected turbine would freeze and cause irreversible damage. The combustion is only approximately isobaric - there is a pressure loss. This is estimated at about 0.7 bar. The combustion chamber is modelled as a 2-reactor Ideal-gas reactors where the 1st reactor is used to handle the stoichiometric combustion process while the air-fuel ratio for natural gas is 17.2 which means only 76.712 kg/s of air is entered with 4.67 of fuel to the 1st reactor and then 2nd reactor is used to dilute the combustion products with the rest of the air 332.8 kg/s. in addition, The simulation aiming to simulate the combustion products and iterative methods are used to find all the variables.

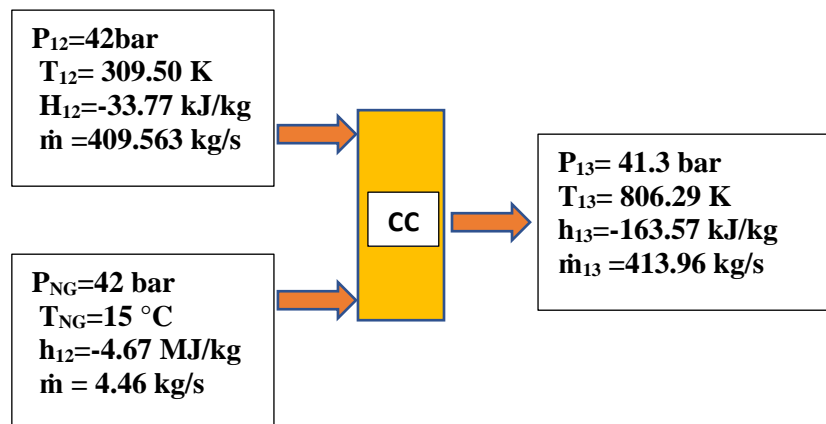


Figure 17 High pressure combustion chamber process flow (points 12-13)

High-pressure turbine (Points 12-13):

After combustion, the gas mixture in the high-pressure turbine is expanded from 41.3 bar to 13.5 bar. The turbine extracts energy from the working medium (air-exhaust mixture) in order to generate a shaft power via the generator of 84.49 MW. The temperature drops from 806.29 K to 624K. Isentropic efficiency of the turbine is 0.894

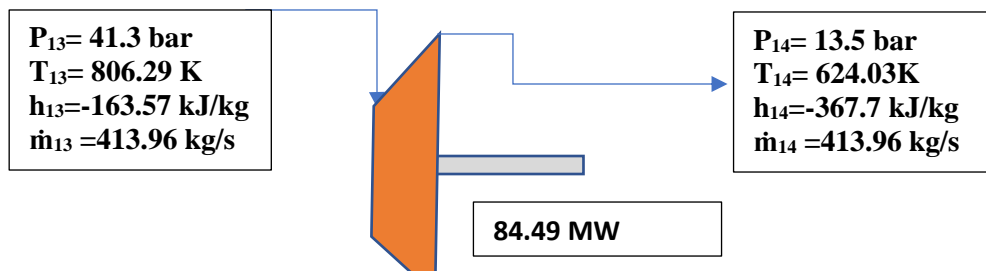


Figure 18 High pressure turbine process flow (Points 13-14)

Low pressure combustion chamber (Points14-15):

In order to increase the temperature of the gas mixture again, it is then mixed with the help of the second combustion chamber again with natural gas and burned again. The temperature is thereby increased from 624.03K to 1255K. Simulation of low-pressure combustion chamber is the same as the high-pressure chamber while the mass flow rate of the fuel entered to the chamber is 6.98 kg/s

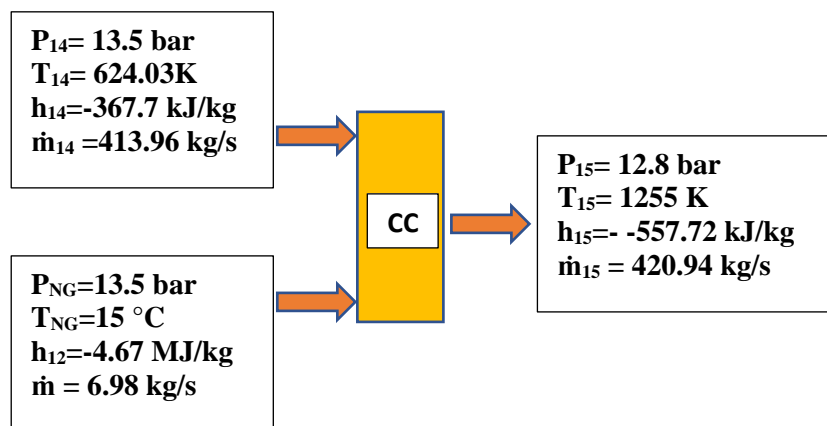


Figure 19 Low pressure combustion chamber (points 14-15)

Low pressure turbine (Points 15-16)

Lastly, we expanded the gas mixture in the low-pressure turbine from 12.8 bar to ambient pressure, giving off a mechanical power of 248.9 MW.

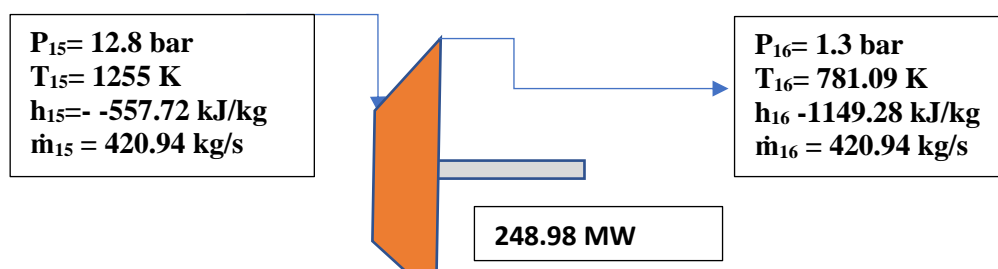


Figure 20 Low pressure turbine process flow (Points 15-16)

Electric Generator:

This electrical power is generated with the generator/motor unit. In the generator mode the nominal efficiency was set at 98.9%.

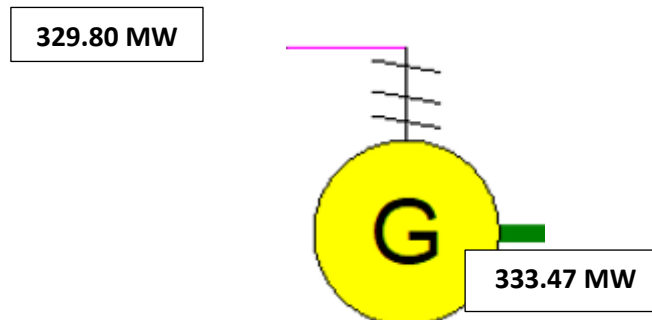


Figure 21 Generator Input / Output

Compressed Air Cavern (Point 10):

A central element of the compressed air storage is the cavern in which the storage medium compressed air is stored for several hours or days. The thermodynamic behaviour of the cavern is complex, since different measured values and cavern properties are not direct or difficult to measure, such as the surface, which is only approximately cylindrical cavities. Also, the exact thermal conductivity of the surrounding salt rock or its temperature can be acquired only by estimated and empirical values. The thermodynamic model of the cavern must be mathematically formulated based on energy and mass balances in order to map the behaviour close to reality.

It should be noted that during the storage process by the increase in pressure in the cavern also results in an increase in temperature of the stored gas (considered as "secondary compression"), or during the discharging process the opposite effect - a decrease in temperature by the drop in the Storage pressure in the cavern (considered as "secondary expansion"). During the storage time in which the mass flow is zero, accordingly, there are dynamic processes within the cavern, since the state variable temperature again adapts to the ambient temperature of the rock (about 50 °C), which has an effect on the pressure in the cavern. For an accurate mathematical representation of this situation a differential equation must be solved. In Fig () a graphical representation of the cavern simulation done by previous work in IEVB by using STEAG's EBSILON Professional software that represent the state inside the cavern.

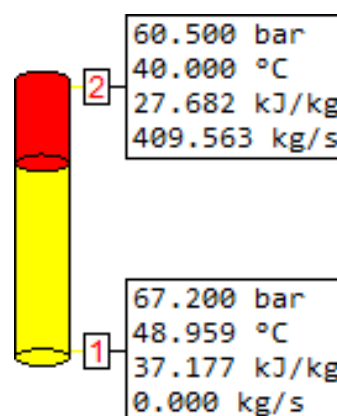


Figure 22 Cavern storage properties Input / Output

3.2.4 Script of Model Simulation

In this thesis, Cantera-Matlab is used which is a tool to measure the thermodynamic properties of all the streams but the system components equations must be modelled so hand numerical calculations was necessary to develop the concept of each point and the possibility to simulate components specially it's not a graphically supported programming as EBSILON enables an intuitive, readable representation of the entire program content in the form of the system flow diagram which has been used in previous work in IEVB ([Institut für Energieverfahrenstechnik und Brennstofftechnik](#)) which is used to make validation for the model made on matlab.

Charging system simulation (Before Cavern):

```
w=Water;
g=GRI30;
%
% Mass flow rates of Air stream (kg/s)
m1=108;
m2=108;
mwcond1=0.2;
m3=m2-mwcond1;
m4=m3;
mwcond2=0.3;
m5=m4-mwcond2;
m6=m5;
mwcond3=0.2;
m7=m6-mwcond3;
m8=m7;
m9=107.3;
%
% Dry Air Mass Composition
YO2=0.231957;
YN2=0.754253;
YAR=0.013896;
%
% Point 1 Entrance of COMP1
%
set(g, 'T', 288, 'P', 101325, 'X', 'H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
h1=enthalpy_mass(g);
s1=entropy_mass(g);
p1=pressure(g);
T1=temperature(g);
%
% Compressor 1 properties
eta_comp1=0.848;
%
% point 2 exit of COMP1
%
p2=6e+5;
set(g, 'S', s1, 'P', p2, 'X', 'H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
h2s=enthalpy_mass(g);
T2s=temperature(g);
h2=(h2s-h1)/eta_comp1+h1;
set(g, 'H', h2, 'P', p2, 'X', 'H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
T2=temperature(g);
s2=entropy_mass(g);
%
% Intercooler Properties 1 & Energy Balance
%
mw=50;
pw1=1.944e+5;
tw1=34.858+273.15;
set(w, 'T', tw1, 'P', pw1);
hw1=enthalpy_mass(w);
sw1=entropy_mass(w);
```

```
pw2=1.939e+5;
tw2=119.229+273.15;
set(w, 'T',tw2 , 'P',pw2);
hw2=enthalpy_mass(w);
sw2=entropy_mass(w);
%EnergyBalance
%
% Point 3 exit of intercooler1
%
p3=5.99e+5;
T3=308;
set(g, 'T',T3 , 'P',p3,'X','H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
h3=enthalpy_mass(g);
s3=entropy_mass(g);

%
% Compressor 2 properties
eta_comp2=0.73;
%
% Point 4 exit of comp2
p4=13.424e+5;
set(g, 'S',s3 , 'P', p4,'X','H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
h4s=enthalpy_mass(g);
T4s=temperature(g);
h4=(h4s-h3)/eta_comp2+h3;
set(g, 'H',h4 , 'P', p4,'X','H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
T4=temperature(g);
s4=entropy_mass(g);
%
% Intercooler 2 properties (points 4,5)
%
pw3=1.941e+5;
tw3=34.858+273.15;
set(w, 'T',tw3 , 'P',pw3);
hw3=enthalpy_mass(w);
sw3=entropy_mass(w);
pw4=1.939e+5;
tw4=96.834+273.15;
set(w, 'T',tw4 , 'P',pw4);
hw4=enthalpy_mass(w);
sw4=entropy_mass(w);
%EnergyBalance

%
% Point 5 exit of int.cooler2
%
p5=13.404e+5;
T5=308;
set(g, 'T',T5 , 'P', p5,'X','H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
s5=entropy_mass(g);
h5=enthalpy_mass(g);

%
% % Compressor 3 properties
eta_comp3=0.76;
%
% Point 6 exit of comp3
p6=30.035e+5;
set(g, 'S',s5 , 'P', p6,'X','H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
h6s=enthalpy_mass(g);
T6s=temperature(g);
h6=(h6s-h5)/eta_comp3+h5;
set(g, 'H',h6 , 'P', p6,'X','H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
```

```
T6=temperature(g);
s6=entropy_mass(g);
%
%Intercooler 3 properties (points 6,7)
%
pw5=1.939e+5;
tw5=34.858+273.15;
set(w, 'T',tw5 , 'P',pw5);
hw5=enthalpy_mass(w);
sw5=entropy_mass(w);
pw6=1.939e+5;
tw6=92.509+273.15;
set(w, 'T',tw6 , 'P',pw6);
hw6=enthalpy_mass(w);
sw6=entropy_mass(w);
%EnergyBalance

%
% Point 6 exit of int.cooler3
%
p7=30.015e+5;
T7=308;
set(g, 'T',T7 , 'P', p7,'X','H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
s7=entropy_mass(g);
h7=enthalpy_mass(g);
%
% % Compressor 4 properties
eta_comp4=0.65;
%
% Point 8 exit of comp4
p8=67.22e+5;
set(g, 'S',s7 , 'P', p8,'X','H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
h8s=enthalpy_mass(g);
T8s=temperature(g);
h8=((h8s-h7)/eta_comp4)+h7;
set(g, 'H',h8 , 'P', p8,'X','H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
T8=temperature(g);
s8=entropy_mass(g);
%
%Intercooler 4 properties (points 8,9)
%
pw7=1.935e+5;
tw7=48.86+273.15;
set(w, 'T',tw7 , 'P',pw7);
hw7=enthalpy_mass(w);
sw7=entropy_mass(w);
pw8=1.935e+5;
tw8=107.968+273.15;
set(w, 'T',tw8 , 'P',pw8);
hw8=enthalpy_mass(w);
sw8=entropy_mass(w);
%EnergyBalance
%
% Point 9 exit of int.cooler4
%
p9=67.2e+5;
T9=322;
set(g, 'T',T9 , 'P', p9,'X','H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
s9=entropy_mass(g);
h9=enthalpy_mass(g);
% end of points to cavern
% Results & Energy Analysis
eta_transmission=0.97;%Transmission losses from the motor to compressor shaft
%
```

```

Wc1=m1*(h2-h1)/eta_transmission;
Wc2=m4*(h4-h3)/eta_transmission;
Wc3=m6*(h6-h5)/eta_transmission;
Wc4=m7*(h8-h7)/eta_transmission;
WcT=Wc1+Wc2+Wc3+Wc4;
% Exergy Analysis
T0=288;
h0=h1;
s0=s1;
Ex1=m1*((h1-h0)-T0*(s1-s0));
Ex2=m2*((h2-h0)-T0*(s2-s0));
Ex3=m3*((h3-h0)-T0*(s3-s0));
Ex4=m4*((h4-h0)-T0*(s4-s0));
Ex5=m5*((h5-h0)-T0*(s5-s0));
Ex6=m6*((h6-h0)-T0*(s6-s0));
Ex7=m7*((h7-h0)-T0*(s7-s0));
Ex8=m8*((h8-h0)-T0*(s8-s0));
Ex9=m9*((h9-h0)-T0*(s9-s0));
% Water IC Exergies
Exw1=mw*((hw1-h0)-T0*(sw1-s0));
Exw2=mw*((hw2-h0)-T0*(sw2-s0));
Exw3=mw*((hw3-h0)-T0*(sw3-s0));
Exw4=mw*((hw4-h0)-T0*(sw4-s0));
Exw5=mw*((hw5-h0)-T0*(sw5-s0));
Exw6=mw*((hw6-h0)-T0*(sw6-s0));
Exw7=mw*((hw7-h0)-T0*(sw7-s0));
Exw8=mw*((hw8-h0)-T0*(sw8-s0));
% Exergy balance
%
% Compressor 1,2,3,4
ExD_C1=Wc1+Ex1-Ex2;
ExD_C2=Wc2+Ex3-Ex4;
ExD_C3=Wc3+Ex5-Ex6;
ExD_C4=Wc4+Ex7-Ex8;
%
% Intercoolers 1,2,3,4
ExD_I1=Ex2+Exw1-(Ex3+Exw2);
ExD_I2=Ex4+Exw3-(Ex5+Exw4);
ExD_I3=Ex6+Exw5-(Ex7+Exw6);
ExD_I4=Ex8+Exw7-(Ex9+Exw8);

ExD_Sum=ExD_C1+ExD_C2+ExD_C3+ExD_C4+ExD_I1+ExD_I2+ExD_I3+ExD_I4;
%
%Exergy balance for the whole system before cavern
ExD_Tot=WcT+Ex1+Exw1+Exw3+Exw5+Exw7-(Ex9+Exw2+Exw4+Exw6+Exw8);
%
% Fraction of Exergy Destruction
Rho_C1=(ExD_C1/ExD_Sum);
Rho_C2=(ExD_C2/ExD_Sum);
Rho_C3=(ExD_C3/ExD_Sum);
Rho_C4=(ExD_C4/ExD_Sum);
%
Rho_I1=(ExD_I1/ExD_Sum);
Rho_I2=(ExD_I2/ExD_Sum);
Rho_I3=(ExD_I3/ExD_Sum);
Rho_I4=(ExD_I4/ExD_Sum);
% Displayed Results
pressureall= [p1;p2;p3;p4;p5;p6;p7;p8;p9]
temperatureall= [T1;T2;T3;T4;T5;T6;T7;T8;T9]
enthalpyall= [h1;h2;h3;h4;h5;h6;h7;h8;h9]
massflowall= [m1;m2;m3;m4;m5;m6;m7;m8;m9]
entropyall= [s1;s2;s3;s4;s5;s6;s7;s8;s9]
exergyall= [Ex1;Ex2;Ex3;Ex4;Ex5;Ex6;Ex7;Ex8;Ex9]
pressurewater= [pw1;pw2;pw3;pw4;pw5;pw6;pw7;pw8]

```

```

temperaturewater= [tw1;tw2;tw3;tw4;tw5;tw6;tw7;tw8]
enthalpywater= [hw1;hw2;hw3;hw4;hw5;hw6;hw7;hw8]
entropywater= [sw1;sw2;sw3;sw4;sw5;sw6;sw7;sw8]
exergywater= [Exw1;Exw2;Exw3;Exw4;Exw5;Exw6;Exw7;Exw8]
x=[Rho_C1 Rho_C2 Rho_C3 Rho_C4 Rho_I1 Rho_I2 Rho_I3 Rho_I4];
pie(x)
title('Exergy destruction percentage')

```

Discharging system simulation (After Cavern):

Modelling this part in Cantera-Matlab is more complex as the components in the power production part has many variables so different sub-programs logarithms is used and then final values of these components products is added to more general code.

1- Combustion chamber Code:

In combustion chamber we divided the chamber into 2 ideal gas reactors as the mass flow rate of air is high which make error in the iterative process and stop the combustion chemical reaction. Pressure control valves are used in the model to connect the 2 reactors and connect the 2nd reactor to the environment reservoir see the below fig (). In which the value of K-constant is so important to be set correctly to reduce the pressure losses in the system make the combustion process almost isobaric. Mass flow controllers is essential to connect the fuel and air reservoirs to the reactors and it helps to set the mass flow rate entering to each reactor.

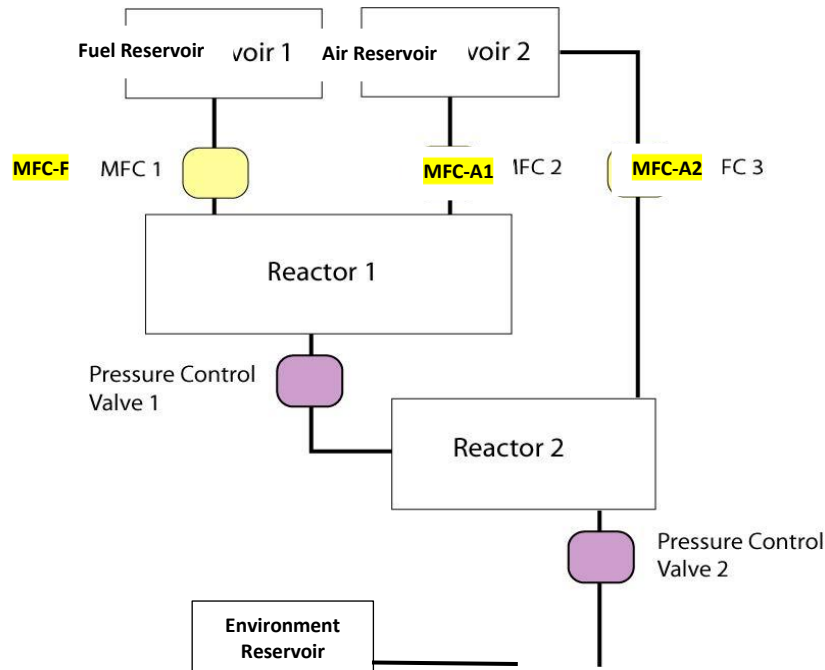


Figure 23 Reactors network modelling flow diagram

```

g=GRI30;
a=Air;
% Mass Flow Rates
mf=4.46; % Fuel inlet to r1
ma1=76.712; % Air Inlet to r1
mrout=mf+ma1; % total outlet of r1
ma2=409.5-ma1; %Air Inlet to r2
mtot=mf+ma1+ma2; % Total out of r2
pp = 42*oneatm;
%
%Reactor 1
%
set(g, 'T',2000, 'X', 'CH4:1.0', 'O2:1.0, N2:3.76');
r1=IdealGasReactor(g);
setInitialVolume(r1,3);
% Reactor 2

```

```

set(g, 'T', 500, 'X', 'O2:0.21, N2:0.79');
%equilibrate(g, 'TP')
r2=IdealGasReactor(g);
setInitialVolume(r2,3);
%
% ENVIRONMENT RESERVOIR
set(a, 'P', pp);
env = Reservoir(a);
% AIR RESERVOIR
set(g, 'T', 310, 'P', pp, 'X', 'H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
A_IN=Reservoir(g);
% FUEL RESERVOIR
set(g, 'T', 288, 'P', pp, 'X', 'CH4:1.0');
F_IN=Reservoir(g);
%
% Mass flow controllers
%Air MFC
MFC_A1= MassFlowController(A_IN, r1);
setMassFlowRate(MFC_A1, ma1);
MFC_A2= MassFlowController(A_IN, r2);
setMassFlowRate(MFC_A2, ma2);
%Fuel MFC
MFC_F= MassFlowController(F_IN, r1);
setMassFlowRate(MFC_F, mf);
% Connection Valve
V1= Valve(r1,r2);
setValveCoeff(V1,100);
% Environment Valve
V2= Valve(r2,env);
setValveCoeff(V2,100);
%
% Reactor Network
network = ReactorNet({r1,r2});
% Time LOOP
t = 0.0;
dt = 1.0e-5;
t0 = cputime;
nn = 1e05;
tim = zeros(nn,1);
temp1 = zeros(nn,1);
temp2 = zeros(nn,1);
x = zeros(nn,4);
for n = 1:nn
    t = t + dt;
    advance(network, t);
    tim(n) = time(network);
    temp1(n) = temperature(r1);
    temp2(n) = temperature(r2);
    % enth1(n) = enthalpy_mass(r1)
    %enth2(n) = enthalpy_mass(r2)
    x(n,1:4) = moleFraction(g,{'CO2','H2O','O2','N2'});
    fprintf(" \n => n = %f p = %f %f",n, ...
        pressure(r1) / oneatm, pressure(r2) / oneatm);
end
disp(['CPU time = ' num2str(cputime - t0)]);
CO2_fraction = x(nn,1)
H2O_fraction = x(nn,2)
O2_fraction = x(nn,3)
N2_fraction = x(nn,4)
Reactor2_temp = temp2(nn)
Reactor1_temp = temp1(nn)
Reactor1_enthalp = enthalpy_mass(r1)
Reactor2_enthalp = enthalpy_mass(r2)
clf;

```

```

subplot(3,2,1);
plot(tim,temp1);
xlabel('Time (s)');
ylabel('Temperature of Reactor 1(K)');
subplot(3,2,2);
plot(tim,temp1,tim,temp2);
xlabel('Time (s)');
ylabel('Temperature of Reactor 2(K)');
subplot(3,2,3)
plot(tim,x(:,1));
xlabel('Time (s)');
ylabel('CO2 Mole Fraction (K)');
subplot(3,2,4)
plot(tim,x(:,2));
xlabel('Time (s)');
ylabel('H2O Mole Fraction (K)');
subplot(3,2,5)
plot(tim,x(:,3));
xlabel('Time (s)');
ylabel('O2 Mole Fraction (K)');
subplot(3,2,6)
plot(tim,x(:,4));
xlabel('Time (s)');
ylabel('N2 Mole Fraction (K)');

```

2- After cavern code:

```

% After Cavern Calculations
g=GRI30;
% Exergy Reference state
T0=288;
h0=-60370;
s0=6850;
%
% Mass flow rates
mf1=4.46;
mf2=6.98;
m11=409.5;
m12=m11;
m13=413.9;
m14=m13;
m15=420.88;
m16=m15;
% Point (11) outlet of the Cavern
p11=68e+5;
T11=314.43;
set(g, 'T', T11, 'P', p11, 'X', 'H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
h11=enthalpy_mass(g);
s11=entropy_mass(g);
%
% After Cavern Expansion Valve.
%
p12=4200000;
T12=309.5;
h12=h11;
set(g, 'T', T12, 'P', p12, 'X', 'H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
s12=entropy_mass(g);

% Importing data from the HPCC reactors simulation
%%
% Fuel properties the HPCC
set(g, 'T', 288, 'P', 4200000, 'X', 'CH4:1.0');

```

```
hf1=enthalpy_mass(g);
sf1=entropy_mass(g);
% Point 13:Outlet of C.Chamber/Inlet of HP Turbine.
%
p13=41.3e+5;
T13=806.29;
set(g, 'T', T13, 'P', p13, 'X', 'H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
h13=enthalpy_mass(g);
s13=entropy_mass(g);
%
% High Pressure Turbine
eta_turb1=0.894;
%
% Point 14 outlet of the turbine.
%
p14=13.5e+5;
s14s=s13;
set(g, 'S', s14s, 'P', p14, 'H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
h14s=enthalpy_mass(g);
T14s=temperature(g);
h14=(eta_turb1*(h14s-h13))+h13;
set(g, 'H', h14, 'P', p14, 'H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
T14=temperature(g);
s14=entropy_mass(g);
% Importing data from the LPCC reactors simulation
%%
% Fuel properties the HPCC
set(g, 'T', 288, 'P', 1350000, 'X', 'CH4:1.0');
hf2=enthalpy_mass(g);
sf2=entropy_mass(g);
%Point 15 outlet of combustion chamber/Inlet of LP turbine
%
p15=12.8e+5;
T15=1261;
set(g, 'T', T15, 'P', p15, 'H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
h15=enthalpy_mass(g);
s15=entropy_mass(g);
%
% Low pressure Turbine
eta_turb2=0.9;
%
%Point 16 outlet of the turbine.
%
p16=1.3e+5;
s16s=s15;
set(g, 'P', p16, 'S', s16s, 'H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
h16s=enthalpy_mass(g);
T16s=temperature(g);
h16=(eta_turb2*(h16s-h15))+h15;
set(g, 'P', p16, 'H', h16, 'H2O:0.006,O2:0.20874,N2:0.77532,AR:0.00994');
T16=temperature(g);
s16=entropy_mass(g);
%
% Turbine power
WTHP=m13*(h13-h14);
WTLP=m15*(h15-h16);
WTot=WTHP+WTLP;
% Exergy Calculations
Ex11=m11*((h11-h0)-T0*(s11-s0));
Ex12=m12*((h12-h0)-T0*(s12-s0));
Ex13=m13*((h13-h0)-T0*(s13-s0));
Ex14=m14*((h14-h0)-T0*(s14-s0));
Ex15=m15*((h15-h0)-T0*(s15-s0));
Ex16=m16*((h16-h0)-T0*(s16-s0));
```



```
Exf1=mf1*51937.5;
Exf2=mf2*51937.5;
%
% Exergy destruction
ExD_TV=Ex11-Ex12;
ExD_HPCC=Ex12+Exf1-Ex13;
Exd_THP=Ex13-WTHP-Ex14;
Exd_LPCC=Ex14+Exf2-Ex15;
Exd_TLP=Ex15-WTLP-Ex16;
Exd_Stack=Ex16;
Exd_sum=ExD_TV+ExD_HPCC+Exd_THP+Exd_LPCC+Exd_TLP+Exd_Stack;
% Turbines
pressureall= [p11;p12;p13;p14;p15;p16];
temperatureall= [T11;T12;T13;T14;T15;T16];
enthalpyall= [h11;h12;h13;h14;h15;h16];
massflowall= [m11;m12;m13;m14;m15;m16];
entropyall= [s11;s12;s13;s14;s15;s16];
exergyall= [Ex11;Ex12;Ex13;Ex14;Ex15;Ex16];
```

Chapter 4 Model validation and Results discussion

Based on the thermodynamic model described in the previous chapter and the associated specification assigned to each component of the system, Cantera-Matlab can calculate all state variables (temperature, pressure, enthalpy, etc.) for each state point of the process. These results are listed by state points for the current plant configuration and to different imaginary scenarios which in turn allow graphical representation of the process or further calculations on the technical work, performance and efficiencies of the overall system and provide all the needed data for the energy and exergy analysis of the power plant in different scenarios.

Figure (24) shows the overall current plant layout in the right-handed process (that is, the process gives energy to the environment), noting that the storage process (left side of the figure) is left-handed, that is, energy "consumed". This is plausible and confirms the general structure of the results.

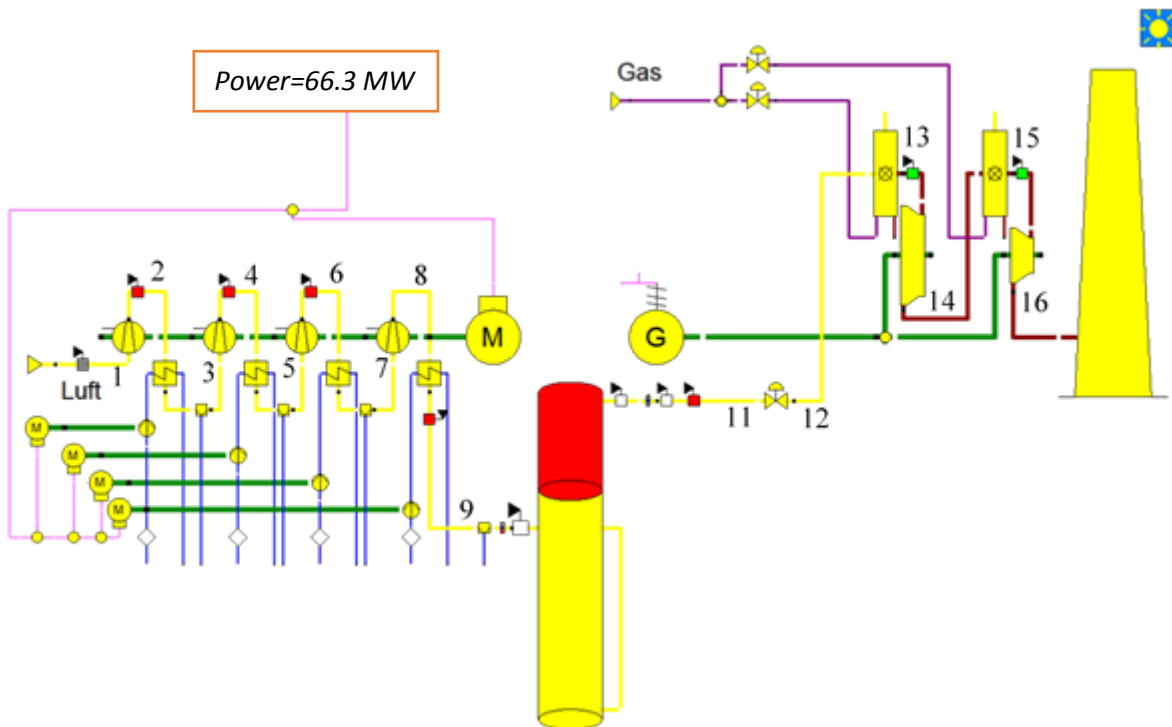


Figure 24 All plant components model layout

4.1 Results data of the current configuration of the power plant.

The data in the table below represent the complete plant state properties calculated by Cantera-Matlab which is used as model for the current configuration of Huntorf power plant in steady-state. These values can be validated comparing the h-s diagram of cycle process created by modelling the plant by STEAG's EBSILON professional from earlier work done by IEVB department in TU Clausthal which has been validated by another model done with EES in the same department.

	p	T	h	\dot{m}	s	Ex
	bar	k	kJ/kg	kg/s	kJ/kg.k	kJ
1	1.01	288.00	-60.37	108.00	6.85	0.00
2	6.00	509.96	165.78	108.00	6.92	22255.59
3	5.99	308.00	-40.25	107.80	6.41	15941.30
4	13.42	416.64	69.86	107.80	6.48	25514.17
5	13.40	308.00	-40.25	107.50	6.17	23070.29
6	30.04	412.36	65.49	107.50	6.24	32471.97
7	30.02	308.00	-40.25	107.30	5.94	30193.43
8	67.22	429.79	83.30	107.30	6.05	40176.36
9	67.20	322.00	-26.14	107.30	5.75	37487.56
11	68.00	314.43	-33.77	409.5	5.73	143281.66
12	42.00	309.50	-33.77	409.5	5.85	128813.06
13	41.30	806.29	482.06	413.9	6.85	224314.78
14	13.50	620.47	281.42	413.9	6.89	136615.83
15	12.80	1261.00	1004.75	420.88	7.70	345098.03
16	1.30	764.00	435.66	420.88	7.79	95142.32

Intercoolers cooling water properties						
	Stream	Pw	Tw	hw	sw	Exw
IC1-IN	w1	1.944	308.008	-15824.57	4.02	143.53
IC1-OUT	w2	1.939	392.379	-15470.39	5.04	3222.24
IC2-IN	w3	1.941	308.008	-15824.57	4.02	143.51
IC2-OUT	w4	1.939	369.984	-15565.05	4.79	2066.09
IC3-IN	w5	1.939	308.008	-15824.57	4.02	143.50
IC3-OUT	w6	1.939	365.659	-15583.26	4.74	1868.56
IC4-IN	w7	1.935	322.01	-15766.10	4.21	393.70
IC4-OUT	w8	1.935	381.118	-15518.08	4.92	2613.47

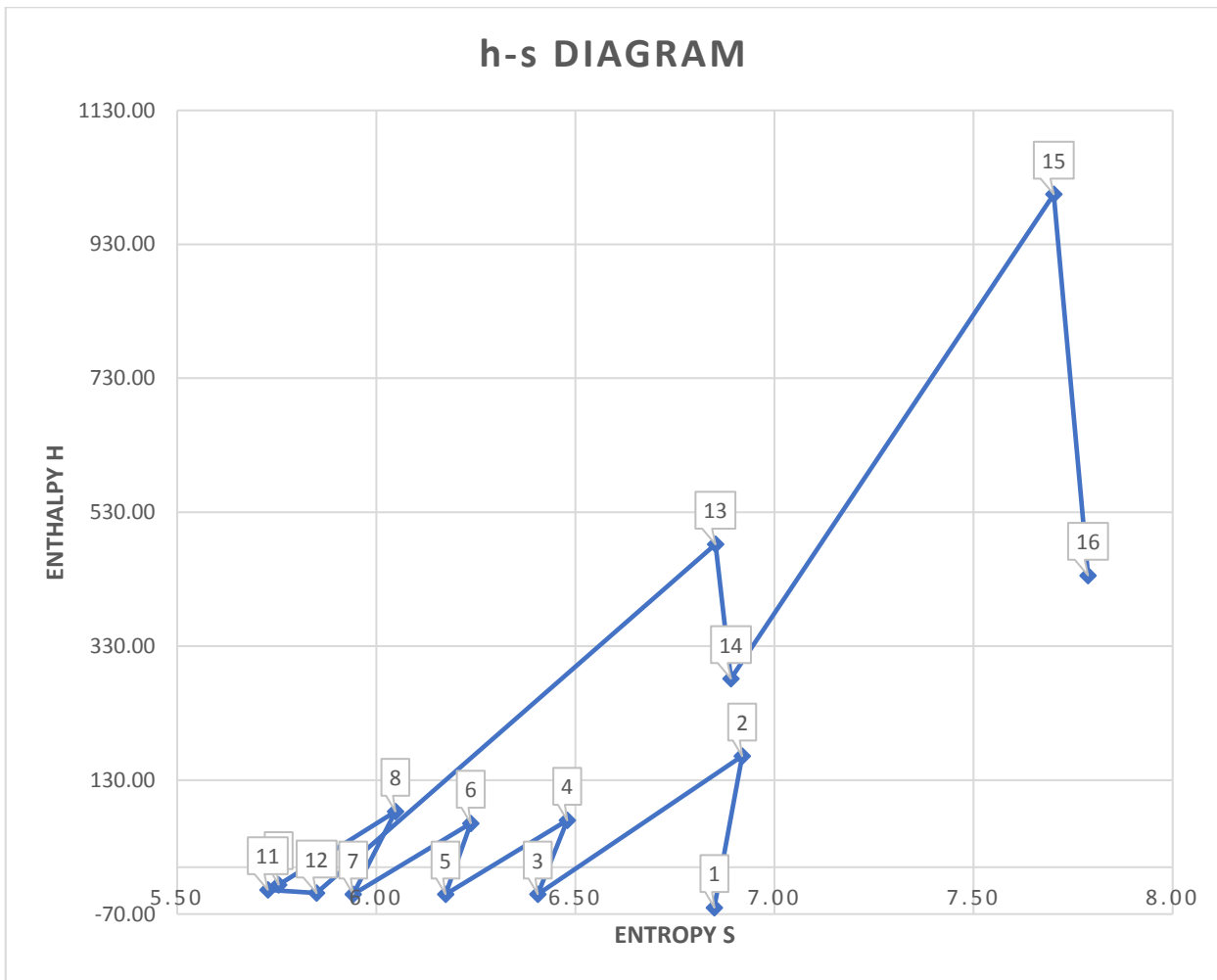


Figure 25 Model Results H-S diagram of thermal power plant

The previous h-s diagram represents the 4 stages of compression with intercoolers after each stage which results lowering the entropy of the flow till the storage point in the cavern after that the heat addition in the high pressure combustion chamber and expansion in the HP turbine. Then the reheat of the flow in the low-pressure combustion chamber to increase the enthalpy of the flow then again to the LP turbine then discharged to environment. This can be compared by the below h-s diagram figure(26) for model validation which has been modelled by another validated work in IEVB and it has identical behaviour like the current model by CANTERA.

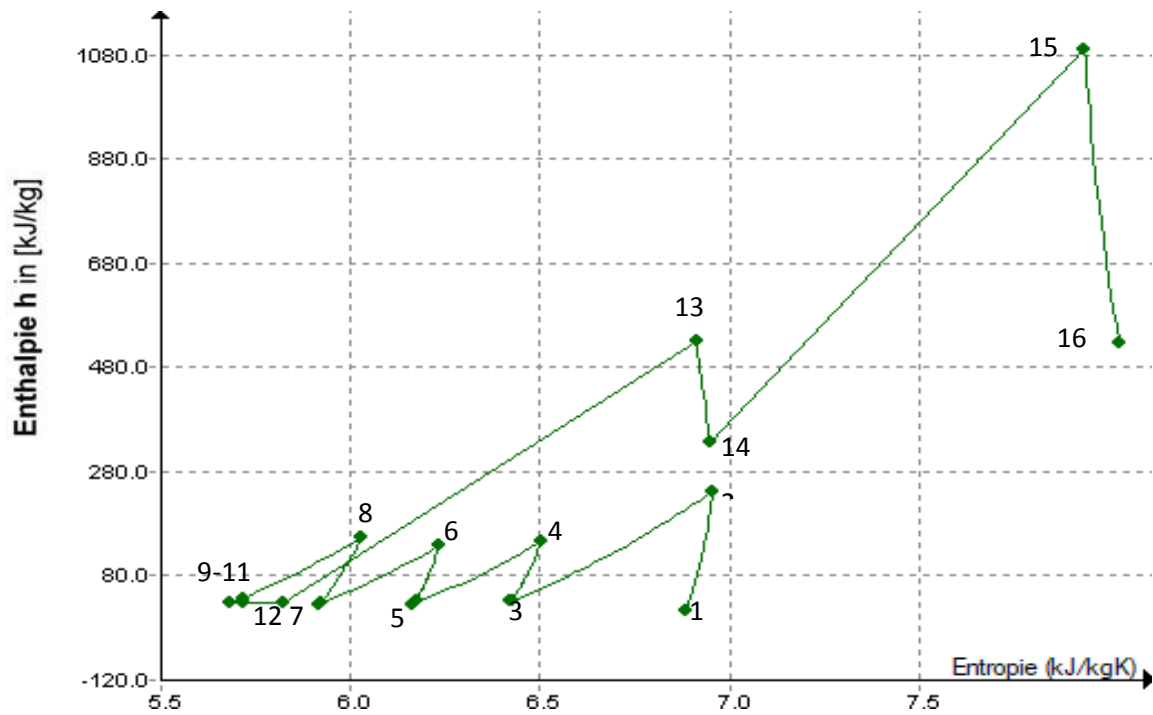


Figure 26 H-S diagram of validating mode I

Reactor simulation trials of High-Pressure Combustion Chamber

In order to get the combustion products properties Reactants enter the reactor at constant pressure and 10^4 iterations is needed for the ideal gas reactor to get the final products out of the combustion process. In figure () we can find the outlet temperature of the stoichiometric reactor which reaches 2300 K then the dilution with the rest of air in second reactor results a mixture of temperature 806.7 K. This mixture composition at the outlet of 2nd reactor has the following molar composition:

$$X_{O_2} = 0.1668 \quad X_{CO_2} = 0.01819 \quad X_{N_2} = 0.76 \quad X_{H_2O} = 0.04388$$

This molar composition used to calculate accurately the thermodynamic properties of the cycle by Cantera specially by introducing GRI30 Gas which molar composition can be changed easily.

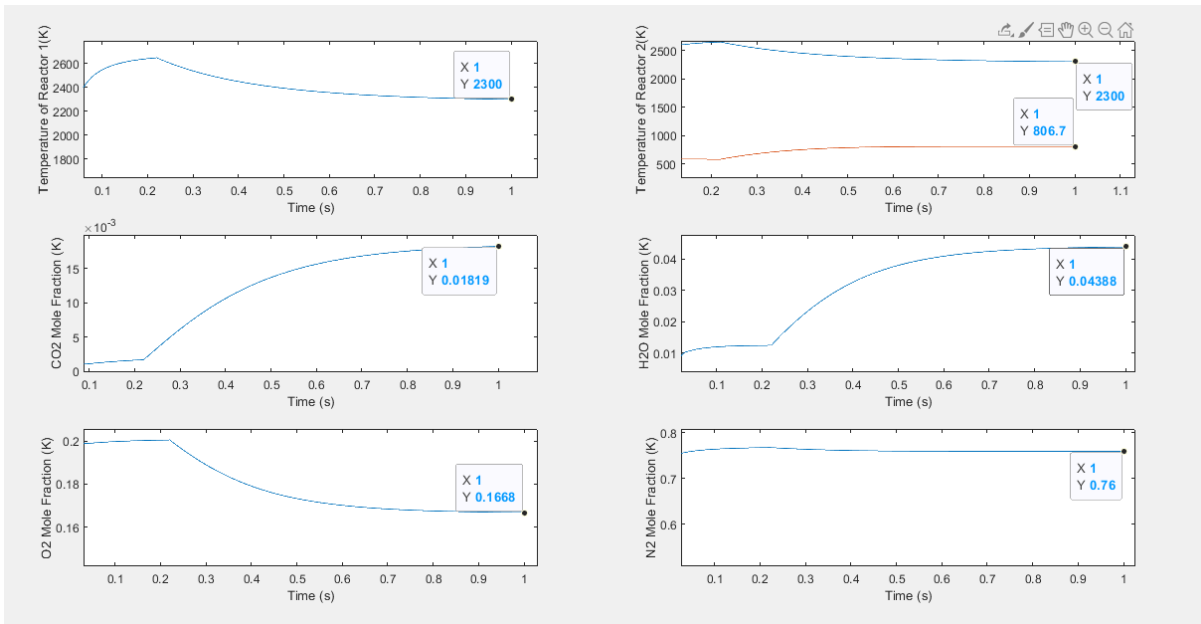


Figure 27 Reactors simulation results of High-Pressure combustion chamber

Reactor simulation trials of Low-Pressure Combustion Chamber

After the expansion in the 1st high pressure turbine the flow enters to the 2nd low pressure combustion chamber which is modelled the same as the High-Pressure combustion Chamber and the outlet from the 1st stoichiometric reactor has temperature of 2041 K and after dilution with the total amount of air reaches temperature of 1262 K with the following molar composition:

$$X_{O_2} = 0.107 \quad X_{CO_2} = 0.04377 \quad X_{N_2} = 0.7449 \quad X_{H_2O} = 0.1008$$

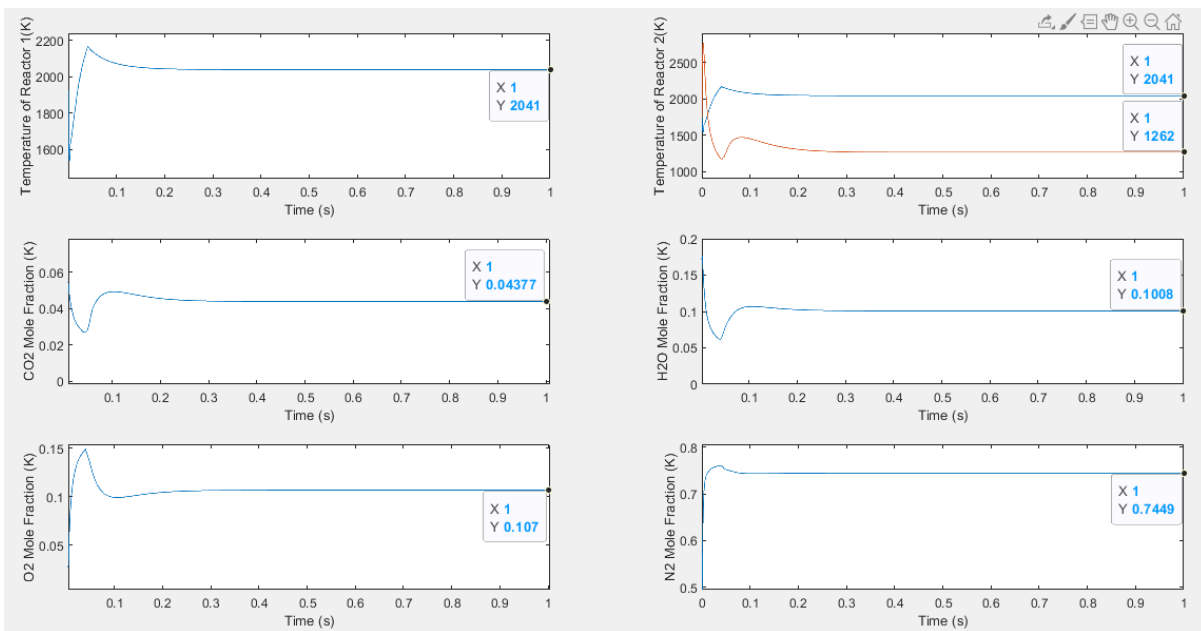


Figure 28 Reactors simulation results of Low-pressure combustion chamber

4.2 Energy and Exergy analysis of charging system.

From the 2nd law of thermodynamics point of view we can evaluate the rational efficiency over the whole control volume of the charging system which indicates the effectiveness of a system relative to its performance in reversible conditions and it can be calculated as the following :

$$\eta_{rational} = \frac{\sum_{out} \dot{Ex}_{out}}{\sum_{in} \dot{Ex}_{in}} = 1 - \frac{\dot{Ex}_{dest, Tot}}{\sum_{in} \dot{Ex}_{in}} = 73.93\%$$

However, if we consider the exergy of water out of the intercooler as waste the rational efficiency of the system will drop to

$$\eta_{rational} = 1 - \frac{\dot{Ex}_{dest, Tot} + Ex_{w2} + Ex_{w4} + Ex_{w6} + Ex_{w8}}{\sum_{in} \dot{Ex}_{in}} = 58.38\%$$

In figure 29 below we can find the values of exergy destruction (ExD) in kJ for all components of the system and the equivalent percentage of exergy destruction (Rho) compared to the total value of exergy destruction considering that the heated water of the intercoolers is useful which is not the case in the real power plant but just to evaluate the components not the system.

Exergy Destruction for charging system		
	Rho	ExD
	percentage	kJ
Comp 1	17.86%	2923.4454
Comp 2	16.28%	2663.7564
Comp 3	14.16%	2316.8896
Comp 4	22.50%	3683.1135
IC 1	19.77%	3235.5678
IC 2	3.19%	521.30858
IC 3	3.38%	553.47739
IC 4	2.87%	469.03681
TOTAL		16366.595

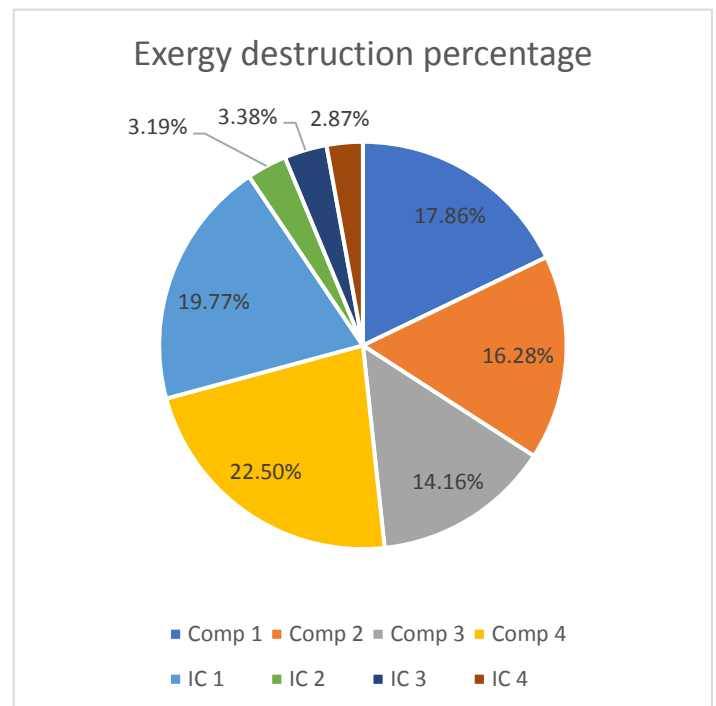


Figure 29 Exergy destruction for charging system

4.3 Energy and Exergy analysis of discharging system.

The discharging systems is crucial to evaluate the thermal power production part which is more complicated than the charging systems and due to the combustion process and the losses in the stack we can find that rational efficiency of the system is much lower than the charging system efficiency and we can calculate it as the following :

$$\eta_{rational} = \frac{\sum_{out} \dot{Ex}_{out}}{\sum_{in} \dot{Ex}_{in}} = 1 - \frac{\dot{Ex}_{dest, Tot}}{\sum_{in} \dot{Ex}_{in}} = 45.22\%$$

Figure 30 indicates the values of exergy destruction (ExD) in kJ for all components of the system and the equivalent percentage of exergy destruction (Rho) compared to the total value of exergy destruction in discharging system and we can see that over 90% of losses happens in the combustion chambers and the stack losses.

Exergy destruction for discharging system		
	ExD	Rho
	kJ	%
Throttle valve	14468.599	3.58%
HPCC	136139.53	33.70%
Turbine 1	3.21E+03	0.79%
LPCC	154041.54	38.13%
Turbine 2	9.80E+02	0.24%
Stack	95142.318	23.55%
Sum	403979.09	100.00%

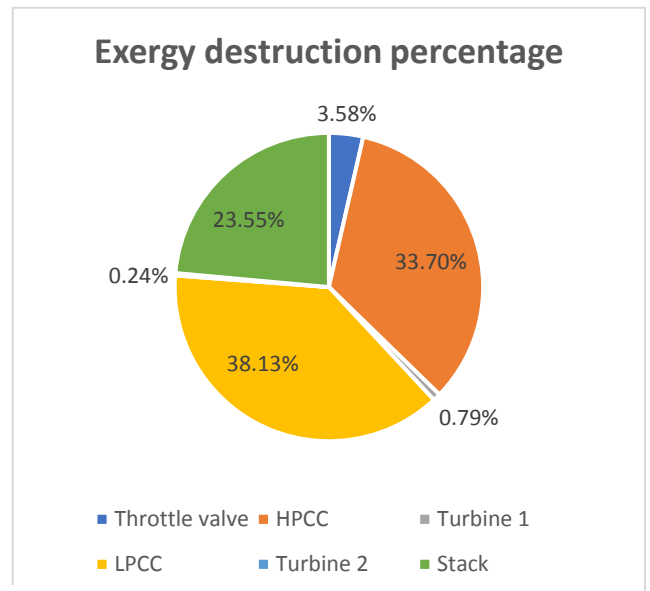


Figure 30 Exergy destruction for discharging system

Based in our model at steady-state which consider the power plant operating at its maximum capacity all the time and neglecting the dynamics of the cavern pressure during the time of operation we can we can take into consideration the point of view of 1st thermodynamics law For the total system of the thermal power plant and get the following thermal efficiency:

$$\eta_{1st\ law} = \frac{\text{useful output}}{\text{Input}} = \frac{\dot{W}_{HPTurb} + \dot{W}_{LPTurb}}{\dot{W}_{Comp, Mech} + \dot{m}_{fuel, Tot} * LHV_{CH_4}} = 52.53\%$$

Conclusion

In this thesis, a simulation model of the compressed air storage power plant in Huntorf was created with the MATLAB-CANYERA software based on measured values of the steady-state operation. The state variables of the actual state of the plant in Huntorf are realistically reproduced by the model.

Based on the Energy and Exergy analysis of the plant we can see that further development to the real power plant is needed as the exergy losses in the plant is high due to many losses such as the neglect of the heat energy taken away from the compressed air in the Intercoolers which is wasted to the environment without any useful usage and the technical reason for this loss is the intermittent operation of the compressors to fill the cavern therefore, smart Ideas should be proposed and analysed based on this model to save this waste of energy which can increase the rational efficiency of the charging system 15% more .

Stack losses is one of the main losses of the plant as it represents almost 25% of the exergy destruction in the discharging system which is simply wasted to the environment without useful usage. Moreover, using this waste of heat energy in the power cycle will reduce the consumption of fuel which will decrease the emissions due to the combustion and will reduce the exergy destruction in the combustion chambers which currently represents more than 70% of exergy destruction in the discharging system.

In conclusion, it can be stated that the compressed air storage power plant has the potential to be operated even more efficiently and therefore possibly more economically. In the context of the energy transition, this should therefore be considered as a good option for maintaining grid stability and increase the share of renewable resources in electricity generation.

Future work:

This model enables IEVB department in Technical university of Clausthal to make further studies related to Huntorf compressed air energy storage power plant which increase the feasibility of CAES plants in the future by applying different scenarios to enhance the efficiency of the power plant and to boost the output power of the plant. Some of the scenarios that has high probability to enhance the plant output are stated below:

- Increasing the storage pressure from the current maximum of 66 bar in the current state to 100 bar which has the potential to double the possible operating time of the power plant
- The installation of a heat recuperator to use the exhaust gas enthalpy to preheat the compressed combustion air
- The installation of an expander unit as a replacement for the throttle valve ensures that the “excess” pressure levels of the accumulator can be used

After the assurance of these scenarios shown above it should be analysed and examined considering the dynamic behaviour of the plant as the accumulator pressure dynamics affects all the results of both charging and discharging system which will allow us to take the economic aspect into consideration and explain the feasibility of applying different scenarios and invest in new components.

Modelling of the cavern will be a big leap to study the Geo-Mechanical properties of the caverns rock in unsteady state during the continuous fill & re-fill of air in the cavern and study the effect of rock temperature in heat transfer to the air volume in the cavern.

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