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SIMULATION OF PROSPECTIVE OXYGEN COMBUSTION THERMODYNAMIC CYCLES BY APPLICATION OF SOFTWARE SETS

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ABSTRACT

In last six decades the atmospheric carbon dioxide content is growing and this is one of the main sources of the global greenhouse effect. Power industry produces about 25% of carbon dioxide emissions which may be mitigated by transition to "zero emission" cycles. These cycles differ from the traditional ones by application of the oxygen combustion and closed circuit cycles with carbon dioxide precipitation for its burial. The goal of numerous parametric studies of power block thermal schemes is to determine structures and parameters that provide maximal thermal efficiency. This problem may be solved mainly by computer simulation methods. Specific features of structure, parameters and working substance chemical contents limit application of software sets traditionally used for power block analysis. The paper presents a review of advanced software sets advantages and shortages and methods used for computer simulation of oxygen combustion thermodynamic cycles. Examples disclose computer simulation results for the oxygen combustion thermodynamic cycle.

Keywords: Thermodynamic cycle, oxygen combustion, computer simulation, software set.

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1. INTRODUCTION

Efficient and environmentally friendly power production is one of the main problems that worldwide attract leading scientists and manufacturers. The renewable power sources (RPS) are being intensively developed but their sharing in the total balance, besides the hydro production, is still below 5% [1] because of the complicated load control and the accumulation necessity accompanying the RPS growth [2]. The nuclear power introduction is concerned with the emergency events risk that cannot be completely avoided in spite of the protection and emergency systems quality and number [3]. More than that, the environmentally harmless treatment of nuclear wastes is a crucial problem. So now electric power is mostly produced by fuel combustion in thermal power plants (TPP) that operate in Rankine, Bryton or Rankine-Bryton cycles.

Most of the operating steam and combined cycle power facilities have efficiency of 39–41% and 55–60% respectively [4]. The air-fuel mixture combustion products mostly consist of greenhouse gases that release most of their thermal energy to operating substance and exit through the exhaust pipe thus increasing the greenhouse atmospheric content.

The TPP harmful emission problem may be solved by construction of closed circuit thermodynamic cycles with oxygen fuel combustion. First versions of these cycles appeared in the end of 20-th century [5]. Their specific advantage against the traditional TPP is the fossil fuel combustion in oxygen that produces water steam and carbon dioxide. This chemical content allows the carbon dioxide precipitation from steam by vapor condensing with minimal energy consumption and the further sequester. More than that, other air components, especially nitrogen, are absent in the combustion zone which provides the “zero” environmental harm of emissions.

The following thermodynamic cycles are widely known: SCOC-CC, MATIANT cycles, Allam cycle, Graz cycles, CES cycle [6]. An important merit of these cycles is the high efficiency achieved by the thermodynamic parameters optimization [7]. The algorithm for optimal parameters selection is usually not disclosed in available papers. The usual practice is to disclose only a reference range of values and a simulation computer code to find the optimum.

The simulation method and the related software set remarkably influence final results. Selection of a specific program code depends upon the thermal system elements, chemical contents of operating substance, thermodynamic parameters and the necessity to apply multi-iteration optimization methods. The chapter below presents a brief review of program tool sets for computer simulation of various thermodynamic cycles.

2. PROGRAM TOOL SETS APPLIED TO THERMODYNAMIC CYCLE SIMULATION AND PARAMETERS OPTIMIZATION

Nowadays the technology for power equipment design always involves powerful program tools. The currently developed and improved tools allow 3D aerodynamic, thermal and strength analysis [8, 9]. Computer simulation of the power production block thermal processes may involve the following tools: Thermoflow, Aspen HYSYS, Aspen Plus, IPSEpro, EES, GateCycle, Boiler Designer.

The Thermoflow tool is often used for simulation of gas turbine and combined cycle blocks [10, 11]. An important advantage of this tool is its library of market available gas turbines with the built-in cycle performance and financial assets that allow effective technical and financial analysis. Thermoflow also allows simulation of closed circuit oxygen combustion cycles. The analyzed cycle may include standard elements like combustor, gas turbine, compressor, heat exchanger, or special elements like an oxygen production facility.

Program tools Aspen Plus, IPSEpro and EES are often applied to the analysis of oxygen combustion thermodynamic cycles. Simulation of the total power production complex may include models for closed thermodynamic circuit, cryogenic oxygen production facility and carbon dioxide burying preparation and thus it may combine application of a few tools [6].

Simulation with special program tools has considerable advantages that are availability of special optimization sets, libraries of standard thermal elements, database of operating substance parameters and friendly graphic interface. The main shortage usually is that in many cases the code approach is the "black box" that does not allow correction of analysis methods. Sometimes this shortage is crucial and it causes the necessity to use more thorough and not flexible but not so convenient methods.

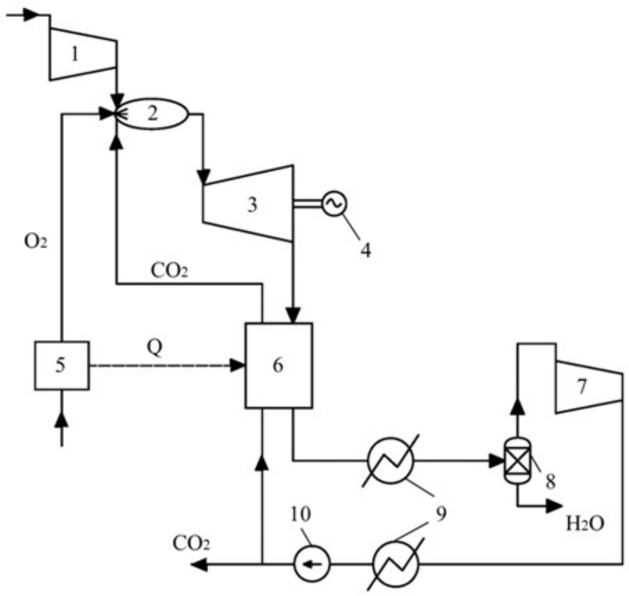
One of these methods is simulation in Mathcad, MATLAB or Excel. These tools allow simulation from the "blank sheet" stage. The automatic simulation process needs program tool communications with available fluid properties databases. Specifically the REFPROP addition may be integrated into the Excel environment for simulation of oxygen combustion cycles. This provides built-in functions for calculation parameters of carbon dioxide, water steam and other agents.

One of the most prospective oxygen combustion cycles is the Allam cycle that promises the net efficiency of 55–59% at natural gas burning [6, 12]. Flexible and transparent simulation technology and the possibility to accurately obtain the multi-component fluid parameters determined selection of Excel plus REFPROP sets for this cycle analysis.

3. ALLAM CYCLE COMPUTER SIMULATION WITH EXCEL AND REFPROP CODES

Allam cycle invention concept was patented in 2010 by Rodney John Allam [13]. The thermal concept scheme of Allam cycle with natural gas fuel is shown in Figure 1. Carbon dioxide is compressed in a multi-stage intercooled compressor to 80 bar, then it is compressed up to the cycle maximal pressure 200–400 bar in a pump. After the pump the carbon dioxide enters the regenerator where it is heated up to 700–750 °C by the turbine exhaust gas and the heated cooling agent that is used for intermediate cooling in the oxygen production facility. Use in the regenerator of the low potential heat obtained from the oxygen inter-cooling reduces fuel consumption for the operating substance heating up to the turbine inlet temperature. Downstream the regenerator the large part of flow enters the combustor as to limit the maximal temperature, the smaller flow is supplied to the turbine cooling. The remaining carbon dioxide flow is mixed with compressed oxygen and also supplied to the combustor. In the combustor the flow temperature grows up to 1150 °C by fuel combustion with oxygen. In the turbine flowpath the flow expands to 20–30 bar pressure that is below the carbon dioxide critical pressure. The turbine exit flow is directed to the regenerator.

The Allam cycle computer simulation model is based on the above described technology. The cryogenic facility process was not simulated and the oxygen production expenses were evaluated according to its assessment [14]. The amount of low potential heat transferred from the cryogenic facility to operating substance was evaluated by application of data [12]. The operating substance here is a carbon dioxide and water steam mixture with the thermodynamic parameters calculated in REFPROP program code. The model input data are summarized in Table 1.



1 – fuel compressor, 2 – combustor, 3 – gas turbine, 4 – power generator, 5 – air split facility, 6 – regenerator, 7 – compressor, 8 – separator, 9 – condenser, 10 – pump

Figure 1 Allam cycle thermal concept scheme

Table 1 Cases main parameters

Parameter	Value
Operating substance massflow, kg/s	100
Gas temperature /pressure at the turbine inlet, °C/MPa	1150/30
Gas pressure at the gas turbine exit, MPa	3
Gas turbine efficiency, %	90
Pump efficiency, %	90
Compressors efficiency, %	85
Mechanical efficiency, %	98
Power generator efficiency, %	99
CO_2 burying pressure, MPa	100

The simulation was carried out in the Excel environment with REFPROP superstructure. The operating mixture of carbon dioxide and water was determined with the special function “Fluidstring”, its thermodynamic parameters were calculated with the built-in functions “Enthalpy” and “Entropy”.

The Allam cycle computer simulation results are shown in Figure 2 in forms of a p,h diagram and a distribution of internal power consumption. The simulation result is the 55.2% net efficiency, and other authors evaluate the Allam cycle efficiency as a 55–59% range [6, 12]. The efficiency result within the reference range confirms the model accuracy and the method applicability to simulation of new thermodynamic cycles with unsteady structural elements.

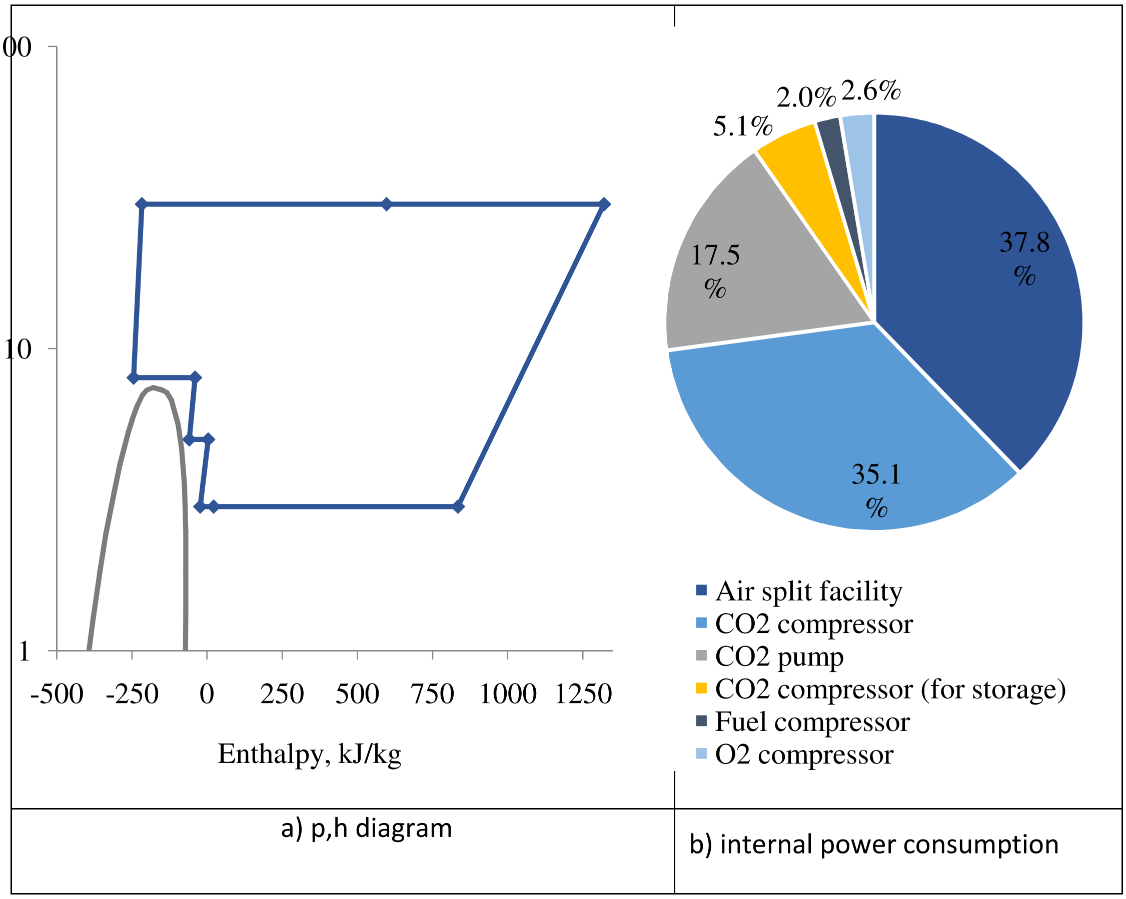


Figure 2 Results of Allam cycle simulation with Excel and REFPROP codes

4. CONCLUSIONS

The review describes software sets that may be used for computer simulation of closed circuit thermodynamic cycles with oxygen fuel combustion. More often are applied Aspen Plus, Aspen HYSYS, IPSEpro and EES. In some cases a few sets are used simultaneously.

The described approach to the Allam cycle analysis involves Excel and REFPROP codes. The evaluation accuracy is approved for the flow thermodynamic parameters and the power production efficiency. Distribution of the internal power consumption is analyzed in details.

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