First-Law-Based Thermodynamic Study of Reheat and Regeneration Rankine Cycles Using an Educational Software

Guillermo E. Valencia¹, Luis G. Obregón² and Jorge Duarte³

¹ Mechanical Eng., Efficient Energy Management Research Group – Kai Universidad del Atlántico, km 7 antigua via Puerto, Colombia

² Sustainable Chemical and Biochemical Processes Research Group Universidad del Atlántico, km 7 antigua via Puerto, Colombia

³ Design of Mechanical and Robotic Systems for Industrial Production Research Group, Universidad del Atlántico, km 7 antigua via Puerto, Colombia

Copyright © 2018 Guillermo E. Valencia, Luis G. Obregón and Jorge Duarte. This article is distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium provided the original work is properly cited.

Abstract

The article presents the use of an interactive graphical user interface developed in Matlab to develop parametric case studies in some thermodynamic power cycles, as an educational experience in the course of thermodynamic that allow to improve the student critical thinking and meaningful learning through the simulation of different operation conditioning in the cycle. The application allows management some parameters such as the temperatures, pressures, energy transferred by heat and work in the devices and the thermal efficiency, due to the fluid thermodynamic properties, and the energy balances are computed for the reheat and regenerative Rankine cycle.

For each operation condition the results were obtained numerically and graphically in the T-s diagram, allowing the user estimate the relation of the condensing pressure and outlet temperature in the boiler on the thermal efficiency, power energy, and heat boiler required. Finally, the results of the case studies presented can be solved in a computational way, without having to incur repetitive manual calculations, which allows students to invest time in knowing the relationship between
the different variables in the energy generation processes through steam power cycles.

**Keywords**: Rankine Cycles, Reheat, Regeneration, educational software, Thermodynamic

### 1. Introduction

The engineering education process for both undergraduate and graduate students is most significant when the educational informatics tools are used. Hence the importance of developing applications that allow students to acquire and strengthen skills in different areas including thermodynamics, which is the main focus of this article. For this reason, it is necessary to apply different learning methodologies so that students can progress according to their level of learning, acquire feedback and adequate supervision from the teacher, and can reach a critical reasoning of the subject matter [1].

Information technologies are an instrument that facilitates the appropriation of knowledge process and skills development, since they allow the reinforcement of the exercises learned in a classroom through computerized academic materials, known as educational software [2], which is a way to generate environments conducive to a proper assimilation of knowledge based on the use of information technology [3]. Studies by Reisman and Carr [4] concluded that students assimilate knowledge 20% through hearing, 40% through visual aids, and 75% through practice. Therefore, computer-based instruction modules have been structured to achieve the goal of 75% of knowledge learned through the interaction of students with multimedia presentation formats, allowing to conclude that software development improves the learning processes of engineering students [5].

The educational programs have been designed to be used in a formal learning process, using a specific design through which knowledge, skills and procedures are acquired for the student to learn [6], the implementation of these has resulted in the development of virtual laboratories as an alternative method that involves students in the use of this technology.

The main contribution of this paper is to show the development of some case studies of Rankine power generation cycles with reheating and regenerative through an educational tool designed to facilitate education, facilitating and ensuring the learning of engineering students in thermodynamics. The software has features such as functionality, usability and reliability, in addition to allowing the development of case studies through which they allow in-depth analysis and development of power cycles.

### 2. Methodology

#### 2.1. General objective of the educational software

The Power Cycle V.2.0 software is an interface developed in MATLAB, registered in the DNDA with the number 13-49-444 [7], was used to solve case studies related
to the different power cycles such as the simple Rankine cycle, Rankine with heating, Brayton or the combined cycle. The software was designed as a didactic support tool for engineering students and professionals, to improve the teaching and learning process of the theoretical concepts related to this topic. In addition, engineering students can use this educational software to quickly and clearly analyze the variation of any thermodynamic property in a power cycle using graphs, as well as the variation of the efficiency of the cycle as function of different parameters.

2.2 Basic equations

The fundamental equations used for the development of the informatic application in Rankine cycles with superheating and regenerative are widely published in the literature [8],[9]. In the case of the ideal Rankine cycle with superheating, the energy transfer by heat leads to

\[ q_{\text{in}} = q_{\text{boiler}} + q_{\text{reheat}} = (h_1 - h_6) + (h_3 - h_2), \]  

where \( q_{\text{in}} \) is the total heat supplied, \( q_{\text{boiler}} \) is the heat in the boiler and \( q_{\text{reheat}} \) is the energy supply in the reheat. On the hand, the total energy transfer by work \( w_{\text{out}} \) is calculated as

\[ w_{\text{out}} = w_{\text{turbine1}} + w_{\text{turbine2}} = (h_1 - h_2) + (h_3 - h_4). \]  

In the case of the regenerative Rankine cycle, the first law of thermodynamic is presented as function of the steam fraction extracted from the turbine \( y = \dot{m}_2/\dot{m}_1 \), where the total energy consumption and delivery by work is calculated as expressed by equations 3 and 4 as

\[ w_{\text{out}} = w_{\text{turbine}} = (h_1 - h_2) + (1 - y)(h_2 - h_3), \]  

\[ w_{\text{in}} = w_{\text{pump1}} + w_{\text{pump2}} = (1 - y)(h_5 - h_4) + (h_7 - h_6). \]  

Finally, the thermal efficiency \( \eta_{\text{ther}} \) for the thermodynamic steam power cycle is

\[ \eta_{\text{ther}} = \frac{w_{\text{out}} - w_{\text{in}}}{q_{\text{in}}} = 1 - \frac{q_{\text{out}}}{q_{\text{in}}}. \]  

3. Results and discussion

This section shows the results obtained of two case studies using PowerCycle V.2.0, consequently, they are compared the fundamental concepts and definitions reported in literature [8].
3.1 Effect of the condensing pressure on the regeneration power cycle

In the case of the regeneration cycle, for a given initial conditions of inlet pressure to the steam turbine ($P_1 = 5$ MPa), outlet pressure to the steam turbine ($P_2 = 1$ MPa), isentropic efficiency of the turbine and pump of ($\eta_{\text{turbine}} = 90\%$) and ($\eta_{\text{pump}} = 85\%$) respectively, was studied the influence of the outlet temperature on the boiler ($T_1$) and the condensing pressure ($P_3$) on the steam fraction, net power energy generated and thermal efficiency of the cycle. The software was used to obtain all the thermodynamic state, the outputs required to applied the energy balance and the respective T-s diagram as shown on Figure 1.

![Figure 1. Main view of the Power Cycle V.2.0 for the regeneration cycle](image)

Figure 2a shows the results obtained for this case study where as the cycle presents a higher efficiency and power energy delivery as both the inlet temperature of the steam to the turbine and the condensing pressure increase, which is according to the energy balance on the turbine due to the worked fluid give to the turbine energy represented as the change of the enthalpy, composed by the internal energy of the fluid and the flow work associated with pushing the steam mass across the systems boundary, which depends of the fluid temperature and pressure.
The variation of the parameters \(P_3\) and \(T_1\) showed a linear behavior for a given power and cycle efficiency, while the vapor fraction behaved inversely proportional to the behavior of the cycle power as shown in Figure 2b, because more flow is allowed to expand in the turbine it will deliver more energy, significantly increasing the net energy obtained in the process, despite the same increase in the energy of pump 1 as it moves more flow.

3.2 Effect of the condensing pressure on the reheat power cycle
In the case of the reheat power cycle, the set operations conditions where the inlet pressure to the first stage steam turbine \(P_1=7\) MPa, outlet pressure from the first stage steam turbine \(P_2=5\) MPa, isentropic efficiency of the turbine stages and pump of \(\eta_{\text{turbine}}=90\%\) and \(\eta_{\text{pump}}=85\%\) respectively. For this case, the parametric study was oriented to study through the educational software as shown in Figure 3, the relation between the condensing pressure \(P_4\), outlet temperature on the boiler \(T_1\) and the heat boiler, power energy and thermal efficiency of the cycle.

Figure 2. Effect of the condensing pressure on a) cycle efficiency, b) vapor fraction.

Figure 3. Main view of the Power Cycle V.2.0 for the reheat cycle
From the results obtained by varying operational parameters such as the condensing pressure and the steam temperature at the boiler outlet, it can be seen that both the cycle power and the heat in the boiler increase with the condensing pressure; however, however for a pressure higher than 0.04 MPa an increase of the delivery power was presented causing a more efficient system. The above result can be explained because of the condensing pressure is both the efficiency and power of the system are very low, involving a large pressure drop in the second stage of the turbine that cause much entropy production in the system, reflected in a significant energy losses in the cycle.

Figure 4. Effect of the condensing pressure on a) boiler heat, b) cycle efficiency

4. Conclusions

The computational tool called Power Cycle V.2.0, developed in Matlab to study the thermodynamic behavior of power generation processes using steam cycles, was used to visualize the main input and output variables that must be taken into account when using regeneration and superheating in these processes.

Some case studies were developed with the help of the software, using the student’s previous knowledge to been involved in the field of thermodynamics, and to strengthen the fundamental concepts of energy balance in these processes, in addition to evaluate the effect of some parameters such as the condensation pressure on the thermal performance of the process.
For each case study, the fundamental equations used were presented, which allow to clarify the theoretical component, the objectives of each experience, and the instructions that the student must follow when using the application to obtain the results and then elaborate the graphs presented.

References


Received: March 30, 2018; Published: April 30, 2018