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Thermodynamic Simulation of Steam Power Cycles using GUI-MatLab Interfaces

Pedro F. Arce, Nian F. Vieira
Chemical Engineering Department, School Engineering of Lorena, University of São Paulo, BRAZIL

ABSTRACT
Steam power cycles are constituted by a series of thermodynamic processes that aim convert the thermal energy of a fluid in mechanical work, which can then be transformed into electrical energy. There are many types of steam power cycles in the world, using various work fluids that may or may not undergo some change in their thermodynamic state. The Rankine Cycle is a steam power cycle that use usually water as work fluid to move turbines and produce work. Nowadays, this steam power cycle is the most used in thermoelectric plants to produce electricity. This work aims the creation of a program in MatLab software with an interface (Graphical Unit Interface, GUI) to simulate many configurations of Rankine cycles, providing to the user the values of the main parameters of these processes, that is: required heat in the boiler; work generated in the turbine; required work in the pumps and the thermal efficiency of the cycle. This program provides good results, showing that it can be used to improve the functions of the equipments in these thermodynamic cycles and to support the teaching disciplines of Applied Thermodynamic.
Keywords: Rankine Cycle, Water, Thermodynamic Simulation, GUI-MatLab

I. INTRODUCTION

Nowadays, the electrical energy is increasingly needed to the humanity, providing the action of many machines in homes and industry. Thus, technologies to produce electricity are the subject of many investments and improvements.

The most part of the electrical energy generated in the world come from power plants, which use coal, gas or uranium to heat a fluid (usually water) and move turbines. After this, mechanical work is converted into electricity.

To convert efficiently the energy of a fluid in work, these power plants use thermodynamic power cycles, which are constituted by many types of equipments, such as pumps, turbines, boilers, condensers, etc. There are many power cycles available to serve this objective. However, the power cycle most used today is the Rankine cycle.

The Rankine cycle is a steam power cycle that uses the phase changes of the thermodynamic state of water to move turbines and produce energy. Ideally, this thermodynamic cycle is constituted by four stages, which are:

- Isobaric heating in the boiler;
- Isentropic expansion in the turbine(s);
- Isobaric cooling in the condenser;
- Isentropic compression in the pump(s).

In these stages, water changes its thermodynamic state of superheated steam until compressed liquid, changing also their values of enthalpy, entropy and specific volume [1-3].

With the current technology and the development of new materials, the temperature and the pressure of the water in the thermodynamic cycle can reach more than 620,0 °C and 300,0 bar, respectively. For becoming the Rankine cycle more efficient, many improvements can be used, just modifying the basic structure of the thermodynamic cycle to reduce the required heat or to produce more work. To reduce the required heat, it is used regenerators, in which a side current, that leaves the turbine, is used to preheat the fluid, which later is going to the boiler. To produce more work, it is used reheating between the turbines, with the first turbine having high values of pressure and the last turbine low values of pressure. These improvements can be used isolated or together, depending of the capacity and the financial resources of the power plants [1-4].

To design properly the equipments of any configuration of Rankine cycle, four parameters should be analyzed, that are:

- Required heat in the boiler;
- Work generated in the turbine(s);
- Required work in the pump(s);
- Thermal efficiency of the cycle.

These parameters can be determinate in a thermodynamic simulation of the process. Nowadays, many computer programs are available for this purpose, working with different ranges and providing to the user simple configurations of Rankine cycle. In this work, a friendly computer program was developed to simulate several configurations of Rankine cycles, by utilizing the mass, energy and entropy balances in turbines, pumps, boilers and condensers in ideal and real situations. The criteria for predicting thermodynamic properties, such as enthalpy and entropy, were taken from previous work [5]. This friendly software can also be used for teaching of Applied Thermodynamics in undergraduate and graduate courses.

II. METHODOLOGY

There are many ways to calculate the thermodynamic properties of a fluid. The prediction of thermodynamic properties can be made by using cubic or non-cubic equations of state or thermodynamic tables of a pure substance [6]. However, it is necessary, at least, the knowledge of two thermodynamic properties of the system, first to determinate the thermodynamic state and then to determinate the other thermodynamic properties. In previous work [5], the authors used these criteria to predict thermodynamic properties of water for several thermodynamic states: compressed liquid, saturated liquid, liquid - vapor mixture, saturated vapor, superheated steam, supercritical fluid.

Main parameters of a Rankine cycle, which are calculated through the mass, energy and entropy balances involving properties of water such as enthalpy and entropy, require the determination of these values to begin the calculation. Based on this, the computer program requests to the user the values of temperature and pressure in some stages of the cycle. Temperature should be provide in ºC and its valid range is between 50,0 and 800,0 ºC. Pressure should be provide in bar and its valid range is between 0,0002 and 500,0 bar. These values are used to find the thermodynamic properties of water through the internal algorithms of the computer program. At the same time, the computer program also requests the configuration of Rankine cycle that user wants to simulate, among the six available ones, such as:

1. Basic Rankine Cycle;
2. Regenerative Rankine Cycle;
3. Rankine Cycle with Reheating;
4. Rankine Cycle with Reheating and Regeneration on the Low Pressure Turbine (LPT);
5. Rankine Cycle with Reheating and Regeneration on the High Pressure Turbine (HPT);
6. Rankine Cycle with Reheating and Regeneration on both turbines (LPT and HPT).

After these specifications, the computer program runs the thermodynamic simulation of a Rankine cycle and provides to the user the results of the mains parameters: mechanical work produced by turbine (W_T), mechanical work provided to pump (W_P), Heat provided to the boiler (Q_B), and efficiency of the Rankine cycle (η). The first three parameters can be obtained through the first and second laws of thermodynamic (open systems, without loss of heat, steady state, disregarding the kinetic and potential energies and reversible conditions in all equipments) and the efficiency of Rankine cycle is calculated from definition of a heat engine. The following equations show how these parameters are obtained:

$$W_T = H_{out} - H_{in} \quad (1)$$

$$W_P = \nu \times (P_{out} - P_{in}) \quad (2)$$

$$Q_B = H_{in} - H_{out} \quad (3)$$

$$\eta = \frac{W_T - W_P}{Q_B} \times 100\% \quad (4)$$

In the interface developed with GUI-MatLab, there is a figure that represents all the configurations of Rankine cycles available in the computer program, numbered according to the order cited above. This image helps users for understanding about the process. This image is shown in Fig. 1.

The user also can decide the irreversibility of the steam power cycle. The sources of irreversibility in a cycle at real conditions may be friction, pressure drops, etc. For this, the user can choose between a cycle at ideal conditions (with an isentropic efficiency of the equipments as 100% or also called reversible process) or a cycle at real conditions or also called irreversible process (with an isentropic efficiency of the equipments being chosen by the user).

In the cycles at real conditions, the values of work in turbines and pumps are corrected according to the following equations:

$$W_{T,real} = W_T \times Ef_T \quad (5)$$

$$W_{P,real} = \frac{W_P}{Ef_P} \quad (6)$$

where E_{fT} and E_{fP} are the isentropic efficiencies of turbine and pump, respectively.

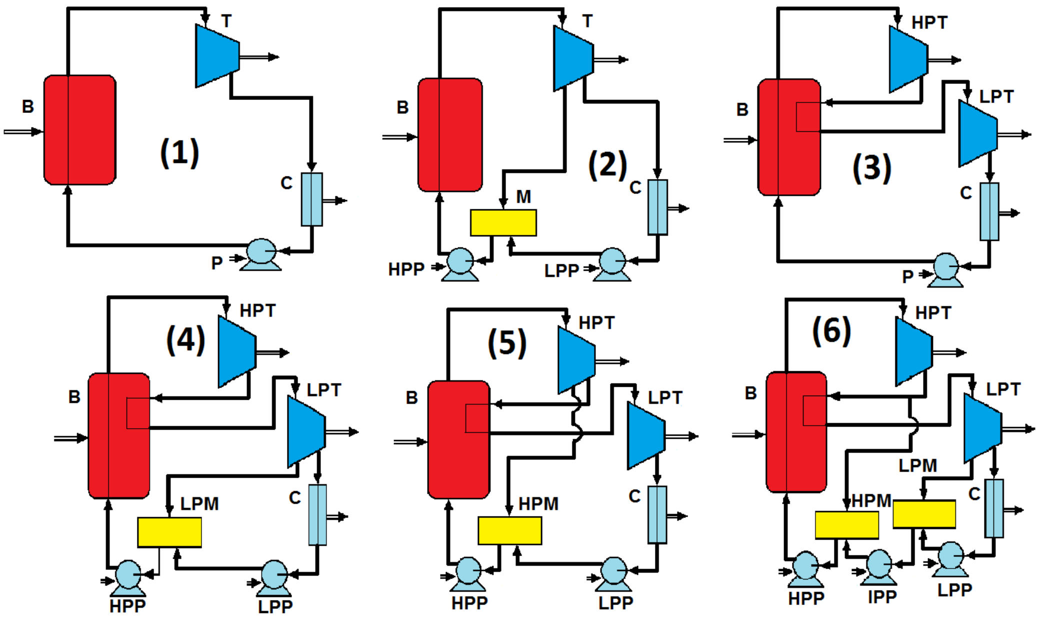

Fig. 1: Configurations of Rankine cycle available in the computer program of this work: (1) Basic Rankine Cycle, (2) Regenerative Rankine Cycle; (3) Rankine Cycle with Reheating; (4) Rankine Cycle with Reheating and Regeneration on the Low Pressure Turbine; (5) Rankine Cycle with Reheating and Regeneration on the High Pressure Turbine; (6) Rankine Cycle with Reheating and Regeneration on both turbines.

With all these options, it was created an interface in GUI-MatLab to help the interaction with the user. This interface is shown in Fig. 2.

III. RESULT AND DISCUSSION

Results obtained with the computer program developed in this work were compared with the other one that simulates Rankine cycles and with examples of books of Applied Thermodynamics.

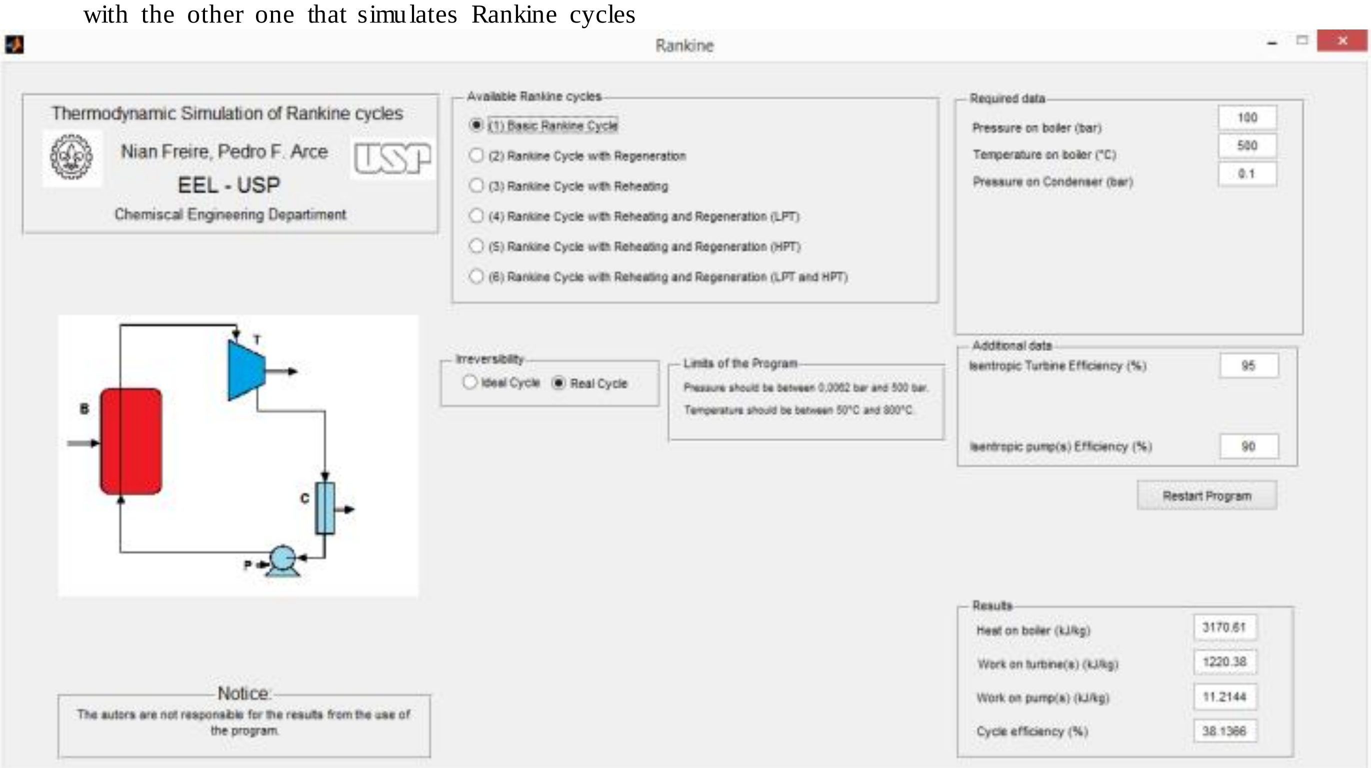

Fig. 2: GUI-MatLab interface after a thermodynamic simulation

The computer program used for comparison is a software available in internet [7]. This software work in a range of pressure and temperature appropriated for Rankine cycles. It software was developed for four configurations of Rankine cycles, that are: basic cycle, regenerative cycle, cycle with reheating and cycle with reheating and regeneration on the low-pressure turbine.

As this computer program doesn't have two of the configurations that the computer program developed in this work has, configurations 5 and 6 are compared with examples of literature [1,8].

Tables 1 to 6 present the results obtained for all the configurations of Rankine cycle available in the computer program of this work, where P_h representing the pressure in the boiler (bar), T_h is the temperature in the boiler (°C), P_c is the pressure in the condenser (bar), P_m is the pressure in the regenerator (bar), P_r representing the pressure in the reheating (bar), T_r is the temperature in the reheating (ºC) and η representing the thermal efficiency of the cycle (%). Although both computer programs provide the four main parameters of a steam power cycle, only the thermal efficiency was used for comparison between the sources, with a relative error calculated for the following equation:

$$E = \frac{|\eta_{work} - \eta_{example}|}{\eta_{work}} \times 100\% \qquad (7)$$

Six configurations of Rankine cycles were analyzed. They are: basic, regenerative, with reheating, with reheating and regeneration on the low-pressure turbine, with reheating and regeneration on the high-pressure turbine and with reheating and regeneration on both turbines. Results for the configurations are presented in Tables 1, 2, 3, 4, 5 and 6, respectively.

Table 1: Results for basic Rankine Cycle

Basic Rankine Cycle					
Program	P_h	T_h	P_c	η	E
This work	150,0	400,0	0,1	39,715	1,055
Link 1				40,134	
This work	100,0	350,0	0,1	37,933	1,181
Link 1				38,381	

Table 2: Results for regenerative Rankine cycle

Regerative Rankine Cycle						
Program	P_h	T_h	P_c	P_m	η	E
This work	150,0	400,0	0,1	40,0	42,550	1,638
Link 1					43,247	
This work	100,0	350,0	0,1	10,0	40,955	1,367
Link 1					41,515	

Table 3: Results for Rankine cycle with reheating

Rankine Cycle with Reheating							
Program	P_h	T_h	P_c	P_r	T_r	η	E
This work	150,0	400,0	0,1	40,0	350,0	40,080	1,108
Link 1						40,524	
This work	100,0	350,0	0,1	30,0	300,0	38,072	1,563
Link 1						38,667	

Table 4: Results for Rankine cycle with reheating and regeneration in the low-pressure turbine

Rankine Cycle with Reheating and Regeration in LPT								
Program	P_h	T_h	P_c	P_r	T_r	P_m	η	E
This work	150,0	400,0	0,1	40,0	350,0	40,0	42,088	1,414
Link 1							42,683	
This work	100,0	350,0	0,1	30,0	300,0	10,0	40,665	1,783
Link 1							41,390	

Table 5: Results for Rankine cycle with reheating and regeneration in the high-pressure turbine

Rankine Cycle with Reheating and Regeration in HPT								
Program	P_h	T_h	P_c	P_r	T_r	P_m	η	E
This work	125,0	550,0	0,2	50,0	550,0	10,0	44,071	1,336
Book [1]							44,660	
This work	100,0	550,0	0,1	8,0	500,0	8,0	44,337	0,142
Book [7]							44,400	

Table 6: Results for Rankine cycle with reheating and regeneration in both turbines

Rankine Cycle with Reheating and Regeration in both turbines									
Program	P_h	T_h	P_c	P_r	T_r	P_{mLPT}	P_{mHPT}	η	E
This work	50,0	400,0	0,1	5,0	400,0	5,0	1,2	38,879	0,049
Book [7]								38,860	
This work	150,0	600,0	0,1	40,0	600,0	40,0	5	49,957	1,515
Book [7]								49,200	

Based on the previous tables, it is possible to observe that the computer program developed in this work provides results with more accuracy and very similar to the results of the other computer [7] and examples of books [1,8]. Relative errors between the sources are smaller than 2,0% in all configurations of Rankine cycles obtained by the thermodynamic simulation in this work.

Analyzing the results and the input values of pressure and temperature, it is observed that, at moderate values of pressure and temperature, such as 100,0 bar and 400,0ºC, the error between the sources is small and less than 1,0%. The more the values of pressure and temperature increase and the closer they come to the critical point of water (374,1ºC and 220,6 bar), relative errors increase. This fact is due to differences in the reference states used to analyze the thermodynamic properties of water in this work and other researches. In previous works for the prediction of thermodynamic properties, authors obtained different values of thermodynamic properties of fluid at different reference states. Thus, each computer program uses different tables of thermodynamic properties of water to simulate its steam power cycles. At low values of pressure, the difference is minimal. However, at high values of pressure, the difference between values of thermodynamic properties, such as enthalpy and entropy, increases, causing relative errors greater than 1,0%.

Besides, errors may also occur due to the interpolation method used in the program code in MatLab ('spline') to predict the thermodynamic properties of water. However, this source of error isn't so big and the results continue being accurate.

It is worth mentioning that, in addition to good accuracy, the computer program developed in this work also have more configurations of Rankine cycles than other computer programs and have the option to choose between ideal and real conditions (reversible and irreversible processes). In the previous tables presented, all the results are obtained assuming Rankine cycles operating under reversible conditions, that is, turbines and pumps with 100% of isentropic efficiency. Real conditions (irreversible processes) were not explored because many computer programs that simulating Rankine cycles haven´t implemented that option.

The computer program developed in this work can be downloaded from the following links:

- For users of MatLab: https://www.dropbox.com/s/1xyzipmizvx7x0k/Thermo_web.rar?dl=0
- For non-users of Matlab: https://www.dropbox.com/s/13bqxff96anoaom/Thermo_mcr.rar?dl=0

IV. CONCLUSION

It is possible conclude that, based on the results, obtained by the computer program developed in this work, have good accuracy, with relative errors less than 2,0% in comparison with other ones obtained of other sources. Besides, this computer program also let to choose several configurations of Rankine cycles than other computer programs available online and provide to the user the option to choose between ideal and real conditions (reversible and irreversible processes, respectively). Thus, the computer program can be used to design equipments, simulate thermodynamically Rankine cycles with water as work fluid and becomes as a useful tool for teaching in courses of Applied Thermodynamics.

LIST OF SYMBOLS

B: boiler
C: condenser
Ef_T: Isentropic Efficiency of the turbine(s) (%)
Ef_P: Isentropic Efficiency of the pump(s) (%)
E: Relative Error (%)
HPT: High-pressure Turbine
HPP : high-pressure pump
HPM : high-pressure mixer tank
Hin : inlet enthalpy (kJ/kg)
Hout : output enthalpy (kJ/kg)
IPP : intermediate-pressure pump
LPT: Low-pressure Turbine
LPP : low-pressure pump
LPM : low-pressure mixer tank
M : mixer tank
P_h: Pressure in the boiler (bar)
P_c: Pressure in the condenser (bar)
P_r: Pressure in reheating (bar)
P_m: Pressure in the mixer tank (bar)
P : pump
Pin : inlet pressure (bar)
Pout : output pressure (bar)
Q_B: Heat provided by the boiler (kJ/kg)
T_h: Temperature in the boiler (°C)
T_r: Temperature in reheating (°C)
T : turbine
v : specific volume (m^3/kg)
W_T: Mechanical Work produced in the turbine(s) (kJ/kg)
W_P: Mechanical Work required in the pump(s) (kJ/kg)
η: Thermal Efficiency of the cycle (%)

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REFERENCES

[1]. Y.A. Çengel, M.A. Boles, *Termodinâmica* (Porto Alegre, Brazil : McGraw Hill Publishers, 2013).
[2]. I. Granet, *Termodinâmica e Energia Térmica* (Rio de Janeiro, Brazil : Prentice-Hall Publishers, 1990).
[3]. C. Borgnakke, R.E. Sonntag, *Fundamentos da Termodinâmica* (São Paulo, Brazil : Blucher Publishers, 2013).
[4]. M.C. Potter, E.P. Scott, *Termodinâmica* (São Paulo, Brazil : Thomson Learning, 2006).
[5]. P.F. Arce, N.V. Freire. Programming and testing of a friendly GUI-MatLab software to predict the thermodynamic properties of water, *International J. of Research in Engineering and Technology, 5 (11), 2016, 52-57.*
[6]. M.L. Michelsen, J.M. Mollerup, *Thermodynamic Models: Fundamentals & Computational Aspects* (Denmark: Tie Line Publications, 2007).
[7]. http://www.engr.siu.edu/staff1/weston/thermo /Rankine/ RankineCycles.html; accessed in May 27, 2015.
[8]. G.H. Milton, *Problemas Resueltos Examenes - UNI y Otros* (Lima, Perú: Ediciones Habich, 1986).