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Computational tool for simulation of power and refrigeration cycles

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Abstract. Small improvement in thermal efficiency of power cycles brings huge cost savings in the production of electricity, for that reason have a tool for simulation of power cycles allows modeling the optimal changes for a best performance. There is also a big boom in research Organic Rankine Cycle (ORC), which aims to get electricity at low power through cogeneration, in which the working fluid is usually a refrigerant. A tool to design the elements of an ORC cycle and the selection of the working fluid would be helpful, because sources of heat from cogeneration are very different and in each case would be a custom design. In this work the development of a multiplatform software for the simulation of power cycles and refrigeration, which was implemented in the C ++ language and includes a graphical interface which was developed using multiplatform environment Qt and runs on operating systems Windows and Linux. The tool allows the design of custom power cycles, selection the type of fluid (thermodynamic properties are calculated through CoolProp library), calculate the plant efficiency, identify the fractions of flow in each branch and finally generates a report very educational in pdf format via the LaTeX tool.

1. Introduction

This work aims to simulate refrigeration cycles and power cycles, specifically cycles *Rankine*. A computational tool was developed in the programming language `C++` using the Qt cross-platform environment. It is also possible to simulate Organic Rankine Cycles (ORC) using a secondary fluid as the working fluid, Tchanche [1] made a detailed analysis of the different types of architectures for these cycles study. Programming in an object-oriented language has many advantages over a structured programming language, such as the work of Jeon [2] and Shirakawa [3], which use class inheritance for creating new models according to the needs. There are several developments in this kind of simulations in steady state and transient state, authors such as Fang [4] and diGenova [5] worked directly with commercial software such as Matlab© and interacted with other software to calculate thermodynamic properties, while authors Kim [6] and Akolekar [7] developed a custom software.

The first part consisted of the design of the models, starting with the modeling of the working fluid for which it was decided to use libraries *CoolProp*[8], modeling of the devices was based on existing in the literature concerning thermodynamic devices operating at steady flow models and then the cycle model was modeled with graph theory. Then it proceeds to solve algebraic

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equations in the model obtained by solving a positive square matrix $N \times N$ using *Cholesky* decomposition. And finally the tool generates a report format *pdf*, and the results were validated with problems encountered in the literature.

2. Modeling

The model of the entire system comprising: modeling fluid; modeling each device and the cycle modeling, which are detailed below.

The calculation of the thermodynamic properties of fluids are made by libraries *CoolProp*[8]. CoolProp is an open source library written in `C++` and it implements pure and pseudo-pure fluid equations of state and transport properties for 114 components and humid air also. It can also interact with the program `REFPROP` [9] for calculating properties.

The modeling of the devices was made to conditions of steady-state flow and generally is defined by the energy balance equation 1 and the mass balance equation 2. These equations use the sign convention [10] for heat and work, which is widespread in the literature.

$$\sum_{out} \dot{m}h - \sum_{in} \dot{m}h = \dot{Q} - \dot{W} \tag{1}$$

where $\dot{m}$ is the mass flow, h enthalpy, $\dot{Q}$ the rate of heat transfer and $\dot{W}$ the power developed or provided.

$$\sum_{in} \dot{m} = \sum_{out} \dot{m} \tag{2}$$

The modeling cycle is divided into two parts, one is the generation of the connection topology of the devices, which was performed using graph theory, and the second is the generation of algebraic equations based on the model of each device and their interconnections.

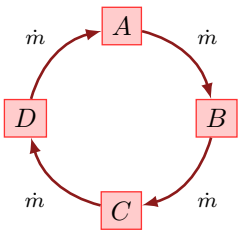


Figure 1. Sequential simulation.

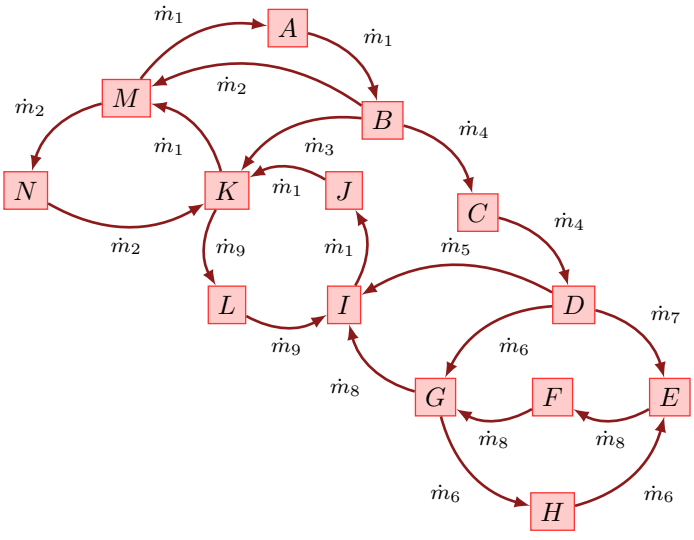


Figure 2. Simultaneous simulation.

Simulation methods cyclic processes can be classified into two categories [11]; sequential simulation or simultaneous simulation. In the sequential simulation as shown in Figure 1, the output of a component is input for the next component, there is no need to iterate and the same value of mass flow circulated throughout the cycle. In a simultaneous simulation as shown in Figure 2, there are many interconnections between the components and the mass flow through

each can be different, involving a solution of a system of equations and in the case of not linear it is necessary to perform iterative process.

The device connections was performed by graph theory, which facilitates the sequential calculation devices. For example for the cycle shown in Figure 3, the equivalent graph is shown in Figure 4.

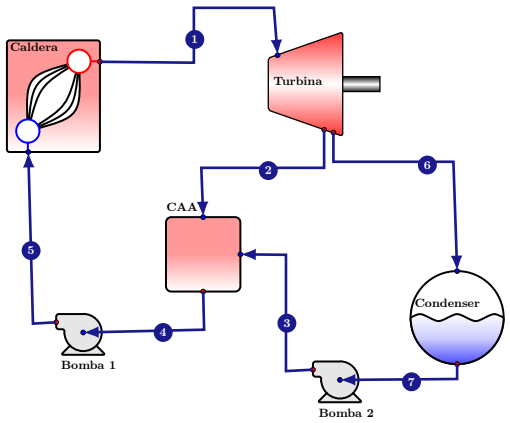


Figure 3. Diagram example of a plant.

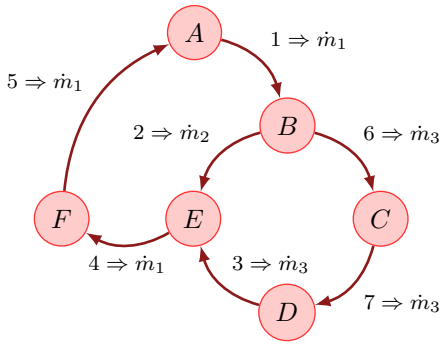


Figure 4. Graph device connections.

Where A corresponding to the boiler, B to the turbine C to the condenser, D to the pump 2, E to the CAA and F to the pump 1. This is a directed graph and it has an associated adjoint matrix as shown in Figure 5, where for a matrix element $a_{i,j}$ if the values is 0, there is no connection between the devices i and j, otherwise if the value of the item is different from 0 the device i connects to the device j with a mass flow of $a_{i,j}$.

$$
\begin{array}{c} \\ A \rightarrow \\ B \rightarrow \\ C \rightarrow \\ D \rightarrow \\ E \rightarrow \\ F \rightarrow \end{array}
\begin{array}{c}
\begin{array}{cccccc} \text{A} & \text{B} & \text{C} & \text{D} & \text{E} & \text{F} \\ \downarrow & \downarrow & \downarrow & \downarrow & \downarrow & \downarrow \end{array} \\
\left[\begin{array}{cccccc}
0 & \dot{m}_1 & 0 & 0 & 0 & 0 \\
0 & 0 & \dot{m}_3 & 0 & \dot{m}_2 & 0 \\
0 & 0 & 0 & \dot{m}_3 & 0 & 0 \\
0 & 0 & 0 & 0 & \dot{m}_3 & 0 \\
0 & 0 & 0 & 0 & 0 & \dot{m}_1 \\
\dot{m}_1 & 0 & 0 & 0 & 0 & 0
\end{array}\right]
\end{array}
$$

Figure 5. Adjoint matrix.

3. Simulation

Simulating a cycle consists of four sequential processes. First in the GUI interface is designed cycle, then the GUI generates an XML file, which is used as input to the main application and finally the report is generated in PDF format.

The application responsible for the simulation takes as input the document *XML* created and generates a report with the results in *pdf* format, through the LaTeX tool. This application was made in `C++` and it has two major classes, the class `Planta` and the class `Dispositivos`. The class diagram `Planta` is shown in Figure 6, it shows how this class makes use of the class `CiclosXML` designed to interact with files *XML* and save this information to a member of the class `Planta`. One member of the class `Planta` is a list of objects of class `Dispositivos` shown

in Figure 7 which is an abstract class that provides the basis for other classes that implement the various methods of each of the specific devices.

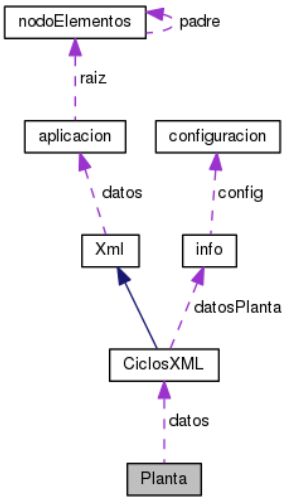


Figure 6. Diagram for the class Planta

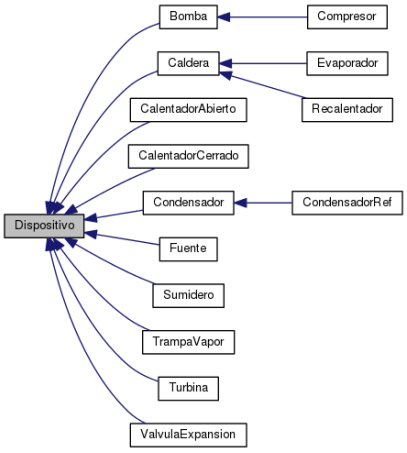


Figure 7. Diagram for the class Dispositivos

4. Results and discussion

The developed model was validated with examples found in the literature, one for a refrigeration system and another for a Rankine cycle. The refrigeration cycle used for validation is shown in Figure 8, with the following inputs: fluid `R134A`, $P_1 = 140\,kPa$, $x_1 = 1$, $P_2 = 800\,kPa$, $P_3 = 800\,kPa$, $x_3 = 0$ and $P_4 = 140\,kPa$.

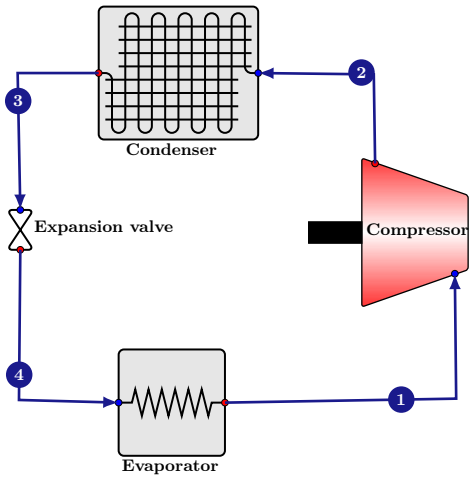


Figure 8. Diagram of the refrigeration cycle

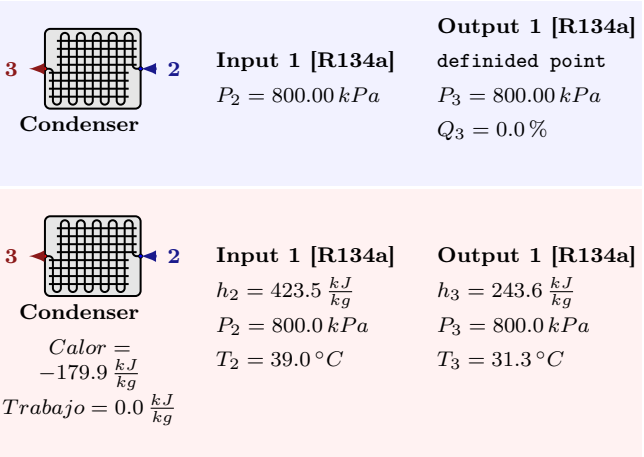


Figure 9. Data input and output for the condenser

The coefficient of performance obtained in the calculations was:

$$\beta_{Refrigerator} = 3.968$$

Table 1. Properties of each point

State	Fluid	Flow[frac]	Pressure [kPa]	Temperature [K]	Enthalpy [kJ/kg]
1	R134a	1.000	140.000	254.390	387.320
2	R134a	1.000	800.000	312.127	423.532
3	R134a	1.000	800.000	304.477	243.645
4	R134a	1.000	140.000	254.390	243.645

The summary of the properties of each point of the refrigeration cycle is shown in Table 1, and the Figure 9 shows example data of calculus for the refrigerator.

The validation for a thermal plant is shown in Figure 10, which is a Ideal Rankine cycle with the following input data: fluid water, $P_1 = 7000\,kPa$, $T_1 = 600°C$, $P_2 = 3000\,kPa$, $P_3 = 1800\,kPa$, $P_4 = 800\,kPa$, $T_5 = 500°C$, $P_6 = 100\,kPa$ and $P_7 = 5\,kPa$.

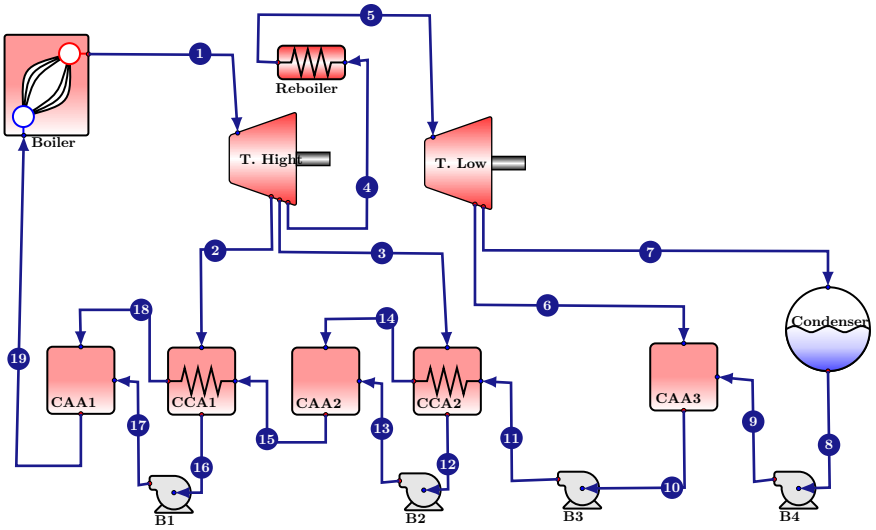


Figure 10. General diagram of the plant

The thermal efficiency of the power cycle was obtained:

$$\eta_{thermal} = 47.052\,\%$$

The summary of the properties on each of the points is shown in Table 2. With these two examples is demonstrated the correct operation of the software tool, which simulated a refrigeration cycle and complex Rankine cycle. In the Rankine cycle, the program calculated the seven different streams found in the cycle as shown in the "Flow" column of Table 2.

5. Conclusions

This computational tool facilitates the configuration of different topologies of power cycles and refrigeration cycles because it performs a series of calculations a quick and easy way. Perform these same calculations manually involve a lot of time in the calculation of thermodynamic properties and in solving a system of equations. The developed program has the ability to simulate different power cycles with different working fluids, for this reason it is possible to simulate organic cycle Rankine power and cooling cycles and it was demonstrated that the program can solve power cycles have some complexity as shown in the results.

Table 2. Properties of each point of the thermal plant

State	Fluid	Flow[frac]	Pressure [kPa]	Temperature [K]	Enthalpy [kJ/kg]
1	Water	1.000	7000.000	873.150	3650.594
2	Water	0.050	3000.000	724.872	3348.719
3	Water	0.158	1800.000	645.915	3191.964
4	Water	0.792	800.000	535.685	2977.341
5	Water	0.792	800.000	773.150	3481.253
6	Water	0.080	100.000	481.278	2891.511
7	Water	0.712	5.000	306.024	2400.193
8	Water	0.712	5.000	306.024	137.768
9	Water	0.712	100.000	306.026	137.842
10	Water	0.792	100.000	372.756	417.500
11	Water	0.792	7000.000	373.230	424.692
12	Water	0.158	1800.000	480.262	884.482
13	Water	0.158	7000.000	481.176	890.518
14	Water	0.792	7000.000	480.262	886.399
15	Water	0.950	7000.000	480.414	887.086
16	Water	0.050	3000.000	507.003	1008.353
17	Water	0.050	7000.000	507.886	1013.143
18	Water	0.950	7000.000	507.003	1009.008
19	Water	1.000	7000.000	507.047	1009.213

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