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DEVELOPMENT OF A SIMULATION SOFTWARE FOR THERMAL SYSTEMS

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Abstract. *This work has the objective to make easier the development of heating, cooling and energy generation efficient machines, besides allowing the already existent systems analysis to improve their energetic efficiency and simplify the Thermodynamics concepts learning. The thermal systems computational simulation is an important ally in the search for greater efficiency in the energy generation and usage, because it provides a set of analytic properties and fundamentals necessary for it. Using the computational simulation, it is possible to develop and analyze certain system, testing easily a huge quantity of conditions that culminate in a project developing that has the less operational cost and investment. In this work, it was developed a thermal systems simulation software whose main differentials are its easy operation and customization by the user. To achieve that, the software was elaborated using an Excel spreadsheet with automatic calculations done by the Macro feature and VBA (Visual Basic for Applications) programming language. The result is that the program operation is as easy as using a common Excel spreadsheet, a task that the typical user of this kind of software is already habituated. The software customization is possible by using he program's ready functions at any worksheet cell or when the user develops his/her own functions using the VBA programming language and the software thermodynamic tables. In this way, the user or company that will use the software will be able to personalize it according to its needs.*

Keywords: *Computational simulation, thermal systems*

1. INTRODUCTION

The Thermodynamics and the thermal systems are fundamental to supply the XXI century human society needs and to increase their quality life (Moran and Shapiro, 2013). It gives essential concepts and methods to allow the design, analysis and operation of important engineering applications, such as heating and cooling systems and electricity generation at thermoelectric plants.

The cooling systems are used for food conservation, air conditioning, gases separation and ice production. The heat pumps are used for environments heating and heat generation at industrial processes. To obtain cooling or heating, in the most of times is necessary to use electric energy. Therefore, more efficient practices applied to that equipment can increase meaningly our energetic posture (Moran and Shapiro, 2013).

The energy consumption is one of the most important indicators to show the development level and the life patterns of a society (Kaushik, et al., 2011). The future points to a greater electric equipment efficiency such as home appliances and air-conditioning systems, reducing the energy consumed by them. (Moran and Shapiro, 2013). However, it is expected also an energy necessity growth due the population increase, urbanization, industrialization and technologic development, because those result directly in an energy consumption. Nowadays, 80% of the electricity produced in the world comes from fossil fuel power plants (Kaushik, et al., 2011). In the future, the petroleum, the mineral coal and the natural gas will be rarer and more expensive, so that power plants will represent a smaller but still significant portion of the consumed energy due to a greater use of energy sources like wind, solar and geothermic (Moran and Shapiro, 2013).

Therefore, there is a challenge that is the supply of society needs allied to a conscious energy use due to the many risks to the human health and the environment that emerge with its utilization (Moran and Shapiro, 2013). As the energy need increase is an inevitable reality, it becomes necessary to develop more efficient processes to supply and use the generated energy.

In this way, this work has the purpose of developing a thermal systems simulation computational program that facilitates the efficient project of heating, cooling and energy generation machines, besides to permit the already existent systems analysis to improve their energetic efficiency.

The thermal systems computational simulation is an important ally in the search for greater efficiency in the energy generation and usage, because it provides a set of analytic properties and fundamentals necessary for it. Using the computational simulation, it is possible to develop and analyze certain system, testing easily a huge quantity of conditions that culminate in a project developing that has the less operational cost and investment.

The computer programs available on the market besides having a high acquisition cost, need many study hours for learning how to operate them. Only then the user can have the benefits of the program usage. So, acquiring a program and hiring a trained professional can represent a high financial cost, which can unfeasible its implementation.

This wok's objective is to elaborate a thermal system simulation software focused on cooling, heating and power generation which is precise and easy to operate to be used at the academic and professional environments.

2. BIBLIOGRAPHIC REVISION

Ahmadi and Toghraie (2016) performed a complete evaluation of each component energetic efficiency of the Shahid Montazeri vapor power plant in Isfahan, Iran. To perform the calculation, the parameters of each one of the 50 studied cycle points were extracted of a plant historical, and by the mass and energy conservation equations application it was possible to determine each equipment status and calculate the not known parameters, all using the program EES (Engineering Equation Solver).

Musa and Adam (2015) analyzed the components energetic losses of a vapor power plant using the program Aspen Hysys, developed by the company Aspentech, besides Autocad and Excel. The authors concluded that to perform this study periodically is important for decision making on maintenance and components substitution and that the computational simulation is fundamental to allow the frequent repetition of this analysis.

Moran and Shapiro (2013) presented the program "Interactive Thermodynamics: IT", used for thermal systems simulation and analysis, besides suppling specific states properties. The system operates through code lines, similar to the EES program, and it is possible to get ready code lines by predetermined scenarios choice at the program menu.

Jamel, et al., (2013) conducted a thermodynamic performance study of the AL-Hartha vapor power plant, localized in Basra, Iraq. The study was performed through computational simulation using the program Cycle-Tempo, developed by the Delft Technology University, in Holland. The authors concluded that the combustor had the highest energetic lost percentage (23,4%), so it needed a modification to reduce the losses and increase the plant thermodynamic performance.

Elsner, et al., (2012) performed a computational Simulation to study a new technology application for a coal power plant. The authors verified that the program IPSEpro, developed by the company Simtech was very limited because the high level of tested parameters by it made the calculation slow. So, they developed an integrated solution between IPSEpro, Matlab and Excel. It was verified that the provided results were practically identical, but the calculation time was much smaller for the integrated solution.

Kotowicz, et al., (2011) analyzed and validated a power generation plant model created through the commercial program GateCycle, developed by the company General Electric. The authors highlighted the software usage for power plants modeling, once it can reduce the necessary time to detect efficiency problems at the plant.

Kaushik, et al., (2011) made a comparison between the performances of a vapor power plant calculated by the First and the Second Thermodynamic Law. The authors indicated that most of the power plants are projected through performance criteria based only on the Thermodynamics First Law (energy balance). The energetic analysis together with the exergetic analysis can offer an even more complete system characteristics representation, because the exergy differences between the energy quantity and quality.

3. THEORETICAL FOUNDATION

Closed systems can share energy with their neighborhoods through work production or reception, or even through heat transference. The Thermodynamics First Law says that the energy is preserved independently of the traveled process between a state and another. (Moran and Shapiro, 2013).

The energy balance for a certain control volume can be expressed by the Thermodynamics First Law applied to control volumes, described in Eq. (1) (Moran and Shapiro, 2013).

$$\frac{dE_{vc}}{dt} = \dot{Q}_{vc} - \dot{W}_{vc} + \sum{}_{e}\dot{m}_e(h_e + \frac{v_e^{\ 2}}{2} + gz_e) - \sum{}_{s}\dot{m}_s(h_s + \frac{v_s^{\ 2}}{2} + gz_s) \quad (1)$$

Where:
$\frac{dE_{vc}}{dt}$ = the energy change rate in the control volume, in W;
$\dot{Q}_{vc}$ = the energy rate that is transferred through heat to the inside or to the outside of a control volume in W;
$\dot{W}_{vc}$ = the energy rate that is transferred through work to the inside or to the outside of a control volume, in W;
$\dot{m}_e$ = mass flow that the working fluid enters the control volume, in kg/s;
$\dot{m}_s$ = mass flow that the working fluid leaves the control volume, in kg/s;

h_e = working fluid enthalpy when it enters the control volume, in kJ/kg;
h_s = working fluid enthalpy when it leaves the control volume, in kJ/kg;
V_e = speed that the working fluid enters the control volume in m/s;
V_s = speed that the working fluid leaves the control volume in m/s;
g = gravity acceleration, in m/s²;
z_e = working fluid entry point vertical elevation in relation to a reference point, in m;
z_s = working fluid exit point vertical elevation in relation to a reference point, in m.

To analyze the thermal systems, there will be considered the period that they work in permanent regime. The transient regime is found in the equipment start and stop periods, and between the start and stop is the permanent regime which working fluid mass flow and energy transference rate by heat and work is constant in time. (Moran and Shapiro, 2013)

Since there is no energy variation, $\frac{dE_{vc}}{dt} = 0$, from Eq. (1) there is Eq. (2) (Moran and Shapiro, 2013).

$$0 = \dot{Q}_{vc} - \dot{W}_{vc} + \sum{}_e \dot{m}_e (h_e + \frac{v_e^{\;2}}{2} + gz_e) - \sum{}_s \dot{m}_s (h_s + \frac{v_s^{\;2}}{2} + gz_s) \tag{2}$$

Considering that more frequently there are found control volumes with only one entry and exit and that permanent regime means that there is no working fluid mass flow variation, the entry mass flow is equal to the exit mass flow. In this way, from Eq. (2) there is Eq. (3) (Moran and Shapiro, 2013).

$$0 = \dot{Q}_{vc} - \dot{W}_{vc} + \dot{m}[(h_e - h_s) + \frac{v_e^{\;2} - v_s^{\;2}}{2} + g(z_e - z_s)] \tag{3}$$

Where:
$\dot{m}$ = mass flow in the control volume, in kg/s.

3.1 Power cycle

The power cycle is the one that receives energy in the form of heat from its neighborhood and performs this energy conversion to the form of work. The energy supplied to the system in the form of head normally comes from fuel burning, nuclear reaction or solar radiation (Moran and Shapiro, 2013).

In the Carnot power cycle, or ideal power cycle, the working fluid passes through four internally reversible processes, being two isothermal and two adiabatic, alternated with each other.

The ideal Rankine cycle is represented in the Eq. (2) and (3). In the ideal cycle, there is no irreversibility or heat share with the neighborhood during the fluid passage through the components, which means that in the boil and condenser there will be no pressure drop and the processes through the turbine and pump will be isentropic (Moran and Shapiro, 2013).

The real Rankine cycle has losses and irreversibility when the working fluid passes through the system components. This phenomenon has influence in the global performance of a power plant (Moran and Shapiro, 2013).

3.2 Cooling and heat pump cycles

The cycle that has the objective of reduce a closed space temperature to less than the environment temperature is the cooling cycle. In an opposite way, the cycle that has the objective of increase a closed space temperature to higher then the environment temperature is the heat pump cycle. In both cycles, from the neighborhood work performing occurs the heat transfer from the cold region to the system, and from the system to the hot region (Moran and Shapiro, 2013).

The Carnot ideal cooling and heat pump cycles are the Carnot power cycle operated in the opposite direction, where the energy transferences occur in the opposite direction too (Moran and Shapiro, 2013).

The steam compression cooling and heat pump cycles presents several deviations in relation to the Carnot ideal cooling and heat pump cycles. To maintain the cold region temperature using a realistic size evaporator, it is necessary that the refrigerant fluid temperature in the evaporator be several degrees below the cold region temperature, so that a sufficient heat transfer rate is achieved. Likewise, it is necessary that the refrigerant fluid in the condenser be several degrees above the hot region temperature, so that a sufficient heat transfer rate to maintain the hot region temperature is achieved (Moran and Shapiro, 2013).

Other characteristics that differ the steam compression ideal cycle from the Carnot cycle are related to the compressor and the turbine. Unlike the Carnot cycle where the compressor operates with a liquid-vapor mixture, the ideal cycle compressor operates only with saturated or superheated steam, once the liquid-vapor mixture proposed on the Carnot cycle is detrimental to the equipment. About the turbine, it is opportunely replaced by the expansion device which also expands the refrigerant but does not have the drawbacks of high initial cost and maintenance (Moran and Shapiro, 2013).

The real steam compression cooling and heat pump cycles have some differences in relation to the ideal cycles. The first one refers to the refrigerant fluid not performing reversible heat exchange between the hot and cold regions: in the condenser, the refrigerant fluid temperature is higher than the hot region temperature, while in the evaporator the refrigerant fluid temperature is lower than the cold region temperature. The second difference is that the compression is also irreversible, what causes a specific entropy increase. Two other characteristics that differ the real cycle from the ideal cycle are the superheated steam exhaust from the evaporator, instead the saturated steam of the ideal cycle, and the subcooled liquid exhaust from the condenser in the real cycle, instead the ideal cycle saturated liquid (Moran and Shapiro, 2013).

4. COMPUTATIONAL METODOLOGY

In this work, it was developed a thermal systems simulation software whose main differentials are its easy operation and customization. To achieve that, the software was elaborated using an Excel spreadsheet with automatic calculations done by the Macro feature and VBA programming language, whose flowchart is shown in Fig. 1.

The result is that the program operation is as easy as using a common Excel spreadsheet, a task that the typical user of this kind of software is already habituated. The software customization is possible by using he program's ready functions at any worksheet cell or when the user develops his/her own functions using the VBA programming language and the software thermodynamic tables. In this way, the user or company that will use the software will be able to personalize it according to its needs.

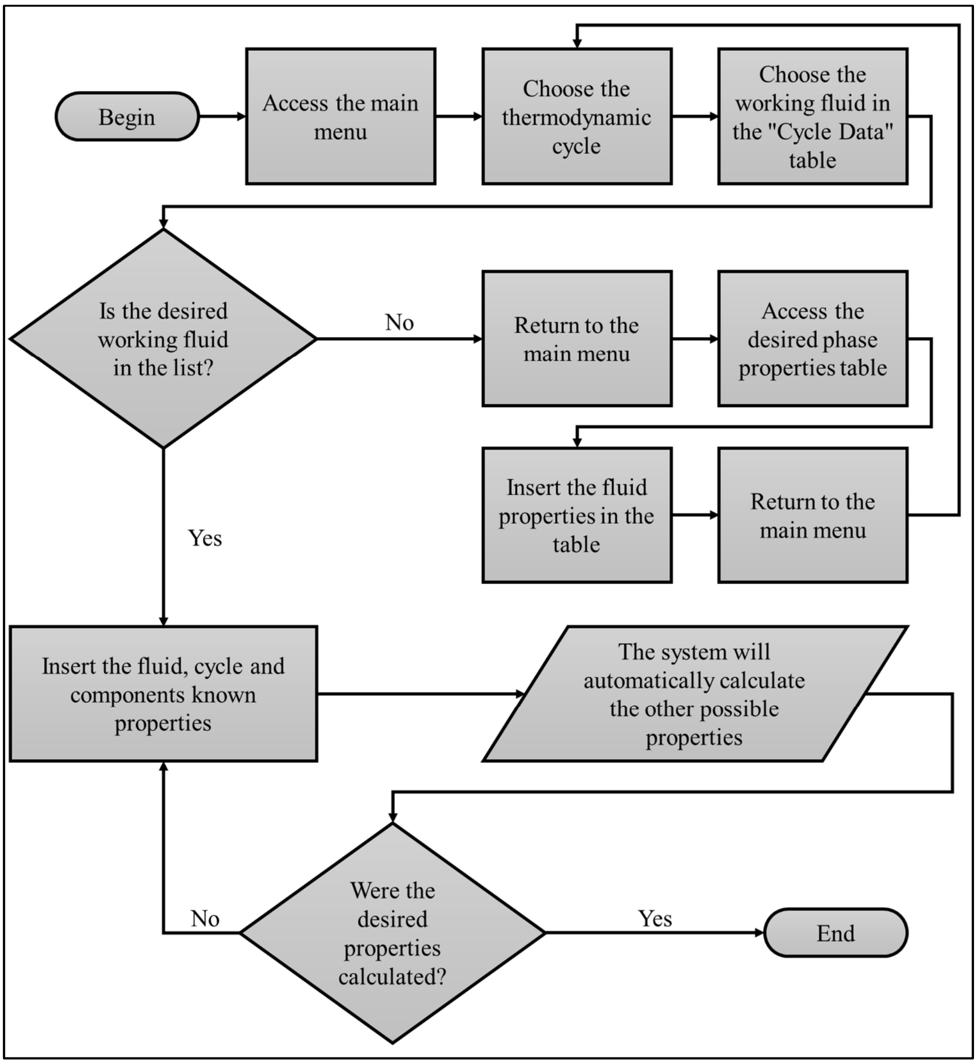


Figure 1. Software operation flowchart

4.1 Aplication example for program validation

A Moran and Shapiro (2013) example will be used to show how the user will operate the program and at the same time certificate that the program works correctly by obtaining the same results of literature.

"**Example 10.1:**

Analyzing a Steam Compression Ideal Cooling Cycle

A steam compression ideal cooling cycle communicates thermally with a cold region at 0 °C and with a hot region at 26 °C. This cycle has as working fluid the Refrigerant 134a. The saturated steam enters the compressor at 0 °C and the saturated liquid leaves the condenser at 26 °C. The mass flow is 0,08 kg/s. Determine (a) the compressor power, in kW, (b) the frigorific capacity, in TR, (c) the performance coefficient and (d) the performance coefficient of the Carnot cooling cycle that operates between the hot and cold regions at 26 °C and 0°C respectively."

The user will first access the main menu, from which he/she will choose the desired thermal cycle, in this case the steam compression ideal cooling cycle. After making this choice, the user will see a screen with the following information: cycle image; temperature-entropy diagram image; cycle thermodynamic properties according to Tab. (1) and cycle data and its components tables according to Tab. (2) a (5).

Table 1 – Thermodynamic properties

State	Temperature °C	Pressure bar	Specific Volume m³/kg	Enthalpy (h) kJ/kg	Entropy (s) kJ/kg.K	Phase
1						
2						
3						
4						

Table 2 – Cooling cycle data

Cycle Data	
Working fluid	
$\dot{m}$ (kg/s)	
T_C (°C)	
T_H (°C)	
T'_C (°C)	
T'_H (°C)	
β_{max}	
β	

Where:

T_C = cold reservoir temperature, in °C;

T_H = hot reservoir temperature, in °C;

T'_C = working fluid temperature in the evaporator at the steam compression ideal cycle, in °C;

T'_H = working fluid temperature in the condenser at the steam compression ideal cycle, in °C;

β_{max} = maximum performance coefficient reached by the Carnot cooling cycle, dimensionless;

β = performance coefficient in the cooling cycle, dimensionless.

Table 3 – Condenser data

Condenser data	
$\dot{Q}_{sai}$ (W)	

Where:

$\dot{Q}_{sai}$ = heat transfer rate from the working fluid to the cooling water or to the environment, in W.

Table 4 – Compressor data

Compressor data	
$\dot{W}_{comp}$ (W)	
η_{comp}	

Where:
$\dot{W}_{comp}$ = entry power necessary for the compressor operation, in W;
η_{comp} = compressor thermal efficiency, dimensionless.

Table 5 – Evaporator data

Evaporator data	
$\dot{Q}_{entra}$ (W)	
$\dot{Q}_{entra}$ (TR)	

Where:
$\dot{Q}_{entra}$ = heat transfer rate from a component to the working fluid, in J/s or W at SI, in Btu/h at English system and in ton of refrigeration (TR).

The user will fill the cycle thermodynamic properties in Tab. (1) and the cycle data in Tab. (2) with the known data, therefore generating the Tab. (6) and (7). If the cycle and its components data are known, the Tab. (3) and (5) can be filled in, otherwise they can be let in blank.

Table 6 – Thermodynamic properties

State	Temperature ºC	Pressure bar	Specific Volume m³/kg	Enthalpy (h) kJ/kg	Entropy (s) kJ/kg.K	Phase
1	0					Saturated Steam
2						
3	26					Saturated Liquid
4						

Table 7 – cooling cycle data

Cycle Data	
Working fluid	Refrigerant 134a
$\dot{m}$ (kg/s)	0,08
T_C (°C)	
T_H (°C)	
T'_C (°C)	0
T'_H (°C)	26
β_{max}	
β	

As the user enters the known information in Tab. (6) and (7), the program will automatically calculate all the unknown properties that are possible with that information, using the necessary cycle components thermodynamic concepts, working fluid properties table interpolations and unit conversions, as shown from Tab (8) to (11).

Table 8 – Thermodynamic properties

State	Temperature ºC	Pressure bar	Specific Volume m³/kg	Enthalpy (h) kJ/kg	Entropy (s) kJ/kg.K	Phase
1	0			247,23	0,9190	Saturated Steam
2		6,8530		264,69	0,9190	Superheated Steam
3	26	6,8530		85,75		Saturated Liquid
4				85,75		

Table 9 – Cooling cycle data

Cycle Data	
Working fluid	Refrigerant 134a
$\dot{m}$ (kg/s)	0,08
T_C (°C)	
T_H (°C)	
T'_C (°C)	0
T'_H (°C)	26
β_{max}	10,5
β	9,24

Table 10 – Compressor data

Compressor data	
$\dot{W}_{comp}$ (W)	1400
η_{comp}	

Table 11 – Evaporator data

Evaporator data	
$\dot{Q}_{entra}$ (W)	12,92
$\dot{Q}_{entra}$ (TR)	3,67

In this way, all the properties requested by the Moran and Shapiro (2013) exercise were automatically calculated, obtaining the same results from the literature. The user will have easy access to the equations used the calculation steps.

5. RESULTS AND DISCUSSION

The user will first access the main menu as shown in Fig. 2. There he/she can choose the thermodynamic cycle, which are ideal and real cycles of heating, cooling and power generation. The user can choose to work with international or English systems. The user can access also the thermodynamic properties tables, the Moran & Shapiro's book official website, the complete work about the program development (which can be used as reference) and the sponsors websites.

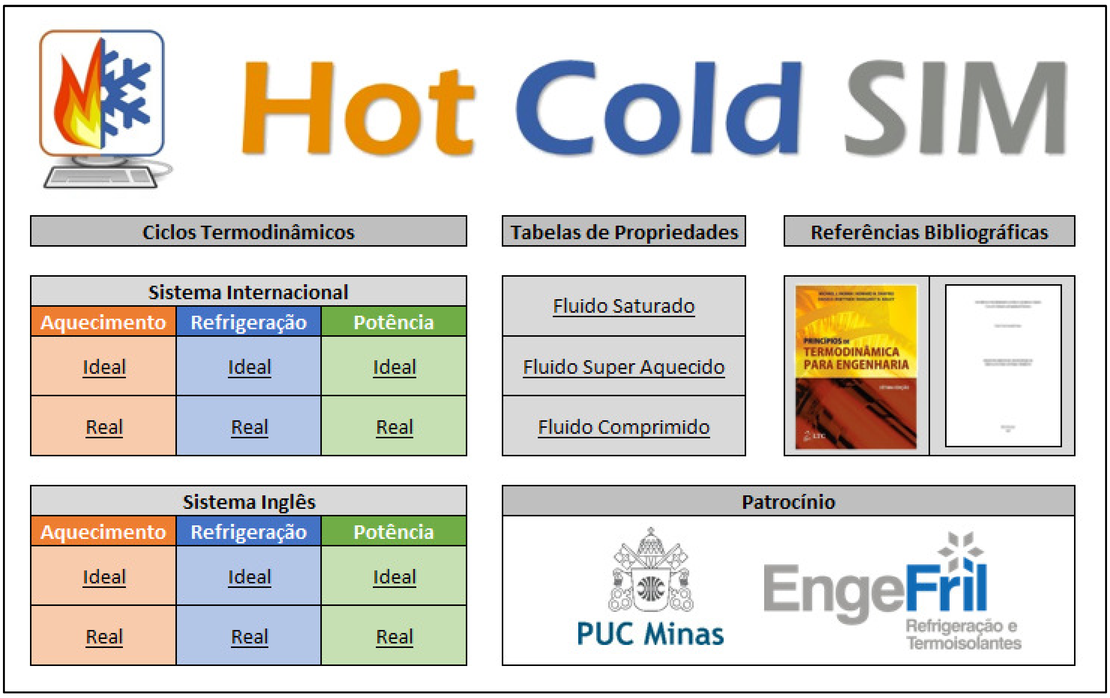


Figure 2. Software main menu

When the user chooses a cycle on the main menu, he/she will see a screen with some information about the cycle, as shown in Fig. 3. The information is: fluid Thermodynamics properties, cycle data, components properties, components scheme, a temperature and pressure unit conversion table and temperature-entropy diagram. If the user inserts the known data, the software will automatically calculate the not known properties that are possible using the thermodynamic concepts, properties interpolation and unit conversions that are necessary for it. The program can be customized according to the user needs by creating new cycles based in the existent ones and adding new components and functions.

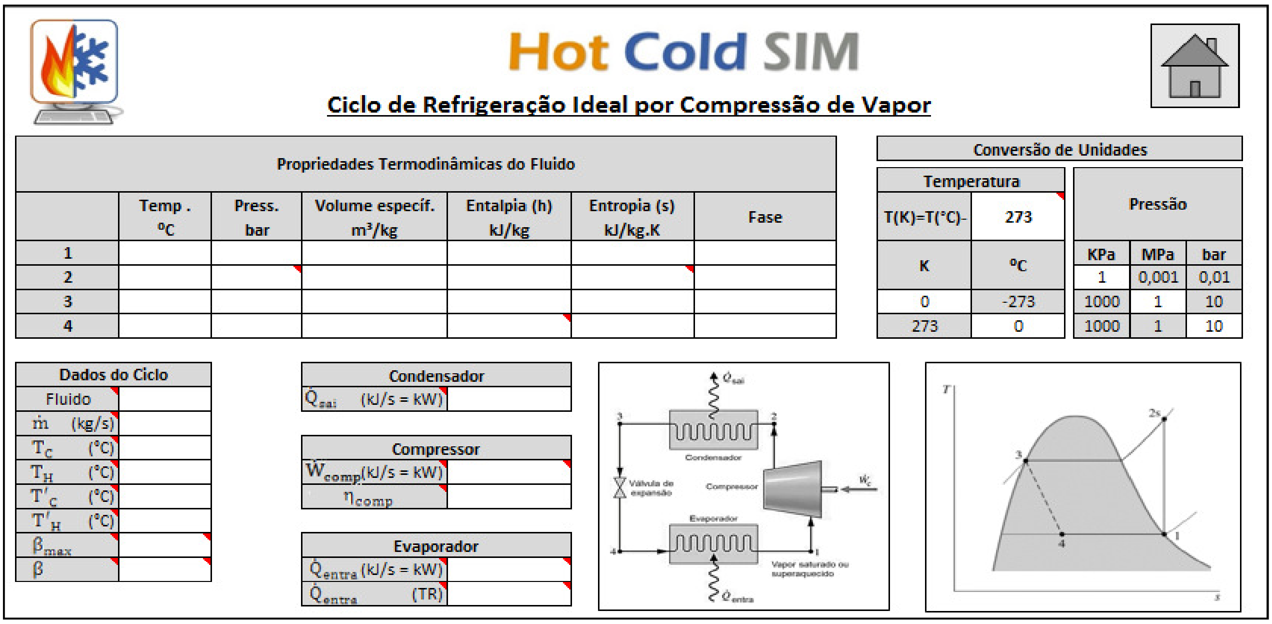


Figure 3. Ideal cooling cycle by steam compression calculation screen

When the user moves the mouse over the cells that have a red indicative arrow, he/she will see balloons showing that property concept or its calculation details with even the bibliographic reference page. On Fig. 4 and 5 there is shown what happens when the user moves the mouse over the "maximum performance coefficient" property cells.

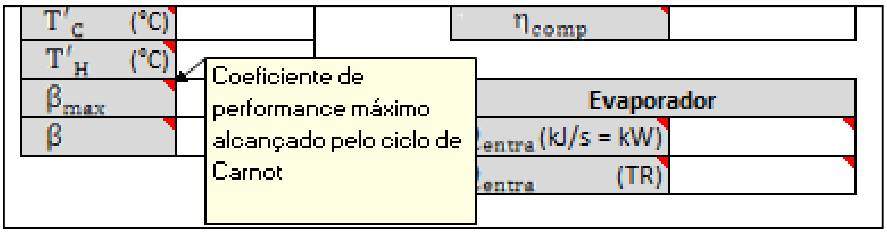


Figure 4. Explicative balloon detail

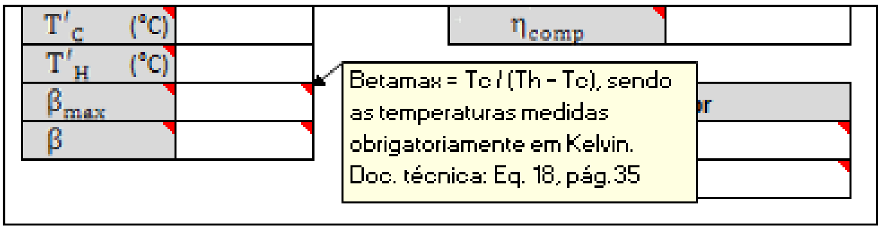
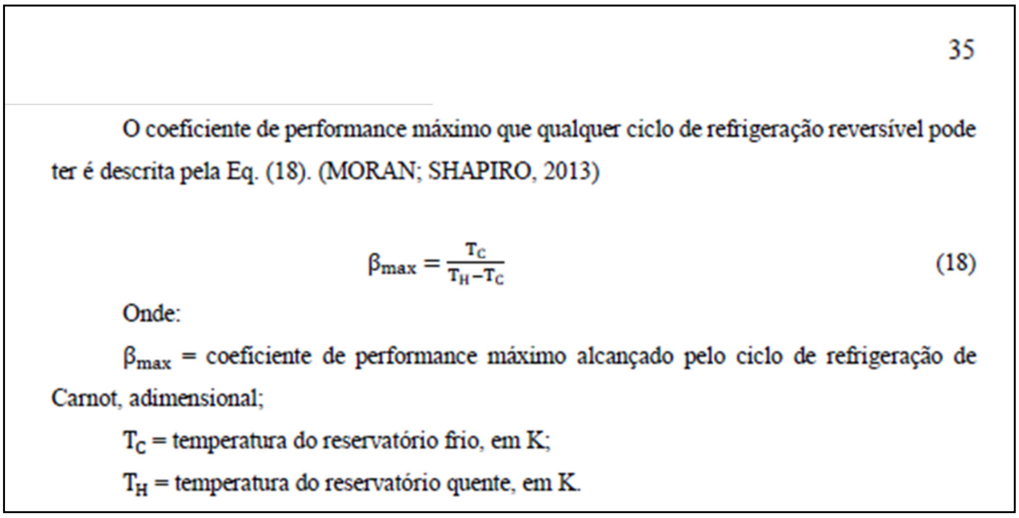


Figure 5. Explicative balloon detail

Note that the balloon at Fig. 5 orients the user to see the equation 18 at the page 35 of the bibliography reference, which is available on the main menu. When accessing that technical documentation, the user will see the explanation for the "maximum performance coefficient" concept, as shown on Fig. 6.



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O coeficiente de performance máximo que qualquer ciclo de refrigeração reversível pode ter é descrita pela Eq. (18). (MORAN; SHAPIRO, 2013)

$$\beta_{max} = \frac{T_C}{T_H - T_C} \quad (18)$$

Onde:

β_{max} = coeficiente de performance máximo alcançado pelo ciclo de refrigeração de Carnot, adimensional;

T_C = temperatura do reservatório frio, em K;

T_H = temperatura do reservatório quente, em K.

Figure 6. Detail of the technical documentation attached to the program

On the center of the main menu as shown on Fig. 2 there are links to access the fluids Thermodynamics properties which tables are registered in the program. When clicking, for example, on the saturated fluid properties table link, the user will access a table with many fluids properties, as shown on Fig. 7. The program comes loaded with the Thermodynamics properties tables available in Moran and Shapiro (2013) text book, but it is important to highlight that the user can easily customize that tables, adding new fluids or adding temperature or pressure intervals that were not covered by the program's pre-loaded tables. Those tables are used automatically by the program to perform calculations, but can be also accessed by the user when he/she wants to perform a manual calculation. Note that there are filters applied to the tables to facilitate the search for a specific data by the user.

					Propriedades de Fluido Saturado (Líquido-Vapor)									
					Volume Específico m³/kg		Energia Interna kJ/kg		Entalpia kJ/kg			Entropia kJ/kg.K		
Tabela	Fluido	Ref	Press. bar	Temp . °C	Líquido Sat. $vfx10^3$	Vapor Sat. vg	Líquido Sat. uf	Vapor Sat. ug	Líquido Sat. hf	Evap. hfg	Vapor Sat. hg	Líquido Sat. sf	Vapor Sat. sg	Temp . °C
A-2	Água	Temp.	0,0061	0,01	1,0002	206,14	0,00	2.375,3	0,01	2.501,3	2.501,4	0,0000	9,1562	0,01
A-2	Água	Temp.	0,0081	4,00	1,0001	157,23	16,77	2.380,9	16,78	2.491,9	2.508,7	0,0610	9,0514	4,00
A-2	Água	Temp.	0,0087	5,00	1,0001	147,12	20,97	2.382,3	20,98	2.489,6	2.510,6	0,0761	9,0257	5,00
A-2	Água	Temp.	0,0094	6,00	1,0001	137,73	25,19	2.383,6	25,20	2.487,2	2.512,4	0,0912	9,0003	6,00
A-2	Água	Temp.	0,0107	8,00	1,0002	120,92	33,59	2.386,4	33,60	2.482,5	2.516,1	0,1212	8,9501	8,00
A-2	Água	Temp.	0,0123	10,00	1,0004	106,38	42,00	2.389,2	42,01	2.477,7	2.519,8	0,1510	8,9008	10,00
A-2	Água	Temp.	0,0131	11,00	1,0004	99,86	46,20	2.390,5	46,20	2.475,4	2.521,6	0,1658	8,8765	11,00
A-2	Água	Temp.	0,0140	12,00	1,0005	93,78	50,41	2.391,9	50,41	2.473,0	2.523,4	0,1806	8,8524	12,00
A-2	Água	Temp.	0,0150	13,00	1,0007	88,12	54,60	2.393,3	54,60	2.470,7	2.525,3	0,1953	8,8285	13,00
A-2	Água	Temp.	0,0160	14,00	1,0008	82,85	58,79	2.394,7	58,80	2.468,3	2.527,1	0,2099	8,8048	14,00
A-2	Água	Temp.	0,0171	15,00	1,0009	77,93	62,99	2.396,1	62,99	2.465,9	2.528,9	0,2245	8,7814	15,00
A-2	Água	Temp.	0,0182	16,00	1,0011	73,33	67,18	2.397,4	67,19	2.463,6	2.530,8	0,2390	8,7582	16,00
A-2	Água	Temp.	0,0194	17,00	1,0012	69,04	71,38	2.398,8	71,38	2.461,2	2.532,6	0,2535	8,7351	17,00
A-2	Água	Temp.	0,0206	18,00	1,0014	65,04	75,57	2.400,2	75,58	2.458,8	2.534,4	0,2679	8,7123	18,00
A-2	Água	Temp.	0,0220	19,00	1,0016	61,29	79,76	2.401,6	79,77	2.456,5	2.536,2	0,2823	8,6897	19,00
A-2	Água	Temp.	0,0234	20,00	1,0018	57,79	83,95	2.402,9	83,96	2.454,1	2.538,1	0,2966	8,6672	20,00
A-2	Água	Temp.	0,0249	21,00	1,0020	54,51	88,14	2.404,3	88,14	2.451,8	2.539,9	0,3109	8,6450	21,00
A-2	Água	Temp.	0,0265	22,00	1,0022	51,45	92,32	2.405,7	92,33	2.449,4	2.541,7	0,3251	8,6229	22,00

Figure 7. Saturated fluid properties table

6. CONCLUSIONS

Through this work it was possible to perceive the thermal systems computational simulation importance for design and dimensioning, improvement studies, thermal losses detection and predictive maintenance, to increase the systems energetic efficiency both in its generation or use. The thermal systems simulation software developed in this work has the differentials of being easy to use, highly customizable, didactic, low cost and permitting a quick consultation to the theoretical foundation during its usage. In this way, the program can become one of the options between the already existent software of its type, allowing many users, companies and institutions to obtain the benefits related to the computational simulation and that the thermal systems be more and more efficient.

7. ACKNOWLEDGMENT

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