AQUESOLGAS

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Abstract. *The use of solar energy combined with natural gas for dwelling water heating requests new sizing techniques. In order to extend these new sizing rules for different systems and places, we developed a software able to simulate the detailed thermal behavior of each component of these systems and the overall system facility itself. This work presents the software, describing its principal features and the numeric methods used to accomplish the simulations. The software AQUESOLGAS was developed in Visual Basic for Windows and it presents friendly interfaces and intuitive operation. The software includes an interface with presentation of graphs of the temperatures and other resulting data along the time, also to facilitate the visualization of the results. The program demonstrates that it is capable to be used to simulate the proposed systems, generating fundamental data for an appropriate system sizing.*

Keywords. *Solar Energy. Water Heating. Solar Energy Heating Systems. Natural Gas Heating Systems*

1. Introduction.

It is plenty known the fact that one of the causes of the energy consumption is the heating of water. The hot water is used in industries, in hospitals, in chemical and cleaning processes, in hotels and residential consumption. Water is mainly heated from electricity or by burning firewood or gas. In Brazil, the electricity is widely used for water heating in dwellings, mainly for bath, through electric showers.

The solar energy, that it is abundant in Brazil, can be used for water heating with equipments of very trustful and simple operation, known as solar collectors. The solar collectors can work without water circulation pump, just with natural circulation, storing warm water during the daytime in thermal reservoirs for night use or for the days in that the solar radiation is weak. The solar collectors are already marketed throughout Brazil and their more intense use depends on popularization and of obtaining the users' trust through the demonstration provided by qualified facilities. In different way from the gas, firewood or electricity heating systems, the facilities of solar energy water heating do not work in an autonomous mode. They depend on another source of energy, called auxiliary energy, to assure the continuity of heating supply in the periods in that the solar radiation is not intense enough. Once again, in the case of consumption of hot water for domestic use, the option of auxiliary energy relapses in the case of electric power, this time because it is easier to control and install. Thus, in Brazil, it was conventionalized to install and to operate solar energy water heating systems with electric auxiliary energy, having been developed a certain sizing systematic and a specific know-how for these facilities.

On the other hand it is known that the Natural Gas (NG) network is in expansion in Brazil offering an opportunity of smaller price than the electricity. As the cities are receiving the distribution pipes for domestic NG consumption, the possibility of demanding this way of energy becomes concrete. Although NG is cheaper than electricity for water heating, it should be thought about its rational use.

Considering these facts, we proposed the use of solar energy water heating systems using NG as auxiliary energy. As the more conventional form of using the auxiliary energy is with electricity, the sizing techniques should be reformulated and adapted for this new proposal. The prices being different, ends for also suggesting proportions very different between solar energy and auxiliary energy, so the system could be classified as " hybrid " [Krenzinger and Lafay, 2002]. The complete analysis of the ideal energy fractions (and how the system should be installed) can be obtained from testing dozens of experimental configurations along several years or through a system of computer simulation if it is complete enough to contemplate the effects of small constructive alterations of the facilities.

The present work presents a computer program (AQUESOLGAS) that accomplishes simulations of the thermal behavior of water heating systems combining solar energy and NG. AQUESOLGAS is described in the next sections, constituting a high quality tool to discover the effects that alterations in the form of mounting the installation can produce in the final heating result.

2. Computer simulation.

A computer simulation can have several detail levels. Even a spreadsheet calculating the temperature evolution of a heat transfer system can be classified as computer simulation. However, for each detail level there will be a different quality in the obtained results. Complex systems with several components even could be simulate with global calculations representing their average behavior, but, for obtaining details of the actual behavior for each component of the system, it is necessary a computational simulation program that is capable to simulate each component individually and to gather the individual results to form the global result.

In the case of water heating systems with solar energy and NG the physical components of the system are: solar collectors, thermal reservoir, gas heater, piping and geometry of the installation. Besides these physical components of the installation, the simulation program should consider logical components as: thermostat activating, pump activating, displacement of tank layers of water in function of their temperature and still some meteorological components as: ambient temperature, solar radiation and wind speed.

There are very few computer simulation programs that allow defining the details of each component in order to assemble the effects in a consolidated result. One of these programs (the most recognized) is TRNSYS (2002) (TraNsient SYstem Simulation Program), developed in a modular system with a library of components to model a variety of energy systems. The potentiality of TRNSYS' simulation is going much beyond the water heating solar energy systems, but this advantage is not important if the user's objective is specifically to analyze these systems. One of the difficulties of the use of this software is the need to inform all the input data with a lot of detail in an arduous way, besides having a quite high cost. Furthermore, the TRNSYS do not support components as a thermal reservoir with flexibility of defining the inlet and outlet positions for different heating circuits operating simultaneously, which is necessary for the purpose of the present work.

The program presented in this work is dressed by a very friendly interface, with all the necessary input data recorded in advance, being enough to the user to modify the installation parameters or the site of the application. The system is adapted to the climate and the technology used in Brazil. In spite of being it application limited to this specific type of system, we attempted to develop a simulation program that approaches all the possible variables.

3. Mathematical approach

The mathematical modeling used for each component has different authors' origin. A deep bibliographical research was accomplished to select the models. Although there are few available simulation softwares for solar energy water heating systems, models for specific components were quite studied and several published proposals exist.

For the development of the mathematical model of the process, a number of simplifying assumptions are made, mostly related to the "quasi-steady" state performance and the treatment of the heat flow as one-dimensional.

3.1 Solar collectors

For the solar collectors the classic Hottel-Bliss-Whillier approach was used (as presented in Duffie and Beckman, 1991). As standard procedure, the performance parameters of the collector are used: $F_R(\tau\alpha)$ and F_RU_L. These parameters represent, respectively, the effects of the optical properties and of the thermal properties of the solar collector and they are obtained in experimental tests for the determination of the thermal efficiency of the collectors, what can be performed following technical norms as ABNT NBR 10184 (1988) and ASHRAE Standard 93-77 (1977). Besides these two parameters, to calculate heating and cooling effects on the solar collectors in the morning and in the afternoon, the materials and constructional dimensions of the collectors are considered.

The energy balance in a fluid element inside of the solar collector, flowing through a length Δx in a pipe, in an instant t, according to the theory of Hottel-Bliss-Whillier, can be represented by the following first order ordinary differential Eq.(1):

$$\left(\frac{\dot{m}_c}{n}\right) c_p \frac{dT}{dx} = W F' \left[S - U_L (T - T_a)\right] \tag{1}$$

where $\dot{m}_c$ is the total mass flow rate in the solar collector; n is the number of tubes in the solar collector; T is the mean fluid temperature inside the collector's tubes; W is the distance between the tubes; F' is the factor of efficiency of the solar collector that represents the ratio between the heat transfer resistance from the fluid to the ambient air and the heat transfer resistance from the absorber plate to the ambient air; S is the solar radiation absorbed by the collector.

3.2 Thermal reservoir

The processes of heat transfer in thermal reservoirs can be accurately simulated with using two-dimensional models, as Oliveski et al 2003, but to proceed calculations of system simulation, one-dimensional multinode models (enhanced in order to contemplate deficiencies) are enough. For the calculation of the temperature distribution in the thermal reservoir we used the model presented by HUSSEIN (2002) modified to allow more accesses of external connections and adapted to use an external instant gas heater. In this model, in each interval of time, some thermal layers of the reservoir are identified when they correspond to physical connection (PC, those that has a tube externally connected to the tank) and when they correspond to thermal equilibrium connection (TC, those in that the temperature is equal to the inlet temperature of the water). The reservoir communicates with 3 external circuits: the demand circuit, the solar circuit and the gas heater circuit. Each circuit has 2 PC and 1 TC, because only the inlet fluid is supposed to have a TC, the outlet fluid is drawn just in its PC. The mass flow rate of the circulating water through the reservoir and each circuit is distributed equally for the layers understood between two corresponding TC, although the real circuit is defined by two PC. [see Morrison and Tran, 1984]. Considering these connections we defined flow factors that command the terms of a general heat and mass transfer equation for each layer of the reservoir. Table 1 presents the definition of the selected layers and the logic operations for defining flow factors.

Table 1. Definition of the selected layers and the logic operations for defining flow factors G^d and F^d for demand circuit, G^C and F^C for collector circuit and G^G and F^G for gas heater circuit and flow fractions A_C, A_S and A_G.

Physical Connection Layers		Thermal Equivalent Connection Layers	
PC_S service water inlet the tank		TC_S service water temperature	
PC_D demand hot water outlet the tank			
PC_C collector outlet water inlet the tank		TC_C collector outlet water temperature	
PC_I collector inlet water outlet the tank			
PC_G gas heater outlet water inlet the tank		TC_G gas heater outlet water temperature	
PC_H gas heater inlet water outlet the tank			
$A_C = \vert PC_C - TC_C \vert$	$A_S = \vert PC_S - TC_S \vert$		$A_G = \vert PC_G - TC_G \vert$
IF	**AND**	**AND**	**THEN**
$TC_C <= PC_C$	$PC_C <= i$	$i <= TC_C$	$G^C(i) = i - TC_C$
$TC_C > PC_C$	$PC_C <= i$	$i <= TC_C$	$G^C(i) = i - PC_C$
$TC_C <= PC_C$	$PC_C < i$	$i <= PC_I$	$G^C(i) = A_C$
$TC_C > PC_C$	$TC_C < i$	$i <= PC_I$	$G^C(i) = A_C$
$TC_G <= PC_G$	$PC_G <= i$	$i <= TC_G$	$G^G(i) = i - TC_G$
$TC_G > PC_G$	$PC_G <= i$	$i <= TC_G$	$G^G(i) = i - PC_G$
$TC_G <= PC_G$	$PC_G < i$	$i <= PC_H$	$G^G(i) = A_G$
$TC_G > PC_G$	$TC_G < i$	$i <= PC_H$	$G^G(i) = A_G$
$TC_S <= PC_S$	$PC_S >= i$	$i >= TC_S$	$G^d(i) = PC_S - i$
$TC_S > PC_S$	$PC_S <= i$	$i <= TC_S$	$G^d(i) = TC_S - i$
$TC_S <= PC_S$	$TC_S < i$	$i >= PC_D$	$G^d(i) = A_S$
$TC_S > PC_S$	$PC_S > i$	$i >= PC_D$	$G^d(i) = A_S$
$h(i) >= h(PC_C)$	$T(i) <= T_{OC}$		$F^C(i)=1$
$h(i) < h(PC_C)$	$h(i) >= h(PC_I)$	$T(i) <= T_{OC}$	$F^C(i)=1$
$h(i) >= h(PC_S)$	$T(i) <= T_{SV}$		$F^d(i)=1$
$h(i) < h(PC_S)$	$T(i) >= T_{SV}$		$F^d(i)=1$
$h(i) >= h(PC_G)$	$T(i) <= T_{OG}$		$F^G(i)=1$
$h(i) < h(PC_G)$	$T(i) >= T_{OG}$		$F^G(i)=1$

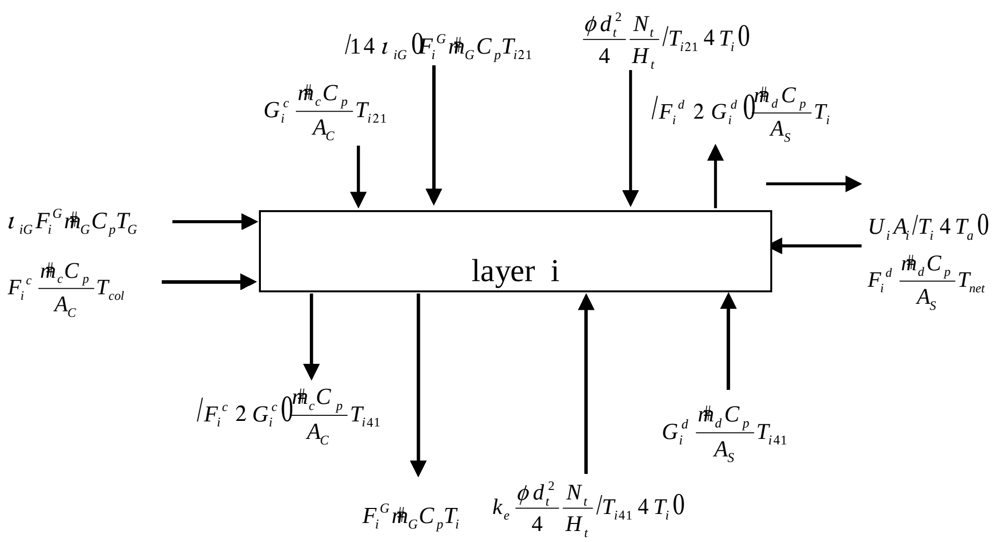


Figure 1. Heat and mass transfer diagram for a generic layer inside the tank.

Figure 1 shows a diagram with all the considered terms of the general heat transfer equation for a generic layer inside the tank. F and G are the flow factors defined in Table 1, the superscripts G, c and d refer respectively to the gas heater circuit, to the solar collectors circuit and to the demand circuit. H_t is the total height of the tank, d_t is the diameter of the tank, N_t is the number of layers adopted (N_t=15), C_p is the specific heat of water, U_i is the overall loss coefficient for this i-layer, A_i is the lateral area related to this layer, T_{col} is the outlet temperature of the solar collectors circuit, T_{net} is the service water temperature, T_a is the ambient temperature, T_G is the outlet temperature of the gas heater circuit, k_e is the effective conductivity across the layer, $\dot{m}$ is the flow mass rate for each circuit, A_S, A_C and A_G are defined in Tab (1) and ι is the Kronecker delta function, being 1 when i = PC_G.

3.3 Gas Instant Heater

The circuit of auxiliary heating is energized with a gas instant heater, which is activated by a pump whenever the thermostat senses a temperature below the set temperature. The pump draws the water through the gas heater lighting the flame automatically. The heater provides a raise of about 20°C being the power of the heater considered constant. Through the efficiency of the heater it is possible to also calculate the consumption of NG during the operation. The flow rate of the pump is prescribed and considered constant. The temperature drop in each pipe of the circuit is calculated resulting in the temperature of the inlet water in the reservoir.

The software has plenty flexibility to admit several geometric values for the connections of the gas heater circuit. The user should also inform the height where is installed the thermostat and the set temperature. According to the positions of the connections and of the thermostat, the system has a different thermal behavior.

Considering Q_{gas} the power of the gas heater and $\dot{m}_G$ the mass flow rate for the circuit, we first calculate an approximate value for the temperature in the entry of heated water in the tank, as Eq. (2). Then is possible to add the losses, Eq.(3),thought the pipe area (A_{1P}+ A_{2P}) insulated with a k_P thermal conductivity material with. thickness e_P.

$$T_G^{try} = \frac{Q_{GAS}}{\dot{m}_G C_p} + T(PC_H) \tag{2}$$

$$T_G = \frac{Q_{GAS}}{\dot{m}_G C_p} + T(PC_H) - \frac{A_{1P} k_P}{e_P}(T(PC_H) - T_a) - \frac{A_{2P} k_P}{e_P}(T_G^{try} - T_a) \tag{3}$$

4. Software Flowchart

The software was developed to be used without the need of spending a long time when inserting data for each component of the system. There are included data that can be used while the user is not skilled in the handling of the screen forms.

The program begins consulting the data used in the last session. This simple providence eliminates the costly task of repeating all the data input every time the user intends to run the simulation. Having interest of modifying some of the data, the user opts to open one of the input data forms on the screen: demand of hot water, data of the solar collectors, data of the system, data of the gas heater, climatic data or data about the installation. Each form, in an independent way, updates the parameters that will be used during the simulation. With all the data defined, the user also defines the simulation interval (from one day up to one year) and runs the program. The time-variable is increased every hour, being the mass flow rate that circulates in the circuit of the collectors calculated equaling the pressure drop of the circuit with the pressure difference caused by the variation in the density of the water when heated up. For each hour the mass flow rate is established, being then calculated the temperatures along all the circuits and in the several layers of the reservoir.

Figure 2 displays the simplified flowchart of the program.

5. Graphic Interfaces

As the flowchart of Fig.(2) indicates, the input of data is made using graphic interfaces. The software includes a database with meteorological information with monthly averaged values. A subprogram called as “climatic data” aids the user to locate the site of application through a map. The site climatic data is used for synthesizing meteorological hourly sequences as described in Krenzinger and Farenzena, 2003. All the other data are informed by changing the text boxes in the specific forms. A drawing of the installation helps the user to identify the meaning of each data. Fig. (3) shows six aspects of graphic interfaces.

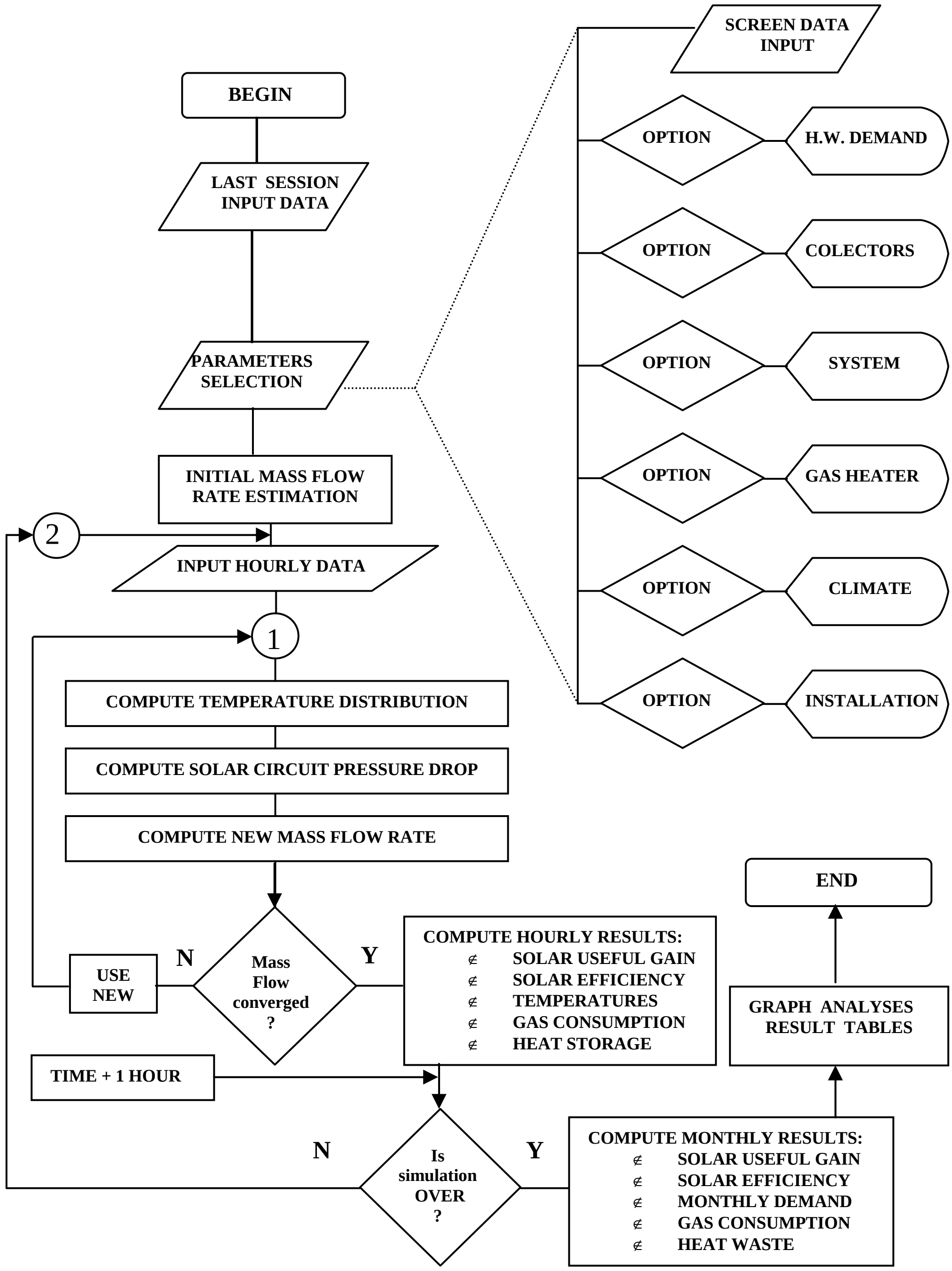
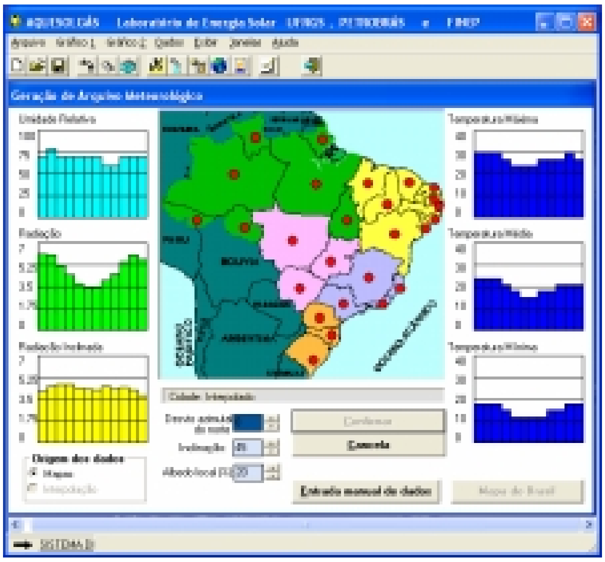


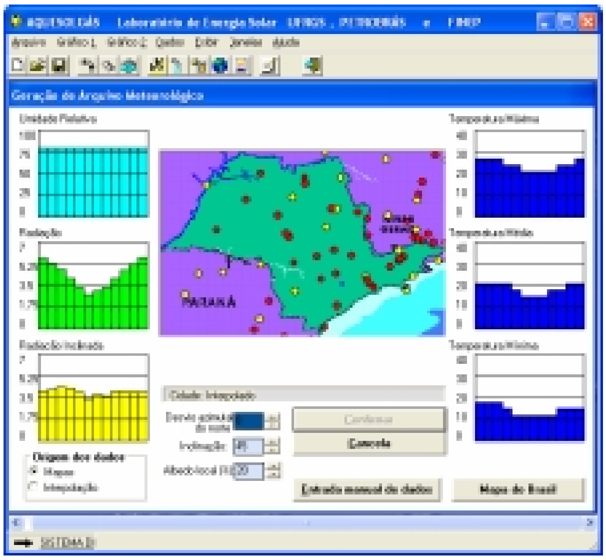
Figure 2 Flowchart showing the simulation path of AQUESOLGAS

None of these interface text boxes are required to be filled, since default data are always activated. Figures 3 (a) and (b) show the “Climatic Data Interface” where the user selects the application site. When the “confirm” button is clicked the software generates a new meteorological input data file. This file can be eventually changed by another manufactured by the user, if it is important for a specific task. Figure 3 (c) shows the “Solar Collector Interface” where the user can inform the collector components dimensions or, as optional way, the efficiency parameters of the collectors. This interface reproduces the efficiency curve at the time the user input dimension data, so this is a helping feature that avoid possible mistakes. Figure 3 (d) shows the “Consumption Profile Interfaces” that allow the user to inform when the hot water is demanded, weekly and monthly, as well as the mean daily consumption for each month. There are *COPY/PASTE* controls in order to make the work easier. Figure 3 (e) shows the “Installation Pipes Interface” where the user can accept or change data about the length and diameter in the pipes of the hydraulic circuits of the installation. Figure 3 (f) shows the “Geometric Data Interface” where the user informs the positions of inlet and outlet connections for each circuit and position of the thermostat sensor.

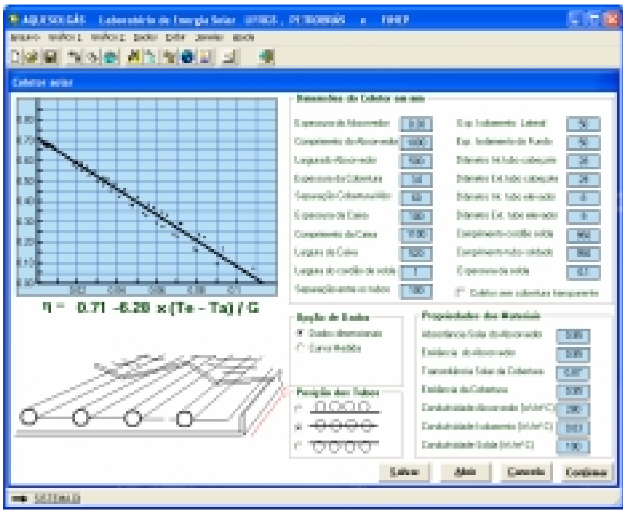
Figure 4 shows the screen capture of AQUESOLGAS after the programmed simulation is over. The final analysis is obtained from the viewing of a dynamic graph that can plot simultaneously various results and gives to the user a powerful tool for performing his task.



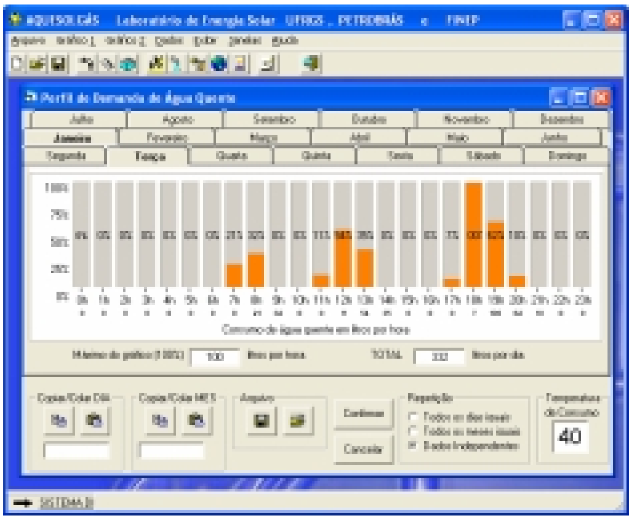
(a) Climatic Data (BRAZIL)



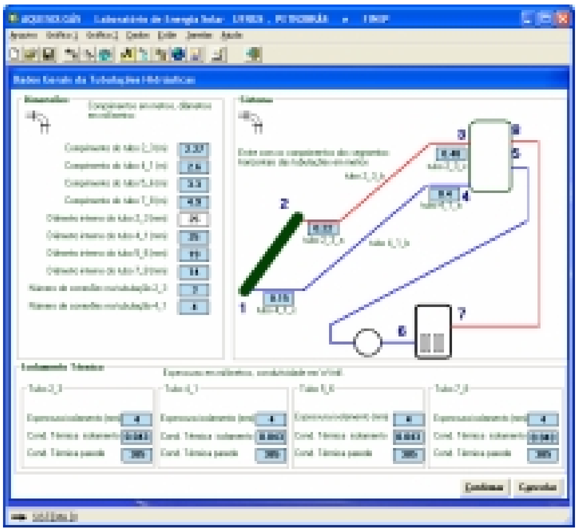
(b) Climatic Data (State of São Paulo)



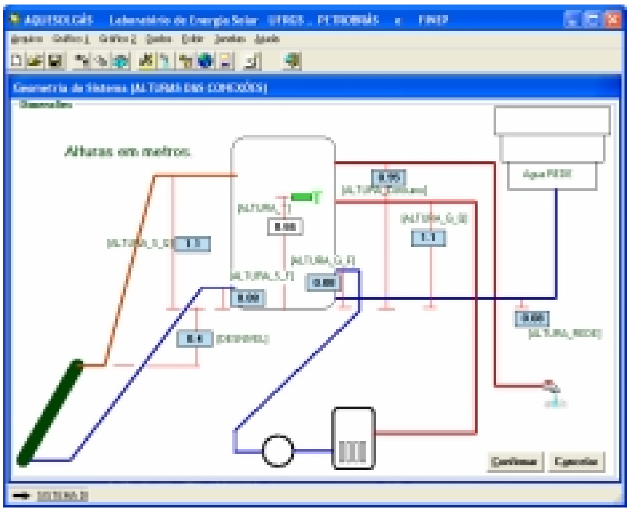
(c) Solar Collector Interface



(d) Consumption Profile Interfaces



(e) Installation Pipes Interface



(f) Geometric Data Interface

Figure 3. Examples of graphic interfaces used in AQUESOLGAS for data input.

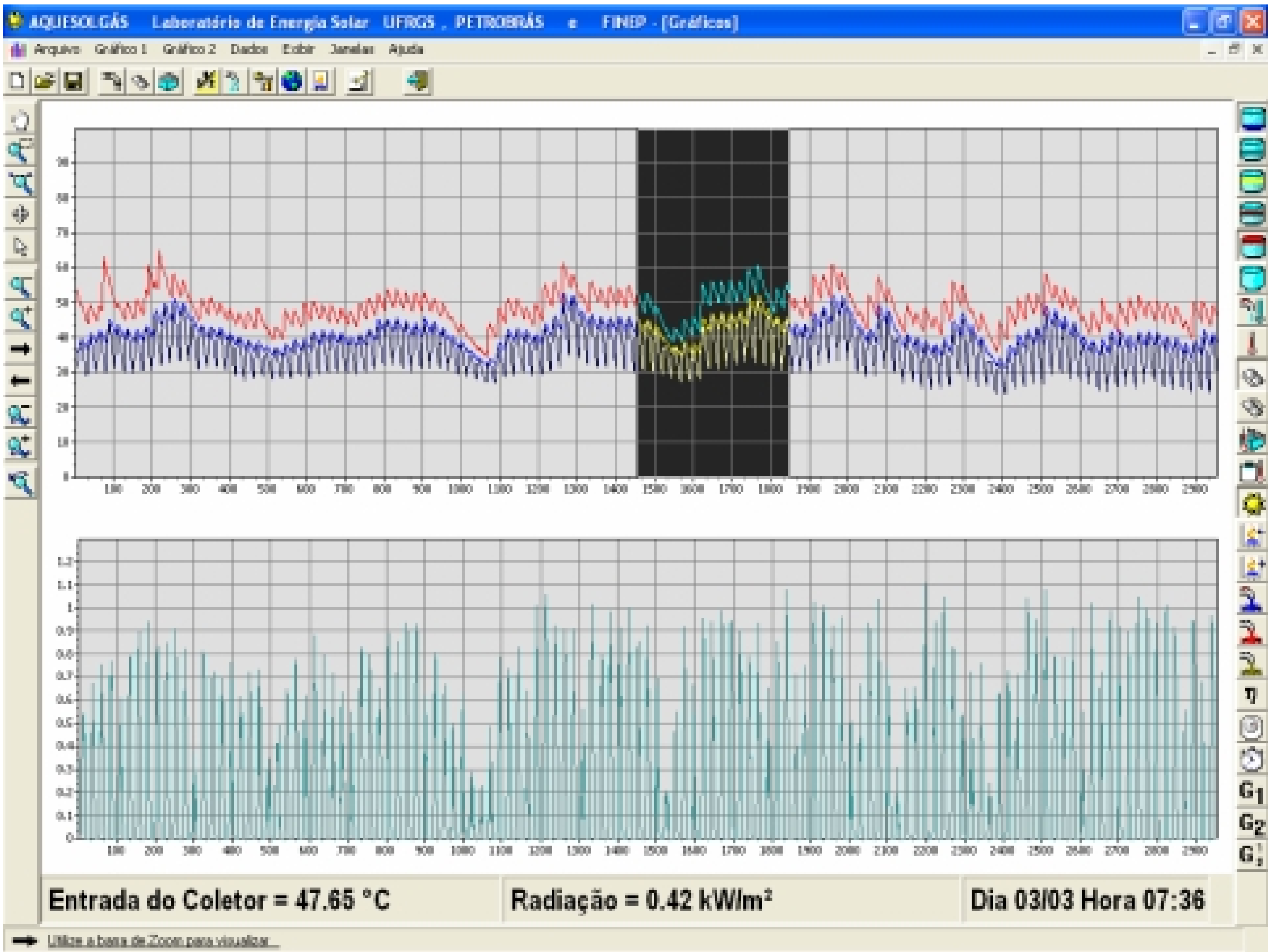


Figure 4. Interface presenting graphs of the results. The results can be selected with mouse clicking operations and there are several zoom options for a careful viewing of the values.

6. Conclusion

We have developed a computer simulation software which is able to reproduce the thermal behavior of several components in a water heating system using solar energy and natural gas. The software includes graphic interfaces that help the user to insert the dimensional information and climatic data. The simulation is processed in hourly base and can be ran from 1 day to 1 whole year real time scope. We had modified existing mathematical approaches in order to adapt the simulation to the studied installation. The results were very satisfactory and we hope that very soon this computer tool can be available to the interested professionals.

7. Acknowledgements

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