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EVOLUTION OF THERMAL AND HYDRAULIC ENERGY IN A BOILER WITH NATURAL CIRCULATION

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ABSTRACT

We present in this paper the coupling of both thermal and hydraulic energy required in the boiler, the analytical and graphical modelling present a natural circulation boiler which occurs in a homogeneous two-phase mixture between water and steam. The overall system consists of a circuit of water, a saver and a higher ball. The bond graph tool allowed us to transform the analytical model to the graphical model. Specific bond-graph simulation software SYMBOLS helped us to validate and submit the results given by the technical specifications.

KEYWORDS

Boiler, Modelling, Simulation, Thermal and hydraulic energy, Bond graph.

1. INTRODUCTION

The industry is currently growing very rapidly with the development of new technologies. The manufacturer cannot do without the old conventional methods that fall into most production lines. For example, the temperature increases in a system requires a boiler [1]. Modelling is a procedure that allows from experimental facts and / or fundamental laws which builds a model. The model of a system is a representation of components and phenomena evolution. Modelling consists to translate the phenomena that occur in technological systems by a mathematical or graphical representation [2]. Wanting to replace the physical complexity of the system by several mathematical equations is not an operation without risk [3].

The main objective of our work is to model and simulate a process by bond graph tool. To illustrate the principles used and results obtained by applying this tool to a boiler type natural circulation [4]. The modelling of various components of the boiler by the bond graph tool consists in the modelling of the supplying water circuit, to the economizer and the higher ball.

The use of simulation software SYMBOLS [5] and operation of integrated tools in this software allow us to present several results of temperature, pressure and mass flow.

2. DESCRIPTION OF THE SYSTEM

A boiler is a heat exchanger or a special set of interchanges. It is designed to convert water into steam and deliver it to a pressure or a desired temperature using a defined heat source [1]. The boiler owes its existence to the exceptional physical properties of water, especially its heat capacity and high heat of vaporization, which combined provide an industrial thermo fluid. The natural circulation boiler is composed by:

- **Burners:** Their role is to cause the mixture between air and fuel to achieve complete combustion thereof, the combustion air is introduced through air adjustable dampers. A burner is designed to burn either gas or oil, or both.
- **Combustion chamber:** This is where the combustion takes place, it is lined tubes, heating surface so-called "shots" it is even larger than the steam flow increases. The floor of the home and the empty spaces are protected by bricks that help the household to maintain a very high temperature.
- **Blowing fan:** It sucks the air needed for combustion in the hearth and sweeps the boiler to remove any gas pockets before ignition.
- **Draft fan:** It sucks the smoke out of the boiler to the back at the fireplace.
- **Fireplace:** It is here where the combustion gases are discharged after dust in a dust collector.
- **Economizer:** It extracts heat from the gases leaving the boiler to raise the temperature of the water supply.
- **Air heater:** It extracts heat from escaping gas from the boiler to raise temperature of the air. The resulting temperature rise of home, hence better combustion and better use.
- **Higher ball (Tank):** Its role is to establish an end point for water from the economizer, a point of arrival and departure for water and steam circulation. Its second role is to ensure the greatest possible purity steam going into the super heater.
- **Beam evaporation:** It is located in the combustion chamber and fed by water from the lower collector.
- **Lower collector:** This is a point of water arrival in the tank down the tubes and the water starting point to the spray beam.
- **Super heater:** It takes the heat from the combustion gases leaving the boiler to raise the temperature of saturated steam which leaves the tank with a small variation in its pressure to make it as dry as possible (fig.1).

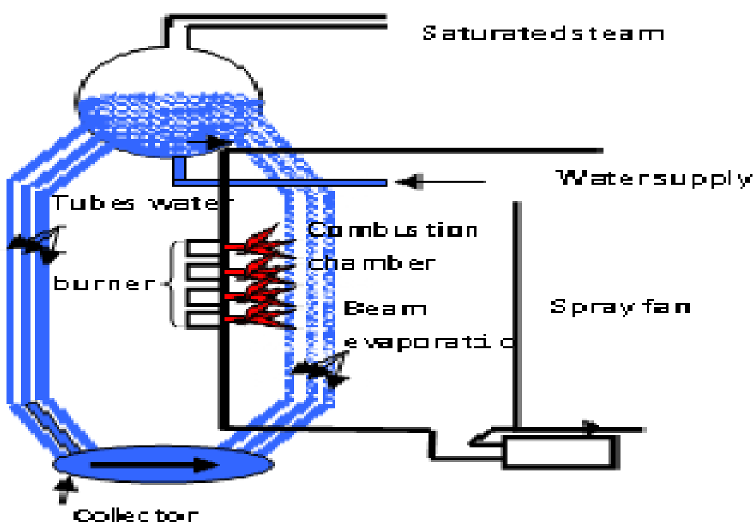

Figure 1. Natural circulation boiler circuit

3. MODELLING OF THE BOILER

We consider that it produces a homogeneous two-phase mixture between water and steam. There is no clear separation between the two phases. The mixture "water and steam" is called "saturated steam" or "wet saturated steam". The saturated steam is defined by its titration *X*; $\dot{H}$ is the enthalpy flow represented by the amount of energy transported per unit time; $\dot{m}$ is the mass flow rate takes into account the compressibility of the fluid; T_e is the temperature of feed water is represented as an effort source measured by sensors, *P* is the high fluid pressure [2], [3], [4].

3.1. Modelling of the water supply circuit

The circuit of water supply which its density is ρ and heated to a constant temperature T_e is composed by a pump displacing fluid under a high constant pressure P_e and a well-insulated pipe of length ℓ and section *A* connected with the economizer.

The inertia of the fluid flow is due to its mass. The pump is represented as an effort source (pressure source). It is obvious to represent the pump by a more complete model taking into account the mechanical and hydraulic energy.

The temperature of water supply T_e is represented as an effort source (temperature source) (Figure 2).

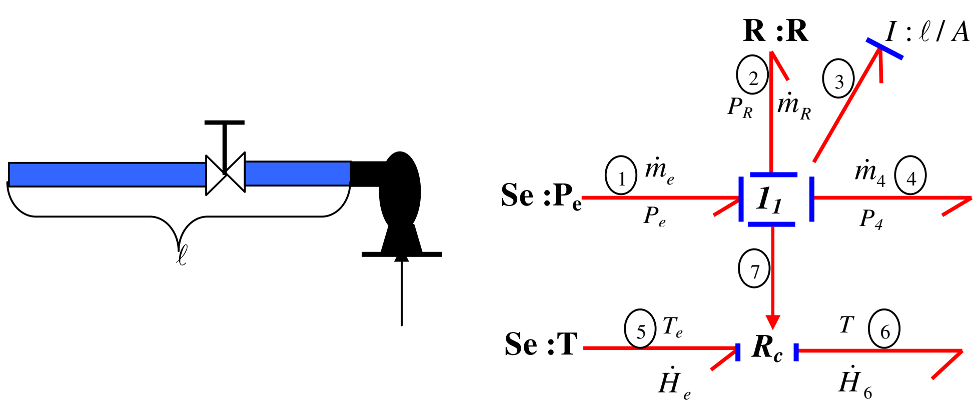

Figure 2. Simple scheme of water supply circuit and the corresponding Bond graph model

The bond graph model of water supply circuit with coupling between thermal and hydraulic energy is composed by R_h element represents hydraulic resistor due to the charge losses and R_c modulated by mass flow is fictitious resistance modelling the coupling of the two energies [2], [3], [4]. On the bond graph model the link number 7 is the information link (arrow) because it is assumed that the power exchanged is null and there is an exchange of information. From the bond graph model we deduce the laws of structural junctions and constitutive equations of the elements.

1_1 junction: common flow because the same flow crosses through the pipe

$$\begin{cases} e_3 = e_1 - e_R - e_4 \Rightarrow P_3 = P_e - P_R - P_4 \\ f_1 = f_3 ,\, f_2 = f_3 ,\, f_4 = f_3 \text{ and } f_7 = f_3 \Rightarrow \\ \dot{m}_e = \dot{m}_3 ,\, \dot{m}_R = \dot{m}_3 ,\, \dot{m}_4 = \dot{m}_3 \text{ and } \dot{m}_7 = \dot{m}_3 \end{cases} \quad (1)$$

The element R models the loss of hydraulic charge by Bernoulli law:

$$e_2 = \Phi_R(f) = R_h f_3^2 \Rightarrow \Delta P = P_2 = R_h \dot{m}_3^2 \quad (2)$$

Where R_h is the flow coefficient.

The flow imposed on the R_h element is the flow inferred from the constitutive equation of I element. The element I models the phenomena of inertia due to the mass of fluid.

$$f_3 = \frac{1}{I}\int e_3 dt + f_3(0) = \frac{1}{I} P_3 + \dot{m}_3(0) = \dot{m}_3 \quad (3)$$

Where P_3 is the variable pulse pressure, which represents the momentum per unit area and the volume flow is:

$$\dot{V} = \frac{A}{\rho \ell} \int P dt = \frac{A}{\rho \ell} . P \quad (4)$$

The inertia of the fluid is then:

$$I = \ell / A \quad (5)$$

3.2. Modelling of the economizer [2], [3], [4]

The economizer is a heat exchanger to raise the temperature of feed water from 20°C to 140 °C (Figure 3):

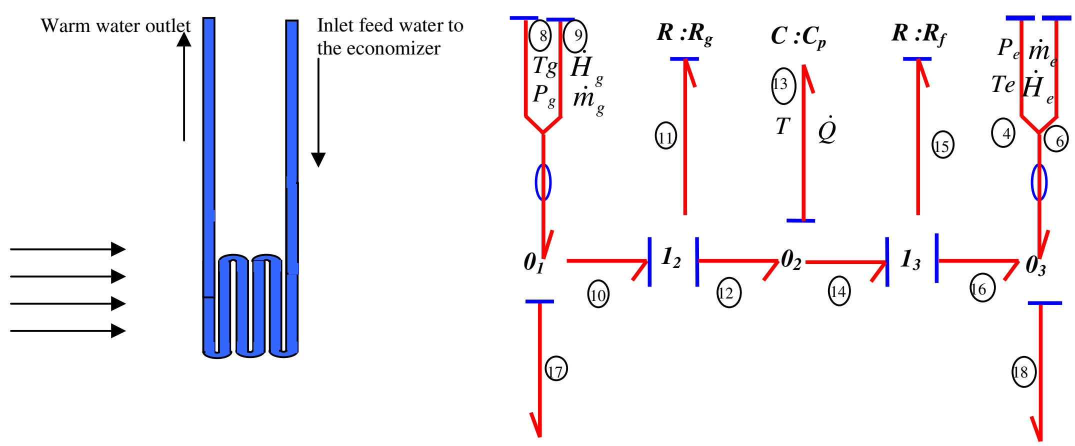

Figure 3. Economizer circuit and the corresponding bond graph model

0_2 junction : The causal equations for the efforts and flows are:

$$\begin{cases} f_{11} = f_{10} - f_{12} \Rightarrow \dot{Q}_{11} = \dot{Q}_{10} - \dot{Q}_{12} \\ e_{11} = e_{10} \text{ and } e_{12} = e_{11} \Rightarrow T_{11} = T_{10} \text{ and } T_{12} = T_{11} \end{cases} \quad (6)$$

Heat exchanger element $Hexa_1$ is defined by the energy conservation:

$$\dot{m}_8 = \dot{m}_{13} \text{ and } \dot{H}_{13} = \dot{H}_g - \dot{Q}_{10} \quad (7)$$

The temperature T_{13} can be easily determined from the mass flow $\dot{m}_{13}$, enthalpy $\dot{H}_{13}$ and specific heat of fluid C_p :

$$T_{13} = \frac{\dot{H}_{13}}{\dot{m}_{13}.C_{p13}} \neq T_g \text{ and } \dot{Q}_{10} = K_{10}(T_{13} - T_{11}) \quad (8)$$

Where $K_{10} = 1/R_g$ is the exchange heat coefficient or thermal conductivity?

Heat exchanger element $Hexa_2$ is defined by the following equations

$$\dot{m}_4 = \dot{m}_{14},\ \dot{H}_{14} = \dot{H}_e + \dot{Q}_{12},\ T_{14} = \frac{\dot{H}_{14}}{\dot{m}_{14}.C_{p14}} \neq T_e \text{ and } \dot{Q}_{12} = K_{12}(T_{11} - T_{14}) \quad (9)$$

Wall capacity C_{paroi} is defined as follows:

$$T_{11} = \frac{1}{C_{paroi}} \int (\dot{Q}_{10} - \dot{Q}_{12}) dt \quad (10)$$

Where C_{paroi} is the overall thermal capacity of the wall. The heat exchange (function (8) and (9)) is generally non linear. The validated model through SYMBOLS software is illustrated by Figure 4.

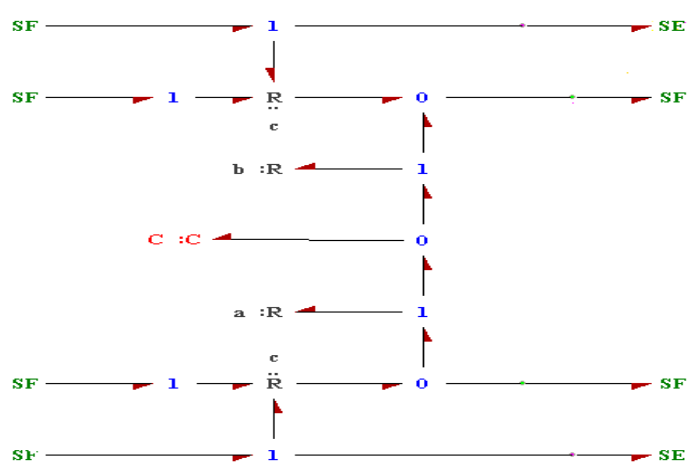

Figure 4. Linearized bond graph model of the economizer on SYMBOLS Software

The resistors R_a and R_b represent the thermal resistance of heat transfer by conduction of gas to the metal tubes in the economizer and the metal to the indoor environment where there is water supply. The two resistors R_c are the resistances fictitious modelling the coupling of both thermal and hydraulic energy. The element *C* represents the thermal characteristics of the material, that is to say the overall thermal capacity of the wall and the energy stored by this metal.

3.3. Modelling of the higher ball

Modelling the ball steam by a pseudo bond graph is more convenient than a true bond graph because power variables used are: the temperature, enthalpy flow, pressure and mass flow which are more intuitive than the voltage and chemical molar flow. The battery is modelled by an element C with two ports. This element is associated with storage of energy (hydraulic and thermal) of the mixture in the tank (Figure 5).

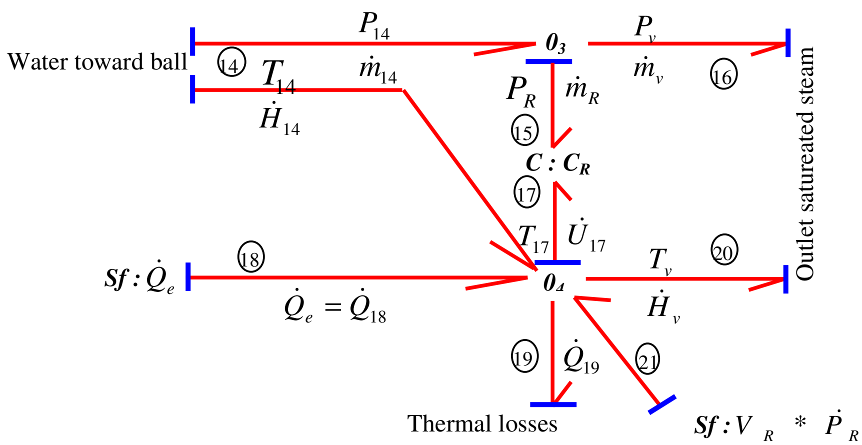

Figure 5. Bond graph model of the higher ball

The equations of energy conservation are given by the structural relationship of the junctions 0_3 and 0_4 :

0_3 junction: common effort because the pressure is uniform at the bottom of the tank:

$$\begin{cases} f_{17} = f_{10} - f_{12} \Rightarrow \dot{m}_R = \dot{m}_{14} - \dot{m}_v \\ e_{15} = e_{14} \text{ and } e_{15} = e_{16} \Rightarrow P_{15} = T_{14} \text{ and } P_{15} = P_{16} \end{cases} \tag{11}$$

0_4 junction: common effort because the temperature is uniform in the tank:

$$\begin{cases} f_{17} = f_{16} + f_{18} + f_{21} - f_{20} - f_{19} \Rightarrow \dot{U}_{17} = \dot{H}_{16} + \dot{Q}_e + V_R \dot{P}_R - \dot{H}_v - \dot{Q}_{19} \\ e_{17} = e_{16},\ e_{17} = e_{18}, e_{17} = e_{21}, e_{17} = e_{20} \text{ and } e_{17} = e_{19} \Rightarrow \\ T_{17} = T_{16},\ T_{17} = T_{18}, T_{17} = T_{21}, T_{17} = T_{20} \text{ and } T_{17} = T_{19} \end{cases} \tag{12}$$

Where $V_R.\dot{P}_R$ is the power supplied by pressurization? V_R : is the geometric volume of the tank. C_R element : The quantities stored in the phase mixture (water-steam) were determined by constitutive equations of the multiport *C* made in integral causality:

$$m_R = \int \dot{m}_{14} - \dot{m}_v dt \;\; ; \;\; U_R = \int \dot{H}_{16} + \dot{Q}_e + V_R.\dot{P}_R - \dot{H}_v - \dot{Q}_{19} dt \qquad (13)$$

In the case of a mixture water-steam (saturated steam), temperature and pressure are not independent and we arbitrarily choose a single parameter, the others are then determined [6]:

$$\begin{aligned} h_{17} &= \frac{U_{17}}{m_{17}} = h_v(p_{17})X + h_l(P_{17})(1-X) \\ v_{17} &= \frac{V_R}{m_{17}} = v_v(p_{17})X + v_l(P_{17})(1-X) \end{aligned} \qquad (14)$$

Where $h_l(P_{17})$, $h_v(p_{17})$, $v_l(P_{17})$ and $v_v(p_{17})$: represent respectively thermodynamic functions of enthalpy, the density and steam. For X = 0 we have a liquid state and for X = 1 we have the dry saturated steam state. The mixture is at saturation, the temperature is a thermodynamic function of enthalpy and pressure given by:

$$T_{17} = f_T(h_{17}) \text{ and } T_{17} = f_P(P_{17}) \qquad (15)$$

The water level is the output variable which is associated with the volume v of water and its mass m, then we can consider that the mass is a output variable $y = [m \quad p]^t$ [5]. The validation of the model is described on (Figure 6):

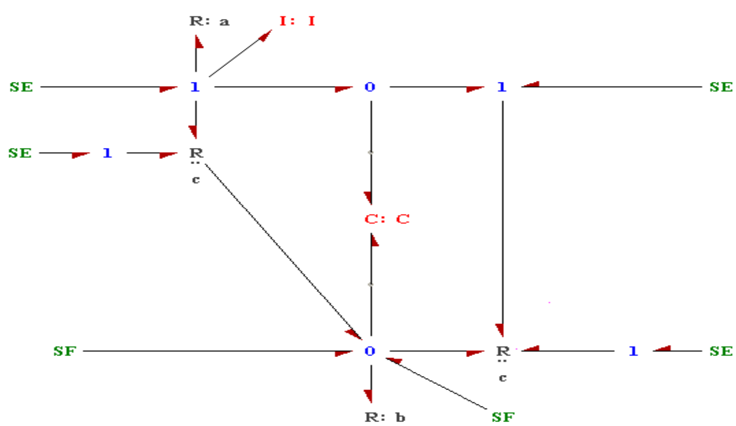

Figure 6. Bond graph model of higher ball on SYMBOLS software

The two resistors *Rc* are the fictitious resistors modelling the coupling of both thermal and hydraulic energy at the input and the output of the tank [6]. The resistor R_b represents thermal losses in the boiler. The element *C* double-port consists of a hydraulic capacity C_{RH} and thermal capacity C_R [7]. These two capacities coupled, associated with constitutive relations are formed by the equations linking the effort and the generalized displacement variables. The element *I* represent the inertia of the fluid in the tube feeding tank flow due to its mass.

4. SIMULATION

The simulation is an experiment on a model, it allows in a first time to validate the model by comparing results given by a technical specification with those of simulation, in a second time to extrapolate experimental conditions in a limited context. The simulation of a continuous-time system is usually obtained by algorithm, the user must choose what is best (method, accuracy and no load).

It provides many advantages over an approach based on experience. It allows the study of phenomena for which the experiment is not possible (climatology, the phenomenon of combustion-explosion). The simulation time depends only on the complexity of the system, on choice and settings of the algorithm and on performance of the machine that runs the computer simulation.

4.1. Technical specifications

The technical specifications (Table 1) of the process installed in the petroleum complex ENIP (Skikda – Algeria) is described as follows:

Tab.1. Technical Specifications

Phenomenon	**Variable**	**Value**
Heat capacity	C_p [JK^{-1}]	0.19
Input flow enthalpy	$\dot{H}$ [W]	559.2
Output flow enthalpy	$\dot{H}$ [W]	335.35
Water level	L_w [m]	0.3
Boiler height	L_b[m]	0.5
Input mass flow	$\dot{m}_{in}$ [kg/s]	10
Output mass flow	$\dot{m}_{out}$ [kg/s]	5
Pressure	P [Pa]	50
Thermal flow	$\dot{Q}_{al}$ [W]	111
Section	S [m^2]	0.2
Input temperature	T_{in} [K]	298
Output temperature	T_{out} [K]	353

4.2. Simulation of the economizer

From the simulator window of SYMBOLS software, we can validate the bond graph model by introduction of the parameters given by the technical specifications [8]. We compile the model until it indicates 0 error 0 warning and we clique on equations then the following window appears (Figure 7.):

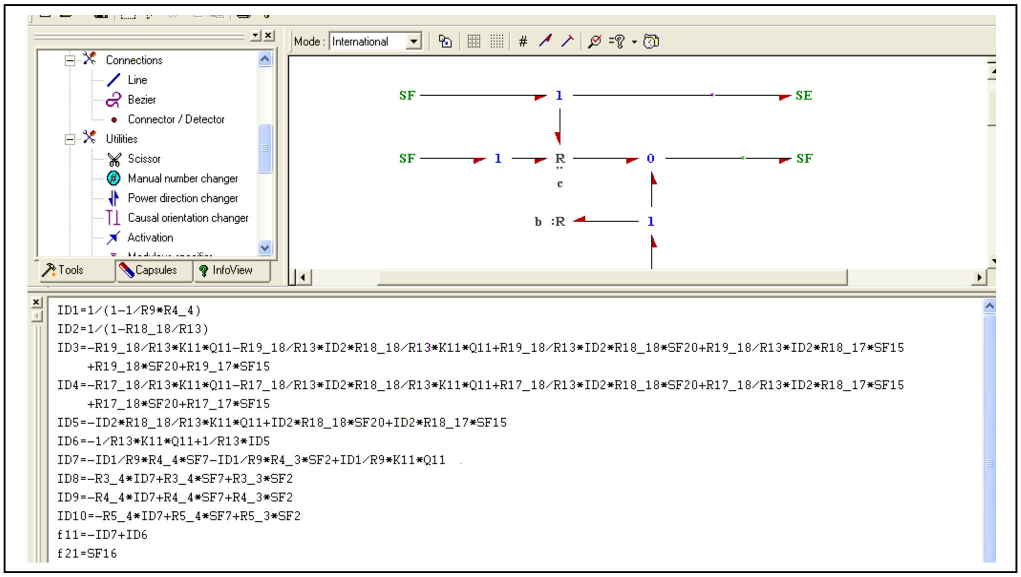

Figure 7. Validation of the Bond graph model of the economizer

The simulation results obtained for water (Figure 8) and gas (Figure 9) in the economizer characterize the temperature and the mass flow [9].

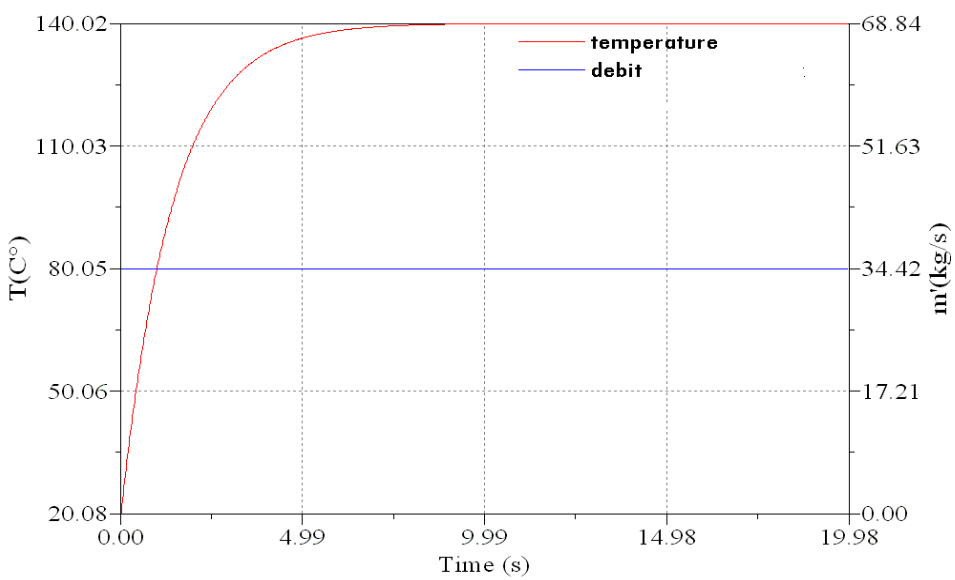

Figure 8. Water in the economizer

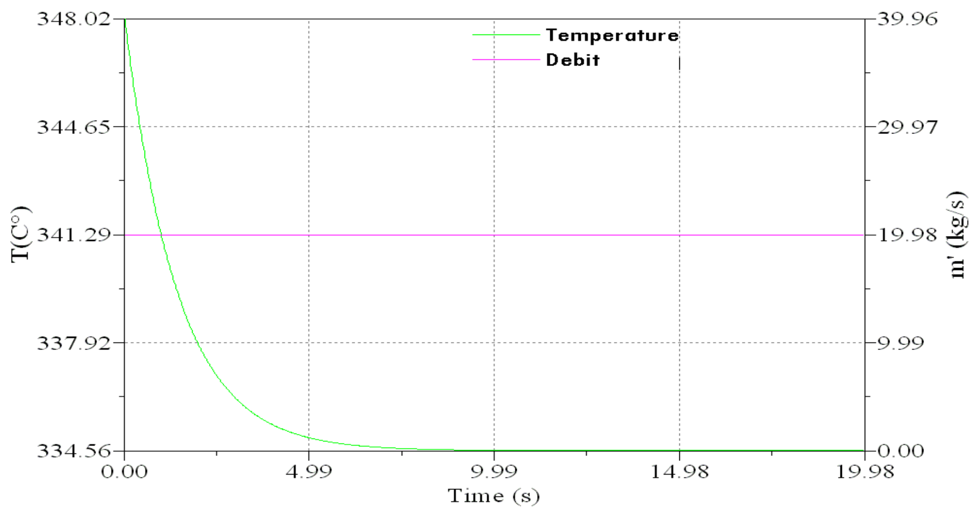

Figure 9. Gas in the economizer

4.3. Simulation of the tank

From the simulator window of SYMBOLS software, we can validate the bond graph model and generate the equations which describe the analytical model of the tank (Figure 10).

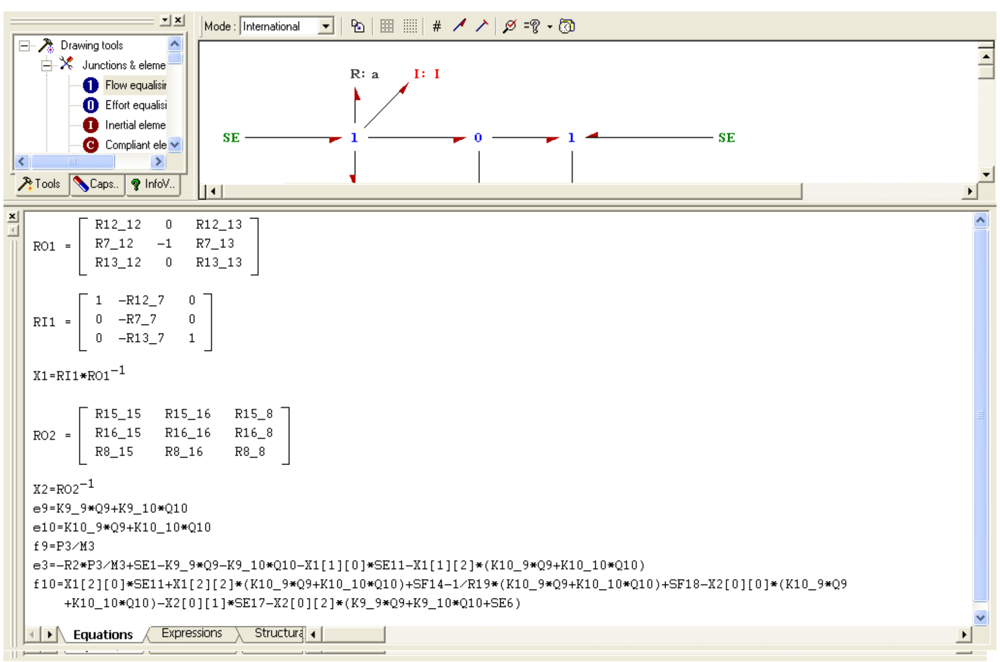

Figure 10. Generation of bond graph model of the tank

The pressure (Figure 11), the temperature (Figure 12) and the mass flow (Figure 13) are illustrated by the following simulation results [10]:

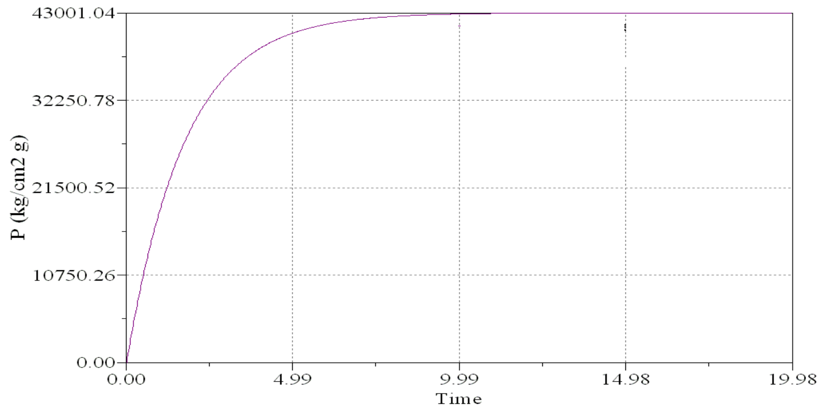

Figure 11. Pressure in the tank

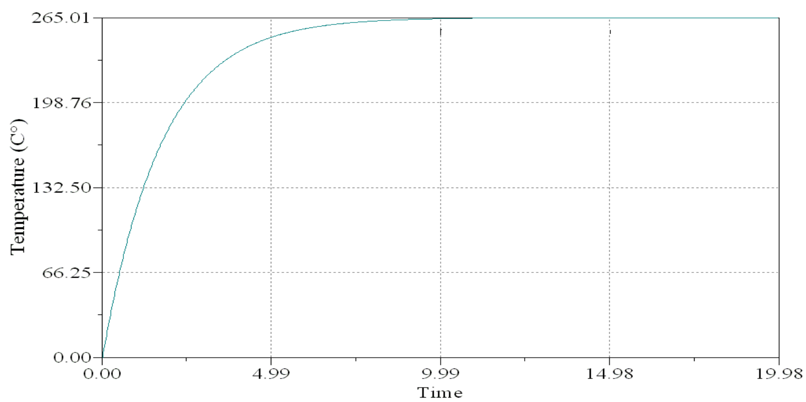

Figure 12. Temperature in the higher ball

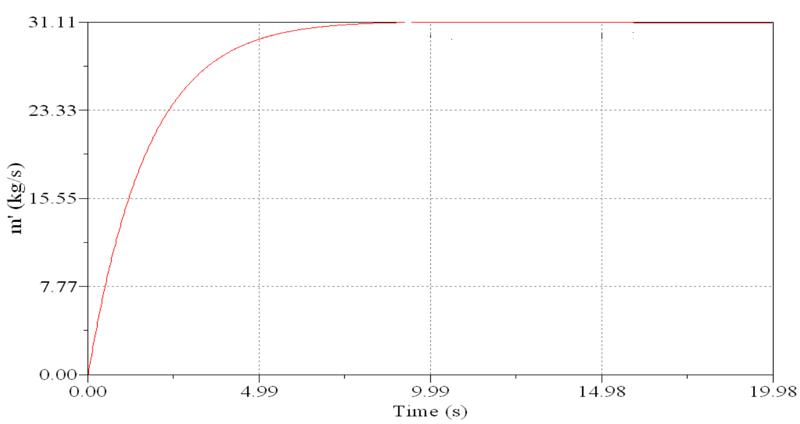

Figure 13. Mass flow in the higher ball

4.4. Interpretation of the results

The curve representing the pressure follows an exponential function of time checking out the empirical equation, this variation is due to the accumulation of residuals in the boiler. Pressure is increased until the value 43001.04 kg/cm^2g then acting on the input and output rule that value to set the desired change of the temperature.

The temperature in the boiler varies exponentially with the time, this is due to the phenomenon of energy storage, at t = 9s the temperature becomes stable, which leads the system in a state of permanent equilibrium.

The enthalpy increases exponentially with time this is due to the influence of the thermal power provided the energy to heat the boiler and at t = 9s, the enthalpy flow becomes stable after the temperature stability.

The total mass in the boiler varies with time exponentially and constantly evolving, this is consistent with the operating of such a process when it is not regulated.

This phenomenon is explained by the fact that the mass accumulates in the tank and then increases as power is supplied.

5. CONCLUSIONS

The importance and desirability of a unifying formalism as the bond graph tool as part of a systems approach have been confirmed.

This methodology has allowed us to model homogeneous systems, in areas of process engineering. They are based on the transformation of matter and energy for analysis of hydraulic and thermal systems.

Coupled with the opportunities offered in terms of analysis by the bond graph, this vision has facilitated the "system" approach to design. This has been done using the tool Bond graph that appears best suited to the knowledge of such physical systems, especially the systems in process engineering. It directly provides the user with the original information.

The search results were interesting because the curves found in the simulation reveal a similarity between the results found and the results expected in the technical specifications.

SYMBOLS software is well suited to simulation problems often encountered in practice, it is a very powerful search and recommended for use in large industrial systems.

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