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Modeling and Simulation of the Distillation Column Boiler

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Abstract: This study describes the use of the multi-energy bond graph for modeling and generating the analytical redundancy relations as failures indicators. The uncoupled bond graph model is introduced by 20-Sim Pro 2.3 software. The failures are simulated for testing the generated residuals sensitivity at total absence of faults or leakage in the actuators.

Key words: Bond-graph, modeling, process engineering

INTRODUCTION

The complex process modeling is an important step in their study, analysis, control and maintenance. It takes up 50 until 80% of the study time. This importance is related to a chosen method for modeling. It must be simple and give more description about the physical phenomena met in the considered process. Process engineering systems are present on the every industrial sectors. They are characterized by great risks caused by their phenomena, so the monitoring was essential. The bond graph methodology allows in process engineering, to contribute to the modeling or the systems design of monitoring. This study suggests a multi-energy bond graph model for the boiler of the discontinuous distillation column. This model is used for the design of residuals generator allows to monitoring. The first idea is to use the junction structure equations for residuals generating called analytical redundancy relations (ARR) which use only known or measured parameters or functions. We have used for simulation the 20-Sim Pro 2.3 software.

BOND GRAPH MODELING

The invention of bond graphs is attached to the need of a common language to model system involving different energetic domains. This tool was created since 1961 at MIT, Boston, USA by Paynter and developed by Karnopp, Rosenberg and Thoma[1,2]. The model can be introduced in a graphical form and simulated using special software. During the ten last years, a bond graph is used not only for modeling but for control and monitoring analysis as well, because of it's structural and causal properties. A bond graph model is a graph which describes power exchange in physical systems Fig. 1. As shown in Fig. 1, the bond graph symbol gives us four information:

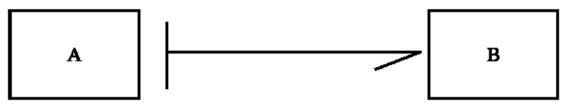

Fig. 1: Power exchange in bond graph model

- The existence of physical link between two systems by the bond. -The type of power (electric, mechanic...) by the power variables.
- The power direction by the half arrow.
- The causality by the stroke.

The key of bond graph modeling is the representation (by a bond) of power with elements acting between these variables and junction structures to put the system together. This is done through power lines called "bond" which in turn contains two variables : effort and flow variables. The vertices of the graph are of two kinds : Basic elements are: The inertial I, capacitance C, resistance R, transformer TF, gyrator GY, junction nodes (0, 1). The variables used in bond graph are: Power variables, efforts e(t) and flows f(t). Energy variables, the momentum p(t) and the displacement q(t). The power P(t) exchanged by two plant items is the product of an effort and a flow (1):

$$P(t) = e(t) \times f(t) \tag{1}$$

There are nine basic bond graph elements, separated into four categories, according to their energy characteristics. These elements and their definition are summarized in Table 1. The power exchanged between two process plants A and B is indicated by a bond and is the product of two variables-a potential variable (i.e., pressure, electrical potential, temperature, chemical potential, force, etc.) called effort (e) and a current variable (volume flow, current, entropy flow, velocity, molar

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Table 1: Bond graph elements

Symbol	Defination	Name
Se —e/f⇀	e=e(t)	Source of effort
Sf —e/f⇀	f=f(t)	Source of flow
—e/f⇀ R	$\Phi_R(e,f)=0$	Resistance
—e/f⇀ C	$\Phi_C(e,q)=0$ $\Phi_C(e,\int f(t)dt)=0$	Capacitance
—e/f⇀ I	$\Phi_I(f,p)=0$ $\Phi_I(f,\int e(t)dt)=0$	Inertance
① ⇀ TF :m ② ⇀	$e_1=m.e_2$ $f_2=m.f_1$	Transformer
① ⇀ GY :r ② ⇀	$e_1=r.f_2$ $e_2=r.f_1$	Gyrator
① ⇀ 0 ③ ⇀, ②	$f_1+f_2-f_3=0$ $e_1=e_2=e_3$	Common effort junction
① ⇀ 1 ③ ⇀, ②	$e_1+e_2-e_3=0$ $f_1=f_2=f_3$	Common flow junction

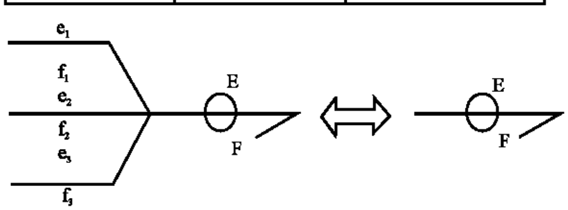

Fig. 2: Multi-energy bond graph2

flow, ...) referred to as flow (f). The bond graph is an advantageous modeling tool because it exhibits both the structure and the behavior of the studied system. The bond graph modeling comprise four modeling levels[2]:

Technological: Modeling by the word bond graph;

Physical: Representation of physical phenomena by the right elements (storage, dissipation, transformation);
A B

Table 2: power variables in process engineering

Domain	True bond graph		Pseudo bond graph	
	Effort	Flow	Effort	Flow
Hydraulic	Pressure P[Pa]	Volume flow $\dot{V}[m^3/s]$	Pressure P[Pa]	Mass flow $\dot{m}[kg/s]$
Thermal	Temperature T[K]	Entropy flow $\dot{S}[W/K]$	Convection	
			Specific enthalpy h[J/kg] or temperature T[K]	Enthalpy flow $\dot{H}[J/s]$
			Conduction	
			Temperature T[K]	Heat flow $\dot{Q}[W/s]$
Chemical	Chemical potential µ[J/mole]	Molar flow $\dot{n}$[mole/s]	Kinetic	
			Concentration C[mole/m³]	Molar flow $\dot{n}$[mole/s]
			Transformation	
			Affinity A[J/mole]	Velocity ξ[mole/s]

Mathematical: Deduction of a mathematical model after causalities affectation;

Algorithmic: Simulation and validation of the deduced model.

The bond graph modeling advantage is the representation ability of multidisciplinary or complex systems like process engineering. For that, the power link contain several energy kinds called multi-energy bond graph Fig. 2.

We find this representation in process engineering in that the hydraulic energy is coupled to thermal and chemical energy[2]. The power variables in process engineering, are pseudo bond graph for removing complexity and unfitness of true bond graph simulation. Table 2 indicates the physical signification and the choice of power variables for the process engineering domains[3].

The coupling between thermal and hydraulic energy is given by (2):

$$H = mh = mc_p T \tag{2}$$

Where: H: Enthalpy flow, m: Mass flow, h: Specific enthalpy, p c: Constant of the specific heat and T: The temperature.

While the coupling between chemical and hydraulic energy[4] is given by the following relation (3):

$$n = C.\upsilon.m \qquad (3)$$

Where: n: Molar flow, C: Concentration, υ: Mass volume.

The process engineering domain presents a great interest for researcher in the world, seen their presence in industrial middle, as steam generator, distillation column and reactor. This study interests itself to the modeling and the monitoring of a boiler of a discontinuous distillation column UOP3 pilot in the industrial chemistry laboratory by the bond graph multi-energy methodology.

BOND GRAPH MONITORING

The aim of the monitoring is to conceive a system capable to produce an alarm defining the presence of a failures in one or several parts of process to study. They exist several methods using this function:

Based model methods:

- States and parameters identification,
- Parity space,
- Bond graph modeling

No based model methods:

- Artificial intelligence,
- Statistical approach
- Shapes recognition.

Because of the complexity of the system modeling method, the use of the bond graph modeling is spilled little. Generally, for bond graph model, two monitoring approaches are possible:

- The use of the junction structure for generating analytical redundancy relations[5,6].
- The graphic causal path course for defining the monitoring components and failures cause identification[7].

These methods are sometimes complementary and are developed for simple energy bond graph models. For the multi-energy, we have interest to an uncoupled bond graph model or/and linearized their components for using these methods. Bond graph model uncoupled depends strongly on the nature of modeling phenomena[2].

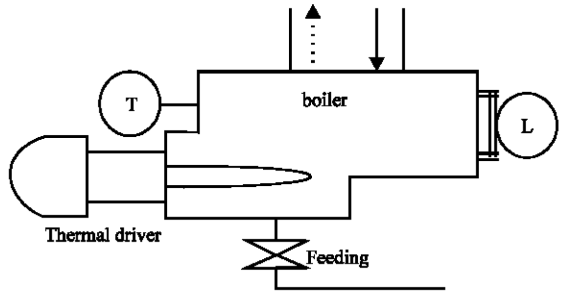

Fig. 3: Functional diagram of the boiler

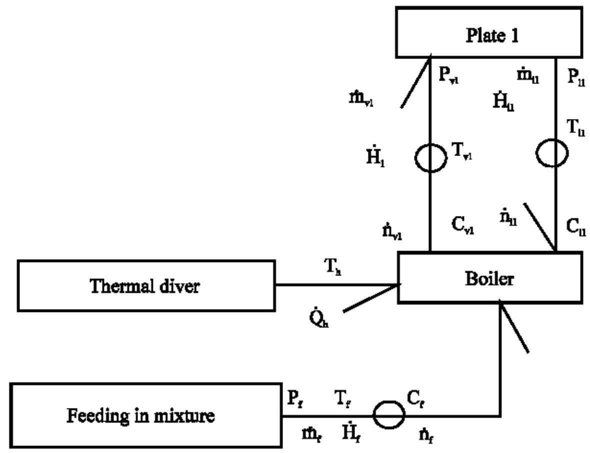

Fig. 4: Word bond graph model of the installation

APPLICATION

The process is the boiler of a discontinuous distillation column UOP3a. A boiler serves to heat a chemical compound mixture from different points of volatility until the evaporation. It is connected by a set of trays punched that assures the transfer of matter between the phases liquid and steam Fig. 3.

Bond graph modeling: After the analysis of the functional principle of the boiler, the word bond graph model of the installation is given by Fig. 4, represents the interconnection of several subsystems of different nature. The thermal diver permits to put a strength of heating to the boiler. A source of feeding in fluid presents the mixture for heating and separated by distillation operating. The boiler that includes himself like an accumulator of energy. Plate superimposed, represented by the flow of the fluid entering and retiring the boiler. The word bond graph model permits to see the interaction between the sub-systems and to define the set of bonds. The multi-energy bond graph model of the boiler is given by Fig. 5.

The elements endowed by (*) are some fictional elements. The flow source (Sf * : VR) represents the thermal contribution of the pressurization strengths, *VR*

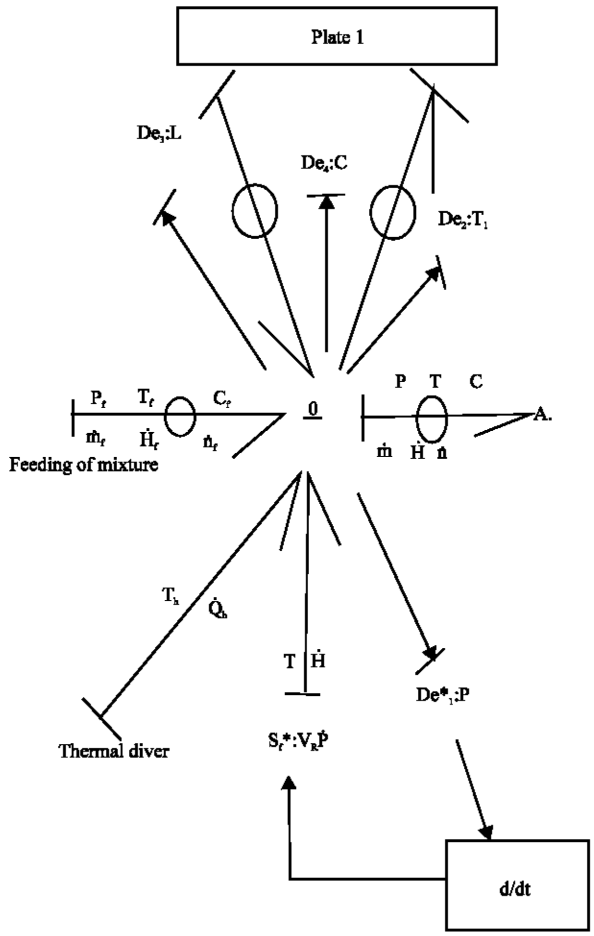

Fig. 5: Multi-energy bond graph of the boiler

is the total volume of the boiler[1,3]. The links are in multi-energy bond graph for the feeding source, the steam and fluid flow respectively entering and retiring the boiler. The accumulation of the hydraulic, thermal and chemical energy is presented by the C element. It doesn't exist a clean separation between phases steam and liquid, so the C element is multi-port[3]. The bond representing the thermal diver is a conduction bond defined by the pair (Q T). The set of instrumentation is formed by a temperature sensor (T De : 2), a level sensor (L De : 3). The mixtures raised are considered like a concentration sensor (C De: 4) and a fictional pressure sensor (P De: *). The uncoupled bond graph model of the boiler is represented by Fig. 6.

Generation of the analytical redundancy relations: For generating the analytical redundancy relations ARRs, we exploit these relations of the junction structure while

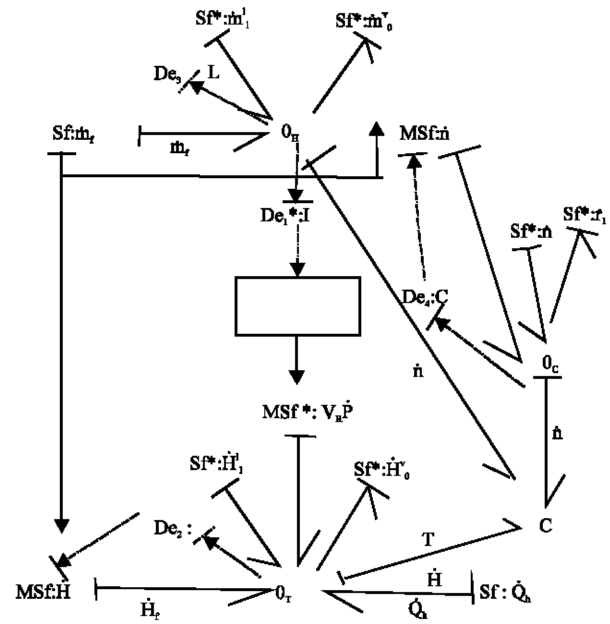

Fig. 6: Multi-energy bond graph of the boiler

basing on the energy conservation principle. This technique is developed on mono-energy bond graph model[5,6]. The generation procedure is expressed as follows:

- Choose the junction kind from monitoring variables.
- Choose one junction of this kind.
- Write the constitutive relation and to express the unknown variables according to the known variables (to monitor) while following the possible causal paths.

To spend to the following junction and to apply the step 3 until to obtain sufficient relations (until to obtain the different failures signatures for monitoring variables). A causal path is an alternation of bond and components (R, C and I). According to causality, the variable crossing is the effort or the flow. To change this variable, we pass through GY element or a passive element (R, C or I)[1].

For the multi-energy bond graph models, the causal path notion is modified, because the complexity of the model. The bond graph model is uncoupled to facilitate their analysis and their simulation. We introduce the generalized causal path notion for the uncoupled bond graph models[7] as being a causal path that can cross the power bonds or the information bond or both. The procedure application described above results the analytical redundancy relations (4), (5) and (6):

$$ARR_1 = C.s.De_1\ \dot{m}_f\ \dot{m}_1^1 + \dot{m}_0^s \qquad (4)$$

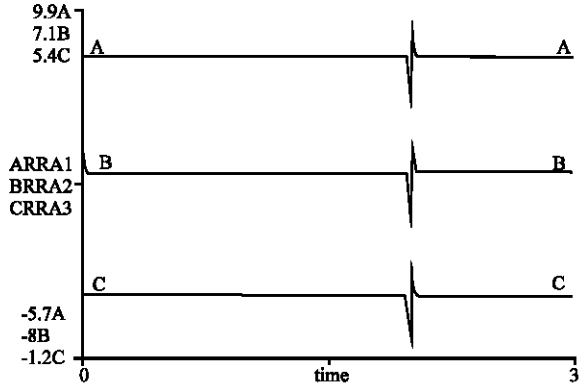

Fig. 7: Reaction of the generated ARRs

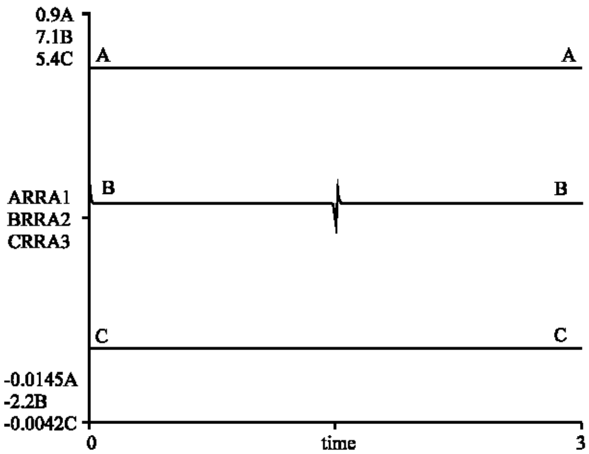

Fig. 8: Heat source failure and sensitivity of ARR2

$$ARR_2 = C.s.De_2\, \dot{H}_f\, \dot{H}_1^1 - \dot{Q}_h\, \dot{V}_R\, \dot{P} + \dot{H}_0^s \quad (5)$$

$$ARR_3 = C.s.De_4\, \dot{n}_f\, \dot{n}_1^1 + \dot{n}_0^s \quad (6)$$

These relations are sensitive to several kinds of sensors, actuators and components failures.

Simulation and interpretation: From 20-Sim Pro. 2.3 software[8], we have implanted the uncoupled bond graph model (Fig. 6). For the faults detection of the boiler we use the precedent analytical redundancy relations (ARRs). We create the faults on monitoring components with this software fault here is considered in the total absence or the deviation of the nominal value given out by the component to monitor. The numeric values of components are not considered, only their presence or absences in the relation are taken in account with evaluation term the operators (+, .). It is the qualitative approach for bond graph monitoring[9].

In the first time, we create a fault between the instant $t_1 = 2s$ and $t_2 = 2.01s$ by the abrupt annulment of the value

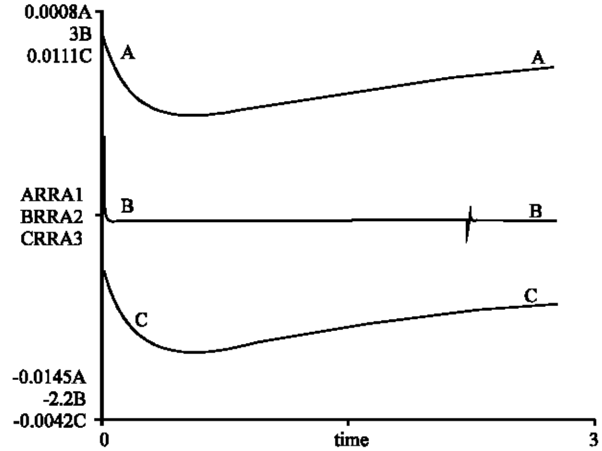

Fig. 9: Matter lsakage in the boiler

of fluid flow provided by the source f m Sf. The generated ARRs reaction is very fast see Fig. 7. The deviation of the relation ARR1 in this time is normal (value near 0) seen the presence of the parameter f m in this relation, whereas the deviation of relations ARR2 and ARR3 translated by the dependence of the thermal and chemical sources to hydraulic source.

The second simulated fault is on the heat source between the instant $t_1 = 1.5s$ and $t_2 = 1.51s$. We see only on Fig. 8 the variation of the relation ARR2, what translates the presence in this relation of the parameter of the source h Q Sf.

The third test on the fault detection is elaborate by the simulation of matter leakage in the boiler. This leak is considered by 25% of matter reduction between the instant $t_1 = 2.4s$ and $t_2 = 2.41s$. In response to this failure, we see that only the residual ARR2 (Fig. 9) is sensitive. The physical interpretation of this sensitivity is the thermal contribution of the pressurization forces bound to the total volume of the boiler, presented by the flow source fictive P V MSf R *.

CONCLUSION

In this study, the bond graph methodology is used to modeling and analysis of a system present in several industrial sectors in process engineering : the boiler. We find this system in distillation column and steam generator.

The method used illustrates the process principle working. We have using the structural junction equations for generating the analytical redundancy relations like failures indicators. This work presents the bond graph tool as the unified modeling method and facilitates the functional and structural analysis of the complex systems.

The multi-energy bond graph based approach used here for fault detection of the complex systems will be in perspective following by fault isolation and identification of eventual failure.

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