

Bond Graph Modeling and Simulation of Thermal Equipment Based on Modelica

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Abstract—Bond graph was introduced to establish different domain system models by using numerable basic elements. Modelica is an object-oriented modeling language for multi-domain system unified modeling, which can compile simulation model for different modeling method, thus developing bond graph model by Modelica language is well suited for multi-domain unified modeling. In the present paper, Bond Graph library BondLib was introduced and improved. We use Deaerator system as an application example to show results on Dymola platform. The digital simulation results obtained from the bond graph model are validated with the operating characteristics.

Keywords—bond graph, Modelica, modeling, simulation

I. INTRODUCTION

Bond graph modeling is a method of modeling dynamic systems which was introduced by Paynter(1961). The idea was furthermore developed by Karnopp and Rosenberg(1968,1975,1983) as well as Thoma(1975), Van Dixhoorn(1982) as a powerful tool in modeling systems, especially in cases where subsystems of different physical character(mechanical, electrical, thermic, hydraulic)interact[1]. Bond graph modeling is based on the law of conversation of energy. Tow basic energy variables (effort variable, flow variable) were introduced to represent the physical variables for different energy domain. On the basis of different relationship between variables, several basic elements were defined such as *resistor*, *capacitor*, *inductor*, *transformer*, etc, intending to establish multi-domain system model by using numerable basic elements. Many scholars exploit different kinds of bond graph simulation software, but most of them use a special language, so the model can't be reused without the support of software environment.

Modelica is a new modeling language for describing the dynamic behavior of physical systems. The aim of the Modelica effort is to unify the concepts and to design a new uniform language for model representation. The main objective is to make it easy to exchange models and model libraries, So it is facilitate multi-domain unified modeling. It is inspired on the principle of object-oriented and non-causal modeling, thus bond graph like ports can be used as interface elements, and the equations need not be specified in a specific computational form[2], but the Modelica standard library has not contained the bond graph library. Cellier first presented a bond graph library *BondLib* in 2003[3], which contains the basic elements definition for the domains for thermic, electronic, hydraulic and so on,

but not contains such as the multi-bond graph elements. This paper extends *BondLib* and establishes the Deaerator system model as an application exmple.

II. BOND GRAPH CONNECTOR CLASS

In Modelica, models and submodels are declared as classes, which include there type of members: *variable*, *function* and *member class*. Modelica classes include the component and function definition.

In Modelica, the basic structuring element is a class. There are seven restricted classes with specific names, such as *package*, *model*, *record*, *type*, *function*, *block* and *connector*. A *connector* must contain all quantities needed to describe the interaction. When developing models and model libraries for a new application domain, it is good to start by defining a set of *connector* classes. For bond graph we just need define effort variable and flow variable in bond *connector* class. In bond graph library *BondLib* the bond-graphic *connector* is programmed as follows:

Real is a basic type. There is a prefix *flow* in Modelica, which is similar to the flow variable in the bond graph, but in Modelica the variable defined by the prefix should comply the *Kirchhoff's law*. This implies two equations as follows:

$$\begin{aligned} p1.e &= p2.e \\ p1.f + p2.f &= 0 \end{aligned} \quad (1)$$


In bond graph, bond is idea connect, this means that the variables should be equal to each other connector of the bond. This implies two equations as follows:

$$\begin{aligned} p1.e &= p2.e \\ p1.f &= p2.f \end{aligned} \quad (2)$$

So the prefix of *flow* in Modelica cann't be used to describe the bond guaph. In addition, Modelica is a non-causal modeling language, but the bond graph is a acausal modeling method, thus there is another directional variable *d* referenced in the connector, which indicates whether the direction of positive flow is into the connector(*d*=+1) of out of the connector(*d*=-1)[4].

III. DOUBLE CHANNEL PSEUDO BOND GRAPHS DESCRIBE BY MODELICA

Cellier basis on the connector class definition established basic bond graph elements, but the library *BondLib* is not perfect and has not contained some special bond graph elements define such as double channel pseudo bond graph.

 is a special bond for thermodynamic bond graph modeling, and were first introduced by Thoma. On the double channel pseudo bond graph we use pressure and

temperature, or specific enthalpy as efforts and mass and enthalpy flows as flows. The bond couples the transferring of hydraulic and thermal energy, whose power variables are defined as the hydraulic power variable (p, \dot{m}) and thermal power variable (h, \dot{H}) . Where p represents the pressure, \dot{m} means the mass flow in or out the control volume in unit time, h is the specific enthalpy which means the value of enthalpy in unit mass fluid, \dot{H} is the enthalpy quantity flowing in or out the control volume in unit time, and have the relation as flow[5]:

$$\dot{H} = \dot{m}h \quad (3)$$

Before establish the bond, we should define the connector class, as show in Figure.2.

We use physical quantities instead *Real* as the variables type define. Because the parameters and variables are more than real numbers. They are physical quantities too. The Modelica standard library provides type declarations for many physical quantities. By this way, it is easy to reduce the chance of error by unit check mechanism.

Consider the acausal of bond graph, there is need to create two kinds of connector class: e-connector, f-connector to establish acausal bond. As show in Figure.3.

Use the two connector, two types of acausal bonds can be created as show in Figure.4.

IV. BOND GRAPHS OF DEAERATOR SYSTEM

The schematic figure of Deaerator system is illustrated in Figure.5. In normal operation, the condensate water from the condenser spray by nozzles, and mix of waste gas which flow into the deaerator through the large and small valve. Using waste heat from waste steam heat condensate water, so as to reach saturation temperature to remove oxygen dissolved in water. The condensate water being heated, steam condensing in the heating process flow into the tank, and then pumped into the supply main by the water pump. Waste gas flow is controlled by adjust the opening of large and small valve. Water level is controlled by adjust the opening of back-water valve and makeup-water valve.

For larger system models it can increase the efficiency and overview to organize and represent them in a hierarchy. Bond graph uses word bond graph for the different components and builds a hierarchy, in which the nodes represent physical components. They can also represented by words or text enclosed by ellipses or circles. These words describe the basic behavior or purpose of a submodel. The word bond graph of Deaerator system is given by the Figure.6.

We use a multi-port bond element represent the mass accumulation and inter energy accumulation in Deaerator. Figure.7 shows the corresponding bond graph with a multi-port C element represent by Modelica.

The valves are represented by multiport R, modulated by boolean variables b . We use pseudo bond graph represent the heat exchange between system and environment. Chose the temperature as the effort variable, heat flow as flow variable, use two resistor element represent heat resistor, use a capacitor represent the metal heat capacity.

Consider a system or control volume of volume V containing a pure substance with mass m at temperature T and pressure p representing specific internal energy u , enthalpy h , and entropy s . Neglecting kinetic and potential energy, the internal energy obeys[6]:

$$\dot{U} = \dot{H}_e - \dot{H}_s - \dot{Q} - p\dot{V} \quad (4)$$

Where \dot{H}_e and \dot{H}_s are the entering and leaving enthalpies, \dot{Q} is exhaust heat flow. Replacing U by $H-PV$ we use the derivative of enthalpy as follows:

$$\dot{H} = V\dot{p} + \dot{H}_e - \dot{H}_s - \dot{Q} \quad (5)$$

So equation 5 introduces an additional power, which is proportional to the derivative of pressure. Using the relationships developed in this paper the bond graph of overall system representation is shown in Figure.8.

V. SIMULATION RESULT

The total bond graph model shown in Figure.8 is testified using the Dymola platform. When the deaerator large valve increase five percent, the variety of pressure, temperature and water level in the deaerator are shown in Figure.9. When the feed water valve increase five percent, the variety of pressure, temperature and water level in the deaerator are shown in Figure.10. From curves we can see that the model can effectively supply dynamic characteristic of process when the work condition is changed.

VI. SUMMARIES

Process engineering requires energies from several domains, just what bond graphs can well handle. Modelica is a uniform language for model representation, so it is facilitate to represent the bond graph and enhance the model reuse. In this paper, a double channel pseudo bond graphic model of Deaerator system was presented. The digital simulation results obtained from the bond graph model are validated with the operating characteristics. The modeling techniques presented in this paper can be used to multi-domain system modeling.

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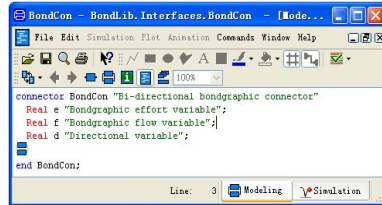


Figure 1. bond-graphic connector in BondLib

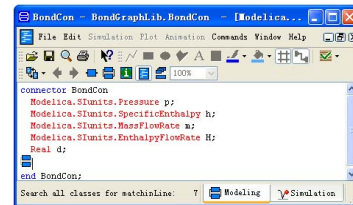


Figure 2. bond-graphic connector in this paper

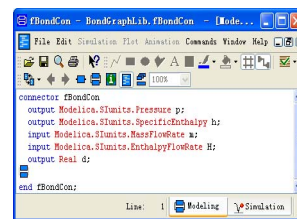
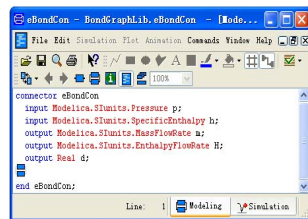


Figure 3. e-connector and f-connector

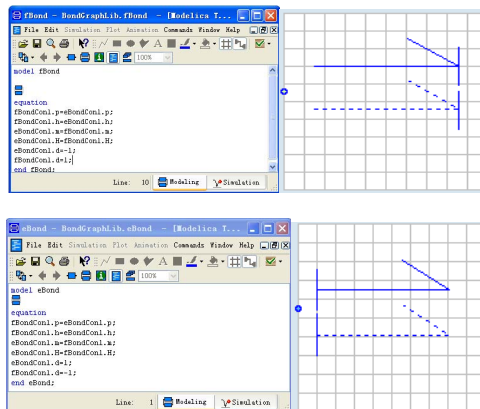


Figure 4. two types of acausal bonds

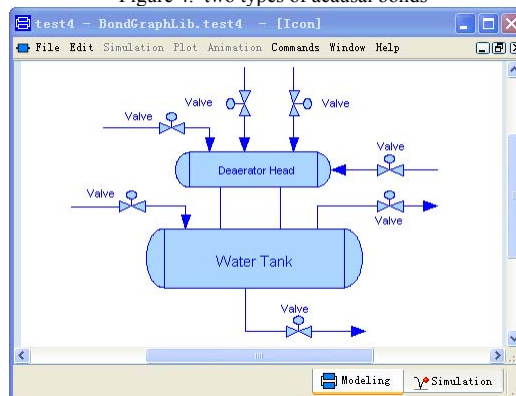


Figure 5. The schematic figure of Deaerator system

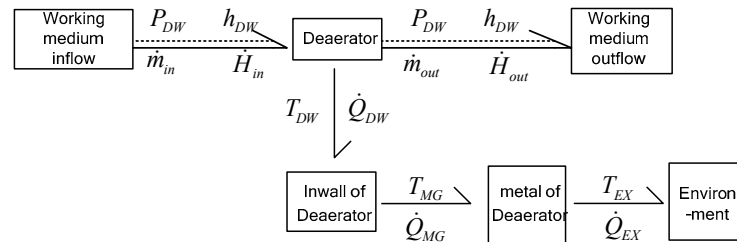


Figure 6. the word bond graph of Deaerator system

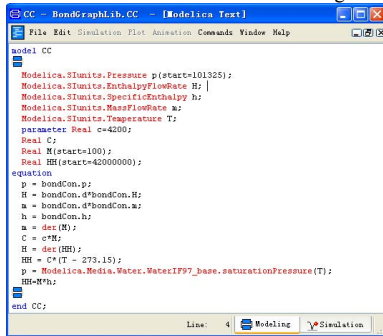


Figure 7. multi-port C bond element

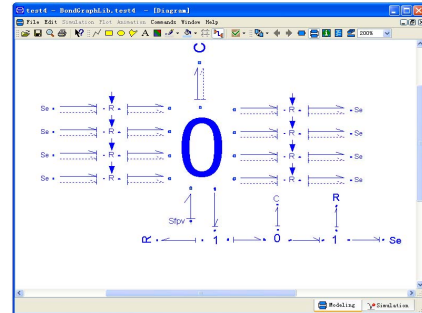


Figure 8. total bond graph of Deaerator system

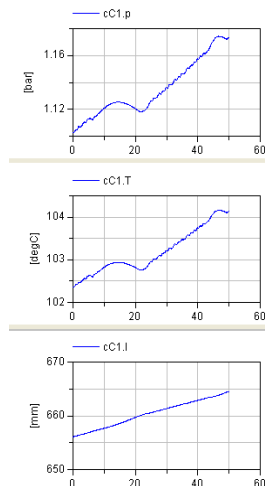


Figure 9. pressure, temperature and water level response of +5% large valve opening

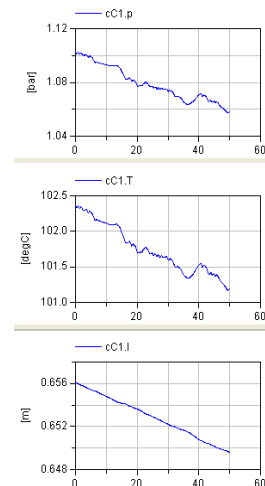


Figure 10. pressure, temperature and water level response of +5% feed water valve opening