APPLICATIONS OF VINYL ACETATE MONOMER (VAM) PLANT MODEL: A NEW BENCHMARK PROBLEM

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Abstract

A rigorous dynamic model of a vinyl acetate monomer (VAM) production plant was developed. This plant model enables the users to experience realistic plant operation, since it reflects the real plant characteristics and practical problems. The plant model provides a new benchmark problem; the users can investigate start-up/shut-down operation, plant-wide process control, fault detection and diagnosis, and others. In fact, the VAM plant model was already used for the study of all-mode plant-wide operation, the development of its Mirror Plant, and others. The advantageous plant model is released from Omega Simulation Co., Ltd. with a free limited license of Visual Modeler, which is a commercial dynamic simulator and can be linked with MATLAB®. This article aims to introduce the VAM plant model, the configuration of the controllers, and the examples of applications of the VAM plant model.

Keywords

Process simulators, process models, dynamic models, chemical industry, plant-wide control

1. Introduction

A test problem which checks the industrial relevance of new ideas and technical developments is of great importance in the study of process control and process data analysis. A great number of researchers have utilized the Tennessee Eastman (TE) challenge problem in various fields including plant-wide control, production efficiency optimization, soft-sensor design, fault detection and diagnosis, etc., since it was introduced more than 20 years ago (Downs and Vogel, 1993). Even now, the Tennessee Eastman problem is the most popular problem.

Later, Luyben and Tyreus (1998) developed a model of a vinyl acetate monomer (VAM) plant, which is a larger system containing standard chemical unit operations for real chemical components. The process design background is well-established in the original paper. Several studies on control system design for this plant have been conducted (Chen and McAvoy, 2003; Olsen et al., 2005; Seki et al., 2010; Tu et al., 2013; Psaltis et., 2014). As a new benchmark problem in lieu of the Tennessee Eastman problem, the advanced VAM plant model was developed by Machida et al. (2016). The advantageous plant model provides multiple scenarios which cannot be simulated by using the conventional TE and VAM process models.

This paper introduces the advanced VAM plant model and its applications such as the study of all-mode plant-wide operation and the development of Mirror Plant. The VAM plant model is implemented on the commercial dynamic simulator, Visual Modeler (Omega Simulation

Co., Ltd). Visual Modeler has found many applications in industry as an operator training simulator. It is capable of handling various modes of plant operations including start-up/shut-down as a prerequisite of the operator training system, whereas the simulator attempts to keep the fidelity of the rigorous nonlinear model as high as possible. The dynamic simulator makes a good compromise between the model accuracy and solvability. We improved the VAM plant model developed by Yumoto et al. (2010) with reference to practitioners' opinions to make realistic operation scenarios.

In the next section, the VAM plant is described. Section 3 shows the configuration of controllers. Section 4 shows the application examples of the VAM plant model. Finally conclusions are drawn.

2. VAM Plant

Figure 1 shows the overall process flow diagram of the VAM plant, which firstly generates VAM product in the reactor, then separates the product from the unreacted materials and by-products by using the distillation column and other units.

2.1 Process Overview

Eight materials appear in the VAM plant as shown in Table 1. Three raw materials are introduced to the process. Ethylene (C2H4) and oxygen (O2) are fed in the gas phase; acetic acid (AcOH) is fed in the liquid phase and vaporized with superheated steam at the vaporizer. These three materials are mixed and introduced to the reactor, in which the following gas phase reactions take place.

[Main reaction]
$C_2H_4 + CH_3COOH + 1/2O_2 \rightarrow CH_2{=}CHOCOCH_3 + H_2O$
[Side reaction]
$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$

The main reaction generates VAM product (CH2=CHOCOCH3) and by-product water (H2O) from C2H4, AcOH (CH3COOH), and O2. The side reaction generates by-product carbon dioxide (CO2) and H2O from C2H4 and O2. Both reactions are exothermic, thus reaction heat is removed by boiler feed water (BFW) circulation and steam is generated at the shell side of the reactor. The reactor outlet gas containing about 5mol% VAM product is cooled down to 37degC with two coolers. Unreacted AcOH, H2O, and VAM are condensed as liquid VAM crude at the separator. On the other hand, separated gas leaving from the separator includes unreacted C2H4, O2, by-product CO2, inert ethane (C2H6), and a small amount of uncondensed VAM. This separated gas is compressed by the compressor to circulate recycle gas flow, then it is introduced to the absorber. The uncondensed VAM is absorbed by the cold AcOH which is fed from the top of the absorber. The mixture of VAM and AcOH is discharged from the bottom of the absorber and mixed with the VAM crude at the intermediate buffer tank.

Part of unreacted C2H4 and O2 removed from the top of the absorber is recycled to the inlet of the process. The remaining part of gas is introduced to the CO2 remover and the gas purge system, which keeps concentration of CO2 around 5~10mol% and C2H6 around 5mol% in the gas recycle line. The VAM crude at the intermediate buffer tank is fed to the azeotropic distillation column. VAM-H2O mixture discharged from the top of the column is condensed at the condenser and separated at the decanter. VAM forms the organic phase and H2O goes to the aqueous phase; VAM product is discharged as organic product from the decanter. Unreacted AcOH is discharged from the bottom and recycled to both the vaporizer and the absorber. Table 2 shows the steady-state main stream data.

Table 1. Materials in the VAM plant

Material	Description
Ethylene (C2H4)	Raw material of VAM
Oxygen (O2)	Raw material of VAM
Acetic Acid (AcOH)	Raw material of VAM
VAM	Product
Water (H2O)	By-product
Carbon Dioxide (CO2)	By-product
Ethane (C2H6)	Accompanying gas of Ethylene
Nitrogen (N2)	Inert gas

2.2 Process constraints

The VAM process must be operated under the following constraints, which come from safety, equipment protection, and product quality requirements.

- The O2 concentration must not exceed 8mol% anywhere in the gas pipeline to avoid an explosion.
- Pressure in the gas pipeline must not exceed 862kPaG because of the mechanical construction limit.
- The peak reactor temperature must remain above 130degC to avoid dew point of AcOH.
- The AcOH concentration in the VAM product must remain below 150ppm as a product specification.
- The VAM concentration in the bottom of the distillation column must remain below 100ppm to prevent polymerization of VAM.
- The compressor must run while O2 is remaining in the gas pipeline to avoid forming of O2 hot spot and explosion.

3. Configuration of controllers

The basic control system designed for the VAM plant model includes flow controllers (FC), temperature controllers (TC), pressure controllers (PC), level controllers (LC), and a concentration controller (CC).

Figure 2 shows the control system configuration around the reactor. Here, the O2 concentration controller and the steam drum pressure controller are crucial since the O2 concentration and the reactor temperature must satisfy the process constraints. Figure 3 shows the control system configuration around the separator and the absorber. Here, the compressed gas flow controller is a key controller because the compressed gas circulation is important to avoid forming of O2 hot spot and explosion. In order to keep the compressed gas flow at its set point, revolution per minute (rpm) of the compressor is controlled by its inverter control. Figure 4 shows the control system configuration around the distillation column and the decanter. Here, the column pressure controller is important since the pressure influenced the boiling point of VAM crude. The column pressure is controlled by split range control; inert N2 is fed into the process in lower pressure, and off-gas flows to the purge line in higher pressure.

This basic control system is not optimal to control the VAM plant; there is a room for improvement by changing the configuration, using multivariable controllers, or tuning control parameters. In the VAM plant model, the control system configuration can be changed easily. Not only the user can use other predefined controllers but also the user can implement original control algorithms in calculation units. The configuration can be switched from the default to those controllers any time.

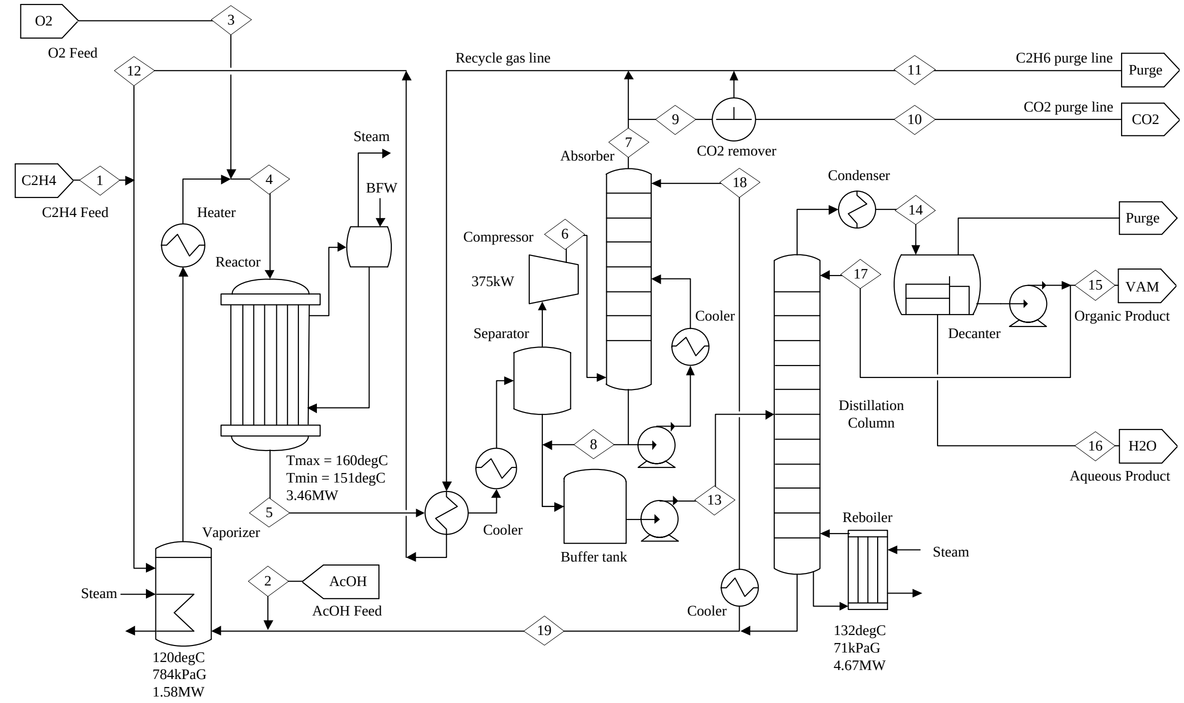

Figure 1. Process flow diagram of the VAM plant

Table 2. Representative steady-state stream data

		Reactor outlet	Column feed	Decanter inlet	VAM product
Stream number		5	13	14	15
Flow	[kmol/h]	1115	240.8	409.1	58.2
Temperature	[degC]	156.9	39.3	39.6	41.0
Pressure	[kPaG]	525.6	59.1	13.4	22.8
O2	[mol%]	0.030	0.000	0.000	0.000
CO2	[mol%]	0.064	0.000	0.000	0.000
C2H4	[mol%]	0.674	0.000	0.000	0.000
C2H6	[mol%]	0.052	0.000	0.000	0.000
VAM	[mol%]	0.052	0.233	0.824	0.963
AcOH	[mol%]	0.066	0.467	22.6ppm	23.6ppm
H2O	[mol%]	0.062	0.300	0.176	0.037
N2	[mol%]	0.000	0.000	0.000	0.000

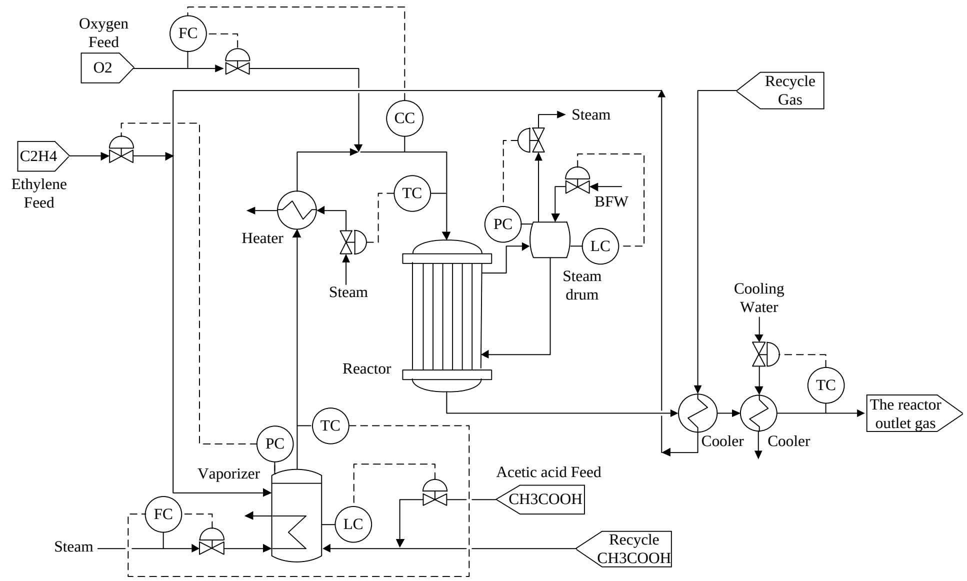

Figure 2. Controllers around the reactor

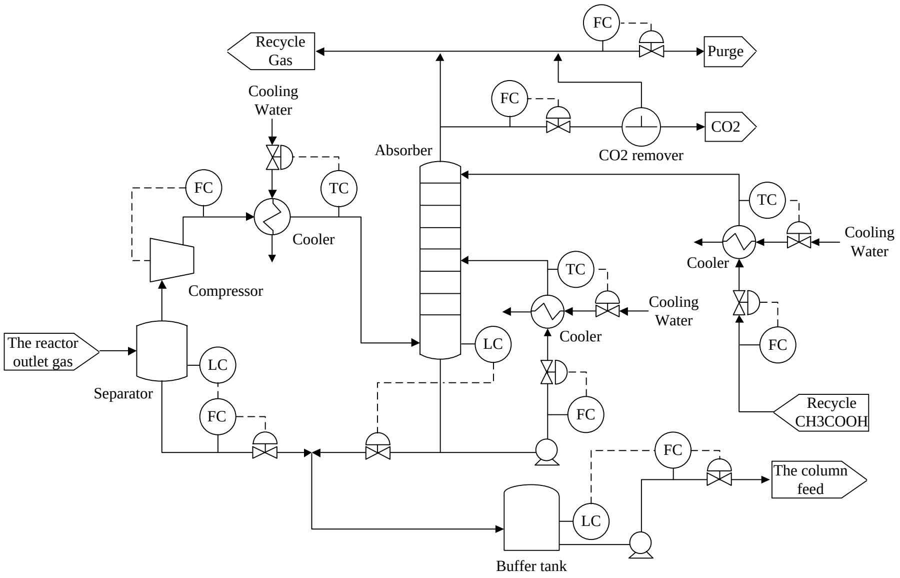

Figure 3. Controllers around the separator and the absorber

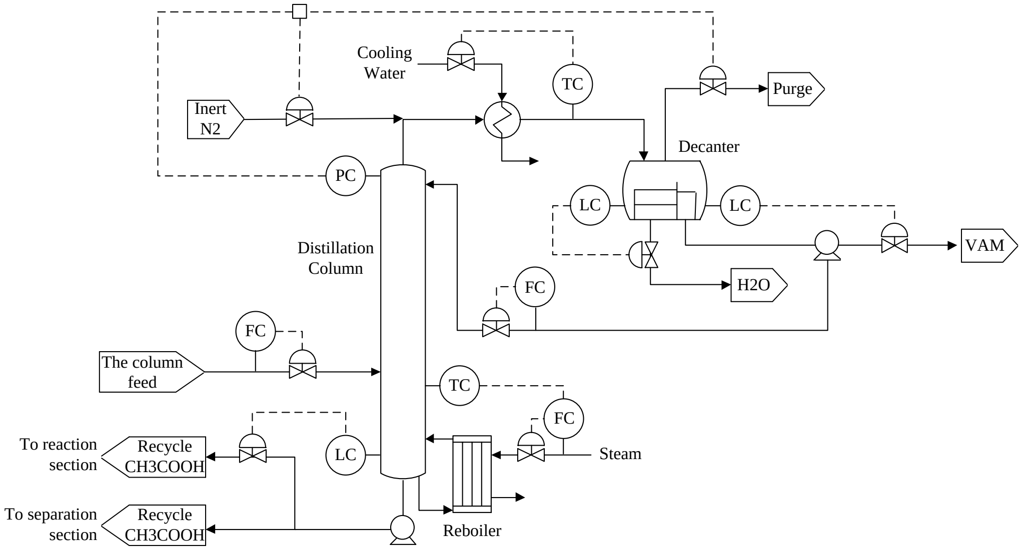

Figure 4. Controllers around the distillation column and the decanter

4. Applications of the VAM plant model

The VAM plant model can be utilized for various studies as follows.

- Plant-wide control system design
- Validation of control algorithms
- Process monitoring (fault detection and diagnosis)
- Soft-sensor design
- Optimization of steady-state/unsteady-state operating conditions
- Start-up operation from the nitrogen pure condition
- and others.

In this section, examples of the following studies using the VAM plant model are introduced.

- All-mode plant-wide operation
- Development of Mirror Plant

4.1 All-mode plant-wide operation

The basic control system was designed primarily for steady-state operation, thus it might not be suitable to automate unsteady-state operation such as start-up. Automation of unsteady-state operation is important to assure the safety and enhance the productivity through preventing human errors (wrong operation). All-mode plant-wide operation, which is a new concept of control system design for unsteady-state operation, was proposed by Workshop No.31 (Process Control Technology) of the Japan Society for the Promotion of Science (JSPS) 143rd committee on Process Systems Engineering. The key idea of all-mode plant-wide operation is designing flexible configurations of controllers and switching to a suitable configuration during unsteady-state operation. For example, controllers for start-up are prepared in advance and a configuration switches with another automatically when required conditions are met. In order to realize all-mode plant-wide operation, which can cover both unsteady-state and steady-state operations of a whole plant, a new control system design methodology was investigated using the VAM plant model. Here, an example of all-mode plant-wide operation during start-up is introduced. In many chemical processes, the reaction section starts after the separation section is ready and waiting. Therefore, the line to the reaction section is unavailable during start-up of the separation section. Figure 5 shows an example of the all-mode plant-wide operation. The level of the column needs to be controlled without using the valve on the line to the reaction section temporarily. Misoperations likely happen in such an irregular situation that usually requires manual operation. In order to realize automation of unsteady-state operations, the temporary level controller is used instead of the column feed flow controller before the start-up of the reaction section. Figure 6 shows the trend of the column level under the manual operation. The column level is unstable and also some irregular manipulations are conducted. The load of monitoring is relatively high. Figure 7 shows the trend of the column level when the column feed flow is temporarily used as the manipulated variable of the column level control. The column level is stable and operators' intervention is unnecessary. In addition, to realize all-mode plant-wide operation, we investigated the following factors during start-up; operation procedure, PID control parameters, ramping speed, etc.

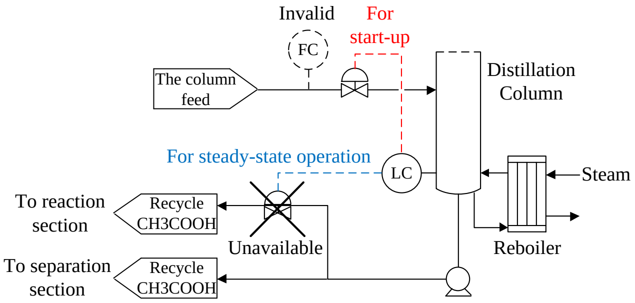

Figure 5. An example of all-mode plant-wide operation

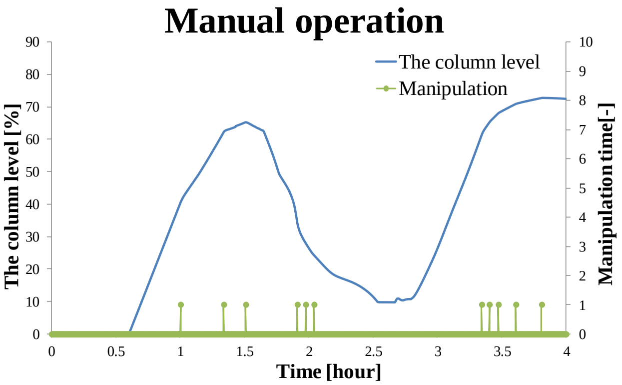

Figure 6. Column level trend in manual operation

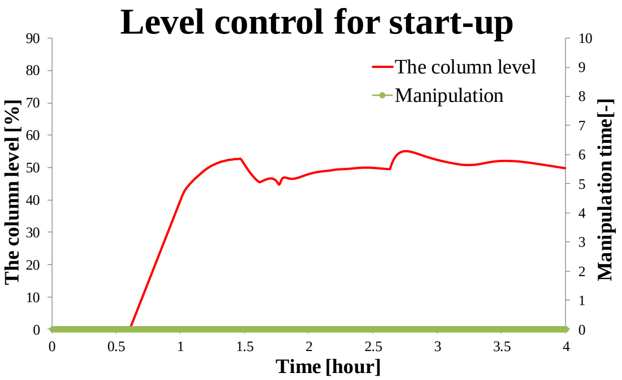

Figure 7. Column level trend achieved by all-mode plant-wide operation

4.2 Development of Mirror Plant

Mirror Plant, which was released from Yokogawa Electric Corp. in 2014, is the dynamic process simulator that runs in parallel with an actual plant and simulates its dynamic behavior. The model parameters are constantly adjusted so that the simulation result gradually matches the actual behavior by using process data obtained from the actual plant (Nakaya et al., 2013). Mirror Plant is able to estimate process variables that cannot be actually measured and predict the future plant behavior precisely by making the computer run faster than real time. Here, we introduce Mirror Plant, which uses the VAM plant model as an actual plant. Figure 8 shows the operation human machine interface (HMI) of Mirror Plant. It helps not only debugging the specific features but also developing applications of Mirror Plant.

The industrial designers in Yokogawa Electric Corp. also took part in the Mirror Plant development project. They considered how to express prediction data on the screen and completed Mirror Plant HMI based on ergonomic design. The following designs were also evaluated using the VAM plant model since the VAM model enabled the designers to experience the realistic plant operation with HMI they developed; color combinations, pop-up window structure, and arrangement of objects, etc.

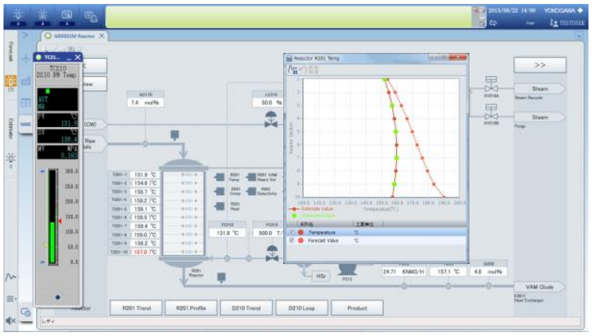

Figure 8. Mirror Plant HMI

5. Conclusions

A rigorous dynamic model of vinyl acetate monomer (VAM) plant was developed. The users can get feelings of the real plant operation through this model. It can also provide a test environment for various studies in the wide-range process control field including start-up operation. The developed VAM plant model with a free limited license of Visual Modeler is already available through the web site of Omega Simulation Co., Ltd.;
http://www.omegasim.co.jp/contents_e/product/vm/cnt4/

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