An on-line simulator MIRROR PLANT for proactive operation and its HMI design

HATSUGAI Emiko[1], and NAKAYA Makoto[2]

1.System Integration D&E Dept. IAPF Global Development Center, Yokogawa Electric Corporation, Nishi Waseda Shinjyuku-ku Tokyo, 169-51, Japan (Emiko.Hatsugai@jp.yokogawa.com)
2. System Integration D&E Dept. IAPF Global Development Center, Yokogawa Electric Corporation, Nishi Waseda Shinjyuku-ku Tokyo, 169-51, Japan (Makoto.Nakaya@jp.yokogawa.com)

Abstract: The number of serious plant accidents increases year by year in Japan, where technology transfer of skilled operator involving operation knowledge has ceased to work well. In order to realize safer plant operation, a proactive operation method is proposed in this paper by which operators will be navigated while seeing future plant behavior. The developed method is an on-line dynamic plant simulator MIRROR PLANT that can simulate the dynamic plant behavior accurately and can also forecast the future plant behavior by simulating faster than real-time. Using thus estimated forecast data, the plant operator can detect abnormal situations which would occur in the plant. Prior to an alarm being activated by the conventional control system, the operator will be able to prevent a serious accident. In this paper, a new human–machine interface (HMI) is designed to realize proactive operation for the vinyl acetate monomer process as an example of MIRROR PLANT.

Keyword: plant simulator; MIRROR PLANT; human–machine interface; proactive operation

1 Introduction

Japan had achieved spectacular economic growth in 1970s, but there has been no end in the war against the plant accidents. In Japan, there was an issue called "Year 2007 problem", when large number of veteran operators employed during the high economic growth era reached retirement age.

Recently there have been a lot of chemical plant accidents which brought extensive social impact in Japan as shown in Fig. 1 on the increasing trend of the number of complex accidents after 2000 in Japan[1]. It may be due to the shortage of labor power while the upsurge of plant machinery, where the technological advancement far exceeded the capability limit of the plant operators. Or it may be due to the decrease of such skilled operators who can sustain safe plant operation with a hunch of good skill.

Figure 2 shows the contributing factors to improve safety performance in the process industry by H.Pasman[2]. In 1970s, in order to decrease the complex accidents, the reliability of the plant machine was increased by improving the materials and redesigning of plant machinery. In parallel, it focused on preventing human errors in misunderstanding plant situation and operation mistake. Therefore the number of plant accident had steadily decreased until 2000 in Japan. However, entering 2000s, the number of plant accident went on increasing again. As the contributing factors of increasing trend of plant accident, it is thought that both the increased automation in the plant system and the stretched maintenance cycle would deprive the plant operators of their manual operation opportunities so that their available chance of getting the process knowledge is decreasing so as to improve the plant by the technical staffs.

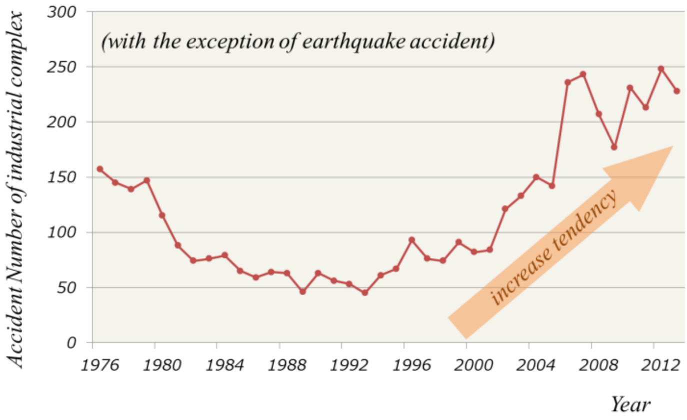

Fig. 1 Trend of industrial complex accident in Japan.

As shown in Fig. 2, many Japanese manufacturing companies introduced the strategic methodology and

Received date: December 1, 2014

the management system to keep plant safety. A good example is the risk management as specified by ISO 31000. Hold the same goal together in the whole members of the organization by utilizing the Plan-Do-Check-Act (PDCA) cycle. This is fundamental to the management to achieve to decreasing the risks. However as shown in Fig. 1, the increasing number of the complex accident is not so much saturated; it rather rises rapidly after 2000. In 2000s it can be seen that the plant machinery is going to be maintained by outside suppliers for the cost reduction. Although the parent company constructs the safety management system, there is no common view regarding the safety between the parent company and the outside suppliers.

According to the international Organization for Standardization (ISO) certification system, it is often said that it is important to authoritatively follow PDCA cycle, but the most important things is to generate creative and tangible ideas to keep safety. Therefore, it is very important how the manufacturing companies can estimate the risk factors and how they can manage the risks by original technique and rules. This is the motivation of the authors of this paper.

2 Technology transfer issues from generation to generation

A plant is a nexus of mutually related individual machinery. In the process industry, it is impossible to directly check the machining state of product and materials with human eyes. Therefore, the plant operator controls the plant machines based on sensor-measured data, such as temperature, pressure, flow rate and level. He also operates a plant and manages product while he estimates reaction and heat transfer state in the reactor and pipes of the process. In case of the existing plant controlled by the distributed control system (DCS), operation information is provided through CRT to the operator. A computer screen has several dozens of pictures evolving a few hundred of sensor data. While the plant operator monitors an enormous quantity of data on CRT, he has to forecast future plant behavior in his head and make decision to actually operate the plant.

The behavior of internal state in the plant is represented using time-variant, distributed parameter systems with large scale and nonlinear with complex phenomenon superposition. Therefore it is very difficult to forecast internal state change of the plant and response to operation.

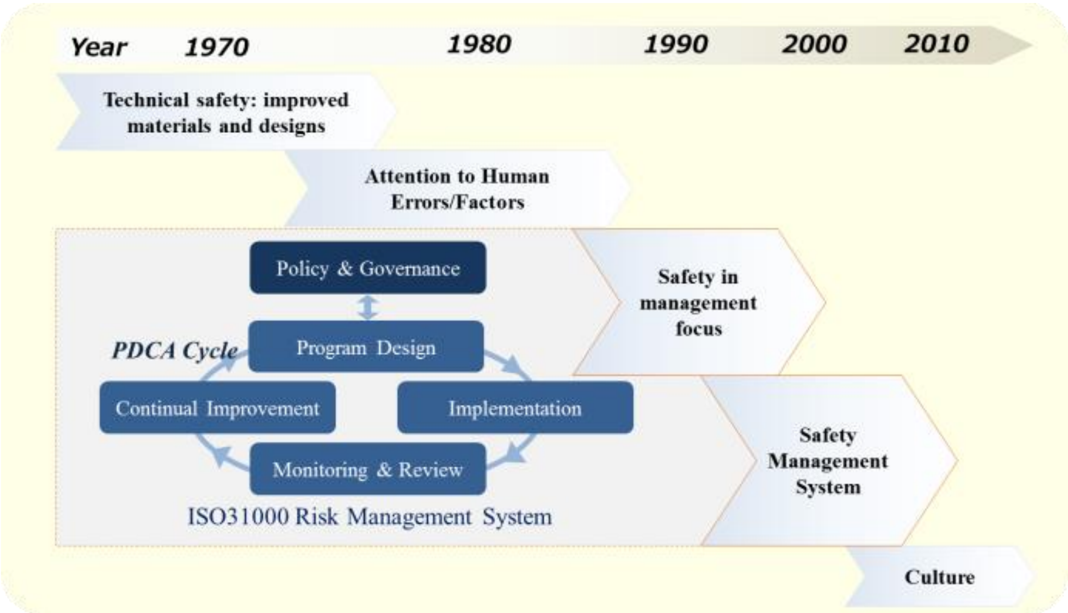

Fig. 2 Contribution factors to improve safety performance in process industry by ISO31000 risk management system.

Table 1 Feature of millennial generation

millennial generation (born from 1981 to 2000)	growing enviroment	Social media as a part of life
		Network connected
		Solving a problem with serching on the internet
	general mind	Thinking always ties with group
		Having no biased view of race and gender
		Loveing particular brand
	work motivation	Not having any loyalties to the company
		Frequent job changing and hopping
		Having enterpreneu's willingness in youth

In 2007 Japan had a serious retirement issue of many skilled plant operators, who were employed during the year of steep economic growth. Even though the delayed retirement and re-employment were introduced, increasing tendency of the plant accident number is seen in the recent years as was shown in Fig. 1. It seems like that the technology transfer involving operational knowledge of veteran operators, which is often called "implicit knowledge", has ceased to work well since 2007.

Looking the generation shift issue as not only for Japan but also for global issue, about half of labor population in USA in 2020, will be occupied by "millennial generation" who was born from 1981 to 2000. The feature of the millennial generation is shown in Table 1. One feature of the millennial generation would have different style to contact with information technology, to be compared with the former generation. As the millennial generation was born and raised under the computer network environment, they always depend on powerful search technology to work. In order to directly resolve their facing problems, they tend to acquire knowledge and skill through searching technology. By this way, the old generation's thinking custom of understanding the principle of the thing in depth fades away in the new generation.

To make non-evasive estimation and decision, it is very important to accumulate the experience of not only "success" but also "failure" as we say "failure is the source of success."

However, the plant operator nowadays is not permitted to show any purposeful mishandling operation for technical transfer education in the actual plant. This is because of safer operation and seeking profit. Therefore, the authors of this paper propose utilizing the virtual world to seek safer and more effective operation condition to support plant operator for technical transfer education in the actual plant.

3 What is on-line plant simulator MIRROR PLANT

There is an operator training system (OTS) for the plant operator. OTS is constructed according to the training scenario described under specified process condition and the plant operator can experience emergency response and start-up training. OTS is calibrated to accurately represent plant behavior in the range of the training scenario. The rigorous plant modeling based on physical and chemical laws is often used in OTS as the plant model. It is general that the plant is seldom operated in accordance with the scenario given by the OTS in daily plant operation. Therefore, it is necessary to calibrate plant models by on-line use to trace exact plant behavior based on plant data.

Figure 3 shows the historical evolution of the plant simulator technology until the on-line use of simulator. The plant simulator has made progress step by step with the advancement of computer technology and algorithm improvement. The plant simulator can be used from plant design phase to the plant operation support. The on-line plant simulator "MIRROR PLANT" [3][4] and its HMI design is introduced as the proactive operation tool which is able to estimate plant internal state and to forecast future plant behavior.

4 Technology of MIRROR PLANT

The MIRROR PLANT which runs in parallel with the actual plant is based on physical and chemical laws. The model parameters inside the simulator will be calibrated on-line, where two model parameter identification methods have been developed: The first method is called “tracking” while the other is called dynamic data reconciliation (DDR). In which follows the technical explanation of MIRROR PLANT.

4.1 Configuration of the MIRROR PLANT system

The configuration of the MIRROR PLANT system is as shown in Fig. 4. The MIRROR PLANT system consists of three models: MIRROR MODEL, IDENTIFICATION MODEL, and ANALYSIS MODEL as described below, respectively.

1) The MIRROR MODEL receives on-line data from the distributed control system (DCS), a part of the actual plant, and it performs real-time simulation to create a mirror image of the actual plant. It also estimates and visualizes state quantities that are not measured.
2) The IDENTIFICATION MODEL periodically estimates performance parameters of equipment to fit the models to actually measured values.
3) The ANALYSIS MODEL performs various operation assistance functions.

4.2 Tracking and DATA reconciliation with dynamic compensation

Figure 5 shows the operation sequence of the MIRROR PLANT, especially the execution flow of the MIRROR MODEL and the data reconciliation with dynamic compensation. The MIRROR MODEL performs dynamic simulation while executing processing to fit the model to the actual plant at each calculation point of a certain time interval. This processing, called tracking, aims to achieve local conformity by the following four means.

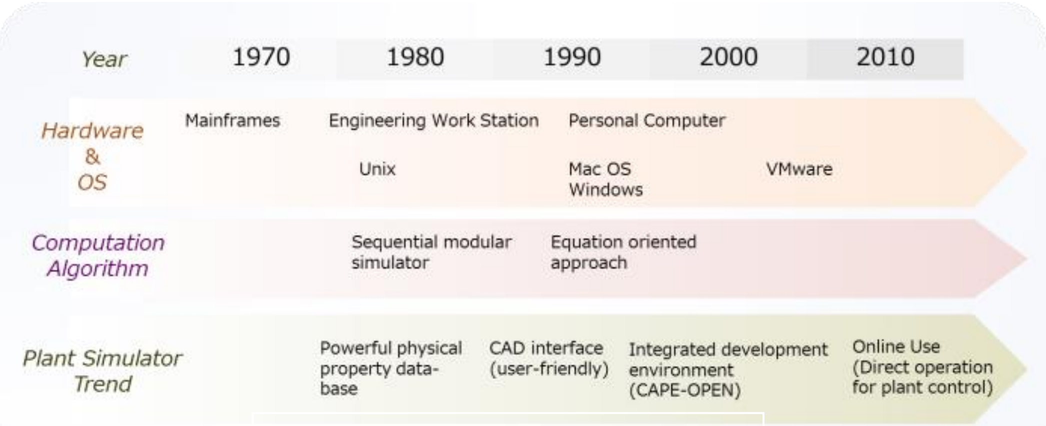

Fig.3 Historical evolution of plant simulator.

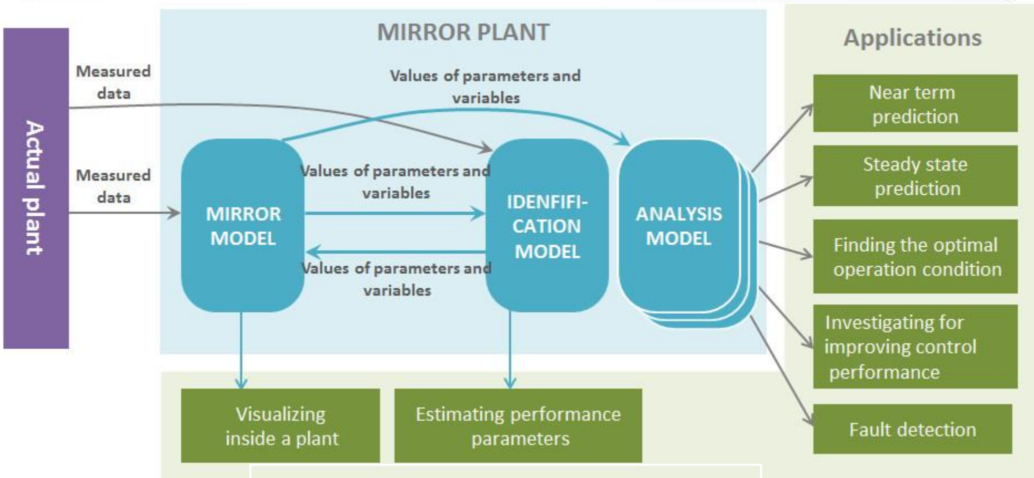

Fig. 4 Configuration of MIRROR PLANT.

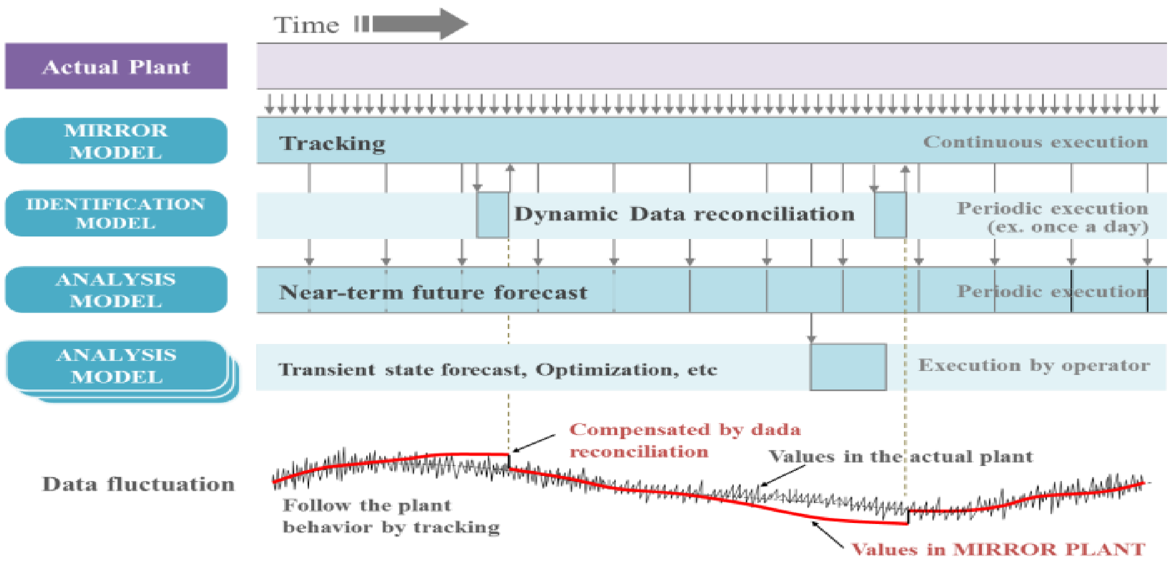

Fig. 5 Operation sequence of MIRROR PLANT.

1) Measurement values such as a temperature or pressure at the boundary of the model are taken into the MIRROR MODEL.
2) The control parameters of the controllers in the DCS including set values (SV), proportional-integral-derivative (PID) parameters, and alarm high/low limit values are taken in as control parameters of the controllers in the MIRROR MODEL.
3) If a control action, *e.g.*, level control, in the MIRROR MODEL is slow and this affects other parameters, such as pressure or temperature, the process value (PV) of the actual plant is taken in as SV of the controller in the MIRROR MODEL . Furthermore, its manipulating value (MV) is provided to the model as a feed-forward signal to enhance responsiveness.
4) In cases where it is important for a state quantity in the model to coincide with that of the actual plant even though it is not controlled in the actual plant, or if the relation between the state quantity and equipment parameter is locally restricted, an equipment parameter in the MIRROR MODEL is adjusted so that the value calculated in the MIRROR MODEL agrees well with the measured value in the actual plant. For example, if the temperature at the outlet of a heat exchanger is an important state quantity, the heat transfer coefficient of the heat exchanger in the MIRROR MODEL is automatically adjusted so that the temperature in the MIRROR MODEL agrees well with the measured value in the actual plant.

On the other hand, although the data reconciliation in the IDENTIFICATION MODEL also aims to fit the model to the actual plant, it deals with relatively slow changes such as catalyst degradation or fouling which are detected by multiple sensors over a wide area. Therefore, data reconciliation is performed by relatively long time intervals, *e.g.*, once a day. Previously, data reconciliation assumed that the process is in a steady-state. In fact, it is difficult to assume that the process is in a steady-state at all times, and therefore the execution timing was limited. Meanwhile, MIRROR PLANT performs tracking to trace the actual plant behaviors in real-time as described before, and simultaneously calculates variation in holdup.

The Omega Simulation Corp (OSC) has been developed by a method for data reconciliation with dynamic compensation, where a data reconciliation calculation method takes this holdup variation into account in addition to constraints of mass balance and heat balance of the IDENTIFICATION MODEL and minimizes the residual sum of squares between the estimated and observed values. This method takes errors caused by dynamic variations into account and achieves more precise data reconciliation.

Figure 6 shows a simple tank system. The data reconciliation with dynamic compensation is explained below by using this figure. When the input flow rate is given by f_i, the output flow rate by f_p, the holdup volume in the tank by U, then the mass balance of the tank is expressed by Eq.(1).

$$\frac{dU}{dt} = f_i - f_p \qquad \cdots (1)$$

In the unsteady state, dU/dt in Eq. (1) is not 0, and therefore $f_i \neq f_p$.

When the estimated value is *given by* f, the observed value by f^*, their residual sum of squares by E, then the following Eq.(2) holds:

$$E = (f_i - f_i^*)^2 + (f_p - f_p^*)^2 \qquad \cdots (2)$$

Data reconciliation is achieved by finding f_i and f_p that minimize E under the constraint conditions Eq.(3) below which is derived from the mass balance equation.

$$f_i = f_p + \frac{dU}{dt} \qquad \cdots (3)$$

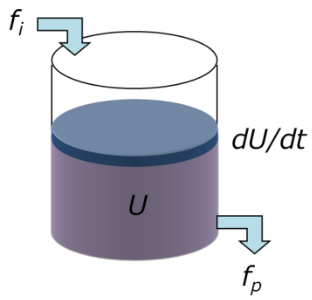

Fig. 6 Tank system.

Existing data reconciliation technology assumes that the process is steady-state, *i.e.*, dU/dt in Eq. (3) is 0. This was achieved by judging the state before data reconciliation or by pre-processing with a moving average filter or other means. However, actual plants cannot be in the steady-state in a precise sense, and moving averages are not always equivalent to steady-state values when operation conditions fluctuate, thus resulting in estimation errors. In contrast, MIRROR PLANT quantifies the dU/dt constantly during tracking and uses this value in the constraint equation for data reconciliation calculation, therefore it enables more precise compensation for dynamic unbalance. This is called dynamic compensation. Although only the mass balance is considered to simplify the explanation, the MIRROR MODEL which uses an exact engineering model can compensate also for dynamic imbalances in heat and composition balances.

5 MIRROR PLANT HMI for proactive operation

5.1 Human-centered HMI design

The strengthening of international competitiveness and improved productivity are required for process plants. Many manufacturing companies in Japanese production sites have already installed automation systems or have renovated the installed control systems of their plants. Wherein, most of those companies consider HMI as a means to improve process efficiency. The HMI plays an important role in connecting the system and operator, and the improved usability can influence the safety of plant control. Some companies have independent guidelines for designing the HMI of control systems, but most of them do not. Thereby, human-centered HMI guidelines are currently undergoing standardization by researchers, institutes, and consortia.

There are a number of approaches to research in this area, including ergonomics engineering (human factors), situation awareness, gestalt, *etc*. The ISO has provided a number of guidelines for ergonomics engineering as the 9241 series giving the outlines of the basic concept and providing actual examples. However, it is difficult to achieve a general HMI for multipurpose use even with these guidelines, because each plant has its own structure of equipment, and differs from each other, with regard to diagnosis and disturbances. Therefore, it may be difficult for a company to integrate the control staff and control room in the plant due to the HMI that has been designed according to the original rules of each control system for each process.

5.2 MIRROR PLANT HMI

The estimated and forecast data of MIRROR PLANT can be displayed on the screen of an existing DCS [5][6][7]. This enables the operators to operate the plant while monitoring near-future plant conditions. However, measured values, estimated values, forecast values of the measured values, and forecast values of estimated values are eventually displayed on the screen of the DCS at the same time, and this increased amount of information may confuse operators and it will trigger misunderstandings or wrong operations. To resolve this potential problem, the following two basic rules were defined:

- Clearly distinguish between forecast data and current or past data based on the time axis.
- Clearly distinguish between actual measured data from the DCS and calculated data from MIRROR PLANT based on the information source.

The layout of displayed information and the background colors for the screen specific to MIRROR PLANT were designed based on the above rules. Other elements of the HMI were designed in accordance with the look & feel of the DCS, allowing operation without any additional knowledge. To distinguish information resources, estimated values of MIRROR PLANT are displayed in parentheses. Figure 7 shows an example of instantaneous value data display. To clearly distinguish "1" from parentheses—*i.e.*, "(" or ")"—a space is added between data characters and parentheses. Although the authors Yokogawa recommend parentheses, other symbols or no symbol can be selected by the engineers depending on the plant-specific HMI design policy.

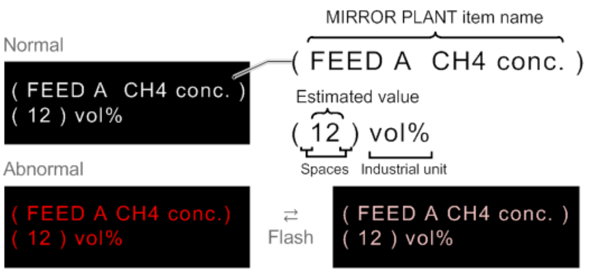

Fig. 7 Example of expression for estimated value by MIRROR PLANT.

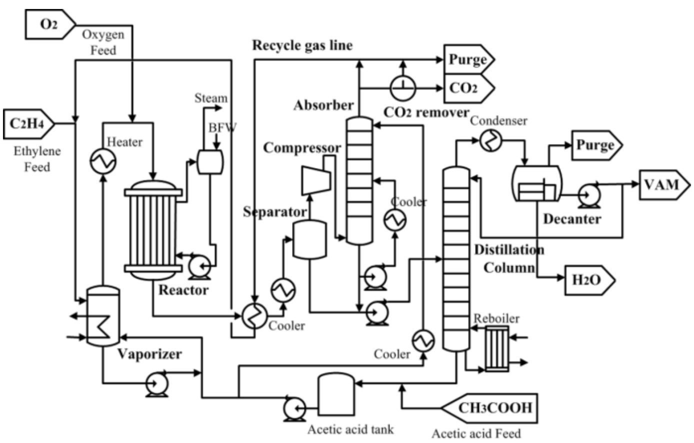

Fig. 8 Process flow of vinyl acetate monomer (VAM).

6 Application to vinyl acetate monomer (VAM) process

6.1 VAM process

MIRROR PLANT was applied to a virtual vinyl acetate monomer (*VAM*) process [8]. A brief overview of the *VAM* process is described in this section. Figure 8 shows the process flow diagram. As the fresh feed, ethylene (C_2H_4), acetic acid (CH_3COOH), and oxygen (O_2) are provided to the reactor to generate vinyl acetate monomer ($CH_2{=}CHOCH_3$).

Both of the main and side reactions are exothermic, with heats of reaction of $(-\Delta H_1) = 176.2$ kJ/mol and $(-\Delta H_2) = 1323$ kJ/mol, respectively. The *VAM* from reactor outlet is sent to the separator where gas and liquid are separated. The vapor from the separator goes to the compressor and the liquid stream becomes part of the feed to the distillation column. The gas from the compressor is recycled back to the reactor through the absorber and CO_2 removal system. The liquid products, *VAM* and H_2O, are withdrawn from the decanter, and the bottom products, *AcOH* and H_2O, are recycled back through the *AcOH* tank.

This process is performed under the following constraints, as suggested by Luyben, *et al*. In 1998.[8]

- The O_2 concentration must not exceed 8 mol% anywhere in the gas recycle loop to remain outside the explosivity envelope of C_2H_4.
- The pressure in the gas recycle loop and distillation column cannot exceed 862 kPaG because of the mechanical construction limits of the vessels.
- The peak reactor temperature along the length of the tube must remain below 200 ℃ to prevent runaway reaction and mechanical damage to the catalyst.
- The reactor inlet temperature and the hot side exit temperature from the feed emission heat exchanger (FEHE) must remain above 130 ℃ to avoid concentration of *AcOH*.
- In the distillation column, the *AcOH* in the decanter organic phase must not exceed 100 ppm as a product specification.

- The *VAM* composition in the bottom stream must remain below 100 ppm to prevent polymerization and fouling in the reboiler and vaporizer.

Those reaction processes as described by Eqs. (5) and (5) below in which C_2H_4 and O_2 are mixed is very dangerous with a risk of explosion.

$$C_2H_4 + CH_3COOH + \frac{1}{2}O_2 \rightarrow CH_2 = CHOCH_3 + H_2O \quad (4)$$

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O \quad (5)$$

6.2 MIRROR PLANT HMI design for VAM

Figure 9 shows an implementation of MIRROR PLANT for the *VAM* process. The *VAM* virtual plant model, MIRROR MODEL, and ANALISIS MODEL in this figure were constructed using Visual Modeler (OSC). The MIRROR PLANT HMI receives the sensor-measured data which is actually calculated in the virtual plant and then displays the estimated and forecast data from MIRROR PLANT.

Figure 10 shows an overall view of the MIRROR PLANT HMI. The vertical bar on the left is the MIRROR PLANT browser bar. Applications of the MIRROR PLANT, such as the estimated value alarm, forecast alarm, and forecast trend, can be started by clicking the icons on this bar. The browser bar is positioned on the left side to ensure a larger area for monitoring, by assuming that wide liquid crystal displays (LCD) will be used widely for this purpose. The icons for starting both the estimated value alarm and forecast alarm which require continuous monitoring are positioned on the upper left, near the alarm icon of the human interface station (HIS), to reduce operator eye movement. The icons for starting both the forecast trend and terminating alarm creation which are expected to be used frequently are always displayed so that operators can activate these functions with a single click. Less frequently used functions can be started by selecting the function displayed on an application list which is displayed by clicking the function launcher icon.

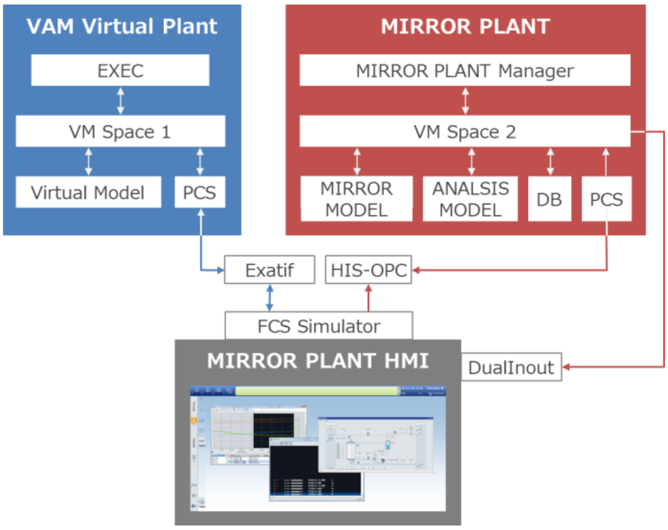

Fig. 9 Implementation of MIRROR PLANT for *VAM* process.

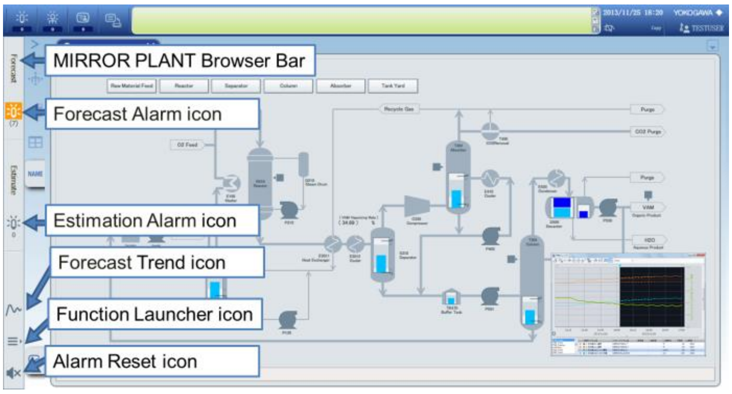

Fig. 10 Overall view of MIRROR PLANT.

Figure 11 shows a window for displaying stream flow data. This window is displayed by clicking the corresponding icon on the piping graphics screen of the HIS. The operators can monitor a temperature, flow rate, pressure, and composition in real-time.

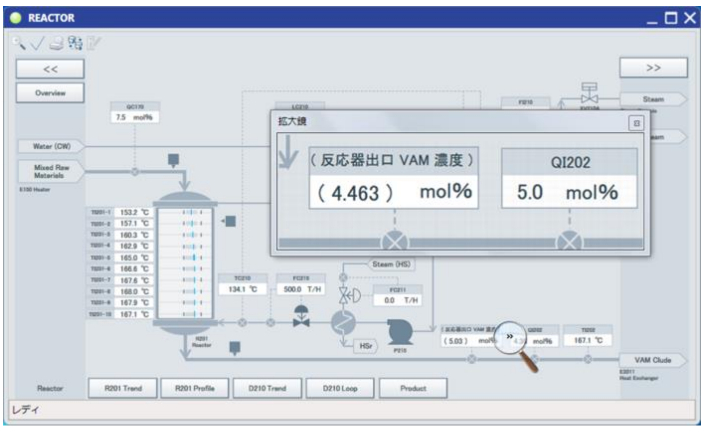

Fig. 11 Display of instantaneous value data.

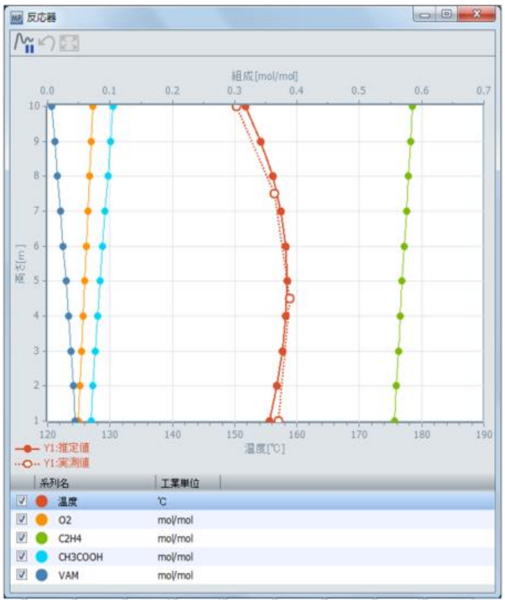

Fig. 12 Window for displaying visualized data inside the reactor.

Figure 12 shows a window for displaying the visualized data inside the reactor. The data can be visualized by clicking the corresponding icon near the reactor in the graphical screen of the HIS. The Y-axis indicates the height in the reactor and the X-axis represents the temperature, composition, *etc*., inside the reactor. Even when an insufficient number of sensors are installed in the vertical direction to provide the distribution, operators can monitor temperature or composition distributions in the reactor from the chart of the estimated values.

Figure 13 shows a forecast trend window, which is displayed by clicking the forecast trend icon on the MIRROR PLANT browser bar or selecting “Trend” on the pop-up menu displayed by right-clicking the window for instantaneous value data display. The current time is shown at the center of this window, and the left and right areas show past and future data, respectively. The background color of the past data area is the same as that of the existing trend display, and the background of the future data area is shown by using a complementary color to show clearly the difference between the past and future data. In the past data area, actually measured values of the DCS and estimated values of MIRROR PLANT are plotted in chronological order. In the area of future data, the values currently being forecast are plotted by small solid circles and the trend of the last forecast values is shown as a solid line. Thus, after completion of the present forecast cycle, the series of small circles turns into a solid line, and the next forecast cycle starts and new small circles are added. To make forecast for the next 1 hour takes about 1 to 2 min depending on the modeling range of the plant by the MIRROR PLANT and hardware specifications. The last trend as well as those in the forecast can be displayed at the same time. Ranges defined by thresholds can be displayed on the forecast trend window, which allows operators to monitor whether the trend in future will go out of or back into the range.

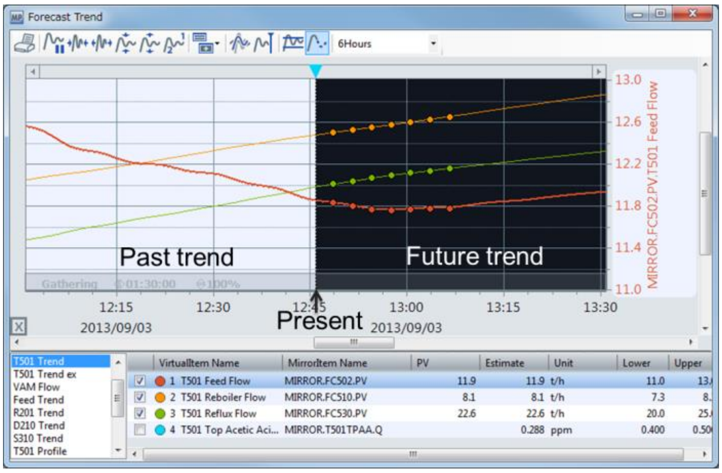

Fig. 13 Forecast trend window.

Figure 14 shows a forecast alarm window displayed by clicking the forecast alarm icon on the MIRROR PLANT browser bar. The background color of this window is the same as that of the future data area in the forecast trend window for ease of identification that it indicates forecast data. Similarly, although not shown, the estimated value alarm window is displayed by clicking the estimated value alarm icon on the MIRROR PLANT browser bar. The information shown in the estimated value alarm window is past data, so its background color is the same as that of the past data area in the forecast trend window. Those colors are useful to identify the time attribute, past or future, of each alarm. The forecast alarm window shows how much later an alarm occurs in numerical values, and also in analog form as a progress bar, which allows operators to intuitively understand the urgency. The importance of each tag is shown as the color of the icon. For example, a red mark indicates higher importance and a shorter progress bar means operators must handle it earlier. By handling possible alarms before they actually occur, operators can achieve safer plant operation.

Figure 15 shows a forecast alarm log window. The predictive alarm window as shown in Fig. 12 is refreshed when each forecast cycle is completed. Past forecast alarm messages can be confirmed in the forecast alarm log window, which is displayed by clicking the launcher icon on the MIRROR PLANT browser bar and then selecting the forecast alarm log in the list. Forecast alarm messages for the forecast alarm log window are saved at each time the forecast cycle starts.

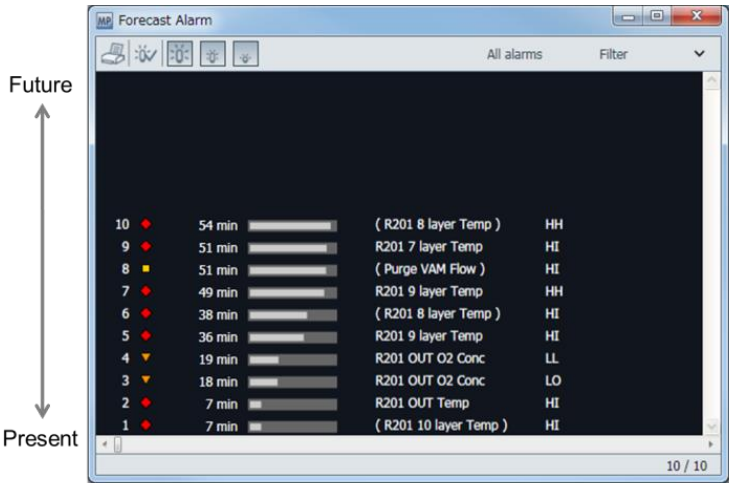

Fig. 14 Forecast alarm window.

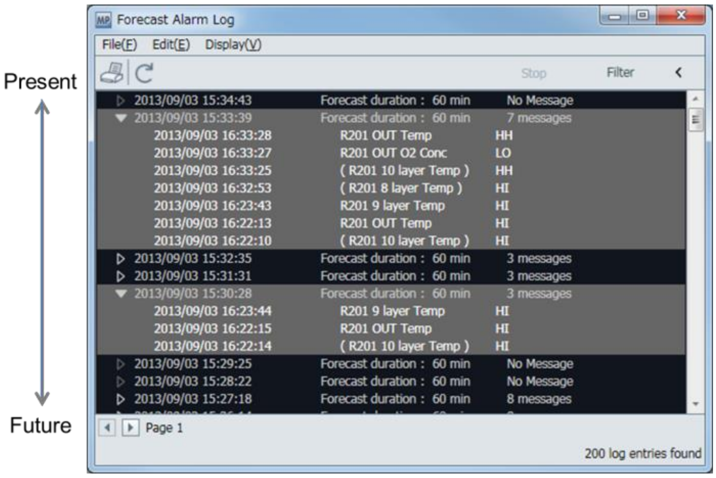

Fig. 15 Forecast alarm log window.

6.3 MIRROR PLANT HMI applications

The target value of production volume is decided by controlling the reactor temperature in the *VAM* process. The operator turns the temperature conditions to increase the production volume, but he cannot observe the operation response immediately because the *VAM* process in the plant has a large time of delay. However, the production volume change can be checked by the forecast trend. It is also possible to confirm whether the operation was correct or incorrect based on the forecast alarm.

In conventional plant operation, the operator changes the set point value of the reactor's temperature in increments of 0.2 or 0.3 ℃ and will wait for the plant to reach the steady-state. This can take a long time (5 to 6 hours). After confirming the safety of the plant, the plant operator will repeat the same action until the target production volume is achieved. By using MIRROR PLANT, the production load change can be performed quickly with maintaining both safety and efficiency.

7 Conclusions

The MIRROR PLANT presented in this paper is an on-line dynamic plant simulator that can perfectly simulate actual plant behavior in real-time. The authors of this paper applied MIRROR PLANT to the dangerous chemical plant as one of the example practice, wherein two model parameter identification techniques have been developed for simulating current plant behavior accurately. The MIRROR PLANT can provide visualization inside the plant and near-term future forecasting to support plant operation called "Proactive Operation". The plant operator and technical staff can gain an in-depth understanding of their process by using MIRROR PLANT, because MIRROR PLANT is constructed based on the "accurate" physical modeling. Therefore, MIRROR PLANT will allow the realization of safer and more effective plant operation.

In the real plant, the plant operation technique should be transferred from old generation to new generation. The new generation called "millennial" has different values from that of old generation. The authors of this paper think the conventional apprentice system may not apply to transfer the operation technology in the manufacturing field, and they propose "Hyper Intuitive Operation" including the proactive operation for next generation. In this paper, the proactive operation is demonstrated by using chemical plant. Lastly, the authors believe that the idea of MIRROR PLANT will surely impact on the nuclear power plant which requires high level safety.

References

[1] Fire and Disaster Management Agency Web site http://www.fdma.go.jp/neuter/topics/fieldList4_16/pdf/0722_05.pdf

[2] PASMAN H.J.: “Process Safety: principle and concept; how to keep my plant safe?”, 2nd mini-symposium :Risk management of process industry,pp.31-42,2013

[3] NAKAYA M.: “MIRROR PLANT for Innovative Plant Operation”, Yokogawa Technical Report, Vol.56, No.1, pp.7-10, 2013

[4] FUKANO G., YOKOYAMA K., and YAHATA Y.: “MIRROR PLANT On-line Plant Simulator and its Applications”, Yokogawa Technical Report, Vol.56, No.1, pp.11-14, 2013

[5] NAKAYA M., HATSUGAI E., OMATA T., IKETSUKI Y., KOUNO A., and TAKANO N.: “New Plant Operation Human-Machine Interface with Forecast by Mirror Plant”, Proceeding of First International Symposium on Socially and Technically Symbiotic Systems, Okayama, Japan, August 29-31, pp.35_1-35_8, 2012

[6] HATSUGAI E., TAKANO N., and IKETSUKI Y.: “HMI of MIRROR PLANT for Facilitating Forecast of Plant Operation”, Yokogawa Technical Report, Vol.56, No.1, pp.11-14, 2013

[7] HATSUGAI E., and NAKAYA M.: “HMI design of MIRROR PLANT for Safe Operation and Application to Vinyl Acetate Monomer Process”, ISOFIC/ISSNP 2014, Jeju, Korea, August 24-28, 2014

[8] MICHAEL LUYBEN L. and BJOM Tyrus D.: “An industrial design/control study for the vinyl acetate monomer process”, Computers and Chemical Engineering, Vol.22, No.7-8, pp.867-877, 1998