Emergency Shutdown of Fluidized Bed Reaction Systems

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ABSTRACT

With several industrial applications of fluidized bed technology recently commercialized worldwide, it becomes essential to develop safe operation methods for fluidized bed reaction systems (FBRSs) to prevent any influence on their process values, which lead to accidents. To preventing any disaster or malfunction in an FBRS, an emergency shutdown system (ESD) is initiated, closing the reaction system in case of any abnormality by effectively isolating the flammable gas. However, an ESD is also prone to the "inactivation problem," in which in the case of failure it initiates the emergency shutdown, even when the operating conditions of the reaction system are abnormal. It is also vulnerable to a "malfunction problem," where the emergency shutdown is performed even when the operating conditions of the reaction system are normal. In this study, these problems were solved by investigating a reaction system through the monitoring of appropriate parameters and setting up of trigger levels, which reflect the uniqueness of an FBRS using an ESD. The parameters were identified by analyzing the scenario leading to an accident. The trigger levels were determined as the points at which the loss is smaller in the presence of an ESD, as compared to the value of the loss function in the presence or absence of an ESD. Furthermore, the ESD design model was applied as a case study in the ammoxidation process of propylene. The results showed that an ESD can prevent an approximately 8 billion yen of loss due to accidents in plant operations, against an investment of 200 million yen.

Keywords:
Fluidized bed reactor
Emergency shut down
Loss function

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1. Introduction

Since its development in the late 19th century, fluidized bed technology has been applied in various manufacturing technologies. So far, the main industrial applications of fluidized beds include coal gasifier, fluid catalytic cracking, synthesis of acrylonitrile by ammoxidation of propylene or propane, polyethylene gas-phase polymerization, and synthesis of maleic anhydride (Vashisth, 2015; Guerrero–Perez et al., 2008; Kusolsongtawee et al., 2018). In general, fluidized bed reactions have been proven to possess advantages such as uniform progress in catalyst-phase reactions, ease in control of reaction temperature, safety in handling explosive mixtures, and simplicity in catalyst loading and unloading. Given the several attributes of a fluidized bed reaction system (FBRS), it is expected to improve and expand its application in various fields in the future.

Recently, gas bubbles and flow conditions affecting the performance of a FBRS have been extensively investigated. Patil et al. (2014) analyzed the transfer through gas bubbles by using a discrete element method. Employing digital image and wavelet coherence analysis, Delgado et al. (2019) investigated the distributor performance effect in gas bubble generation, growth, and interaction. Escudero et al. (2011) studied the effects of bed height and material density on minimum fluidization velocity and gas hold-up. Oke et al. (2015) reported a stable expansion in uniform gas-fluidized beds of different diameters, particle–particle contacts, and wall friction. Upadhyay et al. (2017), examined the influence of air versus O_2/CO_2 as the fluidizing gas on the hydrodynamics of gas–solid flow in a cold-mode circulating fluidized bed using computational particle-fluid dynamics simulation. Guo et al. (2019) monitored the real-time fluidization state using electric current acquisition during a fluidized bed reduction of iron ore fines, which can be used to predict the de-fluidization and localized fluidization state in a plant-scale FBRS. Busciglio et al. (2010) focused on the development of a linear stability criterion for the state of the homogeneous fluidization regime, based on a new mathematical model for gas-fluidized beds. Further, Karimipour et al. (2010) investigated the characteristics of gas streaming in a deep gas–solid fluidized bed containing Geldart's Group A powder, using a 30-cm ID cold flow unit. Bieberle et al. (2012) observed the flow state using the recently developed ultrafast X-ray computed tomography technique.

The stabilization of an FBRS has been of great interest from the viewpoints of ensuring a high yield of the desired product and safety in operation to improve the equipment performance. Dutta et al. (1999) reported the remodeling of a reactor by attaching a dispersion plate to improve the flow characteristics, thereby preventing gas drift in the catalyst layer. Similarly, Taofeeq et al. (2018) investigated the impact of vertical internals on the flow regimes and their transition velocities. In addition, Mccallion (1996) investigated the influence of cyclone types on improving catalyst recovery efficiency. From the perspectives of controlling the reactions and improving the operational efficiency, most previous studies have focused on enhancing timely reaction conditions through online analysis adjustment of the gas reaction products without requiring manual analysis (Goodrich, 1972). Hawkins et al. (1999) reported that fluidized bed reactors can be controlled using multivariate statistical process analysis by predicting changes in the output caused by variations in the input variables. Zhang et al. (2016) studied the attrition in a catalyzed circulation process by understanding the physical deterioration of the catalyst. There are also a few reports on accidents in fluidized bed reactors. Sano et al. (2020) reported accident cases in FBRS, demonstrating that abnormalities can be classified as either "accidents/disasters" or "incidents." Accidents and disasters include events such as explosions, fires, and pressure abnormalities. Incidents describe events that calmed down before the occurrence of an accident/disaster. Psara et al. (2015) studied the development and implementation of a safety risk assessment methodology to highlight potentially prevalent hazards during autothermal reforming of natural gas for hydrogen production in a fluidized bed membrane reactor. They also demonstrated the capability of the newly developed methodology to cover all possible risk scenarios.

As outlined above, fluidized beds have been extensively studied over the years; however, not much research exist regarding the effective operational method of an FBRS to preventing industrial accidents. FBRSs mostly deal with handling flammable gases with high potentials to generate fires, explosions, and even release the flammable gases to the surroundings. Such undesirable occurrences can be prevented by installing effective measures that immediately halt any reaction system in case of abnormal conditions or that isolate the released flammable gases. This calls, for example, for an important system capable of monitoring the operating conditions and detecting whether the trigger level has been exceeded, which allows the automatic activation of emergency valves with predetermined opening and closing directions, as well as the automatic halt of the reaction system. Most importantly, such a system minimizes the leakage of flammable gases and fluidized bed catalyst, reducing the fire/explosion risks. Nevertheless, accidents are more likely in the event of an emergency shutdown failure, called inactivation, during abnormal operating conditions of the reaction system. Similarly, due to malfunctions, an emergency shutdown performed despite normal operating conditions would cause economic losses when restarting the system. Thus, while introducing an emergency shutdown system, it is important to monitor the essential process parameters (i.e., pressure, temperature, flow rate, and material concentration) and set trigger levels that reflect the uniqueness of the FBRS.

To prevent detection of abnormalities (that is, to detect abnormality as normal) and false detection of abnormality (to detect normal as abnormality) in gas-phase reactions using an FBRS, the present study aims to provide a clue in developing an effective FBRS that will accurately detect abnormalities and immediately cease the operation.

2. Typical fluidized bed reactor apparatus

2.1 Internal equipment

Figure 1 shows a typical fluidized bed reactor apparatus. The fluidized bed reactor (1) for gas-phase reactions includes a sparger (5) for supplying the raw-material gas (B) and a distributor (3) supplying the oxygen-containing gas (A) as required (i.e., in oxidation reaction). Cooling coils (6) are installed, and the heat of chemical reactions is dissipated by the circulating water or steam to control the reaction temperature. During the reaction, the inside of the reactor showed a dense phase (9a) of a high density of catalyst at the lower part and a dilute phase (9b) with a low density of catalyst at the top. Most of the reactions occurred in the dense phase (9a). The fluidized bed catalyst in the reaction gas, present in the dilute phase (9b), was separated from the reaction gas at the cyclones (7), and then returned to the dense phase (9a) in the lower part of the reactor.

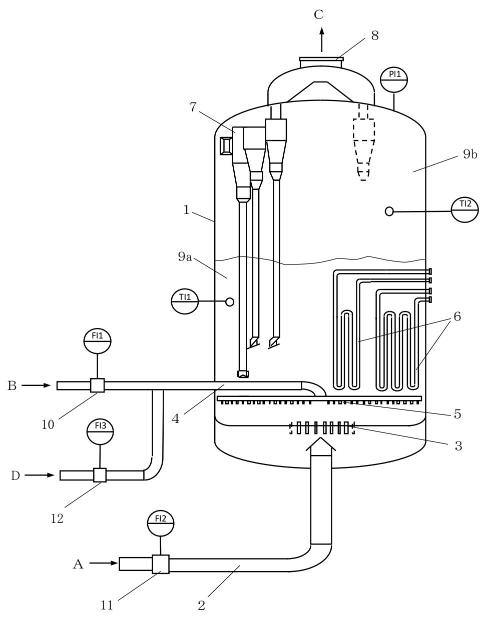

Fig. 1. Typical fluidized bed reactor apparatus. Fluidized bed reactor (1), oxygen-containing gas piping (2), sparger (3), raw-material gas piping (4), sparger nozzles (5), cooling coils (6), cyclones (7), reactor exit piping (8), dense phase (9a), dilute phase (9b), flow rate sensor (10, 11, 12), oxygen-containing gas (A), raw-material gas (B, D), and reaction gas (C).

The flow rates of the raw-material gases (B and/or D) were measured using flow rate sensors (10 and 12) and displayed on the indicators (FI1 and FI3). Similarly, the flow rate of the oxygen-containing gas (A) introduced (as necessary) was measured by a flow rate sensor (11) and displayed on the indicator (FI2). For the reactor temperature measurement, thermometers (TI1 and TI2) were installed in the dense (9a) and dilute (9b) phases, respectively. Subsequently, the reaction pressure was measured using a pressure gauge (PI1) fixed on top of the reactor. These process values were displayed on a control panel like a distributed control system (DCS).

The contact time between the total feed gases and the catalyst was within the 2–5-s estimate. For example, there was no delay time in changes of the reaction heating value and pressure due to the raw-material gas flow rate fluctuation, instead, the followed the trend in the flow rate variation. Moreover, the reactor temperature was affected by the heat capacity, which resulted in a relatively small rate of change but occurring without any overshoot.

2.2. Characteristics of FBRS

Some characteristics of the fluidized bed include the following:

a) Uniform reaction temperature. The temperature can be adjusted precisely and kept uniformly, which results in a few side reactions and product quality that is uniform and good overall.

b) Easy heat removal. Given the large overall heat transfer coefficient, it is easy to remove and replenish the amount of heat even in the reaction of intense heat generation and heat absorption.

c) Less risk of explosion. The fluidized bed catalyst hinders flame propagation from gases in the explosive range.

d) Easy catalyst replacement. The amount of catalyst can be increased or decreased during operation.

These characteristics result from the good fluidization of the catalyst. In other words, a poor fluid state of the catalyst means poor reaction results and heat removal, resulting in accidents.

3. Emergency shutdown evaluation model

3.1. Emergency shutdown control unit

As illustrated in Fig. 1, the FBRS comprises a fluidized bed reactor apparatus and an emergency shutdown (ESD) control unit. The ESD operates in an abnormal state conceptually different from a system that performs reaction control in a normal state, i.e., a DCS. Normally, chemical reactions in an FBRS are controlled based on operating conditions. Herein, the operation conditions were divided in three levels of measured process parameters to be monitored (i) within the range of normal values (green zone), (ii) within the range of a dangerous operation (red zone), and (iii) outside these ranges (yellow zone). The measured values of the monitoring target containing the boundary between the green and yellow zones and between the yellow and red zones were referred to as thresholds (1) and (2), respectively.

In temperature monitoring, for instance, the DCS monitors whether the temperature at a given location would remain in the green zone. When the temperature shows a tendency to move out of the green zone, it is controlled, to prevent it from leaving the zone, by either raising or lowering its value following the feedback and/or feedforward control. Moreover, when the temperature has moved to the yellow zone above threshold (1), the DCS controls to return the temperature to the green zone. When the temperature enters the yellow zone, the reaction system supervisor may artificially control the reaction and the temperature for a return back to the green zone.

Accordingly, an ESD operating in an abnormal state monitors whether the temperature exceeds the threshold (2) from the yellow zone without entering the red zone. When the temperature goes over the yellow zone and enters the red zone, the reaction system is forcibly shut down.

3.2. Concept of setting a trigger level and a risk evaluation model

Figure 2 shows the typical variations of losses with and without ESD as a function of a process value x. Here, the normal operation value is denoted as "a," and the zone is displayed in the color zone described in Section 3.1. Provided that *x* is a small value, the system will experience a larger loss with ESD than without ESD, mainly due to the loss caused by malfunctions. When x > b (i.e., the intersection point), the loss without ESD would be larger than with ESD. Thus, the vicinity of the intersection point of the loss function is considered to be the trigger level.

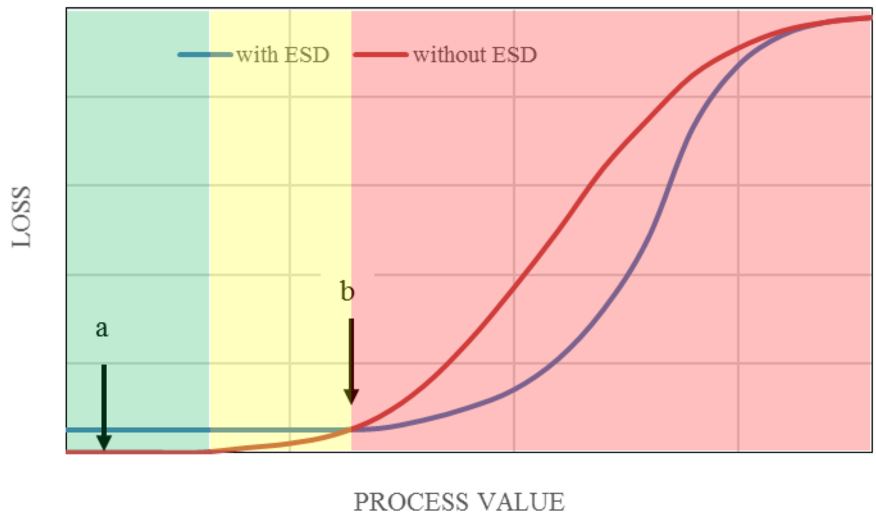

Fig. 2. Typical loss functions of "with ESD" and "without ESD." The blue and red lines respectively show the loss function "with ESD" and "without ESD."

Because the occurrence of disasters and the associated loss depend on the uniqueness of the plant and process, it is necessary to consider the losses when performing risk assessment models. Process values normally fluctuate with the operator's operation error, equipment failure, natural disaster, and intentional destruction, and such a variation depends further on the type and degree of the cause. Considering the uncertainty due to the process value fluctuation, the expected value of the loss function with and without ESD can be calculated following

$$H(\mu) = \int_0^{\infty} h(x) f(x;\mu,\sigma) dx \text{ , (1)}$$

and

$$H_{\mathrm{ESD}}(\mu) = \int_0^{\infty} h_{\mathrm{ESD}}(x) f(x;\mu,\sigma) dx \text{ , (2)}$$

where $h(x)$ and $h_{ESD}(x)$ respectively define the loss function without and with ESD. Here, the loss function describes the loss amount given to the system. Also, f(x)dx represents the probability that a loss will occur in a minute process value section (x, x+dx). A description for was added for f(x), which is the probability density function when the probability that the continuous random variable X moves from x to x+dx is

$$P(x \leq X \leq x + dx) = \int_x^{dx} f(x)dx. \text{(3a)}$$

Here, $f(x;\ \mu,\sigma)$ describes the fluctuation in the process value, and is assumed to follow a normal distribution, and μ and σ are the mean value and standard deviation, respectively. The probability density function can also be expressed mathematically according to

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right], (3b)$$

where the judgment of an emergency shutdown is dictated by the inequality,

$$H(\mu) \geq H_{ESD}(\mu). (4)$$

Accordingly, an emergency shutdown is automatically executed when Eq. (4) is established.

4. ESD design

An ESD is designed to prevent accidents arising from the use of the FBRS. This necessitates coping with all accidents associated with the system, such as a fire, an explosion, or destruction (Sano et al., 2020) . Catalyst deactivation causing economic losses can also be defined as an accident, as a phenomenon that leads to fires and explosions. In essence, the instruments and operating conditions considered for abnormality detection are identified from techniques used in potential hazard and risk analysis, such as fault tree analysis (FTA) and hazard and operability (HAZOP). These instruments and operating conditions that can generate abnormality in the FBRS include the reactor temperature, reactor pressure, raw-material gas flow rate, oxygen-containing gas (or air) flow rate, (oxygen-containing gas flow rate)/(raw-material gas flow rate) (or gas molar) ratio, reaction gas composition, cooling coil's coolant flow rate, fluidized bed catalyst inventory, the valve of the reaction gas pipe, the operating condition of the raw-material gas vaporizers, and the operating condition of the air compressors.

Hence, the objects to be detected by ESD are temperature, pressure, various gas flow rates, and gas compositions, whereas the places to be detected are the reactor main body, various supply pipes that supply the raw-material gas to the reactor, and the outflow pipe. When detecting abnormalities in the FBRS, it is preferable to detect one or more points from abnormalities in all instruments installed in that FBRS, as well as all the equipment connected to it. This is the ideal protocol of execution. However, instrument failures and malfunction/inactivation are possible in an FBRS operating under high temperatures and pressures, thus, it is essential to always monitor all instruments installed in the FBRS and all equipment connected to the FBRS without securing this point. Moreover, an emergency shutdown can be created as soon as one of the parameters enters the red zone. However, this may also cause an emergency shutdown by mistake under the case of a normal operation. Besides, if the cost of the FBRS investment is taken into account, it is non-realistic to install all instruments into the system. Thus, to operate ESD properly, it is required to select the necessary detection means without excess or deficiency. Furthermore, from the viewpoint of eliminating the possibility of instrument failure and malfunction/inactivation, the system configuration may be necessary to ensure the corresponding reliability of the instruments used for abnormality detection. Human factors must also be considered for manual intervention in ESD. Descriptions regarding human factors were excluded in this paper because they deviate from its purpose. The selection of the detection means is described in Section 4.1. Moreover, the security of the instruments and the threshold are outlined in Section 4.2.

4.1. Instruments used for abnormality detection

Accident scenarios were estimated from FTA and HAZOP. From the viewpoint of process monitoring by instruments, a process status was assumptively organized up to the accident. Figure 3 clarifies that an event directly resulting in an "accident," such as fire, explosion, and destruction, is an "abnormal phenomenon," which arises mainly because of factors 1–3. The abnormal phenomenon that directly leads to an accident should be an instrument for abnormality detection. Thus, instruments that detect factors 1–3 are instrument candidates for abnormality detection.

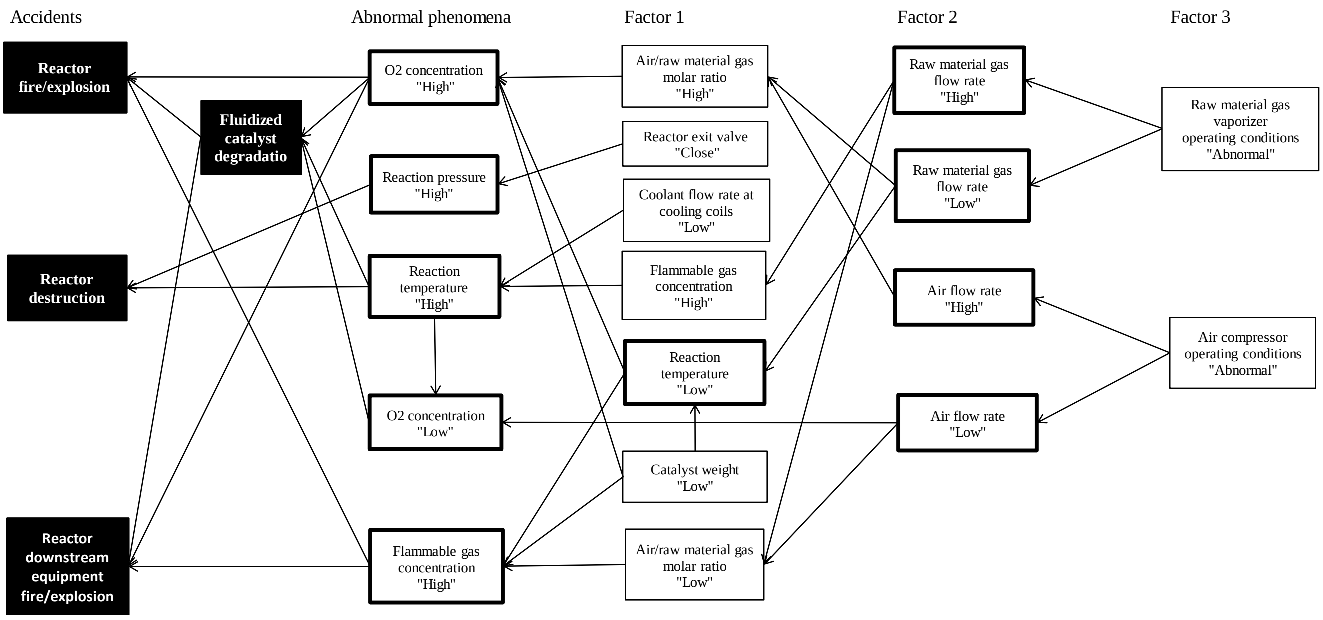

Fig. 3. Analysis chart of the scenario leading to an accident.

Thermometers in the reactor

When the reactor temperature markedly exceeds the design temperature, it may lead to the thermal damage (destruction) accident of the reactor, whereas when the reactor temperature falls, the concentrations of the unreacted materials supplied to the reactor (i.e., the raw material and oxygen-containing gases) will increase. The reaction gas flowing out of the discharge pipe and the gas inside the reactor tend to readily create an explosive gas mixture, causing an accidental explosion. Thus, the reactor temperature is considered an important process parameter. Furthermore, reactor temperatures that are either too high or tool produce peroxidized and over-reduced catalysts, leading to their deactivation. To prevent this, predetermined upper and lower limit values were selected for the temperature in the reactor and set as values for determining an emergency shutdown. The "high" and "low" temperatures are indicated in a bold frame in Fig. 3.

In general, the temperature distribution of an FBRS can be maintained to be relatively uniform. However, a non-homogeneous temperature distribution may emerge due to the presence/absence of a catalyst, reaction rate, and the use of cooling coils. Therefore, the temperature of the lower portion (dense phase (9a)) of the reactor with a high catalyst concentration, where the gas-phase reaction actively occurs, should be monitored using a thermometer (TI1) located lower than the upper end of the cooling coils whereas that of the upper portion (dilute phase (9b)) using a thermometer (TI2) located higher than the upper end of the cooling coils. Assuming a wire breakage or connection failure of the thermometer, a consideration is given to the failure on the safety side, that is, a thermometer that detects high and low temperatures is installed. This way, when the thermometer for high-temperature detection fails, the high temperature is indicated; conversely, when the thermometer for low-temperature detection fails, the low temperature is indicated.

Pressure gauges in the reactor

The reactor may be destroyed when the pressure in the reactor exceeds its design pressure by a large margin, whereas a drop in the pressure may have some effect on the reaction, but less likely towards an accident. Therefore, a predetermined upper-limit value for the pressure in the reactor is selected and set as the value for determining an emergency shutdown. The pressure "high" is indicated by a bold frame in Fig. 3. Moreover, because the pressure in the fluidized bed generally varies with the amount of catalyst and catalyst fluidization, a pressure gauge is installed in the dilute phase (9b).

Nozzle defects (e.g., nozzle blockage) sometimes affect other pressure gauges. From the viewpoint of instrument reliability, it is not a type that branches from one takeout nozzle and connected to two or more pressure gauges, neither the pressure gauge and the reactor are connected one-to-one through the nozzle.

Raw-material gas flow meters

A raw-material gas flow meter is installed at the raw-material gas supply pipe. When the flow rate of the raw-material gas increases, the gas molar ratio also changes, as will be described later. Such an increase is corresponded by an increase in the amount of reaction, raising the heat of reaction and the reactor temperature. If the cooling system works well, the reactor temperature can be easily controlled. If the cooling system is however insufficient, a drastic increase in the temperature would elevate the reactor temperature, leading to a heat damage (destruction) accident of the reactor. In the case where the unreacted raw-material gas abnormally increases due to an increase in the raw-material's gas flow rate, when the raw-material gas is rapidly increased, some of it would remain unreacted due to the imbalance. Subsequently, the fluidized bed catalyst is insufficient relative to the increased gas amount and the deviation of the gas flow path in the reactor, which induce a risk of abnormal combustion and explosion in the reactor, as well as in the equipment downstream of the reactor, particularly in the waste gas incinerator. Here, the change in the unreacted raw-material gas can be detected by a reaction gas composition analysis, which will be described later. Conversely, when the raw-material gas flow rate decreases, both the heat of reaction and reactor temperature also decrease. When the reactor temperature decreases, the unreacted materials of the raw-material gas and the oxygen-containing gas increase to form an explosive gas mixture, leading to an explosion. Even when the flow rate of the raw-material gas decreases, changes will still occur in the gas molar ratio and the reaction gas composition.

In summary, increasing/decreasing the flow rate of the raw-material gas causes (i) an increase/decrease in the gas molar ratio, (ii) an increase/decrease in the reactor temperature, and (iii)a change in the analysis value of reaction gas composition. It should be noted that the raw-material gas flow rate is an important operating condition of the FBRS, thus, a frequent operation of the flow rate is performed, the raw-material gas flow rate change in the beginning causes an abnormal phenomenon, and the reliability of the flow meter's measurements is relatively high. Therefore, the predetermined upper and lower limits for the raw-material gas flow rate are selected and set as values for determining an emergency shutdown. The raw-material gas flow rate is indicated in a bold frame in Fig. 3.

Oxygen-containing gas flowmeter

As described earlier, an increase in the oxygen-containing gas flow rate forms an explosive gas mixture of the raw-material gas, the reaction gas, and oxygen. In contrast, a decrease in the flow rate causes the raw-material gas to react insufficiently, which increases the amount of the unreacted raw-material gas. This situation may lead to an abnormal combustion and explosion in the reactor, as well as in the reactor downstream equipment, such as the waste gas incinerator. The variation in the oxygen-containing gas flow rate also affects the gas molar ratio and the reaction gas composition, and should be carefully monitored. The predetermined upper and lower limit values of the oxygen-containing gas flow rate are selected and set as values for determining an emergency shutdown. The oxygen-containing gas flow rate is indicated by a bold frame in Fig. 3.

(Oxygen-containing gas flow rate)/(raw-material gas flow rate) and gas molar ratio

Although the oxygen-containing gas flow rate and the raw-material gas flow rate can be substituted, the gas molar ratio may be monitored. Because the gas molar ratio is calculated from the two instruments, a system for the calculation is required. The gas molar ratio is indicated by a thin frame in Fig. 3.

Reaction gas analyzers

The reaction gas comprises a product gas and unreacted raw-material gas, and in the case of an oxidation reaction, oxygen is further added. In a normal operation, the oxygen concentration in the reaction gas is controlled to less than the oxygen concentration limit from the viewpoint of explosion prevention. In the case where the catalyst deteriorates in a reducing atmosphere, it is controlled at an oxygen concentration, or more, that inhibits reduction deterioration. If any abnormality occurs at the reaction site, the reaction gas composition would change. In such a case, even if the details of the abnormality in the reaction site are unknown, the occurrence of the abnormality can be known if it can be monitored whether the abnormality occurs in the composition of the reaction gas. Besides oxidation reactions, the concentrations of raw material and/or product gases should also be calculated. Therefore, for the reaction gas analysis, a predetermined upper-limit value is selected and set as the value for determining an emergency shutdown. In the case of oxygen concentration, the lower limit value is set as necessary. The concentration is indicated by a bold frame in Fig. 3.

The composition of the reaction gases is continuously determined using a gas analyzer (DI) at the reactor outlet.

Coolant flow meter at cooling coils

Fluctuations in the coolant flow rate of the cooling coils affect the reaction temperature. Pressurized water at saturated temperature or steam is often used as a coolant. A coolant water absorbs the heat generated in the reactor via the cooling coils, while a part evaporates (at 5%–30%). For water-cooling coils, the cooling efficiency is static even with elevated water flow rates. For steam-cooling coils, the cooling efficiency increases with higher steam flow rate. However, the reaction temperature is less affected by the upper limit of the usable steam flow rate and/or the relatively small number of cooling coils using steam. In the case the flow rate of the coolant decreases, the reaction heat is not successfully removed, which eventually increases the reactor temperature. Therefore, the lower limit value of the cooling coil's coolant flow rate may be selected and set as the value for determining the emergency shutdown, although not compulsory. This is indicated by a thin frame in Fig. 3.

Fluidized bed catalyst inventory

The amount of fluidized bed catalyst does not spontaneously increase during a normal operation; however, when it cannot be captured due to a malfunction in the cyclones and a decrease in the catalyst inventory, the reaction does not proceed and the unreacted materials increase. Here, the concentration of the raw-material gas in the reaction gas would increase, or in the case of an oxidation reaction, the oxygen concentration would increase. If the inventory of the catalyst decreases, it can alternatively be detected through an analysis of the reaction gas composition described above, or be identified as a decrease in the reactor temperature. The fluidized bed catalyst inventory can be calculated indirectly from equipment such as pressure gauges. Moreover, as it can be alternatively detected by the other instruments described above, it is not necessary to select and set as a value for determining an emergency shutdown. This inventory is displayed in Fig. 3 as a thin frame.

Valve at the reaction gas piping

When the valve attached to the pipe for transferring the reaction gas flowing out of the reactor is operated towards the close direction for some reason, the pressure in the reactor may increase and cause the reactor destruction. Valve closure can alternatively be detected with a pressure gauge as the reactor pressure is increased. For the closing of the valve of the reaction gas pipe, alternative detection is possible with the other instruments already mentioned; therefore, it is not necessary to select and set as the value for determining an emergency shutdown. This is represented in Fig. 3 by a thin frame.

Operating conditions and state of raw-material gas vaporizers

The operation of the raw-material gas vaporizers is influenced by the flow rate and temperature of the heat medium, the raw-material liquid level in the raw-material gas vaporizers, and the pressure in the raw-material-gas vaporizers, which eventually affect the raw-material gas flow rate. Accordingly, the operation abnormality of the raw-material gas vaporizers can be indirectly detected by measuring the raw-material gas flow rate. Each condition affecting the operation of the raw-material gas vaporizers also tends not to directly affect the reactor's operation. Abnormality detection related to the operating conditions and state of the raw-material gas vaporizers can be alternatively detected using other instruments as described above. Thus, it is not necessary to select and set a value for determining an emergency shutdown. This is indicated by a thin frame in Fig. 3.

Operating conditions and state of air compressors

The operation of the air compressor is affected by the supply condition of steam or electricity, which is the driving source of the compressors. By contrast, the reactor pressure, the air supply destination, affects the oxygen-containing gas flow rate. The operation abnormality of the air compressors can be detected alternatively by the oxygen-containing gas flow rate; thus, the abnormality detection regarding the operating conditions and state of the air compressors can be alternatively detected using the other instruments already described. By so doing, it is not necessary to select and set a value for determining an emergency shutdown. This is indicated by a thin frame in Fig. 3.

4.2. Instrument reliability

As described above, instruments for abnormality detection should be selected. If a redundant instrument showing an abnormal value (within the "red zone") at each location exceeds a majority of the total number of the installed instruments, then the value of the redundant instrument depends upon the position, and the FBRS is immediately shut down. The term "redundant" is used herein to refer to the same object repeatedly measured using several measuring devices. Within this context, the same type of a measuring device can be placed at the same position for measurement, or the same object can be measured using various measuring methods. Several measuring devices can also be installed in a position range where the measured values can be regarded as identical in the calculation, even if the measurement positions are not completely identical. The redundancy of each instrument is described as follows.

(1) Thermometers

These are instruments used to detect an abnormal phenomenon immediately preceding an accident (see Fig. 3). Thermometers are normally 2 out of 3 to ensure the reliability and economic efficiency related to the prevention of system inactivation and malfunction.

(2) Pressure gauges

The same description as for thermometers.

(3) Flow meters

Even if these instruments cannot detect the abnormality, the upstream instruments shown in Fig. 3 can detect the abnormality. Therefore, it is set to 2 out of 2 from the viewpoint of preventing malfunction.

(4) Reaction gas analyzers

The same as for thermometers.

4.3. ESD operation

ESD urgently shuts down the operation of an FBRS when the values obtained by applying the majority selection methods for the redundant thermometers (TI), pressure gauges (PI), flow meters (FI), and reaction gas analyzers (DI) exceed a predetermined threshold value. Specifically, when at least one of the 10 states of (a1) to (e2) occurs, the operation of the FBRS is shut down immediately.

(a1) Temperature high: Reactor thermal damage and catalyst thermal deterioration prevention

The minimum temperature at which Eq. (4) holds is defined as the first reference value and the state in which the number of thermometers (TI) showing an actual measured value equal to or higher than the first reference value exceeds a majority of the total number of thermometers (TI).

(a2) Temperature low

(i) Prevention of the formation of explosive gas mixtures in a reactor arising from a reduced catalyst activity and the subsequent increase in the unreacted materials, and (ii) prevention of abnormal combustion in the downstream equipment.

The maximum temperature at which the temperature falls below the normal operation value and satisfies Eq. (4), is taken as the second reference value and the state in which the number of thermometers (TI) showing the measured value equal to or lower than the second reference value exceeds a majority of the total number of thermometers (TI).

(b) Pressure high: Reactor destruction prevention

The pressure rises above the normal operating value. The minimum pressure satisfying Eq. (4) is taken as the third reference value, and the state in which the number of pressure gauges (PI) indicating the measured value equal to or higher than the third reference value exceeds the majority of the total number of pressure gauges.

(c1) High oxygen concentration: Prevention of the formation of explosive gas mixtures

The oxygen concentration increases above the normal operation value. The minimum oxygen concentration that satisfies Eq. (4) is taken as the fourth reference value, and the state in which the number of reaction product gas analyzers (DI), which shows the measured value equal to or higher than the fourth reference value, exceeds the majority of the total number of reaction product gas analyzers (DI).

(c2) Low oxygen concentration: Prevention of catalyst reductive degradation

The oxygen concentration is lower than the normal operation value. The maximum value of the oxygen concentration that satisfies Eq. (4) is taken as the fifth reference value, and the state in which the number of reaction gas analyzers (DI) showing the measured value equal to or lower than the fifth reference value exceeds a majority of the total number of reaction gas analyzers (DI).

(c3) High raw-material gas concentration: Prevention of excess capacity of waste gas incinerator

The raw-material gas concentration in the reaction gas increases above the normal value. The minimum value of the raw-material gas concentration that satisfies Eq. (4) is taken as the sixth reference value, and the state in which the number of reaction gas analyzers (DI) showing an actual measurement value equal to or higher than the sixth reference value exceeds a majority of the total number of reaction gas analyzers DI.

(d1) High raw-material gas flow rate: Prevention of catalyst reductive degradation, reactor thermal damage, and catalyst thermal degradation

The raw-material gas flow rate increases above the normal operation value. The minimum value of the flow rate satisfying Eq. (4) is the seventh reference value, and the state in which the number of raw-material gas flowmeters (FI) showing an actual measurement value equal to or higher than the seventh reference value exceeded a majority of the total number of raw-material gas flowmeters (FI).

(d2) Low raw-material gas flow rate: Prevention of explosion from a gas mixture formation

The raw-material gas flow rate is lower than the normal operation value. The maximum value of the raw-material gas flow rate that satisfies Eq. (4) is the eighth reference value, and the state in which the number of raw-material gas flowmeters (FI) showing a measured value equal to or lower than the eighth reference value exceeds a majority of the total number of raw-material gas flowmeters (FI).

(e1) High oxygen-containing gas flow rate: Prevention of explosion from a gas mixture formation

The oxygen-containing gas flow rate rises above the normal operation value. The minimum value of the oxygen-containing gas flow rate that satisfies Eq. (4) is the ninth reference value, and the state in which the number of oxygen-containing gas flowmeters (FI) showing a measured value equal to or higher than the ninth reference value exceeds a majority of the total number of oxygen-containing gas flowmeters (FI).

(e2) Low oxygen-containing gas flow rate: Prevention of catalyst reductive degradation

The oxygen-containing gas flow rate is lower than the normal operation value. The highest value of the oxygen-containing gas flow rate that satisfies Eq. (4) is the tenth reference value, and the state in which the number of oxygen-containing gas flowmeters (FI) showing actually measured values equal to or lower than the tenth reference value exceeds a majority of the total number of oxygen-containing gas flowmeters (FI).

Figure 4 displays a flowchart of the emergency shutdown in states (a1) and (a2). The redundant thermometer system monitored the temperature at the installation site continuously until the end of the reaction. From the figure, the temperature was judged reliable, when the majority decision method exceeded the upper-temperature threshold (1) and did not enter the yellow zone. When threshold (1) crossed the yellow zone, feedback and/or feedforward control was applied in the direction of the decreasing temperature. The temperature increased further regardless of the imposed control. When its level has been determined to be reliable with the majority decision method exceeding the upper-temperature threshold (2) and entering the red zone, the emergency shutdown was activated. Herein, the upper-limit threshold (2) was determined as the first reference value in state (a1).

Similarly, the redundant thermometer system could be used to judge whether the temperature was determined reliable by the majority decision method exceeding the lower temperature threshold (1) but not entering the yellow zone. If it has crossed the yellow zone, feedback and/or feed forward control was applied in the direction of the increasing temperature. Even with the imposed control, the temperature decrease further. When the temperature level has been determined to be reliable by the majority decision method exceeding the lower temperature threshold (2) and entering the red zone, the emergency shut down was activated. Here, the lower limit threshold (2) was determined as the second reference value in state (a2).

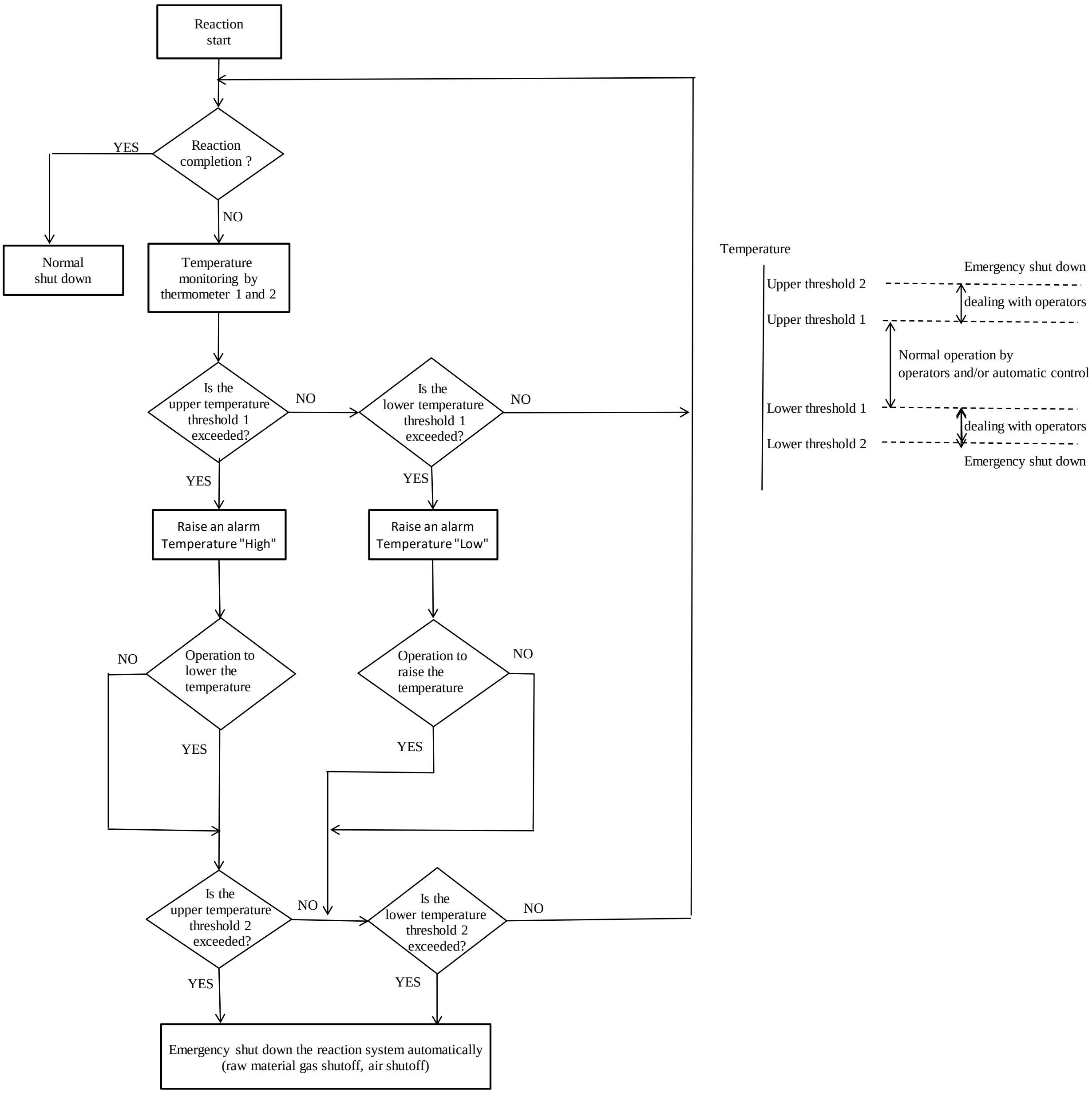

Fig. 4. Emergency shutdown flowchart for temperature.

Figure 5 shows a flowchart of the emergency shutdown scheme in state (b). The redundant pressure gauge system monitored the pressure at the installation site continuously until the end of the reaction. In the figure, the pressure was judged as reliable, when the majority decision method exceeded the upper pressure threshold 1 but did not cross the yellow zone. It the case it entered the yellow zone, feedback or feed forward control was applied in the direction of the decreasing pressure. Even with the imposed control, the pressure rose steadily. When the pressure has been determined as reliable with the majority decision method exceeding the upper pressure threshold (2) and entering the red zone, the emergency shutdown was activated. Herein, the upper-limit threshold (2) was determined as the third reference value in state (b).

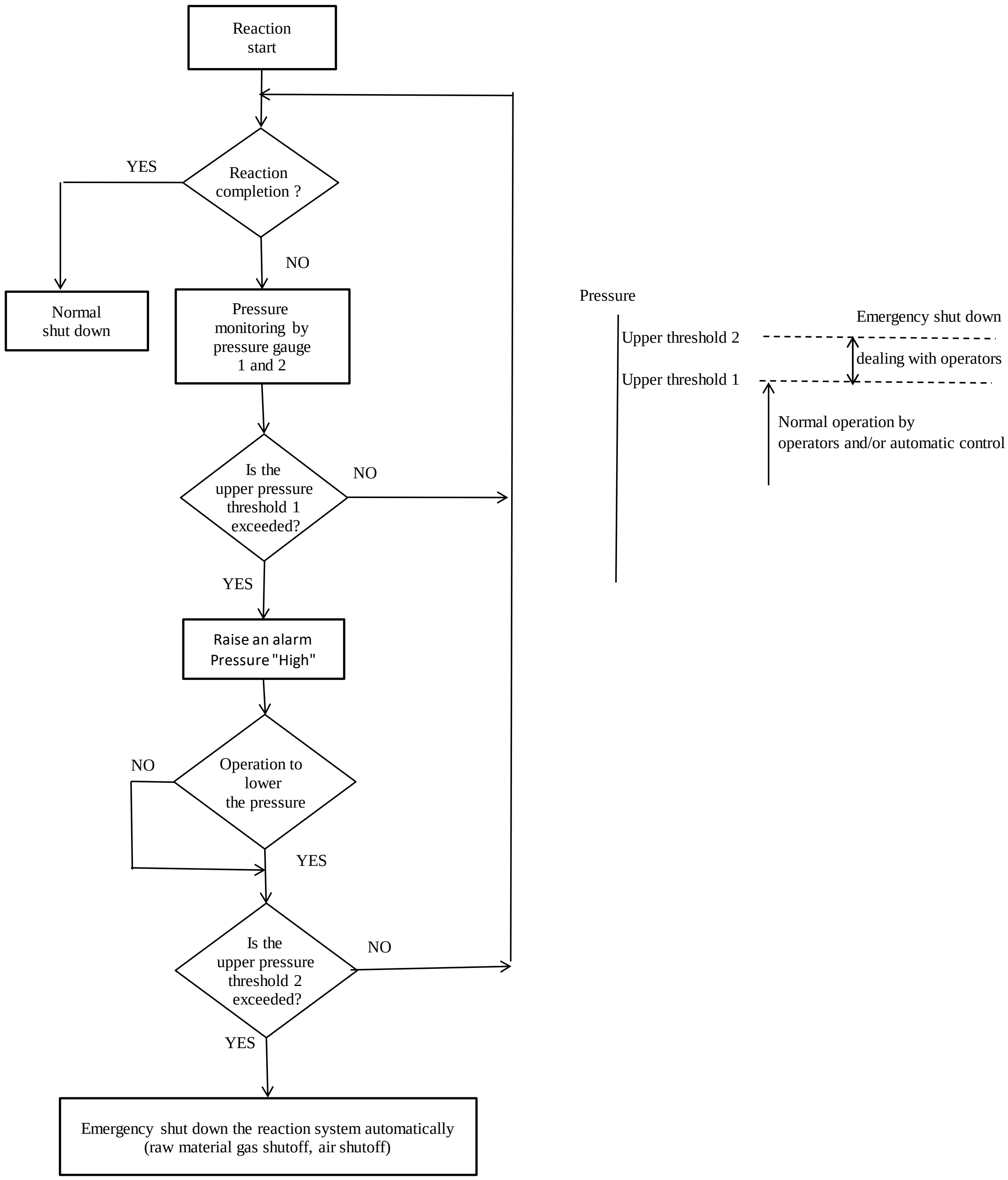

Fig. 5. Emergency shutdown flowchart for pressure.

4.4. Operation upon error detection

When any of the aforementioned instruments of abnormality detection has detected an abnormality, the reaction system was shut down, where all feed gases to the reactor were shut off by closing the control valves (CVs) and the gas shut-off valves, that is, the supply of the raw-material gas and the oxygen-containing gas to the reactor was cut. This was because it is preferable to place a double valve by installing a shut-off valve to prevent leakage by assuming that such leakage would occur in the CVs. Moreover, it was important to secure the destination of the gas flowing out of the reactor and prevent the reactor from being pressurized and destroyed. Typically, the gas flowed out of the reactor in the order: reactor → gas cooling tower → absorption tower → waste gas incineration facility → atmosphere. During an emergency shutdown, the shut-off valve was automatically operated, and the order became: reactor → gas cooling tower → waste gas incinerator → atmosphere. Note that the connection with the absorption tower has been removed. When shared in the presence of several reactors, the absorption tower to which the normal reaction gas was connected would not be put into the unsteady gas. Although the purge of the gas in the reactor with the inert gas was not essential, the reactive gas could be expelled by the inert gas to prevent the performance of the fluidized bed catalyst from deteriorating at high temperatures under the reaction gas atmosphere. When the reactor was not purged with the inert gas, the latter would acquire an appropriate flow rate that does not produce a negative pressure, as a countermeasure to the negative pressure of the reactor experiencing a decrease in temperature. The commonly used inert gas is nitrogen. Moreover, the coolant supply to the cooling coils was maintained.

It is known from the characteristics of the gas-phase fluidized bed reaction that the process value of the FBRS to be studied moves in the direction of improvement without time delay when the abovementioned emergency shutdown is activated, which is further verified from the behavior of the actual plant in the operation of ESD, including the high decreases in the temperature, pressure, and oxygen concentration. The lower temperature drops further but moves in a direction avoiding the gas-phase explosion. When ESD is activated, the occurrence of disasters is immediately suppressed.

5. Case study: Propylene ammoxidation reaction

This section discusses the propylene ammoxidation reactions in a vertical cylindrical fluidized bed reactor. For these reactions, the feed gases are propylene and ammonia, while the oxygen-containing gas is air.

5.1. Simulation methods

(1) Process flow

As described in Fig. 6, the reaction gas leaving the reactor was cooled by the reactor-effluent cooler and quench column, and then supplied to the absorber. The reaction gas analyzers (DI1 and DI2) were installed between the quench column and the absorber.

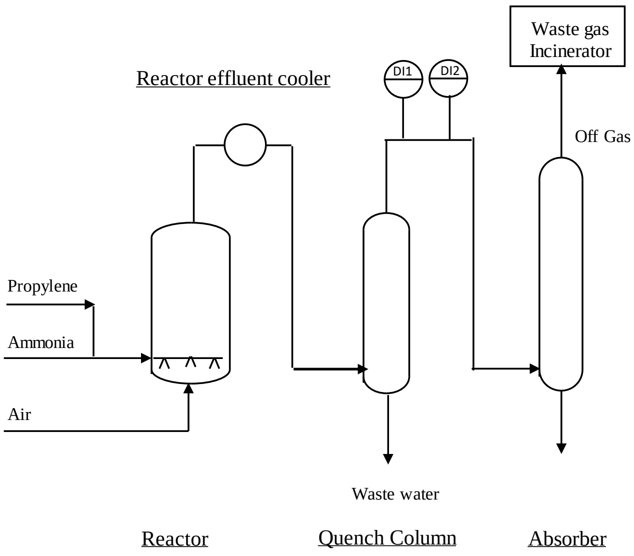

Fig. 6. Ammoxidation of propylene.

The type of reactor depicted in the above figure is the same as in Fig. 1, but with the thermometer, pressure gauge, and flow meter being redundant. Table 1 shows the design temperature and pressure of each equipment.

Table 1 Equipment design.

Parts	Design parameters	Value
Reactor	Temperature	500 °C
	Pressure	0.20 MPaG
Quench	Temperature	200 °C
column	Pressure	0.20 MPaG
Absorber	Temperature	200 °C
	Pressure	0.20 MPaG

(2) Losses

Process loss was determined by summing the amount of each loss. The losses considered here include the construction costs from rebuilding damaged equipment, catalyst purchasing costs, opportunity losses, and reaction losses from operating conditions.

The construction cost of the equipment was calculated as follows. It was first divided into direct costs (equipment purchase, installation work, civil engineering work, piping work, instrumentation work, and electrical work) and indirect costs (design supervision, legal proceedings, and contingency) (Peters, 2004). The construction cost was then correlated with the equipment purchase cost (AACE International, 2011). Assuming that the relation was obtained from the construction results of a Japanese petrochemical plant, the construction cost *TC* could be estimated from the equipment purchase cost *EC* following:

$$\mathrm{TC} = \mathrm{EC} \times 4. (5)$$

In this adaptation example, the purchase cost of the equipment is 650 Myen for a reactor, 150 Myen for a quench column, and 300 Myen for an absorber. Applying Eq. (5), the total amount of installation work from the purchase of the reactor is 650 × 4 = 2,600 Myen. The cost for the construction of the quench column and absorber can be calculated similarly. The total cost of the fluidized bed catalyst is 800 Myen. The opportunity loss is calculated as (marginal profit) × (production amount). Herein, the marginal profit is 30,000 yen/t and the production amount is 300 t/D × (the number of days of suspension D). The reaction loss due to the deviation of the operating conditions was obtained in advance as the relation between the operating condition values and the reaction results, whereas the loss from the reaction result at the appropriate operating condition value was regarded as the loss.

Accordingly, $f(x;\ \mu,\sigma)$ was not considered in Eqs. (1) and (2) for calculating the expected value of the loss function. Moreover, the mode of variation of the process value was simplified because it changed due to the variation in the process value.

(3) ESD introduction cost

The ESD introduction costs mainly accounted for the costs of redundancy of instruments (thermometer, pressure gauge, and flow meter), installation of reaction gas analyzers, installation of shut-off valves, installation of cables, and software construction. It was assumed that the work can be done during the regular repair period, while it was considered that there will be no opportunity loss due to the work. The cost of work is 190 Myen for engineering, purchase, and construction.

5.2. Simulation of reactor pressures

The relation between the reactor pressure and process loss is shown in Fig. 7, where the blue and red lines respectively indicate "with ESD" and "without ESD." The normal operating pressure was 0.065 MPaG. In the area having a higher-than-the-normal operating pressure, ESD was operated with 0.19 MPaG, which is equivalent to the loss "with ESD" and "without ESD." Threshold (2) was 0.19 MPaG. The emergency shutdown by ESD below 0.19 MPaG was due to malfunction, and the loss amount was 63 Myen (30,000 yen/t × 300 t/D × 7D). When the pressure rose above the normal operating pressure, the rate of oxidation of propylene increased, elevating the loss. The dramatic increase in the loss amount at 0.3 MPaG was due to the destruction of the reactor and quench column. The loss amount was 7,285 Myen (reconstruction of a reactor and a quench column, catalyst procurement, and one-year opportunity loss).

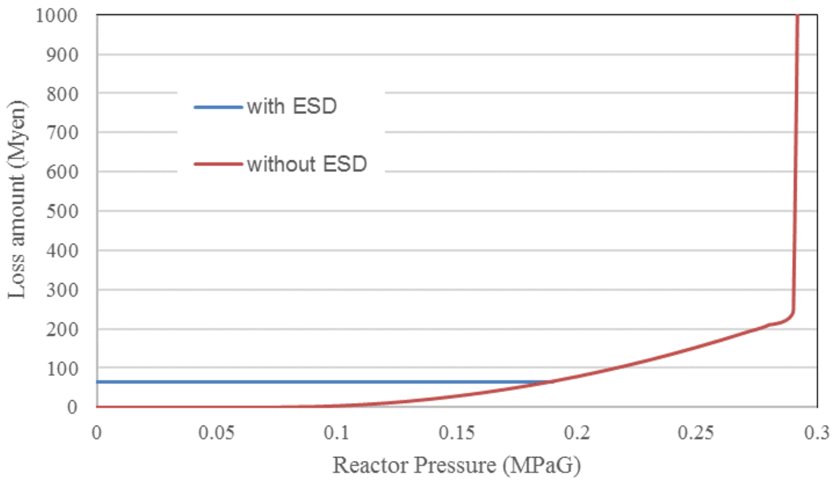

Fig. 7. Relation between reactor pressure and loss amount. The blue and red lines respectively show the loss "with ESD" and "without ESD."

Under the conditions described in Table 2, a simulation was performed assuming that (i) the valve at the exit of the quench column is closed and the reaction gas is not discharged from the reactor, (ii) the gas supply to the reactor is continued, and (iii) the gas inside the device is an ideal gas. Subsequently, the pressure rise was calculated under a fixed volume and a fixed temperature. Figure 8 shows the pressure change in the reactor from the closure of the valve at the exit of the quench column, with the closure point of the valve at the exit of the quench column at 0 s. The time for the reactor pressure to reach the upper threshold from the steady-state value was in the order of tens of seconds and found to be relatively fast. When the pressure in the reactor measured by the redundant pressure gauge PI reached 0.19 MPaG and state (b), the emergency shutdown was activated, the supply of the raw-material gas and air to the reactor was shut off, and the vent valve was opened. Due to the ESD operation, the reactor pressure immediately dropped, not exceeding 0.19 MPaG.

Table 2 Simulation conditions.

Simulation parameters	Units	Value
Propylene flow rate	Nm^3/h	6700
Ammonia flow rate	Nm^3/h	7370
Air flow rate	Nm^3/h	57620
Reaction temperature	°C	440
Reaction pressure	MPaG	0.065
Oxygen concentration	vol.% dry	2.5
Reactor volume	m^3	1300
Piping volume	m^3	30
Quench volume	m^3	250
Catalyst mass	t	160
Reactor mass	t	360
Propylene reaction rate constant	$10^3/h$	6.0
Catalyst heat capacity	kJ/kg °C	0.544
Reactor heat capacity	kJ/kg °C	0.460
Reaction gas heat capacity	kJ/Nm^3 °C	1.61

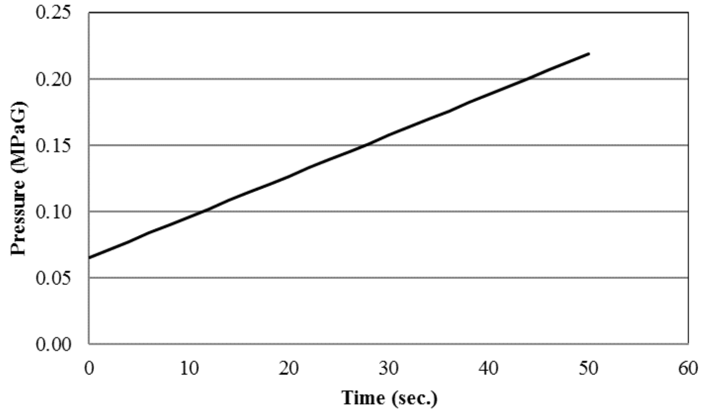

Fig. 8. Simulation of pressure changes in the reactor when the valve at the quench column exit is closed.

The maximum loss due to the pressure rise was estimated at 7,285 Myen. The probability of generating the loss was not evaluated. As shown in Fig. 8, it is difficult to make the operators and/or the technical system judge the situation and deal with it in a few tens of seconds to a few minutes. Moreover, from a crisis management viewpoint, it is significant that the ESD does not generate loss. Therefore, investment in the ESD is considered to be feasible. Note that Fig. 7 is a relation diagram showing the complete depreciation of the ESD investment.

5.3. Simulation of reactor temperature

The relation between the reactor temperature and loss is shown in Fig. 9, with the blue and red lines indicating "with ESD" and "without ESD." Here, the normal operating temperature is 440 °C. The high and low-temperature values of threshold (2) for activating the ESD were 500°C and 380°C. The emergency shutdown by ESD from 380°C to 500°C was due to a malfunction, which is equivalent to the loss amount of 63 Myen. On one hand, the increase in temperature from the normal operating temperature resulted in an increased loss, because the complete oxidation of propylene and product gas proceeded to increase the amount of CO_2. Further, the rapid increase in the loss amount at 520°C was attributed to catalyst degradation (800 Myen). At 560°C, a reactor was rebuilt, with a one-year opportunity loss adding up to 6685 Myen. On the other hand, the decrease in temperature from the normal temperature elevated the loss attributed to reductions in the catalyst activity and in the conversion of propylene. An explosive gas mixture was formed at 360°C leading to an explosion, where the subsequent loss amounts to 8285 Myen for rebuilding the reactor, quench column, and absorber, reloading of catalyst, and opportunity loss for one year.

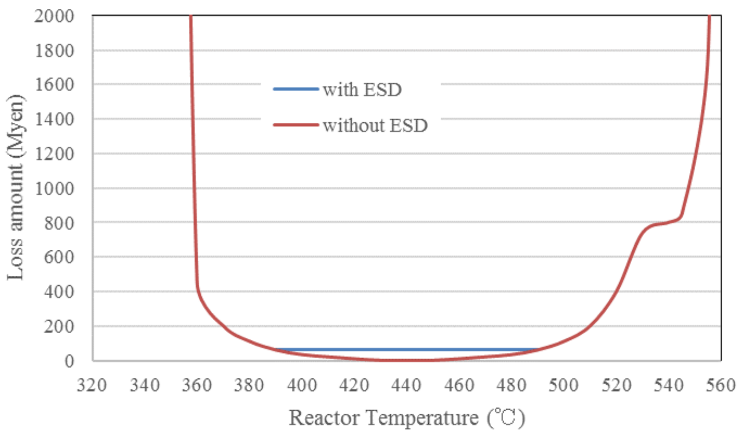

Fig. 9. Relation between reactor temperature and loss amount. The blue and red lines show the loss "with ESD" and "without ESD."

Under the conditions described in Table 2, the reaction temperature was simulated assuming that the coolant in the cooling coils was lost while maintaining the flow rates of the raw-material gas and air. Further, heat removal by the cooling coils dropped to zero. The reaction heat that cannot be removed increased the temperatures of the reaction gas, the reactor body, and the catalyst, which validates the relationship

(Increased reaction heat capacity)=(Increased reaction gas heat capacity)+(Increased reactor body heat capacity)+(Increased catalyst heat capacity), which was used to determine the temperatures of the reaction gas, reactor body, and catalyst temperature. Here, the temperatures of the three elements were the same assuming they are in equilibrium. Further, the change in catalyst activity due to temperature change was not taken into consideration. Figure 10 depicts the temperature change in the reactor from the coolant loss of the cooling coils at 0 min. The time for the reaction temperature to reach the upper-limit threshold from the steady-state value was from several minutes to several tens of minutes and was found to be relatively slow. When the temperature in the reactor measured by the redundant thermometer reached 500°C and state (a1), the emergency shutdown was activated, shutting off the supply of the raw-material gas and air to the reactor. Due to the ESD operation, the reactor temperature dropped immediately, not exceeding 500°C.

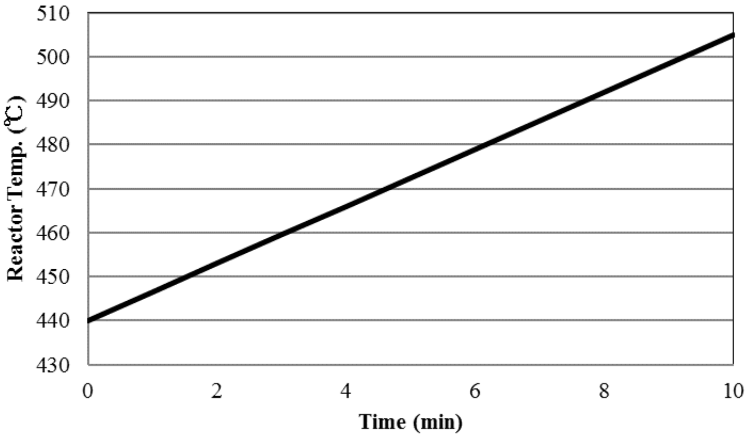

Fig. 10. Simulation of reaction temperature assuming loss of coolant at cooling coils.

Similarly, under the conditions described in Table 2, a simulation was conducted on the assumption of a decrease in the propylene supply. The transition of the reaction temperature in the cases where the propylene flow rate decreased by 1% per minute (solid line) and 5% per minute (dashed line) is shown in Fig. 11. Here, the time for the reaction temperature to reach the lower threshold from the steady-state value was from several minutes to several tens of minutes and was found to be relatively slow. When the temperature in the reactor measured by the redundant thermometer reached 380°C and state (a2), the emergency shutdown was activated to shut off the supply of the raw-material gas and air to the reactor. The formation of the explosive gas mixture was immediately prevented by the ESD operation blocking the raw-material gas and air.

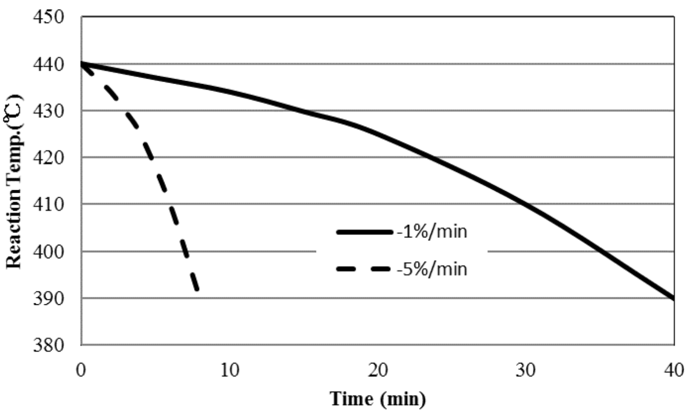

Fig. 11. Simulation of reaction temperature in the case where the propylene flow rate decreases by 1% (solid line) and 5% (dotted line) per minute.

5.4. Simulation of oxygen concentration in the reaction gas

The relation between the oxygen concentration and the loss is shown in Fig. 12, where the blue and red lines indicate "with ESD" and "without ESD." The normal oxygen concentration was 2.5 vol.%. The high- and low-concentration values of threshold (2) to activate ESD were 7vol.% and 0vol.%, respectively. Here, the negative value of the oxygen concentration is a theoretical value obtained by quantifying the oxygen deficiency by stoichiometry calculation. The emergency shutdown by ESD from 0vol.% to 7vol.% was due to a malfunction, which equates to the loss amount of 63 Myen. The reason for the rapid increase in the loss at 11 vol.% is attributed to the formation of the explosive gas mixture that led to an explosion, resulting in the rebuilding of the reactor and quench column, catalyst loss, and one-year opportunity loss (7285 Myen). At 0 vol.%, the loss due to the over-reduction of the catalyst was 800 Myen.

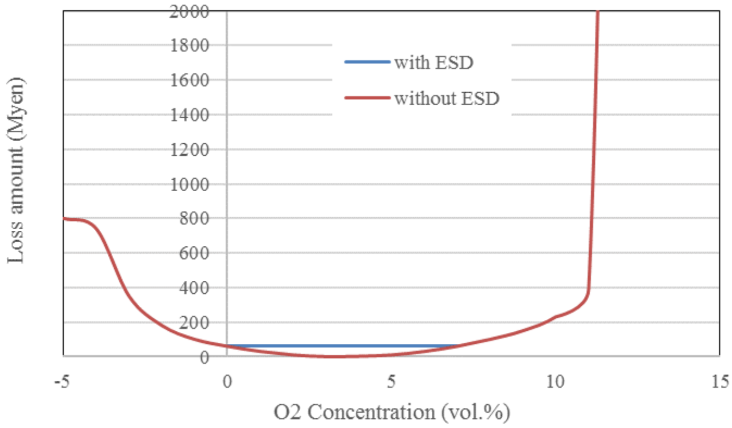

Fig. 12. Relation between oxygen concentration for the reaction gas and loss amount. The blue and red lines show the loss "with ESD" and "without ESD."

Furthermore, under the conditions described in Table 2, a simulation was performed assuming an increase in oxygen concentration by increasing the airflow rate with the raw-material gas flow rate being constant. Moreover, the increase in the airflow rate was assumed to not affect on the reaction, and that the oxygen level simply increased. The transition of the oxygen concentration in the cases where the airflow rate increased by 5% per minute (solid line) and 10% per minute (dashed line) is shown in Fig. 13. From the figure, the time when the oxygen concentration reached the upper threshold from the steady-state value ranged from several minutes to several tens of minutes, which is relatively slow. When the oxygen concentration measured by the redundant reaction gas analyzer DI reached 7 vol.% and state (c1), the emergency shutdown was activated to shut off the supply of the raw-material gas and air to the reactor. Due to the ESD operation, the oxygen concentration dropped immediately, not exceeding 7 vol%.

5.5 Case study results

The following can be generalized from the results of the case study:

(1) Loss increases when the operating value deviates from the normal value. It increases stepwise when the operating value at the limit (critical value) is exceeded, mainly because of the emergence of an irreversible phenomenon, i.e., destruction of the device.

(2) There is a specific time range when the normal operating value reaches the critical value. The time

when the operator can deal with the abnormality is limited. Proper operating conditions monitoring by ESD is effective.

(3) Considering the amount of loss, investing in ESD is fully profitable.

(4) The estimation of the probability of occurrence is a future issue. Although the amount of loss can be directly calculated, it is difficult to calculate the associated risk as there is no probability of occurrence.

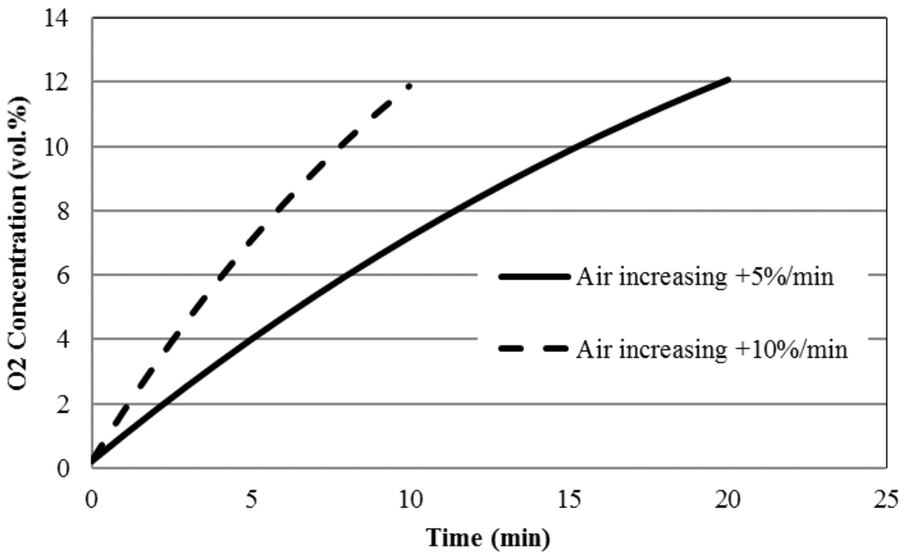

Fig. 13. Simulation of oxygen concentration in the case where the airflow rate increases by 5% (solid line) and 10% (dotted line) per minute.

6. Discussion

The FBRS possesses certain advantages and has been proven suitable for usage in various commercial-scale chemical plants. As mentioned earlier, the focus of the previous various studies was mainly on enhancing the reaction yield by improving the reaction catalyst and equipment. However, it is typically difficult to evaluate the possibility of risk in an FBRS until an accident occurs, due to the implied difficulty in understanding the accident occurrence mechanism. Considering that risks arise from nonlinear interactions between failures and normal operating fluctuations, it is further difficult to think of ways to reduce risks.

The above problems can be dealt with by enhancing the completeness of risk identification. Thus, accident case studies, studies of process and equipment characteristics, and scenarios leading up to an accident are avenues to be evaluated, keeping in mind the need for risk identification. Furthermore, it is possible to add evaluations for natural disasters and terrorist attacks to enhance risk identification. However, even with all these considerations, there is no guarantee that a complete risk identification will be attained.

Operator intervention often depends on a primary protective measure without the full assessment of the possibility of avoiding abnormal phenomena in risk scenarios, which can cause an accident. For example, it is assumed that a reaction temperature rises from a normal operating value and indicates a temperature that is unlikely to be considered from the fluctuation range under a normal operation. The action of the operator who has detected this abnormality is to trust the high-temperature reading from the thermometer and regard it as a real, abnormal situation from where to start the solution, or a case in which the number of occurrences and/or experience of the occurrence is small, where additional information await for confirmation. The reliability of the system to detect abnormalities in the FBRS delays human reaction time. Getty et al. (1995) defined the percentage of positive responses that are actually positive as a positive predictive value (PPV). The low PPV impact of the alarm system is the delay in the human response time, particularly when the PPV falls below 0.25. It can be imagined that more experienced operators are susceptible to the effects of PPV, which may slow down the abnormal coping reaction. Manual operations often have many loopholes to cause an operator error, which has been dealt with process automation to improve plant operation safety. However, it has also been shown that merely replacing the manual control actions with automatic control actions does not readily reduce the risk of accidents (Kletz et al., 1995; HSE, 2003). Ogle et al. (2008) reported the relationship between the complexity of automation and operator error, demonstrating that operators are at the center of the control missions. To intervene and mitigate the process failures effectively, operators must have the necessary information to diagnose the problem, must receive the information within sufficient time to respond, and must possess the appropriate skills and knowledge to perform the corrective actions.

If an operator's intervention is the main protective measure to correct an abnormal phenomenon, it is conceivable to continue implementing the measures that exceed the threshold (2). From the valid perspective of an operator, there is reluctance in wanting to shut down the plant and try to return to normality. Furthermore, as described above, there may be a delay in handling the abnormality. Equipment damage, which can be defined as the destruction or thermal damage of equipment due to fire/explosion, cost of reconstruction, and loss of opportunity, is inevitable in these scenarios. The application example presented in this study calculated the loss that could be recovered to several billion to ten billion yen. As a practical effect, the loss of trust emanating from the society could also be expected.

The significance of ESD in this research encompasses several avenues towards solving issues related to the completeness of risk identification and plant operator errors. Even if the cause is not identified, it is possible to prevent an accident by automatically stopping the plant operation upon detection of an abnormality. As suggested by the application example above, an ESD investment is several hundred million yen, which is a feasible and reasonable amount relative to the loss. One important principle in the use of ESD is the reduction in the loss associated with the operation. Moreover, the ESD should be properly operated to avoid system inactivation and malfunction, which is an important issue discussed in this study.

The future directions of this study may include:

(1) Estimation of probability density function representing process value fluctuation

The causes of the process value fluctuation include operation errors, equipment failures, natural disasters, and intentional destructions, whereas the situation of the process value fluctuation changes with the type and degree of the causes. Although it is possible to estimate the probability density function for each cause, a combination of these causes is a problematic case that requires, say, the setting of several preconditions, and has a room for further study. Thus, the assessment with the greatest risk will be made rather than using the assumed probability, as shown in the application example in the many scenes in industries, where an evaluation is performed with the amount of loss with the probability of occurrence not taken into consideration. It is believed that estimating the probability density function leads to the investigation of the generation process of the cause affecting the fluctuation of the process value and protective analysis and contributes to the improvement in process stability.

(2) Coverage of abnormality detection

The redundancy of the instruments improves the reliability of the measurement and reduces the risk of malfunction. Similarly, the redundancy reduces the risk of inactivation, which is bound to remain in existence, where no instruments are installed to detect an abnormality. For example, although there is a local abnormal heat generation (a hot spot), the thermometer lacks the ability to detect such an abnormality as it is not installed in the hot spot vicinity. Thus, it can be suggested to increase the number of thermometers, but would only be a desirable measure upon consideration of the completeness and economy of the measurement. It is necessary to develop and introduce a measurement system that takes into consideration the uniqueness of the technical system, including the mechanical characteristics of the fluidized bed reactor and catalyst fluidization, in each process.

7. Conclusions

An FBRS is practical in many industrial applications. In the prevention of accidents arising from the operation of the system, the ESD is effective as it shuts down the reaction system at the time of abnormality and isolates the flammable gas. However, there is also an inactivation problem created with the ESD use, where an emergency shutdown is not performed even though the operating condition of the reaction system is abnormal. In the event of a malfunction as well, the emergency shutdown is performed even though the operating condition of the reaction system is normal. In this study, these problems were solved with the monitoring of essential parameters as the trigger levels were set, reflecting the uniqueness of an FBRS in introducing ESD into a plant system. Moreover, parameters were identified by analyzing the scenario leading to an accident. The trigger level was determined as the point at which the loss is smaller in the presence of ESD, based on the comparison of the loss function in the presence and absence of ESD. Furthermore, an application example was shown, that of the ammoxidation process of propylene, which revealed the possibility of preventing a loss of 8 billion yen from accidents related to plant operations, with an investment of just 200 million yen for the emergency system shutdown.

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Conflict of interest

The authors declare no conflicts of interest.

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Figure captions

Fig. 1. Typical fluidized bed reactor apparatus. Fluidized bed reactor (1), oxygen-containing gas piping (2), sparger (3), raw-material gas piping (4), sparger nozzles (5), cooling coils (6), cyclones (7), reactor exit piping (8), dense phase (9a), dilute phase (9b), flow rate sensor (10, 11, 12), oxygen-containing gas (A), raw-material gas (B, D), and reaction gas (C).

Fig. 2. Typical loss functions of "with ESD" and "without ESD." The blue and red lines respectively show the loss function "with ESD" and "without ESD."

Fig. 3. Analysis chart of the scenario leading to an accident.

Fig. 4. Emergency shutdown flowchart for temperature.

Fig. 5. Emergency shutdown flowchart for pressure.

Fig. 6. Ammoxidation of propylene.

Fig. 7. Relation between reactor pressure and loss amount. The blue and red lines respectively show the loss "with ESD" and "without ESD."

Fig. 8. Simulation of pressure changes in the reactor when the valve at the quench column exit is closed.

Fig. 9. Relation between reactor temperature and loss amount. The blue and red lines show the loss "with ESD" and "without ESD."

Fig. 10. Simulation of reaction temperature assuming loss of coolant at cooling coils.

Fig. 11. Simulation of reaction temperature in the case where the propylene flow rate decreases by 1% (solid line) and 5% (dotted line) per minute.

Fig. 12. Relation between oxygen concentration for the reaction gas and loss amount. The blue and red lines show the loss "with ESD" and "without ESD."

Fig. 13. Simulation of oxygen concentration in the case where the airflow rate increases by 5% (solid line) and 10% (dotted line) per minute.

Table captions

Table 1
Equipment design.

Table 2
Simulation conditions.