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Risk Analysis on Out-of-control Burst of Jacketed Reactor Based on Bayesian Network

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Abstract. Reactors are widely used in chemical process, but corresponding accidents occur one after another. In this paper, the process flow diagram of a typical jacketed reactor is taken as an example to analyse the causes of jacketed reactor out-of-control burst. The basic events that cause reaction out of control in reactor are found by establishing the fault tree (FTA). On the basis of the fault tree, the risk of jacketed reactor out-of-control burst is analysed by developing Bayesian network using AgenaRisk program. When jacketed reactor runs with one year, two years and three years, the probability of jacketed reactor out-of-control burst is 0.002%, 0.035% and 0.155%, respectively. With the in-service time extending, the probability of jacketed reactor out-of-control burst increases drastically. After Bayesian reasoning, it is found that the posterior probability of pressure control valve and discharge pump is the largest among all basic events, and the posterior probability is more important than the prior probability in comparing the influence degree which causes jacketed reactor out-of-control burst. This paper assumes that pressure control valve and discharge pump are repaired every three months, six months and one year, and the probability of jacketed reactor out-of-control burst with one, two and three years in-service is calculated, respectively. The results show that compared with the risk of no maintenance, the risk after maintenance drops significantly, and the maintenance period is more shorter, the probability of jacketed reactor out-of-control burst is more lower.

1. Introduction

With the development of chemical, pharmaceutical and food industries, reactors are widely used as typical reaction devices. The jacketed reactor is able to either cool or heat the liquid inside the container compared to the conventional reactors. In order to manipulate the heat transfer, maximum flow is maintained in a circulation loop, while the jacket temperature is adjusted by bringing in and letting out coolant[1], so that the reaction rate can be increased or decreased at a certain range of temperature and pressure. In order to maintain the safe operation of production process, it is necessary to control the temperature, flow, pressure and other parameters of reactors. Once these signals are abnormal, emergency measures should be taken quickly, otherwise there will be an unexpected accident. For example, in October 2011, three people were killed and three injured in an explosion at a workshop in Zhejiang Province, China. The direct cause of the accident was the uncontrolled temperature of the jacketed reactor, which caused pressure in the reactor to rise dramatically and material to boil and flush the feed hole cover. And then methanol vapor and air were mixed to form an explosive gas mixture, while explosion finally occurred due to the spark generated by the operation of non-explosion-proof electrical equipment in the workshop. Therefore, it is necessary to analyse the risk of jacketed reactor.



Many authors have studied different techniques to analyse the risk of potential accident scenarios[2], but common analysis methods such as fault tree, event tree, bow-tie diagram, Hazard and Operability Analysis(HAZOP) and Analytic Hierarchy Process(AHP) have limitations in the case of uncertain data, whose dependencies of the basic events can not be recognized and the risk can not be updated. At present, Bayesian network has been widely used in various fields of petrochemical production. For example, Khakzad et al.[3] analysed the domino effect of chemical infrastructures with Markov chain and Bayesian network; G.P. Haugom et al.[4] analysed the risk of hydrogen refuelling station with risk matrix and Bayesian network; GeunWoong Yun et al.[5] analysed the risk of LNG importation terminals with LOPA and Bayesian network. In Bayesian network, directed acyclic graphs and conditional probability tables(CPT) are indispensable parts. In directed acyclic graphs, each node is connected by an arrow. The node pointed by an arrow is called the child node, while the starting point of an arrow is called the parent node. The node without parent node is called the root node, while the node without child node is called the leaf node. The purpose of this paper is to analyse the risk of out-of-control burst of jacketed reactor using Bayesian network.

2. The process flow of jacketed reactor

Chemical reaction is carried out in the jacketed reactor. In order to control the temperature in reactor, there is a jacket with coolant or heat medium around the reactor. The reaction materials and catalyst are mixed before entering the reactor. The flow rate is controlled by the flow control system consisted of a flow transmitter (FT), a flow controller (FC) and a flow control valve (FCV). It is assumed that there is an exothermic reaction in the reactor, so the coolant is used in the jacket to take away the heat. The coolant enters the jacket through a pump (P1). The temperature control system based on cascade control consists of two temperature transmitters (TT1, TT2), two temperature controllers (TC1, TC2) and a temperature control valve (TCV). In order to maintain the safe operation of the reactor, in addition to the temperature control system, the pressure control system is also required to discharge excess pressure. The pressure control system consists of a pressure transmitter (PT), a pressure controller (PC) and a pressure control valve (PCV). The reacted material is pumped out of a pump (P2) and flows through a level control valve (PCV). The level control valve is controlled by a level transmitter (LT) and a level control valve (LCV) to control the flow rate of product. The process flow diagram of jacketed reactor is shown in **Figure 1**[1].

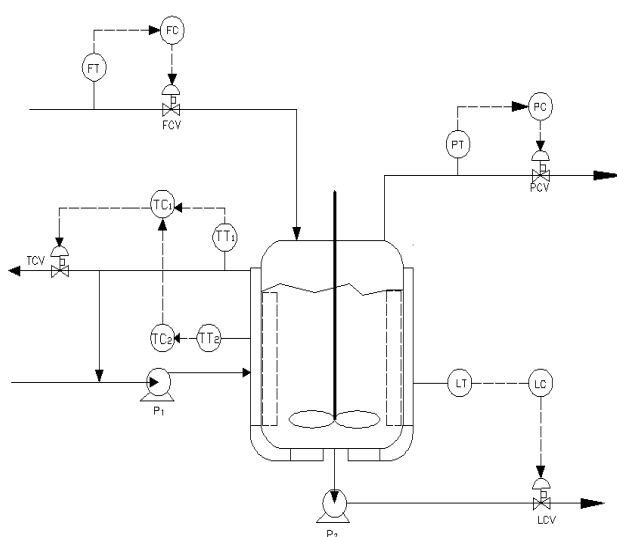


Figure 1. The process flow diagram of jacketed reactor.

3. Fault tree analysis of out-of-control burst of jacketed reactor

In this paper, the risk of out-of-control burst of jacketed reactor is considered in the case of failure of various types of instruments, valves and pumps. When the reactor is in normal operation, once the material is put in too fast, the reaction speed and temperature will increase, and the pressure will rise dramatically. At this time, relying on the control system can effectively prevent the occurrence of accidents. In this paper, the control system consists of three parts: The temperature control system monitors the temperature of the jacket and the reactor in real time, and adjusts the flow rate of the coolant accordingly to take away excess heat in the reactor; the pressure control system discharges excess pressure in real time to ensure that the reactor does not burst due to overpressure; the level control system flows out product in real time to ensure that the material will not be heated constantly to cause decomposition explosion. If the three systems fail at the same time and the material input is too fast, then the temperature inside the reactor may continue to rise and the pressure will not be released, causing a series of accidents. Out-of-control burst of jacketed reactor is taken as the top event. As shown in **Figure 2**, the fault tree is developed. The description of intermediate events is shown in **Table 1**. The failure rates are also provided in **Table 2** and these data originates from OREDA[7].

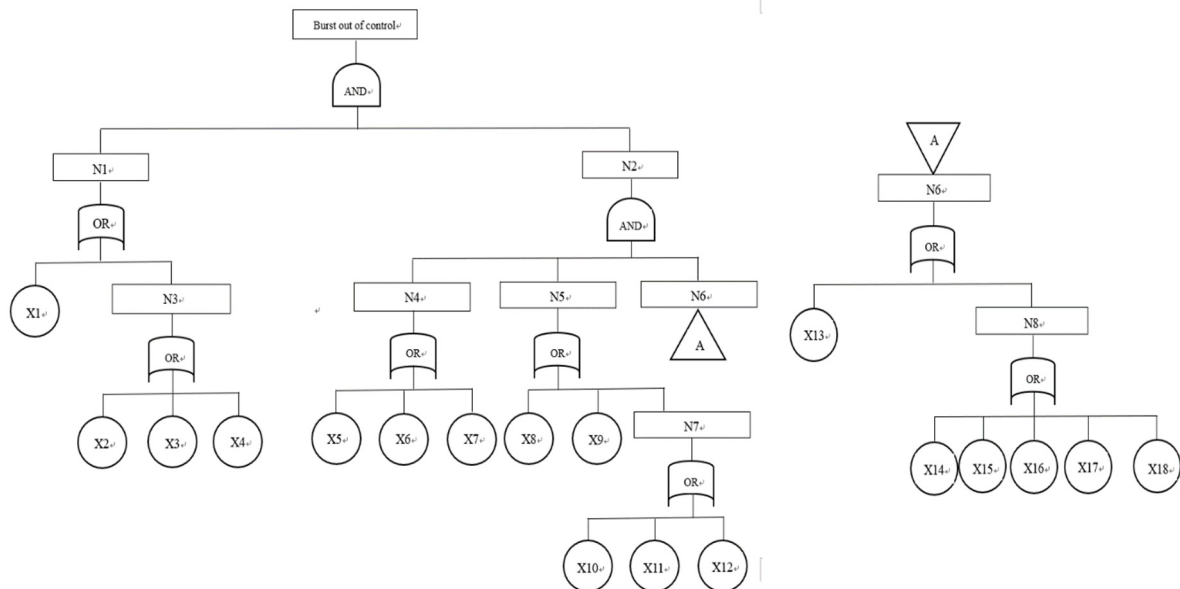


Figure 2. The fault tree of out-of-control burst of jacketed reactor.

Table1. The description of intermediate events.

Symbol	Description
N1	The feeding flow is too high
N2	Control system fail
N3	Flow control system fail
N4	Pressure control system fail
N5	Level control system fail
N6	Temperature control system fail
N7	Level control fail
N8	High temperature control fail

Table2. Component failure mode and failure rate data.

Event	Component	Failure mode	Failure rate			
			per 10 ⁶ hours	per year	per two years	per three years
X1	FT	High output(HIO)	0.68	0.0055	0.011	0.0165
X2	FT	Fail to function on demand (FTF)	2.65	0.0214	0.0428	0.0642
X3	FC	Fail to function on demand (FTF)	2.65	0.0214	0.0428	0.0642
X4	FCV	Fail to regulate (FTR)	0.55	0.0044	0.0088	0.0132
X5	PT	Fail to function on demand (FTF)	0.90	0.0073	0.0146	0.0219
X6	PC	Fail to function on demand (FTF)	0.90	0.0073	0.0146	0.0219
X7	PCV	Fail to open (FTO)	2.46	0.0198	0.0396	0.0594
X8	LT	Loo output (LOO)	0.46	0.0037	0.0074	0.0111
X9	P2	Spurious stop (UST)	5.69	0.0459	0.0918	0.1377
X10	LT	Fail to function on demand (FTF)	0.46	0.0037	0.0074	0.0111
X11	LC	Fail to function on demand (FTF)	0.46	0.0037	0.0074	0.0111
X12	LCV	Fail to open (FTO)	2.81	0.0227	0.0454	0.0681
X13	P1	Spurious stop (UST)	5.69	0.0459	0.0918	0.1377
X14	TT1	Fail to function on demand (FTF)	4.47	0.0360	0.072	0.108

X15	TC1	Fail to function on demand (FTF)	4.47	0.0360	0.072	0.108
X16	TCV	Spurious operation (SPO)	0.61	0.0049	0.0098	0.0147
X17	TT2	Fail to function on demand (FTF)	4.47	0.0360	0.072	0.108
X18	TC2	Fail to function on demand (FTF)	4.47	0.0360	0.072	0.108

4. Bayesian mode of out-of-control burst of jacketed reactor

This model (**Figure.3**) is created depending on the fault tree by using Agenarisk program[8]. The mapping algorithm of fault tree to Bayesian includes both graphic part and numerical part. In graphic mapping, the basic event, intermediate event, and top event in fault tree correspond to the root node, intermediate node and leaf node in Bayesian, respectively; in numerical mapping, the conditional probability table of Bayesian is based on the type of gate in fault tree[6]. Among them, the occurrence probability of the basic event correspond to the prior probability of the root node.

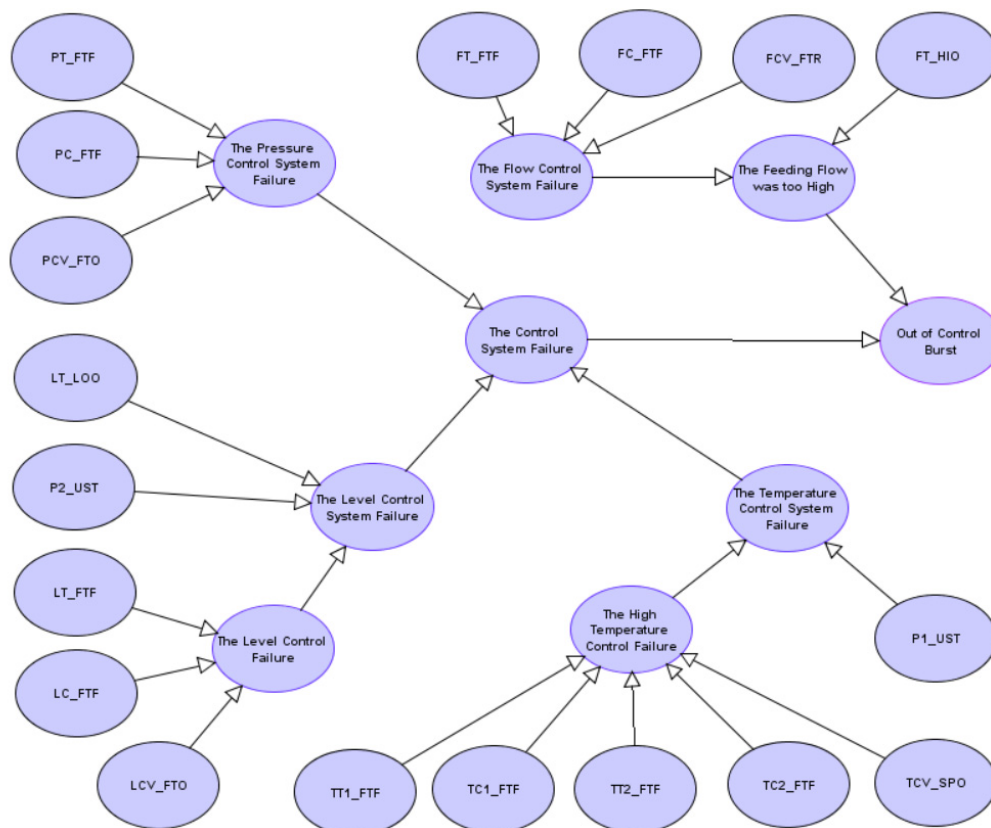


Figure 3. The Bayesian model of out-of-control burst of jacketed reactor.

5. Bayesian inference

After developing Bayesian model, the next step is Bayesian reasoning. Compared to the fault tree, Bayesian reasoning can update the probability of variables in real time[9]. After reasoning, the probability of out-of-control burst of jacketed reactor after one year, two years and three years in service is 0.002%, 0.035% and 0.155%, respectively. As can be seen from (a) in **Figure.4**, the probability of reactor uncontrolled burst increases dramatically with time. It is assumed that the probability of out-of-control burst of jacketed reactor is 100%, the posterior probability of each root node can be referred as shown in (b), (c) and (d), respectively. As can be seen from these figures, regardless of whether the scenario is running for one year, two years, three years or longer, the posterior probability of basic event causing out-of-control burst of jacketed reactor is greater than its prior probability. Moreover, the longer the in-service time is, the greater the posterior probability is, which means that as the in-service time passes, the impact of these basic events on out-of-control burst gradually increases, and the system becomes more dangerous. The posterior probability of an event with large prior probability is not necessarily large, therefore, the posterior probability is more important than the prior probability in considering the impact on the top event. After calculating, the posterior probability of X7 and X9 is the maximum. This paper proposes to shorten the maintenance cycle to reduce the risk of the system. However, considering the minimization of plant input, only the pressure control valve (X7) and discharge pump (X9) that have the greatest impact on out-of-control burst of jacketed reactor are considered[10].

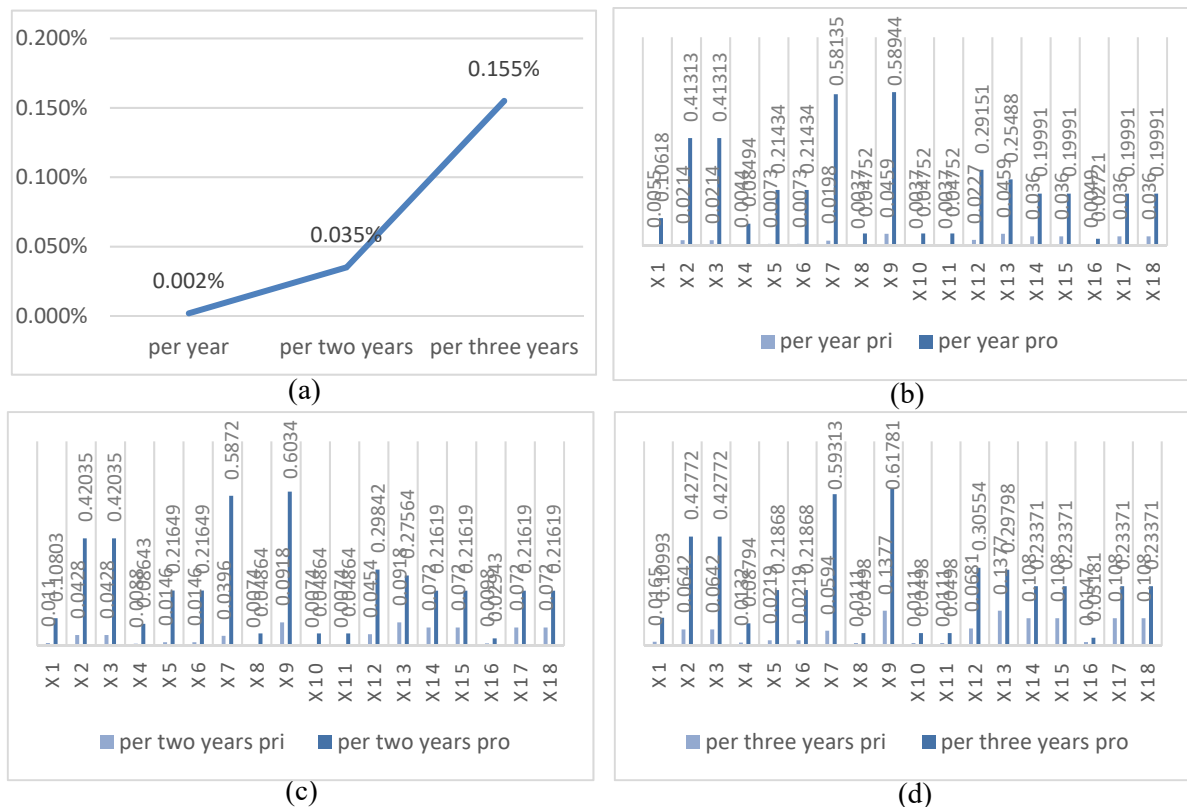


Figure 4. This figure includes four pictures. The probability of out-of-control burst of jacketed reactor with in-service time can be seen as (a). The posterior and prior probability of each root node with one year, two years and three years can be seen as (b), (c) and (d), respectively.

For the convenience of calculation, it is assumed that the failure probability of the pressure control valve and discharge pump should return to the initial state after each maintenance. This paper assumes that the maintenance period is three months, six months and one year. Then the failure probability of

the pressure control valve after each maintenance is 0.0049, 0.0099 and 0.0198, respectively. The failure probability of the discharge pump after each maintenance is 0.0115, 0.0229 and 0.0459, respectively. After calculation, the probability of out-of-control burst of jacketed reactor with one year, two years and three years is shown in **Table 3**.

Table 3. Failure probability after maintenance

Maintenance period	Service time		
	One year	Two years	Three years
Three months	0.001%	0.009%	0.036%
Six months	0.001%	0.011%	0.044%
One year	0.002%	0.018%	0.061%
None	0.002%	0.035%	0.155%

As can be seen from the longitudinal direction of the table, when this scenario is running for a certain period of time, the shorter the maintenance period for the pressure control valve and the discharge pump, the less likely the reactor will burst. From the aspect of the table, it can be seen that even if the maintenance period is short, the failure probability increases rapidly with the increase of the in-service time. Therefore, other safety measures should be taken while maintaining the inspection.

6. Conclusion

In this paper, the process flow diagram of a typical jacketed reactor is analysed, and then the fault tree is established. The Bayesian network is established on the basis of the fault tree, and the following conclusions are obtained through a series of Bayesian reasoning:

- When the jacketed reactor is in service, its failure probability increases rapidly with the passage of time. Therefore, it can not be judged to be safe under a short operating conditions, and the influence of time on the failure probability should also be considered.
- In considering the influence on the accident probability, the posterior probability of the basic event is often more convincing than the prior probability.
- Taking into account the economic benefits, this paper only considers the maintenance period of the pressure control valve and the discharge pump that have the greatest impact on uncontrolled burst of the jacketed reactor. It is found that the shorter the maintenance period is, the lower risk of uncontrolled burst is, demonstrating the utility for reducing the maintenance period of events with the greatest posterior probability.

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References

- [1] Couper, J.R., Penney, W.R., Fair, J.R. (2012) 3 - Process Control. In: Podani, J. (Eds.), Chemical Process Equipment (Third Edition). Butterworth-Heinemann Publishing, Boston. pp. 31-51.
- [2] Zarei, E., Azadeh, A., Aliabadi, M.M., Mohammadfam, I. (2017) Dynamic safety risk modelling of process systems using Bayesian network. *Process Safety Progress*, 36(4):399-407.
- [3] Khakzad, N. (2015) Application of dynamic Bayesian network to risk analysis of domino effects in chemical infrastructures. *Reliability Engineering & System Safety*, 138:263-272.
- [4] Haugom, G.P., Friis-Hansen, P. (2011) Risk modelling of a hydrogen refuelling station using Bayesian network. *International journal of hydrogen energy*, 36(3):2389-2397.

- [5] Yun, G., Rogers, W.J., Mannan, M.S. (2009) Risk assessment of LNG importation terminals using the Bayesian–LOPA methodology. *Journal of Loss Prevention in the Process Industries*, 22(1):91-96.
- [6] Khakzad, N., Khan, F., Amyotte, P. (2011) Safety analysis in process facilities: Comparison of fault tree and Bayesian network approaches. *Reliability Engineering & System Safety*, 96(8):925-932.
- [7] Veritas, D. N. (2002) OREDA-Offshore Reliability Data Handbook. Trondheim, Norway.
- [8] AgenaRisk Software Version 6.1. (2014) Bayesian network and simulation software for risk analysis and decision support. Available at <http://www.agenarisk.com>.
- [9] Bobbio, A., Portinale, L., Minichino, M., Ciancamerla, E. (2001) Improving the analysis of dependable systems by mapping fault trees into Bayesian networks. *Reliability Engineering & System Safety*, 71(3):249-260.
- [10] Barua, S. (2012) Dynamic operational risk assessment with Bayesian network (Doctoral dissertation, Texas A & M University).