A Process Simulation-Based Quantitative HAZOP Analysis Method

Jianlong Chen[1,2] Xiwei Liu[1,3] Sifeng Jing[1,3]
1. The State Key Laboratory of Management and Control for Complex Systems
Institute of Automation, Chinese Academy of Sciences
Beijing, China
2. School of Chemical Engineering and the Environment
Beijing Institute of Technology
Beijing, China
3. Institute of Smart Education Systems,
Qingdao Academy of Intelligent Industries
Qingdao, China
529157040@qq.com

Gang Xiong (Corresponding Author*)[4]

Xiuqin Shang[4] Changjian Cheng[5]
4. Cloud Computing Center, Chinese Academy of Sciences
Dongguan, China
5. Beijing Engineering Research Center for Intelligent Systems and Technology
Institute of Automation, Chinese Academy of Science
Beijing, China
Gang.Xiong@ia.ac.cn

***Abstract*—Hazard and operability (HAZOP) methodology is an important Process Hazard Analysis (PHA) technique for ensuring safety production in chemical industry. Due to the lacks of accuracy and reliability in manual HAZOP analysis, the quantitative HAZOP analysis has gained more and more attention. In this work, a process simulation-based HAZOP analysis method and its flow chart are proposed. And the proposed method is applied to a steam generation subsystem in an ethylene pyrolysis unit on a dynamic process simulation platform. All deviation parameters of system can be calculated and described quantitatively. The case study shows the proposed method is useful for the effective risk prevention and control measures in a chemical process.**

Keywords—Quantitative HAZOP; process simulation; Process Hazard Analysis

I. INTRODUCTION

1.1 Background

With the development of process industry, the probability of accidents is consistently growing during transportation, storage and production of hazardous chemicals. The Bhopal gas leakage accident in Dec, 1984, for example, occurred at the Union Carbide India Limited (UCIL) pesticide plant in Bhopal, Madhya Pradesh. Over 500,000 people were exposed to methyl isocyanate gas and other chemicals. The tragedy resulted in death toll of more than 2500 people. More than 200,000 people were injured in the accident. 670 thousands people were affected by the residual gas. Another catastrophe occurred in August 12. A series of explosions occurred at a hazardous chemicals storage station located in the Binhai New Area of Tianjin, China. The explosions caused 165 people killed and 798 people injured and 304 buildings, 12428 vehicles, 7533 containers damaged. By December 10, 2015, it has approved the direct economic loss of 6 billion 866 million yuan.

The Regulation of Ascertaining Administrative Liability in Safety Disasters and The Law of the People's Republic of China on Work Safety attached more importance on production safety of process industries. Hence engineers apply Process Hazards Analysis (PHA) to evaluate and improve the safety of plants. A wide range of methods such as Checklist, Fault Tree Analysis (FTA) and Hazard and Operability Analysis (HAZOP) are available for PHA [1~2]. Among them, HAZOP is one of the most widely used PHA methods, an important tool and effective measure to identify potential process hazards and prevent accidents in the field of hazardous chemicals. Britain and Canada have passed legislations to promote the use of HAZOP in construction projects. HAZOP is performed by a team of experts who raise safety issues on design, operation and management of the equipment and discuss solutions to solve the problems. Although HAZOP analysis possesses the characteristics of high degree of systematization and centralization of the experience of experts in various fields, manual HAZOP is a qualitative method. The manual evaluation has the shortcomings that can't be overcome:

（1）Process system is a complex and coupling system. A deviation somewhere may cause the deviations of the other positions even systematic abnormity;

（2）Manual HAZOP is time-consuming, laborious and costing;

（3）High dependence on specialized knowledge, expertise of team members and management of the leader;

（4）The verbal discussion method is not thorough and discussions are prone to confusion of concepts.

1.2 Reviews

In view of the shortcomings of the manual HAZOP analysis, adaptation to conventional HAZOP has been made. With the development of computer technology, quantitative and semi-quantitative HAZOP analysis has become a tendency. Generally, computer HAZOP can be mainly divided into computer-aided HAZOP and automating HAZOP.

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In developed countries, the development of computer-aided HAZOP analysis has experienced 3 stages.

Stage 1: Early computer-aided analysis did not innovate the traditional method but help generate HAZOP text. Project management HAZOP software is a kind of computer-aided HAZOP. It realizes logical assistance in data managements and standardization of text input and output. In terms of functional structure, this type of software is close to a special data sheet which focuses on the processing of documents. It plays a key role in managing documents. This greatly reduces the amount of work and enhances efficiency and quality.

Stage 2: Fault Diagnosis Expert System was introduced to reason and propose instructions based on knowledge base. To overcome the shortage of the existing HAZOP expert systems with regard to "non-routine" analysis, Zhao [3] proposed a case based reasoning framework. The case base and the structure of cases are briefly described and the case searching and matching strategies are presented.

Stage 3: Automatic reasoning method of safety evaluation based on deep knowledge is developed. Gradually, numerous intelligent computer-aided systems were developed. The application of automating HAZOP analysis to complex process equipment shows excellent performance. The automating HAZOP analysis models the process system with the aid of computer. By dynamic simulations of instruments, control system, process of heat transfer, process of mass transfer, profess of momentum transfer and the reaction process, the impact of the deviation on the process system is analyzed in the way of the internal mechanism analysis. V. Venkahasubrananian made great progress in applying SDG (Signed Directed Graph) to build HAZOP model. SDG is a qualitative modeling method. SDG-based HAZOP is capable of analyzing the transmission relationship between internal variables of complex system. In 1997, V. Venkahasubrananian [4] developed HAZOPExpert software on the G2 expert system. Chiappetta [5] et al. discussed the method of combining steady process simulation technology and HAZOP analysis to quantify the deviation. On the basis of traditional HAZOP, Liu [6] et al. simulated the effects of different degrees of deviation on the process system by modeling the analysis object. The quantity of HAZOP is achieved through quantifying the HAZOP guidewords and the deviations.

Chinese experts and scholars have started to research intelligent computer-aided HAZOP methods since 2003. At present, computer-aided safety evaluation in mainland China is still in its infancy. The technology used to carry out risk analysis is scarce. Hence, the research on computer-aided HAZOP analysis will be an important field of China's HAZOP analysis [7].

Therefore, in this paper the progress of computer-aided HAZOP and computer automating HAZOP is reviewed respectively in section I. A Quantifying HAZOP method is presented in section II. This method conducts quantitative descriptions of the deviation and the influences to the system by building the object model, which realizes real time monitoring of various parameters, such as temperature, pressure, flowrate etc. Section III carried out a case study of a quantifying HAZOP analysis of Steam Generation System in Ethylene Pyrolysis Unit based on process simulation platform. Conclusions are drawn in section IV.

II. A Quantitative HAZOP Analysis Method Based on Process Simulation System

2.1 HAZOP Analysis

HAZOP is a structural analysis used for identifying design defects, process hazards and operating risk. The analysis is practiced by serial conferences to analyze process diagrams and operation procedures. During the analysis, the analysis group consisting of the professionals systematically studies every single part (i.e. the analysis node) of the system in a prescribed manner. Dividing nodes according to P&ID in advance is a significant part. Correct node dividing in every P&ID ensures effectiveness of the HAZOP report. The node may be a length of pipeline, an equipment or equipment combination in a process. Then the HAZOP analysis is started as above procedures.

Before conducting analysis, the purpose, object and scope of the analysis must be determined. Afterwards, team of 4 to 8 people is founded and the expert team generally consists of leader, secretary, process engineer, instrument engineer, process operator, safety officer and equipment engineer. All documents related to design and operation such as P&ID and PFD must be obtained and systematically audited by the expert team. The analysis object needs to be divided into several parts in order to determine the scope of analysis and prevent the omission of deviations [8].

Expert team analyzes each process unit or operating procedure. Taking the normal process parameters and operating conditions as the standard, all the possible deviations are analyzed term by term and potential hazards is identified. The deviation is led by the guidewords. One purpose of using the guidewords is to ensure that the deviation of all the process parameters is included. The equation is "deviation = parameter + guideword". For example, the parameter "liquid level" and guideword "more" can be selected to identify the deviation. The combination is "liquid level high". Experts discuss 'How likely is it to happen?' and record the results: liquid level control failure, the control valve opens by error; the flow into the container is greater than the amount of discharge, discharge pipeline blocked.

Only when the meaningful combination of the guideword and the parameter, can it be used for analysis. For instance, the combination of "temperature" and "no" is meaningless so the combination is rejected. Meaningful combinations of parameter and guideword are shown in table I. After analyzing and recording all the deviations of the system, HAZOP deviation analysis table can be generated, as shown in table II.

TABLE I. COMBINATIONS OF PARAMETER AND GUIDEWORD

Parameters	**Guideword**					
	None	***Less***	***More***	***Part of***	***Reverse***	***Other than***
Flowrate	√	√	√	√	√	√
Pressure		√	√			√
Temperature		√	√			√

Parameters	Guideword					
	None	*Less*	*More*	*Part of*	*Reverse*	*Other than*
Component				√		√
Liquid Level	√	√	√			√
Phase	√	√	√			√

TABLE II. HAZOP DEVIATION ANALYSIS TABLE

Deviations	*Cause*	*Results*	*Precautions*	*Suggestions*
Deviation 1	Cause 1 Cause 2 Cause 3	Result 1 Result 2	Precaution 1 Precaution 2 Precaution 3	Suggestion 1 Precaution 2

Completing the deviation table, the HAZOP research report can be written. The report should include every analyzed result, significant descriptions of the safety measures and records for each guideword and parameter. The safety measures and corresponding operations must be recorded to ensure that the safety measures can be properly understood by personnel. Manual HAZOP analysis procedure is shown in Fig.1.

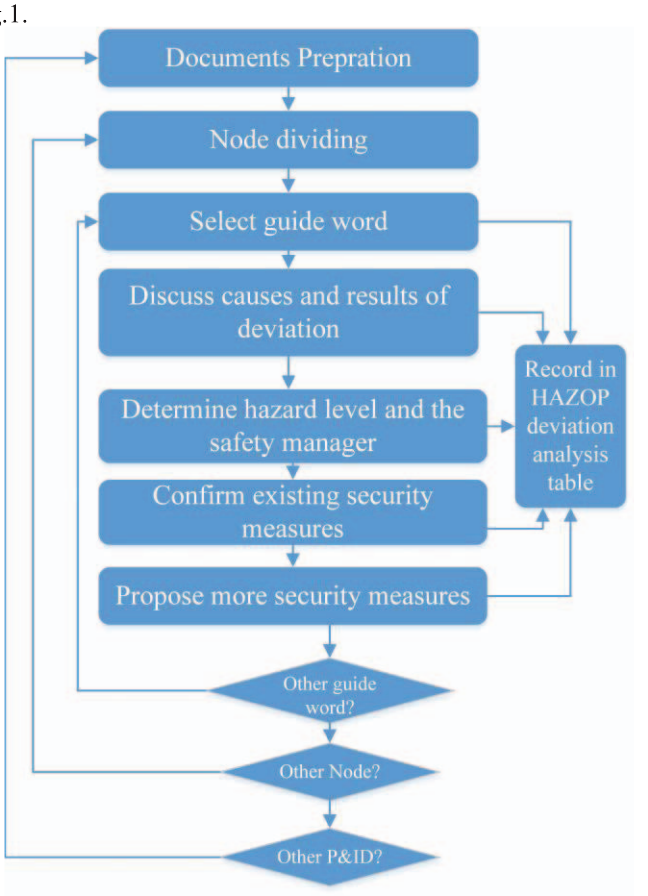

Fig.1 Flow Chart of Manual HAZOP analysis

2.2 Process Simulation Platform

Process Simulation platform is based on SIM4ME architecture. The system takes full advantage of the thermodynamic method in the field of process system engineering to ensure the accuracy of process model. Meanwhile, considering the complexity of the control procedure, the system model is built on the basis of parallel management and control theory of complex systems[9~11], which ensured the reliability and accuracy of the training system, hazard analysis system and emergency drill system based on process simulation platform.

Simulation of the system is carried out by sequential modular approach. The basic idea of this approach is to develop the calculation module for each type of unit in the process and organize the modules to the flow sheet of the actual process; the output data and the parameters of each module are used as input data and parameters to next module to obtain the information of the process state.

Sequential modular approach has been widely used process simulation method, especially in the field of process industrial. This method has the following characteristics in terms of the establishment of simulation model:

(1) One or more algorithms can be chosen to solve the model of process unit, so the accuracy of dynamic simulation of flow sheet can be guaranteed, which is beneficial to meet the requirements of real-time.

(2) The information flow in the model, the mass flow and energy flow in the process are corresponding. This is the basis for model consistency verification

(3) When the model is abnormal, it is easy to diagnose and modify.

(4) Model and module algorithm has good reusability, which improves the efficiency of model establishment, shortens the development cycle and reduces the cost of development.

2.3 A Process Simulation-Based Method for Quantitative HAZOP Analysis

First, control nodes configuration can be began based on the familiar with the control system and process flow sheet of the object system. Simulation of control type must be consistent with P&ID. Next, flow chart configuration is developed according to process flow diagram. Flow chart configuration embraces the setting of static process picture, dynamic value of points, bar charts and alarm status of points. Setting the alarm range should follow the operating procedures, emergency response principles and other documents. If the parameter of one node exceeds the safe range, the triggered alarm needs clear warning signs. Except for point configuration and flow chart configuration, the simulation system is capable of management of algorithm library and supporting user-defined algorithm.

The modeling process can be classified as follows:

(1) Before the start of the analysis, the purpose, object and scope of the analysis should be determined.

(2) All documents concerned about design and operation such as P&ID and PFD must be obtained.

(3) Modeling based on obtained documents in process simulation system.

(4) Dividing nodes, selecting the deviation for simulation system.

In view of the disadvantages such as omissions and wrong assessment of artificial HAZOP analysis, the process simulation-based HAZOP method uses simulation system to simulate the process. The establishment of the simulation model is based on the operating procedures, emergency stop design principles and other related information and once parameters exceed the safe range the alarm is triggered automatically. During the analysis, the production operation such as start-up and emergency shut-down is conducted on the simulation system and all triggered alarms are recorded. The alarm could be any node in whole process system instead of where deviation occurs.

Operations are conducted on the simulation system and the deviation is observable. This makes it possible to observe the influence of deviation on the system. So the causes and the consequences could be inferred. The flow chart of simulation-based HAZOP is shown in Fig.2.

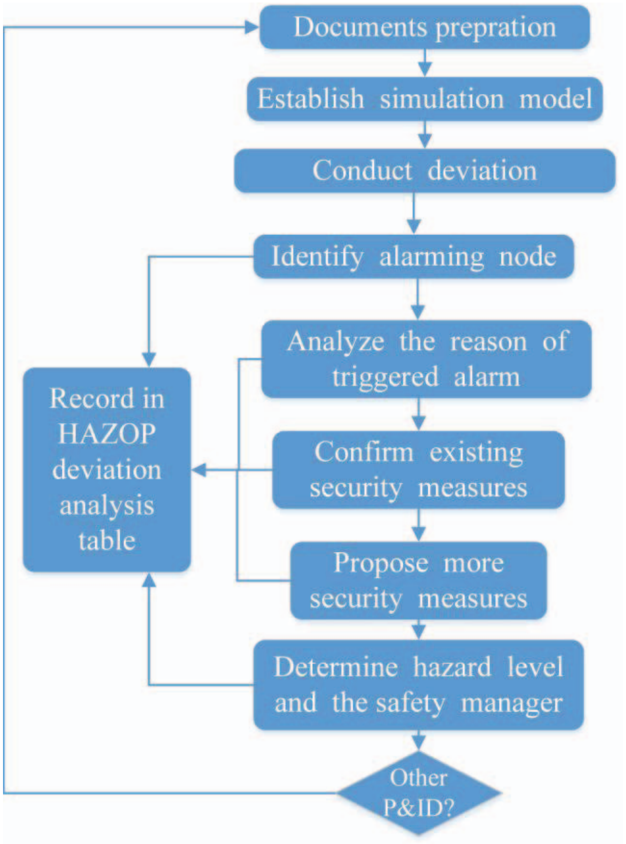

Fig.2 Flow Chart of process simulation-based HAZOP

III. CASE STUDY

3.1 Process of Steam Generation System in Ethylene Pyrolysis Unit

Steam generation system in ethylene pyrolysis section is selected as the analysis object for HAZOP analysis.

In the ethylene pyrolysis process, the naphtha from the boundary limit is cracked in the cracking furnace. In order to avoid coke of pyrolysis gas caused by secondary reactions or decomposition of heavy hydrocarbons, quench exchangers are arranged in the outlet of the furnace. The quench exchanger is mounted on the top of the furnace and every exchanger contains two waste heat boilers. Each waste heat boiler is set up for the heat recovery of the cracking gas from 24 furnace tubes. The waste heat boiler consists of 24 exchanger unis, which is a casing form, inverted U-shaped, two-passes. The fluid in shell-side is boiler feed water (BFW) from the drum and the water cycles based on thermal siphon principle. The distribution pipes at the bottom of boiler evenly distribute BFW into the outside of the tubes of exchanger unit. BFW absorbs heat from the pyrolysis gas and vaporizes, gathered in the upper part of the boiler pipes and goes back to the drum. High temperature steam discharged from the steam drum is used for the heating of the cracking furnace, and the heat recovery is realized.

3.2 Manual HAZOP Analysis of Steam Generation System

The drum of steam generation system is selected as the analysis node, BFW level as parameter and "no" as guide word. They are combined as deviation "BFW interruption". Finishing the manual HAZOP, analysis results are summarized to the HAZOP analysis table (Table III)

TABLE III. MANUAL HAZOP ANALYSIS TABLE

Node	***Deviations***	***Cause***	***Results***	***Suggestions***
Steam Drum	BFW Interruption	Failure in the control valve	Outlet steam temperature decrease; waste heat boiler overheat; cracking reaction interruption	Enable standby heat source; repair pipeline or valve
		Water supple pipeline crack or fracture		
		……		

According to Table III, the manual HAZOP analysis of steam generation system is started with the process parameters and the main nodes including pressure, temperature and flowrate. And then the HAZOP analysis report is formed. It can be combined with expert team advice to make safety measures or put forward other solutions to eliminate risks

3.3 Computer-aided HAZOP Analysis Method Based on Process Simulation System

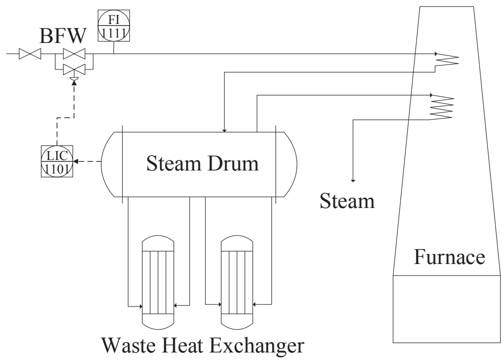

Fig.3 P&ID of steam generation system

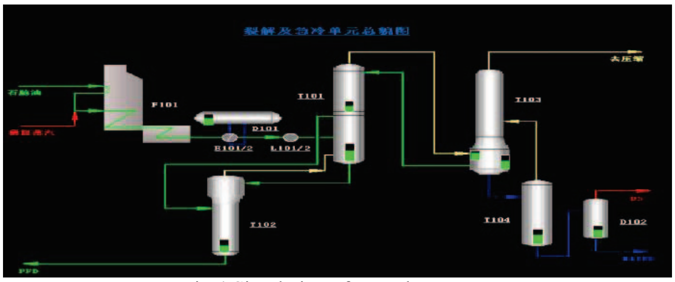

Fig.4 Simulation of quench segment

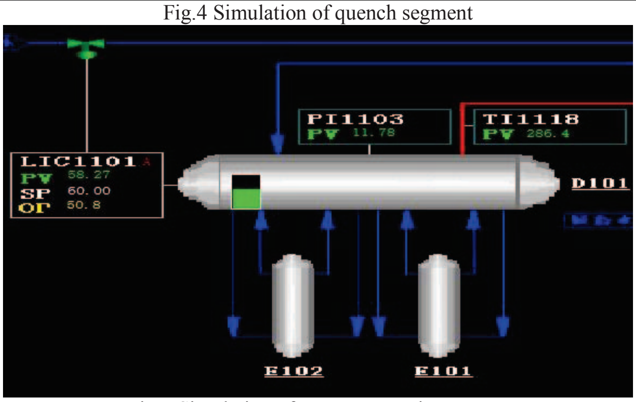

Fig.5 Simulation of steam generation system

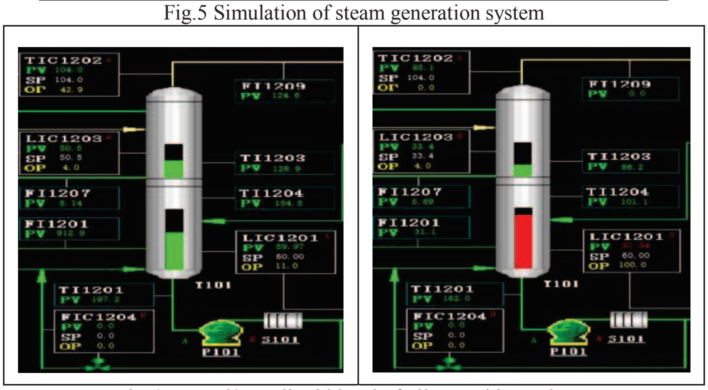

Fig.6 Normal/Low liquid level of oil quenching column

Firstly, according to the P&ID (Fig.3), the steam generation process is simulated by the model established above. And the process model of quenching cooling segment is developed (Fig.4). The simulation corresponding to the steam generation system P&ID is shown in Fig.5.

The drum of steam generation system is selected as the analysis node, BFW level as parameter and "no" as guide word. They are combined as deviation "BFW interruption". Turn off the inlet of BFW in the simulation system and observe the changes of the system. After a while, T101 and T102 tower bottom level triggered the alarm.

T101 is the oil quenching tower. In T101, high temperature pyrolysis gas is cooled by cooling oil from heat recovery of waste heat boiler. T102 is the fuel oil stripping tower. Pyrolysis gas from T101 is condensed in T102. Part of condensation put out as fuel oil product and the other is piped to T101 as cooling oil.

While the system is performing well, liquid level of T101 is about 60% and the alarm value is set at 80%. Once liquid level exceeds 80% the level bar chart turned green to red. Liquid level of T102 is about 50% and the alarm value is set at 80%.

The historical data of each parameter can be obtained in the simulation system. Temperature of steam drum outlet fluid, liquid level of T101 and T102 is obtained and the data is transformed into graphs (Fig. 7~9).

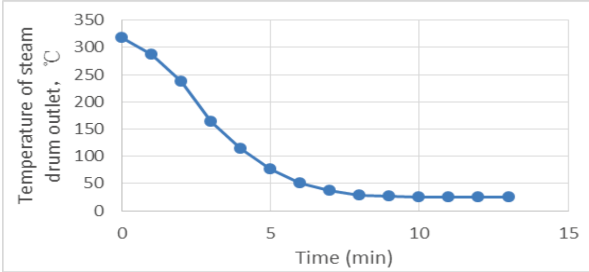

Fig.7 Temperature of steam drum outlet

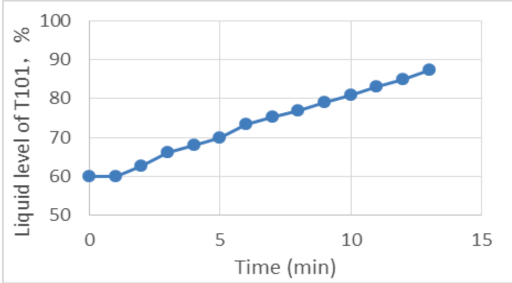

Fig. 8 Liquid level of T101

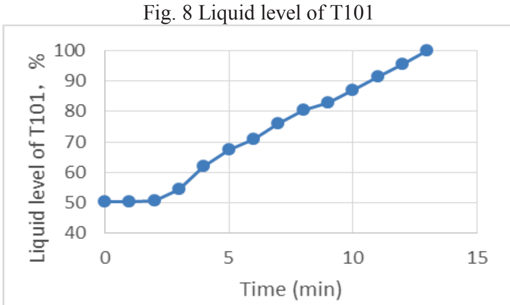

Fig.9 Liquid level of T102

3.4 Discussions

It can be seen through the graphs that the interruption of BFW results in the declining temperature of the outlet of the drum. The water in the shell-side of waste heat boiler become stagnant and heat transfer efficiency decreased severe, which means the heat recovery is spoiled and dry burning may explode the boiler. Meanwhile, liquid level of T101 and T102 is increasing consistently. Normal production process is destroyed and production safety is seriously threatened. Therefore the emergency measures should be taken immediately when the BFW is interrupted.

Through the analysis based on simulation system, it is found that the influence of BFW interruption on the system is much more than damage in the steam generator. The oil quenching tower and fuel oil stripping tower are also seriously affected. In the manual HAZOP analysis, the focus is concentrated on where the deviation occurred instead of the whole system.

Check the existing safety measures based on the alarm to finish remaining of HAZOP analysis table (Table VI). Compared with manual HAZOP analysis, HAZOP method based on simulation system is capable of identifying the misoperation and the impact of each step of the operation to the related section.

TABLE IV. COMPUTER-AIDED HAZOP ANALYSIS TABLE

Node	***Deviations***	***Cause***	***Results***	***Suggestions***
Steam Drum	BFW Interruption	Failure in the control valve	Outlet steam temperature decrease; waste heat boiler overheat; cracking reaction interruption; T101 and T102 liquid level rise	Close intake valve of T101; Emergency shutdown of furnace
		Water supple pipeline crack or fracture		
		……		

IV. CONCLUSION

In this paper, a process simulation-based method for quantitative HAZOP analysis is proposed based on parallel management and control theory. A dynamic simulation process of Steam Generation System in Ethylene Pyrolysis Unit is built based on process simulation platform. A quantitative HAZOP analysis of Steam Generation System is carried out. The risk report from quantitative HAZOP analysis has the following advantages compared with the report from manual HAZOP analysis:

（1）Accurate and intuitive risk report: through the manual HAZOP analysis, the risk report tells us where deviations occurred. While the deviations can be calculated and described based on the quantitative HAZOP analysis proposed in this paper.

（2）Decision-support role: risk report from the quantitative HAZOP analysis plays an important role in supporting safety manager to make corrective and preventive measures according to the quantitative deviations.

（3）Quantization of deviation: The method of guideword is of high uncertainty. For example, the deviation “high liquid level” can’t exactly express the extent of the high level. While the deviation is expressed in exact numbers such as 10% through dynamic simulation. By doing so, the abnormal situation in the whole process could be adjusted by the level control system. And it is necessary to take emergency measures if the deviation is beyond 50%. Through the dynamic simulation of parameter deviation, the degree of deviation is quantitative.

The method proposed in our work has great dependencies on process simulation modeling and also has the problem of missing faults. This tells us there much more work needs to do to improve the method. At the same time, the method used in our work obviously improved the problem of incompleteness of manual HAZOP analysis. The conceptual confusion of verbal discussions can be avoided and the reasons for the deviation can be traced back to the specific equipment and the specific operation based on the method. Therefore, quantitative HAZOP method based on simulation system is an effective supplement to manual HAZOP analysis.

ACKNOWLEDGMENT

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