Diverse analysis method and its application to identify vulnerabilities of emergency protection of sodium generation boilers

Stanislav Gorobchenko¹, Dmitriy Kovalev¹, Maria Taraban², Alexandra Krivonogova², Sergey Voinash³*, Linar Sabitov³⁴, and Ilgam Kiyamov³

¹Saint-Petersburg State University of Industrial Technologies and Design, 18, Bolshaya Morskaya Street, Saint-Petersburg, 191186, Russia
²Saint Petersburg State Forest Technical University named after S.M. Kirov, Institutskiy per., 5, St. Petersburg, 194021, Russia
³Kazan Federal University, 18, Kremlevskaya Street, Kazan, 420008, Russia
⁴Kazan State Power Engineering University, 51, Krasnoselskaya Street, Kazan, 420066, Russia

Abstract. The paper considers the possibility of assessing the development of accidents on the basis of a system-functional approach applied to the analysis of the probability of accidents in soda recovery boilers (SRBs). The main attention is paid to identifying the most vulnerable elements of the SRB and the possibility of diagnosing and preventing accidents based on the development of diagnostic systems in the existing APCS systems of the most important section of the SRB - the black liquor combustion system.

1 Introduction

Accidents at hazardous production facilities lead to negative social, environmental and economic consequences. When using hazardous substances in a technological process, there is always a risk of an emergency as a result of failures of system elements, as well as a combination of various errors of operating personnel.

The probability of occurrence, the development scenario and the scale of the consequences of an emergency are mainly determined by the quality of management in pre-emergency situations and the effectiveness and consistency of the actions of the personnel as the main participant in the management of TP.

The legislation of the Russian Federation establishes the definitions of hazardous production facilities, for which an emergency localization and liquidation plan (ELLP) should be developed, based on scenarios for the occurrence of emergency situations, a stage-by-stage analysis of their development and an analysis of the actions of production personnel to localize and eliminate emergency situations [10].

* Corresponding author: sergey_voi@mail.ru
A significant role in the analysis of emergency scenarios can be played by the so-called sabotage analysis and system-functional analysis of the development of accidents and catastrophes [1-2].

The objective of the article is to assess the vulnerabilities of emergency protection using sabotage analysis based on identifying contradictions in the interaction of the main subsystems of the SRB [8].

2 Black liquor combustion process automation system

From the evaporator plant, black liquor is supplied for combustion in the SRB, which is an energy-technological unit and is designed to burn black liquor and produce steam (Figure 1).

Fig. 1. Black liquor combustion automation scheme: I - superheater; II - boiler drum; III - cascade evaporator; IV - electrostatic precipitator; V - water economizer; VI - firebox.

Black liquor, containing 52-56% solids, in a heated state is pumped through nozzles for combustion into the furnace. The input variables of the liquor combustion process in the SRB are: consumption, humidity, ash content, ash melting temperature, consumption of volatile substances, consumption of added sulfate to replenish sulfur losses, the ratio of primary air - secondary air in relation to absolutely dry substances, temperature in the furnace, etc.

The output variables of the process are the sulfide content of the melt, the amount of alkali in the melt, the coefficient of excess air during the combustion of liquor, the flow rate and steam parameters [5].

The task of automatic control of the SRB is to maintain such a ratio between the flow rates of fuel, air and water supplied to the boiler, in which at any time the steam output of the unit would correspond to the load, i.e. steam consumption selected by the consumer. At the same time, it is necessary to maintain the pressure and temperature of the steam at optimal values.
In the general case, automatic control of the combustion process in boilers is carried out by three control loops: steam pressure and boiler load, fuel combustion efficiency and vacuum in the boiler furnace.

The regulation of the flow rate of the burnt black liquor is carried out using the ACP 1, which stabilizes the pressure in the pipeline before the nozzles. Load regulator 2 changes the fuel supply in accordance with the change in steam flow from the boiler. The efficiency of the combustion process is regulated by the ratio of fuel (liquor) and air consumption 3 with a correction for the oxygen content in flue gases 4.

The secondary air flow rate is regulated using ACP 5 for the ratio of primary and secondary air flow rates by acting on the guide vanes of the secondary air fan.

The position of the water level in the boiler drum depends on the imbalance between the water inflow and steam consumption, on the change in the steam content of the steam-water mixture of the circulation circuit and on the formation of steam in the economizer.

The level in the drum is regulated according to a cascade scheme: the output of the level controller 6 is used as a reference for the water flow control circuit 7. The vacuum in the boiler furnace is stabilized using the ACP 8 by acting on the guide vanes of the smoke exhauster [3].

In the superheater, the temperature of superheated steam 9 is controlled by changing the flow rate of the steam-water mixture in the recirculation circuit, in the heaters, the temperature of liquor 10 and air 11 is controlled and the pressure in the boiler drum 12, pressure 13 and steam temperature 14 are signaled.

The SRB provides for the following interlocks: in the event of an emergency shutdown of all operating smoke exhausters, blowers, main and auxiliary fuel supply pumps should be turned off; when the auxiliary fuel pressure rises or falls above or below the limit values, the auxiliary fuel supply must be turned off; in the event of an emergency shutdown of all operating blowers, the supply of the main and auxiliary fuel should be stopped; when the transport system of electrostatic precipitators is turned off, the voltage from the chambers of electrostatic precipitators should be turned off; when auxiliary fuel flame 8 goes out, the auxiliary fuel supply must be turned off.

On the control panel of the SRB, an alarm is installed for the maximum permissible levels of water in the boiler drum, a decrease in feed water pressure, an increase in the temperature of superheated steam, a decrease in the density of black liquor, an increase in the concentration of green liquor, a cessation of water supply for cooling tapholes, an increase in oil temperature in the bearings of smoke exhausters and fans, lowering the pressure of the primary air, lowering the pressure of the auxiliary fuel, stopping the transport system of electrostatic precipitators, increasing the temperature of the water used to cool the tap holes [7].

### 3 Explosions in recovery boilers

Explosions in recovery boilers (SRBs) can occur for several reasons, including:

- Incorrect process control and control: Inadequate control and control of temperature, pressure, air and fuel flow can lead to out-of-control parameters and unexpected explosions.
- Presence of explosive gases: The presence of combustible gases such as methane or hydrogen in the system can lead to an explosion if they interact with oxygen in the furnace.
- Breach of specifications: Breach of operating specifications, including improper fuel loading, overloading, insufficient cleaning of heating surfaces with soot blowers, etc.,
which can lead to loss of heat dissipation, overheating of screen pipes and unexpected explosions.

- Mechanical damage to the equipment: Mechanical damage to the equipment such as cracks, wear, corrosion, etc. can compromise the integrity of the firebox and increase the risk of explosion. For these purposes, special means of control can be applied, for example, thermal imaging control.

4 Technique of sabotage analysis

A diversionary approach [1] may be used to search for SRB areas that may lead to malfunctions and explosions, including:

- Collection of information about the SRB, its design, technical characteristics, operating modes, possible causes of disruption and explosions, and other problems.
- Problem analysis: the collected information is analyzed and the possible causes of disruption and explosions in the SRB are determined. The SRB is divided into sections and it is determined which sections may be problematic.
- Identification of contradictions: contradictions in the operation of SRB nodes are determined, which can lead to violations and explosions. For example, high temperatures in the furnace can lead to corrosion, and low pressures can lead to the formation of a steam "cloud".
- Search for solutions: based on the identified contradictions and problem areas of the SRB, methods of resolving contradictions and the available databases of accident identification are used to find solutions to eliminate these problems.
- Evaluation and choice of solution: various solutions are evaluated, and the most effective one is selected to eliminate problem areas of the SRB.

To conduct a sabotage analysis of the SRB, the following algorithm of actions was used:

- Collection of information about the system. This may be a description of the SRB, diagrams, photographs, etc.
- Determination of the main functions of the SRB. In this case, this is the production of steam for use in the technological cycle of pulp production.
- Identification of all elements of the SRB that perform the main function. It can be a firebox, an economizer, etc., depending on the requirements for the control of the SRB.
- Conducting a conflict analysis for each element.
- Identification of bottlenecks and the most vulnerable elements of the system, which can lead to malfunctions and explosions in the boiler. For example, it may be overheating of the furnace screen pipes due to incorrect operation.
- Conducting an analysis of possible solutions to eliminate bottlenecks and prevent possible violations and explosions. For example, to prevent overheating of pipes in the furnace, you can install additional temperature sensors and set up automatic control of the operating mode.

Thus, conducting a sabotage analysis of the SRB allows you to identify bottlenecks and problematic elements of the system, as well as to find the best solutions to eliminate them.

4.1 Collection of information

A soda recovery boiler (SRB) is a high-temperature thermal process plant used to produce steam by burning black liquor in a furnace. The main purpose of the SRB is the restoration
of the chemical activity of the mineral part of the liquor, and the auxiliary one is the production of steam for use in the technological cycle of pulp production.

The SRB consists of several technological sections, including:

- Furnace, where liquor is burned and heat is generated;
- Air heaters that use flue gases from the furnace to preheat the air entering the furnace;
- Heating surfaces (wall tubes) where flue gases are used to generate steam;
- An electrostatic precipitator that is used to clean exhaust gases before they are released into the atmosphere.

One of the main risks of SRB is the possibility of explosions. The causes of explosions can be various, including the formation of explosive mixtures in the furnace, overpressure in pipes or their mechanical destruction, non-compliance with operating rules, violation of the cooling system, malfunctions in the flue gas cleaning system, etc.

### 4.2 The main function of the SRB

The main function of the SRB is the restoration of the chemical activity of the mineral part of the liquor, the additional one is the production of steam for use in the technological cycle of pulp production. At the same time, to obtain steam in the SRB, the heat of the combustion products of black liquor is used, which, in turn, contains organic substances and a mineral part [4].

### 4.3 The main elements of the SRB

In the SRB, the following elements are used to perform the main function of cleaning black liquor from organic substances and restoring the chemical activity of the mineral part, and an additional function - steam production - the following elements are used:

- Firebox - the place where the reactions of combustion of black liquor and the restoration of the mineral part take place.
- A bundle of screen pipes (heating surfaces) - an element that allows you to transfer heat from the combustion products of black liquor to water with the formation of steam.
- Air ducts - elements that provide air supply to the furnace to support the combustion reaction.
- Black liquor supply system - an element that ensures the supply of black liquor to the furnace for further processing.
- Smelt tank with a system for ensuring the dilution of the smelt and its transfer to subsequent stages of the recovery of the mineral part.

All these elements work together and together perform the main function of the recovery of the mineral part of black liquor and the auxiliary function of steam production.

### 4.4 Analysis of contradictions of SRB subsystems

Firebox. Controversy: it is necessary to reach high temperatures to ensure the reduction reactions of the mineral part of the liquor, but this can lead to overheating of the furnace and damage to its elements, and in a critical development of events - to an explosion. The solution based on the automation system lies in the better provision of the measuring chain and the early detection of the critical combination of parameters and their warning. In particular, this is the installation of new ACPs in cooling systems, the creation of additional thermal imaging systems for analyzing the state of overheating zones in the boiler furnace and pipes, determining trends in the development of parameters and using them to increase the level of furnace maintenance.
Heating surfaces. Controversy: efficient steam production requires high heat release on the heating surfaces (wall tubes) that exchange heat between flue gases and water, but this can lead to overheating and damage to its elements. Solution: optimization of the temperature regime, use of direct control devices capable of operating at temperatures above 1100°C, development of programs for analyzing the level of soot on heating surfaces and the development of new concepts for diagnosing the pre-emergency state of heating surfaces.

Air ducts. Controversy: for efficient combustion of lye in the furnace, it is necessary to provide sufficient air, but this can lead to heat loss and increased emissions. Solution: optimization of the combustion process with the creation of additional automated control systems in the automated control system, the use of special methods for assessing the level of saturation with oxygen and combustible gases in hazardous and stagnant zones of the boiler.

Black liquor supply system. Controversy: it is necessary to ensure a continuous supply of liquor to the furnace for the efficient operation of the SRB, but this can lead to problems with the management and control of the process. Solution: use of automated monitoring and control systems, regular maintenance and checking the status of the black liquor supply system.

4.5 Identification of vulnerable elements of the SRB

The most vulnerable elements of the SRB, which can lead to malfunctions and explosions in the boiler, are the following:

- The boiler furnace is a bottleneck in the system that can lead to explosions in the boiler if gases and vapors accumulate in it, causing the formation of explosive mixtures or a rise in pressure. Also, if the firebox is not cleaned regularly, overheating may occur, which can also lead to accidents [6].
- Heating surface cleaning system - if the cleaning system is not functioning properly, deposits and impurities can accumulate, which will reduce the efficiency of heat exchange, as well as increase the pressure in the boiler.
- Automatic control system - if the control system does not function properly, this can lead to improper fuel and water flow, overheating of the boiler, as well as an imbalance between air and fuel, which can lead to the formation of explosive mixtures.
- Air supply system - if problems occur in the air supply system, this can lead to an insufficient supply of oxygen to the boiler, which can cause incomplete combustion of the fuel, the formation of explosive mixtures and an increase in carbon monoxide.
- Feedwater System - Too little or too much feedwater in the system can cause overheating, vapor lock and pressure buildup that can cause accidents and explosions [9].
- Combustion products removal system - insufficient efficiency of the combustion products removal system can lead to their accumulation, slagging, plugging, pressure increase and emergency situations.
- Valves and Safety Devices - If valves and safety devices do not function properly, it can lead to pressure failure and accidents.

5 Conclusion

Thus, the technique of sabotage analysis demonstrates well its capabilities in improving the efficiency of tracking emergencies in the SRB. The basis for this is the element-by-element
consideration of the SRB as a system and the identification of the main contradictions that arise both within the system, between the SRB subsystems, and between the elements of the SRB and external perturbations arising associated with the supply of black liquor, air and the impact of the external environment [11].

The analysis carried out showed weak points and links between the subsystems of the SRB, in particular, the black liquor path, which makes it possible to clarify the requirements for the SRB security systems and, on this basis, offer additional solutions to enhance the capabilities of the SRB ACS.

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