Assessment and method for reducing the risk of emergencies at enterprises using equipment operating under excessive pressure

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Abstract. This article assesses the likelihood of an emergency during the operation of excessive pressure equipment. Emergency situations were developed and simulated, their consequences were evaluated. Sketch maps for the implementation of events on the terrain with radii of damage to people and infrastructure were plotted. Simulation of the emergency showed that in case of an explosion of a steam boiler, severe structural damage and complete destruction of a mobile steam unit are possible. Based on the simulation results, a technical solution is proposed aimed at preventing the explosion of a steam boiler due to the implementation of an automated shutdown of fuel and water supply by installing a pressure measurement sensor. The technical solution describes the algorithm of the proposed automation process and the operator’s actions in case of failure of safety valves and the operation of the pressure measurement sensor.

1. Introduction
Ensuring the safe operation of the excessive pressure equipment is one of the most important and urgent tasks of our time.

When operating this type of equipment, there is a risk of various emergencies. Accidents, in turn, lead to the destruction of buildings and structures, injuries and deaths, as well as harm to the environment. In this regard, an early assessment of the likelihood of an emergency can reduce the risk of such events, with the subsequent development of the necessary organizational and technical measures. Since the studied area is located near other production sites and the settlement, it is necessary to simulate the development of an emergency in order to assess the likelihood of an event.

2. Investigation of the likelihood of an emergency
A mobile steam unit (PPU-1600/100) is considered as the study object. This installation is used at the enterprise, the industrial zone of which is located in the city. The layout of the site where the PPU-1600/100 steam mobile units are located is shown in Figure 1.

Mobile steam units belong to the category of hazardous production facilities comprising equipment operating under a pressure of more than 0.07 MPa or at a water heating temperature of more than 115 °C [1-3].

Having examined the most common scenarios, it is worth noting that the scenario - "Failure of safety valves → boiler explosion → fuel tanks explosion → fuel-air mix cloud formation → fuel-air
mix cloud explosion → impact on personnel and the environment" is the most hazardous, since during implementation of this scenario more hazardous substances will be involved in the accident. Modeling of this emergency will be carried out by calculating the necessary indicators and plotting sketch map during the implementation of the events specified in this scenario [4-10].

During an explosion, instantaneous evaporation of pressurized water heated above 100 °C occurs in the boiler due to wall breaking, while the pressure in the boiler decreases. As a result of an instant evaporation of water, a huge amount of steam is formed (1 liter of water, turning into steam, increases in volume by about 1700 times), which in future, can lead to great damage.

There is a need to calculate the mass and volume of the generated steam, which will lead to destruction, as well as the impact on the personnel [7-9]. Parameters necessary for the calculation are given in Table 1.

The mass of water before the explosion $M_B$ (1) is defined as the ratio of the volume of water in the boiler $V_B$, m$^3$ to the specific volume of boiling water at atmospheric pressure in the boiler $\varrho_\text{atm}$, m$^3$/kg.

$$M_v = \frac{V_v}{\varrho_v} , \text{ kg}$$

$$M_v = \frac{0.48}{0.001044} = 469.77 \text{ kg}$$

To determine the volume of steam formed as a result of depressurization of a steam boiler, it is necessary to calculate the reduced mass of boiling water (2):

$$M_{pr} = M_v \frac{h_i - h_{in}}{Q_0} , \text{ kg}$$

where $h_i - h_{in}$ is the difference in enthalpies, kJ/kg; $Q_0$ is constant, which in the calculations is acceptable to be $4.52 \times 10^3$ kJ/kg.

$$M_{pr} = 469.77 \frac{1399 - 419.1}{4.52 \times 10^3} = 101.1 \text{ kg}.$$
Table 1. Initial data for the calculation of explosion parameters.

| Seq. No. | Parameter          | Value   |
|----------|--------------------|---------|
| 1        | $\vartheta$, m³/kg | 0.001044|
| 2        | $h_v$, kJ/kg       | 1399    |
| 3        | $h_{nm}$, kJ/kg    | 419.1   |
| 4        | $r_{hp}$, kJ/kg    | 1329    |
| 5        | $\vartheta_p$, m³/kg | 1.694 |
| 6        | $Q_0$, kJ/kg       | $4.52 \times 10^3$ |
| 7        | $V_v$, m³          | 0.48    |

The mass of steam formed as a result of the explosion is determined by the formula (3):

$$M_p = \frac{M_v \left(h_v - h_{nm}\right)}{r_{hp}}$$, kg \hspace{1cm} (3)

where $r_{hp}$ is the specific heat of water evaporation at atmospheric pressure, kJ/kg.

$$M_p = \frac{469.77 \left(1399 - 419.1\right)}{1329} = 469.77 \text{ kg.}$$

The volume of steam formed during the explosion is determined by the following formula (4):

$$V_p = M_p \cdot \vartheta_p$$, m³ \hspace{1cm} (4)

where $V_p$ is the volume of steam in the boiler, m³; $\vartheta_p$ is the specific volume of steam in a state of saturation at atmospheric pressure equal to 1.694 m³/kg

$$V_p = 346.3 \times 1.694 = 586.6 \text{ m³}$$

The calculations make it possible to conclude that when an explosion occurs in a steam boiler, a large volume of steam is formed - 586.6 m³. At the time of destruction of the walls of the boiler, in which superheated water is located, the pressure falls to atmospheric. As a result, an adiabatic (isentropic) expansion of the medium occurs. Water begins to evaporate intensively, turning into steam and forming a large amount of it, which causes a pressure wave.

One of the main parameters of an explosion of expanding vapor of a boiling liquid is overpressure. To analyze the damage zones and assess the nature of damage to buildings and structures, it becomes necessary to calculate the overpressure [10-16].

According to [9], the overpressure $\Delta P$ is calculated by the formula (5):

$$\Delta P = P_0 \left(0.8 \frac{M_p^{0.33}}{r} + 3 \frac{M_p^{0.66}}{r^2} + 5 \frac{M_p}{r^3}\right),$$ \hspace{1cm} (5)

where $P_0$ is the atmospheric pressure equal to 101.3 kPa; $r$ is the distance to the object in question, m.

Calculate the excess pressure in the radius of the steam units $\Delta P_1, \Delta P_2$, in the zone of the conditional settlement $\Delta P_3$. 

\[ \Delta P_1 = 101.3 \left( 0.8 \frac{101.1^{0.33}}{15} + 3 \frac{101.1^{0.66}}{15^2} + 5 \frac{101.1}{15^3} \right) = 67.8 \text{kPa.} \]

\[ \Delta P_2 = 101.3 \left( 0.8 \frac{101.1^{0.33}}{60} + 3 \frac{101.1^{0.66}}{60^2} + 5 \frac{101.1}{60^3} \right) = 23.5 \text{kPa.} \]

\[ \Delta P_3 = 101.3 \left( 0.8 \frac{101.1^{0.33}}{500} + 3 \frac{101.1^{0.66}}{500^2} + 5 \frac{101.1}{500^3} \right) = 1.04 \text{ kPa.} \]

The calculated value of the overpressure generated as a result of the explosion of the steam boiler makes it possible to determine the destruction zone, Table 2. [17].

3. Research results and proposed solution
Simulation of the most hazardous scenario (explosion of a steam boiler) showed that in case of an accident, complete destruction of the structure in which the mobile steam units are located with subsequent effect on the personnel is possible, Table 2.

Table 2. Destruction Zone Classification.

| Destruction Zone Class | K | \( \Delta P \), kPa | Destruction Zone | Likely consequences, nature of damage to buildings and structures |
|------------------------|---|--------------------|------------------|---------------------------------------------------------------|
| 1                      | 3.8 | \( \geq 100 \)     | Complete         | Complete destruction of buildings with massive walls. Conditional probability of fatal injury is 0.6; severe injuries - 0.37 |
|                        |     |                    |                  | Destruction of the walls of brick buildings with a thickness of 1.5 bricks; movement of cylindrical tanks; destruction of pipeline racks. Conditional probability of fatal injury is 0.49; severe injuries - 0.34 |
| 2                      | 5.6 | 70                 | Hard             | Destruction of ceilings of industrial buildings; destruction of industrial steel supporting structures; destruction of pipeline racks. Conditional probability of fatal injury is 0.01; severe injuries - 0.09. |
| 3                      | 9.6 | 28                 | Moderate         | Destruction of partitions and roofs of buildings; damage to steel structures of frames, trusses. Conditional probability of minor injuries is 0.5. |
| 4                      | 28  | 14                 | Light            | The boundary of the zone of damage to buildings; partial glazing damage. |
| 5                      | 56  | \( \leq 2 \)       | Glazing damage   | The boundary of the zone of damage to buildings; partial glazing damage. |

The entire site of the installations falls into the zone of moderate damage. The likely consequences of such explosion will be the destruction of ceilings and supporting structures.

Sites of the industrial zone fall into the zone of light destruction. The likely consequences for such zone are the destruction of partitions and roofs of buildings. The motor way and the site of the conditional settlement fall into the glazing damage zone. Emergency development model is given in Figure 2.
Figure 2 Emergency development model in case of explosion of a steam boiler.

- Zone of moderate damage ($\Delta P = 67.8$ kPa) - 15.00 m;
- Light damage zone ($\Delta P = 23.5$ kPa) - 60.00 m;
- Glazing destruction zone ($\Delta P = 1.04$ kPa) - 500.00 m.

To prevent the explosion of a steam boiler, it is necessary to consider the possibility of installing additional emergency equipment, as well as develop a technical solution aimed at its safe operation [18-21]. As shown by the analysis of the causes of accidents, an increase in pressure in the boiler and its subsequent explosion can lead to malfunctions of the safety valves. Faults typical for this type of device lead to the fact that with increasing pressure in the steam line, the valve does not operate and an explosion occurs. Since this type of device is the most hazardous, it is necessary to justify the possibility of an automated stop of the production process by installing an MW "Standard" gauge for measuring overpressure.

4. Conclusions

Thus, to increase the level of safety during the operation of equipment operating under excessive pressure, it is necessary to provide an automated process for stopping the operation of equipment in case of failure of safety valves. To achieve the described process, it is necessary to install a MW "Standard" overpressure sensor. The automation process consists in the fact that when the safety valves fail, the fuel supply to the nozzles of the boiler is automatically stopped and the supply of cold water to the boiler is blocked.

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