KAPITEL 4 / *CHAPTER 4* [5]
ASSESSMENT OF HAZARDOUS PARAMETERS OF HYDROGEN-AIR MIXTURE EXPLOSION DURING OPERATION OF THE COOLING SYSTEM OF A POWER PLANT TURBINE GENERATOR

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Introduction

One of the main causes of emergency shutdowns and destruction of turbine generators, synchronous compensators and high-capacity electrical machines cooled by gases, in particular hydrogen, both in our country and abroad is intense contamination of the cooling hydrogen with moisture containing impurities of oxygen and turbine oil. The main impurities that can get into the generator housing are water (with a maximum concentration of 25 - 30 g/m^3), oxygen (0.2 g/m^3), turbine oil (5.0 g/m^3), hydrogen lubricant aerosols (0.15 g/m^3), etc.

In recent years alone, 28 accidents involving the destruction of hydrogen-cooled turbine generators have occurred at power plants in Europe. More than 90% of such accidents are caused by incorrect actions of the maintenance personnel who do not follow the rules for operating the equipment of gas-lubrication systems of turbine generators, as well as the established procedure for conducting flame repairs.

4.1. Causes and conditions of accidents and emergencies in power plant turbine rooms

There have been a number of major accidents at power plants involving fire and partial destruction of the turbine hall due to the combustion of hydrogen and oil. Despite the fact that these accidents were not caused by malfunctions of the gas lubrication system and generator shaft seals, but, as a rule, by increased shaft vibration and bearing damage, the catastrophic development of the accident occurred precisely as a result of hydrogen and oil leakage and combustion after mechanical damage to the seal assembly and fastening of the generator's outer shields.

The gas system of the turbine generator has special equipment that makes it possible to safely fill the generator with hydrogen and remove it by using an inert gas

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as an intermediate agent: it is removed with inert gas, then air, and the air is similarly removed with inert gas, then hydrogen. If these operations are performed incorrectly and there is no control over the composition of the gas mixture, explosive mixtures can also form in the generator housing, float valve, and purge tank. Hydrogen can get into bearing crankcases, tire lines, the stator winding distillate cooling system, and the gas cooler water system, and, when accumulated, at a certain percentage, also forms an explosive environment.

Ignition is possible in any place where hydrogen leaks from the generator housing or gas lubrication system. The degree of danger is determined by the location of the leak, the proximity of people and the possibility of injury, the amount of hydrogen released, and the ability to prevent further combustion without shutting down the turbine unit.

Fires occur when there are significant hydrogen leaks, most often associated with the complete or partial destruction of the generator, or when there are significant oil leaks. Hydrogen combustion is always accompanied by oil combustion. The ignition of oil from outside the generator, if it is intact, does not lead to hydrogen ignition.

An explosion in the housing of a suspended generator is possible only as a result of a gross violation of the rules for displacing and replacing the gas environment in combination with untimely execution and poor quality of the analysis of the hydrogen content in the gas mixture.

The analysis of the causes of accidents and emergencies at turbine generators with a hydrogen cooling system made it possible to identify the main causes and locations of accidents:

- cracks in the generator gasket seals (hydrogen escapes through the gaps into the engine room due to increased hydrogen feeding to the generator);
- cracks in the rubber gaskets of the gas cooler (hydrogen escapes through the gaskets to the engine room due to increased hydrogen consumption);
- decrease in hydrogen pressure in the generator housing due to significant hydrogen leakage along with oil through the detachable connections of the oil drain pipeline;
- violation of safety requirements during gas sampling (hydrogen leakage and ignition are possible when opening the gas station valve);
- accumulation of a hydrogen-air mixture in the bearing crankcase and under the generator protective casing;
- poor quality repair of seals, which leads to the supply of oil to the generator;

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- rupture of the rubber sealing gasket of the generator hatch;

- damage and depressurization of the generator's outer shields as a result of shaft failure (turbine blades tearing off with subsequent vibration).

The analysis of statistical data on accidents at turbine generators revealed that in most cases, the cause of accidents and emergencies is a decrease in the pressure drop of lubricating oil and hydrogen. A decrease in the differential pressure of oil and hydrogen is caused by

- failure or erroneous switching of lubricant supply sources;

- poor quality repair or incorrect adjustment of the oil and hydrogen differential pressure control;

- incorrect closure of the valve (gate valve) on the pressure pipelines from the lubricant supply sources to the differential pressure regulator and further after the regulator to the seals;

- increased hydraulic resistance in the pressure pipelines from the lubrication sources to the differential pressure regulator and further after the regulator to the seals (contamination, etc.);

- violation of the lubrication density on any section of the pressure pipelines;

- significant lubricant consumption.

Disruptions in the operation of gas-lubrication system equipment accompanied by hydrogen leaks and its ignition are divided as follows [3]

- leakage through flanged connections of pipelines and fittings - 20%;

- deformation of sealing rubber gaskets (manhole cover, generator housing flange, between the sealing body and the outer shield, etc.) - 20%;

- breakthrough through the float water seal - 10%;

- hydrogen leakage and spontaneous combustion due to sudden opening of the valve at the gas station - 10%;

- leakage through rubber gaskets of gas coolers - 10%;

- leaks due to a breakthrough in the bearing crankcase - 9%;

- leaks through welded pipeline joints - 6%;

- leakage through flange connections of the float water seal - 6 %;

- malfunctioning of oil and hydrogen differential pressure regulators - 6%;

- leaks through horizontal connectors of end plates - 3%.

The share of hydrogen leaks accompanied by hydrogen explosions is over 15%.

Hydrogen seepage along the shaft through leaks is also possible under normal pressure differential between the lubricant and hydrogen - due to distortions or damage, jamming of the seal liner due to poor seal repair, and contaminated lubricant supply. Hydrogen leakage through the float water seal to the turbine unit bearing drainage system due to a defect in the water seal valve that hangs in the open position is quite dangerous. Explosions of the hydrogen cooling system of generators that occur during a fire in the turbine hall lead to the destruction of lubrication lines and the spread of lubricant on the platforms and at the zero mark, neighboring units, cable tunnels, etc. Fire conditions pose a danger to high-pressure equipment and pipelines.

Thus, the most fire-hazardous violations during the operation of turbine generators with a hydrogen cooling system are those accompanied by a loss of gas density. The most dangerous is the release of hydrogen into the oil drain line and bearing housings: along the shaft through the seals; through the float water seal.

The main reasons for the fire and explosion hazard of turbine generators include the use of a large amount of combustible substances and materials, increased oil pressure in control systems, increased length of oil lines, complication of the control and protection scheme, increased temperature of steam lines, turbine casings, etc.

The 220 MW and 1000 MW turbine generators installed at Ukrainian NPPs are also equipped with a direct hydrogen cooling system. The use of hydrogen as a cooling medium in these turbine generators is due to [3]:

- the increase in the unit power of turbine generators due to the growth of their dimensions is limited by the value of the maximum mechanical loads on the rotor elements;
- to further increase the power, it is necessary to increase the current density in the windings and intensify cooling;
- to intensify cooling, it is necessary to use a more efficient cooling agent - hydrogen, whose thermal conductivity is 6 - 7 times higher than that of air;
- the use of hydrogen also reduces ventilation losses due to its significantly lower density compared to air.

The hydrogen cooling system is the only possible cooling system for high-power turbine generators. The use of this system is associated with the need to create a special lubrication system to supply lubricant to the turbine generator seals, which prevents hydrogen from leaking from the housing through the shaft seals. At the same time, the use of lubricant increases the fire hazard in the turbine compartment.

The increase in hydrogen pressure with increasing turbine generator power is explained by the fact that the thermal conductivity of hydrogen increases with increasing pressure.

Regulatory document [4] regulates, in addition to the purity of hydrogen, the oxygen content of hydrogen in the turbine generator housing (0.8 - 1.2 % depending on the pressure), fluctuations in the hydrogen pressure in the housing - no more than ± 20 kPa (at a pressure of more than 0.1 MPa) and permissible daily hydrogen leakage - no more than 5 % of the total amount of gas at operating pressure.

Hydrogen is supplied to fill the turbine generator housings from the plant-wide pipeline through a special control unit. Emptying the casings of hydrogen in the event of a turbine generator being taken out of service is also carried out through this unit. The diameter of the hydrogen supply pipelines is 25 mm, and the diameter of the hydrogen discharge pipelines is 50 mm. To displace hydrogen from the turbogenerator housing and fill it after hydrogen discharge, a neutral gas supply, nitrogen, is provided to prevent the formation of an explosive mixture of hydrogen and air.

The experience of operating TPP and NPP power units with hydrogen-cooled turbine generators has shown that there have been repeated violations with hydrogen leakage from the turbine generator housing. These violations can be divided by their causes into

- hydrogen leakage due to extrusion of the sealing gaskets between the seal housing and the outer shield or the gasket between the manhole cover and the housing flange;
- hydrogen leakage due to partial destruction of gaskets in horizontal connectors of end shields;
- hydrogen leakage in bearing housings;
- hydrogen leakage in the area of the end shield and the seal housing due to seal failure.

Most violations were not accompanied by fire or were localized and did not have serious consequences due to the low consumption of combustible components. The most dangerous violation with emergency consequences is hydrogen leakage due to the destruction of gas-lubrication seals.

The cause of such accidents is an avalanche-like increase in shaft vibration above the permissible limits due to blade breakage, which led to the destruction of the seals and intensive hydrogen release from the turbine generator housing. In this case, hydrogen combustion occurs. When the burning hydrogen mixes with turbine oil flowing from the lubrication systems destroyed by vibration, a gas-lubrication flame with a very high temperature of more than 2000 ºC is formed, the height of which reached the metal trusses and other metal structures of the turbine hall roof. As a result of this temperature, the metal structures lost their stability and collapsed. Elimination of the consequences of the destruction required significant costs and a long outage of the power unit.

4.2. Prevention of fires, explosions and fires during the operation of hydrogen-cooled turbine generators

Statistics on similar accidents show that the main cause of a fire in the turbine generator's gas seals is an increase in the permissible limits of shaft vibration, which leads to seal failure and hydrogen leakage, as well as leakage of sealing oil. Hydrogen escaping from the turbogenerator housing can ignite under certain conditions and form a flammable plume. The flash point of a hydrogen-air mixture is 4.12 - 75.4 % by volume, the minimum ignition energy is 0.002 MJ, and the self-ignition temperature is 510 ºC [5, 6, 7]. If the sealing grease gets into the plume of burning hydrogen, the grease, which has an ignition temperature of 210 - 220 °C, also ignites and as a result, a gas-lubricating plume with a very high temperature in its core is formed. The height of the plume depends on the gas flow rate, the size of the hole, and the physical characteristics of the combustible product. The leakage rate is determined by the general laws of hydrodynamics, depending on the difference in hydrogen pressure between the turbine generator housing and the environment, the flow coefficient through the emergency hole, and the gas density. The leakage time depends on the volume of gas in the housing and the leakage rate. The results of the calculations for the ТВВ-220-2ФУЗ turbogenerator with a gas volume of 73.0 m^3 are shown in Table1.

Table 1. – Characteristics of hydrogen flare combustion for the turbine generator ТВВ-220-2ФУЗ

Name of the parameter	Diameter of the hole, mm				
	5	10	50	100	200
Height of the flare, m	1.15	2.3	11.5	23	46
Burning time, s	8850	2212	89	22	6
Outflow rate, m/s	420	420	418	413	387

An analysis of the current state of the problems associated with ensuring the fire resistance of steel building structures shows that many facilities use a large amount of combustible gases and substances with high combustion temperatures in the technological process (turbine oil T = 1400 K, hydrogen T = 2200 K). The heat flux intensity at these temperatures reaches 300 - 450 kW/m^2. The modes of fire action in fires at these facilities differ significantly from the «standard temperature regime» (τ = 120 min, T_{max} = 1329 K Fig. 1 (curve 1)), «temperature regime of a hydrocarbon fire» ((τ = 40 min, T_{max} = 1380 K, Fig. 1 (curve 2)), «temperature regime of a modified hydrocarbon fire» (τ = 40 min, T_{max} = 1600 K, Fig. 1 (curve 3)) [8].

Today in Ukraine, there are no methods for theoretical study of the fire resistance of metal structures (minimum fire resistance limit of a steel building structure is R15) under conditions of high flame temperatures and intense heat transfer. It is very difficult and sometimes impossible to study their fire resistance experimentally. The problem of their study is their large overall dimensions. Such structures are widely used at energy facilities (machine shops), oil refineries, chemical plants, etc.

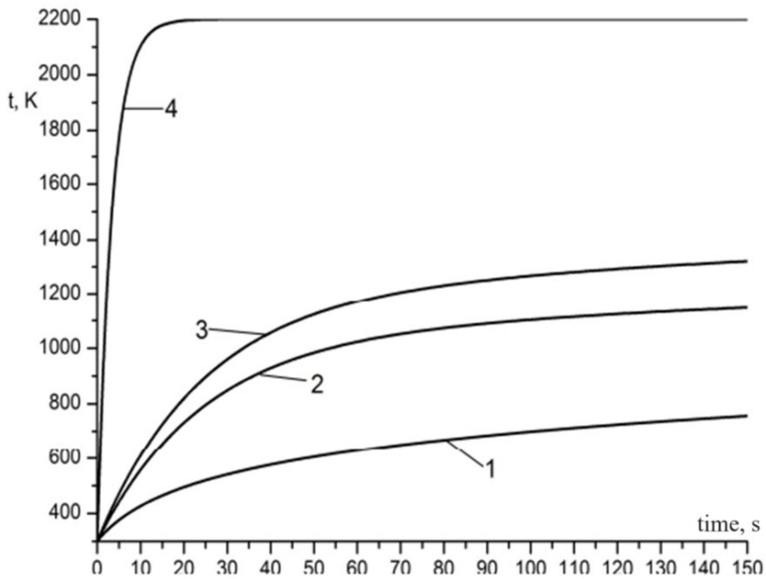

Figure 1 – Temperature regimes of a fire: *1 – «standard fire temperature regime»; 2 – «hydrocarbon fire temperature regime»; 3 – «modified hydrocarbon fire temperature regime»; 4 – «hydrogen fire temperature regime»*

Let us consider the change in the temperature of the flame plume of a hydrogen-air mixture combustion, which ranges from 2200 to 2600 K depending on the hydrogen concentration in the air [7]. The duration of an accidental leakage (combustion) of a hydrogen jet was studied in [9] and is 2.5 minutes. Given that the temperature of the flame plume is 2200 K and is reached in 15 – 20 seconds, the temperature regime of hydrogen combustion can be mathematically modeled as τ

$$T(\tau) = 2200 - (2200 - T_0) \cdot \exp(-0.3 \cdot \tau) \quad (1)$$

where τ is the duration of the fire, s; T_0 is the initial temperature, K.

According to equation (1), the graph of changes in the temperature regime of a hydrogen fire is described by curve 4, shown in Fig. 1.

Conclusions

As a result of the work, it is shown that electricity generation is a complex and dangerous process. The most fire and explosion hazardous technological process of electricity generation at power plants is the process associated with the operation of hydrogen-cooled turbine generators.

The paper investigates the causes and locations of fires and explosions at hydrogen-cooled turbine units and the fire and explosive properties of hydrogen. The possibility of forming a combustible environment and the danger of an ignition source in it are shown.

As a result of the calculations performed, it was found that the actual mode of fire action in the event of fires at these facilities differs significantly from the «standard temperature regime» (duration of 120 minutes, with a maximum temperature of 1329 K), «temperature regime of hydrocarbon fire» (duration of 40 minutes, with a maximum temperature of 1380 K), «temperature regime of modified hydrocarbon fire» (duration of 40 minutes, with a maximum temperature of 1600 K). The duration of the emergency leakage (burning) of the hydrogen jet is 2.5 minutes. Given that the temperature of the flame torch is 2200 K, it is reached in 15 – 20 seconds.