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Article

Study of the causes of the collapse of a high-rise chimney under conditions of long-term operation

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Abstract. This article analyzes the causes of the collapse of a high-rise chimney in Petropavlovsk. A study of the factors of long-term (over 60 years) operation of a high-altitude (H=150 m) chimney was carried out. The analysis of the constructive solution of the pipe was carried out, and the study of the operating conditions was performed. To theoretically assess the technical condition and stress-strain state factors (SSS) of the collapsed chimney, automated verification calculations were carried out based on the actual parameters and characteristics obtained during the last technical inspection. An automated verification calculation of SSS factors determining the bearing capacity of an object (its strength, rigidity, reliability, and durability) has been performed. Theoretically, the physical wear of the object has also been carried out. Based on the study of the available technical documentation and conducting a continuous, detailed instrumental examination of the facility, the expert organization established the significant causes that led to the pipe accident.

Keywords: chimney, industrial buildings and structures, technical inspection, reliability, calculations, physical wear, reliability and stability, defects and damages.

1. Introduction

Currently, the problem of ensuring the safe operation of energy facilities has become more acute. Accidents at Thermal Power Plants (TPPs) are associated with a high percentage of dilapidation of chimneys. The problems of destruction of buildings and structures are well studied, but there is little research in the field of safe operation and monitoring of the technical condition of chimneys. Chimneys of large height, are under continuous action of variable dynamic wind loads, and aggressive high-temperature gas flows [1, 2]. The collapse of chimneys is often associated with their wear and tear, lack of timely diagnostics of technical condition or repair, and the violation of operation and work in an aggressive environment. The articles [3-6] consider the main problems of chimney operation, as well as the issues of development and introduction into practice of a set of methods and measures for operational assessment of chimney wear [7].

No organization specializes in the design, construction, and inspection of chimneys in Kazakhstan today. Most industrial chimneys were built in the 50-70s of the 20th century, therefore, the issue of developing alternative renewable energy sources is rising more frequently [8]. The articles [9-11] discuss the problems that arise in the production of electricity using renewable energy sources. The design life of industrial structures is 50 years, and the periodicity of inspections should be performed at least once every 5 years [12, 13]. Regular inspection makes it possible to identify defects and damages, if detected, it is possible to stop operation and take measures to eliminate them. This makes it possible to keep the structure safe and avoid human, environmental, and economic losses in the process of collapse.

Currently, to control the safety of industrial chimneys various methods are being developed. The articles [14-16] consider a method using an in-line autonomous apparatus capable of determining and registering defects in the lining of the chimney without disconnecting it from the operating boilers. Along with this, surveys of high-altitude chimneys at hazardous production facilities are carried out, so in [17-19] the main task of the survey is to determine the technical condition of the structure, assess the operational suitability and possible recommendations for bringing the object following the requirements of regulatory documentation.

Over the last decades, as a result of a sharp decline in industrial production due to the economic crisis in the country, the rupture of previously established relationships, and privatization of enterprises, significantly changed the modes of operation of industrial chimneys and weakened control over their technical condition, which adversely affects their strength characteristics. The accident that occurred at Petropavlovsk TPP-2 serves as a confirmation of this fact. In the third decade of March 2022, there was a partial collapse of the upper part of the pipe from 150 m to 97 m that destroyed several structures of nearby auxiliary and attached buildings and structures (smoke pump room, gas ducts) [20]. Therefore, this study aims to study the factors of the long-term (over 60 years) operation of a high-rise (H=150m) chimney in Petropavlovsk, as well as the causes that led to its collapse

2. Methods

Figure 1 presents a general view of the Petropavlovsk TPP-2 (Republic of Kazakhstan).

Figure 1 - General view of the chimney of Petropavlovsk TPP-2 after collapse

From the structural point of view, the object under study is a multilayer and variable thickness cantilever conical chimney with a length of about 150 m, the thickness of the chimney varies from

750 mm at the bottom to 160 mm at the top, the concrete of the chimney shaft corresponds to class B15 (grade M200 on Portland cement M400). The chimney is supported by a reinforced concrete round foundation with a diameter of 30.0 meters and a depth of 4.0 meters.

The chimney is three layers thick, the main (bearing) material is monolithic reinforced concrete, mineral wool mats overlapping the gap of 30-50 mm between the layers, and a lined layer made of ordinary bricks of 100 grade on the mortar of 25 grade.

The conditions of long-term operation are as follows: II wind region, flue gas temperature: 151-158ºC (before gas cleaning), 76-85ºC (after gas cleaning); flue gas humidity 8-10%; flue gas dew point temperature up to 30ºC; atmospheric air temperature in the area of chimney location is: -43ºC (in winter); +39ºC (in summer); non-seismic terrain (up to 6 points); normative requirements for the 2nd limit state: allowable crack opening asgs=0.1...0.2 mm; displacement of the chimney top up to 1/75 of its height – 20 cm (from normative wind load).

The content of this article is devoted to the study of the technical causes that led to the emergency collapse of a part of the pipe based on the analysis of the results of a technical inspection conducted by a research and expert organization KazMIRR (Karaganda, Kazakhstan) [20].

The preliminary conclusion (without the results of the necessary verification calculations of the stress-strain state (SSS) of the chimney structures) of the experts is as follows. Partial collapse of the chimney shaft is a consequence of several factors superimposed during the period of long-term operation: low strength of concrete of some sections of the chimney (0.50...0.83% of the design grade); violation of the integrity of the lining of its part of the length and part of the thickness of the chimney, which significantly changed the state of the temperature field of the massif of the structure due to the inhomogeneity of the conditions of heat transfer and heat transfer, which resulted in a significant increase in the values of temperature displacements and directions; increase in the moisture content of the wall of the chimney, as well as to the reduction of the design thickness in certain sections of the pipe, which created conditions for a sharp increase in mechanical stresses as a result of their spontaneous redistribution and concentration in certain sections and joints as a result of the above unfavorable factors, the presence of which created their emergency combination, which sharply reduced the level of VAT of the object led to a partial collapse of the upper part of the pipe, in which the force factor (wind load pulsation) contributed to the conditions of reduction of bearing capacity parameters.

It should be noted that according to the data of the operators on the results of repeated technical inspections (1971, 1977, 1986, 2013), recommendations on the relevant repair works on the chimney were not carried out, moreover, according to the relevant norms the service life of such objects is about 50 years (the chimney under study has been operated for more than 60 years).

3. Results and Discussion

To theoretically assess the technical condition and VAT factors of the collapsed chimney, automated verification calculations were carried out according to the actual parameters and characteristics obtained during the last technical inspection, and the following results were obtained (Figure 2):

- 1.4 times underestimated the actual wind load, for which, for its time, this chimney was designed;

- the load-bearing capacity of the shaft on the first turbine of limit states, on which design sections are not provided (there is an excess of design resistance of concrete to compression);

- since the lining on the 10th section (in the area of +25.0m) is significantly disturbed (according to the results of the last inspection), the chimney shaft is in direct contact with flue gases, as a result of which the total stress from the force and temperature load amounted to 5.79MPa, which exceeds the design resistance of concrete in 5.1MPa (the increase in the total stress is due to the growth of temperature stress from 1.33MPa to 3.4MPa).

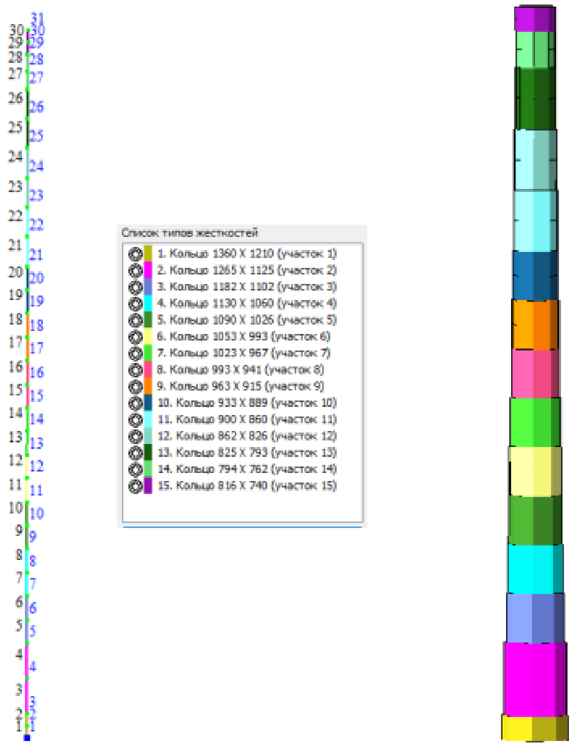

Figure 2 – Calculation diagram of the chimney

Thus, combining the analysis data of the preliminary conclusion on the technical condition of the chimney according to the results of the last (expert) inspection, which revealed a lot of defects and damages of quality and structures, basic materials (monolithic reinforced concrete, brick lining, mineral wool mats) with the results of automated verification calculation of VAT factors that determine the bearing capacity of the object (its strength, rigidity, reliability and durability). It should be noted that the main reason for the partial collapse of the chimney in Petropavlovsk is the physical deterioration caused by a long (excessive) period of operation (more than 60 years), a decrease in the amplitude of wind load during the design of the object according to outdated standards, the presence of defects in concreting and construction technology, failure to meet the deadlines for preventive maintenance and lack of a proper system of inspection and observation of the process of technical condition during the long period of operation of such a unique structure.

To assess the degree of physical deterioration on the technical condition of the object, let us determine theoretically the physical deterioration of the object by Eq. (1):

$$Q_f = 100 \times k_0^t \int 1.036^{t/5} dt \quad (1)$$

Where: the previous limit of integration "0" is taken as t=1 year; k=0,0168 (according to [21], Table 1; for the building of IV group of capitalization normative service life up to 50 years); t - 61 years (service life of the chimney at the time of the last technical inspection).

By (1) we obtain:

$$Q_f = 5 \times 100 \times 0.0168 \times \frac{\left(1.036^{61/5} - 1.036^{1/5}\right)}{\ln 1.036} = 8.4(1.5395 - 1.0071)/0.03537$$
$$= 8.4(0,5324)/0.03537 = 126.44$$
$$Q_f = 126.44\% > 100\%,$$

i.e., the theoretical wear of the chimney in long-term operation (more than 61 years of operation) exceeds the limit (100%) wear.

The theoretical value $Q_f = 126.44\%$ corresponds to the established expert assessment of the technical condition of this object as "emergency" (or "unsuitable" for operation) ([22], Table 3, p.20).

Next, let's determine the statistical probability of further failure-free operation (FRO) of the system (chimney) beyond the service life (t = 61 years), established at the last technical inspection

(May 2022). We assume that the probability of failure follows the one-parameter exponential law of probability distribution [22], then we have:

$$p(t) = e^{-\pi t} \quad (2)$$

Where: t – operation period; π – failure rate.

Let's take theoretical time to first failure (T_p=100 years), then [($\pi=1/T_p$)=(1/100=0.01)].

1/year – failure rate.

Let's build a graph of "FRO" change according to Eq. (2) on the parameter "t" (Figure 3).

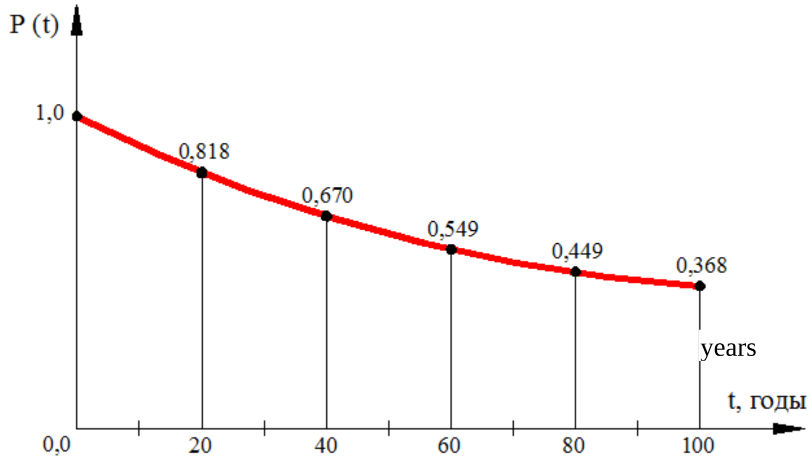

Figure 3 – Dependence of the "FFO" value on the parameter "t"

If we consider that the probability of failure-free operation (FFO) less than 67% is unacceptable from the point of view of reliability of further operation, then according to the graph in Fig. 1, the suitable service life of this chimney should not exceed 40 years. The actual service life of the chimney at the moment of the last technical inspection was more than 61 years, i.e., according to our research, the operation of the collapsed chimney should have been suspended more than 20 years ago.

In the course of the last technical inspection of the chimney, non-destructive methods of testing the strength of concrete R (MPa) with simultaneous determination by ultrasonic device UKS-MG4S of the speed of sound wave passing through the concrete material of the chimney sections were carried out by the device IPS-MG4.03. υ (м/с).

At the same time, the results of tests in 38 sections for 78 control sections constituted a statistical sample with a spread of values in the range of R = (8.8÷35.6) MPa; υ = (1703÷4669) м/с.

Based on these data, in this paper, we will conduct a bivariate regression analysis to establish a correlation relationship between the strength of the concrete of a chimney and the speed of sound traveling through the mass of its material [23, 24]. Further we denote: X_i – this R_i; y_i– υi. Table 1 shows the above concrete test results in the form of a two-dimensional statistical sample N=78, with all data pre-ranked in ascending order of their values by a constant step size in each of the accepted value ranges.

Table 1 – Concrete test results in 2D sample N=78

y_i, m/s / x_i, MPa	y_1=1000÷2000	y_2=2000÷3000	y_3=3000÷4000	$m_{x\gamma}$
X_1=0÷10	3	4	4	11
X_2=11÷20	4	21	12	37
X_3=21÷30	1	14	11	26
X_4=31÷40	–	–	4	4
$m_{y\gamma}$	8	39	31	78

Let us divide the data of Table 1 into two separate worksheets: Table 2 – for parameters x_i(i=1, 2, 3, 4); Table 3 – for y_i(i=1, 2, 3).

Table 2 – X-parameters

x	n	xn	x^2n
10	11	110	1100
20	37	740	14800
30	26	780	23400
40	4	160	6400
Σ	78=N	1790	45700

Table 3 – Y-parameters

x	n	xn	y^2n
2000	8	16000	32000000
3000	39	11700	351000000
4000	31	124000	496000000
Σ	78=N	257000	879000000

Let's calculate the sampling parameters according to the table 2:

a) $\bar{x} = \sum xn / N = 1790/78 = 22.95$; $\bar{x}^2 = \frac{\Sigma x^2 n}{N} = \frac{45700}{78} = 585.90$ – average values

b) Let's calculate the variance:

Dx= $\bar{x}^2 - (\bar{x})^2$ =585.7025-526.7025=59

c) Standard deviation:

σx= $\sqrt{Dx} = \sqrt{59}$ =7.68

According to the Table 3:

a) $\bar{y}$ =3294.87; $\bar{y}^2$=11269230.77

b) Dy=11269230.77-$(3294.87)^2$=393284.23

c) σx=$\sqrt{393284.33}$=627.12

Let's calculate the complex product of values (n×x×y) (Table 4) considering the Table 1 data.

Table 4 – Complex product of values (n×x×y)

x \ y	2000	3000	4000	m_{yi}
10	60000	120000	160000	340000
20	160000	1260000	960000	238000
30	60000	1260000	1320000	2640000
40	–	–	640000	640000
m_{xi}	280000	2640000	3080000	6000000

According to the data in Table 4, we calculate the value of $\overline{xy}$:

$\overline{xy} = \Sigma xny / N$ = 6000000/78=76923.08

Then, using the data in Table 1, we will solve the following probabilistic questions:

1) Calculate the correlation relationship η_{xy} between the values of "x" and "y", by which we will determine the degree of their relationship with each other.

$$\int xy = \delta y / \delta y = \delta x / \delta x \quad (3)$$

Where: $(\delta x, \delta y)$ – "link" correlation coefficients.

If Eq. (3), in our case, yields a value (η_{xy}) close to one, then we can say that the correlation relationship between the statistical variables will be strong (i.e., they are strongly interrelated), otherwise, this relationship is weak.

2) Let's reveal the analytical dependence between the parameters x_i and y_i (Table 1) based on the available statistical sample, considering this dependence to be quadratic, according to Eq. (4).

$$y = a x^2 + вx + c \tag{4}$$

We determine the uncertain coefficients (a, b, c) in Eq. (4) by solving Eqs. (5-7).

$$\Sigma y = a\Sigma x^2 + в\Sigma x + cn \tag{5}$$

$$\Sigma x_i y_i = a\Sigma x^3 + в\Sigma x^3 + c\Sigma x \tag{6}$$

$$\Sigma x_i^2 y = a\Sigma x^4 + в\Sigma x^3 + c\Sigma x^2 \tag{7}$$

Let's determine the values $\bar{y}(x_i)$ (i=1, 2, 3, 4) according to Table 1.

$$\bar{y}(x_1=10) = \frac{\Sigma x_1 y_i}{m_{x\gamma}} = \frac{32000+43000+44000}{11} = 3091.00$$

$$\bar{y}(x_2=20) = \frac{42000+213000+124000}{37} = 3216.22$$

$$\bar{y}(x_3=30) = \frac{13000+143000+114000}{26} = 2961.54$$

$$\bar{y}(x_4=40) = \frac{4*4000}{4} = 4000.00$$

The following calculations are performed in Table 5 below.

Table 5 – Calculations

x	$\bar{y}_к$	m_x	xm_x	x^2m_x	x^3m_x	x^4m_x	$\bar{y}_к m_x$	xym_x	x^2ym_x
10	3091.00	11	110	1100	11000	110000	34001	34010	3400100
20	3216.22	37	740	14800	296000	5920000	119000.14	2380003	47600000
30	2961.54	26	780	23400	702000	21060000	77000.04	2310001	69300030
40	4000.00	4	160	6400	256000	10240000	16000	640000	25600000
Σ	–	78=N	1790	45700	1265000	37330000	246001.18	5670014	145900130

Substituting the data (Table 5) into the Eqs. (5-7) (N=78) we get Eq. (8) below.

246001.18 = (45700)a + (1790)b + (78) c (1/246001.18)
5670014 = (1265000)a + (45700)b + 1790 c (1/5670014)
145900130 = (37330000)a + (1265000)b+(45700)c (1/246001.18145900130)
or
1= (0.1858)a + (0.00728)b + (0.000324)c
1=(0.2231)a+(0.00806)b+(0.000316)c
1= (0.2559)a + (0.00867)b + (0.000313)c (8)

Solving Eq. (8) we determine the uncertain coefficients (a, b, c) in Eq. (9).

a = –1.62574 b = 96.60 c = 1848.19 (9)

Substituting the values of Eq. (9) into the general Eq. (4) we obtain Eq. (10) below – the regression (statistical) relationship between concrete strength (R_i=x_i) (MPa) and sound propagation velocity in the concrete mass ($\vartheta_i = y_i$) (m/s).

$$y_i = 1.62574\ x_i^2 + 96.6\ x_i + 1848.19 \tag{10}$$

Eq. (10), obtained based on statistical processing of the results of in-situ tests of concrete sections of the chimney can be used also for other construction objects. Having determined the actual strength of concrete on this or that object of technical inspection, by Eq. (10) it is possible to determine analytically the speed of sound in concrete. The value υ_i will be used in calculations of wave processes in various reinforced concrete structures.

4. Conclusions

In this paper, we analyzed and conducted an extensive study of the results of technical inspection of the structures of reinforced concrete high-rise chimney. The necessity of the inspection was caused by the fact that in March 2022 at the TPP-2 in Petropavlovsk there was a collapse of its upper part. The expert organization on the basis of the study of the available technical documentation and a comprehensive, detailed, and instrumental examination of the object established the significant causes that led to the failure of the chimney.

Taking into account verification calculations on the basis of generalized results of technical inspection, the following was established:

1. The object is in a significant degree of physical deterioration (service life at the time of the survey was more than 61 years) due to the factors of natural aging of materials that provide the necessary serviceability: concrete degradation, destruction of the integrity of the lining layer, as well as systematic force (wind load pulsation) and temperature (passing through the trunk of the pipe flue gases with increased temperature parameters of influence).

2. The absence of a system of superimposed control over the technical condition of structures by the operators, given that the high-altitude chimney is a complex and unique engineering structure, operated, moreover, in difficult climatic conditions (seasonal and daily temperature fluctuations), in the open atmosphere.

3. despite the recommendations of previous technical inspections (1971, 1977, 1986, 2013) the required preventive and mandatory repairs of the load-bearing parts of the facility were not performed on the chimney.

4. In-situ tests of the actual strength of concrete showed a wide variation of their indicators from 8.7 to 34.1 MPa, which indicates non-homogeneity of mechanical strength of different sections of the pipe, indicating unfavorable distribution of the main stresses along the design length of the structure.

5. Aging of the pipe structures confirmed the determination of the theoretical wear value, which amounted to more than 100%, while the calculation of theoretical wear established that 100% wear of the object should have occurred after 40 years of its operation (the actual period before the collapse - 61 years).

6. In this paper, based on in-situ tests by non-destructive methods of the results of concrete strength of the chimney sections, given by the expert organization during the last technical inspection, regression analysis of the relationship between the strength of concrete "R" and the speed of the sound wave through the sections of the chimney structure was performed; this analysis was performed with a statistical sample of data for 78 sections of the chimney. The analytical Eq. (10) obtained as a result of regression analysis allows determining the wave velocity of concrete of various structures at other construction sites, i.e., it is sufficiently universal.

7. In general, the outcomes and results of this study allow us to expand the scope of knowledge in the field of analyzing possible accidents of construction objects in order to develop a scientific and technical basis for preventing such collapses in the future.

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