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STEAM BOILERS, POWER-PLANT FUELS, BURNER UNITS, AND BOILER AUXILIARY EQUIPMENT

Analysis of the Benefits of TPP's Three-Barrel Smokestacks

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Abstract—The structures of three- and four-barrel smokestacks are compared using the method of total discounted costs. It was revealed that three-barrel stacks are more profitable than four-barrel ones in almost the entire range of used smokestack characteristics with modern cost ratios. Formulas are given for calculating the diameter of the smokestack casing with two identical bores and a third, different in size. A technique has been developed for calculating the diameter of the casing of a three-barrel stack with bores of various diameters. In all compared variants, the same distances were laid between adjacent bores and the barrel and casing. For the first time, a methodology has been proposed for choosing the optimal dimensions of a three-barrel smokestack taking into account the individual conditions of gas transport along each barrel, allowing one to find the optimal distribution of gas velocities over bores of a three-barrel stack and to calculate the minimum total discounted costs for smokestacks with bores of different diameters, flow rates, and gas temperatures in them. It is shown that taking into account the hydrodynamic features in the bores with different gas velocities allows us to propose solutions that reduce the total reduced costs by 7–8% compared to traditional solutions. In the event that the optimal solution is to provide different speeds in the bores, then it is necessary to install confusers on each bore with individual and sufficient small angles of narrowing in order to prevent uneven velocity fields at the mouth of the smokestack and possible vortex formation when the flue gas flows from different bores merge when the stack is operating at maximum load.

Keywords: three- and four-barrel smokestacks, perimeters of barrels and reinforced concrete casing, multibarrel smokestacks with different diameters of barrels, different temperatures of gases in the barrels, optimal speed of flue gases in each barrel

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The first multibarrel smokestack 200 m high for connecting four 500-MW power units was built in England at Eggboro TPP, North Yorkshire, in 1967 and has been operating up to the present. Since then, multibarrel smokestacks have been widely used in world energy. Their advantages were also appreciated in the Soviet Union. Multibarrel smokestacks are effective at large TPPs operating on sulfur dioxide, including CHPPs with a large industrial load [1]. During their construction, higher costs are required in comparison with single-barrel smokestacks, while they provide more reliable operation of gas-air paths of thermal power plants. This is achieved due to the fact that there are hardly any restrictions on the duration in operation of the bearing reinforced concrete casing, and it is also possible to repair the exhaust stacks located in it in turn without disconnecting all equipment connected to the stack. For this purpose, there is a service area inside the reinforced concrete casing, which is also suitable for repairing one of the bores during the rest. At the level of external traffic lights, internal solid areas are also established, which communicate with each other through a passageway in the casing. Between adjacent bores and between the barrel and the casing on the inner platform there are passage gaps. Bores are most often made of steel. Thermal insulation of the bores allows one to ensure the temperature of their inner wall above the dew point temperature, which prevents or significantly slows down the low-temperature corrosion, even when operating on sulfur fuel.

Three- and four-barrel smokestacks are the most commonly used. If the number of connected boilers is a multiple of three, then a three-barrel stack is selected, if it is four then a four-barrel stack is selected. However, with this justification for choosing the number of bores, some significant factors that are considered in this article are not taken into account.

In accordance with the requirements of [2], the width of the free passage of the sites should be at least

600 mm, while it should be at least 800 mm for the maintenance of instrumentation and other equipment. Given the margin for thermal insulation, the minimum distance between adjacent bores is taken to be 1.2 m, and the minimum distance between the barrel and the reinforced concrete casing is 1.0 m. The cost of the bearing reinforced concrete casing is approximately 50%, the bores are 40%, and the foundation is 10% of the cost of a multibarrel stack with a height of 200–250 m. These ratios depend on the perimeters of the casing and bores. Further in this article, the share of the cost of the foundation is assumed to be constant and equal to 10%.

CONDITIONS OF COMPATIBILITY OF VARIANTS FOR CONNECTING EQUIPMENT TO A SMOKESTACK

If the same equipment is connected to the stack, the bores are made of the same size. Figure 1 shows cross-sections of a three- and four-barrel smokestack at the narrowest point on the upper platform.

To calculate the perimeters of three- and four-barrel stacks with bores of the same diameter, it is necessary to use the ratio between the diameters of the bores and the reinforced concrete casing under the accepted assumptions

$$D = \frac{d + 1.2}{\sin\frac{180}{N}} + d + 2, \quad (1)$$

where d is diameter of the barrel and N is the number of bores (three or four).

With the same total cross-sectional areas of the bores, the ratio of the total perimeter of bores P_3 to the total perimeter of the bores of a four-barrel stack P_4 does not depend on the size of the bores and is

$$\frac{P_3}{P_4} = \sqrt{\frac{3}{4}} \approx 0.866. \quad (2)$$

The share of the cost of the bores in the total cost of the smokestack grows with an increase in the total cross-sectional area of the bores f since the ratio of the perimeters of the bores P_{st} increases to the perimeter of the casing P_{cas} (Fig. 2).

Based on Fig. 2 and formula (2) it can be shown that the ratio P_{cas3}/P_{cas4} (where P_{cas3} and P_{cas4} are the casing perimeters of the three-and four-barrel stacks) with a change in the total cross-sectional area from 10 to 100 m^2 (which corresponds to connecting at least one PTVM-100 hot-water boiler and one maximum boiler of the K-500 power unit to one bore) varies from 0.978 to 1.006. Therefore, the perimeter of the casing of a three-barrel stack in the entire range f under consideration hardly exceeds the perimeter of the casing of a four-barrel stack. Thus, instead of a four-barrel, a three-barrel smokestack should be used, since the cost of a three-barrel smokestack is approximately 6% less

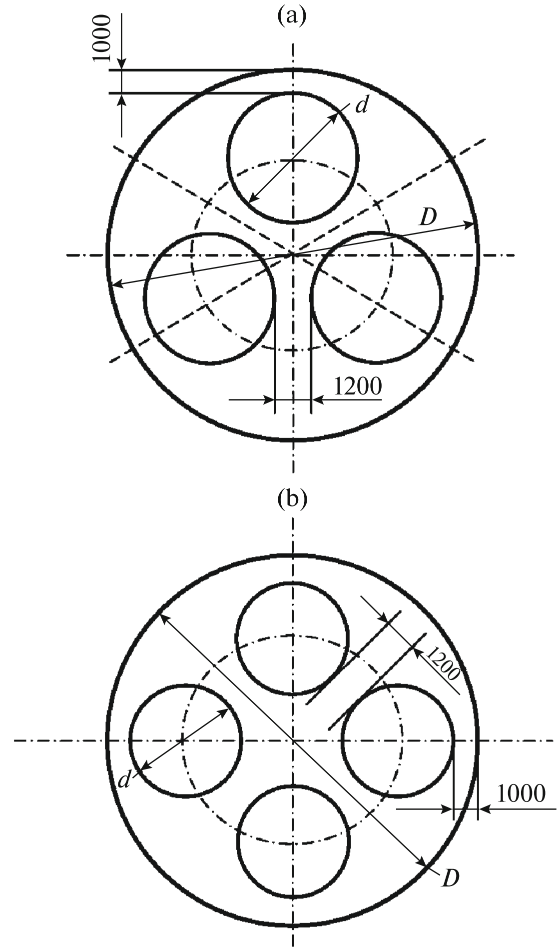

Fig. 1. Cross section of (a) three- and (b) four-barrel smokestacks. D, diameter of reinforced concrete casing; d, barrel diameter.

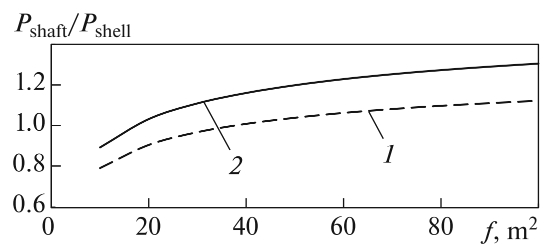

Fig. 2. Dependence of the ratio of the bores' perimeters to the perimeter of the casing on the total cross-sectional area of the bores for (*1*) three-barrel and (*2*) four-barrel stacks.

than the cost of a four-barrel smokestack due to the smaller perimeter of the bores. In addition, the cost of transporting gases in a three-barrel stack will be less due to increased bore diameters.

With four boilers, it is possible to connect two boilers each to its own bore and two boilers to one common bore; with five boilers, one boiler is connected to a sep-

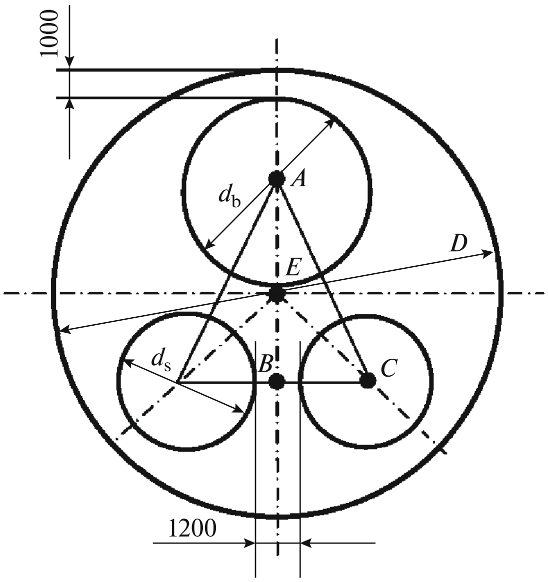

Fig. 3. Cross section of a three-barrel smokestack with two small and one large bore; d_l, d_s are diameters of large and small bores.

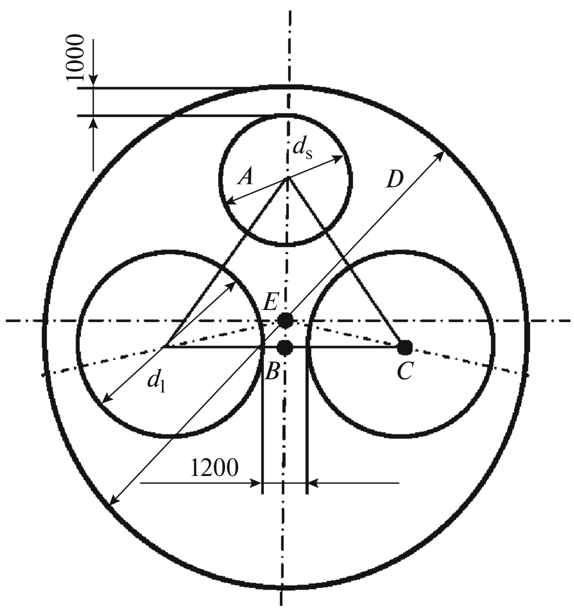

Fig. 4. Cross section of a three-barrel smokestack with two large and one small bores. See Fig. 3 for designations.

arate barrel and the four other boilers to two boilers to one barrel. If we assume that the gas velocity in all the bores is the same, then the cross-sectional area of the large bore will be two times the area of the small bore.

The cross section of a three-barrel smokestack is shown in Fig. 3. The areas of its two small bores are the same as the four-barrel smokestack, and the cross-sectional area of the third (large) barrel is two times larger than the area of a small barrel with the same passage gaps.

Distance $b = AC$ is calculated by the formula

$$b = \frac{d_l}{2} + \frac{d_s}{2} + 1.2. \quad (3)$$

Distance $a = BC$ can be calculated by the expression

$$a = \frac{d_s}{2} + 0.6. \quad (4)$$

To determine the height $h = AB$ right triangle ACB, we can use expression

$$h = \sqrt{\left(b^2 - a^2\right)}. \quad (5)$$

If distance is set as $s = AE$, then the distances $e = BE$ and $c = EC$ can be calculated by the formulas

$$e = h - s; \quad (6)$$

$$c = \sqrt{\left(e^2 + a^2\right)}. \quad (7)$$

From the condition of equality of the casing radii, we can obtain

$$s + \frac{d_l}{2} + 1 = \sqrt{\left[(h - s)^2 + a^2\right]} + \frac{d_s}{2} + 1 \quad (8)$$

or

$$s = \frac{h^2 + a^2 - \left(\frac{d_l}{2} - \frac{d_s}{2}\right)^2}{2\left(\frac{d_l}{2} - \frac{d_s}{2} + h\right)}. \quad (9)$$

After introducing the notation

$$u = \frac{d_l}{2} - \frac{d_s}{2} \quad (10)$$

formula (9) can be represented as

$$s = \frac{h^2 + a^2 - u^2}{2(h + u)}. \quad (11)$$

Taking into account (3)–(11), the formula for calculating the diameter of the reinforced concrete casing takes the following form:

$$D = 2s + d_l + 2. \quad (12)$$

If you need to connect five identical boilers to a three-barrel stack, install two large barrels and one barrel of a smaller diameter (Fig. 4).

By analogy with the previous arguments, we can write

$$s = \frac{h^2 + a^2 - u^2}{2(h - u)}, \quad (13)$$

where

$$a = \frac{d_l}{2} + 0.6. \quad (14)$$

Table 1. Results of the calculation of the parameters and cost of the construction of the smokestack

Parameter, costs	Variant 3	Variant 4
Stack height H, m	252.1	251.5
Optimum flue gas velocity in the bores at the outlet of the stack w_0, m/s	25.2	25.7
Barrel diameter d_b, m:	4.5	–
small d_m	–	4.45
large d_l	–	6.30
Diameter of reinforced concrete casing D, m	14.56	14.47
Cost of stack C_{st}, million rubles	453.4	427.2
Total discounted costs C_d, million rubles	442.4	410.5

The diameter of the casing of such a stack is calculated by the formula

$$D = 2s + d_m + 2. \quad (15)$$

When checking the advantages of a three-barrel stack over a four-barrel condition for comparability of variants, the same total cross-sectional area of the bores should be considered. The ratio of the perimeters of bores of a three-barrel stack with two small and one large bore (variant 1) to the perimeter of bores of a four-barrel stack decreases from 0.866 to 0.854 and that for a stack with one small and two large bores (variant 2) decreases to 0.856. This means that the cost reduction of the bores will be even more significant than for stacks with the same bores in both versions.

The diameter of the casing of a three-barrel stack in variant 1 when changing the total cross-sectional area of the bores from 10 to 100 m^2 will be the same as for a three-barrel stack with the same bores and less than the diameter of a four-barrel stack with the same bores in the interval f = 10–60 m^2. At f = 100 m^2, the diameter of a reinforced concrete casing of a three-barrel stack D_3 will be a little more than a four-barrel D_4: D_3 = 17.42 and D_4 = 17.32 m. Thus, it can be expected that the cost of a three-barrel stack in variant 1 will be 5–6% less than the cost of a four-barrel stack with the same bores. The results for variant 2 may be similar.

TECHNICAL ECONOMIC ANALYSIS

More accurate data can be obtained by calculating the total discounted costs according to the methodology described in [3] and implemented in the software package [4] using the example of a four-bore stack of the Kostroma state district power station, for which a 300-MW power unit is connected to each bore (variant 3), and a three-bore stack with two small bores, to which one power unit is connected, and one large bore with two power units connected to it (variant 4).

The initial data for the calculation are given below:

Flue gas flow rate per stack V, m^3/s	1600
Mass emission of harmful substances M, g/s, for working on fuel oil in terms of nitrogen oxides	2400
Temperature, °C:	
air t_a	20
flue gas t_g	130
Maximum concentration of harmful substances at the level of breathing created by the smokestack c_{st}, mg/m^3	0.1
Impurity deposition coefficient F	1.0
Average thickness of the walls of the bores δ, m	0.014
Absolute roughness of the walls of the bores Δ, m	0.002
Cost of reinforced concrete, thousand rubles/m^3, used in manufacture:	
stack casing $C_{r/c}$	24
foundation C_f	17
Cost of metal (steel) from which bores are made C_s, thousand rubles/m^3	585
Cost of electricity a_{en}, rub/(kWh)	2.0
Share of borrowed funds E1	0.8
Inflation E2, %	5.0
Percentage loan E3, %	10.0
Cost of workday C_{wd}, thousand rubles/day	3.0

The results of the calculation of the smokestack parameters are given in Table 1.

The dependence of the total discounted costs on the rate of exit of flue gases is shown in Fig. 5. As can

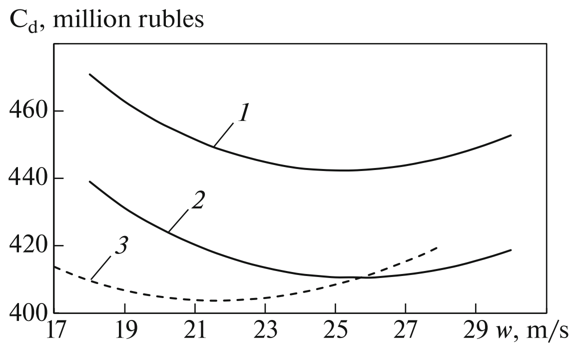

Fig. 5. Dependence of the total discounted costs on the gas exit rate for (*1*) four-barrel and (*2*) three-barrel stacks at constant surface concentrations of harmful substances and for (*3*) a three-barrel stack at its constant height.

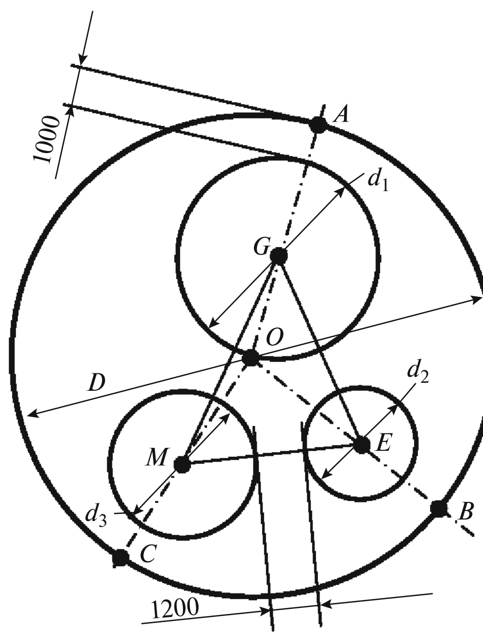

Fig. 6. Cross section of a three-barrel smokestack with three different bores; d_1, d_2, d_3 are bore diameters.

be seen from the figure, the total discounted costs with an increase in the rate of flue gases' exit decrease by 31.93 million rubles or 7.2%.

The results of the second optimization at a constant height of 251.5 m, which was obtained during the first optimization, are presented below:

w_0, m/s	21.6
C_{st}, million rubles	450.4
C_d, million rubles	403.7
d_s, m	4.86
d_k, m	6.87
D, m	15.48

However, the surface concentration of harmful substances will exceed that permissible and will be $c_{st} = 0.108$ mg/m^3.

To provide the concentration $c_{st} = 0.1$ mg/m^3, it is necessary to maintain a gas velocity at the mouth of the stack $w_0 = 25.7$ m/s, and, for this purpose, confusers with a small narrowing angle must be installed in the output part of the bores at a length of 5 m. The diameter of small bores should be reduced from 4.86 to 4.45 m and large from 6.87 to 6.30 m. The narrowing angle for small and large bores is 2.3° and 3.3°, respectively. At the same time, both the cost and aerodynamic characteristics of the smokestack hardly change. Thus, a decrease in the velocity of gases in bores of trilateral bores from 25.7 to 21.6 m/s makes it possible to reduce the total reduced costs by another 6.763 million rubles or just 8.7%. As a result, the cost of the smokestack decreased from 453.4 to 450.4 million rubles.

If the main goal is to reduce not the total discounted costs, but the cost of the smokestack, then you can stop at the variant with the gas velocity in the bores $w_0 = 25.7$ m/s. At the same time, the cost of the stack is reduced from 453.4 to 427.2 million rubles or 6%. In this case, the gas velocities in the bores can also be optimized. If the gas velocity is reduced by 1.5% (to 25.3 m/s) in small bores and increased by 1.5% (to 26.2 m/s) in a large bore, then the total discounted costs will decrease by an additional 72000 rubles. (from 410.490 to 410.418 million rubles).

If the surface concentration of harmful substances needs to be reduced from 0.10 to 0.06 mg/m^3, then the height of the smokestack will be 334.1 m, and the optimal gas velocity will be 28.2 m/s at a total discounted cost of 662.7 million rubles. In this case, an increase in the velocity of gases in a large bore from 28.2 to 28.9 m/s with a decrease in their velocity in small bores from 28.2 to 27.6 m/s allows for reducing the total discounted costs by 235000 rubles (from 662.753 to 662.518 million rubles).

METHOD OF CALCULATING GEOMETRIC PARAMETERS OF THREE-BARREL SMOKESTACKS WITH BARRELS HAVING DIFFERENT DIAMETERS

To calculate the parameters of a three-barrel smokestack with bores of three different diameters, d_1, d_2, and d_3, the cross section of which is shown in Fig. 6, the minimum distance between the bores is taken as equal to 1.2 m and that between the bores and the casing as 1.0 m.

First, we need to develop a methodology for calculating the inner diameter of the reinforced concrete casing of the smokestack. The following conventions are used here: O is the center of the casing's circumference; R is the casing radius; $OA = OB = OC = R$;

$GE = l = \frac{d_1}{2} + \frac{d_2}{2} + 1.2$; $EM = g = \frac{d_2}{2} + \frac{d_3}{2} + 1.2$; $MG = e = \frac{d_3}{2} + \frac{d_1}{2} + 1.2$; $\frac{d_1}{2} - 1 = c_1$; $\frac{d_2}{2} - 1 = c_2$; $\frac{d_3}{2} - 1 = c_3$; p_1, p_2, and p_3 are semiperimeters of triangles *OGE*, *OEM*, and *OMG*; S_1, S_2, and S_3 is the area of triangles *OGE*, *OEM*, and *OMG*.

Seimperimeter *p* of the triangle *GEM* can be calculated by the formula

$$p = (l + g + e)/2.$$

Area *S* of the triangle *GEM* in accordance with the formula of Heron can be represented as follows:

$$S = \sqrt{p(p - l)(p - g)(p - e)}. \quad (16)$$

According to Fig. 6, $OG = R - c_1$, $OE = R - c_2$, $OM = R - c_3$.

Semiperimeters of triangles can be calculated using the following formulas:

$$p_1 = (OG + l + OE/2);$$
$$p_2 = (OE + g + OM)/2;$$
$$p_3 = (OM + e + OG)/2.$$

The area of the triangles is calculated by

$$S_1 = \sqrt{p_1(p_1 - l)(p_1 - OE)(p_1 - OG)}; \quad (17)$$

$$S_2 = \sqrt{p_2(p_2 - g)(p_2 - OE)(p_2 - OM)}; \quad (18)$$

$$S_3 = \sqrt{p_3(p_3 - e)(p_3 - OG)(p_3 - OM)}. \quad (19)$$

To determine the optimum radius of the stack casing, it is necessary to compare the area *S* with the sum of the areas:

$$S_{\text{sum}} = S_1 + S_2 + S_3. \quad (20)$$

The problem is solved by the method of successive approximations. First we need to set the radius of the casing as clearly larger than required, for example $R = d_1 + d_2 + d_3$, then calculate area *S* and S_{tot} and compare them. If the difference $\Delta S = S - S_{\text{tot}}$ is too high, the value *R* should be reduced until ΔS is at an acceptable value, for example, 0.0005 m. After that, the radius and, therefore, the diameter of the stack casing are considered to be found.

The result is correct if each of the values S_1, S_2, and S_3 is greater than zero or equal to zero. If the radical expression in formulas (17)–(19) turns out to be less than zero, this means that a decrease in the diameter of this bore no longer leads to a decrease in the diameter of the casing. For example, when $d_1 = d_2 = d_3 = 5$ m casing diameter $D = 14.159$ m, while the diameter of the casing becomes $D = 13.218$ m with barrel diameter $d_3 = 3.15$ m. A further decrease in the diameter of this bore will not lead to a change in the diameter of the casing. At $d_3 = 3.15$ m and $d_2 = 2.33$ m, the diameter of the casing is $D = 11.362$ m. With a further decrease in bore diameter d_2, the diameter of the casing does not change.

EXAMPLE OF CALCULATION OF OPTIMAL GAS SPEED

The following is an example of calculating the optimal gas velocity in bores of different diameters. With the total gas flow in the stack $V = 1600$ m^3/s, the flow rate on the bores can be distributed as follows: $V_1 = 300$, $V_2 = 500$ and $V_3 = 800$ m^3/s. In this case, the optimal gas velocity at the same velocities in the bores will be equal to $w_0 = 25.7$ m/s and the total discounted costs will be $C_d = 411.884$ million rubles. However, if optimization is carried out for each bore, then the gas velocities in the bores will be: $w_1 = 24.1$, $w_2 = 25.7$, and $w_3 = 26.3$ m/s, and the total discounted costs will decrease to $C_d = 410.551$ million rubles, i.e., will decrease by 1.333 million rubles.

When redistributing speeds along the bores, it is necessary to ensure the constancy of the momentum *wV*. At equal speeds in the bores $wV = 25.7 \times 1600 = 41120$ m^4/s^2 at different speeds $wV = 24.1 \times 300 + 25.7 \times 500 + 26.3 \times 800 = 41120$ m^4/s^2, i.e., the condition of constant momentum is satisfied and the rise of the smoke plume from the stack does not change. The exact equality of the output speeds along the bores can be achieved by changing the cross-sectional area of the bores at the outlet stack section, the length of which is 5 m.

The methodology for calculating the parameters of the smokestack developed by the authors also allows one to take into account possible differences in the temperature of gases in the bores. This can be shown by the example of the calculation variant considered above, in which peak boilers with a volumetric gas flow rate are connected to one bore (no. 1) $V_P = 400$ m^3/s and temperature $t_P = 180$°C. Two other boilers are connected to two other shafts (no. 2, 3) with gas consumption per barrel $V_P = 800$ m^3/s and temperature $t_P = 120$°C. If we assume that the gas velocities in the bores are the same, then the average velocity is optimal $w_0 = 24.4$ m/s, and the total discounted costs will be $C_d = 388.81$ million rubles. In this case, with an increase in temperature in barrel no. 1 or an increase in the diameters of barrel nos. 2 and 3, an increase in the gas velocity in them is possible compared with the average. The predominance of a factor depends on specific conditions. In this case, the influence of increased diameters turned out to be predominant and the optimal speeds are distributed as follows: $w_1 = 24.0$, $w_2 = w_3 = 24.5$ m/s. Total discounted costs decreased to $C_d = 388.775$ million rubles.

If we assume that the temperature of the gases along the bores will be the same and be equal to the weighted average, i.e., t = 132°C, while maintaining the same distribution of gas flow rates, then the average speed at the same gas velocities in the bores is optimal at w_0 = 24.3 m/s, and the total discounted costs will be C_d = 387.352 million rubles. In this case, there is no factor influencing the increase in gas velocity in barrel no. 1; therefore, during optimization, a greater decrease in gas velocity is obtained in barrel no. 1: w_1 = 23.1 for $w_2 = w_3$ = 24.6 m/s. The total discounted costs decreased to C_d = 387.081 million rubles. Thus, it is possible to find the optimal solution taking into account the individual operating conditions of individual bores.

CONCLUSIONS

(1) Calculations by the comparative method developed by the authors showed the advantages of three-barrel smokestacks over four-barrel smokestacks. To ensure optimal gas velocities and equalize gas velocities along the bores at the mouth of the stack, we propose to install confusers with small narrowing angles on each barrel.

(2) When switching from four-barrel to three-barrel smokestacks, total costs are reduced by 7–8%.

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