ISSN 0040-6015, Thermal Engineering, 2020, Vol. 67, No. 3, pp. 157–164. © Pleiades Publishing, Inc., 2020.
Russian Text © The Author(s), 2020, published in Teploenergetika.

A General-Purpose Procedure for the Calculation of the Optimum Gas Velocity in Gas Exhaust Ducts of Stacks at Thermal Power Stations

N. A. Zroichikov[a], *, A. M. Gribkov[b], **, M. I. Saparov[a], *, and K. M. Mirsalikhov[b], ******

[a]*Krzhizhanovskii Energy Research Institute, Moscow, 119991 Russia*
[b]*Kazan State Power Engineering University, Kazan, 420066 Russia*
**e-mail: zna@eninnet.ru*
***e-mail: gribkovalmi@mail.ru*
****e-mail: saparov@eninnet.ru*
*****e-mail: mirsalihovkm@gmail.com*

Received July 15, 2019; revised September 25, 2019; accepted September 25, 2019

Abstract—The regulations on stack designs at thermal power stations (TPS) has been analyzed. It is demonstrated that the applicable guidelines do not consider all the actual problems encountered in designing stacks for TPSs, such as optimization of the stack construction cost and its effective operation. The stack cost depends on its height and diameter, which, at a given connected capacity, are affected by the gas velocity in the stack channel. At present, the effective stack design procedures do not contain the notion of this economically feasible, cost-effective index, and the stack dimeter is selected based on the engineering-and-cost estimation calculation procedures, which have not been approved as mandatory standards. These procedures are supported by the planning-and-distribution model of the country's economic development. The article announces a universal method developed by the authors for calculating the optimal flue gas velocity for any model of economic development irrespective of the trend in prices and expenditures for the production of goods and services. To calculate the optimal flue gas velocity, one should only input initial data valid at the present stage. The calculated results of the price factors' effect on the optimal flue gas velocity for single-flue and multiple-flue stacks are presented. Verification of the procedure against the initial data as of 1975 yields acceptable results.

Keywords: stack, thermal power station, economics, computational method, optimal velocity, ecology, flue gas

DOI: 10.1134/S0040601520030064

The decree of the Government of the Russian Federation [1], which approved the rules for determining the limit (maximum and minimum) capital costs for the implementation of upgrading projects for thermal power station, indexation of these costs, and selection of modernization projects, became effective in February 2019. The scope of a TPS upgrading project may also include the replacement (or construction) of a stack at a coal-fired power station.

In this case, the stack cost is comparable with the cost of the main equipment. For power stations fired with solid fuel, the average cost of stack construction exceeds 70% of the average cost for complete boiler replacement, and the percentage of the construction and erection can be as high as 95%. The facilities and equipment with a total capacity above 40 GW are to be upgraded between 2022 and 2031.

A code [2] was published in 2018 wherein a procedure for the calculation of the critical parameter, i.e., flue gas velocity in the stack, is absent. It is only stated that, for stack operation with condensate formation, the gas velocity at the stack's mouth should not exceed 18 m/s to prevent a large discharge of the condensate into the atmosphere.

According to [3], the minimum flue gas velocity at the outlet of the stack mouth is recommended to be at least 4 m/s in summer or 7 m/s in winter to eliminate the effect of blowout and envelopment of the stack top. It is recommended to determine the maximum outlet velocity from the condition of no positive static pressure along the entire stack flue (except for stacks with gas-tight exhaust flues or backpressure stacks). The flue of a reinforced concrete stack should be designed in the form of a cylinder, truncated cone, or a combination of both (a truncated cone and a cylinder). The ratio of the height of the entire stack or its individual section to the outer diameter should not generally exceed 20/1. The slope of the generatrix of the stack surface to the vertical should be taken to be a maximum of 0.1.

The stacks are the most expensive element of the TPS auxiliaries. Hence, proper selection of their basic characteristics is essential to minimize capital and operating expenditures during construction and operation of TPSs. The basic parameter to be optimized is the flue gas velocity at the stack mouth. The conclusions made in the study [4], performed in compliance with the planning-and-distribution model of the country economic development existing at that time, should be updated to account for the conditions of the present market economy in Russia.

Over the last three decades, the cost indicators of goods (such as steel, concrete, and electricity) and services (such installation and commissioning of equipment) required for the construction of a stack have grown considerably. In addition, taking into account the time factor, the cost of capital has become variable.

The best option for an investment project should be selected based on the criterion of lowest total discounted expenses. Therefore, the optimum gas velocity is that yielding the minimum total discounted cost for the construction of the stack, Cd [5, 6], to be calculated by the formula

$$\mathrm{C_d} = \sum_{\tau=0}^{\tau} \left(\mathrm{K_{inv}} + \mathrm{Ex} + \mathrm{Ex_f}\right)\left(1 + \mathrm{E}\right)^{-\tau}, \tag{1}$$

where $\mathrm{K_{inv}}$ is the investments, Ex is the expenses without depreciation, $\mathrm{Ex_f}$ is the financial expenses, τ is the design service life of the stack, and E is the discounting rate.

The stacks belong to Group 6 of the All-Russia Classifier of Fixed Assets with a maximum service life of 15 years inclusive. Therefore, the design service life for the study of stack performance is taken to be $\tau = 15$.

The discounting rate is calculated according to [6] is calculated by the formula

$$\mathrm{E} = \sum_{i=1}^{n} \mathrm{E}_i a_i, \tag{2}$$

where E_i is the price of the ith captial, a_i is the share of the ith capital in the total investments, and n is the number of capital types in the total investments.

The most widely used stack type is a single-flue stack with a clamped lining. Its load-bearing reinforced concrete shaft with the lining is considered as one solid item. Therefore, the stack cost $\mathrm{K_{st}}$ is calculated by the expression

$$\mathrm{K_{st}} = \mathrm{K_{sh.\,l}} + \mathrm{K_{found}}, \tag{3}$$

where $\mathrm{K_{sh.\,l}} = V_{\mathrm{r/c\,sh.\,l}}\mathrm{P_{r/c\,sh.\,l}} + \mathrm{L_{sh.\,l}}$ is the cost of the shaft with lining (here, $V_{\mathrm{r/c.sh.\,l.}}$ is the volume of the shaft reinforced concrete with lining, m^3; $\mathrm{P_{r./c\,sh.\,l}}$ is the price of the construction material of the shaft with lining, rubles/m^3; $\mathrm{L_{sh.l}}$ is the labor cost for construction of the shaft with lining, rubles; and $\mathrm{K_{found}}$ is the foundation cost, rubles.)

The volume of the reinforced concrete shaft with lining is calculated by the formula from [8]

$$V_{\mathrm{r/c\,sh.\,l}} = 0.01\, H^{2.2} D_0^{0.5} K_{\mathrm{w.l.}}^{0.3} \left(\frac{T_{\mathrm{g}}}{T_{\mathrm{ref}}}\right)^{0.5}, \tag{4}$$

where H is the stack height, m; D_0 is the stack mouth diameter, m; $K_{\mathrm{в.о}}$ is the wind load factor for the stack shaft to be taken depending on the wind region; T_{fg} is the flue gas temperature, K; and $T_{\mathrm{ref}} = 423$ K is the flue gas temperature taken as the reference one.

According to the data given in Table 10.3 from [8], the proportionality factor in formula (4) is taken as 0.01.

The reinforced concrete price consists of the price of concrete and structural steel; at the current wholesale prices and the degree of reinforcement of 200 kg/m^3, it is 11000 rubles/m^3.

As a first approximation, the stack height H_0, m, is calculated according to [9] by the formula

$$H_0 = \sqrt{\frac{A\ M\ F}{c_{\mathrm{st}}\sqrt[3]{V\ \Delta T}}}, \tag{5}$$

where A is the coefficient depending on the meteorological conditions in the climatic region of interest; M is the harmful emission rate, g/s; F is the coefficient accounting for the deposition rate of a harmful substance in atmospheric air; for gaseous emissions, $F = 1$; for ash, $F = 2$–3; c_{st} is the concentration of harmful impurities discharged from the stack at the human being inhalation level, mg/m^3; V is the flue gas volumetric flowrate, m^3/s; and ΔT is the difference in temperature between the flue gases and the ambient air, K.

The stack height considering the emission parameters is calculated by the formula

$$H = \sqrt{m} H_0, \tag{6}$$

where m is determined depending on the complex k/D_0^3 using the data presented in [10]. For a single-flue stack, the coefficient k in the complex k/D_0^3 is calculated by the expression

$$k = 1621 \frac{V^2}{H_0^2 \Delta T}. \tag{7}$$

The volumetric flowrate of flue gases, m^3/s, discharged from the stack mouth is calculated by the formula

$$V = \frac{\pi D_0^2}{4} w, \tag{8}$$

where w is the flue gas velocity at the stack mouth, m/s.

The flue gas velocity minimizing the total discounted costs is optimal w_{opt}.

The labor cost for the construction of the lined reinforced concrete shaft is estimated based on the man-day input (see Table 10.3 from [8]) taking into account the volume of lined reinforced concrete shaft and the price of a man-day, Pm-d, rubles/day, by the formula

$$\mathrm{L}_{\mathrm{found}} = 3.6\, V_{\mathrm{r/c\,sh.\,l}}\mathrm{P}_{\mathrm{m\text{-}d}}. \tag{9}$$

The foundation cost is estimated by

$$\mathrm{K}_{\mathrm{f}} = V_{\mathrm{r/c\,found}}\mathrm{P}_{\mathrm{r/c\,found}} + \mathrm{L}_{\mathrm{f}}, \tag{10}$$

where $V_{\mathrm{r/c.\,found}}$ is the reinforced concrete volume in the stack foundation, m^3; $\mathrm{P}_{\mathrm{r/c.\,found}}$ is the price of reinforced concrete in the stack foundation, rubles/m^3; and $\mathrm{L}_{\mathrm{found}}$ is the labor cost for the construction of the foundation, rubles.

The reinforced concrete volume in the foundation is calculated by the formula

$$V_{\mathrm{r/c\,found}} = 0.004H^{2.3}D_0^{0.45}K_{\mathrm{w.l.}}^{0.2}K_{\mathrm{s}}^{0.25}, \tag{11}$$

where K_{s} is the coefficient accounting for the soil quality.

The dependence of the reinforced concrete volume on the diameter and height of a stack were taken from [11, 12]; the proportionality coefficient value of 0.004 is the weighted average value according to Table 10.2 of [8]. With the foundation reinforcement level of 100 kg/m^3, the reinforced concrete price is 7000 rubles/m^3.

The labor cost for foundation construction is estimated based man-day input according to Table 10.2 of [8] using the formula

$$\mathrm{L}_{\mathrm{ound}} = 0.7V_{\mathrm{r/c\,sh.\,l}}\mathrm{P}_{\mathrm{m\text{-}d}}. \tag{12}$$

In the considered options, the expenses E is calculated as follows:

$$\mathrm{E} = n_{\mathrm{op}}\mu^2 a_{\mathrm{ep}}N_{\mathrm{g.t}}, \tag{13}$$

where n_{op} is the number of boiler operating hours (with an average boiler downtime of 1 month, $n_{\mathrm{o}} = 8000$ h); a_{ep} is the power generation cost (approximately $a_{\mathrm{ep}} =$ 1.5 rubles/(kW h)); μ is the installed capacity utilization factor (approximately $\mu = 0.75$); and $N_{\mathrm{g.\,t.}}$ is the power consumption for gas transportation through the stack, kW:

$$N_{\mathrm{g.t}} = 10^{-3}\frac{V\Delta h}{\eta_{\mathrm{d.f}}\eta_{\mathrm{mot}}}, \tag{14}$$

where Δh is the pressure difference required for flue gas transportation, Pa; $\eta_{\mathrm{d.f}}$ is the efficiency of the draft fan (to be taken as 0.7); and η_{mot} is the efficiency of the draft fan motor (to be taken as 0.98).

The pressure difference consists of the friction loss, Δh_{fr}, the losses due to local resistances, $\Delta h_{\mathrm{l.\,r}}$, the head loss with outlet velocity, $\Delta h_{\mathrm{o.\,v}}$, and the stack effect, $\Delta h_{\mathrm{st.\,eff.}}$:

$$\Delta h = \Delta h_{\mathrm{fr}} + \Delta h_{\mathrm{l.r}} + \Delta h_{\mathrm{o.v}} + \Delta h_{\mathrm{st.\,eff}}. \tag{15}$$

For single-flue conical stacks, the friction loss, Pa, can approximately be taken as

$$\Delta h_{\mathrm{fr}} = 0.3h_{\mathrm{v.h0}}, \tag{16}$$

where $h_{\mathrm{v.h0}}$ is the velocity head at the stack mouth, Pa

$$h_{\mathrm{v.h0}} = \rho_{\mathrm{g}}\frac{w^2}{2}; \tag{17}$$

here,

$$\rho_{\mathrm{g}} = 1.29\frac{273}{273 + t_{\mathrm{g}}}, \tag{18}$$

is the flue gas density, kg/m^3, and t_{g} is the flue gas temperature, °C.

The local resistances, Pa, are calculated by the formula

$$\Delta h_{\mathrm{l.r}} = h_{\mathrm{v.h0}}\sum\zeta, \tag{19}$$

where $\sum\zeta$ is the sum of local resistance coefficients (for single-flue conical stacks, $\sum\zeta = 0$). The coefficient of resistance of the flue gas duct connection to the stack belongs to the local resistances of the flue gas duct.

The head loss with outlet velocity, Pa, is taken to be the velocity head $h_{\mathrm{v.h0}}$ at the stack mouth

$$\Delta h_{\mathrm{o.v}} = h_{\mathrm{v.h0}}. \tag{20}$$

The stack effect, Pa, is calculated as

$$\Delta h_{\mathrm{st}} = (\rho_{\mathrm{a}} - \rho_{\mathrm{g}})gH, \tag{21}$$

where ρ_{a} is the air density, kg/m^3, and g is the gravity acceleration, m/s^2. Air density is calculated by the formula

$$\rho_{\mathrm{a}} = 1.29\frac{273}{273 + t_{\mathrm{a}}}, \tag{22}$$

where t_{a} is the air temperature, °C.

The reference for the further analysis was the data in Fig. 1a, which shows the optimal flue gas velocities in a single-flue reinforced concrete stack based on the prices of 1975. The predictions for the construction of a stack by one’s own funds at a constant cost of capital are shown in Fig. 1b. The average man-day price was taken to be 2000 rubles/man-day. The electricity price growth rate between 1975 and 2018 was much higher than the construction material price increase rate in this period. This fact affected the optimal gas velocities in the stacks. Nowadays, it is more profitable to use relatively cheap construction materials and try to reduce the cost of flue gas transportation, thereby decreasing the optimal flue gas velocities.

The predictions in Fig. 1c show the optimal flue gas velocities in reinforced concrete stacks under the existing construction conditions using loan funds got at 10% annual interest considering an inflation of 5%. The figure also shows that the inflation and the cost of

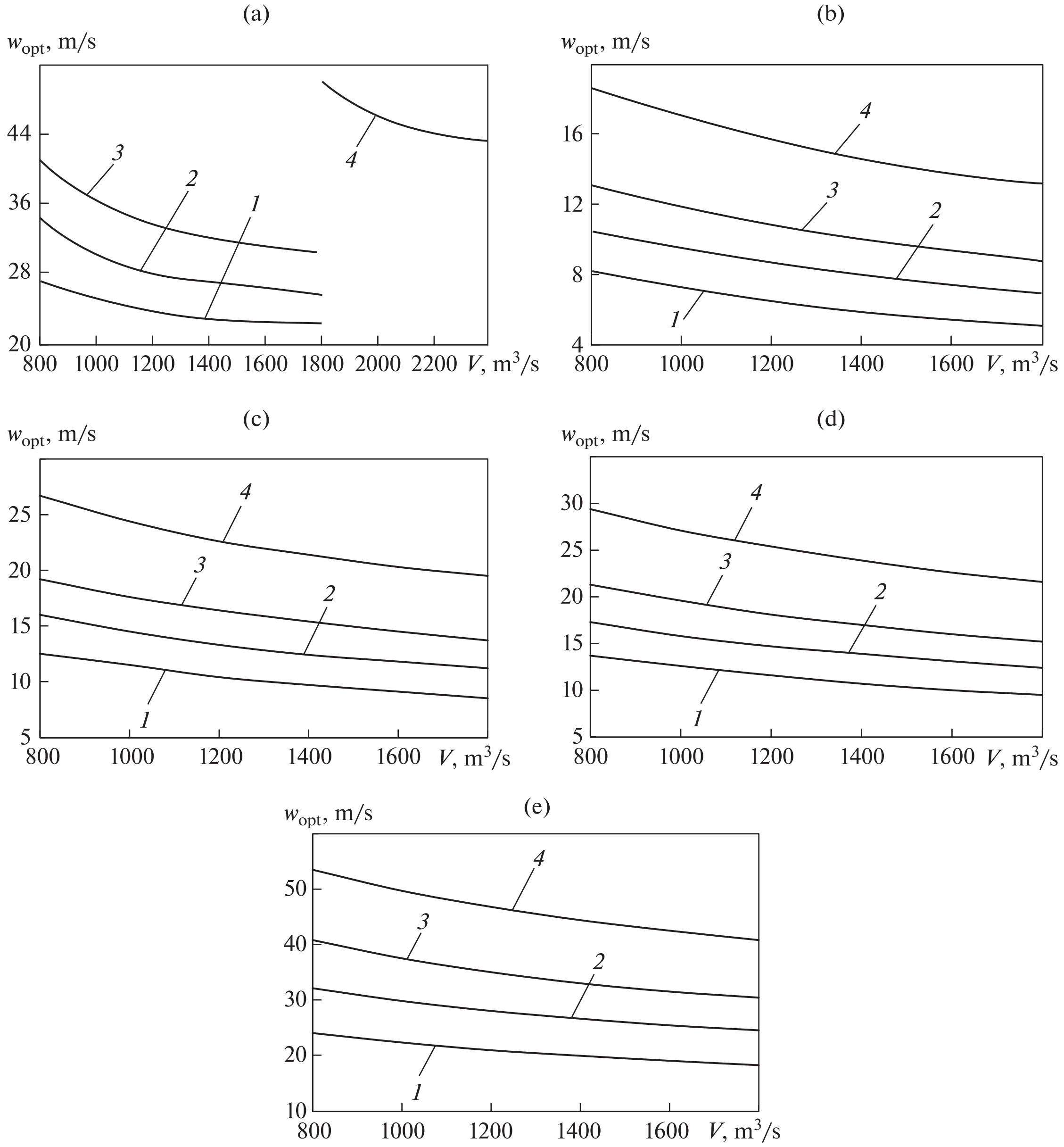

Fig. 1. Dependence of the optimal flue gas velocity at the single-flue reinforced concrete stack mouth on the flue gas volumetric flowrate. (a) as of 1975 [4]; (b) as of 2018 with the constant cost of capital, stack construction using one's own resources, and $P_{m\text{-}d} = 2000$ rubles/day; (c) as of 2018 with the inflation and $P_{m\text{-}d} = 2000$ rubles/day; (d) as of 2018 with the inflation and for $P_{m\text{-}d} = 3000$ rubles/day; (e) as of 1975 with zero inflation and stack construction using one's own resources; H, m: *1*—250; *2*—180; *3*—150; *4*—120.

credit quite noticeably affect the optimal gas velocity. It increases by approximately 4 m/s for 120-m high stacks, 5 m/s for 150- and 180-m high stacks, and 7 m/s for 250-m high stacks.

Under the same conditions, increasing the man-day price by a factor of 1.5 rose the optimal gas velocity by approximately 1.0 m/s for 120-m high stacks, 1.5 m/s for 150- and 180-m high stacks, and 2.5 m/s for 250-m high stacks (see Fig. 1d). However, these velocities are half the optimal velocities specified in the database for 1975 (see Fig. 1a).

To verify the developed procedure, Fig. 1e represents the predictions for the prices for 1975, which were as follows [4]: $P_{r/c.\ sh.\ 1} = 316.8$ rubles/m^3, $P_{r/c.\ found} = 253.4$ rubles/m^3, $P_{man\text{-}day} = 10$ rubles/day, $a_{e.p} = 0.005$ rubles/(kW h). The data presented in Figs. 1a and 1d are nearly the same, especially for a 180-m high stack.

Optimal velocities in a multiflue stack are further analyzed by an example of the most common four-flue stacks, which are basically used at cogeneration power stations (TETs). It is assumed that the average wall thickness of the flues is the same, and all the flues are made of carbon steel with a corrosion allowance of 14 mm. The flues are cylindrical along the entire height, and an increase in the metal volume in the basement is taken into account in the average thickness of the flue walls. The minimum distance between the wall of the flues is 1.2 m, and that between the outer wall of the flue and the inner wall of the reinforced concrete shaft in its upper part is 1.0 m. The cost of a multiflue stack $K_{\text{m-f st}}$ is calculated by the formula

$$K_{\text{m-f st}} = K_{\text{sh}} + K_{\text{found}} + K_{\text{fl}}, \quad (23)$$

where K_o is the shaft cost (without lining in this case); K_{found} is the foundation cost; and K_{fl} is the cost of flues.

The shaft cost is

$$K_{\text{sh}} = V_{\text{r/c sh}} P_{\text{r/c sh}} + L_{\text{sh}}, \quad (24)$$

where $V_{\text{r/c.sh.}}$ is the volume of the shaft reinforced concrete, m^3; $P_{\text{r./c sh}}$ is the price of the construction material of the shaft, rubles/m^3; and L_{sh} is the labor cost for construction of the shaft with lining, rubles.

The reinforced concrete volume in the shaft is calculated by the formula

$$V_{\text{r/c sh}} = 0.09 H_o^{1.75} D_o^{0.6} K_{\text{m-f w.l}}, \quad (25)$$

where H_o is the reinforced concrete shaft height (to be taken 5 m lower than the stack height); D_o is the shaft inner diameter at the stack outlet, m; and $K_{\text{m-f w.l}}$ is the wind load factor for the shaft of a multiflue stack (to be taken according to Table 3 [13]).

The price of reinforced concrete for a multiflue stack was taken to be the same as the price for a single-flue stack, i.e., 11000 rubles/m^3.

The labor costs for the construction of a reinforced concrete shaft in formula (24) are calculated based on the number of expended man-days according to Table 10.3 from [8], which depend on the volume of reinforced concrete and the price of a working day, using the formula

$$L_o = 2.9 V_{\text{r/c sh}} P_{\text{m-d}}. \quad (26)$$

The cost of a multiflue stack foundation is calculated by

$$K_{\text{m-f found}} = V_{\text{r/c sh. found}} P_{\text{r/c sh. found}} + L_{\text{sh. found}}, \quad (27)$$

where $V_{\text{r/c. sh. found}}$ is the reinforced concrete volume in the foundation of a multiflue stack shaft, m^3, to be calculated by formula (11); $P_{\text{r/c. sh. found}}$ is the price of material consumed in manufacturing the reinforced concrete foundation (to be taken the same as that for a single-flue stack, i.e., 7000 rubles/m^3); and $L_{\text{sh. found}}$ is the labor cost for construction of the shaft foundation.

The labor cost for the construction of the multiflue stack foundation was calculated from the number of expended man-days according to Table 10.2 [8], which depends on the reinforced concrete volume and the man-day cost, by the formula

$$L_{\text{ф.o}} = 0.2 V_{\text{m-f found}} P_{\text{m-d}}. \quad (28)$$

The cost of the flues was calculated by the expression

$$K_{\text{fl}} = P_{\text{fl}} V_{\text{m}} + L_{\text{fl}}, \quad (29)$$

where P_{fl} is the flue construction material price (which is approximately P_{fl} = 312 000 rubles/m^3 for steel); V_{m} is the volume of metal consumed for the manufacture of all flues, m^3; and L_{fl} is the labor cost for installation of all flues, rubles.

The volume of metal for construction of all flues is

$$V_{\text{m}} = \pi d_{\text{fl}} H \delta N_{\text{fl}}, \quad (30)$$

where d_{fl} is the flue inner diameter, m; δ is the flue wall thickness (for steel δ = 0.012–0.014 m); and N_c is the number of flues

The flue inner diameter was calculated by the formula

$$d_{\text{fl}} = \sqrt{\frac{4V_{\text{fl}}}{\pi w_{\text{fl}}}}, \quad (31)$$

where V_{fl} is the gas flowrate through one flue, m^3/s; and w_{fl} is the gas velocity in the flue, m/s.

According to [14], the labor cost for the installation of the flues, Lfl, rubles, is

$$L_{\text{fl}} = 60 V_{\text{m}} P_{\text{m-d}}. \quad (32)$$

The predictions for the four-flue stacks with the metal flues in a common reinforced concrete shaft in the prices for 2018 are shown in Fig. 2.

Comparison of the data presented in Figs. 1b and 2a demonstrates that the optimal velocity in the multiflue stack is higher than that in the single-flue stack. This difference is greater for relatively low stacks. The effect of volumetric flow rate and stack height for four-flue stacks is less pronounced than for single-flue stacks. This stems from the fact that the cost of multiflue stacks is considerably greater than the cost of single-flue stacks.

The predictions for the four-flue stacks with the metal flues in a common reinforced concrete shaft in the prices for 2018 with the inflation of 5% and the construction out of borrowed funds made at an interest rate of 10% per annum are shown in Fig. 2b. As is evident from the figure, the inflation and the interest rate have a quite strong effect on the optimal velocity of flue gases in four-flue stacks, which increases by approximately 5 m/s. The optimal gas velocities in 250-m high four-flue (see Fig. 2b) and single-flue (see Fig. 1c) stacks are quite close. If the optimal gas velocities range from 19 to 27 m/s for single-flue stacks, then they range from 23 to 26 m/s for four-flue stacks. For lower stacks, this difference increases.

The effect of the man-day cost for installation activities on the optimal flue gas velocity can be revealed by comparing Figs. 2b and 2c. Increasing the

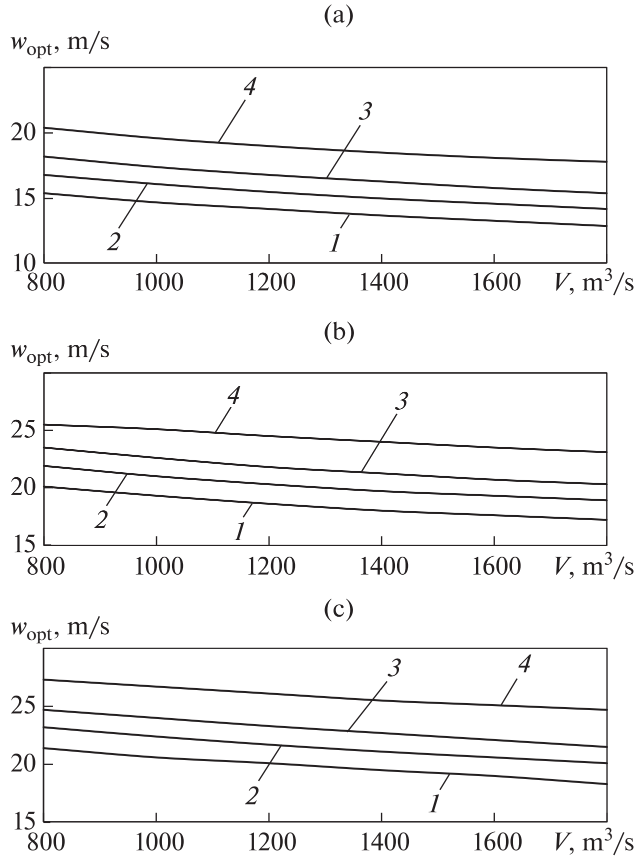

Fig. 2. Dependence of the optimal flue gas velocity on the flue gas volumetric flowrate in four-flue stacks with metal flues as of 2018. (a) with the constant cost of capital; (b) with the inflation and $P_{m\text{-}d}$ = 2000 rubles/day; (c) with the inflation and $P_{m\text{-}d}$ = 3000 rubles/day; *1–4*—see Fig. 1.

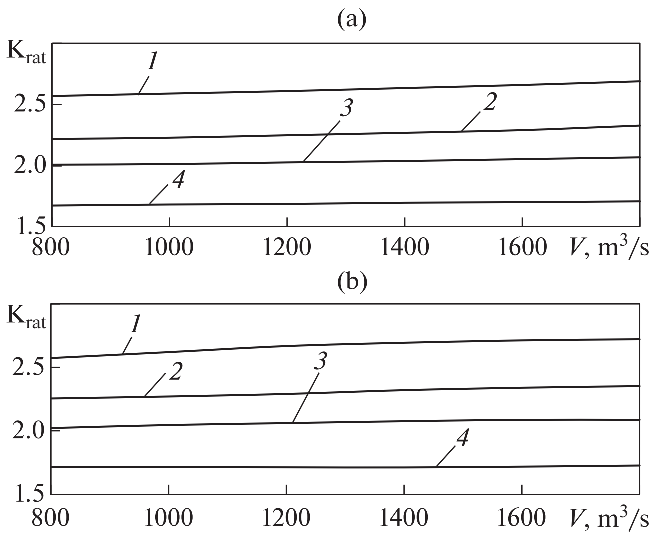

Fig. 3. Dependence of the ratio of the cost of a four-flue stack with metal flues to the cost of a single-flue reinforced concrete stack, both designed for same parameters, in prices for 2018 with (a) the constant cost of capital and (b) with inflation. *1–4*—see Fig. 1.

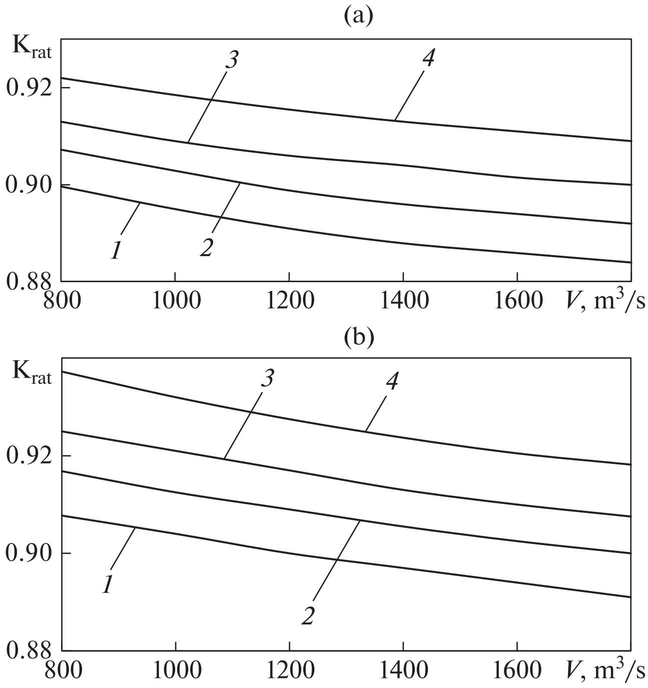

Fig. 4. Dependence of the ratio of the cost of (a) single-flue or (b) four-flue stacks with the inflation considered to the cost of the same stack estimated without inflation on the flue gas volumetric flowrate; *1–4*—see Fig. 1.

man-day cost by a factor of 1.5 raises the optimal velocity by approximately 1 m/s.

In spite of the fact that the diameters of flues and the shaft decrease, the cost of the stack increases by 11–12% irrespective of its height. This is explained by the fact that the effect of increasing labor cost prevails over a decrease in the price of the used construction materials.

The comparison of Fig. 1d with Fig. 2c demonstrates that the optimal gas velocities in 250-m high single-flue and four-flue stacks are comparable. For lower stacks, a considerable difference is evident: the optimal velocity is 20 m/s in four-flue stacks and 10 m/s in single-flue stacks.

Figure 3a shows the ratio of four-flue to single-flue stack cost Krat, which slightly depends on the flue gas volumetric flow but quite considerably on the stack height. This ratio is 2.6 for 120-m high stacks and 1.7 for 250-m high stacks.

Figure 3b shows the ratio of four-flue to single-flue stack cost considering the effect of inflation. Comparison of Fig. 3b with Fig. 3a suggests that these values have changed only slightly, but with the inflation taken into account the stack cost decreases with an increase in the optimal gas velocity. Comparison of Fig. 4a with Fig. 4b demonstrates a more pronounced effect of the inflation on the cost for single-flue stacks.

We have developed the codes for calculating the optimal gas velocity for various stack types (single-flue

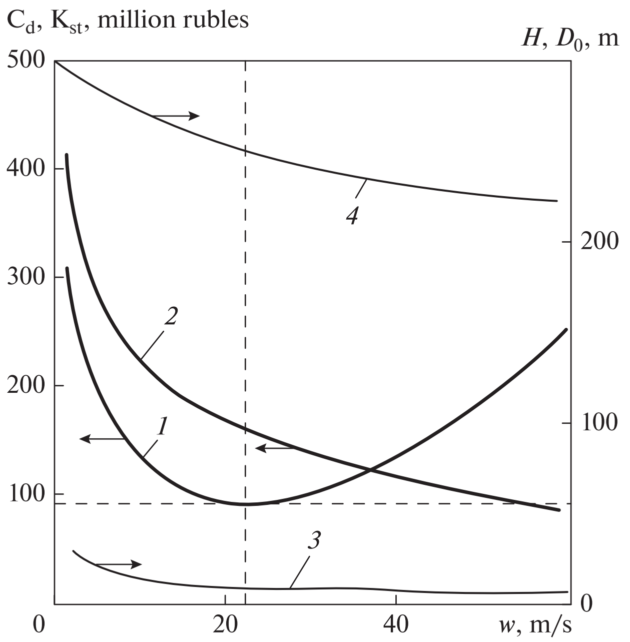

Fig. 5. Predicted optimal velocities of flue gases. *1*—C_d; *2*—K_{st}; *3*—D_0; *4*—*H*.

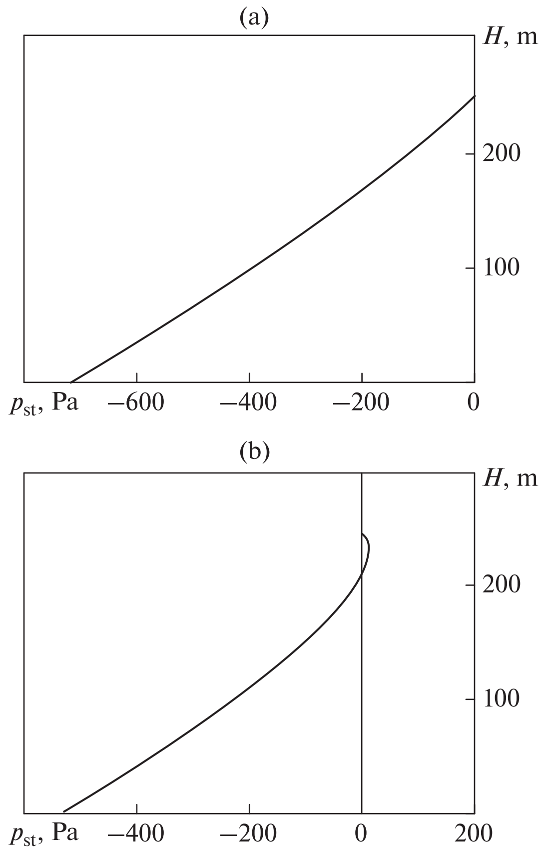

Fig. 6. Static pressure distribution along the stack height. (a) $U = 0.015$; $\Delta_0 = 0.0015$ m; $w_{opt} = 20$ m/s; (b) $U = 0.025$; $\Delta_0 = 0.003$ m; $w_{opt} = 30$ m/s.

stacks with a vented air clearance, three-flue stacks, etc.). Figure 5 represents the predicted optimal flue gas velocities in a 250-m high four-flue stack at a volumetric flowrate of 1600 m^3/s.

The results of the aerodynamic calculation of the distribution of positive static pressures p_{st} along the stack height performed by the procedure described in [15] with account taken for the slope of the stack generatrix, U, and the absolute roughness of the stack inner surface, Δ_0, are shown in Fig. 6.

In the first case (see Fig. 6a), a negative pressure is observed along the entire stack height, which exceeds 700 Pa at the stack bottom, and no limits are imposed on the static pressures in the stack. In the second case (see Fig. 6b), a positive static pressure is built in the top section of the stack. The codes have also been developed for calculating the optimal parameters of a three-flue stack with flues having any diameter.

Thus, the optimal flue gas velocity in exhaust flues in stacks of different designs can be calculated at different emission parameters considering the existing situation in the economics.

CONCLUSIONS

(1) The developed mathematical model and the software package created on its basis have been verified under the conditions of the planning and distribution model of the country's economic development.

(2) The universal procedure proposed by the authors for calculating the optimal flue gas velocity for any model of economic development is universal and does not depend on the trend of prices and costs for productions goods and services. To calculate the optimal flue gas velocity, one should only input the initial information applicable at the present time.

3. Application of the developed software code has yielded that the gas velocity adopted now in designing stacks are considerable overestimated.

REFERENCES

1. "On the selection of modernization projects for generating facilities of thermal power plants," RF Government Decree No. 43 of January 25, 2019.
2. *SP 375.1325800.2017. Industrial Chimneys. Rules for Design* (Izd. Standartov, Moscow, 2018).
3. *SP 43.13330.2012. Constructions of Industrial Enterprises. Updated edition of SNiP 2.09.03-85* (Izd. Standartov, Moscow, 2013).
4. L. A. Rikhter, E. P. Volkov, E. I. Gavrilov, V. G. Lebedev, and V. B. Prokhorov, "Determination of the cost of chimneys of TPPs and optimization of gas velocities in the exhaust pipe," Teploenergetika, No. 4, 12–16 (1975).
5. *Guidelines for Evaluating the Effectiveness and Development of Investment Projects and Business plans in the Electricity Industry (With Typical Examples)*, Vol. 1: *Methodological Features of Evaluating the Effectiveness of*

Projects in the Electric Power Industry (NTsPI, Moscow, 2008).

6. N. D. Rogalev, A. G. Zubkova, I. V. Masterova, G. N. Kurdyukova, V. V. Bologova, and O. Yu. Ponomareva, *Power Industry Economics: Study Aid*, Ed. by. N. D. Rogalev (Mosk. Energ. Inst., Moscow, 2005) [in Russian].
7. *OK 013-2014 (SNS 2008). All-Russian Classifier of Fixed Assets* (Rosstandart, Moscow, 2014).
8. F. P. Duzhikh, V. P. Osolovskii, and M. G. Ladygichev, *Industrial Smoke and Ventilation Pipes: Handbook* (Teplotekhnik, Moscow, 2004) [in Russian].
9. "On approval of calculation methods for dispersion of emissions of harmful (polluting) substances in the air," RF Ministry of Natural Resources and the Environment Decree no. 273 of June 6, 2017.
10. E. I. Gavrilov, "Calculating the height of chimneys of TPPs," Teploenergetika, No. 3, 77–80 (1980).
11. E. I. Gavrilov, *Aerodynamic Characteristics of the Exhaust Pipes and the Output of the Chimneys of High Power*, Candidate's Dissertation in Engineering (Moscow Power Engineering Inst., Moscow, 1973).
12. A. M. Gribkov and E. I. Gavrilov, *Choosing the Optimal Sizes of Chimneys and External Flues: Study Aid* (Mosk. Energ. Inst, Moscow, 1986) [in Russian].
13. L. A. Rikhter, *Gas-Air Tracts of Thermal Power Plants*, 2nd ed. (Energoatomizdat, Moscow, 1984) [in Russian].
14. *GESN 09-06-033-02. Installation of Exhaust, Smoke and Ventilation Pipes with a Diameter of up to 3250 mm from Sheet Steel up to 45 m High*. http://www.defsmeta.com/rgsn14c/gsn_09/giesn-09-06-033-02.php.
15. L. A. Rikhter, "Aerodynamic characteristics of chimneys," Elektr. Stn., No. 4, 11–14 (1968).

Translated by T. Krasnoshchekova

SPELL: OK