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ON THE CONDENSATION OF STEAM FROM COMBUSTION PRODUCTS IN CHIMNEYS

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Compliance of designs of chimneys with the present-day requirements for energy savings is discussed. The possibility of installing coolants of combustion products without the hazardous consequences of steam condensation in the chimney is analyzed. As an example, calculations for particular chimneys are given.

The practically only significant heat loss in a boiler room equipped for the use of gases (with effluent gases) can be markedly reduced at the expense of their cooling, including cooling to below the dew-point temperature, in fin-type heat exchangers (the temperature of effluent gases is practically always above 120–150^{o}C and quite often reaches 300^{o}C). The main obstacle for deeper cooling is the fear that the chimney will be destroyed by the condensate formed on its walls. The steel and brick chimneys currently used in industrial heat power engineering are out of date. Modern materials make it possible to create, for boiler houses to be built anew, cheap chimneys that admit steam condensation in them and, consequently, deep cooling of effluent gases, in particular, in surface, fin-type heat exchangers.

Steel Chimneys. The Building Code and Rules [1] admit the application of steel chimneys "in the case of economic inexpediency of increasing the temperature of flue gases." If the coefficients of heat transfer to the inner surface of the chimney and from its outer surface are taken to be equal (below, their exact values will be given) and the dew-point temperature is assumed to be equal to 60^{o}C (with small reserve), then at a free air temperature of –35^{o} (calculated free air temperature for designing heating systems in Ekaterinburg) the temperature of gases escaping from the chimney should exceed 155^{o}C. In the case of underloaded operational conditions of boilers, where, for example, only one of the four boilers designed for a chimney is operating, combustion products in it are cooled to a greater extent and the heat-transfer coefficient from them to the wall decreases. In this case, the temperature of combustion products at the inlet into the chimney (at the outlet from the boiler) should be much higher (to ensure reliable operation of the chimney) and, with allowance for the necessary reserve (10–15^{o}C), it is close to 200^{o}C.

According to [1], "... chimneys should have, as a rule, outer lagging to prevent condensate formation ... ." The expediency and techniques of applying lags are described in fair detail in the literature [2, 3]. In reality, insulated steel chimneys are not the rule but a rare exclusion, while it is obvious that the economic effect obtained by cooling effluent gases in fin-type heat exchangers, e.g., from 200 to 100^{o}C, proves to be significant even with allowance for the cost of the chimney lagging.

The most common defect of metal chimneys is the "burning through" of the chimney shaft as a result of temperature or chemical corrosion of the metal. In building new, and sometimes in reconstructing boiler houses, it is expedient to use chimneys whose shafts are made from modern corrosion-resistant materials: stainless steel, glass-fayalite [4], glass-reinforced plastic [5], and even titanium [4]. In the chemical industry, flues for releasing aggressive gases are made of stainless steel of small thickness with a steel supporting structure that takes up weight and wind loads. In the power engineering of Russia, there is lack of such flues; foreign companies recommend them for small boilers (flue diameter up to 600 mm, height up to 20 m). In the CIS countries, bimetal chimneys of diameter up to 650 mm are made from carbon steel with a corrosion-resistant cladding layer [6]. Home plants produce bimetal sheets from carbon steel with a thin cladding layer (0.5–1.0 mm) of stainless steel. Chimneys of larger diameter can be made from them. The chemical machine-building industry has experience in the use of welding apparatuses from such sheets.

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Steel chimneys are several times cheaper than brick and concrete ones and are as durable (if their internal corrosion is excluded). Therefore, at a chimney height of up to 45 m and its diameter of no more than 0.8–1.0 m, even the old code [7] recommends the use of steel chimneys. Steel and similar shafts of modern designs can obviously also be used for larger heights and diameters (according to [4], a titanium shaft was installed in a concrete chimney of height 100 m).

Brick and Reinforced Concrete Chimneys. One of the main requirements of the Building Code and Rules [1] and of the norm-based method [7] is the absence of excess pressure inside the chimney in any of its sections in order to prevent penetration of flue gases into the bulk of the structures of brick and reinforced concrete chimneys. This condition for the usually most risky, outlet portion of the chimney (cap) is written in the form (in notation of this paper)

$$\frac{(\xi + 8i)\,\rho_g w_0^2}{2g\,(\rho_{air} - \rho_g)\,d_0} < 1\,. \tag{1}$$

To calculate the value of the friction coefficient ξ several formulas have been proposed in the literature. In [7], it is recommended to take $\xi = 0.05$ for concrete and brick chimneys with account for the circular projections of the setting. Relation (1) defines the maximum velocity at the outlet from a brick or reinforced concrete chimney. It is seen that the smaller the chimney diameter, the lower should be the outlet velocity of gases. Actually, neither [1] nor [7] strictly normalize the minimum permissible velocity; it is recommended to choose it from economic considerations (wiht the only qualification that at natural draft it is taken to be no less than 6–10 m/sec to prevent considerable blowing out at underloads).

According to [2], the velocity of gases at the outlet from the chimney should be high enough so that in a strong wind no self-wrapping of the cap in the fog formed occurs. The absence of self-wrapping is ensured if the dynamic pressure of combustion products $\rho_g w_0^2/2$ is 2.4 times higher than the dynamic pressure of the wind $p_w w_w^2/2$ (or tentatively $w_0 > 1.9 w_w$) [2].

The normative materials place no restrictions on the temperature of combustion products escaping from the chimney; it is only stated that steam condensation in the shafts of brick and concrete chimneys is inadmissible under any operating conditions of boilers [1]. In [7], it is recommended that the diameter of the orifice of brick and reinforced concrete chimneys should be no less than 0.75 m, and that of steel chimneys — no more than 0.8–1.0 m (it can also be larger if economically justified). The normative materials [1, 7] give no methods for calculating the temperature of the inner surface of the chimney and substantiating the absence of steam condensation in the shafts.

The most serious problems, up to the collapse of a chimney, arise from the formation of condensate in the brickwork due to the decrease in the temperature of its inner surface. In calculating boilers, it is recommended to choose the temperature of escaping gases on the basis of the technique-economic estimation [8]. The normative documents do not specify their minimum temperature, except for the general requirement to exclude steam condensation in the brickwork; therefore, the aim of the present work is to elucidate the conditions under which condensation can occur. Many cases have been described, e.g., in [4, 9], where, because of a decrease in the velocity of combustion products, chimney caps got wet and the brickwork froze through and collapsed. As a rule, this is observed in boiler rooms using gaseous fuel whose combustion products contain 12–19% steam. And this most often happens in the cases where in a boiler house having, e.g., 4–5 boilers, only one boiler is operating for technical reasons or because of the decrease in the thermal loading in the fall and spring.

Brick chimneys most commonly collapse in the upper part where the shaft has the least thickness and is not always lined on the inside. Failures show up as appreciable vertical cracks uncovering bricks, which spall and collapse; the masonry mortar loses its strength and bond to the brick. Chimney shafts with considerable defects are to be demolished and relaid.

Heat Transfer in the Chimney. The problem of heat transfer in the chimney has been considered in many papers, e.g., in [10, 11], and the calculation relations presented in them differ markedly. In the works known to us, the heat-transfer coefficient α_{in} from combustion products to the chimney wall is defined by the formulas proposed for smooth tubes. Some authors, referring to [12], use the empirical formula for the convective heat-transfer coefficient α_c averaged over the smooth tube length l proposed by Craussold as far back as in 1932:

$$\mathrm{Nu} = 0.032\mathrm{Re}^{0.8}\mathrm{Pr}^{0.3}\left(\frac{d}{l}\right)^{0.054}, \tag{2}$$

where $\mathrm{Nu} = \dfrac{\alpha_c d}{\lambda_g}$ and $\mathrm{Re} = \dfrac{wd}{\nu}$. For combustion products of medium composition at a temperature of effluent gases of 100^oC, Pr = 0.7. The factor containing the relation d/l permits taking into account the decrease in the heat-transfer coefficient along the tube length; at $l/d > 40$ the mean heat-transfer coefficient remains practically unchanged. In a later work [13], to calculate the local heat-transfer coefficient for the gas flow in a straight smooth tube the following formula, analogous in form to (2), is recommended:

$$\mathrm{Nu} = 0.022\mathrm{Re}^{0.8}\mathrm{Pr}^{0.43}\varepsilon_l. \tag{3}$$

The quantity el is a correction for the change in the heat-transfer coefficient in the initial thermal part: $\varepsilon_l = 1.38(x/d)^{-0.12}$ at $x/d < 15$. Here x is the distance from the beginning of the tube. At $x/d \geq 15$, the local heat-transfer coefficient is stabilized ($\varepsilon_l \approx 1$). The mean value of α_c along the tube length can also be calculated by (3) at $\varepsilon_l = 1$, but in the domestic literature wider use has been made of Mikheev's formula [14]

$$\mathrm{Nu} = 0.021\mathrm{Re}^{0.8}\mathrm{Pr}^{0.43}. \tag{4}$$

For tubes with $l/d < 50$ the found value of Nu is multiplied by the correction ε_l.

Importantly, in formulas (3) and (4) the correction for the tube length is given for the value of α_c in the stabilized part, and in (2) — for the value of α_c in a tube with $l/d = 1$ (in this case $\varepsilon_l > 1$). Some authors [11, 15] overlook this, as a result of which the values of α_c calculated by them are 1.5 times overestimated (0.032/0.021). All of the above formulas are recommended for smooth tubes and give equal results to an accuracy of ±10%.

According to (4), at Pr = 0.7 and $l/d > 40$

$$\alpha_c = 0.0189\frac{\lambda_g w^{0.8}}{\nu^{0.8} d^{0.2}}. \tag{5}$$

As the temperature of the gases decreases from 100 to 50^oC, the value of the complex $\dfrac{\lambda_g}{\nu^{0.8}}$ increases by a factor of 1.070, and as the temperature increases to 150^oC, it decreases by a factor of 1.086. On average, in this temperature range it can be assumed to be equal to 177 $\mathrm{W \cdot sec^{0.8}}$ $(\mathrm{m^{2.6} \cdot K})$. Then, for a tube of diameter d = 1 m, we can write $\alpha_c = 2.73w^{0.8}$ $\mathrm{W/(m^2 \cdot K)}$. An increase or a decrease in the diameter by a factor of 2.5 decreases or increases, respectively, the value of α_c by a factor of 1.2.

The foregoing concerns smooth tubes. However, both brick and steel chimneys fit, in the main, into the category of rough tubes. In a turbulent flow, which practically always takes place in chimneys, roughness of the chimney walls has an effect only in the case where the value of roughness projections Δ exceeds the thickness δ of the laminar sublayer [13], and with increasing Δ therewith the heat-transfer coefficient α_c increases, and at $\Delta >> \delta$ the regime of complete manifestation of roughness sets in when the growth of α_c terminates. This is confirmed by Fig. 1, plotted for a chimney with regular roughness (with circular projections) [16].

The mean value of equivalent roughness of the brickwork on a cement mortar Δ = 0.8–6.0 mm, and for ducts incased in concrete Δ = 0.8–9.0 mm [17]. Since other data are absent, let us take them for the roughness of concrete and brick chimneys. The roughness of a steel (corroded on the inside) chimney can obviously be assumed to be equal to 0.8–1.0 mm [17]. Tubes clad on the inside with stainless steel can be considered to be smooth. It is recommended to calculate the viscous sublayer thickness by the formula [18]

$$\delta \approx b\nu\sqrt{\frac{\rho}{S}}, \tag{6}$$

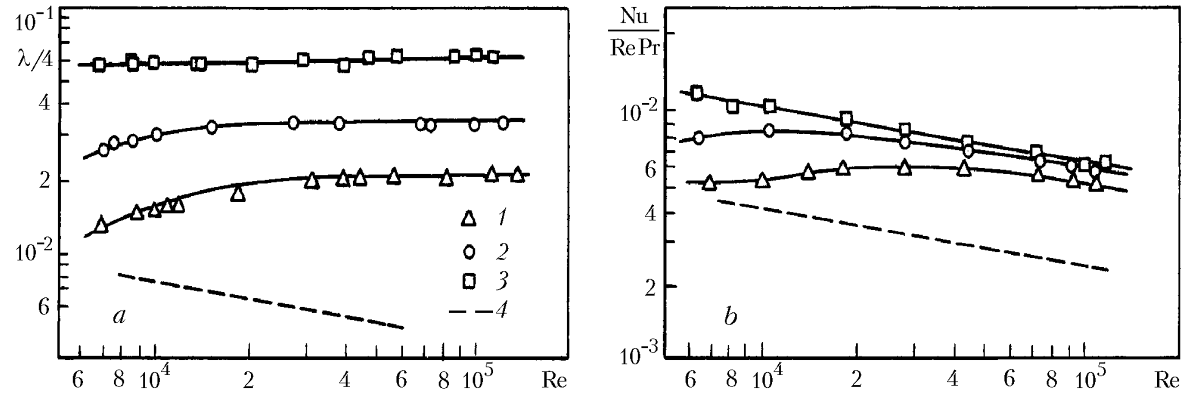


Fig. 1. Influence of the height of roughness projections on the resistance coefficient (a) and the complex $\frac{\text{Nu}}{\text{Re Pr}}$ (b) at Pr = 0.71: 1) $\frac{\Delta}{d}$ = 0.01; 2) 0.02; 3) 0.04; 4) $\Delta = 0$ (for a smooth tube).

where b = 3–5, and with allowance for the thickness of the transition zone (between the viscous sublayer and the turbulent core) b = 12.0–12.7 [18]. In [13], the value of b = 12.0 is also recommended. The stress tangents on the wall [13] are found as

$$S = \frac{\xi}{8} \rho w^2 . \tag{7}$$

In formula (7), the coefficient of friction resistance of the gas flow in a smooth tube

$$\xi = 0.184 \text{Re}^{-0.2} . \tag{8}$$

It should be noted that the thickness of the laminar sublayer is calculated for a smooth tube and is compared to the size of projections in a rough tube, i.e., we can only speak of comparison of the orders of magnitude.

Substituting (7) and (8) into (6), after some cancellations at b = 12.0 we obtain

$$\delta = 79 \left(\frac{\nu}{w} \right)^{0.9} d^{0.1} . \tag{9}$$

From formula (9) it is seen that the value of δ depends on the velocity and the kinematic viscosity coefficient of combustion products, which is determined by their temperature. A change in the tube diameter slightly influences the change in δ. Assuming the temperature of combustion products of medium composition to be equal to 100°C (ν = $20.8 \cdot 10^{-6}$ m^2/sec [8]) and d = 1, let us calculate the dependence of δ on w: at w = 1, 5, 10, 15, 20, and 25 m/sec, δ = 4.8, 1.1, 0.61, 0.42, 0.33, and 0.27.

From a comparison of the values of Δ and δ it is seen that at velocities of gases in the chimney higher than 10 m/sec the heat transfer in brick and even steel chimneys can be calculated by the formulas obtained for the regime of complete manifestation of roughness. At lower velocities it is recommended to use linear interpolation between the α_c values for the smooth surface and the surface in the regime of complete manifestation of roughness [16]. For the latter,

$$\frac{\text{Nu}}{\text{Re Pr}} = \frac{\frac{\xi}{8}}{(n - 8.48) \sqrt{\frac{\xi}{8}} + 1} , \tag{10}$$

where for regular roughness

$$n = 4.5\,(k^+)^{0.24}\,\mathrm{Pr}^{0.44}\,, \quad 25 < k^+ < 300\,, \tag{11}$$

and for irregular (so-called sandy) roughness

$$n = 5.19\,(k^+)^{0.2}\,\mathrm{Pr}^{0.44}\,,$$

$$k^+ = \frac{2\Delta}{d}\,\mathrm{Re}\,\sqrt{\frac{\xi}{8}}\,, \quad \xi = \frac{8}{\left(2.5\,\ln\left(\frac{d}{2\Delta}\right) + 4.75\right)^2}\,. \tag{12}$$

Determine the convective heat-transfer coefficient from combustion products of medium composition with a temperature of 100°C to the wall of a brick chimney of radius 1 m at their velocity of 10 m/sec. Assume Δ = 5 mm. Then the resistance coefficient of the rough tube ξ = 0.03, the reduced roughness k^+ = 296 at Re = $4.8 \cdot 10^5$, by formula (11) n = 15.07 at Pr = 0.7, by formula (10) Nu = 900, the convective heat-transfer coefficient determined by the Nusselt number α_c = 29 W/(m^2·K) at $\lambda_g = 3.18 \cdot 10^{-2}$ W/(m·K). The heat-transfer coefficient to the smooth tube calculated by formula (3) for these conditions is equal to 21 W/(m^2·K), i.e., it is 1.4 times smaller.

In chimneys of large diameter, a certain role can be played by the heat radiation from combustion products onto the chimney wall [15]. The radiant heat-transfer coefficient α_r is defined as [8]

$$\alpha_r = 5.67 \cdot 10^{-8}\,\frac{a_w + 1}{2}\,a T_g^3\,\frac{1 - (T_w/T_g)^{3.6}}{1 - T_w/T_g}\,. \tag{13}$$

The last fraction in expression (13) at close values of the temperatures of the gas T_g and the wall T_w can be taken to be equal to 3.6. The emissive factor of the wall a_w = 0.8, and the emissive factor of combustion products is calculated by the formula

$$a = 1 - \exp\,(-\,kps)\,,$$

where p = 0.1 MPa; $kps = k_g^0 r_{t.g} ps$; $k_g^0 r_{t.g} = \left(\frac{7.8 + 16 r_{H_2O}}{\sqrt{10 p r_{t.g} s}} - 1\right)(1 - 0.37 \cdot 10^{-3} T) r_{t.g}$. The volume content of triatomic combustion products of natural gas at an excess air coefficient α = 1.2 is $r_{t.g} = r_{RO_2} + r_{H_2O}$ = 0.080 + 0.172 = 0.252. The effective thickness of an infinite emitting cylindrical layer $s = 0.9d$.

For a chimney of diameter d = 2.5 m temperature of gases of 100°C, α_r = 4.5 W/(m^2·K). As the temperature is decreased to 50°C or increased to 150°C, the value of α_r will, respectively, decrease or increase by a factor of about 1.5, and at d = 0.25 m and t = 100°C, α_r = 1.8 W/(m^2·K). The total heat-transfer coefficient from combustion products to the internal wall of the chimney $\alpha_{in} = \alpha_c + \alpha_r$. The coefficient of heat transfer from the outer surface of the chimney is calculated, as a rule [2, 9–11, 15], by the formula for the cross flow past a single cylinder [14]:

$$\mathrm{Nu}_{out} = 0.18\,\mathrm{Re}_{out}^{0.62}\,, \tag{14}$$

where

$$\mathrm{Nu}_{out} = \frac{\alpha_{out} d_{out}}{\lambda_{air}}\,; \quad \mathrm{Re}_{out} = \frac{w_{air} d_{out}}{\nu_{air}}\,.$$

Formula (14) holds for values of $\mathrm{Re}_{out} \le 2 \cdot 10^5$. The possibility of its extrapolation to larger values of Re_{out} is not justified. Moreover, the radiation from the chimney surface is ignored. The calculation by (14) at a wind velocity w_{air} = 8 m/sec given in [2] yields α_{out} = 10.5 W/(m^2·K). At the same time, in [19] it is recommended to assume the heat-transfer coefficient from the outer enclosures of buildings to be equal to 23 W/(m^2·K). In amendment 1 to the Building code and Rules [1], in calculating the heat insulation of tubes, it is recommended to take α_{out} = 29 W/(m^2·K) (25 kcal/(m^2·h·^{o}C) at an outer diameter of the pipeline of up 2 m and 35 W/(m^2·K) (30 kcal/(m^2·h·^{o}C) for pipelines of diameter 2 m or more laid outside the building. These numbers seem to be overestimated. Apparently, in calculating chimneys it is expedient to orient oneself to the value of α_{out} = 23 W/(m^2·K).

Calculation of the Temperature of the Inner Surface of the Chimney. Since gases are weakly cooled in the process of rising in a chimney, their temperature in the chimney cap can be calculated approximately assuming that the chimney is cylindrical and the heat-transfer coefficient is constant. Then

$$\frac{t_{cap}^{g} - t_{f.a}}{t_{b}^{g} - t_{f.a}} = \exp\left(-\frac{kF}{V_g c'_g}\right), \tag{15}$$

where $F = \pi d_{av} H$ is the calculated surface of the chimney; V_g is the volume flow rate of combustion products (under normal conditions); c'_g is their specific heat capacity per unit volume (per 1 m^3 under normal conditions).

The heat-transfer coefficient K through a cylindrical tube with a small coefficient of curvature ($d_{out}/d_{in} \le 2$) can be calculated with an accuracy sufficient for practical applications by the formula

$$k = \frac{1}{\dfrac{d_{av}}{\alpha_{in} d_{in}} + \dfrac{\delta_{br}}{\lambda_{br}} + \dfrac{d_{av}}{\alpha_{out} d_{out}}}. \tag{16}$$

Here $d_{av} = \dfrac{d_{out} + d_{in}}{2}$ and $\delta_{br} = \dfrac{d_{out} - d_{in}}{2}$. The heat-transfer coefficient is assigned to the surface of the chimney determined by its average diameter. The maximum error (at d_{out}/d_{in} = 2) in the calculation of the heat resistance of brickwork heat conductivity (the middle term in the denominator of the formula) does not exceed 4% [13]. For a steel chimney this term in the denominator can be omitted and $d_{in} = d_{av} = d_{out}$ can be assumed. In [11], the value of λ_{br} = 0.814 W/(m·K) and in [9] λ_{br} = 0.490 W/(m·K) were suggested. The heat conductivity of a brickwork from building bricks increases with increasing temperature and moisture. In [19], there are no data for taking into account the influence of temperature, and it varies throughout the thickness of the chimney wall only slightly (over the range of 150–200^{o}C). Under dry conditions in a room in a dry climatic zone (brickwork moisture of 1%) λ_{br} = 0.7 W/(m·K). Evidently, for the chimney it is more expedient to take the value of λ_{br} = 0.81 W/(m·K) recommended in [19] for moist or wet conditions (with a brickwork moisture of 2%).

Let us perform calculations for the chimneys of the UGTU-UPI boiler house.

Chimney No. 1. This is a brick chimney of height 80 m; the internal diameter of the cap is 2.50 m, the outer diameter is 3.26 m. It was designed for the operation of two TVGM-30 boilers. The maximum consumption of natural gas under operation of both boilers is 8000 m^3/h. Under these conditions, the flow rate of combustion products is 25.85 m^3/sec, the air excess coefficient in effluent gases α_{ef} = 1.07, t_{ef} = 160^{o}C, and the velocity at the chimney outlet is 8.4 m/sec. Under minimal loading conditions (one boiler is operating on four of the six burners installed in the furnace), the consumption of natural gas is 1700 m^3/h, α_{ef} = 1.10, t_{ef} = 78^{o}C (according to the operational chart), and w_0 = 1.5 m/sec.

The first regime. Let us calculate the temperature of the inner surface of chimney No. 1 under operation of two boilers under maximum loading conditions in the coldest period of the year ($t_{f.a}$ = –35^{o}C). Since the temperature of gases in the chimney cap is unknown, in the first approximation we assume it to be equal to the temperature at the chimney base (160^{o}C) and then perform calculations by the method of successive approximations. The results of the calculation are as follows: the velocity of gases in the chimney cap w_0 = 8.22 m/sec, Re = 7.74·10^5, δ = 0.990·10^{-3} m ≈ 1 mm. Since $\Delta >> \delta$, we calculate the heat-transfer coefficient for the limiting roughness conditions ξ = 0.0360, k^+ = 167, n = 13.14, Nu = 1259, α_c = 181 W/(m^2·K), α_r = 6.9 W/(m^2·K), α_{in} = 25.0 W/(m^2·K), d_{av} = 2.88 m, F = 723.8 m^2, k = 1.8 W/(m^2·K), and t_{cap}^{g} = 153.1^{o}C.

Consequently, in this regime the gases are cooled in the chimney by no more than 7°C. The heat-flow density in the diameter-average cross section of the chimney cap and the temperature of the inner surface of the chimney in the region of the cap are defined as

$$q_{av} = k\,(t^{g}_{cap} - t_{f.a})\,, \tag{17}$$

$$t_{in} = t^{g}_{cap} - q_{av}\,\frac{d_{av}}{d_{in}}\,\frac{1}{\alpha_{in}}\,. \tag{18}$$

We obtain q_{av} = 338.6 W/m^2 and t_{in} = 137.4°C. Thus, the temperature of the inner surface of the chimney in the region of the cap is 22.6°C lower than the temperature of combustion products escaping from the smoke exhausters and considerably (by 80°C) exceeds the dew-point temperature. No condensate will be formed on the inner surface.

The second regime. Consider the operation of one boiler under its minimum load. In the coldest period the boiler house works in the first regime. It is expedient to determine the air temperature at which the second regime is admissible. The difference between the regimes is that the temperature of the inner surface of the chimney cap is known and is equal to the dew-point temperature of the steam in combustion products, and the free air temperature has to be given additionally. At α_{ef} = 1.10, the volume content of steam in combustion products is 0.185 and the dew-point temperature is 58.7°C. Therefore, we assume t_{in} = 58.7°C. Then w_0 = 1.46 m/sec, Re = 2.00·10^5, and δ = 3.34 mm. Since $\delta \approx \Delta$, it is necessary to calculate the heat-transfer coefficients for the smooth and the limiting-roughness tubes and take their average value. For the smooth tube, by formula (5) we obtain α_c = 3.8 W(m^2·K) and for the rough one α_c = 4.4 W(m^2·K). The mean convective heat-transfer coefficient α_c = 4.1 W(m^2·K), the radiant heat-transfer coefficient α_r = 3.7 W(m^2·K), α_{in} = 7.8 W(m^2·K), k = 1.5 W(m^2·K), t^{g}_{cap} = 70.3°C, and $t_{f.a}$ = 19.0°C.

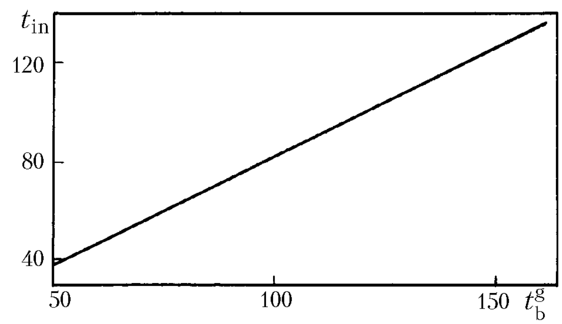
Under these conditions the temperature of the chimney wall becomes equal to the dew point temperature already at $t_{f.a}$ = 19.0°C, and at $t_{f.a}$ < 19.0°C steam will condense on the chimney wall. The heating period begins and ends when the free air temperature lowers or rises to 8°C. This means that when one boiler operates under the minimum load, in the heating period condensation in the chimney will always occur. If one boiler is in full operation, then condensation in the chimney begins at $t_{f.a}$ = –12°C. Indeed, practically as soon as the chimney was put into operation, the bricks in its upper part began to get wet and gradually collapse. This process stopped only after the upper 5 m of the brickwork were replaced by brickwork from acid-resistant bricks.

Chimney No. 2. This tube of height 59.85 m was designed for five boilers, of which in summer only one is in operation. According to the certificate, under operation of five boilers for the chimney the velocity of gases escaping from it is 8.6 m/sec, and under operation of one boiler — 1.1 m/sec. Let us make analogous calculations for this chimney in the two regimes in the coldest period ($t_{f.a}$ = –35°C) when five boilers are in operation (V_g = 26.8 m^3/sec) and in the case of operation of one boiler (V_g = 4.3 m^3/sec). In both cases, the temperature of gases at the chimney base is t^{g}_{b} = 140°C.

The first regime. The results of the thermal calculation of the chimney at a maximum flow rate of combustion products through it are as follows: the velocity of gases in the chimney cap w_0 = 8.17 m/sec, Re = 8.29·10^5, and δ = 0.931·10^{-3} m ≈ 1 mm. Since $\Delta >> \delta$, we calculate the heat-transfer coefficient for the ultimate permissible regime of roughness: ξ = 0.0232, k^+ = 179, n = 13.35, Nu = 1335, α_c = 18.4 W(m^2·K), α_r = 5.8 W(m^2·K), α_{in} = 24.2 W(m^2·K), d_{av} = 2.88 m, F = 541.5 m^2, k = 1.8 W(m^2·K), t^{g}_{cap} = 135.5°C, q_{av} = 307 W/m^2, and t_{in} = 121°C.

Under such conditions, the gases are cooled in the chimney by no more than 5°C and the temperature of the inner surface of the chimney in the region of the cap is 19°C lower than the temperature of the combustion products escaping from the smoke exhausters and considerably (by more than 60°C) exceeds the dew-point temperature. No condensate will be formed on the inner surface.

The second regime. The results of the thermal calculation of the chimney at a minimum flow rate of combustion products through it are as follows: w_0 = 1.26 m/sec, Re = 1.39·10^5, and δ = 4.64 mm ≈ Δ. For the smooth tube, by formula (5) we obtained the value of α_c = 3.2 W(m^2·K), for the rough tube α_c = 3.7 W(m^2·K), and the average heat convective heat-transfer coefficient α_c = 3.45 W(m^2·K), α_r = 5.1 W(m^2·K), α_{in} = 8.55 W(m^2·K), k = 1.6



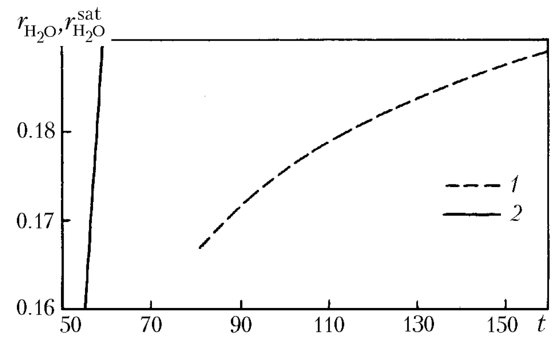


Fig. 2. Temperature of the inner surface of the brick chimney cap versus the temperature of the gas flowing into the chimney. t_b^g, t_{in}, °C.

Fig. 3. Change in the relative volume concentration of steam r_{H_2O} in the process of cooling of combustion products of natural gas in a three-row, fin-type heat exchanger by water with a temperature of 5°C (1) and temperature dependence of the relative volume concentration of dry saturated steam $r_{H_2O}^{sat}$ (2). t, °C.

W(m^2·K), t_{cap}^g = 117°C, q_{av} = 243.2 W/m^2, t_{in} = 85°C. Under these conditions, the effluent gases are cooled in the chimney already by 23°C, the temperature of the chimney wall is about 30°C higher than the dew-point temperature, and the situation is qualitatively the same as in the first regime. The experience of operation of the chimney confirms that there have been no problems with the cap for about 50 years.

Temperature of Effluent Gases That Ensures the Absence of Condensation on the Inner Surface of the Chimney Cap. From formulas (15), (17), and (18) we obtain the relation

$$t_{in} - t_{f.a} = (t_b^g - t_{f.a}) \exp\left(-\frac{kF}{V_g c_g'}\right)\left(1 - \frac{k}{\alpha_{in}} \frac{d_{av}}{d_{in}}\right), \tag{19}$$

using which we can plot the dependence of the temperature of the inner surface t_{in} on the temperature of effluent gases at the inlet into a particular chimney t_b^g at a given temperature of free air $t_{f.a}$ and a given rate of flow through it. As an example, Fig. 2 shows such a dependence for the first regime of operation of chimney No. 1.

In designing hot-water, gas-fired boilers, the temperature of water at the inlet into the boiler is taken to be equal to 70°C in order to prevent steam condensation in coil pies. If we take the same reserve for the temperature of the inner surface of the chimney cap (as is known, the dew-point temperature in combustion products is equal to 50–59°C depending on the excess air coefficient), then from Fig. 2 it follows that the temperature of effluent gases at the inlet into the chimney should be kept at a level not below 86°C (at a free air temperature of –35°C and a flow rate of combustion products of 25.85 m^3/sec). At a higher ambient temperature the minimum permissible temperature of combustion products decreases.

Figure 3 shows the calculated dependence of the relative volume concentration of steam on the temperature of combustion products cooled in a three-row, fin-type heat exchanger by water with a temperature of 5°C (curve 1) (the excess air coefficient is 1.07) and the temperature dependence of the relative volume concentration of dry saturated steam (curve 2). From Fig. 3 it is seen what humidity the gases have at the outlet from the heat exchanger and in what state the noncondensed steam is.

In a three-row heat exchanger, combustion products are cooled from 160 to 81°C, and the steam concentration thereby decreases from 18.9 to 16.7%, i.e., about 10% of the condensation heat of the steam contained in the combustion products is used. The dew-point temperature at r_{H_2O} = 0.167 is 56.5°C. With a reserve equal to 10°C one can take t_{in} = 67°C. Then the temperature of combustion products at the inlet into the chimney at V_g = 25.85 m^3/sec should be not lower than 82°C (see Fig. 2). Steam condensation will not occur more surely if the heat-recovery facility is located behind one boiler and the second one operates without a condensation heat exchanger.

Wetting of the Chimney Brickwork Because of Steam Diffusion. A brick or a concrete chimney can, apparently, collapse near the outer surface because of the condensation of the steam filtered through the brickwork. The

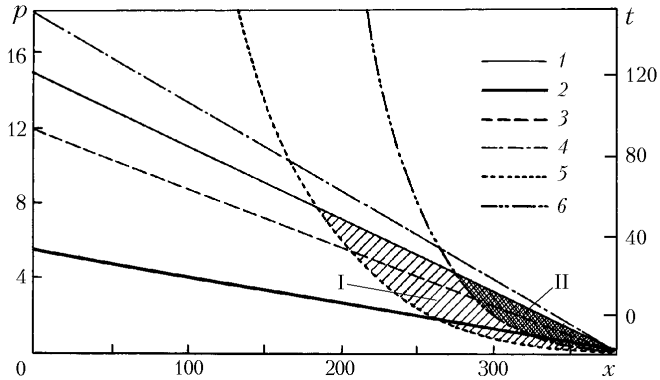


Fig. 4. Change in the partial pressure of steam in the brickwork thickness at steam concentrations in gases r_{H_2O} = 0.15 (1) and r_{H_2O} = 0.055 (2); change in the temperature of the brickwork in its thickness at a temperature of the inner surface of 100°C (3) and 160°C (4) and their corresponding pressures of saturated steam (5) and (6). p, kPa; t, °C; x, mm.

partial pressure of the steam in combustion products of natural gas is 10–19 kPa, and the medium pressure of the steam contained in the free air in the coldest month (January) in Ekaterinburg is 170 Pa [19]. Under the action of this pressure difference, the steam can filter through the chimney brickwork. At a steam penetration factor of the brickwork μ = 0.11 mg/(m·h·Pa) [19], the stationary flow of steam through a wall of thickness 0.38 m will be equal to more than 4 g/(m^2·h). Since the curvature of the chimney wall is small, we shall assume it to be flat. In this case, the partial pressure of the steam p will decrease linearly from 15 kPa on the inner surface to 170 Pa on the outer surface (straight line 1 in Fig. 4). Let us assume that the temperature also changes linearly from 100 to –20°C (straight line 3). Curve 5 gives the pressure p_{sat} of saturated steam corresponding to temperature 3 in the given cross section (at a distance x from the inner surface of the brickwall). If $p < p_{sat}$, then the steam in this cross section is in the superheated state, i.e., it filters in the form of steam. Physically, the value of p cannot be larger than the value of p_{sat} at the given temperature. Consequently, in the cross section where $p = p_{sat}$ the steam will begin to condense, which, under the given conditions, will occur at a distance of 187.5 mm from the inner surface of the brickwall. The entire zone to the right of this cross section is a wetting region (portion I in Fig. 4), the heat-conductivity coefficient of the brickwork here will be higher than that used in the calculation (by 8% as the brickwork moisture is increased by 1%).

The further behavior of this wet layer depends primarily on its thickness. If the layer is thin and the brickwork gets wet slightly, then with increasing free air temperature (in a warm spell) it will get dry. Otherwise plenty of moisture can accumulate in the brickwall and it will freeze, which will leads to the destruction of its outer layer. It is precisely in this case that the influence of sporadic enveloping of the chimney cap by effluent gases leading to the brickwall wetting on the outside can be strong. The thickness of the wetting-through zone can be decreased by increasing the temperature of the inner surface of the brickwork (straight line 4 and its corresponding curve 6 of the saturated steam pressure; the wetting zone corresponds to portion II). The second way is drying of combustion products before the chimney in the surface condensation heat exchanger followed by heating of the dried gases. If the gases are dried to the same temperature that they had before the condensation heat exchanger, only the condensation heat is efficient, but it is more sound economically to heat the gas to a lower temperature. When the steam pressure in combustion products is equal to 5.5 kPa (straight line 2), the moisturing zone considerably narrows, even at a temperature of the inner surface of the brickwork equal to 100°C.

CONCLUSIONS

1. The chimney is an engineering structure operating under severe conditions of wind loads, temperature drops, and aggressive action of fluent gases. The certificate of brick and concrete chimneys should incorporate a regime chart containing calculated dependences analogous to those given in Figs. 2 and 4 and specifying the regimes of its safe (without steam condensation in the masonry) operation throughout the range of rates of flow of combustion products through it and their outlet temperatures.

2. The problem of upgrading the efficiency of using natural gas requires a deeper cooling of combustion gases, up to the recovery of the condensation heat of the steam contained in them. For boiler rooms equipped for the use of gases, erection of an individual metal chimney (or a chimney from a more modern material) for each boiler (or individual metal shafts in one shell) may turn out to be more expedient than one chimney (as a rule, a brick one) for the whole boiler house as recommended in [1].

3. Chimneys from carbon steel have to be heat-insulated on the outside to prevent steam condensation in them. In the case of installing behind boilers heat exchangers for deep cooling of combustion products, it is expedient to build chimneys from bimetal (the inner surface clad with stainless steel), glass-reinforced plastics, fayalite, acid-resistant bricks, and other materials that are resistant to acidified condensation and withstand the temperatures that combustion products will have upon emergency switching-off of the deep-cooling heat exchanger, as well as to use chimneys of special design, for example, chimneys with an internal, gas-impenetrable, gas-withdrawing shaft.

NOTATION

a, emissivity factor; c'_g, specific volume heat capacity of gases, J/(m^3·K); d, diameter of the chimney, m; F, surface area, m^2; g, gravitational acceleration, m/sec^2; H, height of the chimney, m; i, incline; k, heat-transfer coefficient, W/(m^2·K); k^+, dimensionless parameter; kps, total optical thickness of combustion products; k_g^0, absorption coefficient of beams by the gaseous phase of combustion products; l, tube length, m; n, dimensionless parameter in formulas (10)–(12); Nu, Nusselt number; Pr, Prandtl number; p, pressure, Pa; q_{av}, heat-flow density in the diameter-average cross section of the chimney cap, W/m^2; Re, Reynolds number; r, relative volume concentration; S, shear stress, Pa; s, effective thickness of the emitting layer, m; T, t, temperature, K, ^{o}C; V_g, volumetric rate of flow of combustion products, m^3/sec; w, velocity, m/sec; x, distance from the base of the chimney, m; α, heat-transfer coefficient, W/(m^2·K); Δ, equivalent roughness, mm; δ, thickness of the wall, of the laminar sublayer, m; ε_i, correction for the change in the heat-transfer coefficient; λ, heat-conductivity coefficient, W/(m·K); μ, steam penetration factor, mg/(m·h·Pa); ν, kinematic viscosity coefficient, m^2/sec; ρ, density, kg/m^3; ξ, coefficient of friction resistance. Subscripts: g, gas; air, air; in, inner, c, convective; br, brickwork; r, radiant; out, outer; sat, state of saturation; f.a, free air; cap, cap; b, base, av, average; w, wall; t.g., triatomic gases; ef, effluent gases; 0, orifice of the chimney.

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