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CALCULATION OF PLANE POROUS RADIATORS WITH SURFACE COMBUSTION

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Results of theoretical and experimental studies of porous radiators for heating various materials are compared.

In the present article, which is a continuation of [1], we discuss a procedure for calculating porous radiators, and also compare analytic and experimental results.

Figure 1 is a schematic diagram of a commercial installation used for the heat treatment of metal products. The filterable injectant is a mixture of methane and air with volume concentrations $Y_f \approx 0.10$, $Y_A \approx 0.90$, which corresponds to the stoichiometric composition. Air and methane are fed through valves 1 and 4 and rotameters 2 and 6, which determine the flow rates of these gases, to the mixer 3. The prepared fuel mixture is then forced to the porous plate 8 by the rotary gas blower 14. The flow rate of the mixture is measured by the type RS-100 gas meter 13. A constant ratio between the components of the injectant is maintained by the null regulator 5 in the supply line. This regulator is a proportioning device consisting of a valve and cavities for methane and air separated by two diaphragms whose deformation depends on the pressure of the supplied gas. The null regulator 5 was described in detail in [2]. The pressure of the gas–air mixture supplied to the gas distributing cavity of the burner was monitored by U-tube water manometers 7.

The operating conditions of the radiator (burner) under consideration depend on the heat load on the surface of the permeable plate, its porosity, the thermophysical properties of the interacting media, the form of the injectant and its rate of injection, and also on the fuel–air ratio. The temperature T_2 of the radiator surface depends strongly on the excess air ratio $\overline{\alpha}$, as follows from Fig. 2a. Our experiments were performed for $\overline{\alpha} = 1$, values of ξ_Σ from 15.98 to 80.10, temperatures of the radiator surface T_2 from 1040 to 1400°K, and a filtration rate of the fuel–oxidant mixture v_Σ from 0.04 to 0.10 m/sec. According to [3], the optimum limits of the variation of the injection velocity for porous radiators with surface combustion are 0.10–0.17 m/sec, for which the values of the temperature of the radiator surface T_2 are maximum, and obtaining higher velocities v_Σ in standard commercial installations is economically inexpedient. As follows from Fig. 2b, this conclusion agrees with our experimental results. For heat loads $q_2 \leq 4.5 \cdot 10^5$ W/m², where $q_2 = j_F Q_F$, the radiator temperature T_{2F} averaged over a time interval $\tau = 600$ sec is increased as a result of increased heat release at the surface of the porous plate proportional to the transverse flux density of the fuel gas j_F. For larger values of q_2 the flame is observed to separate from the surface of the porous wall, and the values of T_{2F} are decreased.

The empirical relation for determining the filtration velocity of the fuel–air mixture $v_{\Sigma 0}$ for which there is a separation of the flame from the surface of the porous plate for $\overline{\alpha} \sim 1$ has the form [3] $v_{\Sigma 0} = 5.42 \times 10^{-3} dT_2^2$, where d is the pore diameter in meters. Thus, for the plate we studied for $T_2 = 1300$°K and $d = 10^{-4}$, we obtain $v_{\Sigma 0} = 0.91$ m/sec. The experiments reported in the present article were performed with injection velocities appreciably lower than $v_{\Sigma 0}$ (cf. Fig. 2b).

The coefficient η, defined by Eq. (10) of [1] and characterizing the completeness of combustion of the injectant, can be written as

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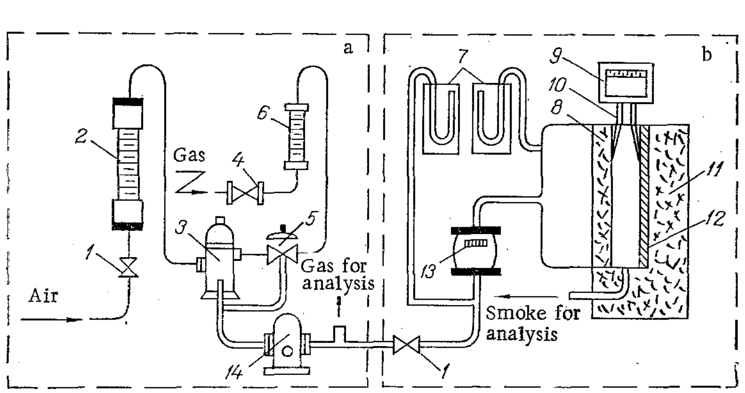

Fig. 1. Schematic diagram of a porous radiator (a – equipment for preparing combustible fuel–oxidant mixture; b – porous radiator): 1) valve for air supply; 2) RS-7 rotameter; 3) mixer; 4) valve for fuel gas supply; 5) null regulator; 6) RS-5 rotameter; 7) U-tube manometer, 8) porous plate of type ShLB-0.4 ultralight weight fireclay; 9) KSP-4 potentiometer; 10) Chromel-alumel thermocouples with 0.4 mm diameter wires; 11) layer of thermal insulation with a high content of VGR-150 aluminum oxide fiber; 12) heated plate of 50S2G steel 0.01 m thick; 13) RS-100 gas meter; 14) rotary gas blower.

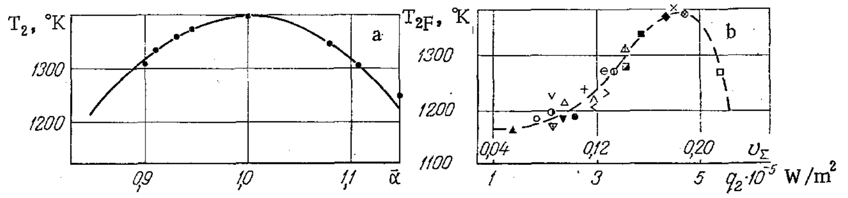

Fig. 2. Surface temperature of porous radiator T_2 and T_{2F} (°K) as a function of a) excess air ratio $\bar{\alpha}$; b) heat load $q_2 \cdot 10^{-5}$ W/m^2 (notation in Fig. 2b is the same as in Fig. 3); v_Σ, m/sec.

$$\eta = 1 - Q_g/Q_F^L,$$

where Q_g is the heat lost with the exhaust flue gases, and Q_F^L is the lower heating value of the fuel. For methane, the dependence of η on the temperature of the flue gases is given in [4] in the form $\eta = 1.12 - 4.38 \cdot 10^{-4}\, T_g$. According to our experimental data $T_g = T_{3F}$, where $T_{3F} = \sqrt{T_{3I} T_{3U}}$ is the geometric mean temperature of the heated article.

In a number of studies [5-8] there was rather complete combustion of the gas on the porous surface as a result of optimum preparation of the mixture and the catalytic effect of the incandescent walls of the radiator on the course of the oxidation reaction. Our check analyses of combustion products [9] showed no components of incomplete combustion of the mixture for $\bar{\alpha} = 0.99 - 1.02$ over the whole range of heat loads investigated (Table 1). The experiments were performed for values of the flow rate of the injectant V_F and the pressure drops ΔP across the thickness of the porous wall for which the temperatures T_2 of the radiator were maximum. Since the composition of the flue gases for $\bar{\alpha} \cong 1$ corresponds to the concentrations of the flue gases (Table 1) to within ±2%, the values of λ_g were determined with the formula $\lambda_g = -7.32 \cdot 10^{-4} + 8.62 \cdot 10^{-5}\, T_{(2-3)F}$, W/m·°K, where $T_{(2-3)F} = \sqrt{T_{2F} T_{3F}}$, °K. The concentration of the fuel gas (methane) in the filterable fuel–gas mixture was monitored continuously with an OA-2309 gas analyzer. The location of the test sample in Fig. 1a is denoted by the legend "gas for analysis." The concentration of the components of the gas were determined for each set of operating conditions of the porous radiator by analyzing the combustion products of the fuel–air mixture in a tube filled with a chromocobaltic catalyst. The concentration was measured on a type LKhM-7A chromatograph. Injection needles with a 1 mm outside diameter were used for test samples from the combustion zone (denoted by "smoke for analysis" in Fig. 1b). This procedure for determining the concentrations of the components under the combustion conditions considered is the most accurate [2], whereas the introduction of a gaseous water-cooled tube into the study zone appreciably disturbs the heat-transfer conditions.

TABLE 1. Dependence of Composition of Flue Gases on the Air Excess Factor $\bar{\alpha}$ for the Combustion of Methane*

Composition of flue gases vol.%					$\bar{\alpha}$	$V_{f\varepsilon}$, m^3/h	ΔP, mm H_2O	T_2, °K
O_2	CO	CO_2	H_2O	N_2				
0	4,0	9,0	7,3	79,7	0,91	1,80	45	1288
0	4,0	9,0	7,3	79,7	0,91	2,15	53	1308
0	4,0	9,0	7,3	79,7	0,91	2,25	55	1268
0	4,0	9,0	7,3	79,7	0,91	2,90	65	1213
0,8	0,6	8,6	5,4	81,8	1,15	1,80	45	1246
0,8	0,6	8,6	5,4	81,8	1,15	2,15	53	1258
0,8	0,6	8,6	5,4	81,8	1,15	2,25	55	1256
0,8	0,6	8,6	5,4	81,8	1,15	2,40	58	1201
0,2	0,2	11,6	9,5	78,5	1,11	1,80	45	1281
0,2	0,2	11,6	9,5	78,5	1,11	2,15	53	1303
0,2	0,2	11,6	9,5	78,5	1,11	2,30	57	1308
0,2	0,2	11,6	9,5	78,5	1,11	2,55	67	1256
0	0,4	11,6	9,5	78,5	1,08	1,80	45	1283
0	0,4	11,6	9,5	78,5	1,08	2,00	50	1323
0	0,4	11,6	9,5	78,5	1,08	2,25	55	1333
0	0,4	11,6	9,5	78,5	1,08	2,65	62	1346
0,2	0,4	11,2	9,2	79,0	1,00	3,15	72	1269
0	0,2	12,6	10,7	70,5	1,00	2,15	53	1360
0	0,2	12,6	10,7	70,5	1,00	2,40	58	1373
0	0,2	12,6	10,7	70,5	1,00	2,80	65	1398
0,2	1,80	10,40	8,50	79,1	0,97	3,05	68	1386
0	3,0	9,8	8,0	79,1	0,94	2,40	58	1371
0	3,0	9,8	8,0	79,1	0,94	2,65	62	1387
0	3,0	9,8	8,0	79,1	0,94	2,80	65	1387
0	3,0	9,8	8,0	79,1	0,94	3,00	67	1377
0	3,6	9,2	7,5	79,7	0,93	2,40	58	1358
0	3,6	9,2	7,5	79,7	0,93	2,55	61	1373
0	3,6	9,2	7,5	79,7	0,93	2,65	62	1373
0	3,6	9,2	7,5	79,7	0,93	2,80	65	1363
0	4,4	8,8	7,2	79,6	0,91	2,10	52	1332
0	4,4	8,8	7,2	79,6	0,91	2,25	55	1340
0	4,4	8,8	7,2	79,6	0,91	2,40	58	1339
0	4,4	8,8	7,2	79,6	0,91	2,55	61	1333

*The experiments were performed for the combustion of methane on the surface of a sample of type BL-0.4 ultralight weight fireclay 0.097 m in diameter with radiation into empty space.

The emissivity ε_2 of the radiating porous surface can be varied from 0.85 to 1. For porous granular packings $\varepsilon_2 = 0.85$, and this value increases as the heat load is increased [8]. In [8] it was found that $\varepsilon_2 = 1$. For porous surfaces with pyramidal protuberances $\varepsilon_2 = 0.96$ [3]. Since such protuberances are characteristic for the ultralight weight type BL-0.4 fireclay used in our experiments, we took $\varepsilon_2 = 0.96$. For type 50S2G oxidized steel $\varepsilon_3 = 0.85$ [10]. According to [4], in the combustion of methane the abosrption coefficient $\varkappa$ of the combustion products is 0.3 m^{-1}. Since our experiments were performed for gas layers of thickness $l_g = 0.024$ and 0.042 m, the values of ε_g determined with the formula $\varepsilon_g = 1 - \exp(-1.8\, l_g \varkappa)$ were equal respectively to 0.0127 and 0.022. The thermophysical coefficients in Eq. (10) of [1], i.e., c_{pF}, c_{pA}, c_{pmix}, λ_r, λ_{mix}, and λ_Σ, were found for $T_{2F} = \sqrt{T_{2I}T_{2U}}$, c_{p3} and ρ_3 for $T_{3F} = \sqrt{T_{3I}T_{3U}}$, and λ_g for $T_{(2-3)F}$. With this choice of defining temperature, the magnitudes of the thermophysical coefficients practically agree with their actual values. Therefore, the error of the calculation due to the assumption of the constancy of the thermophysical properties becomes negligible, of the order of ±7%. The maximum difference between the theoretical and calculated results, as will be shown later, is ±15%. The accuracy of the calculations is also increased by performing them for relatively small temperature ranges of the article $\Delta T_3 = T_{3U} - T_{3I} = 100$°K, corresponding to various values of $\Delta T_2 = T_{2U} - T_{2I}$, and averaging all the thermophysical coefficients only over the indicated limits ΔT_2 and ΔT_3. The transverse flux density of the fuel gas j_F and oxidant (air) j_A entering with a coefficient in the dimensionless injection parameters ξ_F and ξ_Σ given by Eqs. (10) of [1] were determined from the relation $j_i = (\rho V)_{i\varepsilon}/F_3$, where i = f or A, and $\rho_{i\varepsilon}$ is the weight density of the filterable gases; $V_{i\varepsilon}$ is their volumetric flow rate. The values of the remaining parameters used in the calculation of a porous radiator are:

$$C_f = 0{,}061;\ C_A = 0{,}939;\ T_\infty = 293\,°\mathrm{K};\ t_\varepsilon = 1;\ F_2 = 0{,}3\ \mathrm{m}^2;$$

$$\rho_{f2} = 0{,}68\ \mathrm{kg/m^3};\ c_{pf2} = 4{,}1529\ \ \mathrm{kJ/kg\cdot°K};\ \ \Pi = 0{,}4;$$

$$Q_f = 51\,000\ \mathrm{kJ/kg};\ \ l_3 = 0{,}01\ \mathrm{m};\ y_1 = 0;\ y_2 = 0{,}065\,\mathrm{m};$$

$$\bar{y}_3 = 1{,}369\ \text{for}\ \ l_g = 0{,}024\ \mathrm{m};\ \bar{y}_3 = 1{,}646\ \text{for}\ \ l_g = 0{,}042\ \mathrm{m};$$

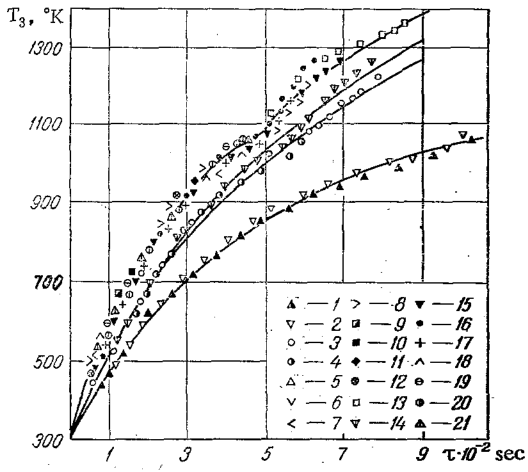

Fig. 3. Final temperature of heated article T_3 (°K) as a function of time $\tau \cdot 10^{-2}$ sec for various values of the transverse flux density of the fuel gas j_F (kg/m²·sec) and $\bar{\alpha} = 1$: 1) $j_F \cdot 10^5 = 261$; 2) 304; 3) 365; 4) 369; 5) 389; 6) 417; 7) 557; 8) 592; 9) 677; 10) 729; 11) 832; 12) 948; 13) 1056; 14) 390; 15) 410; 16) 460; 17) 494; 18) 545; 19) 592; 20) 635; 21) 677 (2-6 and 14-21: $l_3 = 0.024$ m; 7-13: $l_3 = 0.042$ m).

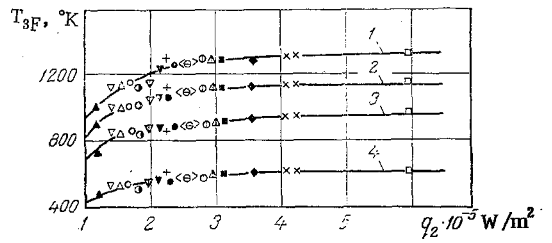

Fig. 4. Temperature dependence of a heat article T_{3F} (°K) averaged over an interval $\tau = 600$ sec on the heat load $q_2 \cdot 10^{-5}$ W/m² for various values of τ, sec: 1) $\tau = 700$; 2) 500; 3) 300; 4) 100.

The values of T_3 increase with increasing injection rate j_F (Fig. 3). The agreement of the experimental points and the calculated curves is quite satisfactory — the difference does not exceed ±15%. The average temperature of a heated article T_{3F} for various durations τ of the heating process at first increase (for heat loads $q_2 \leq 2.5 \cdot 10^{-5}$ W/m²) (Fig. 4), and then remain practically constant in spite of the increase in q_2. This is accounted for by the decrease of the difference $(t_2^4 - t_3^4)_F$ appearing in Eqs. (21) and (22) of [1].

The theoretical and experimental results of the investigation of surface combustion on a porous plate shown in Figs. 2-4 are confirmed also by the data of Table 2.

The data of Table 2 show that the difference of the values of t_3 in the first two lines was taken greater ($\Delta t_3 = 0.785$, which corresponds to $T_{3I} = 293$°K and $T_{3U} = 523$°K) than in all the following lines where $\Delta T_3 = 100$°K, since at the start of the process there is intense heating of the metal article, and $dT_3/d\tau$ is practically constant (cf. Fig. 3). All the parameters characterizing the combustion conditions and the heating of an article which we investigated are stabilized at $T_3 \approx 520$°K.

The data listed in Table 2 also confirm the good agreement of the theoretical and experimental results.

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TABLE 2. Theoretical and Experimental Results of Investigation of a Porous Radiator with Surface Combustion

τ, sec	$c_{p3}\rho_3$, kJ/kg	$c_{pmix}\cdot 10^3$, kJ/kg·deg	$\lambda_{g\Sigma}\cdot 10^4$	$E\cdot 10^4$	$\xi_f\cdot 10^3$	$\xi_\Sigma\cdot 10^3$	$t_3\cdot 10^3$	Calculation: $dT_3/d\tau$, deg/sec	Calculation: t_2	Experiment: $dT_3/d\tau$, deg/sec	Experiment: t_2
0							100				
111	3855	1414	1895	3035	2148	34962	178	2,113	4,1266	2,070	3,9859
160	4240	1421	2849	3088	2126	34608	2126	1,996	4,1137	2,040	4,0630
216	4374	1425	3137	2981	2113	34396	2468	1,929	4,0658	1,790	4,1091
282	4732	1430	3386	2951	2099	34166	2809	1,739	4,0448	1,515	4,1603
362	5273	1437	3602	2910	2080	33854	3150	1,372	4,0521	1,250	4,1605
485	6498	1455	3793	2862	2054	33491	3491	0,913	4,0924	0,813	4,1609
595	4710	1452	3965	2808	2032	33078	3833	1,036	4,1707	0,910	4,2425
725	4657	1465	4135	2756	2007	32646	4225	0,969	4,3025	0,885	4,4801
0							100				
96	3855	1417	1888	3035	2325	37849	178	2,185	4,2656	2,390	4,0193
142	4240	1427	2834	2973	2293	37329	2126	2,121	4,2465	2,170	4,1228
189	4374	1433	3118	2938	2275	37035	2468	2,092	4,1880	2,130	4,1857
237	4732	1440	3359	2896	2254	36684	2809	1,942	4,1539	2,080	4,2593
303	5273	1446	3576	2860	2235	36383	3150	1,550	4,1504	1,510	4,2598
398	6498	1454	3366	2811	2211	35981	3491	1,087	4,1765	1,000	4,2863
445	6734	1461	3883	2773	2191	35659	3611	0,845	4,2142	0,745	4,2895
0							100				
140	3855	1388	1949	3202	1057	17388	178	1,550	3,6914	1,554	3,6924
220	4240	1396	2914	3161	1049	17257	2126	1,330	3,6940	1,334	3,6940
315	4374	1412	3168	3047	1024	16838	2468	1,160	3,6718	1,159	3,6707
435	4732	1418	3416	3012	1016	16709	2809	0,964	3,6971	0,954	3,6901
575	5273	1426	3627	2960	1004	16515	3150	0,775	3,7591	0,756	3,7601
775	6498	1439	3803	2881	986	16223	3491	0,508	3,8591	0,509	3,8600
1020	5446	1451	3921	2816	972	15981	3662	0,500	3,9636	0,432	3,8603
0							100				
96	3855	1417	1888	3035	2325	37849	178	2,770	4,2656	2,390	4,0193
142	4240	1427	2834	2973	2293	37329	2126	2,400	4,2465	2,170	4,1228
189	4374	1433	3118	2938	2275	37035	2468	2,100	4,1880	2,130	4,1857
237	4732	1440	3359	2896	2254	36684	2809	1,770	4,1539	2,080	4,2593
303	5273	1446	3576	2860	2235	36383	3150	1,555	4,1504	1,510	4,2598
398	6498	1454	3766	2811	2211	35981	3491	1,087	4,1765	1,000	4,2863
445	6734	1461	3883	2773	2191	35659	3611	0,870	4,2142	0,745	4,2895

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