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Figure 1: Fig. 1. Motor gasoline. A –d = 1.1 cm; –3.0 cm; –15 cm; –30.0 cm; –130.0 cm

Abstract

Full Text

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ON CERTAIN REGULARITIES IN THE DIFFUSION COMBUSTION OF LIQUIDS

(Presented by Academician G. M. Krzhizhanovsky, 16 XI 1956)

The study of the combustion of motor gasoline, kerosene, diesel fuel, solar oil, and a number of other petroleum products in reservoirs of various diameters made it possible to establish a number of important regularities of this type of diffusion combustion of liquids.

1. Figure 1 shows photographs of flames of motor gasoline burned in cylindrical reservoirs with diameters of 1.1; 3; 15; 30; and 130 cm. From the photographs it is evident that, as the reservoir diameter increases, the appearance and structure of the flame change substantially. The gasoline flame in a reservoir with a diameter of 1.1 cm has a conical shape, which does not change with time. As the burner diameter increases, the flame of petroleum products begins to pulsate with a maximum frequency of approximately 18-20 Hz. With a further increase in diameter, the flame pulsation decreases. At $d = 3$ cm the upper part of the flame becomes unstable. With increasing d, the boundary of the unstable part shifts downward. At $d = 15$ cm the entire flame has bizarre, rapidly changing outlines. In a gasoline flame,

Fig. 1. Motor gasoline. **A** –$d = 1.1$ cm; –3.0 cm; –15 cm; –30.0 cm; –130.0 cm

burning in a tank with a diameter of 130 cm, random turbulent motions are clearly visible. The same picture is observed in the combustion of other liquids.

2. The combustion of a liquid is the combustion of a vapor jet. Table 1 gives the values of the Reynolds numbers Re for vapor jets of some of the petroleum products studied, calculated on the basis of experimental data. It is seen from the table that Re is small for a tank of small diameter. At

$d > 8$ cm, a rapid increase in Re with increasing diameter is observed, and for tanks with diameters of 130 cm, Re is large and exceeds the critical value.

The photographs and the data of Table 1 show that, in the combustion of liquids in tanks, two regimes occur: laminar—when liquids burn in tanks whose diameter is small, and turbulent—when they burn in tanks whose diameter is greater than 1 m.

3. It is seen from Table 1 that the dependence $v(d)$ for all the liquids studied has the same character, similar to the character of the dependence $v(d)$ for aviation gasoline described in (^{1}). The velocity v at first decreases with increasing tank diameter, tending to a certain limiting value; at $d > 10$ cm, v increases with increasing diameter, while for d exceeding 1 m, the velocity v practically does not change with changes in d. Thus, the entire region investigated is divided into three parts, in each of which a dependence $v(d)$ characteristic of that part is observed.

The values of Re for different d and the photographs of the flames give grounds for concluding that the first of the indicated regions is the region of laminar combustion, and the third that of turbulent combustion of liquids; the second region is transitional from the laminar regime to the turbulent one.

4. The change of v as a function of d in the region of laminar combustion is described rather well by the relation $v = a + bd^{-n}$, where a and b are constants depending only on the nature of the liquid. The value of a ($a = v$ at $d = \infty$) is, for motor gasoline, 1.4; tractor kerosene, 1.1; illuminating kerosene, 0.9; solar oil, 0.5; diesel fuel, 0.8; and transformer oil, 0.5 mm/min, while the exponent n is, respectively, 1.73; 1.61; 1.51; 1.54; 1.31; and 1.5.

Simple calculations show that the decrease in the specific velocity of laminar combustion of liquids with increasing tank diameter is due mainly to the relative decrease in the amount of heat received by the liquid from the flame through the tank wall.

5. Table 1 shows that, in laminar combustion, the ratio of the volume Q of liquid burned per unit time to the flame height δ does not depend on the tank diameter and, consequently, the quantity $u = Q/\delta d$, characterizing the burning velocity referred to unit flame surface, changes in proportion to $1/d$.

These results are easy to explain. Indeed, in laminar combustion of unmixed gases the flame height (^{1,2}) is $\delta \approx wd^2/D$, where w is the flow velocity of the combustible gas; D is the diffusion coefficient of oxygen. If ρ_p and ρ denote the density of the vapor and of the liquid, then $w\rho_\mathrm{p} = v\rho$. Since $Q = \pi wd^2/4 = \pi v\rho d^2/4\rho_\mathrm{p}$, then, after substituting the latter result into the expression by which δ is determined, we obtain that, for the given liquid in laminar combustion, $Q/\delta = \mathrm{const}$, $u = \mathrm{const}/d$.

6. From the experimental data given in Table 1 it follows that the specific velocity of turbulent combustion of liquids practically does not depend on d: when the tank diameter was increased 18-fold (from 1.3 to 22.9 m), the burning velocity of motor gasoline and kerosene changed hardly at all (the changes lie within the limits of observational error). This fact leads to an interesting conclusion.

It is obvious that the rate of evaporation, and consequently also of combustion, of a liquid is determined by the amount of heat q which the liquid receives from the flame per unit time (^{3}). But $q = q_1 + q_2 + q_3$, where q_1, q_2, and q_3 are co-

Table 1*

Petroleum product	Parameters	0.37	0.50	0.60	0.71	1.1	2.0	3.0	4.7	8.0	14.8	30	50	80	130	260	863	2290
Gasoline	v mm/min	–	–	18.0	13.2	5.5	3.4	2.2	1.8	1.4	1.6	2.5	4.1	–	4.1	–	3.8	3.4
Gasoline	δ cm	–	–	9.5	9.7	11.9	20.3	24.2	31.4	–	–	100	–	–	300	440	–	3900
Gasoline	$Q : \delta$	–	–	0.05	0.05	0.05	0.05	0.06	0.10	–	–	1.77	–	–	18.2	–	–	380
Gasoline	$\delta : d$	–	–	16	13.5	10.4	10.3	8.1	6.7	–	–	3.3	–	–	2.3	1.7	–	1.7
Gasoline	$Re \cdot 10^3$	–	–	0.15	0.12	0.08	0.14	0.08	0.10	0.14	0.26	0.92	2.53	–	6.60	–	–	98
Tractor kerosene	v	12.0	7.5	6.4	4.8	3.2	1.9	1.4	1.4	0.9	1.2	1.8	3.0	3.4	4.0	4.2	–	3.6
Tractor kerosene	δ	3.6	5.4	6.3	6.3	9.6	15.3	20	29.5	41.3	68	–	–	–	208	–	–	–
Tractor kerosene	$Q : \delta$	0.03	0.03	0.03	0.03	0.03	0.4	0.05	0.08	0.11	0.31	–	–	–	25.5	–	–	–
Tractor kerosene	$Re \cdot 10^3$	0.06	0.05	0.05	0.05	0.05	0.05	0.06	0.09	0.10	0.24	0.74	2.05	3.8	7.1	14.9	–	112
Diesel fuel	v	6.9	5.0	4.2	3.5	2.5	1.7	1.3	1.1	0.6	0.7	–	–	2.7	3.3	3.5	–	–
Diesel fuel	δ	3.0	3.9	4.3	5.0	7.8	13.0	19.0	27	40	–	–	–	–	220	312	–	–
Diesel fuel	$Q : \delta$	0.025	0.03	0.03	0.03	0.03	0.04	0.05	0.07	0.07	–	–	–	–	20	60	–	–
Diesel fuel	$\delta : d$	8.1	7.7	7.2	7.0	6.8	6.5	6.4	5.7	5.0	–	–	–	–	1.7	1.2	–	–
Diesel fuel	$Re \cdot 10^3$	0.04	0.04	0.04	0.03	0.04	0.05	0.05	0.07	0.07	0.14	–	–	3.0	6.0	12.7	–	–

Petroleum product	Parameters	0.37	0.50	0.60	0.71	1.1	2.0	3.0	4.7	8.0	14.8	30	50	80	130	260	863	2290
Solar oil	v	9.3	5.1	4.1	3.3	2.4	1.1	0.6	0.6	0.6	0.6	0.8	1.7					
Solar oil	δ	3.0	4.0	4.4	4.9	7.9	11.8	14.5	20.7	–	31	100	–					
Solar oil	$Q:\delta$	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.05	–	0.31	0.56	–					

* The values of burning rates in a tank with a diameter of 23 m are taken from data published by the Central Scientific Research Institute of Fire Defense, and the data on burning rates in tanks with diameters of 1.3 and 2.6 m were obtained during experiments conducted by the authors jointly with a group of workers of the Central Scientific Research Institute of Fire Defense.

amount of heat supplied to the liquid, respectively, through the wall, by thermal conduction, and as a result of flame radiation. When burning in tanks whose diameter is greater than 1 m, the quantities q_1 and q_2 are small in comparison with q_3. Thus, the constancy of v in turbulent combustion shows that the amount of radiant energy received by 1 cm^2 of the liquid surface per unit time does not depend on d.

7. The data in Table 1 show that the relative flame height δ/d in the turbulent regime does not depend on the diameter of the tank. This result is easy to justify if one assumes (as is often done) that in the turbulent regime the diffusion coefficient $D \approx wd \approx vd$. But $\delta \approx wd^2/D$, and consequently, $\delta \approx d$.

In conclusion, the authors consider it their pleasant duty to express their gratitude to L. A. Volodina and A. A. Koryakina for their assistance in carrying out the experimental part of the work.

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