EVALUATING THE FRACTURE ENERGY OF A MATERIAL FROM ITS HEAT CONTENT

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A relationship between the fracture energy of a material and its heat content is established from analysis of literature and experimental data. Simple relations are proposed for evaluating the heat of vaporization and rate of fracture of materials.

The amount of heat that a material can absorb when it is heated to the melting point of the surface is determined by its mass and heat capacity. A significant part of the heat supplied goes into phase transformations during fracture of the surface. The heat content of the material can be determined from the simple expression

$$H(T)=\bar{c}_pT. \tag{1}$$

At the same time, the fracture processes taking place in the thin layer adjacent to the surface are complicated and have not been well studied. This is related to the high temperature level and the fact that, in contrast to a gaseous boundary layer, the methods of equilibrium thermodynamics [1] cannot be used in this case.

1. The heat of vaporization for most pure substances can be determined from the Pikte–Truton rule:

$$\Delta Q_v\approx 90T_b,\ \text{kJ/mole}. \tag{2}$$

As calculations show, this rule is satisfied better for substances with a melting point no greater than 1000°K. However, the discrepancy between the heat of vaporization found from (2) and experimental data increases with melting point and is greater than 50% for high-melting metals and compounds (such as SiO_2). It follows from (2) that the entropy of most substances changes little during evaporation and is equal to about 90 kJ/(mole·K). Since this coefficient has the dimension of heat content, which depends on temperature, to expand the applicable range of (2) we can represent this relation in the form $\Delta Q_v \approx \text{const}\, c_pT_b$, where

$$c_p=a+bT+cT^{-2}. \tag{3}$$

It was established from analysis of literature data that the heat of vaporization of most substances can in fact be calculated from the formula

$$\Delta Q_v\approx 3{,}4H'(T_b), \tag{4}$$

where $H'(t_b) = \bar{c}_pT_{mt} + \bar{c}_p^{l}(T_b - T_{mt})$. In this relation, the heat content of a substance heated to the boiling point is examined separately for the liquid and solid states. Since the heat content changes little in the melted state for most substances, it is usually taken as constant. However, the temperature dependence of heat content must be taken into account for solids, and its mean-integral value in the temperature range from 0°K to t_{mt} is used in calculations.

With an increase in pressure, the enthalpy of the liquid increases, and it reaches a maximum at the critical pressure and temperature. In turn, the heat of vaporization decreases with an increase in pressure and is equal to zero at the critical pressure. Comparison of the enthalpies of the liquid and vapor on the saturation line for individual substances presented in [2] shows that in the entire range from 0 to P_{cr} the sum $H(T_b) + \Delta Q_v$ differs little

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TABLE 1. Critical Parameters of Certain Substances

Substance	T_{cr}, K	$P_{cr} \cdot 10^{-5}$, Pa	$V_{cr} \cdot 10^3$, m^3/kg	Source	$Z_{cr} = \frac{RT_{cr}}{P_{cr} V_{cr}}$
H_2	32,98;	12,93	31,85	[2]	3,30
norm..	33,244	12,97	32,26	[3]	3,28
O_2	154,77;	50,9	2,46	[2]	3,21
	154,78	50,8	2,44	[3]	3,24
N_2	126,25;	33,96	3,29	[2]	3,35
	126,25	33,99	3,22	[3]	3,43
NH_3	405,6;	112,9	4,25	[2]	4,12
	405,5	112,8	4,25	[3]	4,12
H_2O	647,28;	221,2	3,15	[2]	4,29
	647,3	221,3	3,13	[3]	4,32
Hg	1763;	1510	0,182	[2]	2,66
	1460±20	1662±50	0,2—0,24	[3]	1,46—1,9
K	2250;	160	6,25	[2]	4,78
	2228±300	162	5,35	[3]	4,73—6,2
Na	2500;	370	5,56	[2]	4,4
	2570±350	355	5,05	[3]	4,48—5,9
Li	3800;	970	10,0	[2]	4,69
	3200±600	689	9,51	[3]	4,75—6,95
Rb	2100;	160	2,86	[2]	4,47
	2093±35	159	2,89	[3]	4,36—4,51
Cs	2050;	117	2,33	[2]	4,71
	2057±40	147	2,34	[3]	3,67—3,81

from the enthalpy of the substance at the critical point. For example, at atmospheric pressure this difference is no greater than 20%. If we examine heat content without heat of vaporization, the divergence is even smaller. Thus, as a first approximation we can assume that a decrease in heat of vaporization to zero is accompanied by a corresponding increase in the enthalpy of the substance at the critical point. Here, the ratio of the gas parameters determined from the expression

$$z = \frac{RT}{PV} \tag{5}$$

increases by a factor greater than two. Values of this coefficient at the critical point are shown in Table 1. Since monatomic gases, including the vapors of metals, obey the ideal gas laws, the analogous relation for them at the boiling point and $P = 10^5$ Pa is equal roughly to unity.

It is evident from Table 1 that there is currently enough reliable data on critical parameters only for substances with a boiling point no greater than that of water. The error of the determination of the critical coefficient may be as large as 50% for mercury and the alkali metals. In connection with this, the available data cannot be used as a basis for making a definite conclusion regarding the presence of a link between the critical coefficient and the heat content of a substance at the critical point. However, if on the basis of the above we permit the existence of a relation of the form $H'(T_b) + \Delta Q_v \approx H(T_{cr}) \approx z_{cr} H'(T_b)$, then we obtain

$$\Delta Q_v \approx (z_{cr} - 1) H'(T_b). \tag{6}$$

It follows from Table 1 that the mean value of the critical parameter for metals can be taken as about 4.4, so that the coefficient 3.4 in (4) agrees with (6).

Table 2 shows values of latent heat for 55 substances taken from [1-9] and calculated from (2), (4), and (6). The heat of vaporization of the first fifty substances was calculated from (4), while that of the last five was calculated from (6). When possible, data obtained from the same given study (the first line of each substance) was inserted into these expressions. The mean-integral heat capacity in the temperature range from 298°K to T_b was determined from the dependence of heat capacity on temperature (3) presented in [4], while in the temperature range 0-250°K it was determined from the data in [3]. Mean-integral heat capacity for certain substances was found from the values of enthalpy in [2, 5] taken at the corresponding boiling point without the heat of fusion. In a few cases, when there were no data on the heat capacity of the substance in the liquid state, it was taken to be equal to the heat capacity of the solid at the melting point (Kr, Xe, Ir, Os).

An additional error connected with determination of the mean-integral values of heat capacity may be present in calculations with (4). However, for the simple substances shown in Table 2, the difference between the literature data on heat of vaporization and the values calculated with (4) averages no more than 7%. The accuracy of this relation for monatomic substances with a melting point to 1000°K is nearly equal to the accuracy of (2), while it is four times more accurate for substances with a melting point in the range 1000-3700°K. The greatest discrepancy between the calculation and literature data is seen for the alkali metals (K, Rb, Cs) and barium. These elements are characterized by a strong temperature dependence of heat capacity in the liquid state.

It follows from Table 2 that the heat of vaporization of some of the most stable substances can also be found from (6). However, it is evident from the example of carbon that the estimate obtained from (4) or (6) diverges increasingly from the available data as the number of atoms in a molecule of the substance increases. For substances with molecules consisting of two or more atoms, (4) and (6) may be of very limited use. In this case, the Pikte-Truton rule is satisfied with a smaller error. Since nearly all calculations performed by (4) and (6) for complex substances give overstated values of ΔQ_V, the heat of vaporization of a substance should evidently be no greater than $3.4H'(T_b)$.

The following rule can be formulated on the basis of the above: the heat of vaporization of most simple substances is roughly 3.4 times greater than the heat content of the substance at the boiling point without allowance for the heat of fusion.

2. It was shown in [1] that the quasisteady rate of fracture of a thermally protective material for a given heat flux depends on the total latent heat of the processes taking place on the surface, the heat capacity, and the effect of injection:

$$\rho\bar{V}_\infty = \frac{q_0}{\Gamma\left[\Delta Q_w + \gamma (I_e - I_w)\right] + \bar{c}_p (T_w - T_0)}, \tag{7}$$

where $q_0' = q_0 - \varepsilon\sigma T_W^4$. The denominator in these expressions is a characteristic of the energy content of fracture of the material and has been termed the effective enthalpy of fracture. The effective enthalpy is not a thermodynamic parameter, since it considers the effect of interaction of the material with the environment – the effect of injection. Such interaction cannot be referred to the thermodyanmic characteristics of condensed systems. However, in those cases when the fraction of the injection effect in the heat balance is small, the effective fracture enthalpy of a material can be evaluated by means of its heat content by using (4).

The total latent heat ΔQ_W, for example, in the fracture of glassy materials, includes the heat of vaporization ΔQ_V and part of the heat of dissociation of the molecules of glass ΔQ_{SiO_2} and oxygen ΔQ_{O_2}. The final expression for the total latent heat of surface processes obtained in [1] is fairly complicated in form:

$$\Delta Q_w = \Delta Q_V + \frac{G_w + (\alpha/c_p)_w}{G_w} C_{SiO}\left[\Delta Q_{SiO_2} + \frac{\varkappa}{2+\varkappa}\,\frac{M_O}{M_{SiO}}\,\Delta Q_{O_2}\right].$$

The change of ΔQ_W in the temperature range 2500-3000°K is about 20%. Nevertheless, at $P = 10^5$ Pa it is equal to within 3% to $3.4H(T_W)$, where $H(T_W)$ is the heat content of silicon dioxide taken from [5] at the corresponding temperature.

Comparison of the experimental and theoretical rates of fracture of a quartz glass-ceramic determined from (7) in [10] resulted in good agreement. These data show that with a stagnation enthalpy up to 15,000 kJ/kg, the contribution of the injection effect to the heat balance is no greater than 30%. Considering the above and the relation $q_{av}' \sim q_0'/\Gamma$ from [10], we write the following expression for the rate of fracture of thermally protective (ablative) materials

$$\rho\bar{V}_\infty \approx \frac{q_{av}'}{\mathrm{const}\,\bar{c}_p (T_w - T_0)}, \tag{8}$$

where

$$q_{av}' \approx \frac{q_c + q_0}{2} - \frac{1}{4}\varepsilon\sigma T_w^4.$$

TABLE 2. Heat of Vaporization of Certain Individual Substances

Substance	T_{mt}, K	T_b, K	$\bar{c}_p^l$, $\bar{c}_p$, $\frac{kJ}{kg \cdot K}$	ΔQ_v, kJ/kg		
	Literature data				calc. from (2)	calc. from (4), (6)
Ar	83,86 [2], 83,78 [3]	87,29 [2, 3]	0,589 [3], 0,986 [2]	163,2 [3], 159,6 [2]	197,6	179,5
Kr	115,96 [3], 115,76 [2]	119,96 [3], 119,78 [2]	0,245 [3], ~0,34 [3]	107,7 [3], 107,9 [2]	129,0	101,2
Xe	161,3 [2, 3]	165,06 [3]	0,2 [3], ~0,26 [3]	96,27 [3], 96,05 [2]	110,6	113
Hg	234,3 [2, 3]	629,89 [3], 630,11 [2]	0,119 [3], 0,139 [3]	294,7 [3], 294,9 [2]	283	281,8
Ga	303,0 [4, 5]	2700 [4], 2500 [3]	0,27 [5], 0,386 [5]	3643 [3]	3485	3424
Rb	312,0 [4, 5], 311,86 [3], 312,7 [2]	952 [4], 974 [3], 959,2 [2]	0,298 [5], 0,366 [2, 5]	887 [4], 809,5 [3], 795 [2]	1002	1113
K	336,4 [2, 3, 4], 336,86 [5]	1052 [4], 1032,2 [2], 1027 [3]	0,629 [3, 5], 0,746 [5]	2022 [4], 1982 [3], 1920 [2]	2421	2536
Na	371 [2, 3, 4] 371,01 [5]	1187 [4], 1163 [3], 1156 [2]	0,93 [3], 1,287 [2, 4]	4260 [4], 3873 [3], 3900 [2]	4646	4744
In	430 [3, 4, 5]	2440 [3,4], 2348 [7]	0,209 [5], 0,238 [5]	1968 [3], 1962 [4]	1912	1932
Li	459 [4], 454 [2, 3], 453,69 [5]	1640 [4], 1590 [3], 1600 [2]	2,80 [3, 5], 4,21 [4, 5]	19595 [4], 21343 [3], 19412 [2]	21264	21274
Sn	505 [3, 4, 5]	2960 [3], 2473 [4]	0,206 [5], 0,244 [5]	2447 [3], 2388 [6], 1940 [4]	2245	2390
Bi	544 [3, 4]	1900 [4], 1832 [3]	0,117 [3, 4], 0,150 [3, 4]	823 [4], 725 [3]	818	908
Tl	577 [3, 4, 5]	1730 [3, 4]	0,128 [5], 0,142 [5]	795 [3, 4]	762	808
Cd	594 [3, 4]	1040 [4], 1038 [3]	0,217 [3, 4], 0,264 [4]	889 [3, 4]	832	839
Pb	600,6 [3, 4]	2023 [4], 2024 [3]	0,125 [3, 4], 0,137 [4]	858 [4], 866 [3], 842 [6]	873	918
Zn	693 [3, 4, 6]	1180 [3, 4], 1179 [6]	0,366 [3], 0,48 [3, 4]	1755 [3], 1754 [4], 1781 [6]	1624	1657
Te	723 [3, 4]	1263 [3], 1360 [4]	0,192 [3], 0,295 [4]	894 [3], 390 [4]	890,8	1014
Mg	923 [3, 4]	1393 [3, 4]	1,01 [3, 4], 1,378 [4]	5427 [4], 5421 [3], 5514 [6]	5158	5372
Al	933,6 [5], 931,7 [4]	2720 [3], 2600 [4]	0,901 [5], 1,174 [5]	10885 [3[, 10536 [4]	9072	9994
Ba	977 [4], 983 [3]	1911 [4], 1910 [3]	0,173 [4], 0,225 [4]	1087 [4], 1099 [3]	1252	1289
Sr	1043 [3, 4]	1657 [4], 1640 [3]	0,28 [4], 0,367 [4]	1606 [4], 1585 [3]	1702	1759
Ca	1115 [5], 1123 [4]	1755 [4], 1760 [3]	0,751 [5], 0,776 [5]	4032 [4], 3743 [3]	3941	4536
La	1193 [3, 5], 1153 [4]	3643 [3], 3000 [4]	0,226 [5], 0,236 [5]	2880 [3], 2412 [4], 2829 [7]	2360	2882
Ge	1232 [4], 1210 [3]	2980 [4], 3103 [3], 3125 [7]	0,347 [3, 4], 0,422 [4]	3931 [4], 4601 [3]	3695	3961
Ag	1234 [3, 4]	2485 [3, 4]	0,237 [4, 8], 0,319 [8]	2357 [4], 2354 [3]	2073	2351
Au	1336 [3, 4], 1337 [8]	2933 [4], 2800 [8], 2973 [3]	0,135 [3, 4], 0,149 [3, 4]	1577 [4], 1647 [3]	1340	1422
Cu	1356 [3, 4]	2868 [3, 4], 2630 [6]	0,398 [3, 4], 0,494 [3, 4]	4797 [4], 4784 [3], 3596 [6]	4062	4374
Be	1560 [5], 1556 [3]	2750 [3], 2720 [7]	2,485 [5], 3,354 [5]	32622 [3]	27463	26750
Si	1683 [4], 1696 [3]	2750 [4], 2628 [3]	1,04 [3, 4], 1,104 [4]	10575 [4], 14046 [3]	8812	9956
Ni	1728 [4], 1726 [3]	3110 [4], 3073 [3]	0,499 [3, 4], 0,656 [4]	6453 [4], 6483 [3], 6475 [9]	4768	6014

TABLE 2 (continued)

Substance	T_{mt}, K	T_b, K	$\bar{c}_p^l$, $\bar{c}_p$, $\frac{kJ}{kg \cdot K}$	ΔQ_v, kJ/kg		
	Literature data				calc. from (2)	calc. from (4), (6)
Co	1766 [4], 1765 [3]	3370 [4], 2528 [3]	0,54 [3, 4], 0,59 [4]	6600 [4], 6499 [3]	5146	6460
Y	1801 [5], 1750 [4], 1773 [3]	3473 [3], 3500 [4], 3610 [7]	0,367 [5], 0,445 [5]	4420 [3], 4240 [4]	3516	4777
Fe	1808 [3, 4]	3043 [4]	0,578 [3, 4], 0,75 [4]	6805 [4]	4904	6702
Sc	1814 [5], 1670 [3, 4]	3000 [4], 2970 [7]	0,73 [5], 0,979 [5]	7452 [4], 6782 [3]	6006	8450
Pd	1824 [4], 1825 [3, 8]	3440 [4], 3833 [3], 4253 [8]	0,266 [3, 4], 0,354 [4]	3505 [4], 4182 [8]	2910	3595
Ti	1944 [5], 1941 [3], 2000 [4]	3550 [3, 4], 3530 [7]	0,66 [5], 0,975 [5]	8977 [3], 8829 [4], 9841 [7]	6670	9683
Th	2023 [5], 1968 [3]	4470 [3], 4500 [4]	0,198 [5], 0,144 [5]	2344 [3], 2346 [4]	1734	2633
Pt	2042 [4, 8]	4580 [3], 4800 [8]	0,149 [3, 4], 0,193 [4]	2620 [4], 2660 [8]	2113	2700
Zr	2125 [4], 2128 [3]	3900 [4], 4653 [3]	0,317 [3, 4] 0,367 [4]	4582 [4], 6380 [3]	3848	4505
Cr	2176 [3], 2173 [4]	2915 [3], 2495 [4], 2700 [7]	0,61 [3, 4], 0,754 [4]	6712 [3], 5875 [4]	5046	6415
V	2220 [5], 2003 [3]	3653 [3], 3582 [7], 3800 [4]	0,599 [5], 0,907 [5]	8990 [3], 9010 [7]	6454	8937
Rh	2239 [8], 2233 [3], 2240 [4]	4770 [8], 4233 [3], 4150 [4]	0,309 [3, 4], 0,366 [4]	5620 [8], 5167 [4]	4172	5502
Hf	2506 [5], 2493 [3]	5473 [3], 5670 [7]	0,188 [5], 0,244 [5]	3703 [3]	2760	4060
Ir	2716 [8], 2727 [4]	5570 [8], 4623 [3]	0,159 [3, 8], ~0,205 [4]	3310 [8]	2608	3457
Nb	2750 [5], 2760 [4]	5400 [7], 5173 [3]	0,323 [5], 0,45 [5]	7667 [7], 7491 [3]	5231	7076
Mo	2896 [5], 2898 [3], 2883 [4]	5100 [7], 5073 [3]	0,334 [5], 0,416 [5]	6800 [7], 6191 [3], 7400 [9]	4784	6409
Ta	3295 [5], 3269 [3], 3250 [4]	5673 [3], 5570 [7]	0,167 [5], 0,248 [5]	4161 [3], 4168 [7]	2822	3883
Os	3320 [8], 2940 [4]	5770 [8]	0,168 [3, 8], ~0,19 [4]	3561 [8]	2730	3479
W	3695 [5], 3653 [3]	5800 [3], 6170 [7]	0,175 [5], 0,245 [5]	4346 [3], 4957 [7]	2839	3952
SiO_2	1996 [5]	2770 [9]	1,058 [5], 1,443 [5]	~11 000 [1]	4150	10976
†H_2 norm.	13,8 [2], 13,96 [3]	20,28 [2], 20,4 [3]	203,6* [2]	457 [2], 448,4 [3]	905	468
O_2	54,35 [2], 54,19 [3]	90,18 [2], 90,16 [3]	1,136 [3], 1,56 [2]	212,3 [2], 213 [3]	254	260
N_2	63,15 [2], 62,99 [3]	77,35 [2], 77,17 [3]	1,09 [3], 1,938 [2]	197,6 [2], 199,1 [3]	248	226
NH_3	195,3 [2], 195,27 [3]	239,6 [2, 3]	1,439 [3], 4,424 [2]	1368 [2], 1371 [3]	1266	1488
H_2O	273,16 [2]	373,16 [2]	1,192 [9], 4,195 [2]	2257,2 [2], 2270 [4]	1864	2451

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*Heat content of hydrogen without heat of fusion.

†The heat of vaporization of substances was subsequently calculated by means of the critical coefficient.

TABLE 3. Test Regimes for Ablative Materials

No. of regime	q_c, kW/m²	q_r, kW/m²	I_e, kJ/kg	$p_e \cdot 10^5$, Pa	$(\alpha/c_p)_0$, kg/(m²·sec)	Flow characteristic
1	6000	—	7400	1,028	0,86	Subsonic air jet
2	6000	—	9000	1,017	0,70	
3	8000	—	10500	1,021	0,76	
4	10500	—	10600	1,045	1,03	
5	10500	—	12300	1,028	0,89	
6	12000	—	13500	1,029	0,92	
7	14000	—	12300	1,054	1,18	
8	14000	—	15000	1,034	0,96	
9	19500	—	15400	1,063	1,3	
10	4000	—	6600	1,01	0,65	Subsonic nitrogen jet
11	6000	—	9000	1,014	0,70	
12	8000	—	10800	1,018	0,77	
13	10000	—	12300	1,021	0,84	
14	12000	—	14000	1,025	0,89	
15	14000	—	15200	1,029	0,95	
16	5000	6300	8200	1,014	0,65	Subsonic air jet
17	10000	6300	12000	1,025	0,87	
18	10500	5200	12300	1,026	0,89	
19	14000	6300	15000	1,034	0,96	
20	18800	6300	14300	1,055	1,36	
21	5000	10500	8200	1,014	0,65	Subsonic air jet
22	10500	10500	12300	1,025	0,89	
23	14000	10500	15000	1,034	0,96	
24	18800	10500	14300	1,055	1,36	
25	14700	—	13000	0,34	1,17	Supersonic air jet
26	14700	6300	13000	0,34	1,17	
27	14700	8400	13000	0,34	1,17	
28	14700	—	4700	3,5	3,34	Supersonic jet of combustion products, $\alpha = 1.2$

Tables 3-5 show regimes and results of tests of specimens of three classes of materials: pure and quartz-alloyed glass-ceramic, an asbestos–textolite, and a glass-plastic in subsonic and supersonic air jets from an electric-arc heater [11], on a unit providing simultaneous radiative and convective heating [12], and in the supersonic jet of a gas generator operating on kerosene–oxygen fuel. These materials were also tested in nitrogen to check the effect of combustion on the rate of fracture of asbestos–textolite and glass-plastic on an epoxy binder. The fracture rates were calculated using surface emissivities in [13], while the values of ρc from [14-16] at the mean temperature $T' = (T_w + T_0)/2$ were 2640 for the quartz glass-ceramic, 1650 for the asbestos–textolite, and 1800 kJ/(m³·K) for the glass-plastic on the epoxy binder.

Analysis of the experimental results showed that the constant in (8) is twice as great as the constant in (4), and is equal to 6.79. In this case, the difference between the experimetal and calculated data for most of the heating regimes does not exceed the experimental error, i.e., 20%.

Comparison of the results of tests of asbestos–textolite and glass-plastic in flows of nitrogen and air shows that combustion has a significant effect at heat fluxes below 8000 kW/m². Appreciable ablation from the surface of the specimens of quartz glass-ceramic and glass-plastic in the jet of the electric-arc heater begins at $T_w \approx 2500°K$, which corresponds to a heat flux of 6000 kW/m². In connection with this, the tables include results of tests of the materials beginning with a heat flux of 6000 kW/m². It should be noted that the experimental results differ from the calculated data by more than 20% at ablation rates of about 0.5 mm/sec. Thus, the validity of (8) at $\bar{V}_\infty > 0.5$ mm/sec will require further substantiation.

NOTATION

T, temperature; T_w, T_b, T_{mt}, temperature of the heated surface and boiling and melting points of the material; T_0, temperature of the unheated material; H(T), heat content; $H'(T_b)$, heat content of the substance at the boiling point without the heat of fusion; ΔQ, latent heat; ΔQ_v, latent heat of vaporization; c_p, specific heat (heat capacity); $\bar{c}_p$, $\bar{c}_d^l$, mean-

TABLE 4. Comparison of Experimental and Calculated Values of Linear Ablation Rate for Asbestos–Textolite and Glass-Plastic

Heating Regime	Material									
	asbestos–textolite					glass-plastic on epoxy binder				
	T_w, K	q'_{av} kW/m²	$\bar{V}_\infty \cdot 10^3$, m/sec		σ, %	T_w, K	q'_{av} kW/m²	$\bar{V}_\infty \cdot 10^3$, m/sec		σ, %
			exp.	calc. from (8)				exp.	calc. from (8)	
2	2760	4300	0,21	0,15	29	2830	4200	0,17	0,14	18
3	2890	5900	0,24	0,2	17	2800	6100	0,24	0,2	17
5	3000	8000	0,28	0,26	7	2780	8500	0,33	0,28	15
6	3030	9300	0,3	0,3	0	2750	10000	0,39	0,33	15
8	3060	11200	0,33	0,36	10	2730	12000	0,45	0,4	11
10	2500	2700	0,11	0,11	0	2500	2800	0,09	0,1	1
11	2740	4400	0,15	0,16	7	2600	4600	0,17	0,16	6
12	2890	6000	0,17	0,2	18	2640	6400	0,24	0,22	8
13	—	—	—	—	—	2670	8100	0,29	0,28	3
14	—	—	—	—	—	2680	10000	0,35	0,34	3
15	—	—	—	—	—	2690	12000	0,39	0,41	5
16	2700	7900	0,27	0,29	7	—	—	—	—	—
17	2980	11700	0,37	0,39	5	—	—	—	—	—
19	3060	15200	0,42	0,49	17	—	—	—	—	—
20	3060	19300	0,47	0,62	32	—	—	—	—	—
21	2980	10500	0,37	0,34	8	2800	10500	0,5	0,34	32
22	2980	15100	0,46	0,5	9	2800	15200	0,6	0,5	17
23	3060	18500	0,52	0,59	13	—	—	—	—	—
24	3060	22000	0,59	0,72	22	—	—	—	—	—
25	2850	12000	0,45	0,42	7	2500	12800	0,56	0,48	14
26	2790	16400	0,5	0,58	16	—	—	—	—	—
27	—	—	—	—	—	2500	19300	0,64	0,72	13
28	2380	10400	0,6	0,45	25	2380	10250	0,45	0,4	11

TABLE 5. Comparison of Experimental and Calculated Values of Linear Ablation Rate for Quartz Glass-Ceramic ($\rho \approx 2000$ kg/m³)

Heating regime	Glass-ceramic	T_w, K	q'_{av} kW/m²	$\bar{V}_\infty \cdot 10^3$, m/sec		σ, %
				expt.	calc.	
1	Alloyed	2650	4190	0,08	0,1	25
4		2710	8340	0,16	0,19	19
7		2820	11370	0,21	0,25	19
9		2900	16480	0,3	0,35	17
18		2840	11900	0,28	0,26	7
22		2840	16300	0,5	0,36	28
28		2610	9360	0,19	0,23	20
8	Pure	2840	11900	0,25	0,26	4
23		2840	18000	0,46	0,4	13
28		2420	10270	0,27	0,27	0

integral heat capacities of the substance in the solid and liquid states; R, universal gas constant; P, pressure; V, specific volume; T_{cr}, P_{cr}, V_{cr}, temperature, pressure, and specific volume of substance at the critical point; z_{cr}, critical coefficient; ρ, density; $\bar{V}_\infty$, quasi-steady ablation rate; q_0, heat flux delivered to the surface of the material at T_w; ε, emissivity; σ, Stefan–Boltzmann constant; Γ, gasification parameter; γ, injection coefficient; I_e, P_e, stagnation enthalpy and pressure of flow; I_w, enthalpy of gas at the temperature of the surface of the material; q_c, q_r, calorimetric convective and radiant heat fluxes; $(\alpha/c_p)_0$, heat-transfer coefficient; $(\alpha/c_p)_w$, heat-transfer coefficient with allowance for injection; G_w, rate of evaporation from the surface; ϰ, ratio of partial pressures of atoms and molecules of oxygen; C, concentration; M, molecular weight; q_{av}', mean-integral heat flux during the time of establishment of T_w; q_0', heat flux delivered to the surface with allowance for the radiative loss; α, coefficient of excess oxidant.

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DIFFUSION—CONVECTIVE VAPORIZATION OF DROPS BY INTENSIVE OPTICAL RADIATION WITH AN ALLOWANCE FOR THE TEMPERATURE DEPENDENCES OF THE TRANSFER COEFFICIENTS

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A quasistationary solution is obtained for diffusion—convective vaporization of drops by intensive optical radiation with an allowance for the temperature dependences of the transfer coefficients. Comparisons with experimental data are provided.

Convective drop vaporization in a gaseous medium by intensive optical radiation was considered in [1-5]. In [1, 2] it was assumed that the temperature drop values in the gas surrounding a drop are small during the vaporization process, while the transfer coefficients $\varkappa$ and D were assumed to be constant (independent of the temperature). Attempts were made in [3, 4] to account for the temperature dependence of the transfer coefficients in convective drop vaporization. However, the actual temperature dependences of $\varkappa$ and D [6] are substantially different from those used in [3, 4]. Consideration of the temperature dependences of $\varkappa$ and D is especially important in the case of arbitrary drops in temperature, since the accuracy in describing the heat and mass transport in the gas surrounding a drop determines

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