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THE ATOMIZATION OF LIQUID AND TWO-PHASE FLOWS

M. S. Volynskii

Foreign Technology Division
Wright-Patterson Air Force Base, Ohio

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M. S. Volynskiy

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13. ABSTRACT

The theory of the spraying of a liq. fuel into a supersonic gaseous stream and of the flow of the dispersed liq. is examd. Systems of equations are presented for 2 phase flow at the initial and main portions of the stream. These equations were solved with a computer and the region of vaporization of the fuel into the supersonic jet was detd. Calcns. for streams at Mach 2 are in good agreement with expt.
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Block	Italic	Transliteration
А а	*А а*	A, a
Б б	*Б б*	B, b
В в	*В в*	V, v
Г г	*Г г*	G, g
Д д	*Д д*	D, d
Е е	*Е е*	Ye, ye; E, e*
Ж ж	*Ж ж*	Zh, zh
З з	*З з*	Z, z
И и	*И и*	I, i
Й й	*Й й*	Y, y
К к	*К к*	K, k
Л л	*Л л*	L, l
М м	*М м*	M, m
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Р р	*Р р*	R, r
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Щ щ	*Щ щ*	Shch, shch
Ъ ъ	*Ъ ъ*	"
Ы ы	*Ы ы*	Y, y
Ь ь	*Ь ь*	'
Э э	*Э э*	E, e
Ю ю	*Ю ю*	Yu, yu
Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

II

THE ATOMIZATION OF LIQUID AND TWO-PHASE FLOWS[1]

M. S. Volynskiy

In chambers with gas flow, mixing in the zone of motion and evaporation of the drops precedes the combustion of the liquid fuel.

In this article we mainly examine mixing under conditions of supersonic flows. A number of the devices (certain chambers, a jet engine nozzle) is characterized by a two-phase mixture flow under operating conditions at a Mach number of $M > 1$ [1]. This phenomenon which consists of the atomization, the motion and the vaporization of drops in a fuel flame and in which thermal, gas-dynamic and aeromechanical factors are combined, requires a complex investigational method.

In this article the author mainly examines the physical side of the problem – the construction of a model of the phenomenon, making it possible to reduce the real flow to an idealized two-phase gas-drop flow setup. The process being investigated is broken down into its basic stages described by its own systems of equations which are solved on computers. The results of the calculations are compared with the experimental data on the injection of a liquid into a free jet having supersonic velocity.

[1]V. N. Suchkov and R. I. Piskun took part in the experimental part of the work.

Designations

x, y, $y_в$, z, $z_в$ – the coordinates of the flame boundaries and of the shock wave;

τ – the time of drop motion;

y^*, z^* – the ordinates of the flame asymptote in planes xOy and xOz;

w, P, ρ, T, M, c_p – velocity, pressure, density, temperature, Mach number, specific heat of the gas;

w_1, P_1, ρ_1, T_1, M_1, c_{p_1}, k_1 – velocity, pressure, density, the temperature, Mach number, specific heat, adiabatic index in the incoming gas flow (initial cross section);

v_1, a_1, $T_{ж_1}$, $C_{ж_1}$ – initial velocity, diameter, temperature, specific heat of a drop;

v, a, $T_ж$, $c_ж$, $\rho_ж$ – the current velocity, diameter and temperature, the specific heat and density of a drop;

ΔP – the pressure differential in the liquid feed;

β^* – the concentration of liquid in the asymptotic section of the cold flame;

d_c – the diameter of the atomizer aperture;

m', w', T', P', ρ', M', β', k' – the flow rate, velocity, temperature, pressure, density, Mach number of gas, concentration of liquid, adiabatic index in the initial cross section of the main part of the atomization flame;

P_0, T_0 – pressure and stagnation temperature in the incoming flow;

X – calculated interval of total vaporization;

σ – surface tension of the liquid;

$L_э$ – experimental interval of total vaporization;

$\bar{Z}$ – the volatility of the liquid (fraction of vaporized substance);

m^* – gas flow rate in the asymptotic cross section of the cold flame;

m, $m_ж$ – gas and liquid flow rates;

$M_{п.с}$ – Mach number of the gas beyond the normal shock;

$We_{кр}$ – critical Weber number.

INJECTION OF A LIQUID INTO A SUPERSONIC FLOW

Work [1] set forth the experimental procedure and certain results of the investigation of the injection of a liquid into a supersonic flow in the absence of phase transitions (vaporization). The liquid is fed through a direct-jet aperture (with the center at the origin of the coordinates) from the surface of a well streamlined atomizer along axis Oy, at an angle 90° to the flow direction (axis Ox). Here the zone of boundary layer separation near the root of the atomization flame is small and the shock wave is close to a normal shock. Photographs (made by Toepler's method) show the presence (Fig. 1) of an external flame boundary which is sharply outlined and approaches the horizontal asymptote.

The processing of the photographs makes it possible to plot dependences for the ordinates of the flame asymptote y*, z* in two projections

$$y^*/d_c;\ z^*/d_c = A\,(2\Delta P/k_1 P_1 M_1^2)^n\, M_1^{m_1}, \qquad (1)$$

in the parentheses – the ratio of the ram pressure of the liquid stream and of the gas; A and n – experimental constants, different for planes xOy and xOz.

Then, the initial sections of the flame boundaries with the coordinates y, z and of the shock wave $y_в$, $z_в$ can be described by the approximate criterial relationships

$$y/y^*,\ y_в/y^* = F\,(x/y^*;\ M_1) \qquad (2)$$

and

$$z/z^*,\ z_в/z^* = \varphi\,(x/z^*;\ M_1) \qquad (3)$$

within the limits $0 \leq x/y^*;\ x/z^* \leq 2\text{-}3$. Figure 2 shows a curve in dimensionless coordinates $y_в/y^*;\ x/y^*$ for $M_1 = 2$ and 2.9.

GRAPHICS NOT REPRODUCIBLE

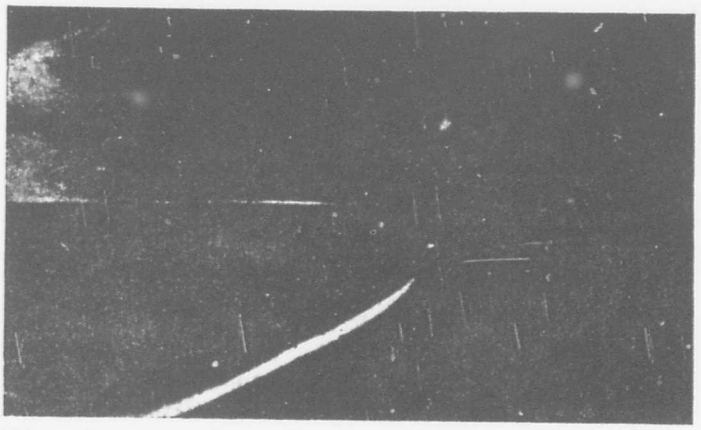

Fig. 1. An alcohol atomization flame in a supersonic air flow (M = 2.9, T_0 = 293°K, P_0 = 16 atm(abs.), ΔP = 40 atm(gage), d_c = = 1 mm).

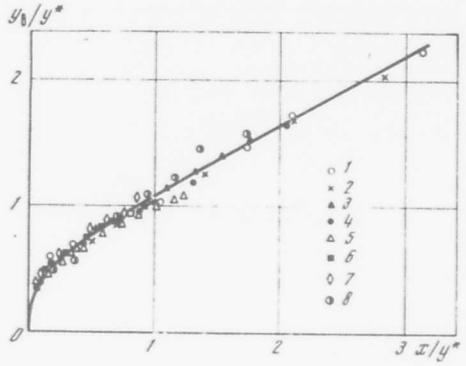

Fig. 2. Shock wave of the atomization flame (T_0 = 293°K). 1 — alcohol (M_1 = 2.9, ΔP = 40 atm(gage), d_c = 1 mm, P_0 = = 16 atm(abs.)); 2 — alcohol (M_1 = 2.9, ΔP = 15 atm(gage); d_c = 1 mm, P_0 = 16 atm(abs.)); 3 — gasoline (M_1 = 2.9, ΔP = 23 atm(gage), d_c = 2.5 mm, P_0 = 16 atm(abs.)); 4 — gasoline (M_1 = 2.9, ΔP = 40 atm(gage), d_c = 0.4 mm, P_0 = = 16 atm(abs.)); 5 — water (M_1 = 2.85, ΔP = 40 atm(gage), d_c = 1 mm, P_0 = 47 atm(abs.)); 6 — water (M_1 = 2.85, ΔP = = 65 atm(gage), d_c = 1 mm, P_0 = 47 atm(abs.)); 7 — alcohol (M_1 = 2, ΔP = 40 atm(gage), d_c = 1 mm, P_0 = 12 atm(abs.)); 8 — alcohol (M_1 = 2, ΔP = 20 atm(gage), d_c = 1 mm, P_0 = = 12 atm(abs.)).

Work [2] has examples of dependences of the type in (2). An extremely important characteristic of the injection process is the coarseness of the atomization (appropriate formulas are given in work [1]). The coarseness of the drops (5-15 μm) is substantially less than the coarseness of the particles in subsonic atomization (diameter 20-150 μm).[1] Knowledge of the flame shape, the shock wave and drop coarseness will make it possible to set up a method for rating the flow within the flame in the case of phase transitions.

THE THEORY OF A TWO-PHASE MIXTURE FLOW

The process in a certain (main) section of the atomization flame in a heated flow can be approximately compared to a steady-state one-dimensional flow, in which occur phase transitions (vaporization). Flows of this type are encountered in various technical devices. The investigation of a two-phase gas-drop or gas-solid particle mixture is of interest per se.

In contrast to the original setup, the simplest setup for calculating the vaporziation of a single drop [2] in this type of setup takes into account not only effect of the gas on the drops, but also the effect of the drop on the gas, which leads to a variation in its parameters: velocity, temperature, pressure, the composition, and consequently the rate of evaporation. The dependence of the physical constants on the composition and the temperature of the gas are accordingly considered.[2]

The drops do not interact with each other. The mixture, for simplicity, is taken to be monodisperse; the diameter spectrum can be considered in the general case. The gas and drop flow with

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[1]The discussion concerns an average, median diameter of drop spectrum.

[2]A similar approach was employed by G. A. Varshavskiy.

phase transitions is described by a system of three differential equations: equations of motion, heating and drop vaporization [2]. and conventional equations of one-dimensional steady-state gas dynamics: conservation of energy consumption, of the momentum of a gas-drop mixture and gas state equation.

The parameters of the drops a, v, $T_{ж}$ and of the gas w_1, T_1, P_1 will be the initial and boundary conditions in an initial cross section of area F_1 and the shape of the channel is $F = F(x)$. The desired values are: volatility $\overline{Z}$ – the portion of evaporated substance, characteristics a, v, $T_{ж}$, w, T, P as a function of coordinate x or time τ and the interval of total vaporization $\overline{L}$ when $\overline{z} = 1$ and $a = 0$.

Some results of the solution of this system for flow in a cylindrical pipe, obtained with computers, are depicted on graphs (Figs. 3 and 4). A two-phase mixture consists of an air stream containing drops of gasoline. The obtained dependences are conveniently presented as functions of dimensionless time

$$\tau = \tau/\tau^*, \quad \tau^* = a_1^2/\theta_1, \qquad (4^1)$$

where τ – the time of the motion of a drop; τ^* – the time of total static vaporization of a drop with a diameter of a_1 at equilibrium temperature $T_{ж} = T_{p_1}$ (T_{p_1} – the temperature of isothermal vaporization of the liquid which corresponds to the initial cross section) using invariable initial gas parameters.

Figure 3 presents the volatility curves $\overline{Z}$; the drop diameters are characteristic for atomization in a supersonic flow.

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[1]Function θ_1 is readily calculated from known formulas of the theory of vaporization [2] and depends on the concentration of vapor on the surface of a drop and also in the surrounding flow.

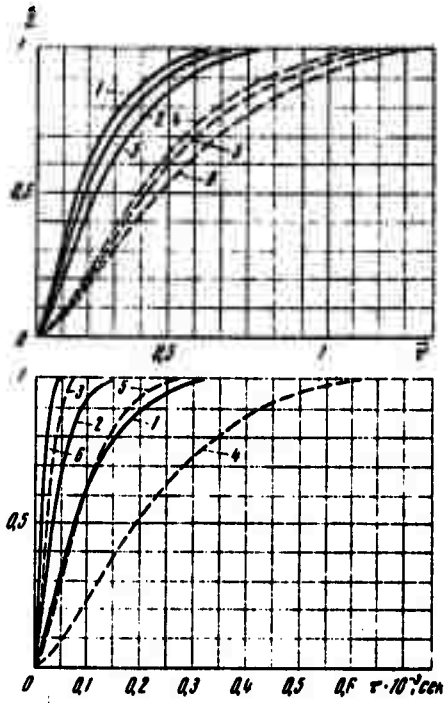

Fig. 3. The volatility of gasoline in a supersonic flow (β = = 1.3, M = 2.8, T_1 = 1050°K, w_1 = 1780 m/s, P_1 = 1 atm(abs.), T_w = 293°K).
1 and 4 – a = 16 μm; 2 and 5 – a = 10 μm; 3 and 6 – a = 5 μm.
Designation: сек = s.

The time of total vaporization is fractions of a microsecond and substantially increases with an increase in particle dimensions. Curves are given for the two extreme values of initial relative drop velocity $u_1 = v_1 - w_1$, namely $u_1 = 0$ (broken lines) and u_1 = = 620 m/s (solid lines). The first group of curves corresponds to the absence of the drop blowing in the initial section, the second – to initial blowing at transonic speed. The numerical solution of the equation of motion of a single drop in the parameter field beyond the shock wave gives the relative velocities less than the speed of sound. In a two-phase mixture flow in a cylindrical pipe the relative drop velocities also nowhere exceed sonic speed.

Figure 4 gives the calculated dependences for the relative gas parameters: velocities w/w_1; pressures P/P_1; temperatures T/T_1 in the cross section, where vaporization is carried out, and the length of the total interval X, on the gas Mach number M_1 in the initial flow section.

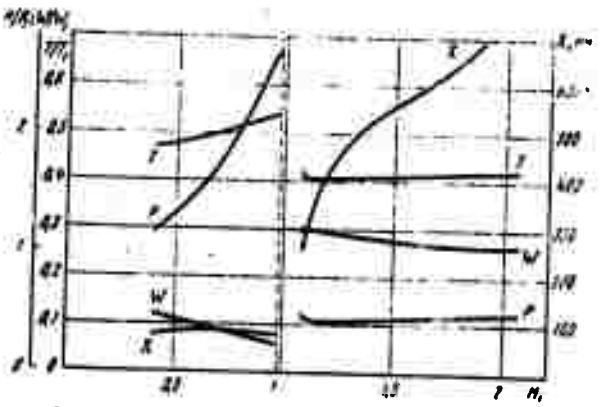

Fig. 4. Gas-dynamic characteristics and interval of total vaporization in a two-phase mixture (a_1 = 16 μm, β = 1.8, P_1 = 1 atm(abs.), T_1 = 1700°K, $T_{м1}$ = 293°K, u_1 = 0); gasoline in air.

Upon the transition of value M_1 through unity an abrupt change is detected in the values and character of the regularities for the indicated parameters. When $M_1 < 1$ the motion of the gas and the particles is decelerated ($w < w_1$), and the temperature increases. An increase of the time the drops remain in the heated flow gives small intervals X. In this case the heavier drops overtake the gas. For $M_1 > 1$ the flow velocity is substantially greater, and the temperature less than in the first case, which sharply increases X.

ATOMIZATION FLAME IN A SUPERSONIC FLOW

Let us now move on to an analysis of a real atomization flame, breaking it down into three sections: initial, main and mixed (Fig. 5). In the initial section (with a length of the order of ordinate y*) decay of the liquid stream, and breaking up of the drops occur which then move along disordered and unsteady trajectories. Vaporization here is insignificant, since the drop concentration is great, and their temperature still low. Toward the end of the section (section F') the drops acquire a velocity, close to the flow velocity, emerging in a system of ordered trajectories. The subsequent, main section is characterized by a more uniform

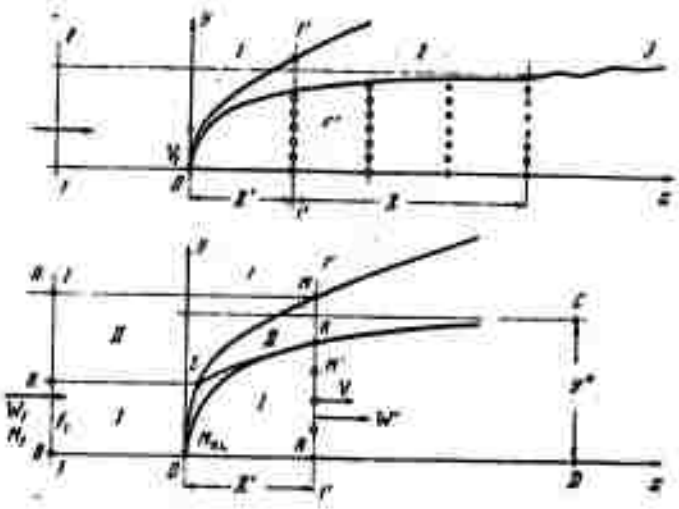

Fig. 5. Flow setup in an atomization flame. 1 – initial flame section; 2 – main flame section; 3 – mixed section; KB – cross section F_1; RN – cross section; F' – the exit cross section for the initial section and entry cross section for the main section; MN – the shock wave cross section F_M; CD – asymptotic section F*; KSR – the flow boundary I and II.

field of distribution of all parameters and regular particle motion. In this case, intense vaporization occurs accompanied by cooling of the gas. Experiment shows that the vaporization section is not very extended.

We will therefore assume that in the vaporization section the interaction of the intra-flame two-phase flow with the surrounding medium does not play a decisive role and occurs mainly on the periphery of the flame. Employing gas-dynamic terminology, the initial section can be compared to a mechanical nozzle, and the main section – to a combination of mechanical, thermal and flow rate nozzle. The third section (it is not examined in the article) is characterized by mixing of the intra-flame flow with the surrounding medium.

For calculating the processes in the main section we use the one-dimensional theory of two-phase flow mentioned above. However, it is necessary to know the parameters of the gas and drop mixture at the entry to the main section F'. They should differ significantly from the parameters of the incoming flow.

The problem of determining values w', T', P', β' at exit from the initial section arises. Let us visualize atomization flame as a certain "liquid lattice" possessing hydraulic resistance which consists of wave resistance and resistance connected with the flow of a drop cluster after the wave. The gas flowing from section AB, is divided into two flows. Flow I penetrates inside the flame, and flow II around about its boundaries from without. Of the entire maximum flow rate $F'w_1\rho_1$ going towards the flame, only the part $m' = F'w'\rho'$ penetrates inside it, and that is why the drop concentration in section F'

$$\beta' = \frac{m' + m_{ж}}{m'} \tag{5}$$

will be greater than nominal

$$\beta^{\circ} = \frac{m^{\circ} + m_{ж}}{m^{\circ}}, \tag{6}$$

and parameters w', T', P' – significantly differ from the parameters w_1, T_1, P_1.

Let us make the following hypotheses about the initial flame section.

1. We disregard the processes of phase transition (vaporization) in small section X' and let us not consider the interaction of flows I and II.

2. Let us disregard in section F' the vertical components of rates w_y' and v_y' which are small here.

3. Let us not consider the frictional forces on the monitoring surfaces and let us disregard the reduction in the cross sectional flow area F' caused by the drops.

The selection of length X' is to a certain extent arbitrary. It cannot be taken too large due to the smallness of vaporization or too small, following the condition of ordered flow and horizontality of the flow lines. The photographs of a vaporizing flame make it possible to assume that $0.7y^* \leq X' \leq 1.2y^*$. Let us write a system of gas-dynamic conservation equations for flows I and II between sections 1-1 and 1'-1'. Figure 5 depicts the appropriate monitoring surfaces: flow I – monitoring surface BKSRNB, flow II – monitoring surface KAMRSK, total flow I + II – monitoring surface BAMNR. The areas of the characteristic flow cross sections F', $F_м$, F* are known, if we know the shape of the flame and the shock wave. It is possible, for example, to approximately calculate them as areas of ellipses with semi-axes y'/2, z', $y_в/2$, $z_в$, y*/2, z*. The system will consist of equations of flow rate, energy and state for flows I and II – i.e., of six equations and of the momentum equation for total flow I and II – a total of seven equations relative to eight unknowns F_1, w', P', T', ρ', w", T", ρ" (equality of the static pressures P" = P' over entire flow cross section is assumed $F_м$).

The equation of conservation of flow rate in flow I is

$$F_1 w_1 \rho_1 = F' w' \rho' = m_1 = m'. \tag{7}$$

The equation of the conservation of energy in flow I is

$$m'\left[i_{в_1} + \frac{Aw_1^2}{2g}\right] + m_{ж}\left[i_{ж_1} + \frac{Av_1^2}{2g}\right] = m'\left[i'_в + \frac{Aw'^2}{2g}\right] + \\ + m_{ж}\left[i'_{ж} + \frac{Av^2}{2g}\right], \tag{8}$$

where

$i_{в_1} = i_н + c_{p_1} T_1$; $i'_в = i_н + c'_p T'$ – the enthalpies of the gas;

$i_{ж_1} = i_{нж} + c_ж T_{ж_1}$; $i'_ж = i_{нж} + c'_ж T_ж$ – the enthalpies of the liquid fuel;

$i_н$, $i_{нж}$ – the initial enthalpies. For the majority of real flows the enthalpy of a liquid is small in comparison with the enthalpy of a gas.

The gas state equation in flow I is

$$P'/\rho' = gRT'. \tag{9}$$

The equation of the conservation of flow rate in flow II + I is

$$F_н\rho_1 w_1 = m' + m'' = F'\rho' w' + (F_н - F')\rho'' w''. \tag{10}$$

The equation of conservation of energy in flow II is

$$i_{в_1} + \frac{Aw_1^2}{2g} = i_в'' + \frac{Aw''^2}{2g}, \tag{11}$$

where $i_в'' = i_н + c_p'' T''$.

The gas state equation in flow II is

$$P'/\rho'' = gRT. \tag{12}$$

The equation of conservation of momentum for the total flow I and II in projections on the Ox axis is

$$P_1 F_н + \rho_1 w_1^2 F_н + m_{нж} V_{1x} = P' F_н + m'' w'' + m' w', \tag{13}$$

where

$$m'' = (F_н - F')\rho'' w''.$$

This system of equations is open; the number of equations for unity is greater than the number of unknowns. Solving it, it is possible to express all unknowns through any one of them. As such a free unknown, let us select the Mach number M' of gas in cross section F'

$$M' = \frac{w'}{\sqrt{k'gRT'}}. \tag{14}$$

Assuming for simplicity the assumption that the specific heats in cross sections F_1 and F' are identical and $k' = k_1$, the system

of relationships (7)-(14) can be reduced to an algebraic equation of the sixth degree relative to dimensionless velocity w'/w_1; let us call it an indicial equation

$$F\left(\frac{w'}{w_1};\ M'\right)=0. \tag{15}$$

Its coefficients apart from the initial data and characteristic cross sections of the flame contain the free parameter M'. Recording determined value M', it is possible to solve equation (15) and with the aid of simple formulas to find the other unknowns: T'/T_1, P'/P_1, w''/w', T''/T_1, β', F_1/F^*.

Let us estimate the unknown parameters – the velocity v' and temperature T' of the drops in the cross section, going into the initial equations. Relative velocity u' should not exceed the maximum speed u_{max}, at which a drop will break apart (in cross section F' the process of liquid steam disintegration is already completed); $v' = w' = u'$. Velocity u_{max} is determined by the fragmentation number [2] or by the critical Weber number

$$We_{кр}=\frac{\rho_1 u_{max}^2 a_1'}{\sigma}.$$

Then

$$u_{max}=\sqrt{\frac{\sigma We_{кр}}{\rho' a_1}}\approx\sqrt{\frac{\sigma We_{кр}}{\rho_1 a_1}},$$

because values ρ' and ρ_1 are close.

Thus, u' can vary within the narrow limits $0 \le u' \le u_{max}$. In magnitude u_{max} is noticeably less than w', therefore the estimate of u' can be rather rough. In the calulations let us take the average in the indicated range of values

$$u'=\frac{1}{2}\sqrt{\frac{\sigma We_{кр}}{\rho_1 a_1}};\quad We^{кр}\approx 10. \tag{16}$$

Value $T'_{ж}$ is estimated roughly as the average between the initial temperature and the boiling point, since the enthalpy of the drops is small in comparison with the enthalpy of the gas. Variation in u' and $T'_{ж}$ has comparatively little effect on the final results. Thus, in accordance with everything that has been

stated, in the given cross section F' we obtain a whole set of solutions for the desired values as a function of the free parameter – M_1 number. The question of selecting any single solution arises.

A considerable part of the flow flowing into the flame after the powerful shock wave has the number M < 1. The supersonic flow elements (the zones beyond the section of the weak shock wave), in passing through dense cluster of drops, apparently, also become subsonic except, perhaps, for the peripheral region). Subsequently, the removal of work from the gas on the entrainment of drops – the process which is considered predominant here, accelerates flow. Consequently, the Mach number of the subsonic flow on the average increases, approaching unity, but it does not attain it (since the sign of the gas-dynamic effect does not change): $M_{n.c} < M < 1$.

As a hypothesis let us suppose that in the exit cross section of the initial flame section F' the M' number approaches unity (remaining somewhat less than it), i.e., $M' \approx 1$. Thus, the exit section F' is close to critical. It can also be noted that at other comparatively close values of M' number, for example, at M' = 0.75, the values of all the desired parameters do not vary very significantly.

The accepted hypothesis of "critical cross section" at the exit from the initial section of the atomization flame closes the system of equations and makes it possible to select a single solution. Other methods of selection are also possible.[1] The table gives the results of the solution, obtained on a computer, of systems of equations (7)-(15). Indicial equation (15) has two real very close roots w'/w_1 (for each M'). For purposes of uniformity

[1]This theory can be perfected, by closing the system of equations with the equation of the gas entropy of flow II, which has passed the shock wave (eliminating the hypothesis $M' \approx 1$).

it is always possible to take, for example, the first root. The parameters in the table show that the flow in the cross section is sharply decelerated and is more heated, than the incoming flow, and the gas flow rate in the flame is noticeably less than the gas flow rate in the incoming flow, which leads to high concentrations of fuel β' and to small values of the coefficient of air excess.

Data of the theory and experiment for gasoline ($M = 2.85$; $P_1 = 1$ atm(abs.); $T_{ж_1} = 293°K$).

β_0	d_c, мкм	ΔP, атм	v_1, м/сек	d_{max}, мкм	w', м/сек	$T'_к$, °K	β'	y^*, мм	$l_э$, мм	X, мм
$T_1 = 1050°$ K; $w_1 = 1730$ м/сек										
1,30	0,8	44	105	10	887	1940	1,9	10,3	48	44,3
1,25	0,6	76	137	10,6	882	1920	2,0	13,5	50	50,5
1,34	1,0	40	100	13	887	1940	1,9	16,3	72	68,3
1,27	1,0	64	126	14	882	1920	2,0	20,5	70	77,5
1,34	1,45	39	100	16	887	1910	1,9	23,3	84	93,3
1,49	0,6	19,6	70	9	880	1900	2,0	6,8	52	34,8
1,49	1,0	19,6	70	12	880	1900	2,0	11,4	63	56,4
1,49	1,45	19,6	70	15	880	1900	2,0	16,5	73	78,5
$T_1 = 870°$ K; $w_1 = 1610$ м/сек										
1,32	0,6	39	100	10,6	804	1590	1,9	9,7	51	50,6
1,23	0,6	75,5	136	11	799	1570	2,0	13,4	60	58,4
1,32	1,0	39	100	12,7	804	1590	1,9	16,1	75	71,1
1,25	1,0	65	126	13,6	801	1580	2,0	20,8	79	80,7
1,32	1,45	39	100	16	804	1590	1,9	23,3	111	99,3

Designations: атм = atm(abs.); м/сек = m/s; мкм = μm.

A COMPARISON OF THE DATA OF THE THEORY AND THE EXPERIMENT

Having generalized what has been stated, we obtain a final method for the approximate computation of flow processes with phase transitions in the atomization flame.

1. From the initial data of the incoming flow and the fuel feed (M_1, P_1, T_1, d_c, ΔP, $T_{ж_1}$) and the physical constants of the gas and fuel let us determine the flame boundaries, its characteristic cross sections and the drop coarseness.

2. Let us find all the parameters (w', P', T', β') at inlet F' into the main section of the flame, having selected, for example, $x'/y^* = 1$.

3. Let us place the obtained values as initial values into system of equations (1)-(4) and let us carry out the calculation of the flow of a two-phase gas-drop mixture, considering the intra-flame flow one-dimensional and noninteracting with the surrounding medium. In this case it is possible to determine all the characteristics – volatility $\overline{Z}$, drop velocity, gas parameters – as a function of length or time.

Let us carry out the calculation of flame volatility, as for a flow in a cylindrical pipe, at the inlet to which the two-phase flow has the initial parameters w', P', T', β'. We will characterize the lengths by the interval of total vaporization X obtained in the calculation, where all the liquid particles of the real flame vaporize; the dimensions of the largest drop a_{max} of the atomization spectrum are put into the calculation.[1] The pressure in the isolated flow will differ somewhat from pressure inside the flame. However, in the range of obtained values P this effect on the vaporization interval is comparatively small (8-15%). The results of theory X are compared with the data of experiment $L_э$ with respect to injection into a free supersonic jet in the calculated gas exhaust heated to 1050 and 870°K and number $M_1 = 2.85$. B-70 gasoline was fed from the surface of a cooled atomizer with different d_c and ΔP. The interval of total vaporization $L_э$ was determined with the aid of photographs obtained by Toepler's method (Fig. 6). The experiment showed that the fuel manages to vaporize on comparatively short (of the order of tens millimeters) sections. A small interval of vaporization in the flow, where a drop, it seemed, moves with supersonic speed, was at first somewhat

[1]The processes of the mixing of the intra-flame flow with the surrounding gas were not considered, since this overstated the vaporization interval.

strange. However, our theory gives a simple explanation for it. The flow in the main section with initial subsonic parameters in section F' (their values w' and T' are placed in the table) is kept subsonic to the end (as a result of intense heat withdrawal during vaporization of the drops). This leads to small X (see Fig. 4); a drop of the same dimensions in a supersonic flow would have a several times greater vaporization interval (small retention times).

GRAPHICS NOT REPRODUCIBLE

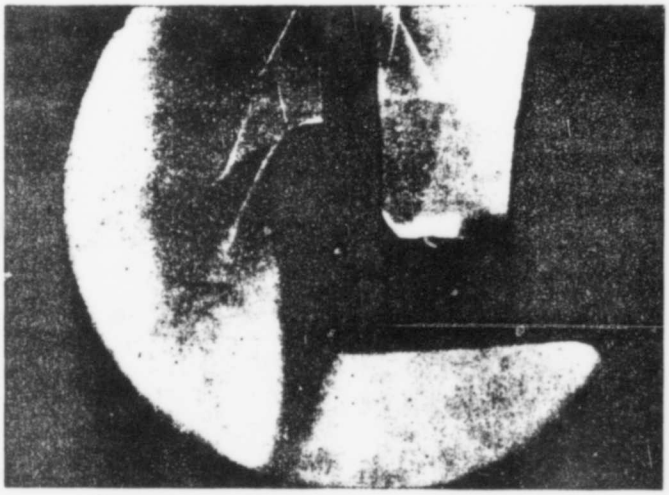

Fig. 6. A vaporized atomization flame of gasoline in a supersonic flow (M_1 = 2.85, T_1 = 1050°K, P_1 = 1 atm(abs.), ΔP = 40 atm(gage), d_c = 1 mm).

Taking the complexity of the studied process and the degree of approximation of the solution method into account which consists of several separate stages, the obtained agreement of the results of the theoretical and experimental investigations can be taken to be satisfactory.

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