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# RADIAL EXPANSION OF A PERFECT AND VIBRATIONALLY RELAXING GAS DUE TO A SUDDENLY CONNECTED SOURCE IN A VACUUM

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Radial expansion of a gas due to a suddenly connected stationary source is the model for a theoretical investigation of the process of stationary flow shaping in supersonic nozzles and strongly underexpanded jets during their onset [1, 2]. A flow is usually started up either by means of shock or explosive gas compression in the forechamber or by disruption of the diaphragm between the high-pressure chamber and the nozzle. In the former case the gas has a high temperature, in which connection the question of relaxation of the vibrational degrees of freedom of the molecules [3] becomes important, while in the latter case of high density, the question of gas condensation arises [4]. In their energetic characteristics both of these phenomena may exert significant influence on the gas flow. The question of vibrational relaxation is also important for gasdynamic lasers with shock heating of the gas [5].

The problem of the flow of a vibrationally relaxing gas due to a suddenly connected source during expansion into a vacuum is considered in this paper. For a perfect gas this problem was examined in [1], where the main attention was paid to calculating the buildup time of the stationary flow. A numerical solution is obtained below for the problem for a perfect gas, which corresponds to the case of a "frozen flow," and a vibrationally relaxing gas (up to equilibrium flow). It is shown that an approximate self-similar representation exists for the gas velocity and density distribution at large times. By using this representation, an estimate is obtained of the location of the vibrational temperature "freezing" point which describes its dynamics and agrees well with results of numerical computations. The results presented can be used to estimate the influence of the condensation process.

1. Statement of the Problem. There is a radial gas source with a surface of radius $r_1$. The pressure is $p_\infty = 0$ in the surrounding space. At the time $t = 0$ the source is connected, and the gas velocity v, the pressure p, the temperature T and the vibrational energy $\varepsilon_V$ on the surface of the source $r = r_1$ acquire the given values $v_1 > 0$, $p_1$, $T_1$, $\varepsilon_{V1}$, which do not change with time, by a jump. Determine the behavior of the gas parameters with time for $r > r_1$.

Taking account of vibrational relaxation, the nonstationary one-dimensional gas flow is described by the following system of equations (in a Lagrange coordinate system) [6, 7]:

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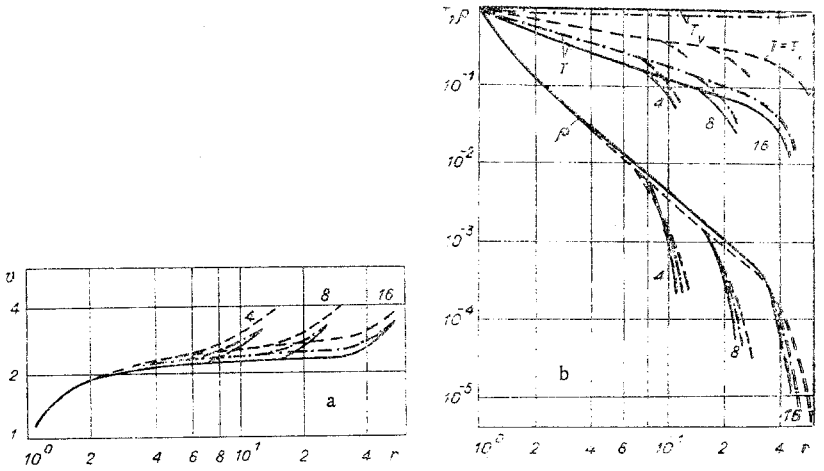


Fig. 1

$$\frac{\partial v}{\partial t} + \frac{n+1}{\varkappa_f M_1^2} r^n \frac{\partial p}{\partial s} = 0, \quad \frac{\partial r}{\partial t} = v,$$

$$\frac{\partial}{\partial t}\left(\frac{1}{\rho}\right) - (n+1)\frac{\partial}{\partial s}(r^n v) = 0,$$

$$\frac{\partial}{\partial t}(\varepsilon + \varepsilon_V) + (n+1)\, p \frac{\partial}{\partial s}(r^n v) = 0, \quad \frac{\partial \varepsilon_V}{\partial t} = \frac{\varepsilon_V^0 - \varepsilon_V}{\tau},$$

where t is the time, r is the radius of a liquid particle, $s = \int_{r_1}^{r} \rho r^n dr$ is the Lagrange mass variable, n is the flow symmetry superscript, $\varepsilon_V^0$ is the equilibrium value of the vibrational energy, $\tau$ is the relaxation time, and $\varepsilon_V + \varepsilon$ is the internal energy of the gas. All the quantities are dimensionless, and the values $s_1 = \rho_1 r_1^{n+1}/(n+1)$, $v_1$, $\rho_1$, $p_1 = \rho_1 R T_1$, $\varepsilon_1 = c_{Vf} T_1$, where $c_{Vf}$ is the specific heat of the gas with frozen vibrational degrees of freedom, are selected as scales for the variables s, v, $\rho$, p, $\varepsilon$. The Mach number is $M_1 = v_1/c_1$, where $c_1$ is the frozen speed of sound at the source $c_1 = \sqrt{\varkappa_f R T_1}$, and $\varkappa_f = (c_{Vf} + R)/c_{Vf}$. The time scale is $t_1 = r_1/v_1$. The vibrational energy $\varepsilon_V$, $\varepsilon_V^0$ is referred to $\varepsilon_1$.

The boundary conditions have the form

$$\begin{aligned} t = 0: &\text{ for } r = 1 \quad v = 1, \quad \rho = 1, \quad T = 1, \quad \varepsilon_V = \varepsilon_{V1}, \\ &\text{for } r > 1 \quad p = 0, \\ t > 0: &\text{ for } r = 1 \quad v = 1, \quad \rho = 1, \quad T = 1, \quad \varepsilon_V = \varepsilon_{V1}, \\ &\text{for } r = r_i \quad p = 0, \end{aligned}$$

where $r_i$ is the radius of the contact surface (the front of the escaping gas).

The problem was solved numerically. An implicit difference scheme of accuracy $O[\Delta t + (\Delta s)^2]$ was used with iterative resolution of the system of difference equations at each time spacing [6]. Additional transformations are made in the approximation of the relaxation equation in order to compute almost-equilibrium flows [8]. The computations were executed with constant time $\Delta t$ and mass $\Delta s$ spacings.

All the computations were performed for the case of a $CO_2$ flow from a spherically symmetric source (n = 2) with Mach number $M_1 = 1$, $\varkappa_f = 1.4$, $T_1 = 2000°K$. The equilibrium vibrational energy $\varepsilon_V^0$ was calculated by means of the formula for a harmonic oscillator with all kinds of $CO_2$ molecule vibrations taken into account: $\varepsilon_V^0 = \sum_j \hbar\omega_j/(e^{\hbar\omega_j/kT} - 1)$, where $\hbar\omega_j/k$ is the characteristic temperature of the j-th mode. It is assumed in the computation of the relaxation that all the levels relax with the same time [9] determined by the formula $\tau p = \exp(36.5T^{-1/3} - 3.9)$ 0.1033Pa·sec.

After having gone over to dimensionless variables $\tau p = A \exp(BT^{-1/3} - 3.9)$, where $A = c_1 M_1/p_1 r_1$ and $V = 36.5 T_1^{-1/3}$. For a given temperature $T_1$ at the source, the flow for this gas depends only on one parameter $p_1 r_1$. The cases $p_1 r_1 = 0$ and $p_1 r_1 = \infty$ here correspond to frozen and equilibrium flows [10].

2. Perfect Gas Flow. Results of a computation for $\varkappa = \text{const} = 1.4$, which corresponds to the frozen, isentropic escape of $CO_2$, are presented by continuous curves in Fig. 1a and b. The velocity distributions over

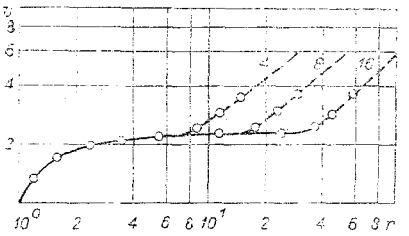


Fig. 2

the radius are presented at the times t = 4, 8, 16 in Fig. 1a, and the temperature and density distributions at the same times in Fig. 1b. It is seen from the distributions presented that the flow consists of two domains [1]: the stationary flow domain [11] and a nonstationary rarefaction wave connecting the stationary flow to a vacuum. The stream parameters in the nonstationary rarefaction wave vary considerably more strongly than in the stationary flow domain.

When escaping into a vacuum, the front of the escaping gas moves at a constant velocity corresponding to the maximum escape velocity $v_{mH} = (\varkappa + 1)/(\varkappa - 1)$ and its radius is $r_i = v_{mH}t + 1$ [1]. The maximal value of the velocity $v_{mH}$ is not achieved in these numerical computations and the front is itself near the source. This is because the mass variable s is used in the computations. On the gas front $\rho = 0$, where $\rho r^3$ diminishes as $r^{-\alpha}$ with $\alpha \gg 1$ as the front is approached (see below). Consequently, the gas layer abutting on the front will always be thinner than the real layer when using a central second-order approximation in s, and secondly, it is difficult to achieve the layer width necessary by diminishing the mass spacing $\Delta s$, and thereby approaching the theoretical front. Presented as an illustration in Fig. 2, the continuous curves are the velocity distributions for the computation spacing $\Delta s = 0.1$, used to perform the main computations, while the points are for a spacing one-tenth the size. It is important that the parameter distributions in the domain where they had been earlier should not undergo changes. Moreover, the behavior of the parameters near the front has a regular tendency. Thus, if the linear nature of the behavior of the velocity in the nonstationary rarefaction wave is taken into account, and it is extrapolated to the value $v_{mH}$, as is done in the dashed lines in Fig. 2, the location of the gas front agrees well with the theoretical value. It must be noted that in the case of an escape into a vacuum, the gas motion near the front is not described by the theory of an ideal fluid.

Let us investigate the asymptotic behavior of the stream parameters for large times. Let us first examine the nonstationary rarefaction waves. Since the maximal velocity of nonstationary expansion with which the excaping gas front moves is much greater than the initial gas velocity [by $(\varkappa + 1)/(\varkappa - 1$ times)] the gas motion in the nonstationary rarefaction wave is almost exactly the same as for the dissipation of a finite mass of gas. This is confirmed by the nature of the parameter behavior in the given domain and by a comparison of the results of solving the problem under consideration with computations of the dissipation of a finite mass as performed by the authors in [12].

It is known that the flow "forgets" the initial size of the bunch during dissipation of a finite mass of gas into a vacuum at distances much greater than the initial radius of the bunch, and is determined by two quantities of independent dimensionality, the mass of the bunch and its energy [13, 14]. The problem here has a self-similar solution determined by the single self-similar variable $\lambda = r/t$, where the gas velocity is $v = \lambda$ and the combination is $\rho t^3 = \varphi(\lambda)$. The other parameters of the gas state are determined from the condition of isentropicity of the flow. These results can be extended even to the gas motion in the nonstationary rarefaction wave.

The stationary flow from the source at large distances also does not depend on the source dimensions, and is determined by the mass and momentum fluxes [2, 11]. In this case, $\lambda = r/t$ will be the self-similar variable, as before. The velocity is $v = \sqrt{(\varkappa + 1)/(\varkappa - 1)}$, and only the combination $\rho t^2$ will be a function of $\lambda$.

At large times the boundary between the stationary flow and the nonstationary rarefaction wave domains moves at a constant speed $\sqrt{(\varkappa + 1)/(\varkappa - 1)}$ [1] (see Fig. 1a). Hence, in a self-similar representation with the variable $\lambda = r/t$, the whole flow domain from the source will, as $t \to \infty$, be separated by a boundary with the fixed value $\lambda = \sqrt{(\varkappa + 1)/(\varkappa - 1)}$, and the distribution of the velocity v will extend over the whole flow domain. Such an extension is represented in Fig. 3a for the times t = 4, 9, 16, 32. It is seen that in the stationary flow section the velocity tends to a constant value corresponding to the maximal stationary escape velocity into a vacuum $v_{mc} = \sqrt{(\varkappa + 1)/(\varkappa - 1)}$ ($v_{mc} = 2.45$ for $\varkappa = 1.4$), and to the distribution $v = \lambda$ in the nonstationary rarefaction wave domain. This limit solution is shown by the dashed line in Fig. 3a.

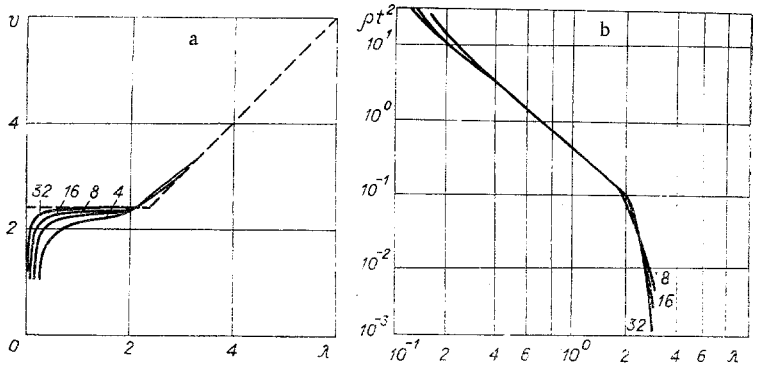


Fig. 3

The following can be said relative to the density. It is impossible to extend the density distribution over the whole flow domain analogously to the velocity. However, as computations show, for the nonstationary flow (strictly speaking, with the exception of the domain near the front), the quantity $\rho t^3$ is almost a power-law function of the self-similar variable $\lambda$ with a large negative exponent $\rho t^3 \sim \lambda^{-\alpha}$, $\alpha \approx 10$. Consequently, the quantity $\rho t^2 = \rho t^3/t$ can approximately be considered a function also of $\lambda$, which indeed permits the construction of an approximate self-similar representation for the density in the whole flow domain from the source (it is exact on the stationary flow section). This is quite convenient for a different kind of estimate and computation. The results of such an extension are represented in Fig. 3b.

Let us note that the mass of gas enclosed in the nonstationary flow domain tends to the finite value $s_H = 2$ (in dimensionless quantities) as $t \to \infty$. This means that the gas escaping from the surface of the source up to the time $t = 2$ is here diverted to the formation of the stationary rarefaction wave.

3. Flow with Vibrational Relaxation. Flows with vibrational relaxation were computed for the initial conditions mentioned in Sec. 1, and the values $p_1 r_1 = 10^{-5}$, $10^0$, $10^1$, $10^3$, $10^5$. Certain results of the computations are represented in Fig. 1a and b: the dashed curves are for $p_1 r_1 = 10^5$, the dash–dot curves for $p_1 r_1 = 10$. Within the limits of graphical error, the parameter distributions for $p_1 r_1 = 10^{-5}$ agree, for the given times, with the distributions for $\varkappa = 1.4$ corresponding to the case of "frozen" flow. The distributions for $p_1 r_1 = 10^5$ can be considered equilibrium distributions since a further increase in $p_1 r_1$ does not result in their changing.

The behavior of the temperature for the case $p_1 r_1 = 10^3$ is represented in Fig. 4; for this case the velocity and density distributions are close to the distributions for $p_1 r_1 = 10^5$.

It is seen from the graphs presented that, as in the case of perfect gas expansion, the whole flow domain consists of two domains at each time, a stationary flow and a nonstationary rarefaction wave domain. Taking account of vibrational relaxation, the stationary flow during gas expansion into a vacuum was investigated in [8].

Let us examine the nature of the parameter behavior in the nonstationary flow domain. Under given initial conditions, considerable energy, commensurate with the energies of the translational and rotational degrees, is stored in the vibrational degrees of freedom; consequently, as the flow approaches equilibrium its difference from the case $\varkappa = \text{const} = 1.4$, corresponding to the "frozen" flow, becomes significant. This concerns principally the translational and vibrational temperatures, whose change is a quantity on the order of the values of the temperatures themselves, and the density to a lesser degree if its large gradient in the rarefaction wave is taken into account. The velocity change reaches 15-20%.

Let us turn to the behavior of the vibrational degrees of freedom. Although the assumption of equilibrium within the vibrational degrees of freedom and between them was used in the computations, and the computations were carried out in terms of the vibrational energy, it is convenient to go over to the vibrational temperature to represent the results. It was found in terms of the value of $\varepsilon_V$ from the expression for the energy of a harmonic oscillator with all types of $CO_2$ molecule vibrations taken into account, which had been used to evaluate the equilibrium energy $\varepsilon_V^0 = \varepsilon_V^0(T)$.

As is seen from Fig. 4, the vibrational temperature rises in the nonstationary rarefaction wave as the escaping gas front is approached. This is because the vibrational relaxation in the gas layers adjoining the front is worse than in the subsequent layers because of the large degree of gas expansion. In particular, the gas in the layer closest to the front does not succeed in relaxing generally and expands with an initial value of $T_{V1}$. As already noted above, the computation method used does not permit obtaining the value of the parameters on the gas front; hence, the vibrational temperature does not reach the value $T_{V1}$ in the computations.

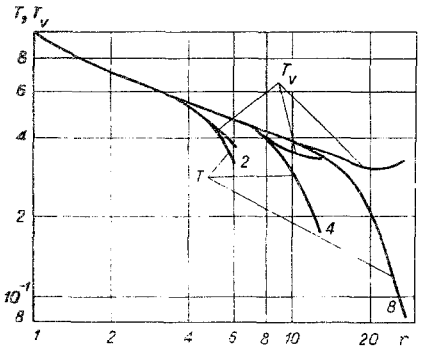


Fig. 4

Exactly as in a gas flow with $\varkappa = \text{const} = 1.4$, approximate self-similar representations exist for the velocity and density: $v = v(\lambda)$, $\rho t^2 \simeq \varphi(\lambda)$ for every $p_1 r_1$ in the case of gas expansion with vibrational relaxation in large times, where $\lambda = r/t$, as before. They differ exactly as the velocity and density distributions differ for these values of $p_1 r_1$ in a fixed and sufficiently large time, for $t = 16$, say.

The vibrational relaxation is felt principally in that the magnitude of the limit velocity of both the stationary and nonstationary flows increases. Moreover, because of the singularity in the behavior of the vibrational temperature during the approach to the escaping gas front, reconstruction of the velocity behavior occurs: it tends more to its limit dependence in the area of the nonstationary rarefaction wave than in the case of the "frozen" flow.

In conclusion, let us estimate the position of the vibrational temperature "freezing" point in the areas of the stationary flow and the nonstationary rarefaction wave.

The "freezing" point is defined as the point where the magnitude of the deviation from equilibrium reaches the order of magnitude of the function itself [10]. In this case $(d\varepsilon^0/dt)_f = \varepsilon_f^0/\tau$. We use the vibration frequency $\omega_2$ corresponding to the deformation mode of the $CO_2$ vibrations with characteristic temperature 960°K. The "freezing" point is then determined from the condition

$$(dT/dt)_f\, k\,(\hbar\omega_2/kT_f)^2 = \hbar\omega_2/\tau_{Vf},$$

where T corresponds to the equilibrium case.

Let us use the approximate self-similar representation of the density $\rho t^2 = \varphi(\lambda)$, where

$$\varphi(\lambda) = \begin{cases} a_1\lambda^{-2}, & a_1 = 0{,}43 \quad \text{for} \quad 0 \leqslant \lambda \leqslant \sqrt{(\varkappa+1)/(\varkappa-1)}, \\ a_2\lambda^{-10}, & a_2 = 2{,}32\cdot 10^3 \quad \text{for} \quad \sqrt{\dfrac{\varkappa+1}{\varkappa-1}} \leqslant \lambda \leqslant \dfrac{\varkappa+1}{\varkappa-1}. \end{cases} \tag{3.1}$$

Then taking into account that $T \sim \rho^{\varkappa-1}$ and $dT/dt = (\varkappa-1)\,d\ln\rho/dt = 2(\varkappa-1)T/t$, we obtain for the "freezing" point $t_f = (\gamma\hbar\omega_2/kT_f)\tau_{Vf}$, where $\gamma = 2(\varkappa-1)$. After substituting the expression for $\tau_V$ we finally have $t_f = (\gamma\Theta_2/T_f p_f)\exp(BT_f^{-1/3} - C)$; $\Theta_2 = \hbar\omega_2/k$ is the characteristic temperature.

In the stationary flow domain, we obtain the following expression to determine the freezing point

$$r_f^{3-4\varkappa}\left(\frac{\varkappa+1}{\varkappa-1}\right)^{\varkappa}\frac{1}{a} = \exp\left[b\left(\frac{\varkappa-1}{\varkappa+1}\right)^{-\frac{\varkappa-1}{6}} r^{\frac{2}{3}(\varkappa-1)} - C\right],$$

where $a = \dfrac{\Theta_2}{T_1 p_1 t_1}$; $b = \dfrac{B}{\Theta_2^{1/3}}\left(\dfrac{\Theta_2}{T}\right)^{1/3}$; $C = 3.9$, by going from the time variable to the radius by means of the formula $t = r/v_{mc}$ in dimensionless variables.

For the estimate we take $\varkappa \approx 1.25$, $\Theta_2 = 1000$°K, $T_1 = 2000$°K, $p_1 r_1 = 10^3$. Then $r_f = 12$ (in the computations $r_f = 12$–$15$).

The position of the freezing point in the nonstationary flow domain, obtained under the condition that the gas expands in equilibrium in the stationary flow domain, is determined by the expression

$$\lambda t^{\frac{2(2\varkappa-1)-1}{\alpha(2\varkappa-1)}} = \frac{a_2^{\frac{1}{\alpha}}}{a^{\frac{1}{\alpha(2\varkappa-1)}}}\exp\left[-\frac{b a_2^{\frac{1-\varkappa}{3}}}{\alpha(2\varkappa-1)}\lambda^{\frac{\alpha(\varkappa-1)}{3}} t^{\frac{2}{3}(\varkappa-1)} - \frac{C}{\alpha(2\varkappa-1)}\right],$$

$\alpha = 10$ (see expression (3.1)).

Under the same conditions as in the stationary flow domain, we obtain

$$\lambda = r/t = 3{,}66t^{-0{,}133}.$$

For instance, for t = 4 this yields $r_f = 10$ (in the computations $r_f = 10$-12).

As is seen from the last expression, the freezing point in the nonstationary flow domain slowly moves to the stationary flow section with time.

In conclusion, we make a remark about the influence of condensation on the gas flow. Vibrational relaxation influences the gas flow during expansion principally because of heat transfer from the vibrational to the translational degrees of freedom. An analogous phenomenon of heat transfer (latent heat of vapor formation) occurs even during gas condensation. It is shown in [15] that a change occurs in the distribution of the stream parameters during stationary gas expansion (velocity, density, pressure, and translational temperature) qualitatively identically in these two cases. There is no foundation to consider that this analogy is spoiled in the nonstationary case.

The maximum mass fraction of condensate does not usually exceed 20-30% during gas expansion. In this case energy will be liberated into the stream, which is approximately equal to the energy stored in the vibrational degrees of freedom under the conditions considered in this paper ($T_1 = 2000$°K).

Therefore, the influence of condensation on the gas flow can be traced qualitatively by means of the results presented above for the flow of a vibrationally relaxing gas, where the maximal influence will not exceed, in order of magnitude, the difference between the stream parameter distributions for the equilibrium and the "frozen" flows.

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