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EQUATION OF EQUILIBRIUM EMISSION AND RETARDATION PARAMETERS IN NUCLEAR-POWER-PLANT TURBINES WITH DISSOCIATING NITROGEN TETROXIDE

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UDC 621.039.534

The equation of emission, retardation parameters, and expressions for quantities at the flow crisis are obtained for the case of dissociating nitrogen tetroxide.

I. Equations of Gas Emission and Flow Rate

The most interesting of the prospective heat carriers and working media in nuclear power plants is dissociating nitrogen tetroxide, i.e., the dissociating system

$$N_2O_4 \rightleftarrows 2NO_2 \rightleftarrows 2NO + O_2.$$

In [1] expressions were obtained for the isentropic heat incidence in a nozzle network, at the working blades, and in the turbine, written respectively in the form

$$h_{\text{n. }l} = \frac{w_{1t}^2 - w_0^2}{2} = \frac{R}{\mu}\frac{k_T}{k_T - 1}\bar{\eta}T_0\left[1 - \left(\frac{p_1}{p_0}\right)^{(k_T - 1)/k_T}\right] - \frac{R}{\mu}T_0[(Z_{1\text{ef}})_{T_0} - (Z_{0\text{ef}})_{T_0}], \tag{1}$$

$$(L_0)_{\text{w. b}} = \frac{R}{\mu}\frac{k_T}{k_T - 1}\bar{\eta}T_1\left[1 - \left(\frac{p_2}{p_1}\right)^{(k_T - 1)/k_T}\right] - \frac{R}{\mu}T_1[(Z_{2\text{ef}})_{T_1} - (Z_{1\text{ef}})_{T_1}] - \frac{w_{2t}^2 - w_1^2}{2}, \tag{2}$$

$$H_0 = \frac{R}{\mu}\frac{k_T}{k_T - 1}\bar{\eta}T_0\left[1 - \left(\frac{p_2}{p_0}\right)^{(k_T - 1)/k_T}\right] - \frac{R}{\mu}T_0[(Z_{2\text{ef}})_{T_0} - (Z_{1\text{ef}})_{T_0}]. \tag{3}$$

The quantity $(k_T - 1)/k_T$ appears in Eqs. (1)-(3). In [1], the following dependence was established

$$\omega = \frac{C_p}{R/\mu}\frac{k_T - 1}{k_T}. \tag{4}$$

For dissociating nitrogen tetroxide, Eq. (4) is written in the form

$$\frac{k_T - 1}{k_T} = \frac{R}{\mu_{N_2O_4}}\frac{\omega}{C_{p\,\text{ef}}}. \tag{5}$$

M. Azizbekov Azerbaidzhan Institute of Petroleum and Chemistry, Baku. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 43, No. 2, pp. 201-209, August, 1982. Original article submitted March 30, 1981.

0022-0841/82/4302-0846$07.50

The quantity ω appearing here, obtained in [2] for dissociating nitrogen tetroxide, is expressed in the form

$$\omega = Z(1+\alpha_{\mathrm{I}0}+\alpha_{\mathrm{I}0}\alpha_{\mathrm{II}0}) + T\left\{(1+\alpha_{\mathrm{I}0}+\alpha_{\mathrm{I}0}\alpha_{\mathrm{II}0})\left(\frac{\partial Z}{\partial T}\right)_p + \left(1+\sum_{i=1}^{3}\sum_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)\left\{1+\alpha_{\mathrm{II}0}\right)\frac{x_{\mathrm{I}0}(1-\alpha_{\mathrm{I}0})}{6RT^2}\times\right.$$

$$\times\left[\Delta H_{p1}(3+3\alpha_{\mathrm{I}0}-\alpha_{\mathrm{II}0}+\alpha_{\mathrm{I}0}\alpha_{\mathrm{II}0})+\alpha_{\mathrm{II}0}\Delta H_{p2}(2+3\alpha_{\mathrm{I}0}+\alpha_{\mathrm{I}0}\alpha_{\mathrm{II}0})\right]+$$

$$\left.+\frac{\alpha_{\mathrm{I}0}\alpha_{\mathrm{II}0}(1-\alpha_{\mathrm{II}0})}{6RT^2}\left[\Delta H_{p2}(2+\alpha_{\mathrm{I}0}\alpha_{\mathrm{II}0})-\Delta H_{p1}(1-\alpha_{\mathrm{I}0})\right]\right\}\Bigg\}, \qquad (6)$$

ΔH_{p1} = 623.4·10³·92 J/kmole in the temperature range 300-450°K; ΔH_{p2} = 1225.9·10³·92 J/kmole in the temperature range 400-1300°K.

The partial derivative appearing in Eq. (6) is

$$\left(\frac{\partial Z}{\partial T}\right)_p = -\frac{1}{T}\left[\pi\left(\frac{a_{11}}{\tau}+\frac{2a_{12}}{\tau^2}+\frac{3a_{13}}{\tau^3}+\frac{4a_{14}}{\tau^4}\right)+\right.$$

$$\left.+\pi^2\left(\frac{a_{21}}{\tau}+\frac{2a_{22}}{\tau^2}+\frac{3a_{23}}{\tau^3}+\frac{4a_{24}}{\tau^4}\right)+\pi^3\left(\frac{a_{31}}{\tau}+\frac{2a_{32}}{\tau^2}+\frac{3a_{33}}{\tau^3}+\frac{4a_{34}}{\tau^4}\right)\right], \qquad (7)$$

where $\tau = T/T_{cr} = T/431.35$; $\tau = p/p_{cr} = p/102.492$; p, bar.

From the Klepatskii equation [3]

$$Z = 1+\sum_{i=1}^{3}\sum_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}. \qquad (8)$$

The coefficients a_1, a_2, a_3 are taken from Table 1.

The coefficient $\bar{\eta}$ appearing in Eqs. (1)-(3) is understood to mean, respectively, the following mean values: $\bar{\eta} = (\eta_0+\eta_1)/2$, $\bar{\eta} = (\eta_1+\eta_2)/2$, $\bar{\eta} = (\eta_0+\eta_2)/2$. In [2], an expression for η was obtained in the form

$$\eta = Z(1+\alpha_{\mathrm{I}0}+\alpha_{\mathrm{I}0}\alpha_{\mathrm{II}0}) - p\left\{(1+\alpha_{\mathrm{I}0}+\alpha_{\mathrm{I}0}\alpha_{\mathrm{II}0})\left(\frac{\partial Z}{\partial p}\right)_T - \right.$$

$$-\left(1+\sum_{i=1}^{3}\sum_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)\left[(1+\alpha_{\mathrm{II}0})\frac{\alpha_{\mathrm{I}0}(1-\alpha_{\mathrm{I}0})}{6p}(1+\alpha_{\mathrm{I}0}+\right.$$

$$\left.\left.+\alpha_{\mathrm{I}0}\alpha_{\mathrm{II}0})(3+\alpha_{\mathrm{II}0})+\frac{\alpha_{\mathrm{I}0}\alpha_{\mathrm{II}0}(1-\alpha_{\mathrm{II}0})}{6p}(1+\alpha_{\mathrm{I}0}+\alpha_{\mathrm{I}0}\alpha_{\mathrm{II}0})\right]\right\}. \qquad (9)$$

The partial derivative $(\partial Z/\partial p)_T$ appearing here is written in the form

$$\left(\frac{\partial Z}{\partial p}\right)_T = \frac{1}{p}\left[\pi\left(a_{10}+\frac{a_{11}}{\tau}+\frac{a_{12}}{\tau^2}+\frac{a_{13}}{\tau^3}+\frac{a_{14}}{\tau^4}\right)+\right.$$

$$\left.+2\pi^2\left(a_{20}+\frac{a_{21}}{\tau}+\frac{a_{22}}{\tau^2}+\frac{a_{23}}{\tau^3}+\frac{a_{24}}{\tau^4}\right)+3\pi^3\left(a_{30}+\frac{a_{31}}{\tau}+\frac{a_{32}}{\tau^2}+\frac{a_{33}}{\tau^3}+\frac{a_{34}}{\tau^4}\right)\right]. \qquad (10)$$

The coefficients a_{ij} are given in Table 1.

Finally, the expressions Z_{ef} appearing in Eqs. (1)-(3) with different subscripts are written in the form

$$(Z_{0\mathrm{ef}})_{T_0} = (1+\alpha_{\mathrm{I}0}+\alpha_{\mathrm{I}0}\alpha_{\mathrm{II}0})_{p_0,T_0}\left(1+\sum_{i=1}^{3}\sum_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)_{p_0,T_0}, \qquad (11)$$

$$(Z_{1\mathrm{ef}})_{T_0} = (1+\alpha_{\mathrm{I}0}+\alpha_{\mathrm{I}0}\alpha_{\mathrm{II}0})_{p_1,T_0}\left(1+\sum_{i=1}^{3}\sum_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)_{p_1,T_0}, \qquad (12)$$

$$(Z_{2\mathrm{ef}})_{T_0} = (1+\alpha_{\mathrm{I}0}+\alpha_{\mathrm{I}0}\alpha_{\mathrm{II}0})_{p_2,T_0}\left(1+\sum_{i=1}^{3}\sum_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)_{p_2,T_0}, \qquad (13)$$

TABLE 1. Coefficients a_{ij} of the Interpolational Equations of State [2] for Eq. (8)

i	a_{1j}	a_{2j}	a_{3j}
0	6,724331	—1,920155	4,22444
1	—13,12774	—0,2206247	—5,990096
2	—4,561842	1,044964	—8,061043
3	21,69903	10,70347	16,69250
4	—10,85284	—9,995447	—6,835001

$$(Z_{1\text{ef}})_{T_1} = (1 + \alpha_{I0} + \alpha_{I0}\alpha_{II0})_{p_1,T_1}\left(1 + \sum_{i=1}^{3}\sum_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)_{p_1,T_1}, \tag{14}$$

$$(Z_{2\text{ef}})_{T_1} = (1 + \alpha_{I0} + \alpha_{I0}\alpha_{II0})_{p_2,T_1}\left(1 + \sum_{i=0}^{3}\sum_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)_{p_2,T_1}. \tag{15}$$

Thus, all the dependence for finding the quantities expressed by Eqs. (1)-(3) in relation to dissociating nitrogen tetroxide are now available.

From Eq. (1), the theoretical rate of outflow from the nozzle is

$$w_{1t} = \sqrt{2\frac{R}{\mu_{N_2O_4}}T_0\left\{\bar{\eta}\frac{k_T}{k_T-1}\left[1-\left(\frac{p_1}{p_0}\right)^{(k_T-1)/k_T}\right] + (Z_{0\text{ef}})_{T_0} - (Z_{1\text{ef}})_{T_0}\right\} + w_0^2}. \tag{16}$$

Using the continuity equation Gv = Fw and solving it together with Eq. (16), and also assuming the counterpressure p_1 to be variable ($p_1 = p$), the expression for the flow rate of dissociating nitrogen tetroxide is written in the form

$$G = F\sqrt{2\frac{R}{\mu_{N_2O_4}}T_0\frac{1}{v^2}\left\{\bar{\eta}\frac{k_T}{k_T-1}\left[1-\left(\frac{p}{p_0}\right)^{(k_T-1)/k_T}\right] + (Z_{0\text{ef}})_{T_0} - (Z_{1\text{ef}})_{T_0}\right\} + \left(\frac{w_0}{v}\right)^2}. \tag{17}$$

In general form, the equation of state may be written as

$$pv = Z_{\text{ef}}\frac{R}{\mu_{N_2O_4}}T. \tag{18}$$

Writing Eq. (18) for the initial conditions p_0v_0 and the variables pv, and taking into account that $T_0/T = (p_0/p)^{(k_T-1)/k_T}$, simultaneous solution leads to the result

$$v = v_0\frac{(Z_{\text{ef}})_{p,T}}{(Z_{\text{ef}})_{p_0,T_0}}\left(\frac{p_0}{p}\right)^{1/k_T}. \tag{19}$$

Substituting the value of v from Eq. (19) into Eq. (17) and solving the equation with respect to the nozzle cross section, simple manipulations lead to the result

$$F = G\Bigg/\sqrt{2\bar{\eta}\frac{k_T}{k_T-1}\frac{p_0}{v_0}\frac{(Z_{\text{ef}})_{p_0,T_0}}{(Z_{\text{ef}})_{p,T}}\left[\left(\frac{p}{p_0}\right)^{2/k_T}-\left(\frac{p}{p_0}\right)^{(k_T+1)/k_T}\right]+A}, \tag{20}$$

where

$$A = \frac{(Z_{\text{ef}})_{p_0,T_0}}{(Z_{\text{ef}})_{p,T}}\left(\frac{p}{p_0}\right)^{2/k_T}\left\{2\frac{p_0}{v_0}\left[\frac{(Z_{\text{ef}})_{p_0,T_0}}{(Z_{\text{ef}})_{p,T}}-1\right]+\left(\frac{w_0}{v_0}\right)^2\frac{(Z_{\text{ef}})_{p_0,T_0}}{(Z_{\text{ef}})_{p,T}}\right\}. \tag{21}$$

On passing to a nondissociating and ideal gas, when $(Z_{\text{ef}})_{p_0,T_0} = (Z_{\text{ef}})_{p,T} = 1$; $k_T = k$, the following well-known expression is obtained

$$F_{\text{non}} = G\Bigg/\sqrt{2\frac{k}{k-1}\frac{p_0}{v_0}\left[\left(\frac{p}{p_0}\right)^{2/k}-\left(\frac{p}{p_0}\right)^{(k+1)/k}\right]+\left(\frac{w_0}{v_0}\right)^2\left(\frac{p}{p_0}\right)^{2/k}}. \tag{22}$$

II. Retardation Parameters

Taking account of the adiabatic equation $T_1/T_0 = (p_1/p_0)^{(k_T-1)/k_T}$, Eq. (1) is written in the form

$$\frac{w_{1t}^2 - w_0^2}{2} = \frac{R}{\mu_{N_2O_4}} \frac{k_T}{k_T - 1} \bar{\eta} T_0 \left(1 - \frac{T_1}{T_0}\right) - \frac{R}{\mu_{N_2O_4}} T_0 [(Z_{1ef})_{T_0} - (Z_{0ef})_{T_0}]. \tag{23}$$

With retardation of the flow, $T_1 = T_{ret}$; $p_1 = p_{ret}$; $T_0 = T$; $p_0 = p$; in this case, the flow velocity is reduced from $w_0 = w$ to $w_{1t} = 0$:

$$(Z_{1ef})_{T_0} = (Z_{ef})_{p_{ret},T}, \quad (Z_{ef})_{T_0} = (Z_{ef})_{p,T}.$$

In connection with the retardation conditions, Eq. (23) may be rewritten as

$$\frac{R}{\mu_{N_2O_4}} T \left[(Z_{ef})_{p_{ret},T} - (Z_{ef})_{p,T} + \bar{\eta} \frac{k_T}{k_T - 1} \left(\frac{T_{ret}}{T} - 1\right)\right] = \frac{w^2}{2}. \tag{24}$$

Hence, in view of Eq. (5), simple manipulations lead to the result

$$T_{ret} = T + \frac{1}{\bar{\eta}} \frac{w^2}{2C_p} \omega - \frac{1}{\bar{\eta}} \frac{RT\omega}{\mu C_p} [(Z_{ef})_{p_{ret},T} - (Z_{ef})_{p,T}]. \tag{25}$$

Equation (25) shows the relation between the retardation temperature and the flow temperature in terms of the flow velocity, effective specific heat, and quantities characterizing the properties of any dissociating gas.

For nondissociating gas ($\bar{\eta}_{non} = 1$; $\omega_{non} = 1$; $C_{ef'} = C_{ef}$; $Z_{ef} = 1$) the usual dependence known in gas dynamics is obtained

$$(T_{ret})_{id} = T + \frac{w^2}{2C_{id}}. \tag{25'}$$

In [2], an expression was obtained for the velocity of sound in dissociating nitrogen tetroxide in the form

$$a = (1 + \alpha_0 + \alpha_0 \alpha_{10}) \left(1 + \sum_{i=1}^{3} \sum_{j=0}^{4} \frac{a_{ij}\pi^i}{\tau^j}\right) \sqrt{RT/\mu_{N_2O_4} \left(\eta - \frac{R}{\mu_{N_2O_4} C_{pef}} \omega^2\right)}, \tag{26}$$

where

$$(1 + \alpha_0 + \alpha_0 \alpha_{10}) \left(1 + \sum_{i=1}^{3} \sum_{j=0} \frac{a_{ij}\pi^i}{\tau^j}\right) = Z_{ef}. \tag{27}$$

Introducing the notation

$$x = Z_{ef} \Big/ \sqrt{\eta - \frac{R}{\mu_{N_2O_4} C_{ef}} \omega^2}, \tag{28}$$

Eq. (26) is written in the form

$$a = x \sqrt{RT/\mu_{N_2O_4}}. \tag{29}$$

Solving Eqs. (24) and (29) simultaneously and introducing the Mach number M = w/a, it is found that

$$\frac{T_{ret}}{T} = 1 + \frac{1}{\bar{\eta}} \frac{k_T - 1}{k_T} \left\{\frac{1}{2} x^2 M^2 - [(Z_{ef})_{p_{ret},T} - (Z_{ef})_{p,T}]\right\} \tag{30}$$

or

$$\frac{T_{ret}}{T} = 1 + \frac{1}{\bar{\eta}} \frac{k_T - 1}{k_T} \left\{\frac{1}{2} x^2 M^2 - \left[(1 + \alpha_{10} + \alpha_{10}\alpha_{110})_{p_{ret},T} \times \right.\right.$$

$$\left.\left. \times \left(1 + \sum_{i=1}^{3} \sum_{j=0}^{4} \frac{a_{ij}\pi^i}{\tau^j}\right)_{p_{ret},T} - (1 + \alpha_{10} + \alpha_{10}\alpha_{110})_{p,T} \left(1 + \sum_{i=1}^{3} \sum_{j=0}^{4} \frac{a_{ij}\pi^i}{\tau^j}\right)_{p,T}\right]\right\}. \tag{31}$$

On the basis of the equation

$$\frac{T_{\text{ret}}}{T}=\left(\frac{p_{\text{ret}}}{p}\right)^{(k_T-1)/k_T} \tag{32}$$

Eq. (31) is written in the form

$$\frac{p_{\text{ret}}}{p}=\left\{1+\frac{1}{\bar{\eta}}\,\frac{k_T-1}{k_T}\left\{\frac{1}{2}x^2M^2-\left[(1+\alpha_{10}+\alpha_{10}\alpha_{110})_{p_{\text{ret}},T}\times\right.\right.\right.$$
$$\left.\left.\left.\times\left(1+\sum_{i=1}^{3}\sum_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)_{p_{\text{ret}},T}-(1+\alpha_{10}+\alpha_{10}\alpha_{110})_{p,T}\left(1+\sum_{i=1}^{3}\sum_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)_{p,T}\right]\right\}\right\}^{k_T/(k_T-1)}. \tag{33}$$

We write the following equation of state [2].

$$p_{\text{ret}}=\rho_{\text{ret}}\,(1+\alpha_{10}+\alpha_{10}\alpha_{110})_{p_{\text{ret}},T_{\text{ret}}}\times\left(1+\sum_{i=1}^{3}\sum_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)_{p_{\text{ret}}\;T_{\text{ret}}}\frac{R}{\mu_{N_2O_4}}T_{\text{ret}}, \tag{34}$$

$$p=\rho\,(1+\alpha_{10}+\alpha_{10}\alpha_{110})_{p,T}\left(1+\sum_{i=1}^{3}\sum_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)_{p,T}\frac{R}{\mu_{N_2O_4}}T. \tag{35}$$

Simultaneous solution of Eqs. (31), (32), (34), and (35) yields

$$\frac{\rho_{\text{ret}}}{\rho}=\frac{(1+\alpha_{10}+\alpha_{10}\alpha_{110})_{p,T}}{(1+\alpha_{10}+\alpha_{10}\alpha_{110})_{p_{\text{ret}},T_{\text{ret}}}}\;\frac{\left(1+\sum\limits_{i=1}^{3}\sum\limits_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)_{p,T}}{\left(1+\sum\limits_{i=1}^{3}\sum\limits_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)_{p_{\text{ret}},T_{\text{ret}}}}\left\{1+\frac{1}{\bar{\eta}}\,\frac{k_T-1}{k_T}\right.$$
$$\times\left\{\frac{1}{2}x^2M^2-\left[(1+\alpha_{10}+\alpha_{10}\alpha_{110})_{p_{\text{ret}},T}\times\right.\right.$$
$$\left.\left.\left.\times\left(1+\sum_{i=1}^{3}\sum_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)_{p_{\text{ret}},T}-(1+\alpha_{10}+\alpha_{10}\alpha_{110})_{p,T}\left(1+\sum_{i=1}^{3}\sum_{j=0}^{4}\frac{a_{ij}\pi^i}{\tau^j}\right)_{p,T}\right]\right\}\right\}^{1/(k_T-1)}. \tag{36}$$

Equations (31), (33), and (36) derived here show the desired relation between the retardation parameters (respectively, the temperature, pressure, and density) and the flow parameters, expressed in terms of the Mach number, taking account of all the properties of dissociating nitrogen tetroxide.

It is simple to obtain the well-known dependences for nondissociating gases from the expressions obtained, as a particular case. When $k_T = k$; $y = 1$; $\bar{\eta} = 1$; $Z_{ef} = 1$; $\alpha_{10} = 0$; $\alpha_{110} = 0$, the following ordinary expressions for an ideal gas are obtained:

$$\left(\frac{T_{\text{ret}}}{T}\right)_{\text{id}}=1+\frac{k-1}{2}M_{\text{id}}^2, \tag{37}$$

$$\left(\frac{p_{\text{ret}}}{p}\right)_{\text{id}}=\left(1+\frac{k-1}{2}M_{\text{id}}^2\right)^{k(k-1)}, \tag{38}$$

$$\left(\frac{\rho_{\text{ret}}}{\rho}\right)_{\text{id}}=\left(1+\frac{k-1}{2}M_{\text{id}}^2\right)^{1/(k-1)}. \tag{39}$$

In finding the retardation parameters, the flow parameters and the Mach number must be specified. The calculation is conducted by means of the method of successive approximation.

III. Values at the Flow Crisis

Turning to the derivation of analytic dependences at critical flow conditions, the Mach number M = 1 in this case, and hence Eqs. (31), (33), and (36) take the form

$$\frac{T_{\text{ret}}}{T_{\text{cr}}}=1+\frac{1}{\bar{\eta}}\,\frac{k_T-1}{k_T}\left\{\frac{1}{2}x_{\text{cr}}^2-[(Z_{\text{ef}})_{p_{\text{ret}}\;T_{\text{cr}}}-(Z_{\text{ef}})_{p_{\text{cr}},T_{\text{cr}}}]\right\}, \tag{40}$$

where

TABLE 2. Adiabatic Heat Incidence according to Eq. (3)

Quantity	Literature source and equation number	Initial conditions: $p_0 = 90$ bars; $T_0 = 580$°K; $S_0 = 5.07478$ kJ/kg·g; $H_0 = 1259.07$ kJ/kg	Final conditions: $p_1 = 50$ bars; $T_1 = 540$°K; $S_1 = 5.07086$ kJ/kg·g; $H_1 = 1199.81$ kJ/kg
α_{I}	[3]	0,9837	0,9783
α_{II}	[3]	0,0397	0,0269
Z	(8)	0,971423	0,972457
Z_{ef}	(11)—(14)	1,964946	1,949397
$\left(\frac{\partial Z}{\partial p}\right)_T$	(10)	—0,000409	—0,000861
η	(9)	2,126	2,120
$\left(\frac{\partial Z}{\partial T}\right)_p$	(7)	0,0006971	0,000861
ω	(6)	3,2719	2,7876
$\overline{\eta}$	(9)	2,1233	
Z_{ef}	(12)	2,02336	
$(H_0)_{hs}$, kJ/kg	[3]	59,26	
$(H_0)_{\mathrm{rec}}$ kJ/kg	(3)	60,14	
$\frac{(H_0)_{hs} - (H_0)_{\mathrm{rec}}}{(H_0)_{hs}}$, %		1,485	
$(H_0)_{\mathrm{id}}$	(47)	14,57	
$\frac{(H_0)_{hs} - (H_0)_{\mathrm{id}}}{(H_0)_{hs}}$, %		—75,5	

$$x_{\mathrm{cr}}^2 = (Z_{\mathrm{ef}}^2)_{\mathrm{cr}} \Big/ \left[\eta_{\mathrm{cr}} - \frac{R}{\mu_{\mathrm{N_2O_4}} (C_{p\mathrm{ef}})_{\mathrm{cr}}} \omega_{\mathrm{cr}}^2 \right]; \tag{41}$$

$$\frac{p_{\mathrm{ret}}}{p_{\mathrm{cr}}} = \left\{ 1 + \frac{1}{\overline{\eta}} \frac{k_T - 1}{k_T} \left\{ \frac{1}{2} x_{\mathrm{cr}}^2 - [(Z_{\mathrm{ef}})_{p_{\mathrm{ret}}, T_{\mathrm{cr}}} - (Z_{\mathrm{ef}})_{p_{\mathrm{cr}}, T_{\mathrm{cr}}}] \right\} \right\}^{k_T/(k_T - 1)}. \tag{42}$$

In accordance with Eq. (29), the critical velocity is reached at T = T_{cr}, and hence

$$a_{\mathrm{cr}} = x_{\mathrm{cr}} \sqrt{R T_{\mathrm{cr}} / \mu_{\mathrm{N_2O_4}}} \tag{43}$$

and by analogy with Eq. (28)

$$x_{\mathrm{cr}} = (Z_{\mathrm{ef}})_{\mathrm{cr}} \Big/ \sqrt{\eta_{\mathrm{cr}} - \frac{R}{\mu_{\mathrm{N_2O_4}}} \frac{\omega_{\mathrm{cr}}^2}{(C_{p\mathrm{ef}})_{\mathrm{cr}}}}. \tag{44}$$

The critical velocity may also be expressed in terms of the retardation temperature. To this end, substituting the value of T_{cr} from Eq. (40) into Eq. (43) leads to the result

$$a_{\mathrm{cr}} = x_{\mathrm{cr}} \sqrt{\frac{R}{\mu_{\mathrm{N_2O_4}}} \frac{T_{\mathrm{ret}}}{1 + \frac{1}{\eta_{\mathrm{cr}}} \frac{k_T - 1}{k_T} \left\{ \frac{1}{2} x_{\mathrm{cr}}^2 - [(Z_{\mathrm{ef}})_{p_{\mathrm{ret}}, T_{\mathrm{cr}}} - (Z_{\mathrm{ef}})_{p_{\mathrm{cr}}, T_{\mathrm{cr}}}] \right\}}}. \tag{45}$$

Hence it is simple to obtain the usual expression for an ideal (nondissociating) gas ($Z_{\mathrm{ef}} = 1$; $k_T = k$; $\eta_{\mathrm{cr}}^2 = 1$; $x_{\mathrm{cr}}^2 = k$) in the form

$$(a_{\mathrm{cr}})_{\mathrm{id}} = \sqrt{2 \frac{k}{k+1} \frac{R}{\mu} T_{\mathrm{ret}}}. \tag{46}$$

To elucidate the degree of accuracy of the dependences obtained, the adiabatic heat incidence is calculated from Eq. (3) obtained here (Table 2).

The value of the adiabatic heat incidence is also found from the table of [3], where values of the enthalpy and entropy are given for different p and T. The difference between the initial (H_0) and final (H_1) value of the enthalpy at constant energy is denoted as $(H_0)_{hs}$ and shown in Table 2.

Comparison of the values of the adiabatic heat incidence $(H_0)_{rec}$ from the recommended Eq. (3) with the values of $(H_0)_{hs}$ shows good convergence, with a deviation of 1.48%. This accuracy of the result calculated for the heat incidence is obtained because the orientation in deriving the dependences was toward p and T, which gave negligible variation in $(k_T-1)/k_T$ and thereby ensured the constancy of $(k_T-1)/k_T$ in the corresponding integration in the course of the manipulations.

However, calculation from the expression for an ideal gas state by means of the usual expression of adiabatic heat incidence for an ideal gas — specifically from the dependence

$$(H_0)_{id}=\frac{R}{\mu}\,\frac{k}{k-1}T_0\left[1-\left(\frac{p_2}{p_0}\right)^{(k-1)/k}\right], \tag{47}$$

when $(H_0)_{id} = 14.57$ kJ/kg — shows a deviation from the true $(H_0)_{hs}$ of 75.5%.

Thus, the dependences obtained here, including Eq. (3), which is sufficiently accurate, completely justify themselves, and may be recommended for use in the corresponding calculations with the analytic method of determining the heat incidence.

NOTATION

p, v, T, ρ, pressure, volume, temperature, density; p_{ret}, ρ_{ret}, T_{ret}, retardation parameters; R, universal gas constant, k_T, temperature adiabatic coefficient of dissociating gas; k, adiabatic coefficient of ideal gas; $\mu_{N_2O_4}$, molecular mass of nitrogen tetroxide; C_v, C_p, isochoric and isobaric mass specific heat; Z, compressibility coefficient; Z_{ef}, effective coefficient taking account of the influence both of dissociation and of nonideality of the gas; α_{I0}, α_{II0}, degree of dissociation in the first and second stages of the reaction, respectively; a, velocity of sound in dissociating nitrogen dioxide; a_{cr}, critical velocity of dissociating nitrogen tetroxide.

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