

INTERPOLATION OF THE THERMODYNAMIC MODEL
FOR WATER IN THE REGION OF UNIFORM
AND TWO-PHASE STATES

S. V. Bobrovskii, V. M. Gogolev,
M. G. Menzhulin, and R. V. Shilova

UDC 536.715

To solve many problems in gasdynamics, a single mathematical description of the thermodynamic properties of water over a wide range of states covering both normal and superhigh pressures and temperatures is necessary. Existing equations of state (e.g., those given in [1-4] etc.) hold over limited ranges of variation of the thermodynamic parameters. In [5] a method is proposed for constructing interpolation equations of state of water and water vapor over a wide range of uniform states, and thermodynamic functions are obtained which describe with satisfactory accuracy the properties of the medium in the pressure range $p > 10^8$ Pa (1 Pa = 10^{-5} bar). In this paper we refine and develop the results obtained in [5] in order to construct a single analytical description of the properties of water in the region of uniform and two-phase states.

The description of the thermodynamic properties over the whole region of uniform states is based on the determination of the thermodynamic functions of the medium for certain reference states and a fairly smooth interpolation between these states. To construct interpolation thermodynamic functions, we will represent the free energy in the form

$$F = E_x + F_R + F_{OH} + \Delta F_1 + \Delta F_2 + F_e, \quad (1)$$

where E_x is the energy of elastic interaction when $T=0$, F_K is the thermal part of the free energy of the condensed state of the medium, F_{OH} is the free energy of the hydrogen bonds and other effects not taken into account by the terms in (1), ΔF_1 and ΔF_2 are corrections that take into account evaporation and dissociation, respectively, and F_e is the free energy of the electron state.

The hydrogen bonds exist in the region below the critical temperature T_{cr} . Hence, in the region $T > T_{cr}$ we assume $F_{OH} = 0$.

An expression for F_K can be obtained from the assumption that in the condensed state the water molecule executes translational vibrations in three mutually perpendicular directions, rotational vibrations in two directions perpendicular to the dipole axis, and free rotation around the dipole axis. The free energy of the translational and torsional oscillations can be described in the Debye approximation [6]. Then, using well-known relations from statistical physics [6] we obtain

$$F_R = \frac{R}{\mu} T \ln \left[(1 - e^{-\Theta_D/T})^3 \left(\frac{\Theta_r}{T} \right)^{1/2} \frac{1}{\delta} \prod_{i=1}^3 (1 - e^{-\Theta_i/T}) \right], \quad (2)$$

where R is the universal gas constant, μ is the molecular weight of water, Θ_D is the characteristic Debye temperature

$$\Theta_r = h^2/8\pi^2kI, \quad (3)$$

I is the moment of inertia of the water molecule around the dipole axis, h is Planck's constant, k is Boltzmann's constant, $\delta=2$ is the symmetry factor of the water molecule, and $\Theta_1, \Theta_2, \Theta_3$ are the characteristic temperatures of internal vibrations of the water molecule ($\Theta_1=5510$ K; $\Theta_2=2370$ K; $\Theta_3=5660$ K).

As in [7], we define the correction ΔF_1 in the form

Leningrad. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 130-139, September-October, 1978. Original article submitted September 20, 1977.

$$\Delta F_1 = \frac{R}{\mu} T \ln(1 + Z_1^{n_1})^{1/n_1}, \quad (4)$$

where $Z_1(v, T)$ is a certain unknown function.

We will determine it in such a way that when $Z_1 \gg 1$ expression (2) reduces to the free energy of an ideal-gas nondissociative state of the water molecule [6]

$$F_{ig} = \frac{R}{\mu} T \ln \left[\left(\frac{h^2}{2\pi m k T} \right)^{3/2} \left(\frac{N_A}{2.72 \mu v} \right) \left(\frac{\Theta_{r_1} \Theta_{r_2} \Theta_{r_3}}{T^3} \right)^{1/2} \frac{2}{\sqrt{\pi}} \prod_{i=1}^3 (1 - e^{-\Theta_i/T_i}) \right] + F_{eH_2O},$$

where v is the specific volume, m is the weight of the water molecule, N_A is Avogadro's number, Θ_{r_1} , Θ_{r_2} , Θ_{r_3} are the characteristic temperatures defined by expression (3), in which I_1 , I_2 , and I_3 correspond to the moments of inertia of the water molecule around three mutually perpendicular directions, and $\Theta_{r_1} = 40.1\text{K}$; $\Theta_{r_2} = 20.9\text{K}$; $\Theta_{r_3} = 13.3\text{K}$.

From the limiting-transition condition we obtain

$$Z_1 = A_1 v^{-1} T^{-5/2} [1 - \exp(-\Theta_D/T)]^{-5}, \quad (5)$$

where $A_1 = \left(\frac{h^2}{2\pi m k} \right)^{3/2} \frac{N_A}{2.72 \mu} (\Theta_{r_1} \Theta_{r_2})^{1/2} = 0.02 \text{K}^{5/2} \cdot \text{m}^3 \cdot \text{kg}^{-1}$.

As in (4) we define the correction ΔF_2 in the form

$$\Delta F_2 = -\frac{R}{\mu} T \ln(1 + Z_2^{n_2})^{1/n_2} \quad (6)$$

and we require that when $Z_2 \gg 1$ expression (6) reduces to the free energy of an ideal-gas completely dissociated mixture of components of the water molecule consisting of atoms of oxygen and hydrogen

$$F_d = -\frac{R}{\mu} T \ln \left[\frac{h^2 2^{4/3} (N_A/\mu)^{2/3}}{2\pi m_O^{1/3} m_H^{2/3} (2.72)^{2/3} k T v^{2/3}} \right]^{3/2} + F_{eO} + F_{eH},$$

where m_O and m_H are the masses of the oxygen and hydrogen atoms, and F_{eO} and F_{eH} are the free energies of the electron state of the atoms of oxygen and hydrogen, respectively.

The constants n_1 and n_2 in expressions (4) and (6) are free parameters. Their values ($n_1 = 0.4$ and $n_2 = 0.5$) are chosen so as to obtain the best correspondence between the thermodynamic functions obtained and the experimental data. The free energy of the electron state F_e can be represented in general form as follows:

$$F_e = -\frac{R}{\mu} T \ln g_0 e^{-\varepsilon_0/kT} + F_{eB}, \quad (7)$$

where g_0 and ε_0 are the statistical weight and energy in the ground state, respectively, and F_{eB} is the free energy of the electron excitation.

Then from the limiting-transition conditions we have

$$\begin{aligned} Z_2 &= A_2 v^2 T^{-3/2} \exp(-\varepsilon/kT) \quad \text{for } T \leq 7.38 \cdot 10^4 \text{ }^\circ\text{K}, \\ Z_2 &= A_2' v^2 T^{3/2} \exp(\varepsilon/kT) \quad \text{for } T > 7.38 \cdot 10^4 \text{ }^\circ\text{K}, \end{aligned}$$

where

$$A_2 = \frac{(2\pi)^3 k^3 \mu^{1/2} \mu_O^{3/2} \mu_H^3 2.72^2 g_{eO} g_{eH}^2}{4h^6 N_A^2 g_{0H_2O} \pi^{1/2}} \prod_{i=1}^3 \Theta_{r_i} \prod_{i=1}^{3'} \Theta_i = 8.6 \cdot 10^9; \quad (8)$$

$A_2' = 1.067 \cdot 10^{-6}$, μ_O and μ_H are the atomic weights of oxygen and hydrogen, and ε is the dissociation energy of the water molecule into oxygen and hydrogen atoms.

In this paper the expression for F_{eB} is not constructed. To describe the pressure p_e and the energy E_e of thermal excitation of the electrons, we use interpolation formulas, refined compared with those in [8], constructed on the basis of numerical calculations of the Tomas-Fermi model of the atom [9]. Using (1), (2), and (4)-(8) and well-known thermodynamic relations, we obtain the following expressions for the pressure and the internal energy:

$$p = p_x + p_K + p_{OH} + \Delta p_1 + \Delta p_2 + p_e; \quad (9)$$

$$E = E_x + E_K + E_{OH} + \Delta E_1 + \Delta E_2 + E_e, \quad (10)$$

where p_x and E_x are the pressure and energy of elastic interaction,

$$\begin{aligned}
p_x &= 5 \frac{R}{\mu} \frac{\gamma}{v} \frac{\Theta_D}{\exp(\Theta_D/T) - 1}, \quad \gamma = -\frac{\partial \ln \Theta_D}{\partial \ln v}, \\
\Delta p_1 &= \frac{R}{\mu} \frac{T}{v} \left[1 - 5\gamma \frac{\Theta_D/T}{\exp(\Theta_D/T) - 1} \right] Z_1^{n_1} / (1 + Z_1^{n_1}), \\
\Delta p_2 &= 2 \frac{RT}{\mu v} \frac{Z_2^{n_2}}{1 + Z_2^{n_2}}, \\
p_e &= \frac{R}{\mu} \frac{10^{-4} T^2}{1.235 v^{1/3} + T v \cdot 10^{-5}} \left(1 + \frac{\bar{v}^{1/2}}{1.02 + 7.69 \cdot 10^{-10} T^{3/2} \bar{v}} \right)^{-1} \frac{1}{\left(\frac{10^{12}}{v T^3} + 1 \right)}, \\
E_x &= \frac{RT}{\mu} \left[5 \frac{\Theta_D}{T} \frac{1}{\exp(\Theta_D/T) - 1} + \frac{1}{2} + \sum_{i=1}^3 \frac{(\Theta_i/T)}{\exp(\Theta_i/T) - 1} \right], \\
\Delta E_1 &= \frac{5}{2} \frac{RT}{\mu} \left[1 + 2 \frac{\Theta_D}{T} \frac{1}{\exp(\Theta_D/T) - 1} \right] \frac{Z_1^{n_1}}{1 + Z_1^{n_1}}, \\
\Delta E_2 &= \frac{RT}{\mu} \left(\frac{\varepsilon}{kT} - \frac{3}{2} \right) \frac{Z_2^{n_2}}{1 + Z_2^{n_2}}, \\
E_e &= p_e v \left[\frac{3}{2} \frac{(0.358 T^{8/9} + 1.825 \cdot 10^4) \bar{v}^{1/3} \cdot 10^4}{T^{3/2} + 2.94 \cdot 10^8 + 25.1 T \bar{v}} \right] \left[1 + \frac{2.1 \cdot 10^6 \bar{v}^{-0.261} T^2}{(T + 1.665 \cdot 10^6 \bar{v}^{-0.223})^3} \right],
\end{aligned} \tag{11}$$

where $\bar{v} = v/v_0$ and $v_0 = 10^{-3} \text{ m}^3/\text{kg}$. In Eq. (11) γ is Gruneisen's constant. We can assume that γ and the temperature Θ_D are functions only of the specific volume. We will then have the relation [6]

$$\Theta_D = \Theta_{D_0} \exp \left(- \int_{v_0}^v \frac{\gamma}{v} dv \right).$$

The quantity Θ_{D_0} can be found from data on the velocity of sound in a normal volume v_0 . Using the Debye approximation and assuming that the water molecule possesses five Debye degrees of freedom, we obtain

$$\Theta_D = (h/k)(5N/4\pi v)^{1/3} a.$$

For $v_0 = 1.0018 \cdot 10^{-3} \text{ m}^3/\text{kg}$ and $a_0 = 1483 \text{ m/sec}$, we have $\Theta_{D_0} = 170^\circ\text{K}$.

We will determine the form of the function $\gamma(v)$ on the basis of the following representations. Asymptotic values of this function are known [6, 10]

$$\lim_{v \rightarrow 0} \gamma(v) = 0.5, \quad \lim_{v \rightarrow \infty} \gamma(v) = 2/3.$$

To obtain intermediate points we use a series of experimental isochores in the supercritical region of states, in which $p_{\text{OH}} = 0$.

A consideration of the isochores enables one to eliminate p_x for each pair of temperatures, and to determine the quantities γ and Θ_D from (9). The calculated values of $\gamma(v)$ can be approximated by the relations

$$\begin{aligned}
\gamma &= 0.4053 + 29.10(\sigma - 0.0949)^2 \text{ for } \sigma \leq 0.1, \\
\gamma &= 0.3437 + 0.3530(\sigma + 0.32)^2 \text{ for } 0.1 \leq \sigma \leq 1, \\
\gamma &= 0.0282 + 0.9305\sigma \text{ for } 1 \leq \sigma \leq 1.2, \\
\gamma &= 1/2 + [\sigma/(1.8\sigma^2 - 4.15294\sigma + 3.88593)]^2 \text{ for } \sigma \geq 1.2,
\end{aligned}$$

where $\sigma = v_0/v$.

The function p_x was found in several stages. In the density range $\sigma < 1.3$, we used well-known data on the relation between p , v , and T of water and water vapor [3, 4]. The value of p_x was found in the supercritical temperature range in which $p_{\text{OH}} = 0$. The value of p_x was found as the difference between the total pressure and the thermal part of Eq. (9). Assuming these values of p_x to hold in the temperature range $T < T_{\text{CR}}$ and using data on the relation between p , v and T , and also Eq. (9) we obtained the components of the pressure p_{OH} .

This enabled us to use data on the dynamic compressibility of water to determine p_x in the density range $1.3 < \sigma < 2.3$ using Eqs. (9) and (10) and the general conditions on the front of a shock wave (for example, [11]). In the range of superhigh compressions we used the results of a calculation of the cold component of the pressure using the Tomas-Fermi model [9].

The function $p_x(v)$ was smoothly interpolated between these regions. The results of a calculation of p_x are shown in Table 1 in the form of interpolation relations $p_x = \left(a_0 + \sum_{i=1}^4 a_i \sigma^{n+i-1} \right) 10^{-1} \text{ Pa}$.

TABLE 1

Range of σ	a_0	a_1	a_2	a_3	a_4	n
$0 \leq \sigma \leq 0,0080784$	0	$-6,6526024 \cdot 10^{11}$	$1,33225625 \cdot 10^{14}$	$-1,6864122 \cdot 10^{16}$	$8,0978158 \cdot 10^{17}$	2,0
$0,0080784 \leq \sigma \leq 0,042517$	0	$-1,7942026 \cdot 10^{10}$	$-1,2060940 \cdot 10^{10}$	$6,0175218 \cdot 10^{12}$	$-6,3459992 \cdot 10^{13}$	1,44
$0,042517 \leq \sigma \leq 0,17094$	0	$-4,1586522 \cdot 10^9$	$3,3000393 \cdot 10^{10}$	$-3,4012734 \cdot 10^{11}$	$8,3668054 \cdot 10^{11}$	1,02
$0,17094 \leq \sigma \leq 0,490196$	0	$-1,0757083 \cdot 10^{10}$	$1,0062254 \cdot 10^{10}$	$-2,3676922 \cdot 10^{10}$	$1,7967211 \cdot 10^{10}$	1,48
$0,490196 \leq \sigma \leq 0,654879$	0	$-1,5344311 \cdot 10^{10}$	$3,5785266 \cdot 10^{10}$	$-7,4356182 \cdot 10^{10}$	$4,7128044 \cdot 10^{10}$	1,48
$0,654879 \leq \sigma \leq 0,863111$	0	$-2,5459750 \cdot 10^{10}$	$8,1761643 \cdot 10^{10}$	$-1,3050207 \cdot 10^{11}$	$6,9192589 \cdot 10^{11}$	1,26
$0,863111 \leq \sigma \leq 0,931706$	0	$-2,7513792 \cdot 10^{11}$	$9,2381612 \cdot 10^{11}$	$-1,0720450 \cdot 10^{12}$	$4,4848707 \cdot 10^{11}$	1
$0,931706 \leq \sigma \leq 1$	0	$-2,2820456 \cdot 10^{11}$	$6,9884679 \cdot 10^{11}$	$-7,5132430 \cdot 10^{11}$	$2,7538647 \cdot 10^{11}$	1
$1 \leq \sigma \leq 1,2676$	$-1,8348368 \cdot 10^{11}$	$5,8663189 \cdot 10^{11}$	$-6,9172535 \cdot 10^{11}$	$3,1924274 \cdot 10^{11}$	$-3,5961795 \cdot 10^{10}$	1
$1,2676 \leq \sigma \leq 1,86$	$-1,3010434 \cdot 10^{12}$	$3,7015286 \cdot 10^{12}$	$-3,9265916 \cdot 10^{12}$	$1,8022451 \cdot 10^{12}$	$-2,8912872 \cdot 10^{11}$	1
$1,86 \leq \sigma \leq 3,15$	0	$6,5015692 \cdot 10^9$	0	0	0	4,9
$3,15 \leq \sigma \leq 4,8$	$-1,0885294 \cdot 10^{14}$	$1,1213753 \cdot 10^{14}$	$-4,3434498 \cdot 10^{13}$	$7,5522370 \cdot 10^{12}$	$-4,8402842 \cdot 10^{11}$	1
$\sigma \geq 4,8$	—	—	—	—	$0,258 \cdot 10^{12}$	2,1

TABLE 2

$p \cdot 10^{-5}$, Pa	Deviation from [4], %				
	δT	δv_l	δv_g	$\delta(E-E_0)_l$	$\delta(E-E_0)_g$
1	-0,12	-0,04	-0,1	-0,8	+4,3
2	-0,05	+0,02	-0,6	+0,1	+4,0
4	-0,04	-0,04	-0,04	+0,3	+3,7
6	-0,03	-0,05	+1,7	+0,3	+3,4
8	+0,01	-0,01	+3,1	+0,4	+3,3
10	+0,06	+0,04	+3,4	+0,4	+3,2
20	+0,06	-0,02	+1,1	0,0	+2,1
40	+0,01	-0,18	-4,3	-0,8	-0,42
80	-0,19	-0,17	-0,5	-1,5	-1,1
100	-0,16	+0,08	+2,3	-1,5	-1,0
120	+0,02	+0,04	+2,1	-1,8	-1,0
140	-0,08	-0,32	-0,5	-1,8	-1,0
160	-0,08	-0,41	+4,6	-1,9	+0,1
180	-0,5	+0,30	+12	-1,5	+1,5
200	+0,03	+0,64	+1,1	-0,7	+0,6
215	0	-4,2	+9	-1,8	+2,7

The function $p_{OH}(v, T)$ can be represented in the form

$$p_{OH} = f_1(\bar{v})f_2(T), \quad (12)$$

where

$$f_1(\bar{v}) = 7.08(\bar{v} - 0.84467)(1.90956 - \bar{v})\exp[-1.94(\bar{v} - 1)];$$

$$f_2(T) = [85.7935(100/T)^3 - 25.9612(100/T)^2 + 1.040624(100/T)] \cdot 10^6 \text{ Pa}$$

with $T < 353^\circ\text{K}$;

$$f_2(T) = 8.0963 \cdot 10^{13} (100/T)^{12.23} \text{ Pa for } T \geq 353^\circ\text{K}.$$

The component of the internal energy E_x is found using the relation $E_x = - \int_{v_0}^v p_x(\sigma) dv$.

To determine E_{OH} we used the thermodynamic identity

$$(\partial E / \partial v)_T = T(\partial p / \partial T)_v - p. \quad (13)$$

Substituting relation (12) into (13) and integrating with respect to v from $v_0 = 10^{-3} \text{ m}^3/\text{kg}$, we obtain

$$E_{OH} = E_{OH}(v_0, T) - \psi(T) 0.365 \exp[-1.94(\bar{v} - 1)] (\bar{v} - 1) (0.7233 - \bar{v}) 10^3 \text{ J/kg},$$

where

$$\psi(T) = -13.23 f_2(T) \text{ for } T \geq 353^\circ\text{K};$$

$$\psi(T) = -3.4317 \cdot 10^{11} (100/T)^3 + 7.78 \cdot 10^{10} (100/T)^2 \text{ for } T \leq 353^\circ\text{K}.$$

We found the function $E_{OH}(v_0, T)$ using the experimental isochore $v = v_0$ and Eq. (10). Approximation of the results obtained gives the following relation:

$$E_{OH}(v_0, T) = 0.4616 \cdot 10^{-3} \frac{-2.2 \cdot 10^3 + 6.8T - 5.25 \cdot 10^{-3} T^2}{1 + \frac{3.32}{\left[1 - \exp\left(-\frac{170}{T}\right)\right]} T} \text{ J/kg}.$$

The thermodynamic functions obtained are suitable for describing the uniform states of a liquid and gas. They agree with the data given in [3, 4] to within 5% with respect to the pressure and internal energy in the range $p > 5 \cdot 10^6 \text{ Pa}$.

We will consider the problem of describing the thermodynamic properties in the region of the two-phase states. For an analytical description of the parameters of the state at the two-phase boundary, we approximated the existing data. The boundary of the region of two-phase states was determined from the well-known conditions consisting of equating the pressure, temperature, and Gibbs energy on both sides of it.

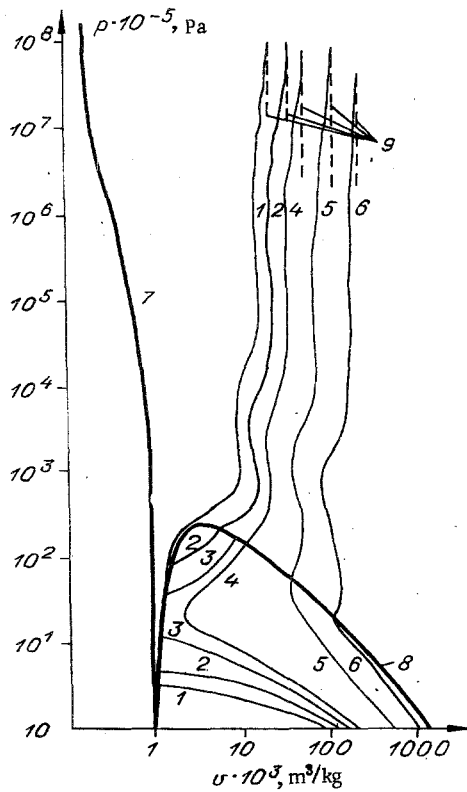


Fig. 1

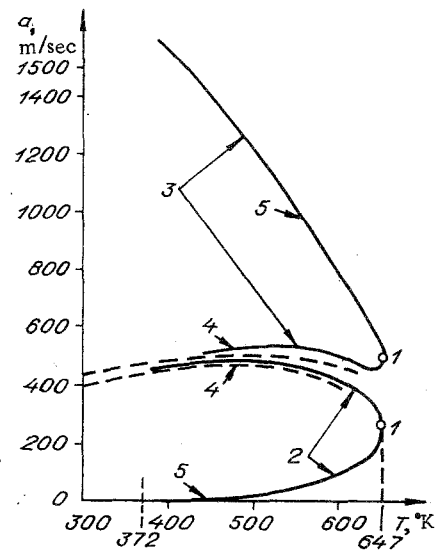


Fig. 2

Table 2 compares the results of calculations with the data given in [4].

In the approximation we used asymptotic representations of the parameters in the neighborhood of the critical point (v_{cr}, T_{cr}) , obtained using the well-known asymptotics [6] for the pressure and volume

$$E \approx -[T_{cr} A/2 - (B/12)(v_{cr} - v)^2](v_{cr} - v)^2 - (p_{cr} - CT_{cr})(v_{cr} - v) + \text{const},$$

$$S \approx -(A^2/2)(v_{cr} - v)^2 - C(v_{cr} - v) + \text{const},$$

where S is the entropy, $C = 2.8 \cdot 10 \text{ N/m}^2 \cdot \text{°K}$, $A = 0.14 \cdot 10^{12} \text{ J/m}^6 \cdot \text{°K}$, and $B/A = 16 \cdot 10^6 \text{ kg}^2 \cdot \text{°K/m}^6$.

As a result, the following relations are obtained:

$$E_l - E_0 = 2.056 \cdot 10^{-3} - [0.00655(T_{cr}^2 - T^2) + 68.8 \sqrt{T_{cr} - T}] 10^{-3} f_E, \text{ J/kg}, \quad (14)$$

$$S_l - S_0 = S_1 + 3.18 \cdot 10^{-3} - [0.01313(T_{cr} - T) + 0.1212 \sqrt{T_{cr} - T}] 10^{-3} f_S, \text{ J/kg} \cdot \text{K}, \quad (15)$$

$$v_l = v_{cr} - 0.433 \sqrt{T_{cr} - T} 10^{-3} f_{vK}, \text{ m}^3/\text{kg},$$

$$v_g = v_{cr} + 0.433 \sqrt{T_{cr} - T} 10^{-3} f_{vK}, \text{ m}^3/\text{kg}.$$

where

$$f_E = 1 - 0.055[(T_{cr} - T) \exp(-(T_{cr} - T)/200)]^{1/2};$$

$$f_S = 1 - 0.455[1 - (1 - (T_{cr} - T)/190)^4]^{0.65};$$

$$f_{vK} = 0.221 + 0.779 \exp[-(T_{cr} - T)^{0.55}/9.4];$$

$$S_0 = S[T = 273\text{K}, v = 10^{-3} \text{ m}^3/\text{kg}];$$

$$S_1 = S[T = 372\text{K}, p = 10^5 \text{ Pa}] \approx 1.3 \cdot 10^{-2} \text{ J/kg} \cdot \text{K};$$

$$T_{cr} = 647\text{K}; v_{cr} = 3.17 \cdot 10^{-3} \text{ m}^3/\text{kg}$$

(the subscripts l and g relate to the condensate-two-phase state boundary and the two-phase state-gas boundary, respectively).

For the pressure both at the boundary of the phase and over the whole two-phase region, the following interpolation relation holds:

$$p = [(T - 247)/125]^4 \cdot 65 \cdot 10^5 \text{ Pa}. \quad (16)$$

TABLE 3

u/a_0	0-0,5	0,5-1,5	1,5-150	≥ 150
a	1	1,15	1,8	-10
b	2	1,7	1,25	1,33

For the two-phase region, we will have

$$E(v, T) = [T \partial p / \partial T - p(T)] [v - v_l(T)] + E_l(T),$$

$$S = S_l(T) + [v - v_l(T)] dp/dT,$$

where E_l , S_l , and $p(T)$ are found from (14), (15), and (16).

In order to check the accuracy of the model obtained, we made a series of comparisons with existing experimental and theoretical data.

A comparison of the shock adiabat [1] with the data of model (9) and (10) showed that the difference between them with respect to pressure is not more than 2%, while the pressures on the isentropics differ by not more than 5%.

The difference between the data on the velocity of sound [12-14] in the region of uniform states and the data given by (9) and (10) does not exceed 1%, and in the region of the two-phase states it does not exceed 5%. The isochore heat capacity (15) differs from that given by (9) and (10) by not more than 5%.

Below we give as an illustration some theoretical data on the shock adiabat and the velocity of sound which is of interest for analyzing different gasdynamic problems.

Figure 1 shows the results of calculations of the shock adiabat of water (1-6 are the shock adiabatics starting from the region of the two-phase states for $p_0 = 10^5$ Pa and $v_0 = 0.1, 0.16, 0.2, 0.22, 0.5,$ and 1.0 m³/kg, respectively; 7 is the shock adiabat of water starting from the point of the normal state ($T_0 = 293^\circ\text{K}$ and $p_0 = 10^5$ Pa), 8 is the boundary of the two-phase region, and 9 is the asymptotic of the limiting compression for $v_0/v = 4$).

The results of calculations of the shock adiabat, starting from the normal state, can be approximated to within 2% by the relation

$$N/a_0 = a + bu/a_0,$$

where a_0 is the velocity of sound in the unperturbed medium (Table 3).

It is seen from Fig. 1 that the shock adiabatics, starting from the two-phase state, in a number of cases have an anomalous form: When the pressure is increased the degree of compression decreases. This effect is similar to the well-known shock compression effect of porous condensed media.

Under certain conditions the shock adiabatics from the region of the two-phase state enter the region of the condensed state and then return. It should be noted that in the limit at high pressures all the shock adiabatics approach a limiting fourfold compression with respect to the initial volume.

Figure 2 shows curves of the distribution of the velocity of sound along the two-phase curve both the two-phase side and from the uniform side (the continuous curves are our calculations, and the dashed curves are the results obtained in [14]; 1, critical point; 2, two-phase medium; 3, uniform medium; 4, gas; 5, condensed medium); it is seen that when changing from the condensed state into the two-phase region the velocity of sound decreases from 10^3 to $(1-10^2)$ m/sec.

From the gas side this transition is accompanied by a jump of several percent. From the gasdynamic point of view the boundary between the condensed state and the two-phase state is inert with respect to the propagation of small perturbations, which may lead to the occurrence of different flow singularities.

On the whole the comparison and the calculations carried out show that the interpolation functions obtained reflect quite satisfactorily the well-known thermodynamic properties of water and water vapor in the pressure range $p > 10^5$ Pa. Hence, the model can be used to solve different applied problems in the mechanics of continuous media, problems of the thermal conduction with phase transitions, etc.

LITERATURE CITED

1. M. H. Rice and J. M. Walsh, "Equation of state of water to 250 kbar," *J. Chem. Phys.*, 26, No. 4, 824 (1957).
2. N. M. Kuznetsov, "Equation of state and heat capacity of water over a wide range of thermodynamic parameters," *Zh. Prikl. Mekh. Tekh. Fiz.*, No. 1 (1961).
3. J. Juza, "An equation of state for water and steam," *Naklad. Čěskoslov. Acad. VĚD Praha* (1966).
4. M. P. Bukalovich, *Thermal Properties of Water and Water Vapor* [in Russian], Mashinostroenie, Moscow (1967).
5. B. V. Zamyshlyayev and M. S. Menzhulin, "Interpolation equation of state of water and water vapor," *Zh. Prikl. Mekh. Tekh. Fiz.*, No. 3 (1971).
6. L. D. Landau and E. M. Lifshits, *Statistical Physics* [in Russian], Nauka, Moscow (1964).
7. S. B. Kormer et al., "Dynamic compression of porous metals and the equation of state with variable heat capacity at high temperatures," *Zh. Ėksp. Teor. Fiz.*, 42, No. 3 (1962).
8. S. V. Bobrovskii, V. M. Gogolev, and B. V. Zamyshlyayev, "The construction of approximate shock adiabatics of solids in the hydrodynamic region," *Dokl. Akad. Nauk SSSR*, 184, No. 3 (1969).
9. R. Latter, "Temperature behavior of the Tomas-Fermi statistical model for atoms," *Phys. Rev.*, 29, No. 6 (1955).
10. V. P. Kopyshchev, "Gruneisen's constant in the Tomas-Fermi approximation," *Dokl. Akad. Nauk SSSR*, 161, No. 5 (1965).
11. A. A. Bakanova, V. V. Zubarev, Yu. N. Sutulov, and R. F. Trunin, "Thermodynamic properties of water at high pressures and temperatures," *Zh. Ėksp. Teor. Fiz.*, 68, No. 3 (1975).
12. L. S. Bark, P. P. Ganson, and N. A. Meister, "Tables of the velocity of sound in sea water," *Vychisl. Tsentr, Akad. Nauk SSSR, Moscow* (1961).
13. A. H. Smith and A. W. Lawson, "The velocity of sound in water as a function of temperature and pressure," *J. Chem. Phys.*, 22, No. 3 (1954).
14. V. V. Sychev, "Velocity of sound in water and water vapor on the saturation line," *Inzh.-Tekh. Zh.*, 4, No. 6 (1961).
15. A. M. Mamedov, "Equation of state, enthalpy, and heat capacity of water according to new international skeleton tables of water and water vapor," *Teplofiz. Vys. Temp.*, 6, No. 4 (1968).