2) particle cooling near the surface is quite substantial and amounts to 150-400°K for the first row from the wall at T_{ss} = 573°K and T_{bc} = 873-1498°K.

Thus, the results of the calculations and their comparison with experimental results make it possible to more rigorously determine the role of radiation in high-temperature heat exchange and the limits of the applicability of the hypothesis on the additivity of convective and radiative heat transfer.

NOTATION

σ, Stefan–Boltzmann constant; ε, degree of blackness; T, temperature, °K; r, reflection coefficients; τ, transmission factor; r_i, τ_i, reflection coefficients and transmission factors of i translucent planes, respectively; t, temperature, °C; r_i^+, r_i^-, reflection coefficients of i translucent planes and one of the planes bounding the system; q, heat flux, $W/m^2 \cdot deg\ C$; α, heat-transfer coefficient, $W/m^2 \cdot deg\ C$; W, number of fluidizations; α_p^*, interphase heat-transfer coefficient, $W/m^2 \cdot deg\ C$; y_p, distance between particles in d_p; d_p, particle diameter. Superscripts: +, flow in the direction of the bed core; −, flow in the direction of the wall; rad, radiative; inc, incident; subscripts: cr, corrected; e, effective; bc, core of the bed; ss, surface submerged in the bed; p, particles; con, conductive; r, radiant; Σ, total.

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HIGH-TEMPERATURE THERMAL CONDUCTIVITY OF NEON AT TEMPERATURES UP TO 5000°K AND ARGON UP TO 6000°K

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UDC 536.23

We fit the experimental data on the thermal conductivity of neon at temperatures of T = 600-5000°K and of argon for T = 500-6000°K.

In [1] we fitted the experimental data on the thermal conductivity of krypton and xenon at temperatures up to 5000°K and atmospheric pressure, and we showed that, starting from some value of the temperature, the thermal conductivity of these gases can be represented by a power equation with a specified value of the exponent for T. In the present paper we conduct a similar examination of neon and argon.

Neon. The available experimental studies on the thermal conductivity of neon at atmospheric pressure in high temperature ranges are shown in Table 1. It can be seen from Table 1 that up to 2700°K the thermal conductivity of neon has been measured by various methods: for T > 2700°K there are, as yet, only the data of [2], obtained by means of a shock tube.

Figure 1 shows the available experimental data (Table 1) in coordinates of log λ vs log T. It can be seen that in the 600-5000°K range the experimental results lie close to a straight line. This indicates that in this temperature range the thermal conductivity of neon can be described by a power equation with a constant value of the exponent of T.

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TABLE 1. Studies on the Thermal Conductivity of Neon at High Temperatures

Year	Author	Literature source	Method of investigation	Temp. range, °K	Error, % (as estimated by authors)
1959	Zaitseva	[12]	Hot wire	413—800	—
1966	Collins and Menard	[2]	Shock tube	1500—5000	12
1968	V. K. Saxena and S. C. Saxena	[9]	Heat-conduction column	373—1473	2
1971	Vargaftik and Yakush	[10]	Hot wire	310—1073	2,2
1973	Springer and Wingeier	[3]	Heat-conduction column	1000—1500	3,2
1974	Jain and Saxena	[4]	Same	273—1650	2
1974	Jain and Saxena	[5]	"	400—2400	1,5
1975	Jody and Saxena	[6]	"	323—2723	2
1976	Stefanov, Zarkova, and Oliver	[8]	"	1100—2200	3
1976	Nain, Aziz, Jain, and Saxena	[7]	"	300—2600	2—3
1977	Marchenkov and Aleinikova	[11]	Hot wire	400—1500	2—4

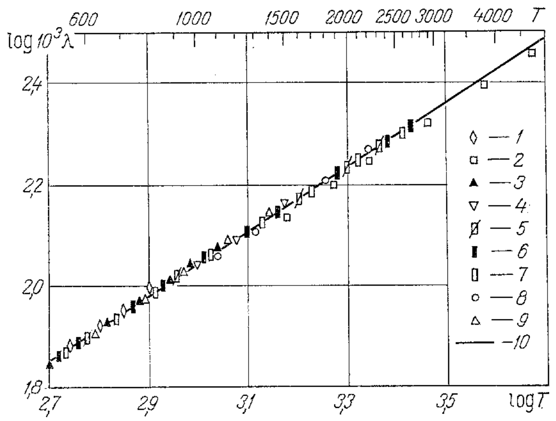

Fig. 1. Thermal conductivity of neon from the data of: 1) Zaitseva [12]; 2) Collins and Menard [2]; 3) Vargaftik and Yakush [10]; 4) Springer and Wingeier [3]; 5) Jain and Saxena [5]; 6) Jody and Saxena [6]; 7) Nain et al. [7]; 8) Stefanov et al. [8]; 9) Marchenkov and Aleinikova [11]; 10) (1); λ, $W \cdot m^{-1} \cdot °K^{-1}$; T, °K.

For T < 600°K the experimental results lie well below the straight line obtained for T > 600°K. Consequently, at temperatures below 600°K the variation of the thermal conductivity of neon as a function of temperature is different.

Figure 1 shows good agreement of all the available high-temperature experimental data obtained by various authors [3-9] on various types of equipment, using stationary methods: the deviation does not exceed the admissible values of the experimental error.

The most detailed investigation of the thermal conductivity of neon in the 600-2700°K range was conducted by Saxena et al. [4-7, 9] using the heat-conduction column method; the results of the later investigations [4-7] practically confirmed the original data of [9]. In this research a great deal of attention was devoted to the experimental study of the fundamental corrections introduced in the determinations of the heat flux through the gas layer investigated. The results concerning the thermal conductivity of neon that were obtained by the Saxena group agree, to within the limits of measurement error, with the data of other investigations using the hot-wire method [10, 11] and the heat-conduction column method [3, 8].

High-temperature experimental data on the thermal conductivity of neon were first obtained with a shock tube [2]. As can be seen from Fig. 1, they lie approximately 4% below the results of all subsequent studies. This systematic displacement is observed over a fairly wide range (1500-2700°K) in which the temperature intervals of the shock-tube investigations [2] overlap with those of the heat-conduction column investigations [3-8]. This downward deviation, as in the case of krypton [1], is essentially due to the fact that the authors of [2] used a power function of temperature as the thermal conductivity of neon, beginning at 300°K. As noted above, this is unjustified for the case of neon.

An analysis of the experimental data showed that at atmospheric pressure, in the 600-5000°K range, the thermal conductivity of neon can be represented by the power equation

$$\lambda = 0.0801 \left(\frac{T}{600}\right)^{0,630} \quad [W \cdot m^{-1} \cdot °K^{-1}]. \tag{1}$$

TABLE 2. Thermal Conductivity of Neon and Argon, $\lambda \cdot 10^3$, $W \cdot m^{-1} \cdot {}^\circ K^{-1}$

T, K	Ne	Ar	T, K	Ne	Ar
500		26,9	2600	202	81,9
600	80,1	30,4	2700	206	84,1
700	88,3	33,8	2800	211	86,2
800	96,0	37,0	2900	216	88,2
900	104	40,1	3000	221	90,2
1000	111	43,0	3200	230	94,3
1100	118	45,8	3400	239	98,1
1200	124	48,6	3600	248	102
1300	131	51,2	3800	257	106
1400	137	53,9	4000	265	109
1500	143	56,5	4200	273	113
1600	149	59,0	4400	281	117
1700	155	61,4	4600	289	120
1800	160	63,9	4800	297	123
1900	166	66,3	5000	305	127
2000	171	68,6	5200		131
2100	176	70,9	5400		134
2200	182	73,1	5600		137
2300	187	75,3	5800		141
2400	192	77,5	6000		144
2500	197	79,7			

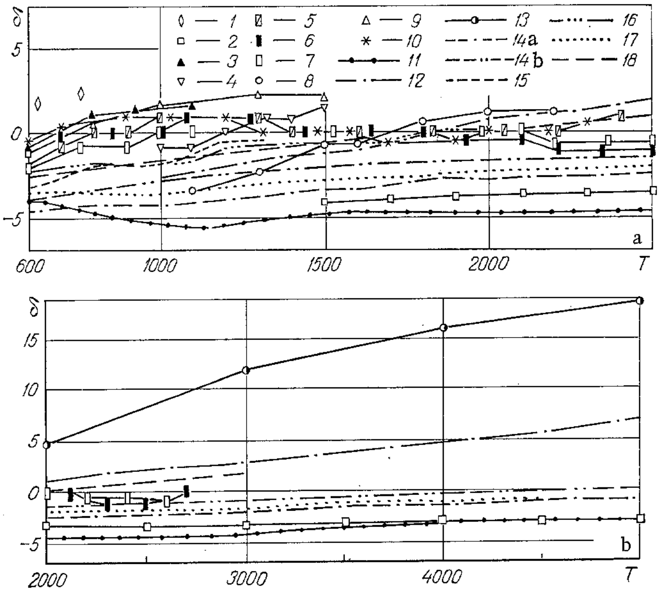

Fig. 2. Deviation $\delta = (\lambda - \lambda_p)/\lambda_p$, %, from the generalization for neon using the power equation (1), according to the data of: 1-9) same notation as in Fig. 1; 10) Vargaftik, Filippov, et al. [14]; 11) Touloukian et al. [13]; 12) Amdur and Mason [16]; 13) Kamnev and Leonas [20]; 14) Swehla [18] (a, from viscosity; b, from thermal conductivity); 15) Rabinovich [15]; 16) Watson [17]; 17) Sevast'yanov and Zykov [19]; 18) Jody, Saxena, et al. [21].

The error in the values of the thermal conductivity of neon calculated by formula (1) is 2% for T = 600-2500°K and 4% for T > 2500°K. The values of the thermal conductivity of neon calculated by the generalized equation (1) are shown in Table 2.

In Fig. 2a, b we show the deviation of the experimental data available in the literature from formula (1). The data of Zaitseva [12] in the high-temperature range and the results of the later work by Stefanov et al. [8] for T = 1100-1200°K show a deviation of up to 3% from Eq. (1). The results of other studies using stationary methods deviate by up to 1-2% from Eq. (1).

TABLE 3. Studies on the Thermal Conductivity of Argon at High Temperatures

Year	Author	Literature source	Method of investigation	Temp. range, °K	Error, % (as estimated by the authors)
1955	Rothman and Bromley	[24]	Coaxial cylinders	273—1073	—
1957	Schafer and Reiter	[25]	Hot wire	273—1379	—
1957	Smiley	[30]	Shock tube	1100—3300	8
1959	Zaitseva	[12]	Hot wire	316—800	—
1960	Vines	[35]	Coaxial cylinders	533—1173	—
1964	Vargaftik and Zimina	[26]	Hot wire	373—1200	2,5
1964	Lauver	[31]	Shock tube	665—8580	—
1966	Timrot and Umanskii	[29]	Heat-conduction column	800—2000	7
1966	Collins and Menard	[2]	Shock tube	1500—5000	12
1968	V. K. Saxena and S. C. Saxena	[27]	Heat-conduction column	350—1500	2
1968	Matula	[23]	Shock tube	1500—4800	—
1968	Kmonicek, Mastovsky, and Malesak	[33]	Same	1000—9000	10
1970	Polyakov and Spirin	[34]	"	1000—5000	—
1972	Gorshkov and Umanskii	[36]	Pulsed heating	343—1102	2,5
1972	Zemlyanikh	[32]	Shock tube	1000—6000	20
1973	Springer and Wingeier	[3]	Heat-conduction column	800—2500	4
1975	Chen and Saxena	[28]	Same	350—2500	1,5
1976	Nain, Aziz, Jain, and Saxena	[7]	"	400—2600	2—3
1976	Stefanov, Zarkova, and Oliver	[8]	"	1100—2200	3

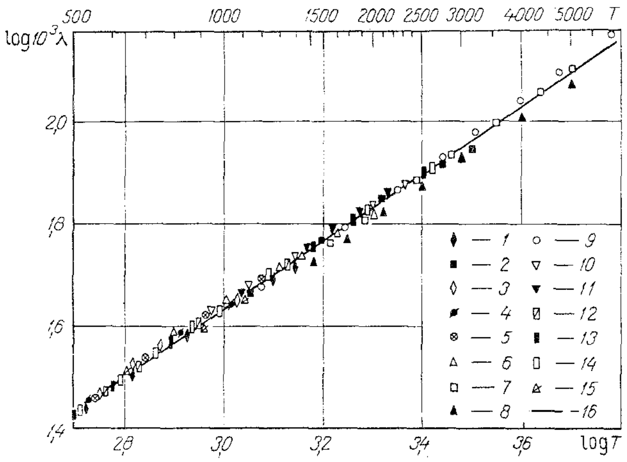

Fig. 3. Thermal conductivity of argon according to the data of: 1) Schäfer and Reiter [25]; 2) Smiley [30]; 3) Zaitseva [12]; 4) Vines [35]; 5) Vargaftik and Zimina [26]; 6) Timrot and Umanskii [29]; 7) Collins and Menard [2]; 8) Matula [23]; 9) Zemlyanykh [32]; 10) Springer and Wingeier [3]; 11) Stefanov et al. [8]; 12) S. C. Saxena and V. K. Saxena [27]; 13) Chen and Saxena [28]; 14) Nain et al. [7]; 15) Gorshkov and Umanskii [36]; 16) (2); λ, $W \cdot m^{-1} \cdot °K^{-1}$; T, °K.

An analysis of all the experimental data on the thermal conductivity of neon shows that in the T = 600-5000°K range the results of the investigations on this gas have fairly high reliability. Therefore neon can be recommended as a standard gas for the calibration of apparatus used in investigations of heat conduction in the range of high temperatures.

Figure 2 shows the deviations from Eq. (1) found in the results of the most widely known generalizations of the thermal conductivity of neon by Touloukian et al. [13], Vargaftik et al. [14], and Rabinovich [15]. The results of the fit in [13] are, on the average, 5% lower. The values of the thermal conductivity of neon given in [14] agree to within 1% with results of the generalizations of the present study. The recommended values given in [13] up to 1000°K are 2-3% lower; as the temperature increases, the deviation decreases to 0.5% at 1300°K.

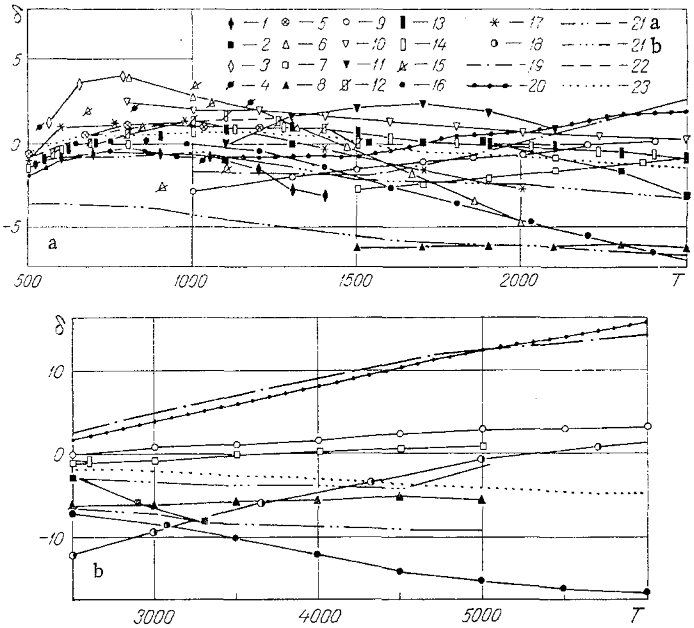

Fig. 4. Deviation $\delta = \lambda - \lambda_p / \lambda_p$, %, from Eq. (2) for argon according to the data of: 1-15) same notation as in Fig. 3; 16) Lauver [31]; 17) Vargaftik et al. [14]; 18) Kamnev and Leonas [20]; 19) Amdur and Mason [16]; 20) Touloukian et al. [13]; 21) Swehla [18] (a, from viscosity; b, from thermal conductivity); 22) Rabinovich [15]; 23) Sevast'yanov and Zykov [19].

A number of calculation studies on the thermal conductivity of neon at high temperatures are available today [16-21]. It can be seen from Fig. 2 that the results of the calculations carried out on the basis of the strict kinetic theory of gases [22], in which the parameters of the selected potential functions for the interatomic interaction are determined from the experimental data on viscosity or thermal conductivity [17, 18, 21] or some complex of properties [19], are in satisfactory agreement with the generalized experimental data based on the power equation (1). The calculated results in most cases lie somewhat below the experimental values: at temperatures of 600-1000°K they are 2-3% lower and as the temperature increases the divergence decreases. Amdur and Mason's calculated results [16], obtained on the basis of experiments on the scattering of atomic beams, deviate from Eq. (1) by an amount which lies within the limits of error, estimated by the authors at 10%. The calculated results of Kamnev and Leonas [20], also obtained on the basis of experiments relating to the scattering of gas beams, at a temperature of 3000°K are about 12% lower than the generalization (1); as the temperature increases, the divergence increases to 18% at 5000°K.

Argon. Among all the inert gases, argon has been the subject of the most detailed investigations relating to thermal conductivity at high temperatures. This is confirmed by Table 3, which lists the available experimental studies on measurements of the thermal conductivity of argon at high temperatures and nearly atmospheric pressure.

The experimental data on the thermal conductivity of argon are shown in logarithmic coordinates in Fig. 3. It can be seen from Fig. 3 that the results of the various investigations in the 500-6000°K range lie close to a straight line. Only the data of Matula's study [23], obtained on an apparatus using a shock tube, show values of λ which are systematically 5-6% lower. It follows from this that in the indicated temperature range the variation of the thermal conductivity of argon as a function of temperature is given by a power function. Below 500°K this function changes, since the experimental data deviate to the area below the straight line observed for $T > 500$°K.

The first experimental data on the thermal conductivity of argon at high temperatures, obtained by Rothman and Bromley [24], were presented by the authors only in graphical form, and they are difficult to compare with the experimental values of other investigators. In [25] the results obtained for temperatures above 1200°K are too low. This is pointed out by the authors of [26], who carefully analyzed all the corrections in the hot-wire method. Special attention was given to the determination of the correction for the temperature discontinuity, which becomes substantial at high temperatures. The unduly low experimental values of the thermal conductivity of argon found in [25] were the result of disregarding this correction.

The results of the investigations carried out by the heat-conduction column method [3, 7, 8, 27, 28] agree quite satisfactorily with one another: the divergence is within the 2-4% error limits indicated in these studies. The data of the first study [29] on argon carried out by this method, for the entire temperature range investigated, increase slowly as temperature increases, and at 2000°K the values are 4-5% lower than the experimental results obtained by other, later investigations. However, even in this case the divergence does not exceed the limits of the allowable experimental error in [29], estimated by the authors at 7%.

Of special interest are the latest investigations on the thermal conductivity of argon, carried out by the heat-conduction column method under the leadership of Saxena [7, 28] in the 350-2600°K range. In these studies the fundamental corrections of the method were investigated experimentally. It can be seen from Fig. 3 that the data obtained in the studies are in good agreement with the results of the detailed investigations made in [26] by the hot-wire method: in the region of overlap of the temperature ranges investigated, the divergence is no more than 2%.

In addition to stationary methods, shock tubes were repeatedly used for measuring the thermal conductivity of argon. As can be seen from Fig. 3, the results of the first investigation of the thermal conductivity of argon using a shock tube, carried out by Smiley [30], agree quite satisfactorily with the data obtained by stationary methods up to 2000°K, while at higher temperatures Smiley's data are too low. The results of the second study using a shock tube [31], beginning at 1500°K, vary only very slightly with temperature (Fig. 4). It should be noted that these were the first studies measuring the thermal conductivity of gases at high temperatures by means of shock tubes, and the method used for carrying out the measurements and processing the results had not yet been perfected. This apparently could have been the reason for the marked downward error of the data of [31] at high temperatures, and this is also the reason that Smiley [30] limited his experiments to 3300°K.

The experimental data of subsequent studies on argon using shock tubes [2, 32] are in good agreement with the results obtained by stationary methods. In studies using shock tubes [33, 34] the exploratory results concerning the thermal conductivity of argon were presented only in graphical form, and it is difficult to use them for comparison.

An analysis of all the available experimental data on the thermal conductivity of argon showed that in the 500-6000°K range, at atmospheric pressure, they can be described by the power law

$$\lambda = 0.0269\,(T/500)^{0.675}\ [\mathrm{W \cdot m^{-1} \cdot {}^\circ K^{-1}}]. \quad (2)$$

The error in the estimate of the thermal conductivity of argon according to Eq. (2) is 3% when T = 500-2500°K and 5% for T > 2500°K. The values of the thermal conductivity of argon calculated by Eq. (2) are shown in Table 2.

Figure 4 shows the deviations from Eq. (2) for the experimental data available in the literature (Table 3). Figure 4 also shows the divergence between the generalization by Eq. (2) and the results of the known generalizations of experimental data on the thermal conductivity of argon [13-15].

The data of the handbook by Touloukian et al. [13] differs from Eq. (2) by about 1% up to 2000°K; for T > 2000°K the deviation gradually increases to 18% at 6000°K. The reason for this is that when the authors of [13] were working on their handbook, they had for T > 2000°K only data on argon which were obtained by calculation from experiments on scattering [16], and these proved to be too high for high temperature values.

The results of the generalization obtained by Vargaftik et al. [14] agree with Eq. (2) within 1% up to 1500°K, and as the temperature increases, the divergence increases to 2.8% at 2000°K. The generalized data on the thermal conductivity of argon in [15] deviate from Eq. (2) by no more than 2%.

Figure 4 also shows the deviations of the results of other calculation studies on the thermal conductivity of argon at high temperatures. Investigations carried out by Kamnev and Leonas [20], analogous to [16], yielded results which were 15% lower, on the average, than those of [16]. These data in [20] lie 15% below those of Eq. (2) at 2000°K, and as the temperature increases, the deviation decreases to zero at 5500°K.

The calculations carried out by Swehla [18], using experimental data on viscosity, yield values 5-9% lower than Eq. (2). Similar calculations carried out in [18] by using the parameters of the potential (12-6), found from experimental data on the thermal conductivity of argon given in [25], yielded better results. The calculated values obtained by Watson [17] over the entire 500-2100°K range deviate from Eq. (2) by less than 1%. The deviation of the calculated data of Sevast'yanov and Zykov [19] is no more than 2% up to 3000°K, while for T > 3000°K the deviation increases to 5% at 6000°K.

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EQUATIONS OF GENERALIZED THERMOELASTICITY OF A COSSERAT MEDIUM IN STRESSES

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UDC 539.377

Thermoelasticity equations in stresses are derived in this paper for a Cosserat medium taking into account the finiteness of the heat propagation velocity. A theorem is proved on the uniqueness of the solution for one of the obtained systems of such equations.

The development of experimental investigation of the interaction between optical radiation and a substance evokes interest in a detailed study of the thermoelastic phenomena occurring in solids subjected to laser radiation. Such radiation requires taking account of the finiteness of the heat propagation velocity in connection with the quite rapid nature of the heat liberation process. Taking this circumstance into account requires insertion of an additional term in the Fourier heat conduction law, as is assumed in, e.g., [1, 2]. The polycrystalline or granular construction of many materials used in force optics evokes a requirement to involve a nonsymmetric Cosserat model in the analysis, which describes the behavior of such media more accurately under deformation [3]. The equations of isothermal nonsymmetric elasticity theory have been investigated in detail in [4-6]. The papers [7-9] and a section of the monograph [3] are devoted to the theory of nonsymmetric thermoelasticity without taking account of the finiteness of the heat propagation velocity. The equations of generalized thermoelasticity of a Cosserat continuum have been obtained in [10]. The system of equations in the displacement vector $\mathbf{u}$, the small rotation vector $\boldsymbol{\omega}$, and the relative temperature deviation ϑ from the initial value Θ_0 has the form

$$
\begin{gathered}
(\mu+\alpha)\nabla^2\mathbf{u}+(\mu-\alpha+\lambda)\nabla\nabla\cdot\mathbf{u}+2\alpha\nabla\times\boldsymbol{\omega}+\mathbf{X}-\nu\Theta_0\nabla\vartheta=\rho\ddot{\mathbf{u}};\\
(\gamma+\varepsilon)\nabla^2\boldsymbol{\omega}+(\gamma-\varepsilon+\beta)\nabla\nabla\cdot\boldsymbol{\omega}+2\alpha\nabla\times\mathbf{u}-4\alpha\boldsymbol{\omega}+\mathbf{Y}=\mathbf{I}\cdot\ddot{\boldsymbol{\omega}};\\
k\nabla^2\vartheta-\tau_0 m\Theta_0\dot{\vartheta}-m\Theta_0\dot{\vartheta}-\nu\tau_0\nabla\cdot\ddot{\mathbf{u}}-\nu\nabla\cdot\ddot{\mathbf{u}}=-\Theta_0^{-1}w-\tau_0\Theta_0^{-1}\dot{w};\\
\vartheta=(\Theta-\Theta_0)\Theta_0^{-1}.
\end{gathered}
\tag{1}
$$

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