DETERMINATION OF THE CHARACTERISTICS OF THERMOACOUSTIC PRESSURE OSCILLATIONS ASSOCIATED WITH HEAT TRANSFER IN A VARIABLE DUCT WITH ARBITRARY ENERGY INPUT

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The thermoacoustic pressure oscillations associated with heat transfer in a turbulent flow of a fluid at supercritical pressure is investigated theoretically. The characteristics of the thermoacoustic pressure oscillations as a function of the regime parameters of the process are determined.

The heat-transfer process in a fluid at supercritical pressure in the case of turbulent flow of a heat-transfer medium and large heat fluxes is often accompanied by thermoacoustic pressure oscillations (TAPO). This effect is observed when the temperature of the heating surface acquires pseudocritical values and the flow core has a temperature far from the critical. Calculations show that a fluid layer with a low sound velocity exists near the wall in this regime. On the basis of the conjecture that the existence of a wall layer of fluid with an elevated compressibility is the cause of the onset of TAPO and the enhancement of heat transfer, it has been possible to formulate physical and mathematical models of the process in application to ducts of constant cross section with a constant heat input along its length. Formulas describing the dynamical and thermal fields in the first approximation and taking into account the variation of the sound velocity within the duct cross section are proposed in [1]. The results of a theoretical determination of the domain of instability of the heat-transfer process are given in [2, 3]. Relationships have been established between the frequencies and amplitudes of the oscillations, on the one hand, and the hydrothermodynamic conditions existing in a constant duct, on the other [3]. The influence of the sound field on the heat transfer has been investigated [4, 5].

Real heat exchangers frequently have heating elements of complex geometrical configuration in which the energy input varies in an arbitrary way. To determine the velocity and pressure fields in the general case, it is necessary to solve a multidimensional nonlinear problem, which is attended by mathematical difficulties. However, the hydraulic lines can be treated as one-dimensional of a variable cross section. We assume in this case that the variation of the duct area is small over one wavelength of the acoustic disturbance. This condition can be written formally as follows:

$$\frac{1}{F}\frac{dF}{dx}\frac{2\pi c_s}{\omega}=\varepsilon_2\ll 1. \quad (1)$$

We assume that all the parameters of the process can be represented in the form

$$z^{(i)}=z_0^{(i)}+z_1^{(i)}. \quad (2)$$

We consider the steady-state Mach number M_0 and the acoustic Mach number $M_1 = \varepsilon_1$ to be small. We assume that the frequencies of the TAPO are so high that the parameters in the wave $z^{(i)}_1$ have appreciable transverse gradients only in the immediate vicinity of the wall ($\bar{\beta}_1 \gg 1$).

A major simplification of the stated problem is achieved by transforming from the multidimensional to one-dimensional differential equations by means of integration over the cross section of the duct and transformation to the average parameters $\bar{z}^{(i)}$. In the integration we let

$$\overline{z^{(i)}z^{(j)}}\approx\overline{z^{(i)}}\;\overline{z^{(j)}};\quad \overline{\mu^{(i)}z^{(j)}}\approx\overline{\mu^{(i)}}\;\overline{z^{(j)}}, \quad (3)$$

where $\mu^{(i)}$ is some thermophysical parameter.

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Equations (3) are approximately valid by the assumption of a weak dependence of $z^{(i)}_1$ and $z^{(i)}_0$ on the transverse coordinate outside the acoustic boundary layer and the laminar sublayer, which have small relative dimensions.

Below, we consider the problem in the second approximation with respect to ε_1. We restrict the formulation of the basic system of equations to squared terms in the velocity, pressure, and density and to linear terms in the entropy. This is associated with the fact that the linear-entropy term in the equation of state is a second-order small term. In the energy equation we neglect the work done by the forces of viscosity and pressure. Then the basic system acquires the form

$$\dot{\bar{\rho}}_1 + (\rho_{0f} + \bar{\rho}_1)\,\bar{U}' + \bar{U}\bar{\rho}_1' = 0, \tag{4}$$

$$F(\rho_{0f} + \bar{\rho}_1)\dot{\bar{U}} + \rho_{0f}F\,\bar{U}\,\bar{U}' - \rho_{0f}F\,\langle \bar{U}_1\bar{U}_1' \rangle = -F\bar{P}_1' + \left(\mu_3 + \frac{4}{3}\mu_2\right)(\bar{U}_1F)'' + \Phi_8, \tag{5}$$

$$F\dot{\bar{S}}_1 = \frac{\chi_f}{\rho_{0f}T_{0f}}\,(\bar{T}_1F)'' + \dot{\Phi}_7, \tag{6}$$

$$\bar{P}_1 = \rho_{0f}c_{sf}^2\left(\frac{\bar{\rho}_1}{\rho_{0f}} + \frac{\Gamma_f - 1}{2}\left(\frac{\bar{\rho}_1}{\rho_{0f}}\right)^2\right) + \left(\frac{\partial P}{\partial S}\right)_\rho \bar{S}_1, \tag{7}$$

where

$$\dot{\Phi}_7 = \frac{\chi_w}{\rho_{0f}T_{0f}} \oint_\Pi \frac{\partial T_1}{\partial n}\, d\Pi \tag{8}$$

$$\Phi_8 = \mu_{2w} \oint_\Pi \frac{\partial U_1}{\partial n}\, d\Pi. \tag{9}$$

The fundamental hypothesis underlying the ensuring arguments is expressed in the inequality

$$\varepsilon_1 \ll \varepsilon_2 \ll 1. \tag{10}$$

It states that the scale of variation of the duct area is smaller than the scale of the wave distortion due to nonlinearity and dissipation.

The system (4)-(7) enables us to derive the basic equation by a procedure similar to that described in [3]. We note that the quantity F in the nonlinear and viscosity terms can be taken outside the derivative, because this operation induces terms of the order of $\varepsilon^2_1\varepsilon_2$, which are neglected.

From now on we omit the bar over the parameters averaged over the cross section. We then obtain

$$\ddot{U} - c_{sf}^2\left(\frac{(UF)'}{F}\right)' = -\frac{1}{\rho_{0f}}(\rho_1\ddot{U} + \dot{\rho}_1\dot{U} + \rho_{0f}\dot{U}U' + \rho_{0f}U\dot{U}') + \frac{c_{sf}^2}{\rho_{0f}}((\rho_1U')' + (U\rho_1')') + (\Gamma_f - 1)\frac{c_{sf}^2}{\rho_{0f}^2}(\rho_1\dot{\rho}_1)' + \frac{\gamma - 1}{\alpha_{pf}}\frac{\dot{\Phi}_7'}{F} + \frac{b}{\rho_{0f}}\dot{U}_1'' + \frac{1}{\rho_{0f}}\frac{\dot{\Phi}_8}{F}, \tag{11}$$

where $b = \mu + \frac{4}{3}\mu_2 + \frac{\chi_f(\gamma - 1)}{c_{pf}}$.

We investigate Eq. (11) by the multiple-scale method [6]. We introduce the new functions and variables

$$x_m = \varepsilon_1^m x, \quad m = 0,\ 1,\ \ldots,\ N, \tag{12}$$

$$z_1 = \sum_{m=1}^{N+1} \varepsilon_1^m z_{m0}(x_0,\ x_1,\ \ldots,\ x_N,\ t). \tag{13}$$

Consolidating terms of the order of ε_1 and $\varepsilon_2\varepsilon_1$, we obtain an equation describing the influence of the duct geometry on wave propagation:

$$\frac{1}{c_{sf}^2}\frac{\partial^2(U_{10}F)}{\partial t^2}+\frac{1}{F}\frac{dF}{dx_0}\frac{\partial(U_{10}F)}{\partial x_0}-\frac{\partial^2(U_{10}F)}{\partial x_0^2}=0. \tag{14}$$

We seek a solution of Eq. (14) in the form of a series in the TAPO frequency:

$$U_{10}F=\exp(i\omega(t-\sigma(x_0)))\sum_{k=0}^{\infty}H_k(x_1,\ x_0)(i\omega)^{-k}. \tag{15}$$

Substituting (15) in (14) and equating terms in like powers of $i\omega$, we arrive at the solution

$$U_{10}=\sum_{n=1}^{\infty}(H_{1n}(x_1)\chi_{1n}(x_0)\exp(in\tau_1)+H_{2n}(x_1)\chi_{2n}(x_0)\exp(in\tau_2)), \tag{16}$$

where

$$\chi_{jn}(x_0)=\left(1+i(-1)^j\frac{c_{sf}}{2n\omega}\int_0^{x_0}D(\eta)\,d\eta-\frac{c_{sf}^2}{4n^2\omega^2}\left(D(x_0)+\frac{1}{2}\left(\int_0^{x_0}D(\eta)\,d\eta\right)^2\right)+\ldots\right)\cdot\frac{1}{\sqrt{\overline{F}}},\quad j=1,\ 2; \tag{17}$$

$$D(x_0)=\frac{1}{2\overline{F}}\frac{d^2\overline{F}}{dx_0^2}-\frac{3}{4}\frac{1}{\overline{F}^2}\left(\frac{d\overline{F}}{dx_0}\right)^2,\ \overline{F}=F/F_0.$$

We note that the quantity F_0 in the foregoing expression is arbitrary.

To obtain the second-approximation equation, it is necessary to substitute expressions (12) and (13) in (11) and to consolidate terms of the order of ε^2_1. In transforming the nonlinear components of expression (11) we can regard U_{10} and ρ_{10} as depending only on τ_j. The differentiation of the function χ_{jn} with respect to x_0 and of the function H_{jn} with respect to x_1 induces on the right-hand side of (11) terms of the order of $\varepsilon^2_1\varepsilon_2$ and ε^3_1, which are disregarded. Setting $U_{10} = U_{11}(x_1,\ \tau_1) + U_{12}(x_1,\ \tau_2)$ and carrying out transformations similar to those in [3], we obtain the equation

$$4\frac{\partial^2U_{20}}{\partial\tau_1\partial\tau_2}=\frac{\partial L_1(U_{11})}{\partial\tau_1}-\frac{\partial L_2(U_{12})}{\partial\tau_2}+l_3(U_{11},\ U_{12}), \tag{18}$$

where

$$L_j(U_{1j})=2\frac{\partial U_{1j}}{\partial\tilde{x}_1}-\frac{\Gamma_f+1}{c_{sf}}U_{1j}\frac{\partial U_{1j}}{\partial\tau_j}+(-1)^j\frac{b\omega}{\rho_{0f}c_{sf}}\frac{\partial^2U_{1j}}{\partial\tau_j^2}-$$
$$-\frac{\gamma-1}{\alpha_{pf}c_{sf}F}\frac{\partial\Phi_7}{\partial\tau_j}+(-1)^j\frac{1}{\rho_{0f}\omega}\frac{\Phi_8}{F},\quad j=1,\ 2; \tag{19}$$
$$l_3(U_{11},\ U_{12})=\frac{\Gamma_f-3}{c_{sf}}\left(U_{11}\frac{\partial^2U_{12}}{\partial\tau_2^2}-U_{12}\frac{\partial^2U_{11}}{\partial\tau_1^2}\right).$$

We assume that the functions U_{1j} are bounded together with their primitives and first and second derivatives; Φ_7 and Φ_8 are also bounded and can be represented in the form $\Phi_j = \Phi_{j1}(x_1,\ \tau_1) + \Phi_{j2}(x_1,\ \tau_2)$. Under these conditions it can be proved that Eq. (18) is equivalent to three equations, two of which are analogous to the equations for nonlinear traveling waves:

$$L_1(U_{11})=0,\quad L_2(U_{12})=0, \tag{20}$$

and one equation that characterizes the interaction of traveling waves:

$$4\frac{\partial^2U_{20}}{\partial\tau_1\partial\tau_2}=l_3(U_{11},\ U_{12}).$$

We note that the indicated proof establishes a fact equivalent to the elimination of secular terms from the expansion by the multiple-scale method.

Equations (20) differ from their counterparts in [3] by the inclusion of derivatives of the form $\partial U_{1j}/\partial\tilde{x}_1$, which make it possible to treat the expressions Φ_7 and Φ_8 as functions of the coordinate x_1, i.e., to take into account their variation along the length of the duct. This amounts to taking into account the variation of the energy input.

The functions Φ_7 and Φ_8 characterize the thermal and dynamical interaction of the acoustic disturbance with the heating surface and can be determined from the known two-dimensional velocity and temperature fields in a harmonic wave [1]. We assume that the eigenfunctions of Eq. (14) are nearly harmonic. The explicit expressions for the required functions, obtained on the assumption that the acoustical parameter $\bar{I}_T \gg 1$, have the form

$$\frac{\Phi_{8jn}}{\omega\rho_{0f}F} = -\frac{1+i}{2\bar{\beta}_1}\sqrt{n}\, U_{1j}\exp(in\tau_j), \tag{21}$$

$$\frac{(\gamma-1)\Phi_{7jn}}{\alpha_{pf}c_{sf}F} = -\frac{(-1)^j\bar{\varkappa}_0\bar{I}_T}{2\bar{\beta}_1\sqrt{n}}(\bar{\theta}_1(\varphi_n)+i\bar{\theta}_2(\varphi_n))U_{1j}\exp(in\tau_j), \tag{22}$$

where

$$\bar{\varkappa}_0 = \frac{(\gamma-1)T_{\text{кр}}c_{pw}\bar{\gamma}_3}{\alpha_{pf}T_{0f}c_{sf}^2(\bar{\gamma}_1+\bar{\gamma}_3)};$$

$$\bar{\theta}_1(\varphi_n) = \exp(-\varphi_n)\left(\cos\varphi_n - \left(1+\frac{1}{\varphi_n}\right)\sin\varphi_n\right);$$

$$\bar{\theta}_2(\varphi_n) = \frac{1}{\varphi_n}(1-\exp(-\varphi_n)\cos\varphi_n) - \exp(-\varphi_n)(\cos\varphi_n+\sin\varphi_n).$$

The parameter φ_n represents the ratio of the thickness δ_1 of the laminar sublayer, which depends on the local velocity U_0, to the thickness of the acoustic boundary layer, which is defined as $1/(\gamma_1\sqrt{n}) = \sqrt{2a_{1w}/(n\omega_0)}$. We assume that a wave of arbitrary profile is expanded in a series in harmonic functions. Then the interaction function can be represented in the form of series or integrals.

Expressions (21) and (22) can be used to write Eqs. (20) in the developed form

$$2(-1)^{j+1}\frac{\partial M_j}{\partial\tilde{x}_1} - \frac{\Gamma_f+1}{2}\frac{\partial M_j^2}{\partial\tau_j} - D_0\frac{\partial^2 M_j}{\partial\tau_j^2} + \frac{1}{2\pi}\int_0^{2\pi}P(\tilde{x}_1,\ \tau_j-\zeta)M_j(\tilde{x}_1,\ \zeta)\,d\zeta = 0, \tag{23}$$

where

$$P(\tilde{x}_1,\ \eta) = \sum_{n=1}^{\infty}2n(\tilde{C}_{n1}(\tilde{x}_1)\sin n\eta + \tilde{C}_{n2}(\tilde{x}_1)\cos n\eta);$$

$$\tilde{C}_n = \tilde{C}_{n1}+i\tilde{C}_{n2} = \frac{1}{2\sqrt{n}\,\bar{\beta}_1}(-(1+\bar{\varkappa}_0\bar{I}_T\bar{\theta}_{1n}) + i(1-\bar{\varkappa}_0\bar{I}_T\bar{\theta}_{2n})).$$

Calculations show that the term containing the factor $D_0 = b\omega/(\rho_0 fc^2 st)$ can be neglected by virtue of its smallness.

We seek a solution of Eqs. (23) in the series form (16), in which we take $\chi_{jn} = 1/\sqrt{F}$. The inclusion of the terms rejected in expressions (17) induces terms of the order of $\varepsilon^2{}_1\varepsilon_2$ in the second-approximation equations (23). The substitution of expression (16) in (23) yields the system of ordinary differential equations

$$2(-1)^{j+1}\frac{dH_{jn}}{d\tilde{x}_1} - in\frac{\Gamma_f+1}{2}\frac{Q_{jn}}{\sqrt{F}} - inH_{jn}\tilde{C}_n = 0,\quad j=1,\ 2, \tag{24}$$

where

$$Q_{j,\,2r-1} = \sum_{p+k=2r-1}H_{jp}H_{jk} + \sum_{m-l=2r-1}H_{jm}H_{jl}^*;$$

$$Q_{j,\,2r} = \sum_{\substack{p+k=2r\\ p\neq k}}H_{jp}H_{jk} + \frac{H_{jr}^2}{2} + \sum_{m-l=2r}H_{jm}H_{jl}^*. \tag{25}$$

The system (24) is solvable, subject to specification of the boundary conditions. We consider the elementary case where the duct contains two obstacles, each of which provides total internal reflection of the propagating wave. We assume for definiteness that the ends of the duct with the coordinates $\tilde{x}_1 = 0$ and $\tilde{x}_1 = \tilde{x}_{10}$ are closed. Then the boundary conditions take the form

$$H_{2n}(0) = H_{1n}(0), \tag{26}$$

$$H_{2n}(\tilde{x}_{10}) = H_{1n}(\tilde{x}_{10}) \exp(-2in\tilde{x}_{10}). \tag{27}$$

We now estimate the order of magnitude of the variation of the quantities H_{jn} in a section of the duct of length x_{10}. We consider the steady-state wave process, where the amplitude of the oscillations does not depend on the initial disturbances (limit cycle). Then the terms of Eqs. (24) must be of the same order of smallness, which means that the following estimates are valid:

$$\frac{\Delta H_{jn}}{H_{jn}} \sim n\omega_0 \frac{x_{10}}{2c_{sf}} \| \tilde{C}_n \| \simeq 2\sqrt{n} \cdot 10^{-4}\bar{x}_{10}. \tag{28}$$

Expressions (28) are real for small n and have been derived on the assumption that $|\tilde{C}| \to 0$ for the higher harmonics. Hence we infer that the variation of the first-harmonic amplitudes is small for a duct having a height of the order of $5 \cdot 10^{-3}$ m and a length of the order of one meter. This fact permits us to represent the functions H_{jn} as the sum of a constant term and a small variable increment in $\tilde{x}_1$:

$$H_{jn}(\tilde{x}_1) = H_{jn0} + H_{jn1}(\tilde{x}_1), \quad \frac{\max |H_{jn1}|}{|H_{jn0}|} = \varepsilon_3 \ll 1. \tag{29}$$

Substituting the expansions (29) in Eqs. (24), neglecting small terms of the order of ε_3 and higher, and then integrating, we arrive at the expressions

$$H_{jn1}(\tilde{x}_1) = (-1)^{j+1} \frac{in}{2} \left(\frac{\Gamma_f + 1}{2} Q_{jn0} \Phi_0(\tilde{x}_1) \tilde{x}_1 + H_{jn0} \int_0^{\tilde{x}_1} \tilde{C}_n(\zeta)\, d\zeta \right), \tag{30}$$

in which

$$\Phi_0(\tilde{x}_1) = \frac{1}{\tilde{x}_1} \int_0^{\tilde{x}_1} \bar{F}^{-0,5}\, d\eta.$$

The quantities Q_{jn0} are constants and must be evaluated according to Eqs. (25), in which it is required to substitute H_{jn0} for H_{jn}. To compute the functions $H_{jn1}(\tilde{x}_1)$, it is necessary to determine the quantities H_{jn0}, which can be obtained from the system of nonlinear algebraic equations deduced from the boundary conditions (26) and (27). The substitution of (29) and (30) in (26) leads to the conclusion that $H_{1n0} = H_{2n0}$, $Q_{1n0} = Q_{2n0}$, and $H_{1n1}(x_1) = -H_{2n1}(x_1)$. Now condition (27) takes the form

$$H_{1n1}(\bar{x}_{10}) - H_{1n0}\, i \operatorname{tg} k_0 n \bar{x}_{10} = 0. \tag{31}$$

It is readily shown that a standing wave can occur only when the condition $k_0\bar{x}_{10} = m\pi$, $m = 1, 2, 3, \ldots$, is satisfied. Otherwise the quantity $\tan(k_0 n\bar{x}_{10})$ will not be small for sufficiently large n, thus contradicting inequality (29), which follows from the requirement that the solution be independent of the initial conditions. Consequently, the equality $H_{1n1}(\bar{x}_{10}) = 0$ follows from (31), and from the solution (30) we obtain an algebraic system governing the constants H_{jn0}:

$$Q_{jn0} = C_n H_{jn0}, \quad n = 1, 2, \ldots, N, \tag{32}$$

where

$$C_n = \frac{-1}{\bar{x}_{10}} \int_0^{\bar{x}_{10}} \frac{\delta_1 \sqrt{\Pr_w}}{(\Gamma_f + 1)\varphi_n} \left(-(1 + \varkappa_0 \bar{T}_\tau \bar{\theta}_1(\varphi_n)) + i(1 - \varkappa_0 \bar{T}_\tau \bar{\theta}_2(\varphi_n))\right) d\bar{x}. \tag{33}$$

In the derivation of (32) we set

$$\Phi_0(\tilde{x}_{10}) = 1. \tag{34}$$

Equation (34) is the equation for the determination of F_0, i.e., the scale factor required for the single-valued determination of the functions χ_{jn} according to Eqs. (17).

System (32) has exactly the same form as the system in [3], which was derived for the case of constant values of $\bar{\delta}_1$, $\bar{I}_T$, and $\bar{\varkappa}_0$. The fundamental problem in relation to system (32) is to determine the conditions under which a nontrivial solution exists. It is solvable in finite form only for the case N = 3. The condition for the existence of a nonvanishing solution has the form

$$|C_3|^2 \operatorname{Im}\{C_1C_2\}(\operatorname{Im}\{C_2C_3^*\} - 2\operatorname{Im}\{C_2C_3\}) - |C_2|^2(\operatorname{Im}\{C_1C_3\})^2 - \\ - 4\operatorname{Im}\{C_1C_3\}\operatorname{Im}\{C_2C_3\}\operatorname{Re}\{C_1C_2\} - 4|C_1|^2(\operatorname{Im}\{C_2C_3\})^2 = 0. \quad (35)$$

Equation (35) determines the relationship between the functions $\bar{\varkappa}_0$, $\bar{I}_T$, and $\bar{\delta}_1$ and the TAPO frequency in the parameters φ_n as deduced from the explicit expressions for C_n. The known quantity ω_0 can be used to determine the values of the amplitudes of the first three harmonics according to formulas given in [3]. We note that the functions $\bar{\varkappa}_0$ and $\bar{I}_T$ depend on the distribution of the energy input; the function $\bar{\delta}_1$ is determined mainly by the velocity distribution of the heat-transfer medium along the duct.

Determination of the constants H_{jn0} and the frequency ω_0 completes the solution of the general problem of determining the characteristics of a nonlinear standing wave of finite amplitude.

The local values of the harmonic amplitudes are determined by the series (16). Here the functions $\chi_{jn}(x)$, which depend on the configuration of the duct, are determined according to Eqs. (17) from the known values of ω_0 and F_0. The functions $H_{jn1}(x)$, which are given by expressions (30), describe the influence of the variation of the heat input and the flow velocity of the heat-transfer medium on the local amplitudes of the TAPO.

NOTATION

x, t, coordinate and time; U, velocity; P, ρ, T, S, pressure, density, temperature, and entropy μ_2, μ_3, dynamic viscosity coefficients; c_p, χ, a_1, a_3, isobaric specific heat, thermal conductivity, and thermal diffusivities of the heat-transfer medium and wall material, respectively; α_p, coefficient of thermal expansion; F, L, area and hydraulic radius of duct; δ_1, $\bar{\delta}_1 = \delta_1/L$, thickness of laminar sublayer; c_s, ω, isentropic sound velocity and angular frequency; M, Pr, Mach and Prandtl numbers. Indices: 1, unsteady value in wave; 0, steady value; f, value in flow core; w, value at wall; $\bar{\beta}_1 = \sqrt{\omega\rho_{0w}/(2\mu_{2w})}$; $\bar{\gamma}_j = \sqrt{\omega/(2a_{jw})}$; $\varphi_n = \sqrt{n}\,\bar{\gamma}_1\,\bar{\delta}_1$; $\bar{x} = x/L$; $\tilde{x} = \omega x/c_{sf}$; $\bar{c}_s = c_s/c_{sf}$; $\tau_j = \omega(t + (-1)^j x_0/c_{sf})$; $M_j = (-1)^{j+1}U_{1j}/c_{sf}$; $\Gamma = 1 + (\partial^2P/\partial\rho^2)_s\,(\rho_0/c_s^2)$; $\bar{T} = T/T_{cr}$; $\bar{I}_T = -I_T/\sqrt{Pr_w}$; $I_T = \int_{\bar{T}_{0w}}^{0.5} (\bar{c}_s^{-2} - 1)\,d\bar{T}$.

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