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The heat exchange with a shock deformed material

Deforming of elementary particle of continuous environment in the shock wave (SW) leads to increasing its specific inner energy: $\varepsilon > \varepsilon_0$. If deforming is not elastic, then the parts of substance which already had passed through the shock front (that parts which settle down at $x \le x_s$)* warm up: its temperature becomes higher than it was until deforming. Arise a heat exchange: this parts of substance give the heat to that parts which meanwhile is found in front of shock front (that is at $x > x_s$), what is provided by the heat flow $\vec{q}'(x,t)$ (see for example [1,2]).

Every heat exchange, of any nature and mechanism, is wrote by the term $div\vec{q}$ in a differential equation of energy conservation (moving system):

$$\frac{\partial}{\partial t}\rho\left(\frac{\upsilon^2}{2}+\varepsilon+\Pi\right)+div\left[\rho\vec{\upsilon}\left(\frac{\upsilon^2}{2}+\varepsilon+\Pi\right)-\mathbf{P}\bullet\vec{\upsilon}+\vec{\mathrm{q}}\right]-\rho\vec{\mathcal{F}}\bullet\vec{\upsilon}=0, \tag{1}$$

since by definition

$$-\rho dQ/dt = div\vec{q} \equiv \aleph(x,t) \tag{2}$$

Here ρ - the density, $\vec{\upsilon}$ - the mass velocity, Π - the specific potential energy in an external power fields, $\mathbf{P}$ - the stress tensor, $\vec{\mathcal{F}}$ - the specific mass force, dQ - the elementary (in a time dt) specific influx of heat to the particle, $\aleph$ - the specific power of heat sources.
Integration of (1) from x_s to x_s+0 in common with equations of conservation of the mass and impulse, at $\Pi=0$ and $\vec{\mathcal{F}}=0$, leads to the system of boundary conditions on the SW , the first two from which coincide with an equotions of the mass and impulse of Rankine - Hugoniot system, but last have a form:

$$\begin{aligned}&\varepsilon-\varepsilon_0=Q_s+\frac{1}{2}(p+p_0)(V_0-V),\\ &Q_s\equiv\frac{1}{\rho_0\upsilon_0}\int_{x_s}^{x_s+0}\aleph(x,t)dx;\end{aligned} \tag{3}$$

by index "0" here are marked the parameters at x_s+0, and those which settle down at x_s are leaved without index. In consequence of (2), the definition $(3)_2$ can be written as

$$Q_s=(q_0-q)/\rho_0\upsilon_0 \tag{4}$$

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* For the sake it considers the plane stationary SW moving along an initial ("immovable") axis X; an axis x is directed along X and is hard unite with the shock front, which coordinates are $x=x_s$ and $X=X_s(t)$.

Address now to a mentioned at the beginning the heat exchange between a parts of substance behind and in front of SW - the heat flow $\vec{q}'(x,t)$, $div\vec{q}' \equiv \aleph(x,t)$ - in a not elastic compress wave. Then, as it was noted above,

$$(\varepsilon > \varepsilon_0) \Rightarrow (T > T_0)^* \qquad (5)$$

and

$$Q_s' = \frac{1}{\rho_0 \upsilon_0} \int_{x_s}^{x_s+0} \aleph'(x,t) dx = (q_0' - q') / \rho_0 \upsilon_0 \qquad (6)$$

As the heat cross from the places with a bigger temperature to places with a smaller temperature, then $\vec{q}'(x,t)$ is directed along axis x and $q' \geq q_0'$ (in a stationary regime the particle at $x = (x_s + 0)$ can not to give at periphery the heat (q_0'), more than it receive from the substance at $x = x_s$ (that is q'); even if for same reason or other, in any moment, suddenly it was found $q_0' > q'$, then after some transitional process of establishment its correlation anew would return to $q' \geq q_0'$). And as soon as $\upsilon_0 = \left(-\dot{X}_s\right) < 0$, then in any stationary regime $Q_s' \geq 0$. Substitution of $Q_s' > 0$ in $(3)_1$ leads to an absurd result: because of transference of the heat to periphery the energy of substance behind the front becomes not smaller but a more than at absence such a transference. The only had been physical justified result is

$$Q_s' = 0, \quad q' = q_0' \qquad (7)$$

- and, if it considers only the heat exchange between the parts of substance behind and in front of the shock front (and by other possible forms of heat transference it is neglected), the energy equation on the SW $(3)_1$ is found the known Hugoniot equation (as it have place, for example, in [1,2]).

Meanwhile in a works [3,4,] it is proved: the Hugoniot equation is valid then and only then when the shock deforming is a linear elastic (descend according to Hooke law). But whith the elastic deformations no heat exchange is possible: the part of energy of deforming which had been "embezzled" because of heat exchange might not been given back to external bodies, accomplishing the deforming, at the retarn it in the primary position, as it must be with an elastic process in according with its definition. Hence it inevitable follows: if the deforming in the wave was not elastic, then the energy equation $(3)_1$ can not be the Hugoniot equation, $Q_s' = 0 \neq Q_s$, and full heat flow had not been reduced to the flow providing the heat exchange between the parts of substance behind and in front o the shock front: $\vec{q}(x,t) \neq \vec{q}'(x,t)$ and, accordingly, $\aleph(x,t) \neq \aleph'(x,t)$.

But heat exchange between this parts of substance (behind and in front of shock front) already had been wrote by the heat flow $\vec{q}'(x,t)$. Now the only remained possibility - it is to take into consideration the heat exchange that substance which in given moment is found on the shock front itself, with its encirclement: not equal to nought value $Q_s \neq Q_s'$, defining the shock heat exchange in the equation $(3)_1$ for a not elastic deforming (later on it would be means as $\hat{Q}$) is a specific heat effect (the heat "flow") that elementary particle of substance which in given moment (during infinitesimal time interval) is exposed to deforming on the front:

* Correlation (5) is fair every time as soon as the particle is deformed by surrounding substance; that's easy at the compress it is more habitual.

$$\hat{Q} = \frac{1}{\rho_0 \upsilon_0} \int_{x_s}^{(x_s+0)} \aleph(x,t) dx = (q_0 - q) / \rho_0 \upsilon_0 \tag{8}$$

The physical cause of appearance $\hat{Q}$ is simple. In any wave of inconstant profile $\rho(x) \neq Const.$ with a not elastic deformations the part of a deforming work pass to the heat, give birth to a heat sources $\aleph(x,t)$; its specific power rise with a rise of rate of deforming. On that parts of Δx, where the profile is continuous, the rate of deforming - and with it the power of heat sources - are finite, and visible heat effect can be observed (that is it can be measured) only at $\Delta x \neq 0$; just so it is behind the front $x \leq x_s$. But on the shock front itself the rate of deforming, and with it the power of heat sources, turns into a infinity, and (in general not a little) the heat effect displays already at $\Delta x = 0$: the heat containing of elementary particle crossing shock front exchanges by jump, exactly so as by jump exchanges its strained state. This effect – the shock heat exchange - is wrote by the term $\hat{Q}$. Just this phenomenon defines all specific peculiarities of the unelastic deformations in the shock waves; its detailed analysis had been fulfiled in [4].

The remark. In the given text everywhere the material environment in which take place an examined processes supposes as continuous, homogeneous and isotropic, and the shock front - as a rupture of the continuity of the profile of wave. Physically it with a high exactitude (in a space treatment near angstrem) corresponds to condensed bodies, fluids and dense gases, where the wave functions of put together of it "corpuscles" are essentially covered again. For a rare gases the given considerations once ought to perceive as approximate.

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