Temperature anomalies of shock and isentropic waves of quark–hadron phase transition

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Abstract. In this work, we consider a phenomenological equation of state, which combines statistical description for hadron gas and a bag-model-based approach for the quark–gluon plasma. The equation of state is based on the excluded volume method in its thermodynamically consistent variant from Satarov et al [2009 Phys. At. Nucl. 72 1390]. The characteristic shape of the Taub adiabats and isentropes in the phase diagram is affected by the anomalous pressure–temperature dependence along the curve of phase equilibrium. The adiabats have kink points at the boundary of the two-phase region, inside which the temperature decreases with compression. Thermodynamic properties of matter observed in the quark–hadron phase transition region lead to hydrodynamic anomalies (in particular, to the appearance of composite compression and rarefaction waves). On the basis of relativistic hydrodynamics equations we investigate and discuss the structure and anomalous temperature behavior in these waves.

1. Introduction
The applicability of lattice quantum chromodynamics (QCD) to describe the thermodynamics of hot nuclear matter is limited to small values of the baryon chemical potential. This is the reason why a phenomenological approach is widely used, which combines statistical description of hadron gas and the bag-model-based equation of state (EOS) of the quark–gluon plasma (QGP). Originally, in the framework of this approach, hadron matter was considered as an ideal gas (nucleons, anti-nucleons, and π-mesons). More accurate models take into account intensive short-range repulsion of hadrons (“excluded volume” effect), as well as an existence of great variety of free particles and resonances (see, for example, review [1], or [2]). Most of existing theoretical models predict first order phase transition (PT) from hadronic “gas” (HG) to quark–gluon plasma state of matter under compression far beyond “normal” nuclear density and at high temperatures. It is very important that both compression (Hugoniot–Taub) and expansion (Poisson) adiabats of dense nuclear matter cross the two-phase region of this hypothetical quark–hadron phase transition (QHPT). It is crucial that both the adiabats, compression and expansion, enter and leave the QHPT two-phase region in p–V plane in contrast to the ordinary VdW-like phase transition. It is well known (see e.g. [3]) that two corresponding kinks in both adiabatic trajectories, compression and expansion, lead to remarkable hydrodynamic
consequences. Actually, simple hydrodynamic scenarios of single-wave compression and single-wave expansion (release) became hydrodynamically unstable, and more complicated combined structures are realized in both the cases (see below). Namely: (i)—extended “plateau” appears in all kinematic profiles \( Y(x, t) \) (pressure, density, temperature etc.) in the point of entering two-phase region (see e.g. [3, figure 11.54]). And (ii)—second shock appears (in addition to the first one) in composite compression wave (see e.g. [3–5]). And more, the so-called rarefaction shock appears in addition to the mentioned above plateau in composite rarefaction wave (see e.g. [3, figure 11.55]).

It was emphasized in [6] that thermodynamic state of matter within the mentioned above plateau at the point of expansion isentropic path entering the two-phase region corresponds exactly to the binodal of the crossed boundary of phase transition (boiling curve in the case of gas–liquid-like phase transition (see [7, 8]) or hadronization border in the case of the QGP “fireball” expansion through QHPT [6]. Just because of this fact it was proposed to call this object (the uniform and extended peace of matter, contained within the plateau) by the term “binodal layer” (BL) and to call whole the scenario of sticking for finite portion of adiabatically expanding matter within the BL as “phase freezeout” (see [6, 9]).

The both combined scenarios of compression and expansion were calculated and discussed already in [5] on the base of simplified version of QHPT [10]. In present paper we consider anomalous features of compression and expansion hydrodynamics. But present study is based on the more realistic and adequate EOS for hadronic phase [2], which takes into account main non-ideality effect—intensive short–range repulsion of hadrons (“excluded volume” effect). The most crucial and important sequence of this hadronic EOS modification is that resulting quark–hadron phase transition changes its type from “enthalpic” one with slightly increasing \( p(T) \)-dependence to “entropic” one with strongly decreasing \( p(T) \)-dependence (see figure below). It was proposed in [11] to introduce additional classification of all 1st-order phase transitions onto two subclasses: enthalpic and entropic ones, where just the sign of \( p(T) \)-dependence of the PT boundary is the basic feature for distinguishing enthalpic PTs (i.e. ordinary VdW-like ones) from essentially non-standard entropic PTs.

Main reason for this additional classification is the fact that entropic PTs have significantly more complicated and anomalous properties than the enthalpic PTs (see [12, 13]). First of all it is anomalous negative sign of great number of usually positive second cross derivatives on thermodynamic potential, such as thermal expansion coefficient \( (\partial V/\partial T)_p \), isochoric pressure—temperature coefficient \( (\partial p/\partial T)_V \) etc. The most important anomalies of thermodynamics of entropic PT for hydrodynamic applications are negativity of the Grueneisen coefficient and the isentropic pressure–temperature coefficient \( (\partial T/\partial p)_S \). In particular, the straightforward topological sequence of decreasing character of \( p(T) \) boundary for QHPT is that non-standard anomalous order of temperature behavior appears at thermodynamics of a matter, when it crosses two-phase region of QHPT under shock compression or isentropic release. Namely, temperature decreasing part appears in shock compression Hugoniots adiabat and oppositely, temperature increasing part appears in isentropic expansion path when both the paths cross two-phase region of QHPT (see e.g. [12, equations (8), (9)]). In this paper we consider these temperature anomalies of flows within combined scenarios of shocks and rarefaction waves.

It should be noted that mentioned above anomaly (the temperature decreasing under shock compression) is known in high energy density physics under the term “shock cooling”. For example, this phenomenon was observed experimentally in strong shock compression of nitrogen (see e.g. [14]) and was discussed actively in many theoretical papers (see e.g. [15, 16] etc). The same anomalous shock cooling is realized in the case of crossing by Hugoniots decreasing parts of \( p(T) \) boundaries of melting (see e.g. [17]) or polymorphic (crystal–crystal) transitions (see e.g. [18]). As for anomalous temperature behavior along adiabatic expansion (“isentropic heating”) it is was obtained already for the case of QHPT in e.g. [2].
In the present paper, we emphasize, first of all, the discussed temperature anomalies within non-standard composite compression and rarefaction waves.

2. Equation of state

2.1. Ideal hadron gas

The grand canonical partition function of the ideal gas is defined by the following integrals over the phase space [10]

$$\ln Z_i^{\text{id}}(T, \mu_i, V) = \frac{g_i V}{6\pi^2 T} \int_0^\infty \frac{dk}{\sqrt{k^2 + m_i^2}} \exp \left[ \frac{1}{(\sqrt{k^2 + m_i^2} - \mu_i)/T} \right] \pm 1.$$  (1)

Here, $m_i$ is the mass, $\mu_i$ is the chemical potential, $g_i$ is the degeneracy factor of the particles of sort $i$. The signs $(\pm)$ and $(\mp)$ correspond to fermions and bosons, accordingly. Here and below the system of units is used in which $\hbar = k = c = 1$. From the known partition function one can calculate pressure, particle densities and energy density of hadron gas using well-known thermodynamic relations:

$$p = \sum_i p_i(T, \mu_i, V) = \frac{T}{V} \sum_i \ln Z_i^{\text{id}}(T, \mu_i, V),$$  (2)

$$n_i = \frac{T}{V} \frac{\partial}{\partial \mu_i} \ln Z_i^{\text{id}}(T, \mu_i, V),$$  (3)

$$e = \sum_i e_i = \frac{T^2}{V} \frac{\partial}{\partial T} \sum_i \ln Z_i^{\text{id}}(T, \mu_i, V) + \frac{T}{V} \sum_i \mu_i \frac{\partial}{\partial \mu_i} \ln Z_i^{\text{id}}(T, \mu_i, V).$$  (4)

According to the common approach (see, for example, [1, 2, 10]), which is adopted in this work, the integrals arising after the substitution of (1) into (2)–(4) and their differentiation are evaluated numerically. The accuracy of the calculation is governed by the convergence control. The combination of ideal hadron gas and the MIT-bag model was one of the first phenomenological wide-range EOS of hot nuclear matter [10].

A significant drawback of this EOS is that it can be constructed only for a very narrow range of bag model parameter $B$, which defines a constant energy density of the vacuum and keeps quarks and gluons confined to small regions of space. For this narrow range of $B$ the critical temperature of QHPT is about 110 MeV, that is significantly less than the accepted value for this parameter. Outside the valid range of $B$ the internal energy density of the QGP becomes less than the internal energy density of ideal hadron gas for some part of the phase equilibrium curve.

2.2. Hadron gas with particles repulsion

Relations (1)–(4) correspond to the ideal gas model. It is known, that taking into account of the hadron repulsion has significant influence on thermodynamic properties of hadron gas in the QHPT region, and hence, on the phase equilibrium and features of the phase diagram. One way to take into account the effect of the interaction of hadrons is to apply the concept of excluded volume.

$$\ln Z_i = \frac{g_i V}{6\pi^2 T} \int_0^{V - \sum_j N_j v_j} dv \int_0^\infty \frac{dk}{\sqrt{k^2 + m_i^2}} \exp \left[ \frac{1}{(\sqrt{k^2 + m_i^2} - \mu_i)/T} \right] \pm 1.$$  (5)

Here, $v_j = v = (16/3)\pi r_h^3$, $r_h = 0.3$–0.6 fm is the excluded volume per particle of the radius $r_h$. 


For the approximation of (5) we use the approach based on the substitution into (2) of the shifted value of particle chemical potential, see [19]. On the first step the hadron gas pressure is calculated from the solution of the transcendental equation
\[ p = \sum_i p_i^\text{id}(T, \tilde{\mu}_i, V) = \frac{T}{V} \sum_i \ln Z_i^\text{id}(T, \tilde{\mu}_i, V), \quad \tilde{\mu}_i \equiv \mu_i - \nu p. \] (6)

Chemical potential of a particle \( i \) in (6) is determined by a set of quantum numbers that characterizes a given particle
\[ \mu_i = B_i \mu_B + S_i \mu_S + Q_i \mu_Q. \] (7)

Here, \( \mu_B \) is the baryon chemical potential, \( \mu_S \) is the strange chemical potential, and \( \mu_Q \) is the electric chemical potential. The pressure in the chemical equilibrium is a function of four variables [2]
\[ p = p(\mu_B, \mu_S, \mu_Q, T), \] (8)
which must satisfy the thermodynamic identity
\[ dp = s dT + \sum_{\alpha=B,S,Q} n_{\alpha} d\mu_{\alpha}, \] (9)
where \( s \) and \( n_{\alpha} \) are the entropy density and the charge density, respectively.

On the second step, energy density, pressure, entropy and the charge density of particles are calculated using the formulas for the ideal gas at the shifted value of chemical potential. Then, the obtained values are corrected by multiplying by a factor that depends on the density of hadrons
\[ s = r \sum_i \frac{\partial p_i^\text{id}}{\partial T}(\tilde{\mu}_i, T), \quad e = r \sum_i e_i^\text{id}(\tilde{\mu}_i, T), \quad n_{\alpha} = r \sum_i q_{\alpha} \frac{\partial p_i^\text{id}}{\partial \tilde{\mu}_i}(\tilde{\mu}_i, T), \] (10)
where \( r = \frac{1}{1 + v \sum_i n_i^{\text{id}}} \) and \( n_i^{\text{id}} = \frac{\partial p_i^\text{id}}{\partial \tilde{\mu}_i}(\tilde{\mu}_i, T) \)
is the density of the particles of sort \( i \) in the ideal gas approximation at the shifted value of chemical potential.

Thus, the account of hadrons repulsion in thermodynamic characteristics of hadron gas (6), (10) is thermodynamically consistent, ensuring the implementation of the basic thermodynamic relations, see [2]. In an EOS of hot nuclear matter for hydrodynamic simulation in the problem of ultra-relativistic nuclei collision one usually suppose \( \mu_Q = 0 \); thus the conservation of electric charge is neglected.

2.3. The EOS of QGP and the phase equilibrium
For the description of thermodynamic properties of the quark–gluon plasma the model [2] is applied. Plasma is considered as a Fermi gas of quarks and gluons, the interaction is taken into account in the framework of the MIT-bag model. As in the case of the hadron gas, pressure, energy density and charge densities of gas of quarks and gluons are functions of temperature and chemical potentials [2]
\[ p_{\text{QGP}} = -B + (N_g + \frac{21}{2} N_f) \frac{\pi^2 T^4}{90} + N_f \left( \frac{\mu^2 T^2}{18} + \frac{\mu^4}{324 \pi^2} \right) + p^{(s)}, \] (11)
\[ (n_B)_{\text{QGP}} = N_f \left( \frac{\mu T^2}{9} + \frac{\mu^3}{81 \pi^2} \right) + n_B^{(s)}, \] (12)
\[ e_{\text{QGP}} = B + (N_g + \frac{21}{2} N_f) \frac{\pi^2 T^4}{30} + N_f \left( \frac{\mu^2 T^2}{6} + \frac{\mu^4}{108 \pi^2} \right) + e^{(s)}, \] (13)
Figure 1. Influence of the hadron repulsion on the pressure distribution in $n$–$T$ plane: EOS based on ideal hadron gas model [10] (a) and excluded volume model (b).

Taking into account the quark mass $m_i = 150$ MeV, the chemical potential $\mu_i$, and statistical weight $g_i = 6$, the contribution of strange quarks and antiquarks is given by (2), (3).

At a given temperature, baryon number density and strange charge, excluding the chemical potentials and taking into account the condition $n_S = 0$ we arrive at the equation of state of quark–gluon plasma in the following form:

$$ p_{\text{QGP}} = p_{\text{QGP}}(T, n_B), \quad e_{\text{QGP}} = e_{\text{QGP}}(T, n_B). $$

(14)

The phase equilibrium is determined by the equality of pressure, temperature and chemical potentials of the hadron gas and QGP:

$$ p_{\text{HG}}(T, \mu_B, \mu_S) = p_{\text{QGP}}(T, \mu_B, \mu_S). $$

(15)

This condition is supplemented by the relations, expressing the conservation of charge (baryon number, strangeness)

$$ n_\alpha = \lambda(n_\alpha)_{HG} + (1 - \lambda)(n_\alpha)_{QGP}, \quad (\alpha = B, S), $$

(16)

where $\lambda$ is the volume fraction of the hadronic phase. Internal energy density is determined by the contributions of the coexisting phases according to volume fractions

$$ e = \lambda e_{\text{HG}} + (1 - \lambda)e_{\text{QGP}}. $$

(17)

In the framework of this approach, the interface energy is neglected.

2.4. Influence of hadron repulsion on the phase diagram

Comparison of $p$–$T$–$n$ plots for EOS based on the ideal gas model (a) and the excluded volume model (b) is given in figure 1. The pressure distribution in the two-phase region is relatively flat in the first case. Taking into account particle repulsion results in the rise of pressure at high densities of baryon number. As a result, the derivative $dp/dT$ along the equilibrium curve
is negative. Thus, temperature decreases at compression in the two phase region, therefore isentropes have a segment with negative slopes in $p-T$ plane (see, for example, [2]).

2.5. Remark on relativistic casuality violation

The introduction of repulsion of hard spheres (in the framework of the method of excluded volume) for describing the interaction of hadrons has a side effect, manifested in superluminal values of the adiabatic sound velocity, determined by the derivatives of the equation of state:

$$c_s^2 = \left. \frac{\partial p}{\partial e} \right|_{s/n} = \frac{\partial p}{\partial e} \Bigg|_n + \frac{n}{p + e} \frac{\partial p}{\partial n} \bigg|_e > 1$$

or, for the EOS given in the parametric form $p = p(T, n)$, $e = e(T, n)$,

$$c_s^2 = \frac{n}{p + e} \frac{\partial p}{\partial n} \bigg|_T - \left(1 - \frac{n}{p + e} \frac{\partial e}{\partial n} \bigg|_T \right) \frac{\partial p}{\partial T} \bigg|_n \left( \frac{\partial e}{\partial T} \bigg|_n \right)^{-1} > 1.$$  \hspace{1cm} (19)

The inequality (19) is valid in the narrow part of the phase diagram, see figure 2(a), adjacent to the two-phase region. The effect was discussed in literature. It is apparently connected with the fact that the model of solid body contradicts relativistic theory and the correct model of hadron repulsion should take this into account.

3. Temperature anomalies in composite compression and rarefaction waves

3.1. The Taub adiabats crossing QHPT region

In relativistic hydrodynamics pre- and post-shock states are related to each other by the equation of the Taub shock adiabat [20]

$$n^2 X^2 - n_0^2 X_0^2 - (p - p_0)(X + X_0) = 0,$$  \hspace{1cm} (20)

where $p$ is the pressure; $X = (e + p)/n^2$ is the generalized relativistic volume. The characteristic shape of the Taub shock adiabats in the phase diagram is similar to the shape of isentropes. The adiabats have kinks at the boundary of the two-phase region, within which the post-shock

Figure 2. (a) 1—region of relativistic casuality requirement violation; 2—test Taub adiabats; (b) the shape of Taub adiabats 1–3 with different initial states in $p-T$ plane.
Figure 3. Taub adiabats with different initial states 1–3 passing through the two-phase region.

temperature decreases with the growth of the post-shock pressure. The shape of some test shock adiabats in $p-T$ variables in the phase transition region is shown in figure 2(b). The dashed line in the figure denotes the coexistence curve of the QHPT. The negative slope of the shock adiabats results from the character of the phase transition, namely from the fact that the derivative $dp/dT$ along the coexistence curve is negative.

3.2. Composite waves
The shape of the Taub adiabats in $X-p$ plane is shown in figure 3. The theory of stability of relativistic shock waves predicts the decay of the shock waves with dissipative structure under the condition of ambiguous representation of the shock wave discontinuity [21,22]. In the case of the shock adiabats presented in the figure, instead of a single shock wave a composite compression wave that includes two shocks, takes place. The second shock in the composite wave is a wave of a partial or full phase transition. The initial state of the second shock is the point in $X-p$ plane, in which the primary shock adiabat intersects the boundary of the two-phase region (the first kink point on the shock curve).

The Taub adiabat corresponding to the second shock passes through the QHPT region, and hence, has the segment where the post-shock temperature is lower than the pre-shock one. It should be noted that within the structure of the composite compression wave the temperature in hadron gas is higher than the temperature in QGP. The temperature difference can reach 10 MeV depending on the initial state and the shock wave intensity. It is known that in the case of non-convex isentropes (in $X-p$ plane) instead of a single rarefaction wave a composite rarefaction wave is formed. The composite wave includes the following elements: an isentropic rarefaction...
wave in QGP, a rarefaction shock with hadronic post-shock state, an isentropic rarefaction wave in hadron gas. Provided the initial state of the shock is in the two-phase region, the anomalous temperature behavior takes place within the part of the primary isentrope, which belongs to the two-phase region.

3.3. Numerical calculations

Numerical calculations of composite compression and rarefaction waves are fulfilled on the basis of the equations of relativistic hydrodynamics, which include conservation of energy and momentum [23]

\[ \nabla_\beta T^{\alpha\beta} = 0, \]  

(21)

where the energy-momentum tensor has the form

\[ T^{\alpha\beta} = (e + P)u^\alpha u^\beta - g^{\alpha\beta}P, \]  

(22)

and the baryon number density

\[ \nabla_\alpha (nu^\alpha) = 0. \]  

(23)

Here, \( g^{\alpha\beta} = \text{diag}(1, -1, -1, -1) \) is the metric tensor; \( u^\alpha = (\Gamma, v\Gamma)^T \) denotes velocity 4-vector; \( \Gamma = 1/(1 - v^2)^{1/2} \) is the Lorentz factor. The system of equations (21) and (22) is closed by the equation of state described in the previous section with \( B^{1/4} = 210 \text{ MeV}, \) \( v^{\text{ex}} = 0.5 \text{ fm}^3, \) \( \mu_S = 0, \) \( \mu_Q = 0. \) Consider the initial value problem with initial data corresponding to the shock wave, such that an ambiguous representation of the shock-wave discontinuity takes place. This shock wave is unstable and splits with the formation of a composite wave, which includes two shocks.

**Figure 4.** Pressure and temperature in a composite compression wave.
The solution of the problem is shown in figure 4. The initial state is denoted by A, the final state by C. The state B corresponds to the point of intersection of the primary shock adiabat and the boundary of the two-phase region. The anomalous temperature effect manifests itself in drop of the temperature in the second shock wave in the wave-split configuration. In figure 5 the structure of composite rarefaction wave is presented. The initial state, which corresponds to QGP state at the boundary of the two phase region, is denoted by A, the final state by D. B–C is the rarefaction shock. The anomalous temperature effect consists in the rising of the temperature in the isentropic rarefaction wave in the two-phase region. In the both considered cases the temperature of hadron-gas-rich matter is higher than the temperature of QGP.

4. Conclusion
The Taub adiabats for the phenomenological EOS of hot nuclear matter have been calculated. The segments of the adiabats in the two-phase region have negative slope in the temperature-density plane. In the composite compression and rarefaction waves the quark–gluon plasma has lower temperature than the hadron-gas-rich matter. The anomalous temperature effects are confirmed by the numerical calculations on the basis of the relativistic hydrodynamics. High energy density matter generated at collisions of heavy relativistic ions is suggested to demonstrate collective behavior. Thermodynamics of QHPT is considered as a possible source of signals of the QGP formation [24,25]. The anomalous temperature effects could give additional information on the character of supposed quark–hadron phase transition.

Figure 5. Pressure and temperature in a composite rarefaction wave.
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