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The Gibbs Variational Method in Thermodynamics of Equilibrium Plasma. 2: The Equation of State for Plasma

by Michael Grinfeld and Pavel Grinfeld

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The Gibbs Variational Method in Thermodynamics of Equilibrium Plasma. 2: The Equation of State for Plasma

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14. ABSTRACT In Part 1 of this series of reports, we formulated a novel approach to the thermodynamics of heterogeneous systems completely or partially filled with a liquid substance in plasma state. The approach is based on the use of the Gibbs variational principles, and it enables efforts to address a variety of problems relating to equilibrium and stability of such systems. To develop a quantitative theory based on the relationships established in Part 1, one more critical element is required: the equation of state (EoS) for the substance in the plasma state. In this report, we postulate one such representative EoS that permits analytic study with several essential advantages over purely computer-based studies. We demonstrate this by finding an explicit solution of the problem of distribution of ionized gas in a vessel with flat boundary plates.					
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1. Introduction

In Part 1 of this series of reports,¹ we formulated a novel approach to thermodynamics of heterogeneous systems completely or partially filled with a liquid substance in a plasma state. The approach is based on the use of the Gibbs variational principles, and it enables efforts to address a variety of problems relating to equilibrium and stability of such systems.

The general relations, established in Grinfeld and Grinfeld,¹ are quite instructive on their own, and permit one to make several qualitative conclusions. At the same time, no quantitative theories can be developed until the general system is supplemented with the appropriate equations of state (EoSs). The term EoS has different meanings in different communities. Mostly it is used rather loosely. In Grinfeld² and references therein, we tried to make the usage of this term more systematic. In particular, we distinguish the incomplete and the complete EoS. Equilibrium thermodynamics can provide researchers with the consistent strategies for extracting an EoS from experimental data (see the discussions in the series of technical reports *Operational Equations of State: 1–4*).² At the same time, it does not permit finding the EoS based on purely theoretical reasoning.

To some extent, the EoS can be established with the help of statistical thermodynamics based on a set of mathematically formulated axioms. The classical approach of statistical physics automatically generates the complete EoS. Yet the approach of statistical thermodynamics appeals to some hypotheses regarding the microstructure of the substance, which cannot be directly verified experimentally. We do not dwell on this approach here.

Another popular approach does not appeal to any hypotheses about the micro and/or nano features of the substance. This approach is totally macroscopic in nature but also relies on various conjectures. The second approach is mostly based on the more or less intuitive *postulating* of an appropriate EoS. This approach involves the accumulated research experience from prior modeling efforts.

The essential constraints in the choice of the EoS include the necessity to obey the fundamental principles of mechanics and thermodynamics. It also involves extensive use of the principles of symmetry. We pursue that very approach in the following.

Our goal was to propose an EoS form for liquid or gaseous substances that is instructive and convenient for modeling phenomena that include nonlocal interaction—electromagnetic and/or gravitational. By “instructive” we mean an

EoS that is sufficiently close to those widely used in hydro-s or gas dynamics. By “convenient” we mean an EoS that leads to mathematical models permitting analytical treatment. In particular, this EoS form can be used for verification purposes when fulfilling the validation and verification (V&V) procedures.

We begin with explicit postulation of the novel EoS form. Then we demonstrate its application to the simplest 1-D problem of a charged gas inside a vessel in the form of flat layer.

2. The Novel EoS

Here, we formulate the EoS for a charged liquid medium. Following the discussions of Grinfeld,² the complete EoS is just the appropriate thermodynamic potential referred to its natural thermodynamic arguments. For instance, when formulating the complete EoS in the form of the free-energy density ψ , the natural variables include the mass density ρ (or the specific volume $V \equiv 1/\rho$) and the absolute temperature T . An equivalent EoS would be the internal-energy density e expressed in terms of mass density ρ (or the specific volume $V \equiv 1/\rho$) and the entropy density S . Even mathematically, thermodynamically, and physically equivalent EoS form can be nonequivalent from the standpoint of the convenience for particular engineering applications. That is why the different forms of conceptually equivalent EoSs each possess their own value.

We begin by postulating the novel complete EoS in terms of the free-energy density and then demonstrate how to transform it to the equivalent EoS in terms of the internal-energy density.

3. The Main Definition of the Novel EoS

We postulate the free-energy density $\psi(\rho, T)$ per unit mass such that

$$\psi(\rho, T) - \psi_0 = a^2 \frac{1}{2\rho} (\rho - \rho_0)^2 + p_0 \left(\frac{1}{\rho_0} - \frac{1}{\rho} \right) - C \left(T \ln \frac{T}{T_0} - T + T_0 \right) - S_0 (T - T_0), \quad (1)$$

where ρ_0 , T_0 , ψ_0 , S_0 , p_0 , a^2 , and C are constants.

Here, ρ_0 and T_0 are the density and the absolute temperature in the ground state. The constants ψ_0 and S_0 are the free-energy and entropy density per unit mass in the ground state; p_0 is the pressure in the ground state.

The following relationships can be easily verified:

$$T\psi_{TT} = -C. \quad (2)$$

$$(\rho\psi)_{\rho\rho} = a^2. \quad (3)$$

The physical meaning of the relationship (Eq. 2) is rather transparent: the quantity $-T\psi_{TT}(\rho, T)$ is just the specific heat capacity of the substance at fixed mass density or specific volume. Thus, for the postulated model, the heat capacity at fixed volume remains the same for any state (ρ, T) . This is just the same property as the one valid for the perfect gas model.

The identity (Eq. 3) is the very heart of the novel model postulated in this report. As we see later in this report, this postulate makes the postulated model particularly convenient for analytical study of gaseous plasma. The physical meaning of postulate Eq. 1 is rather straightforward. The relationship (Eq. 1) can be rewritten as

$$p_\rho(\rho, T) = a^2 \rho, \quad (4)$$

where $p(\rho, T)$ is the pressure as function of the density and the absolute temperature; thus, $p_\rho(\rho, T)$ is the isothermal sound speed in the gaseous plasma. Thus, according to Eq. 4 the isothermal sound speed grows as a square root at growing density. This is a quite realistic physical assumption. Remember that the isothermal sound speed of the so-called “perfect gas” does not depend upon the density at all.

In the postulated EoS (Eq. 1), the ground state (ρ_0, T_0) can be chosen arbitrarily. Also, we can assign arbitrarily the constants ψ_0 and S_0 . In other words, when choosing any other values of these constants, all the physical properties of the substance will not change. At the same time, when changing the parameters p_0 , a^2 , and C , the corresponding physical parameters or effects will change also.

The temperature-related term in the postulated EoS (Eq. 1) resembles the analogous term in the Segletes EoS.^{3,4}

4. Thermodynamic Relationships Implied by the Postulated EoS

Let us use the thermodynamic identities

$$S(\rho, T) = -\frac{\partial\psi(\rho, T)}{\partial T} \quad (5)$$

and

$$C_v(\rho, T) = T \frac{\partial S(\rho, T)}{\partial T} \quad (6)$$

for the specific entropy per unit mass and the specific heat capacity at constant volume, respectively.

Then, combining the identities (Eqs. 6 and 7) with the postulated EoS (Eq. 1), we get, respectively,

$$S(\rho, T) = S_0 + C \ln \frac{T}{T_0} \quad (7)$$

and

$$C_v(\rho, T) \equiv T \frac{\partial S(\rho, T)}{\partial T} \equiv C = \text{const.} \quad (8)$$

In the following, we use $C_v(\rho, T)$ and C interchangeably.

Combining the thermodynamic identity for the pressure $p(\rho, T)$,

$$p(\rho, T) \equiv \rho^2 \frac{\partial \psi(\rho, T)}{\partial \rho}, \quad (9)$$

with the postulated EoS (Eq. 9), we get the following relationship for the pressure function:

$$p(\rho, T) - p_0 = a^2 \frac{\rho^2 - \rho_0^2}{2}. \quad (10)$$

We then get the following instructive relationships:

$$p_\rho(\rho, T) = a^2 \rho. \quad (11)$$

$$p_T(\rho, T) = 0. \quad (12)$$

5. The Postulated EoS in the Form of the Internal-Energy Density

To present the postulated EoS in the form of the internal-energy density $e = e(\rho, S)$, we have to compose the internal energy as

$$e = \psi(\rho, T) + TS(\rho, T), \quad (13)$$

and then exclude the absolute temperature T by means of its expression in terms of ρ and the specific entropy S : $T = T(\rho, S)$. For the postulated model, the function $T(\rho, S)$ can be extracted from the relationship in Eq. 7, which implies

$$\frac{T(\rho, S)}{T_0} = \exp\left(\frac{S-S_0}{C}\right). \quad (14)$$

The specific free-energy e as function of ρ , S is defined as

$$e(\rho, S) \equiv \psi(\rho, T(\rho, S)) + ST(\rho, S). \quad (15)$$

After some cumbersome calculation, shown in Eq. 18, we get

$$e(\rho, S) - e_0 = a^2 \frac{1}{2\rho} (\rho - \rho_0)^2 + p_0 \left(\frac{1}{\rho_0} - \frac{1}{\rho} \right) + CT_0 \left(\exp\left(\frac{S-S_0}{C}\right) - 1 \right), \quad (16)$$

where the constant e_0 is the internal-energy density in the ground state:

$$e_0 \equiv \psi_0 + S_0 T_0. \quad (17)$$

To derive Eq. 16, we inserted the expression (Eq. 14) of the absolute temperature T in terms of the entropy density S in the definition (Eq. 15). Using, in addition, our main definition (Eq. 13), we get

$$\begin{aligned} e &= a^2 \frac{1}{2\rho} (\rho - \rho_0)^2 + p_0 \left(\frac{1}{\rho_0} - \frac{1}{\rho} \right) - C \left(T \ln \frac{T}{T_0} - T + T_0 \right) - \\ &S_0 (T - T_0) + \psi_0 + ST_0 \exp\left(\frac{S-S_0}{C}\right) = \\ &a^2 \frac{1}{2\rho} (\rho - \rho_0)^2 + p_0 \left(\frac{1}{\rho_0} - \frac{1}{\rho} \right) - C \left(T_0 \exp\left(\frac{S-S_0}{C}\right) \frac{S-S_0}{C} - T_0 \exp\left(\frac{S-S_0}{C}\right) + T_0 \right) - \\ &S_0 T_0 \left(\exp\left(\frac{S-S_0}{C}\right) - 1 \right) + \psi_0 + ST_0 \exp\left(\frac{S-S_0}{C}\right). \end{aligned} \quad (18)$$

Further transformations of Eq. 18 imply the following:

$$\begin{aligned}
e &= a^2 \frac{1}{2\rho} (\rho - \rho_0)^2 + p_0 \left(\frac{1}{\rho_0} - \frac{1}{\rho} \right) - \left(T_0 \exp\left(\frac{S-S_0}{c}\right) (S - S_0) - CT_0 \exp\left(\frac{S-S_0}{c}\right) + CT_0 \right) - \\
& S_0 T_0 \left(\exp\left(\frac{S-S_0}{c}\right) - 1 \right) + \psi_0 + ST_0 \exp\left(\frac{S-S_0}{c}\right) \Rightarrow \\
a^2 \frac{1}{2\rho} (\rho - \rho_0)^2 + p_0 \left(\frac{1}{\rho_0} - \frac{1}{\rho} \right) - T_0 \exp\left(\frac{S-S_0}{c}\right) S + S_0 T_0 \exp\left(\frac{S-S_0}{c}\right) + CT_0 \exp\left(\frac{S-S_0}{c}\right) - CT_0 - & (19) \\
& S_0 T_0 \exp\left(\frac{S-S_0}{c}\right) + S_0 T_0 + \psi_0 + ST_0 \exp\left(\frac{S-S_0}{c}\right) \rightarrow \\
a^2 \frac{1}{2\rho} (\rho - \rho_0)^2 + p_0 \left(\frac{1}{\rho_0} - \frac{1}{\rho} \right) + CT_0 \left(\exp\left(\frac{S-S_0}{c}\right) - 1 \right) + S_0 T_0 + \psi_0 &
\end{aligned}$$

The last relationship in Eq. 19 can be rewritten as Eq. 16, which is the required explicit form of the complete EoS for our model in terms of the internal-energy function.

Using the EoS (Eq. 16), we get the following for the pressure function $p(\rho, S)$:

$$p(\rho, S) - p_0 = a^2 \frac{\rho^2 - \rho_0^2}{2}, \quad (20)$$

as implied by the chain

$$p(\rho, S) \equiv \rho^2 e_\rho(\rho, S) = a^2 \frac{\rho^2 - \rho_0^2}{2} + p_0.$$

We then get

$$p_\rho(\rho, S) = a^2 \rho. \quad (21)$$

In particular, we get

$$p_\rho(\rho_0, S_0) = a^2 \rho_0. \quad (22)$$

Comparing Eqs. 18 and 21, we get

$$p_\rho(\rho_0, S_0) - p_\rho(\rho_0, T_0) = 0. \quad (23)$$

6. The Perfect Gas EoS

Per Landau and Lifshitz,⁵ the ideal gas characterizes by the internal energy $e(\rho, S)$:

$$e(\rho, S) - e_0 = CT_0 \left[\exp\left(\frac{S-S_0}{C}\right) \left(\frac{\rho}{\rho_0}\right)^{\frac{R}{C}} - 1 \right], \quad (24)$$

where R is the universal gas constant and C is the heat capacity at constant volume.

Using Eq. 24, we get

$$T(\rho, S) = T_0 \exp\left(\frac{S-S_0}{C}\right) \left(\frac{\rho}{\rho_0}\right)^{\frac{R}{C}} \quad (25)$$

and

$$p(\rho, S) = CT_0 \exp\left(\frac{S-S_0}{C}\right) \left(\frac{\rho}{\rho_0}\right)^{\frac{R}{C}} \frac{R(R-C)}{C^2} = \frac{R}{C} \left(\frac{R}{C} - 1\right) CT(\rho, S). \quad (26)$$

For the free-energy function $\psi(\rho, T)$, we get

$$\psi(\rho, T) - \psi_0 = RT \ln \frac{\rho}{\rho_0} + CT_0 \left(\frac{T}{T_0} - 1\right) - CT_0 \frac{T}{T_0} \ln \frac{T}{T_0}. \quad (27)$$

Using Eq. 27, we get

$$p(\rho, T) = \rho RT \quad (28)$$

and

$$S(\rho, T) = -\psi_T(\rho, T) = C \ln \frac{T}{T_0} - R \ln \frac{\rho}{\rho_0}. \quad (29)$$

We then get

$$C(\rho, T) \equiv T \frac{\partial S(\rho, T)}{\partial T} = C = \text{const}. \quad (30)$$

7. One-Dimensional Equilibrium Configuration of Gaseous Plasma

Consider an infinite domain Ω , confined by two parallel plates located at $z = \pm H$. Let the domain be filled with the charged gas of, say, electrons. The parts of the gas experience the action of two forces: the Coulomb repulsion and the standard gas pressure. In the absence of the wall's confinement, the charged particles would go to infinity, thus diminishing both the Coulomb forces and the pressure. In the closed vessel, however, they cannot do so, and will try to approach the vessel's walls. In the absence of pressure, all the particles will be distributed over the walls with the finite surface density ρ_s . In fact, this means that the gas will be compressed to an infinite density. The distribution of the density ρ_s can be calculated with the help of the classical system of electrostatics. Of course, this model has an obvious limitation since in reality the gas density cannot be infinite.

To fix this limitation the internal energy of the gas should be taken into account. In the first report¹ of this series, we demonstrated how this idea can be implemented in the quantitative continuum theory of thermodynamic equilibrium of charged gases, establishing the relevant equations of equilibrium. The system, however, is not closed on its own. To close the system, the EoS is required. The postulated EoS allows one to get the closed system and calculate the physical parameters of the equilibrium configurations.

Generally speaking, the calculations require computer-based numerical methods, especially for complex geometries of the vessel. Only for some very special geometries does the closed system permit analytical solutions. Those analytical solutions play two important roles. First, they allow exploration of the physics of the phenomena at hand; in this respect, the analytical closed-form solution has a big advantage over the numerical solutions. This is especially important for analysis of the special asymptotic shapes like needles or pancakes. The second role of analytical closed-form solutions concerns the V&V procedure of numerical implementations. The advantage of having the exact solution for verification purposes is self-obvious.

8. General Equilibrium Equations

Let us dwell on the simplest 1-D geometry, shown in Fig. 1. In this case, the equilibrium electrostatic field is orthogonal to the boundary plate and depends on

the vertical z -coordinate only. The same is true regarding the electrostatic potential $\phi(z)$ and the density distribution $\rho(z)$.

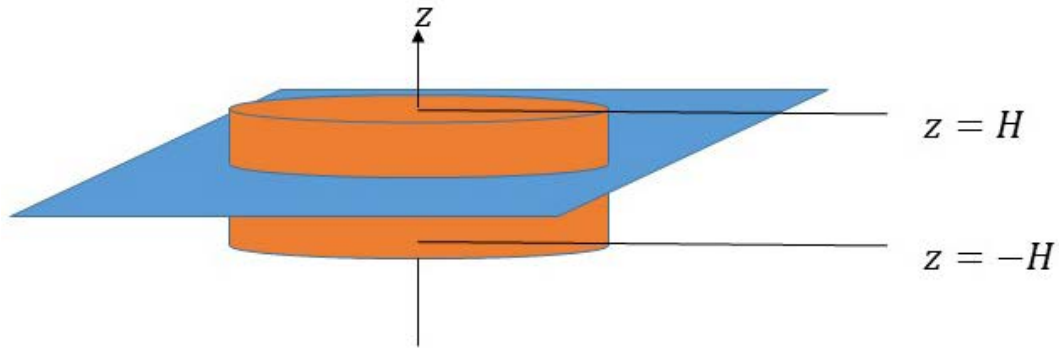


Fig. 1 One-dimensional distribution of charged compressible substance between parallel plates

Per the analysis of Grinfeld and Grinfeld,¹ the entire system of equilibrium equations includes the following three elements:

- 1) the condition of thermal equilibrium

$$T = const \tag{31}$$

throughout the whole configuration,

- 2) the electrostatics system

$$\frac{d^2\phi}{dz^2} = -4\pi\sigma\rho, \tag{32}$$

where σ is the electric charge per unit mass, and

- 3) the electrochemistry equation

$$(\rho e)_\rho + \sigma\phi = \Lambda, \tag{33}$$

in which Λ is the indefinite Lagrange multiplier.

To determine the Lagrange multiplier, we have to use the equation dealing with the total charge (or mass) of the system. Let M be the total mass of the gas per unit cross section. This leads to the relationship

$$\int_{-H}^H dz \rho(z) = M. \tag{34}$$

Differentiating Eq. 33, we get

$$a^2 \frac{d\rho}{dz} + \sigma \frac{d\phi}{dz} = 0 \quad (35)$$

or

$$\frac{d\phi}{dz} = -\frac{a^2}{\sigma} \frac{d\rho}{dz}. \quad (36)$$

Inserting Eq. 36 in Eq. 32, we get

$$\frac{d^2\rho}{dz^2} - \frac{4\pi\sigma^2}{a^2} \rho = 0. \quad (37)$$

Equation 37 has the following general solution:

$$\rho(z) = C_s \sinh(\Delta z) + C_c \cosh(\Delta z), \quad (38)$$

where

$$\Delta \equiv \sqrt{\frac{4\pi\sigma^2}{a^2}}. \quad (39)$$

Combining Eq. 38 with Eq. 39, we get

$$\frac{d\phi}{dz} = -\frac{a^2}{\sigma} \frac{d\rho}{dz} = -\frac{a^2\Delta}{\sigma} (C_s \cosh(\Delta z) + C_c \sinh(\Delta z)). \quad (40)$$

The solution should be symmetric with respect to the midplane of the domain $|z| \leq H$; thus, we get

$$\rho(z) = C_c \cosh(\Delta z). \quad (41)$$

We then get

$$M = 2C_c \frac{\sinh(\Delta H)}{\Delta}, \quad (42)$$

implying

$$C_c = \frac{M}{2} \frac{\Delta}{\sinh(\Delta H)}, \quad (43)$$

and eventually we get

$$\rho(z) = \frac{M\Delta}{2} \frac{\cosh(\Delta z)}{\sinh(\Delta H)}. \quad (44)$$

9. Conclusion

We postulated a novel EoS for analysis of an electrically charged gas. The newly formulated model is given in the form of the free-energy density function Eq. 1 or, equivalently, in the form of the internal-energy function Eq. 16. The postulated free-energy density function depends on the two thermodynamic variables: the mass density ρ and the absolute temperature T . In addition, it depends on seven constants: ρ_0 , T_0 , ψ_0 , S_0 , p_0 , a^2 , and C . The constants ρ_0 and T_0 are the density and the absolute temperature in the ground state. Needless to say, among all the feasible states, the ground state can be chosen arbitrarily. The constants ψ_0 and S_0 are the free-energy and entropy density per unit mass in the ground state, while p_0 is the pressure. The remaining material constants a^2 and C characterize the substance compressibility and the heat capacity at fixed density, respectively.

We demonstrated how to use the postulated EoS for the analysis of the 1-D problem of the electrostatic equilibrium of a charged gas existing between two parallel nonpenetrable plates. We found the exact, explicit solution of this problem, which can be used for V&V purposes.

10. References

1. Grinfeld M, Grinfeld P. The Gibbs variational method in thermodynamics of equilibrium plasma: 1: General conditions of equilibrium and stability for one-component charged gas. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2018 Apr. Report No.: ARL-TR-8348.
2. Grinfeld M. Operational equations of state for modeling high-rate phenomena. In Chalivendra V, Song B, Casem D. Dynamic behavior of materials. Volume 1. New York (NY): Springer-Verlag; 2013. p. 337–344.
3. Segletes SS, Walters WP. On theories of the Gruneisen parameter. *J Phys Chem Solids*. 1998;3:425–433.
4. Segletes SS. A frequency-based equation of state for metals. *Int J Impact Engng*. 1998;21(9):747–760.
5. Landau LD, Lifshitz EM. *Statistical physics*. Oxford (UK): Butterworth-Heinemann; 1980.

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