Electrical resistivity of liquid expanded metals by Ziman approach

K P Migdal\textsuperscript{1,2}, Yu V Petrov\textsuperscript{2,3}, V V Zhakhovsky\textsuperscript{1,2} and N A Inogamov\textsuperscript{1,2}

\textsuperscript{1} Dukhov Research Institute of Automatics (VNIIA), Sushchevskaya 22, Moscow 127055, Russia
\textsuperscript{2} Landau Institute for Theoretical Physics of the Russian Academy of Sciences, Akademika Semenova 1a, Chernogolovka, Moscow Region 142432, Russia
\textsuperscript{3} Moscow Institute of Physics and Technology, Institutskiy Pereulok 9, Dolgoprudny, Moscow Region 141700, Russia

E-mail: kir-migdal@yandex.ru

Abstract. Transport properties of metals near the critical points were intensively studied. Using quantum dynamics simulations, we consider the structures of liquid aluminum and copper at high equilibrium temperatures and strong expansion. On the other hand, we carry out classical molecular dynamics simulations using the embedded atom method interatomic potentials. Both approaches provide data for resistivity calculations based on the well-known Ziman–Evans formula. The results of these calculations show a weak dependence on the used methods of ion structure computations. Also, we demonstrate that an effect of electron exchange and correlation is taken into account in electron–ion screening function, makes electric resistivity smaller in all considered situations.

1. Introduction

In this paper, we consider electrical resistivity of liquid aluminum, copper, and gold along their binodal curves. Kubo–Greenwood calculations combined with quantum molecular dynamics (QMD) is a well-known method to investigate transport properties of liquid metals [1–4]. But using this method for the systems near the critical point is a very challenging task due to the huge value of fluctuation in comparison with the available linear size of QMD supercell which is few nanometers. Therefore, it may be useful to have an alternative approach, where we can consider atomic configurations of significantly greater size. The aim of this work is to provide data on the electrical resistivity of strongly expanded metals at high temperatures. These data can be used in the magnetohydrodynamic simulations of electric explosions of wires [5–7] which is a powerful method of experimental investigation of the discussed state of metals [8, 9].

The simplicity of the method proposed by Ziman [10, 11] and adopted by Evans [12] allows to divide task on some independent calculations. According to [12], we should determine the cross-section due to Coulomb interaction of electrons on ions and also calculate structure factor and chemical potential. Thus, the task is a sum of two problems:

- a collision of a single electron on charged ion;
- atomic distribution at considered thermodynamic conditions.
Figure 1. (a) CMD results for structure factors of Al at temperatures 5, 7.5 and 10 kK for density of 2 g/cm$^3$ (blue, green and red lines). (b) CMD results for $S(q)$ of Al at densities 1, 1.5 and 2 g/cm$^3$ for temperature of 10 kK (green, red and black lines) in comparison with the result of QMD calculation for 500 atoms (1 g/cm$^3$ and 10 kK) shown by purple line.

In the first case, we can use density functional theory (DFT) to investigate charge distribution inside the charged ion and beneath them. Using of classical molecular dynamics (CMD) we can obtain a solution of the second problem more easily for large systems with $10^4$–$10^5$ atoms.

Calculations of electrical conductivity of metals based on the ZE formula are the subjects of many investigations [13–15] where this formula is often used in modified form. We need to emphasize the main features of our calculation. The first one is a usage of charge distribution obtained by DFT to define a radius of the excluded inner core in the Ashcroft pseudopotential [16]. The second feature is taking into account a change of the radius mentioned above with electron temperature. It will be shown below that such a change has a value comparable with an effect of volume expansion. The third peculiarity is a focus of our work on the resistivity of metals at thermodynamic conditions close to their critical points. To provide calculations based on the ZE formula, we used previously developed two-parabolic approximation [17] and taken into account strong volume expansion at isobaric heating of metals.

In this work, we consider states of metals where electrons and ions are in equilibrium. On the other hand, we use here the form of Abarenkov–Heine [18] proposed by Ashcroft et al [16]. In this form, the inner sphere of core electrons are excluded, and a radius of this sphere can change with growth of electron or ion temperature. Both effects should be taken into account, but now only electron heating is investigated using density functional theory. As we neglect an effect of ion redistribution due to the increase of temperature and melting, we consider at this step an ideal lattice of metals called above.

For some cases, we also provided QMD calculations of ionic configurations which were used in Kubo–Greenwood calculations. We obtained structure factor and transport properties of hot and strongly expanded aluminum at $T = 10000$ K and density 1 g/cm$^3$. Also we considered copper at $T = 7500$ K and density 5 g/cm$^3$. These states are close to the measured or predicted critical points in many works [19–25].
Figure 2. (a) Distribution of electron density in aluminum. Results of FP-LAPW calculation are represented by solid black line. Dashed green and blue lines correspond to the best exponential fit for the areas of core electrons. Yellow dotted area is a region where the possible rcut should be determined. (b) The comparison between our data for aluminum at ρ = 2.7 g/cm³ (solid lines) and the results of pseudopotential calculation [26] (circles). Black line and circles correspond to normal conditions and data shown by red is obtained at high electron temperature 6 eV.

2. Calculation details

To investigate electron structure of metals and the states of strong expansion we carried out all-electron calculations using full-potential linearized augmented plane waves (FP-LAPW) code Elk [27]. Exchange-correlation contribution to energy functional was evaluated with the help of Perdew–Burke–Ernzerhof (PBE) form of generalized gradient approximation [28] for discussed metals but gold where local density approximation (LDA) in the Perdew–Zunger parametrization [29] were used. The latter choice was caused by more accurate prediction of equilibrium density for gold in LDA. The Monkhorst–Pack grid [30] has 25 × 25 × 25 points in the first Brillouin zone and the product of muffin-tin radii and maximum electron momentum was 8.5.

Calculation of ionic configuration by QMD was carried out by use of projected-augmented waves (PAW) [31] method realized in the VASP code [32, 33]. Approximations for exchange-correlational functional were chosen in the same manner as for the all-electron calculations. To obtain ionic configurations which correspond to considered thermodynamic states of liquid metals we provided QMD simulations similar to one discussed in the previous work [34].

In the case of aluminum near its critical point, we consider the supercell with 500 atoms initially placed in fcc lattice positions. For the gold and copper, the supercells were smaller (128 atoms) due to the greater number of electrons per atom. The Monkhorst–Pack grid has more than one points (3 × 3 × 3 for Al, 4 × 4 × 4 for Au, Cu) which is necessary to reproduce electronic structure and ionic configurations in the states we consider more properly.

In our CMD simulation the LAMMPS code was used [35] and interatomic potentials in the embedded-atom model were chosen in the parametrization provided in [36]. Here, the supercells with 108 000 atoms were obtained to evaluate radial distribution functions g(r) with good accuracy for long-range density correlations (rmax = 30 Å). Hereafter, we used the well-
known relation between structure factor and radial distribution function. The results of this transformation for aluminum are shown in figure 1. In our calculation we used Ziman–Evans (ZE) formula for electrical resistivity expressed as:

\[ \rho(T) = \frac{m_{s}^{2}}{12\pi^{3}\hbar^{3}n_{i}Z_{e}^{2}e^{2}} \int_{0}^{+\infty} f(k/2) |U(k)|^{2} S(k)k^{3}dk. \]  

(1)

Here, \( m_{s} \) is the effective mass of sp-band electrons, \( n_{i} \) is the concentration of ions, \( Z_{e} \) is the number of free electrons per ion. Square electron charge and the Planck constant (in CGSE units) are denoted as \( e^{2} \) and \( \hbar \), respectively. This expression is obtained using partial integration for the initial ZE formula [12]. We can do such a transformation due to the special form of differential scattering cross section \( d\sigma/d\theta = F(k, \theta) \), where \( \theta \) is an angle of scattering. Indeed, we can write using the second Born approximation [37]:

\[ \frac{d\sigma}{d\theta} = \frac{|U(k)|^{2}}{4\pi^{2}}, \]

(2)

where the differential cross-section is a function of single argument.

The condition of weakness for electron–ion interaction \( U(k) \) was satisfied because the Ashcroft empty-core form [16] of Abarenkov–Heine pseudopotential was used:

\[ U(k) = \frac{4\pi Z_{e}e^{2} \cos(kr_{\text{cut}})}{k^{2}}. \]

(3)

The single parameter of this potential is the radius of excluded inner charge \( r_{\text{cut}} \). This value was determined by use of the data of all-electron calculations for electron charge density. We obtained a density distribution along some directions in the face centered cubic (fcc) lattice which are connecting the closest atoms in this structure. The used path in the unit cell was set by points \( A(1/2, 0, 0) \rightarrow B(0, 0, 1) \rightarrow C(0, 0, 0) \rightarrow D(1, 0, 0) \rightarrow E(1, 1/2, 0) \rightarrow F(1/2, 1/2, 1/2) \rightarrow G(0, 0, 0) \rightarrow H(3/4, 3/4, 0) \rightarrow I(1, 1, 0) \).
Figure 4. Density of states of aluminum at 1 g/cm$^3$. The result of all-electron calculation for ideal fcc lattice are shown by black line. The data of QMD calculation are presented by purple line.

As was said in section 1, we do not take into account any effects caused by the temperature of ions. Thus, we used density-functional calculations to reproduce the distribution of electron density for core electrons of the considered metals. As we will show below, the radius of the excluded core in the approach [16] is approximately two times smaller than the half of minimum interatomic distance for all metals we investigated. The distribution of electron density shown in figure 2(a) can be divided into three areas. The first one can be interpreted as a sphere where $1s^2$ electrons placed. In logarithmic scale the behavior of $n(r) \approx \alpha_1 r$ seems like linear according to figure 2(a). It corresponds to the exponential fit which was defined the form $n_1(r) = a_1 \exp(-\alpha_1 r)$ where $a_1$ is equal to $1.013 \times 10^4$ Å$^{-3}$ and $\alpha_1$ is equal to $41.59$ Å$^{-1}$. The second area is analogous to the first one, but the electrons placed here are $2s^2$ and $2p^6$. The best fit is also exponential as before with constants $a_2 = 3.38 \times 10^2$ Å$^{-3}$ and $\alpha_2 = -9.45$ Å$^{-1}$. At the same time, the agreement between them and the result of the calculation is not so good. We can interpret this fact as a manifestation of the more difficult functional form of eigenfunctions for $2s$ and $2p$ electrons in contrast with $1s$ band where the exponential solution is exact in the case of hydrogen.

In the third area we can not see any manifestation of exponential decay of electron distribution function $n(r)$. On the other hand, the result of integration in the ranges of the first and the second areas gives approximately ten electrons. Here we use the simple form for a dependence of some electrons inside a sphere of radius $r$:

$$N(r) = 4\pi \int_0^r r' 2n(r')dr'.$$

Therefore, we can use the boundary of the second and third areas in figure 2(a) as a definition of the radius of excluded inner charge $r_{cut}$. In figure 2(b) the comparison between our data and the results of pseudopotential calculation [26] for two electron temperatures is provided.
Table 1. Electron structure parameters of Al, Au and Cu.

|       | ρ (g/cm^3) | ε_F − ε_s (eV) | z_s | r_cut (Å) |
|-------|------------|-----------------|-----|-----------|
| Aluminum |            |                 |     |           |
| 1     | −5.8       | 3               | 0.79|           |
| 1.5   | −7.8       | 3               | 0.76|           |
| 2     | −9.0       | 3               | 0.71|           |
| 2.7   | −11.1      | 3               | 0.69|           |
| Gold  |            |                 |     |           |
| 6     | −3.0       | 1               | 1.32|           |
| 10    | −5.4       | 1               | 1.25|           |
| 14    | −7.4       | 1               | 1.22|           |
| 17    | −8.0       | 1               | 1.16|           |
| 19.3  | −9.2       | 1               | 1.09|           |
| Copper |            |                 |     |           |
| 5     | −6.4       | 2               | 0.95|           |
| 8     | −9.5       | 2               | 0.9 |           |

According to figure 2(b), we see a qualitative agreement between two different calculations: at high electron temperatures electron density redistributes more close to a nucleus. At the same time, our calculation predicts weak response to the growth of electron temperature in comparison with the data of work [26].

We neglected any angular dependence of electron density distribution due to the following reasons. The first one is our choice to consider core electrons and estimate a radius of a sphere where they are collected. The second reason is the independence of electron distribution n(r) on the directions of the path we used. As shown in figure 3, we have the same behavior of n(r) in three considered different directions with respect to a nucleus: (x,0,0), (x,x,0) and (x,x,x) where x → 0.

Number of free electrons was determined with the use of the density of states (DOS) obtained simultaneously with charge density. According to figure 4, density of states for aluminum with proper distribution of hot ions (T_i = 10000 K) is drastically change with respect to the result of FP-LAPW calculation where the density and electron temperature were the same (1 g/cm^3 and 10000 K), but ions were in ideal fcc lattice positions. On the other hand, the Fermi energy according to our QMD calculation is subjected to the scaling E_F ∼ √N_e [38, 39] where N_e is electron density. Due to simplicity of the aluminum electronic structure, we propose that N_e = ZN_at where Z = 3 at the considered conditions. Using the value of E_F = 11.1 eV at 2.7 g/cm^3 (aluminum DOS does not depends on electron temperatures up to 6 eV [40]), we can write for density of 1 g/cm^3 E_F ≈ 8 eV which is in good agreement with the data shown in figure 4. To determine chemical potentials of aluminum, copper, and gold, we used two-parabolic model [41]. In this model, we replace the density of states obtained by DFT calculation on the sum of two contributions (or one for aluminum) corresponding to the valence bands of the
considered metals. These contributions have a form similar to the case of free electron gas, where effective electron masses and band energies are taken from DFT or QMD calculation. In our calculation, the effective number of electrons in table 1 used in formula (1) ever coincides with the number of electrons determined by s-parabola. This means that we neglect by the contribution of d-electrons of copper or gold in their electric conductivity. In our previous works [17, 41], we shown that such a contribution is sufficiently small if we use the relaxation time approximation to solve the Boltzmann kinetic equation.

The dependence of electron distribution in the spherical slab on the radius $r$ for aluminum is shown in figure 5(a). We see the results obtained at four densities in the range of 1–2.7 g/cm$^3$ (see also table 1). According to these data, the radius of excluded core charge changes significantly smaller than the minimum interatomic distance at such an expansion. Indeed, the latter has grown on 39% while $r_{cut}$ increased only on 15%.

In the case of gold, we should answer the question about a change of electronic structure with temperature of electrons. This effect was shown firstly in work [40] and was determined after that for other noble metals [41]. We provided an investigation of the influence of electron heating on electron distribution close to nuclei at equilibrium gold density (19.3 g/cm$^3$). The results are shown in figure 5(b) can be considered as a proof of sufficiently smaller change of $r_{cut}$ at the temperatures limited by 10 000 K.
Table 2. Electrical resistivity obtained by using of Lindhard $\rho_L^e$ and Singwi–Sjoelander $\rho_{SS}^e$ form of screening function for expanded and hot liquid metals in comparison with the data of first-principles Kubo–Greenwood calculation $\rho_{QMD}^e$ and experiments $\rho_{exp}^e$.

| $\rho$ (g/cm$^3$) | $T$ (kK) | $\rho_L^e$ (µOhm m) | $\rho_{SS}^e$ (µOhm m) | $\rho_{QMD}^e$ (µOhm m) | $\rho_{exp}^e$ (µOhm m) |
|---|---|---|---|---|---|
| Aluminum | | | | | |
| 1 | 10 | 1.02 | 0.66 | 2.46 ± 0.07 | 3.25 [42] |
| 1 | 11.6 | — | — | — | 11 ± 3 [43] |
| 1 | 10 | — | — | — | 12 ± 2 [44] |
| 1.5 | 10 | 0.85 | 0.68 | — | 0.9 [45] |
| 1.5 | 11.6 | — | — | — | 5 ± 4 [43] |
| 1.5 | 7.5 | 0.63 | 0.46 | — | 1.3$^a$ [9] |
| 2 | 10 | 0.73 | 0.63 | — | — |
| 2 | 11.6 | — | — | — | 0.6 ± 0.2 [43] |
| 2 | 7.5 | 0.71 | 0.61 | — | — |
| 2 | 5 | 0.69 | 0.59 | — | — |
| 2 | 3.7 | — | — | — | 1.4 ± 0.3 [43] |
| 2 | 2 | 0.63 | 0.58 | 0.34 ± 0.04 | 0.36 [46] |
| 2 | 2 | — | — | — | 0.39 [47] |
| 2.7 | 2 | 0.63 | 0.56 | — | — |
| Gold | | | | | |
| 6 | 10 | 1.67 | 1.26 | — | — |
| 10 | 10 | 1.21 | 1.04 | — | — |
| 10 | 7.5 | 0.99 | 0.81 | — | — |
| 14 | 10 | 1.12 | 1.03 | — | — |
| 14 | 7.5 | 1.01 | 0.92 | — | 0.8$^b$ [48] |
| 17 | 2 | 0.52 | 0.48 | 0.51 ± 0.05 | 0.47$^c$ [48] |
| 19.3 | 2 | 0.28 | 0.27 | 0.44 ± 0.05 | — |
| 19.3 | 7.5 | 0.47 | 0.45 | 0.59 ± 0.07 | — |
| Copper | | | | | |
| 5 | 7.5 | 1.63 | 1.37 | 0.98 ± 0.07 | 1.0$^d$ [49] |
| 5 | 7.5 | — | — | — | 0.6$^e$ [50] |
| 5 | 7.5 | — | — | — | 0.8$^f$ [45] |
| 8 | 7.5 | 1.08 | 0.99 | 0.60 ± 0.05 | 0.352$^g$ [51] |

$^a$ Measured at density of 1.4 g/cm$^3$.
$^b$ Measured at temperature of 3500 K.
$^c$ Measured at density of 16 g/cm$^3$.
$^d$ Measured at temperature of 8000 K and density of 4 g/cm$^3$.
$^e$ Measured at temperature of 6000 K.
$^f$ Measured at temperature of 10 000 K.
$^g$ Measured at density of 7.5 g/cm$^3$. 
3. Results

In table 1 the parameters of electron structure used in the calculations based on the ZE formula are given. We should note that the width of s-band below the Fermi energy was evaluated using FP-LAPW calculations with ideal fcc lattice. As shown below in figure 4, this method gives an error of few eV according to the data of quantum molecular dynamics where large supercell (500 atoms) and dense k-grid (3 × 3 × 3) were used. Thus, one of possible improvements of our current computations may be related with further investigation of a proper ion configuration to define an electron structure.

The structure factors of aluminum for some expanded states are shown in figure 1. We see that the results of QMD and CMD calculations are in good agreement when the values of \( q \) are great enough for 500-atomic (2.8 nm) ionic configuration used in QMD. The smoothness of structure factors represented in figure 1(a) show that our choice of supercell size is sufficient for this task. According to figure 1(b) the results of CMD and QMD calculations of the structure factor at 1 g/cm\(^3\) and 10 000 K are in good agreement at \( q \) greater than 1 Å\(^{-1}\). This fact demonstrates a good parametrization of used interatomic potential at these conditions. At smaller values of \( q \) the supercell used in the QMD calculation is not enough to reproduce ion distribution at such long ranges.

Electronic structure of aluminum in the state close to its critical point is found different by all-electron calculation for atoms in the ideal fcc lattice and by additional calculation of DOS using four configurations obtained in QMD run at the final stage where NVE ensemble was used. According to figure 4 at such a low density as 1 g/cm\(^3\) there is the gap between 3s and 3p electrons. In the case of QMD structures, the DOS is more similar to the well-known one-parabolical picture.

The results of electrical resistivity calculations are collected in table 2. We see that in the case of strongly expanded aluminum our results based on the ZE formula is significantly smaller than experimental data and even the result of Kubo–Greenwood calculation. At the conditions which are close to liquid–vapor coexistence curve of aluminum, the analytical approach provides an underestimation of electrical resistivity with respect to other methods called above. We see the almost monotonous growth of electrical resistivity obtained by the ZE formula with the expansion of aluminum and gold. In the case of gold, the results of ZE computation is more close to the data of Kubo–Greenwood approach and also to the known experimental data.

In some cases, we provide data of the published measurements [9, 45, 48–51] with the non-significant difference of considered thermodynamical conditions and designate these results by letters in alphabetical order. It makes possible to compare the results which were evaluated for expanded and hot copper. Here, analytical calculation gives a value of electrical resistivity significantly greater than one has been found in the experiments [45,49,50]. This conclusion can also be done for the copper at the density of 8 g/cm\(^3\) and temperature of 2000 K which is close to the binodal [51].

Despite on our attempts to improve this method in the framework of the second Born approximation, its accuracy is enough only for rough estimation of electrical resistivity. There are some works where the approximation mentioned above was omitted, and t-matrix approach was applied [52, 53]. Thus, we can conclude that probable solution may lie in the improvement of description a differential scattering cross-section.

4. Conclusions

The results obtained by the ZE formula allow reproducing the qualitative behavior of electrical resistivity with density and temperature. At low temperatures, our analytical results for Al and Cu based on the ZE formula overestimate the electrical resistivity with respect to the known reliable data. In the case of high temperatures and strong expansion the results of this analytical approach give almost the same value of maximum \( \rho_\infty \) for all considered metals which are close
to 1 $\mu$Ohm.m. The exclusion should be made for copper where the situation is opposite. We can note a good agreement of our analytical results for gold. The effect of electron exchange and correlation on electron–ion interaction included in Fourier transform of screened Coulomb operator results in the moderate decrease of electrical resistivity.

Acknowledgments

The authors are grateful to Dr D V Knyazev for his improvement and supplement to the VASP code for Kubo–Greenwood calculations. PYV, MKP, VVZ, and INA are also grateful to the Russian Science Foundation for support (grant No. 14-19-01599).

References

[1] Desjarlais M P, Kress J D and Collins L A 2002 Phys. Rev. E 66 025401
[2] Recoules V and Crocombette J P 2005 Phys. Rev. B: Solid State 72 104202
[3] Zhiilyaev P A, Norman G E and Stegailov V V 2013 Dokl. Phys. 58 334–8
[4] Knyazev D V and Levashov P R 2014 Phys. Plasmas 21 073302
[5] Tkachenko S I, Levashov P R and Khishchenko P R 2006 J. Phys. A: Math. Gen. 39 7597
[6] Oreskin V I, Khishchenko K V, Levashov P R, Rousskikh A G and Chaikovskii S A 2012 Teplofiz. Vys. Temp. 50 625–37
[7] Povarnitsyn M E, Andreev N E, Apfelbaum E M, Itina T E, Khishchenko K V, Kostenko O F, Levashov P R and Veysman M E 2012 Appl. Surf. Sci. 258 9480–3
[8] Wilthan B, Cagran C and Pottlacher G 2005 Int. J. Thermophys. 26 1017–29
[9] Korobenko V N, Rakhel A D, Savatimski A I and Fortov V E 2005 Phys. Rev. B: Solid State 71 014208
[10] Kresse G and Furthmüller J 1996 Phys. Rev. B: Solid State 54 1755–8
[11] Perdew J P, Burke K and Ernzerhof M 1996 Phys. Rev. Lett. 77 3865–9
[12] Perdew J P and Zunger A 1981 Phys. Rev. B: Solid State 23 5048–79
[13] Blöchl P E 1994 Phys. Rev. B: Solid State 50 17953
[14] Kresse G and Furthmüller J 1996 Phys. Rev. B: Solid State 54 1169
[15] Kresse G and Joubert C 1999 Phys. Rev. B: Solid State 59 1758–64
[16] Migdal K P, Petrov Yu V and Inogamov N A 2013 Proc. SPIE 9065 906503
[17] Landau L and Lifshitz E 1986 Statistical Physics (Butterworth-Heinemann)
[18] Petrov Yu V, Migdal K P, Inogamov N A and Levashov P R 2016 J. Phys.: Conf. Ser. 774 012103
[19] Plimpton S 1995 J. Comput. Phys. 117 1–19
[20] Zhakhovsky V V, Inogamov N A, Petrov Yu V, Ashitkov S I and Nishihara K 2009 Appl. Surf. Sci. 255 9592
[21] Landau L and Lifshitz E 1981 Quantum Mechanics: Non-Relativistic Theory (Elsevier)
[22] Landau L and Lifshitz E 1986 Statistical Physics (Butterworth-Heinemann)
[23] Recoules V, Clerouin J, Zerah G, Anglade P M and Mazevet S 2006 Phys. Rev. Lett. 96 055503
[24] Migdal K P, Petrov Yu V and Inogamov N A 2013 Proc. SPIE 9065 906503
[25] Kresse G and Furthmüller J 1996 Phys. Rev. B: Solid State 54 1169
[26] Kresse G and Joubert C 1999 Phys. Rev. B: Solid State 59 1758–64
[27] Migdal K P, Petrov Yu V and Inogamov N A 2013 Proc. SPIE 9065 906503
[42] Clerouin J, Noiret P, Korobenko V N and Rakhel A D 2008 Phys. Rev. B: Solid State 78 224203
[43] Oreshkin V I, Baksht R B, Ratakhin N A, Shishlov A V, Khishchenko K V, Levashov P R and Beilis I I 2004 Phys. Plasmas 11 4771–6
[44] DeSilva A and Rakhel A D 2005 Contrib. Plasma Phys. 45 236–42
[45] Sheftman D and Krasik Ya E 2010 Phys. Plasmas 17 112702
[46] Gathers G R 1983 Int. J. Thermophys. 4 209
[47] Desai P D, James H M and Ho C Y 1984 J. Phys. Chem. Ref. Data 13 1131
[48] Kaschnitz E, Nussbaumer G, Pottlacher G and Jäger H 1993 Int. J. Thermophys. 14 251–7
[49] DeSilva A W and Kunze H J 1994 Phys. Rev. E 49 4448
[50] Sasaki T, Nakajima M, Kawamura T and Horioka K 2010 Phys. Plasmas 17 084501
[51] Matula R A 1979 J. Phys. Chem. Ref. Data 8 1147
[52] Rozsnyai B F 2008 High Energy Density Phys. 4 64–75
[53] Starrett C E 2016 High Energy Density Phys. 19 58–64