Thomson scattering diagnostics of thermal plasmas: Laser heating of electrons and the existence of local thermodynamic equilibrium

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A number of assessments of electron temperatures in atmospheric-pressure arc plasmas using Thomson scattering of laser light have recently been published. However, in this method, the electron temperature is perturbed due to strong heating of the electrons by the incident laser beam. This heating was taken into account by measuring the electron temperature as a function of the laser pulse energy, and linearly extrapolating the results to zero pulse energy to obtain an unperturbed electron temperature. In the present paper, calculations show that the laser heating process has a highly nonlinear dependence on laser power, and that the usual linear extrapolation leads to an overestimate of the electron temperature, typically by 5000 K. The nonlinearity occurs due to the strong dependence on electron temperature of the absorption of laser energy and of the collisional and radiative cooling of the heated electrons. There are further problems in deriving accurate electron temperatures from laser scattering due to necessary averages that have to be made over the duration of the laser pulse and over the finite volume from which laser light is scattered. These problems are particularly acute in measurements in which the laser beam is defocused in order to minimize laser heating; this can lead to the derivation of electron temperatures that are significantly greater than those existing anywhere in the scattering volume. It was concluded from the earlier Thomson scattering measurements that there were significant deviations from equilibrium between the electron and heavy-particle temperatures at the center of arc plasmas of industrial interest. The present calculations indicate that such deviations are only of the order of 1000 K in 20 000 K, so that the usual approximation that arc plasmas are approximately in local thermodynamic equilibrium still applies.

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I. INTRODUCTION

Thomson scattering of laser light is a widely used diagnostic method for the measurement of electron and ion temperatures in plasmas. The temperatures are usually derived from the spectral distribution of the scattered light [1,2]. The results of a number of Thomson scattering measurements of electron and ion temperatures in atmospheric-pressure thermal plasmas, such as welding arcs and plasma jets, have been reported since 1993. It has been concluded from these measurements that the electron temperature is many thousands of kelvin higher than the ion temperature. Snyder, Lassahn, and Reynolds [3] measured an electron temperature of $20\,900 \pm 1700$ K and an ion temperature of $14\,200 \pm 700$ K at a position 2 mm below the cathode of a 100 A free-burning arc in argon. Bentley [4] repeated the electron temperature measurements, using a different method to derive the temperature from the spectrum of the scattered light, and obtained a temperature of $20\,400 \pm 500$ K. Spectroscopic measurements of a similar arc yielded an excitation temperature of 16 600 K, in agreement with the temperature given by a laser-scattering technique in which the ion temperature was obtained from the scattered signal integrated over a range of wavelengths [5]. Tanaka and Ushio [6] compared Thomson scattering measurements of electron and ion temperatures and spectroscopic measurements of excitation temperature of 50 and 150 A arcs in argon. They found that the ion and excitation temperatures were comparable, but that the electron temperature was about 5000 K higher. Measurements performed in an atmospheric-pressure plasma jet also gave electron temperatures far in excess of the ion temperatures and excitation temperatures. For example, the electron temperature was measured to be $22\,000 \pm 1000$ K at a position 2 mm downstream of the plasma torch in a 900 A argon jet [7], compared to an ion temperature of $12\,600 \pm 900$ K and an excitation temperature of 14 500 K at the same position [8].

The large differences between electron and ion temperatures suggested by these measurements are difficult to reconcile with the conclusions of most theoretical and experimental studies of thermal plasmas, which indicated that the central regions of welding arcs and plasma jets at atmospheric pressure are in local thermodynamic equilibrium (LTE). LTE requires that the composition corresponds to that calculated assuming local chemical equilibrium, that the translational energy distributions of all species are Maxwellian, that the excitation energies of bound electrons follow a Boltzmann distribution, and that the temperatures defined by these distributions are the same for all species.

It has been demonstrated that deviations from LTE do in fact occur in some regions of thermal plasmas. For example, an underpopulation of excited atomic states occurs within 1 mm of the cathode of free-burning arcs [9]; it has been shown that this is due to the rapid convective influx of cold gas caused by the pinch effect. Deviations from LTE also occur near the anode [10]. In the fringes of the plasma, an overpopulation of excited states due to resonance absorption of radiation has been measured [11]; further, the steep gradients lead to diffusion that is more rapid than some recombi-

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nation reactions, resulting in deviations from local chemical equilibrium composition [12]. However, the bulk of the theoretical [13,14] and experimental [5,15] evidence is that the regions away from the electrodes and fringes are in or close to LTE for electron densities above about 10^{23} m^{-3}, owing to the rapid equilibration of states due to the high collision rates. Such electron densities occur at temperatures above 12 800 K in atmospheric-pressure argon plasmas in LTE.

The assumption of LTE is used in almost all computational models of thermal plasmas. It greatly simplifies calulations of properties of arc plasmas which occur in industry, such as in plasma torches, arc welding, and circuit breakers. LTE is also assumed in the derivation of fundamental atomic data derived from electric arc measurements. Such data are used in fields as diverse as astrophysics and chemical analysis. For these reasons, there has been an intensive effort to investigate the validity of the Thomson scattering electron temperature measurements. As indicated above, the temperature measurements have been reproduced at a number of laboratories. Other workers have investigated the validity of the Thomson scattering technique as applied to thermal plasmas.

In plasmas relevant to nuclear fusion, Thomson scattering is regarded as the most reliable technique for the measurement of electron temperature. However, the much higher electron densities and much lower electron temperatures in thermal plasmas mean that there is significant heating of the electrons by the laser radiation in such plasmas. This heating has been taken into account in all the studies referred to above by measuring electron temperature as a function of laser pulse energy, and linearly extrapolating the resulting curve to zero pulse energy. Murphy [16] has demonstrated that there are number of problems with this extrapolation. In the current paper, I expand on the results and arguments presented in Ref. [16], and consider the problems inherent in measuring temperature in a plasma whose temperature is changing. Further, I elucidate the difficulties associated with measurements performed with an expanded laser beam. In these measurements, the electron heating was greatly reduced because of the lower energy density of the laser beam; nevertheless, electron temperatures much greater than the ion and spectroscopic temperatures were obtained [7,17,18].

Other workers have pursued different explanations of the anomalously high Thomson scattering electron temperatures. Gregori *et al.* [17] presented measurements that suggested that electron temperatures calculated from the measurements depended strongly on the scattering angle (the angle between the incident laser beam and the measurement axis). They proposed that this dependence arose as a result of the steep density gradients within the scattering volume, and suggested that these gradients were responsible for the anomalously high electron temperatures. They estimated that the electron temperature was in fact around 10 500 K on the axis of the plasma jet. Snyder, Crawford, and Fincke [19], however, attributed the angular dependence to collisional broadening of the electron feature, which had only a minor influence on the electron temperatures that were derived from the measurements. Taking this broadening into account yielded an electron temperature of about 18 000 K, still much higher than the excitation and ion temperatures. Terasaki *et al.* [20] provided support to the results of Snyder, Crawford and Fincke by showing that there is no dependence of electron temperature on scattering angle in a helium arc, for which the collisional broadening is expected to be insignificant.

Gregori *et al.* [18] recently suggested that the standard method [1,2] of deriving the electron temperature from the spectrum of the scattered signal was not applicable to thermal plasmas because of the low number of electrons in a Debye sphere. They suggested instead the use of a memory function method. Gregori *et al.* found that this method, which requires an additional free parameter to be fitted to the measured spectrum, gave an electron temperature of 15 700 $\pm$500 K in a plasma jet, much lower than the electron temperature obtained using the standard method, and within 1500 K of the excitation temperature. However, the question of the most appropriate method for deriving electron temperature from the scattered signal cannot be regarded as settled. The work presented in the current paper is aimed at demonstrating that the anomalously high electron temperatures obtained in Thomson scattering measurements can be explained even when the standard method for deriving electron temperatures from the scattered light spectrum is used.

II. LASER HEATING OF ELECTRONS

The measurement of electron temperature from the spectral profile of the Thomson scattered signal requires that there is sufficient scattered radiation relative to the background radiation from the plasma, necessitating the use of a high-powered pulsed laser. Typically, a frequency-doubled Nd yttrium aluminum garnet (YAG) laser, with wavelength 532 nm, is used. The interaction of the laser beam with the plasma rapidly heats the electrons by linear inverse bremsstrahlung [21]. To take this effect into account, workers have measured electron temperature as a function of laser pulse energy, fitted a straight line to the results, and extrapolated the line to zero pulse energy to obtain the electron temperature free of influence from laser heating. An example of this procedure is shown in Fig. 1.

The use of a straight line fit has been justified [3,4,6,17] by reference to Hughes [21]. Hughes, however, gives the following expression for absorption of laser light by a thermal plasma:

$$\alpha=\frac{n_e n_i Z^2 e^6[1-\exp(-\hbar\omega/k_B T_e)]}{\mu 6\pi\epsilon_0^3 c\hbar\omega^3 m_e^2}\left(\frac{m_e}{2\pi k_B T_e}\right)^{1/2}\frac{\pi}{3}\bar{g}, \tag{1}$$

where α is the absorption coefficient, n_e and n_i are the electron and ion number densities, respectively, T_e is the electron temperature, Z is the average ionization level of the plasma, μ is the refractive index of the plasma, ω is the laser frequency, and the constants e, m_e, $\hbar$, k_B, and c are the electron charge and mass, Planck's constant, Boltzmann's constant, and the speed of light respectively. Equation (1) shows that absorption of the laser light depends on T_e, n_e, and n_i, both directly, and through the average Gaunt factor $\bar{g}$.

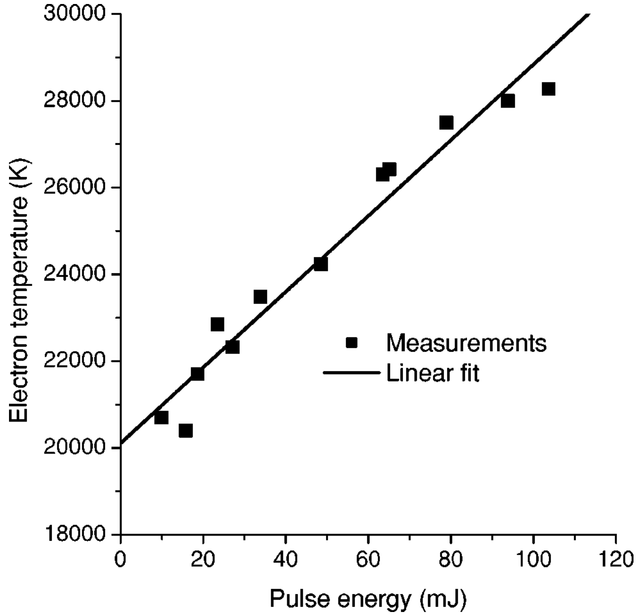

FIG. 1. Dependence of measured electron temperature on laser pulse energy on the arc axis 2 mm below the cathode in a 100 A free-burning arc in argon, and linear least-squares fit to the measurements (from Bentley [4]).

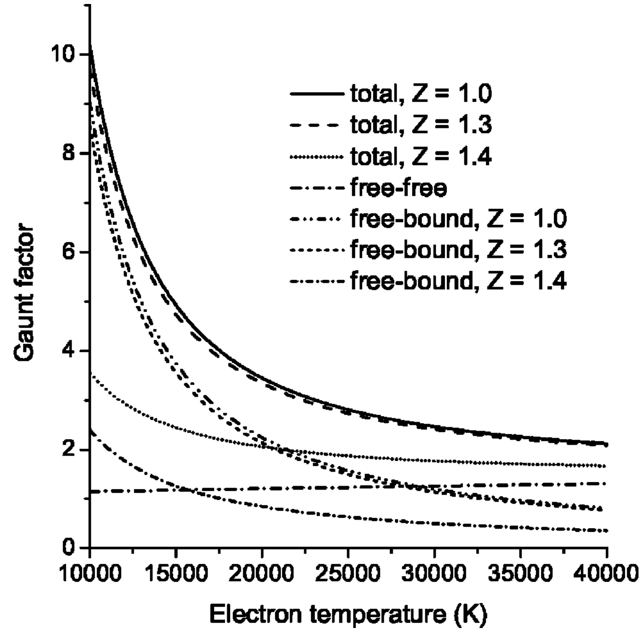

FIG. 2. Gaunt factors for different values of the average ionization level Z at a wavelength of 532 nm. The total Gaunt factor is the sum of the free-free and free-bound factors. The free-bound factor has a step-function decrease at just above $Z=1.3$.

Brussaard and van de Hulst [22] showed that the average Gaunt factor (the Gaunt factor averaged over a Maxwellian distribution) should take into account both free-free and free-bound transitions, and should be written as the sum of the free-free and the free-bound Gaunt factors. The free-free Gaunt factor is taken from the tabulation of Berger [23]. The free-bound Gaunt factor is calculated using the expression given by Brussaard and van de Hulst [22]. Figure 2 shows the electron temperature dependence of the average Gaunt factor and its components for a wavelength of 532 nm. Note that the free-bound factor is almost independent of Z for values of Z between 1.0 and 1.3, and has a step-function decrease as Z increases above 1.3.

It is clear from Eq. (1) and Fig. 2 that the absorption coefficient α depends on the electron temperature, the electron density, and the ion density, both directly and through the Gaunt factor. Since the electrons are heated during a laser pulse, the absorption coefficient will therefore vary with time during the pulse, and the total absorbed energy will have a nonlinear dependence on the laser pulse energy.

III. FLUID DYNAMIC MODELING OF LASER HEATING

A. The model

The heating of the electrons through absorption of laser radiation is balanced by cooling of the electrons due to collisional and radiative processes. The collisional processes can be separated into three particular types of interaction: collisions with other electrons (or electron thermal conduction), elastic collisions with heavy particles, and inelastic collisions with heavy particles (or electron-impact ionization).

The heating and cooling of electrons during a laser pulse can be described by a one-dimensional energy conservation equation in polar geometry. The center of the laser beam cross section corresponds to $r=0$, where r is the radial coordinate. It is assumed that the electron temperature does not vary in the azimuthal and axial directions; this requires that the plasma, before perturbation by the laser beam, is uniform across the diameter of the laser beam, and that the laser beam is cylindrical. These assumptions are reasonable, given the small diameter to which the laser is focused (typically 200 μm) and the long focal length (typically 1.5 m). The equation takes a form similar to that given by Lelevkin *et al.* [10,24] for electron temperature in an arc, with ohmic heating replaced by laser heating:

$$\frac{\partial}{\partial t}\left(\frac{5}{2}k_B n_e T_e\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(r k_e \frac{\partial T_e}{\partial r}\right)+\frac{\alpha E_p}{A\tau_p}-W_{eh} -\sum_{i=1}^{2} R_i E_i - U, \quad (2)$$

where E_p and τ_p are the laser pulse energy and duration, respectively, A is the cross-sectional area of the laser beam, r is the radial coordinate ($r=0$ corresponds to the center of the laser beam cross section), t is the time, k_e and U are the electron thermal conductivity and the radiative emission coefficient, respectively, R_i is the rate of ith ionization of argon, and E_i is the ith ionization energy of argon.

The rate of transfer of energy from electrons to heavy particles through inelastic collisions, W_{eh} is calculated using the expression of Lelevkin *et al.* [10,24], extended to take into account doubly ionized atoms

$$W_{eh}=2\frac{m_e}{m_h}\frac{3}{2}k_B(T_e-T_i)n_e\nu_{eh}, \quad (3)$$

where m_e and m_h are the electron and heavy-particle masses, T_i is the heavy-particle temperature (it is assumed that ions and atoms are at the same temperature) and the electron–heavy-particle collision frequency is given by

$$\nu_{eh}=\left(\frac{8k_BT_e}{\pi m_e}\right)^{1/2}\left(\sum_{i=1}^{2} n_iQ_{ei}+n_0Q_{e0}\right). \tag{4}$$

Here n_0, n_1, and n_2 are the number density of neutral, singly ionized, and doubly ionized argon atoms, respectively,

$$Q_{ei}=\pi\left(\frac{ie^2}{12\pi\varepsilon_0k_BT_e}\right)^2\ln\left\{\frac{1}{4\pi\varepsilon_0n_e}\left[\frac{4\pi\varepsilon_0k_BT_e}{e^2(1+T_e/T_i)}\right]^3\right\} \tag{5}$$

is the electron-ion collision cross section, and

$$Q_{e0}(\mathrm{m}^2)=[3.6\times10^{-4}T_e(\mathrm{K})-0.1]\times10^{-20} \tag{6}$$

is the electron-atom collision cross section. Equation (6) is a fit to the electron-atom collision cross-section data given by Devoto [25].

Values of the electron thermal conductivity k_e were taken from Devoto, and values of the radiative emission coefficient from Cram [26]. Note that the inclusion of radiative emission in Eq. (2) takes into account the inelastic transfer of energy from electrons to atoms and ions that results in excitation, but not ionization, of the atoms and ions. Hence, although the energy is radiated by the heavy particles, it originates from the electrons, and therefore should be included in the electron energy conservation equation.

The rates of first and second ionization, R_1 and R_2, are given by

$$R_i=k_i\left[n_en_{i-1}-\left(\frac{n_{i-1}}{n_en_i}\right)_{\mathrm{eq}}n_e^2n_i\right], \tag{7}$$

where k_1 and k_2 are the coefficients of electron-impact ionization of neutral and singly ionized argon atoms, respectively. Values of these ionization coefficients were taken from Almeida *et al.* [27]. The subscript "eq" denotes values calculated for a plasma in LTE.

The values of the number densities n_0, n_e, n_1, and n_2 are calculated as a function of time using the equations

$$dn_0/dt=-R_1, \tag{8a}$$

$$dn_1/dt=R_1-R_2, \tag{8b}$$

$$dn_2/dt=R_2, \tag{8c}$$

$$dn_e/dt=R_1+R_2, \tag{8d}$$

where the initial number densities are calculated assuming LTE.

Equation (2) was solved numerically, using a finite-difference method [28]. It was assumed that the laser beam profile was Gaussian, and that the pulse shape was square in time. It was assumed, unless otherwise noted, that initially the ion and electron temperatures were equal. It was further assumed that the heavy-particle temperature was constant during the pulse. This is consistent with Thomson scattering measurements, which show that the ion temperature is independent of laser pulse energy [3]. A laser wavelength of 532 nm was used.

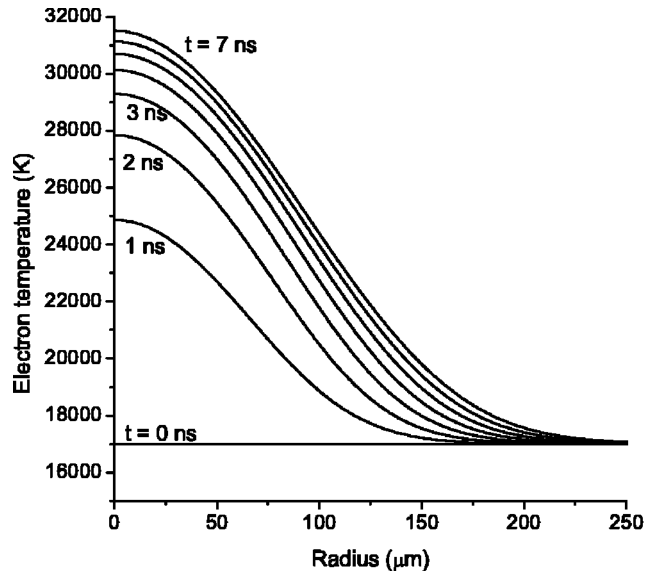

FIG. 3. Calculated radial dependence of the electron temperature in the region heated by the laser beam, at time intervals of 1 ns during a 7 ns laser pulse. The initial temperature is 17 000 K, the laser pulse energy is 100 mJ, and the laser beam radius is 100 μm.

The laser beam diameter (full width at half maximum) and the laser pulse duration were chosen to be 200 μm and 7 ns, respectively, in accordance with the experimental parameters [3,4]. The calculation region extended over a radius of 350 mm, with an evenly spaced 1-mm grid. The time step used was 0.1 ns. The adequacy of these choices was tested by doubling the time and grid resolution and the extent of the calculation region. This resulted in a smaller than 0.1% change in the calculated electron temperatures.

B. Results

Figure 3 shows typical results of the calculations for the evolution of the electron temperature during the laser pulse. The rate of temperature increase is greatest in the early part of the pulse, decreasing rapidly with time. The central electron temperature increases by 7900 K in the first nanosecond of the pulse, and by less than 400 K in the final nanosecond. The electron temperature profile is peaked on the laser beam axis due to two factors, the Gaussian laser beam profile and the transport of energy to larger radii by thermal conduction.

Figure 4 shows the evolution of the species number densities during the laser pulse, together with the electron temperature. Results are shown for $r=0$, i.e., on the axis of the laser beam. The plasma is initially singly ionized, with some ions becoming doubly ionized during the laser pulse. The electron density increases by around 5%; this is consistent with the increase measured by Bentley [4] for a similar electron temperature increase. In contrast, Snyder *et al.* [3] measured no change in the electron density during the laser pulse.

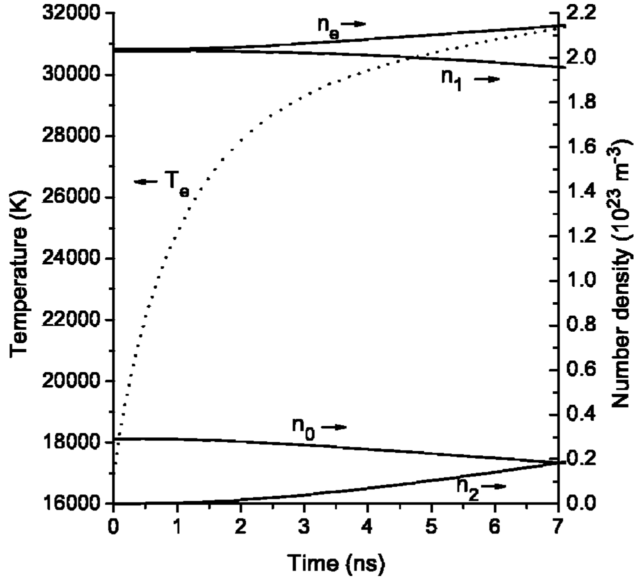

FIG. 4. Evolution of the electron temperature and species number densities at the center point of the laser beam during a 7 ns laser pulse. Parameters are as in Fig. 3.

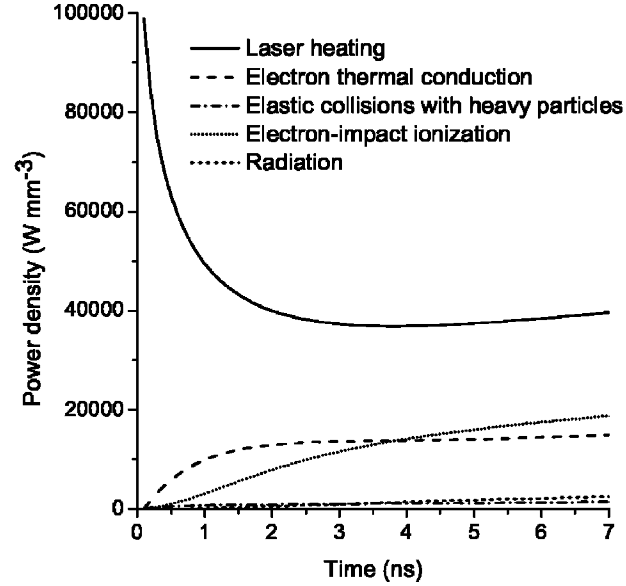

FIG. 5. Evolution of the power density of the laser heating and the different cooling processes at the centerpoint of the laser beam. Parameters are as in Fig. 3.

Figure 5 shows that the rate of absorption of laser energy decreases rapidly in the first nanoseconds of the pulse. This is predominantly a result of the electron temperature increase. The absorption increases slightly towards the end of the pulse, because of the influence of the electron density increase, which at this stage more than compensates for the relatively slow increase in electron temperature. The rate of energy loss through each of the four cooling processes increases during the pulse. Energy transfer to heavy particles through electron impact ionization and electron thermal conduction are the dominant electron cooling processes. Elastic energy transfer to heavy particles and radiative emission are much less important.

The fact that the laser power absorbed by the electrons is much greater than the rate of transfer of translational energy from the electrons to the heavy particles indicates that equilibrium is not established between the electrons and heavy particles during the laser pulse. Further, the low rate of energy transfer to heavy particles validates the assumption that the heavy particle temperature is constant throughout the laser pulse. Note that this energy transfer term would be even smaller if the heavy particle temperature were to increase, as shown by Eq. (3).

The very low radiative emission from the plasma indicates that this is not a source of deviation from LTE; while such deviations can occur in plasmas at much higher temperatures, they are not important in atmospheric-pressure arcs.

C. Application of fluid dynamic model to Thomson scattering measurements

It has been shown in Sec. III B that the absorption of laser energy decreases as the electron temperature increases, and that the rate of cooling of the heated electrons increases as the electron temperature increases. Since the electron temperature depends on the pulse energy, this implies that the electron temperature has a nonlinear dependence on the pulse energy. In this section, I examine the extent of the deviation from the linear relationship that was used to derive unperturbed electron temperatures in the works of Snyder *et al.* [3] and Bentley [4]. In so doing, I use the fluid dynamic model described in Sec. III A to fit the measured results presented in these works.

For the purposes of comparison of the electron temperatures calculated from the fluid dynamic model with the measured electron temperatures, the following procedure was adopted. For each set of measured electron temperature and pulse energy data, a least-squares fitting routine was used to find the values of the initial or unperturbed temperature T_{e0}, and a constant C by which the absorption coefficient α was multiplied, which give values of electron temperature closest to the experimental values. Deviations from $C=1$ were required to take into account experimental uncertainties in the laser beam's spatial profile and diameter, in the time dependence of the laser pulse energy, and in the spatial and temporal averaging of the electron temperature. In the initial set of calculations, the initial electron temperature and ion temperature were assumed to be equal. I consider the validity of this assumption later.

An electron temperature was obtained from the fluid dynamic model for a given pulse energy using a simple time average over the duration of the laser pulse, and a spatial average over the laser beam diameter, weighted according to the Gaussian laser beam intensity profile. The question of determining an average electron temperature is discussed further in Sec. IV.

Figures 6 and 7 show comparisons of least-squares linear fits to the measurements of Snyder *et al.* [3] and Bentley [4], respectively, with least-square fits to solutions of Eq. (2). The least-squares best fit to the measurements of Snyder *et al.*

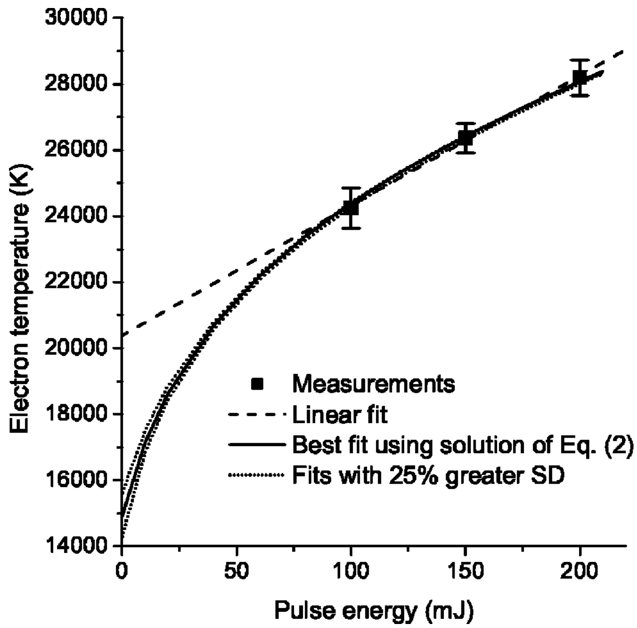

FIG. 6. Comparison between the best fit obtained using solutions to Eq. (2), and the line of best fit, to the measured data of Snyder *et al.* [3]. Also shown are fits obtained using solutions to Eq. (2) for which the standard deviation from the experimental points is 25% greater than for the best fit.

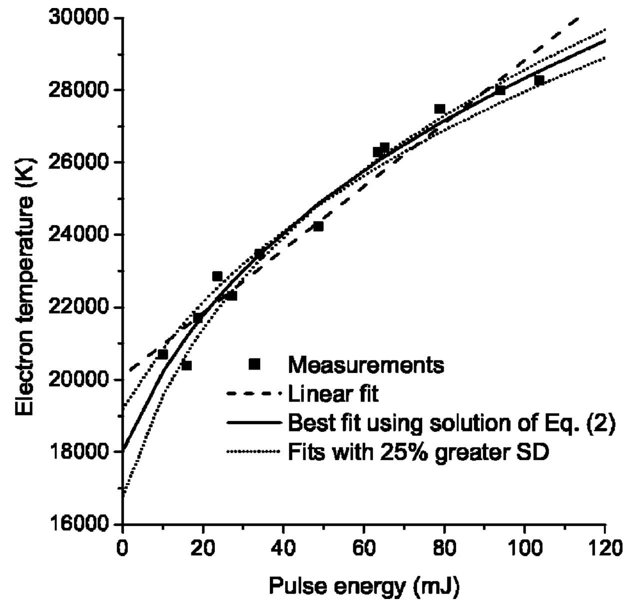

FIG. 7. As for Fig. 6, but using the measurements of Bentley [4].

using solutions of Eq. (2) was obtained with $T_{e0} = 14\,920$ K and $C = 1.29$. This is significantly less than the value of $T_{e0} = 20\,400$ K obtained from the linear fit. It is close to the ion temperature measured by Thomson scattering of $14\,200 \pm 700$ K [3]. As a measure of the sensitivity of the least-squares fit to Eq. (2), fits for which the standard deviation is 25% greater than the minimum were calculated; the deviation in T_{e0} is around 700 K.

The least-squares best fit to the measurements of Bentley using solutions of Eq. (2) was obtained with $T_{e0} = 18\,060$ K and $C = 1.71$. This is again significantly below the value of $T_{e0} = 20\,200$ K obtained from the linear fit. The deviation in T_{e0} corresponding to a 25% increase in standard deviation is in this case 1200 K. The excitation temperature, and the ion temperature measured by laser scattering, were around 16 600 K for the same conditions [5]. It is apparent from Fig. 7 that the dependence of T_e on pulse energy calculated from Eq. (2) better corresponds to the shape of the measured data than does a straight line. The values of T_{e0} calculated using best fits to the solution of Eq. (2) are between 2000 K and 6000 K lower than those obtained using a linear fit, and are within 1500 K of the ion temperature and excitation temperature.

Note that while both Snyder *et al.* and Bentley quote identical values for laser beam parameters, the electron heating shown in Fig. 7 is significantly greater than that shown in Fig. 6. Hence a larger value of C is required to fit the results shown in Fig. 7.

The reader may note that there are small differences between the best-fit values of T_{e0} and C reported here and those given previously [16]. This is because of a minor correction to the method of calculation of the width of the Gaussian profile in the computer code.

While the results presented so far indicate that the measured dependence of electron temperature on pulse energy admits unperturbed electron temperatures T_{e0} well below those given by a linear fit to the data, they do not in themselves rule out the possibility that T_{e0} is close to that given by the linear fit, since it could be conjectured that equally good fits of Eq. (2) to the experimental data may be obtained with higher values of T_{e0}. To investigate this possibility, I repeated the fitting procedure while constraining T_{e0} to be equal to the value given by the linear fit. In this case, C was the only variable in the least-squares fitting procedure. The ion temperature was set to the value given by the respective laser-scattering measurements (14 200 K for the Snyder *et al.* measurements and 16 600 K for the Bentley measurements), and the initial species number densities were set to the LTE values corresponding to T_{e0}.

Results of the calculations are given in Figs. 8 and 9. The best fits were obtained with $C = 0.670$ for the data of Snyder *et al.* and $C = 1.390$ for the data of Bentley. It can be seen, particularly in Fig. 9, in which more measured data points are available, that the fitted curve overestimates the electron temperature at low pulse energies and underestimates the electron temperature at high pulse energies. This provides strong evidence that the unperturbed electron temperatures are in fact significantly lower than those given by a linear fit to the data.

As noted above, the values of T_{e0} calculated using best fits to the solution of Eq. (2) are within 1500 K of the measured ion temperature and excitation temperature. There are significant uncertainties in the transport and rate data used in the calculation, and the results of calculations obtained using lower values of T_{e0} fit the measured data almost equally well. It is reasonable to conclude that the results presented here are consistent with values of electron temperature that

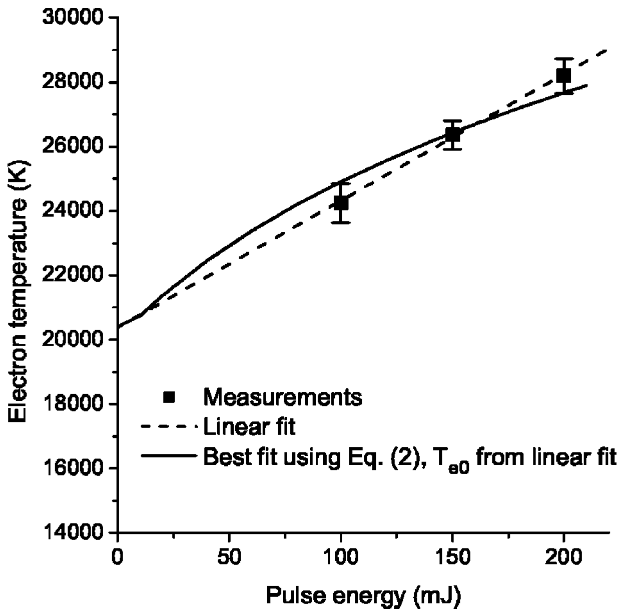

FIG. 8. The best fit to the measured data of Snyder *et al.* [3] obtained using solutions to Eq. (2), with the unperturbed electron temperature set equal to that given by a linear fit. The linear fit to the measured data is also shown.

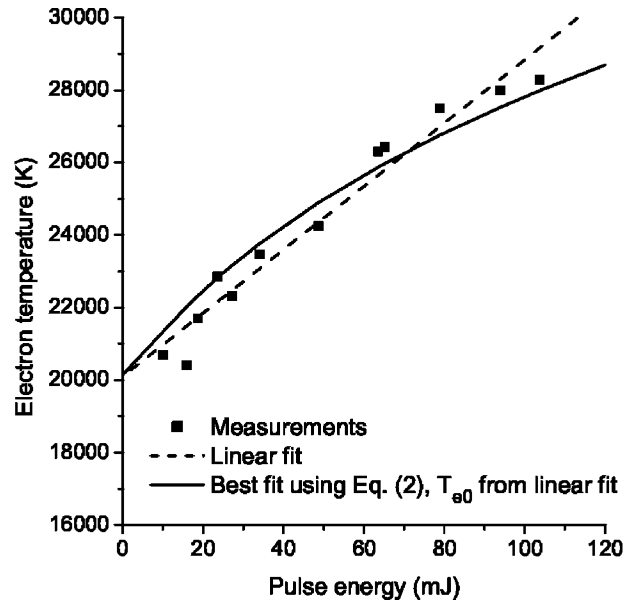

FIG. 9. As for Fig. 8, but using the measurements of Bentley [4].

are approximately in agreement with measured ion and excitation temperatures.

Similar calculations have been performed using a single fluid approach, in which the electrons and heavy particles are considered together [29]. The energy conservation equation used was

$$\frac{\partial(\rho h)}{\partial t}=\frac{1}{r}\left(\frac{r k_t}{c_p}\frac{\partial h}{\partial r}\right)+\frac{\alpha E_p}{A t_p}-U, \qquad (9)$$

where ρ, c_p, h, and k_t are the mass density, specific heat, enthalpy, and thermal conductivity of the plasma, respectively. These were calculated as a function of the electron and heavy-particle temperatures using standard methods [30]. Equation (9) is valid if the plasma composition can be described by a two-temperature Saha equilibrium. The level of ionization is in fact lower than at equilibrium, owing to the short duration of the laser pulse. Nevertheless, similar results were obtained, with the best fit to the results of Bentley being obtained with $T_{e0}=16\,800$ K, and the best fit to the results of Snyder *et al.* being obtained with $T_{e0}=15\,900$ K.

Thomson scattering can be performed at a wide range of wavelengths; although the spectrum of the scattered signal is wavelength dependent, the total Thomson scattering cross section is independent of wavelength. For example, Snyder *et al.* [19] presented results obtained at 355 nm. It is therefore interesting to consider the dependence of laser heating of the electrons on the laser wavelength. I consider here the wavelengths accessible using a Nd-YAG laser, i.e., the fundamental wavelength of 1064 nm and the frequency-tripled wavelength of 355 nm.

Equation (1) indicates that the absorption coefficient depends on the wavelength λ through the term $\lambda^3[1-\exp(-2\pi\hbar c/\lambda k_B T_e)]$ and through the Gaunt factor. The first term increases as wavelength increases, while the Gaunt factor tends to decrease. For example, at $T_e=20\,000$ K and $Z=1$, the first factor increases by a factor of 5.3 at 1064 nm, and decreases by a factor of 2.9 at 355 nm, relative to its value at 532 nm. The Gaunt factor decreases by a factor of 1.7 at 1064 nm, and increases by a factor of 4.6 at 355 nm, again relative to its value at 532 nm. The absorption coefficient therefore increases in both cases relative to its value at 532 nm, by a factor of 3.1 at 1064 nm and a factor of 1.6 at 355 nm. Similar results are obtained for the range of temperatures present in arc plasmas. Laser heating of the plasma will therefore be stronger at 355 nm and 1064 nm than at 532 nm, which is expected to lead to a more strongly nonlinear dependence of electron temperature on laser power.

IV. DERIVATION OF TEMPERATURE FROM THE SPECTRUM OF THOMSON SCATTERED RADIATION

The heating of electrons by the laser pulse causes a further complication in Thomson scattering measurements, in addition to that described in the previous section. In the measurements, the electron temperature is derived from the spectrum of the scattered light collected over the duration of the laser pulse, and across the full cross section of the laser beam. The temperatures present cover a wide range; for the conditions of Fig. 3, for example, they range from 17 000 K to 31 540 K. The spectrum of the Thomson scattered radiation is a complicated function of electron temperature and density. Sample spectra are shown in Fig. 10. The measured scattered signal will be an average of the spectra over the range of temperatures present in the scattering region during the laser pulse. The derivation of a single electron temperature from the average spectrum is clearly a procedure of dubious validity, and this alone casts significant doubt on the reported electron temperature measurements.

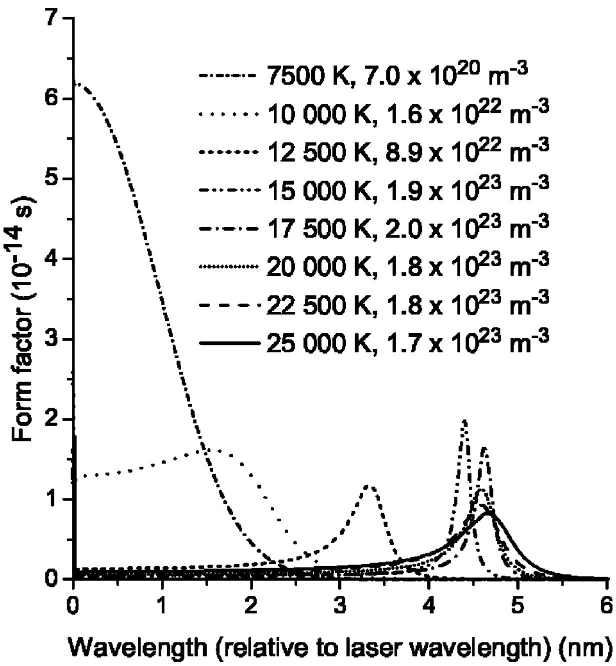

FIG. 10. Spectral distribution of Thomson scattering electron feature for different temperatures in an LTE plasma for scattering at 90° to the laser beam. The laser wavelength is 532 nm and the electron density is given in each case. The wavelength of the peak in the spectrum increases as the electron density increases. At temperatures above about 17 500 K, the electron density is roughly constant, and the main effect of increasing temperature is a broadening of the peak.

For temperatures above about 17 000 K, the plasma is essentially fully ionized, and as shown in Fig. 10, the main effect of a temperature increase is a broadening of the Thomson scattering peak, so the temperature derived from the average spectrum is likely to fall within the range of the temperatures that are present in the scatterting region. For example, for the conditions of Fig. 3, the initial temperature is 17 000 K, and the final central electron temperature is 31 540 K. An average Thomson scattered spectrum was calculated by averaging the spectra for the electron temperatures and densities present over the duration of the laser pulse, and across the laser beam diameter, with weighting according to the Gaussian laser beam intensity profile. A least-squares fitting routine was then used to derive an electron temperature and electron density from the average spectrum. The best-fit electron temperature and density were 26 800 K and 1.95×10^{23} m^{-3}, respectively. While the electron temperature is within the range of electron temperatures present within the laser beam cross section during the laser pulse, the derivation of a single electron temperature from a Thomson scattered spectrum averaged over such a wide range of electron temperatures and densities must nevertheless be considered a significant additional source of error.

It is worth noting that the average temperature, calculated as in Sec. III C (a simple time average over the duration of the laser pulse, and a spatial average over the laser beam diameter, weighted according to the Gaussian laser beam intensity profile) is 25 190 K in this case, which is comparable with the best-fit temperature to the average spectrum. While the calculated temperatures used to fit the measured data in Sec. III C would ideally be generated from the average Thomson spectra, the time required for such computations is prohibitive.

Figure 10 shows that if electron temperatures lower than around 17 000 K are present in the laser beam cross section, the position of the peak in the Thomson spectrum can shift significantly as electron temperature changes, with the result that the average spectrum has a broader peak than the spectrum of any of the temperatures that are represented; this can lead to a significant overestimate of the temperature. This is demonstrated in Sec. V.

V. MEASUREMENTS PERFORMED WITH AN EXPANDED BEAM

In some Thomson scattering measurements of plasma jets [17,18], an expanded laser beam diameter of 2 mm was used, with pulse energies from 50 mJ to 400 mJ and a pulse length of 10 ns. This was done to avoid laser heating of the electrons. The electron temperatures derived from the scattered signals using standard Thomson scattering theory were 18 000 K–20 000 K, similar to those obtained by Snyder *et al.* [7] in their Thomson scattering measurements of electron temperatures in plasma jets.

A problem with the use of an expanded laser beam is that, because of the steep gradients of temperature and density in plasmas, a range of temperatures and densities will be present within the beam cross section. To examine the influence of this gradient, I have simulated the heating of the electrons for the conditions used in the expanded laser beam measurements. As an initial electron and ion temperature profile, I used an approximation of the ion and spectroscopic temperatures measured by Snyder *et al.* [7] for similar plasma jet parameters; a central temperature of 14 000 K, decreasing linearly to 12 500 K at a radius of 1 mm, then to 10 000 K at 2 mm and 5000 K at 3 mm. (Note that, owing to the one-dimensional geometry, it is assumed that this profile is axisymmetric, whereas in a plasma jet the radial temperature profile differs from the axial temperature profile. The results are nonetheless expected to be reasonably representative of those for a two-dimensional simulation.) The central electron temperature was calculated to reach 17 760 K for a laser pulse energy of 400 mJ, and 15 520 K for a pulse energy of 200 mJ. The respective average electron temperatures, calculated as in Sec. III C (i.e., a simple time average over the duration of the laser pulse, and a spatial average over the laser beam diameter, weighted according to the Gaussian laser beam intensity profile) were 13 890 K and 13 490 K.

As noted in Sec. IV, the electron temperature is derived in the experiments by averaging the Thomson scattered spectrum over all temperatures present, and by calculating a temperature from this integrated spectrum. This procedure was simulated by calculating such an average Thomson scattered spectrum, and using a least-squares fitting routine to derive an electron temperature and electron density from the average spectrum. The average spectrum, and the best-fit Thom-

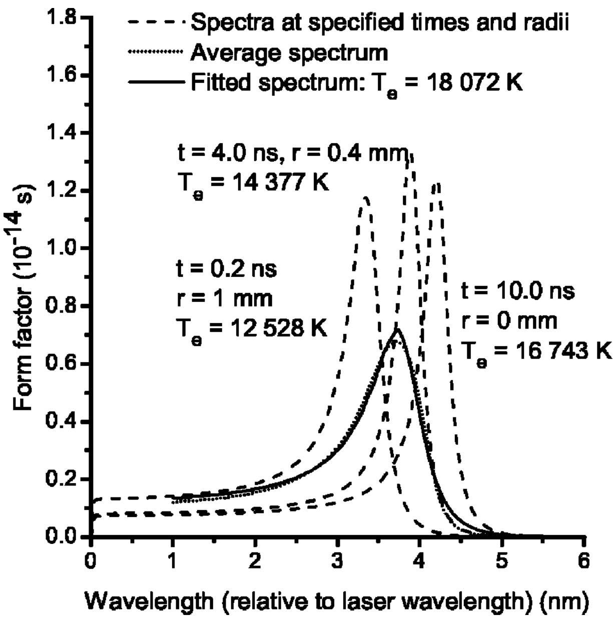

FIG. 11. Average Thomson spectrum calculated for expanded laser beam measurement of a plasma jet (pulse energy $=400$ mJ, pulse length $=10$ ns, beam radius $=1$ mm, initial central electron temperature $=14\,000$ K, laser wavelength $=532$ nm, scattering at 90° to the laser beam), and the least-squares best-fit spectrum. Also shown are spectra for the electron temperatures and densities present at three times and positions during the laser pulse.

son spectrum, are shown in Fig. 11.

The electron temperature derived by this method was 18 070 K for a pulse energy of 400 mJ, and 17 550 K for a pulse energy of 200 mJ. The electron density was 1.04 $\times 10^{23}$ m^{-3} in both cases. These calculated electron temperature values are significantly higher than the electron temperatures present anywhere in the plasma. This is the result of the artificial broadening of the average spectrum due to the presence of a range of temperatures and electron densities. This effect is important for plasmas at relatively low temperatures (below about 15 000 K for a plasma in LTE) for which the electron density is below its maximum value of around 2×10^{23} m^{-3}, since as shown in Fig. 10, the spectral position of the Thomson peak depends strongly on the electron density for such plasmas.

The calculation demonstrates that, at least for the relatively low temperatures present in a plasma jet, the use of an expanded laser beam leads to significant distortion of the measured Thomson line shape, which leads to the derivation of anomalously high electron temperatures from this line shape. These electron temperatures and densities are comparable to the values of 18 000 K and 1.17×10^{23} m^{-3}, and 20 000 K and 0.68×10^{23} m^{-3}, respectively, reported in the papers by Gregori *et al.* [17,18]. This provides evidence that the anomalously high electron temperatures measured with the expanded laser beam are an artifact due to the averaging of the Thomson line shape over a range of electron temperatures and densities.

VI. CONCLUSIONS

It has been shown from energy balance calculations that great care needs to be exercised in deriving the electron temperature of thermal plasmas from laser-scattering measurements. In particular, the perturbation of the electron temperature by the laser has a highly nonlinear dependence on laser energy. This means that the method, used in the previous measurements, of deriving an unperturbed electron temperature by linearly extrapolating measurements of electron temperature as a function of laser-pulse energy, is physically invalid. Furthermore, there are significant problems in correctly accounting for the averages that must be made in a typical laser-scattering measurement over the volume from which scattering of laser light occurs, within which there will be significant temperature variation, and also over the duration of the laser pulse, which causes a continuous variation in temperature.

Previous reports of laser-scattering measurements have concluded that there are significant differences between the electron and heavy-particle temperatures in the plasmas present in free-burning arcs and plasma jets. In the present work, I have reanalysed some of these measurements, concluding that the electron temperature and heavy-particle temperatures are similar, and that the usual assumption of local thermodynamic equilibrium for the central regions of industrial arc plasmas is indeed still likely to be a reasonable approximation. The existence of local thermodynamic equilibrium is of course an assumption that greatly simplifies calculations of the properties of industrial arc plasmas, such as are used in plasma torches, arc welding, and circuit breakers.

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