Title	Reinterpretation of Laser Scattering Measurements of Welding Arc Temperature and the Existence of Local Thermodynamic Equilibrium in Arcs(Physics, Processes, Instruments & Measurements, INTERNATIONAL SYMPOSIUM OF JWRI 30TH ANNIVERSARY)
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Citation	Transactions of JWRI. 2003, 32(1), p. 1-9
Version Type	VoR
URL	https://doi.org/10.18910/5530
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Reinterpretation of Laser Scattering Measurements of Welding Arc Temperature and the Existence of Local Thermodynamic Equilibrium in Arcs †

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Abstract

Thomson scattering measurements of electron temperature in atmospheric-pressure free-burning arcs and plasma jets have indicated that the electron temperature in these thermal plasmas is up to 7000 K greater than the ion temperature and the excitation temperature measured by spectroscopy. In the Thomson scattering measurements, the electrons were strongly heated by the 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. It is shown here that the absorption of laser energy by the electrons, and the collisional and radiative cooling of the electrons, are strongly dependent on the electron temperature, and therefore on the pulse energy. A one-dimensional fluid dynamic model is developed that takes into account these processes. The use of this model to extrapolate the measurements gives unperturbed electron temperatures in much closer agreement with ion and excitation temperatures than the electron temperatures obtained using linear extrapolation.

The laser heating of the electrons means that, over the duration of the laser pulse, scattering occurs from electrons at a range of temperatures. The difficulty in deriving an electron temperature from the resulting spectrum of scattered radiation is pointed out. The accuracy of Thomson scattering measurements that use an expanded laser beam to minimise the electron heating is also examined. The defocusing of the laser beam, combined with the large temperature gradients that occur in thermal plasmas, again leads to scattering from electrons at a range of temperatures. Simulations indicate that the resulting distortion of the spectrum of scattered radiation can lead to the derivation of electron temperatures that are significantly greater than those existing anywhere in the scattering volume.

It is concluded that Thomson scattering measurements significantly overestimate electron temperatures, and do not provide reliable evidence of deviations from local thermodynamic equilibrium, in free-burning arcs and plasma jets at atmospheric pressure.

KEY WORDS: (Thomson scattering) (Measurement) (Arc) (Thermal plasma) (Electron temperature) (LTE)

1. Introduction

The question of whether thermal plasmas, such as welding arcs and plasma jets, at atmospheric pressure are in local thermodynamic equilibrium (LTE) has been an ongoing subject of discussion and debate. LTE requires 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 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[1]; it has been shown that this is due to the rapid convective influx of cold gas caused by the pinch effect[2]. Deviations from LTE also occur near the anode[3]. In the fringes of the plasma, an overpopulation of excited states due to resonance absorption of radiation has been measured[4]; further, the steep gradients lead to diffusion that is more rapid than some recombination reactions[5]. However, the bulk of the theoretical[6,7] and experimental[8,9] 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.

Since 1993, the results of a number of Thomson scattering measurements of electron and ion temperatures in thermal plasmas, in which the temperatures have been derived from the spectral distribution of the scattered light[10,11], have been reported. These measurements have indicated that all regions of the plasma are far from LTE; in particular, the measurements have shown that the electron temperature is some thousands of kelvin higher than the ion temperature. Snyder et al.[12] measured an electron temperature of 20900 ± 1700 K and an ion temperature of 14200 ± 700 K at a position 2 mm below the cathode of a 100 A free-burning arc in argon. Bentley[13] repeated the electron temperature

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Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka 567-0047, Japan

measurements, obtaining a temperature of 20400 ± 500 K. Spectroscopic measurements of a similar arc yielded an excitation temperature of 16600 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[14]. Tanaka and Ushio[15] 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 22000 ± 1000 K at a position 2 mm downstream of the plasma torch in an 900 A argon jet[16], compared to an ion temperature of 12600 ±900 K and an excitation temperature of 14500 K[17] at the same position.

The very large deviations from LTE indicated by these measurements are difficult to reconcile with the theoretical and experimental studies referred to at the start of this section. For this reason, there has been an intense effort to investigate the validity of the Thomson scattering results. As indicated above, the results 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 fusion plasmas, 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 the there is significant heating of the electrons by the laser radiation. This heating has been taken into account by measuring electron temperature as a function of laser pulse energy, and linearly extrapolating the resulting curve to zero pulse energy. Murphy[18] has demonstrated that there are number of problems with this extrapolation. In this paper, I expand on the results and arguments presented in the initial paper. 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, similarly high electron temperatures were obtained[16,19,20].

Other workers have pursued different explanations of the anomalously high Thomson scattering electron temperatures. Gregori et al.[19] presented measurements that suggested that electron temperatures calculated from the measurements depended strongly on the scattering angle. They proposed that this dependence arose as a result of the steep density gradients within the scattering volume, and suggested that this could explain the anomalously high electron temperatures. Snyder, Crawford and Fincke[21], 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. Gregori et al.[20] recently suggested that the standard method[10,11] of deriving the electron temperature from the spectrum of the scattered signal was not applicable to thermal plasmas, and 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 15700 ± 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.

2. 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. This in turn necessitates the use of a high-power pulsed laser. Typically, a frequency-doubled Nd-YAG laser, with wavelength 532 nm, is used. The interaction of the laser beam with the plasma heats the electrons by linear inverse bremsstrahlung[22]. To take this effect into account, workers have measured electron temperature as a function of laser pulse energy. A straight line has then been fitted to the results, and extrapolated to zero pulse energy to obtain the electron temperature free of influence from laser heating. An example of this procedure is shown in **figure 1**.

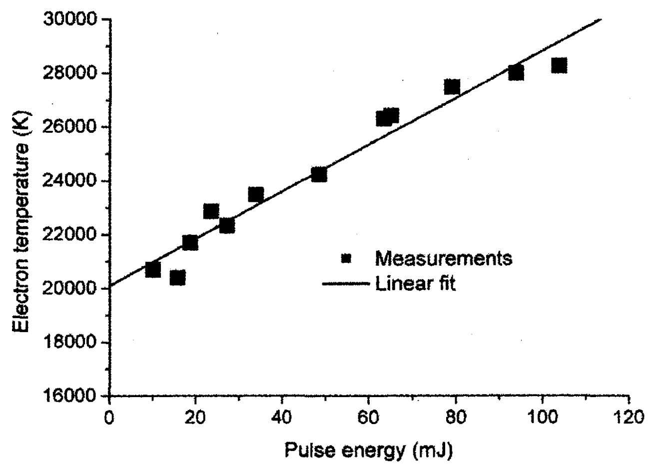

Fig. 1 Dependence of measured electron temperature on laser pulse energy, 2 mm below the cathode in a 100 A free-burning arc in argon, and linear least-squares fit to the measurements (from Bentley[13]).

The use of a straight-line fit has been justified[12,15,19] by reference to Hughes[22]. Hughes, however, gives the following expression for the coefficient of absorption of laser light by a plasma:

$$\alpha = \frac{n_e n_i Z^2 e^6 \left[1-\exp(-\hbar\varpi/k_B T_e)\right]}{6\pi\varepsilon_0^3 c\hbar\varpi^3 m_e^2}\left(\frac{m_e}{2\pi k_B T_e}\right)^{1/2}\frac{\pi}{3}\bar{g} \quad (1)$$

In equation (1), n_e and n_i are respectively the electron and ion number densities, T_e is the electron temperature, Z is the average ionisation level of the plasma, ω is the laser frequency, and the constants e, m_e, $\hbar$, k_B and c are respectively the electron charge and mass, Planck's constant, Boltzmann's constant, and the speed of light in vacuum.

Brussaard and van de Hulst[23] showed that the average Gaunt factor $\bar{g}$ (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[24]. The free-bound Gaunt factor is calculated using the expression given by Brussaard and van de Hulst[23]. **Figure 2** shows the electron temperature dependence of the average Gaunt factor and its components; note that there is a step function decrease in the free-bound factor as Z increases above 1.3.

It is clear from equation (1) and figure 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.

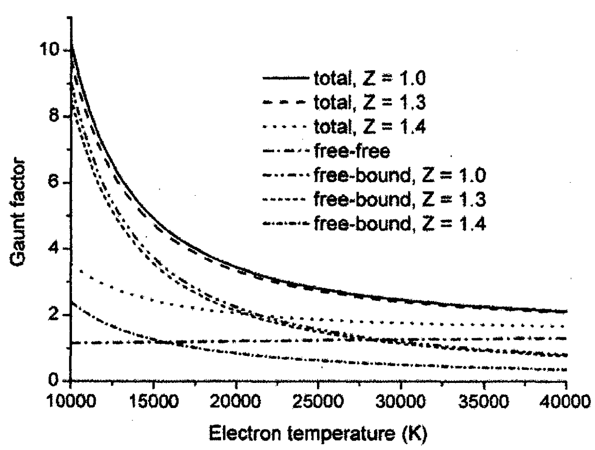

Fig. 2 Gaunt factors for different values of the average ionisation level Z. The total Gaunt factor is the sum of the free–free and free–bound factors. The free–bound factor has a step-function decrease at just above $Z = 1.3$.

3. Fluid Dynamic Modelling of Laser Heating

3.1 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 former 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 ionisation).

The heating and cooling of electrons during a laser pulse can be described by a one-dimensional equation in polar geometry. The centre 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.[2,25] 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 A is the cross-sectional area of the laser beam and t is time; E_p and τ_p are respectively the laser pulse energy and duration; k_e and U are respectively the electron thermal conductivity and the radiative emission coefficient, R_i is the rate of ith ionisation of argon, and E_i is the ith ionisation energy of argon.

The rate of transfer of energy from electrons to heavy particles through inelastic collisions, W_{eh}, is calculated using the expressions of Lelevkin et al.[2,25], extended to take into account doubly-ionised atoms:

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

where m_e and m_h are the electron and heavy-particle masses, and the electron-heavy collision frequency is given by

$$\nu_{eh} = \left(\frac{8k_B T_e}{\pi m_e}\right)^{1/2}\left(\sum_{i=1}^{2} n_i Q_{ei} + n_0 Q_{e0}\right) \quad (4)$$

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

$$Q_{ei} = \pi\left(\frac{ie^2}{12\pi\varepsilon_0 k_B T_e}\right)^2 \ln\left\{\frac{1}{4\pi\varepsilon_0 n_e}\left[\frac{4\pi\varepsilon_0 k_B T_e}{e^2\left(1+T_e/T_i\right)}\right]^3\right\} \quad (5)$$

where T_i is the ion temperature, and

$$Q_{e0}\left(m^2\right) = \left(3.6\times10^{-4}\,T_e(K) - 0.1\right)\times10^{-20} \quad (6)$$

Equation (6) is a fit to the electron-atom collision cross-section data given by Devoto[26].

Values of the electron thermal conductivity k_e were taken from Devoto[26], and values of the radiative emission coefficient from Cram[27]. The rates of first and second ionisation, R_1 and R_2, are given by

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

where k_1 and k_2 are respectively the rates of electron-impact ionisation of neutral and singly-ionised argon atoms. Values of these ionisation rates are taken from Almeida et al.[28]. The subscript 'eq' denotes values calculated for a plasma in LTE.

The values of the number densities can be calculated as a function of time using the equations

$$dn_0/dt = -R_1,\ dn_1/dt = R_1 - R_2,$$
$$dn_2/dt = R_2,\ dn_e/dt = R_1 + R_2 \quad (8)$$

Equation (2) was solved numerically, using the finite-difference method of Patankar[29]. It was assumed that the laser beam profile was Gaussian, that the pulse shape was square in time, and that initially the ion and electron temperatures were equal. It was further assumed that the ion 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[12]. In solving equation (2), the number densities of the species were calculated as a function of time using equations (8), with the initial values calculated assuming LTE.

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[12,13]. The calculation region extended over a radius of 350 μm, with an evenly-spaced 1 μm 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.

3.2 Results

Figure 3 shows typical results 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 8400 K in the first nanosecond of the pulse, and only 500 K in the final nanosecond.

Figure 4 shows the evolution of the species number densities during the laser pulse, together with the electron temperature. The plasma is initially singly-ionised, with some ions becoming doubly-ionised during the laser pulse. The electron density increases by around 5%; this is consistent with the increase measured by Bentley[13] for a similar electron temperature increase. In contrast, Snyder et al.[12] measured no change in the electron density during the laser pulse.

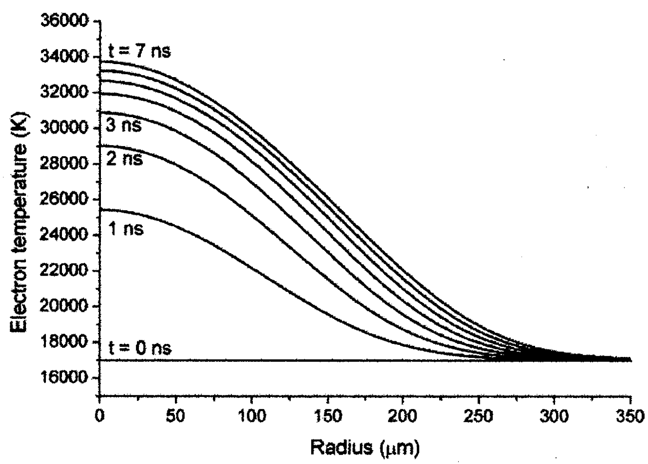

Fig. 3 Radial dependence of the electron temperature in the region heated by the laser beam, at time intervals of 1 ns during a 7 ns laser pulse. The initial temperature is 17000 K, the pulse energy is 100 mJ, and the beam radius is 100 μm.

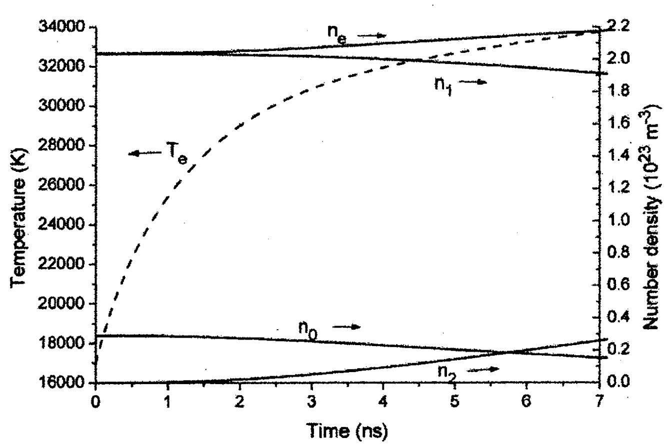

Fig. 4 Evolution of the electron temperature and species number densities at the centre point. Parameters are as in figure 3.

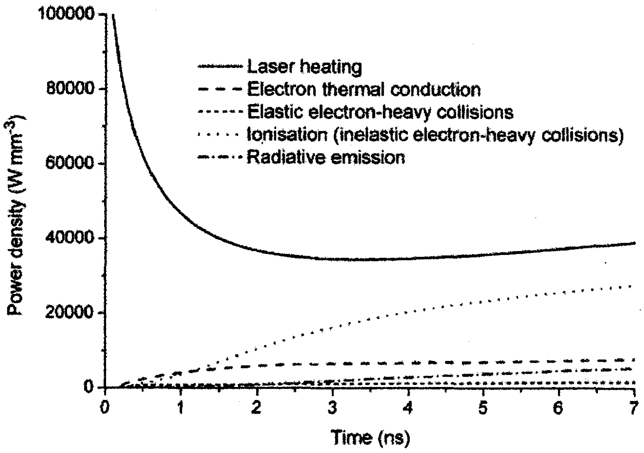

Fig. 5 Evolution of the laser heating and the four cooling processes at the centre point. Parameters are as in figures 3 and 4.

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 ionisation is the dominant electron cooling process; electron thermal conduction is also significant. Elastic energy transfer to heavy particles and radiative emission are less important.

3.3 Application of fluid dynamic model to Thomson scattering measurements

It has been shown in section 3.2 that the absorption of laser energy decreases as the electron temperature increases, and the 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, the extent of the deviation from the linear relationship used to derive unperturbed electron temperatures in previous works will be examined by using the fluid dynamic model described in section 3.1 to fit the measured results presented in the previous 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, that give values of electron temperature closest to the experimental values. Deviations from $C = 1$ were required to take into account experimental un-

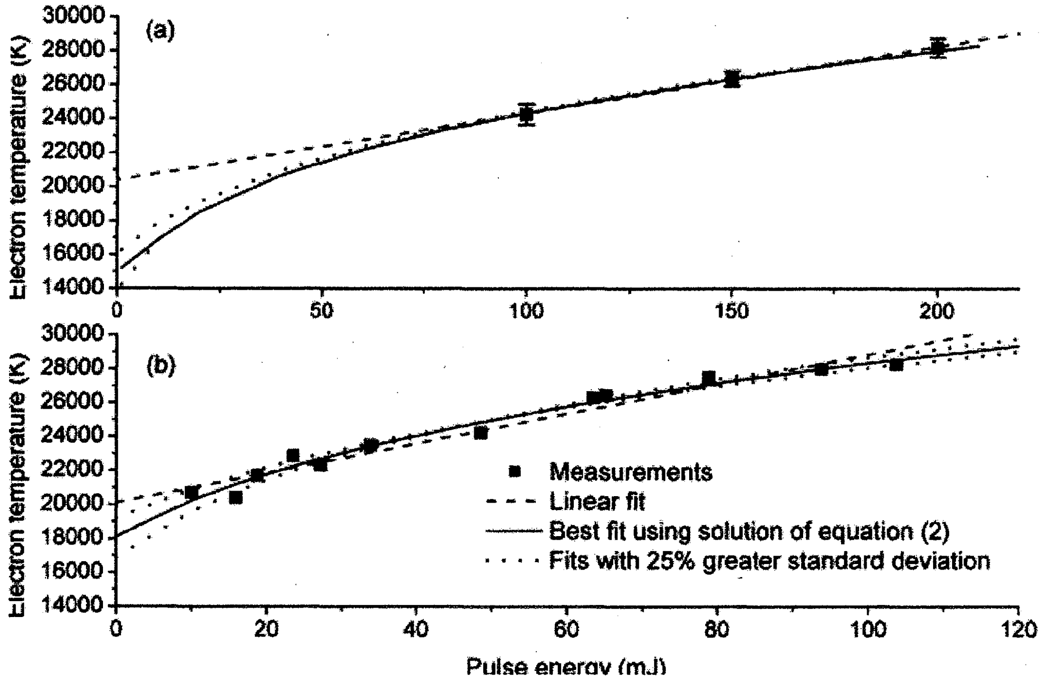

Fig. 6 Comparison between the best fit obtained using a solution to equation (2), and the line of best fit, to the measured data of (a) Snyder et al.[12] and (b) Bentley[13]. Also shown are fits obtained using solutions to equation (2) for which the standard deviation from the experimental points is 25% greater than for the best fit.

certainties 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. The ion temperature was set equal to the initial electron temperature.

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 section 4.

Figure 6 compares least-squares linear fits to the measurements of Snyder et al.[12] and Bentley[13] with least-square fits to solutions of equation (2). The least-squares best fit to the measurements of Snyder et al. shown in figure 6(a) is obtained for T_{e0} = 15200 K and C = 1.05. This may be compared with the ion temperature measured by Thomson scattering of 14200 ± 700 K[12]. As a measure of the sensitivity of the least-squares fit, fits for which the standard deviation is 25% greater than the minimum were calculated; the deviation in T_{e0} is around 1000 K.

The least-squares best fit to the measurements of Bentley shown in figure 6(b) is obtained with T_{e0} = 18100 K and C = 1.455. The deviation in T_{e0} corresponding to a 25% increase in standard deviation is in this case 1300 K. The excitation temperature, and the ion temperature measured by laser scattering, were around 16600 K for the same conditions[8]. It is apparent from figure 6(b) that the dependence of T_e on pulse energy calculated from equation (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 equation (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. Since there are significant uncertainties in the transport and rate data used in the calculations, and since the results of calculations using lower values of T_{e0} fit the measured data almost equally well, we conclude that the results admit values of electron temperature that are in fair agreement with ion and spectroscopic temperatures. Hence, the results of the measurements of electron temperature by Thomson scattering, when analysed correctly, are consistent with the existence of LTE.

4. 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 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 figure 3, for example, they range from 17000 K to 33800 K. The spectrum of the Thomson-scattered radiation is a complicated function of electron temperature and density. Sample spectra are shown in **figure 7**. The measured scattered signal will be an average of the frequency spectra over the range of temperatures present. 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.

For temperatures above about 17000 K, the plasma is essentially fully-ionised, and as shown in figure 7, 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 represented. For example, for the conditions of figure 3, the initial temperature is 17000 K, and the final central electron temperature is 33800 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 29890 K and 1.99 × 10^{23} m^{-3} respectively. While the electron temperature is within the range of electron temperatures present

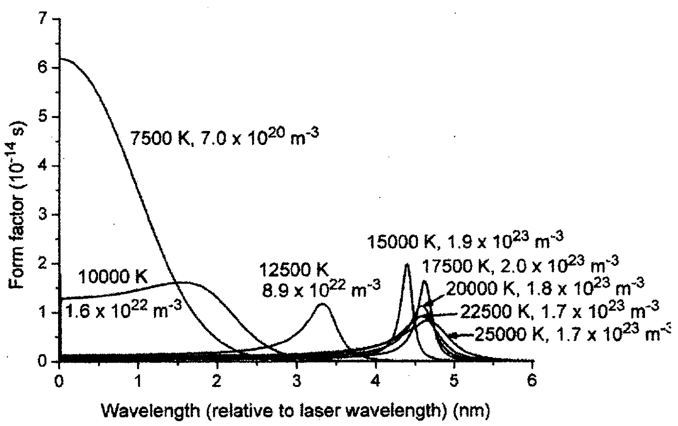

Fig. 7 Spectral distribution of Thomson scattering electron feature for different temperatures in an LTE plasma. The electron density is shown in each case. The wavelength of the peak in the spectrum increases as the electron density increases. At temperatures above about 17500 K, the electron density is roughly constant, and the main effect of increasing temperature is a broadening of the peak.

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 section 3.3 (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 28360 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 section 3.3 would ideally be generated from the average Thomson spectra, the time required for such computations is prohibitive.

Figure 7 shows that if electron temperatures lower than around 17000 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 section 5.

5. Measurements Performed With an Expanded Laser Beam

In some Thomson scattering measurements of plasma jets[19,20], 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. The aim was to avoid laser heating of the electrons. The electron temperatures derived from the scattered signals using standard Thomson scattering theory were around 20000 K, similar to those obtained by Snyder et al.[16] 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.[16] for similar plasma jet parameters; a central temperature of 14000 K, decreasing linearly to 12500 K at a radius of 1 mm, then to 10000 K at 2 mm and 5000 K at 3 mm. (Note that, owing to the one-dimensional geometry, it is assumed that this pro-

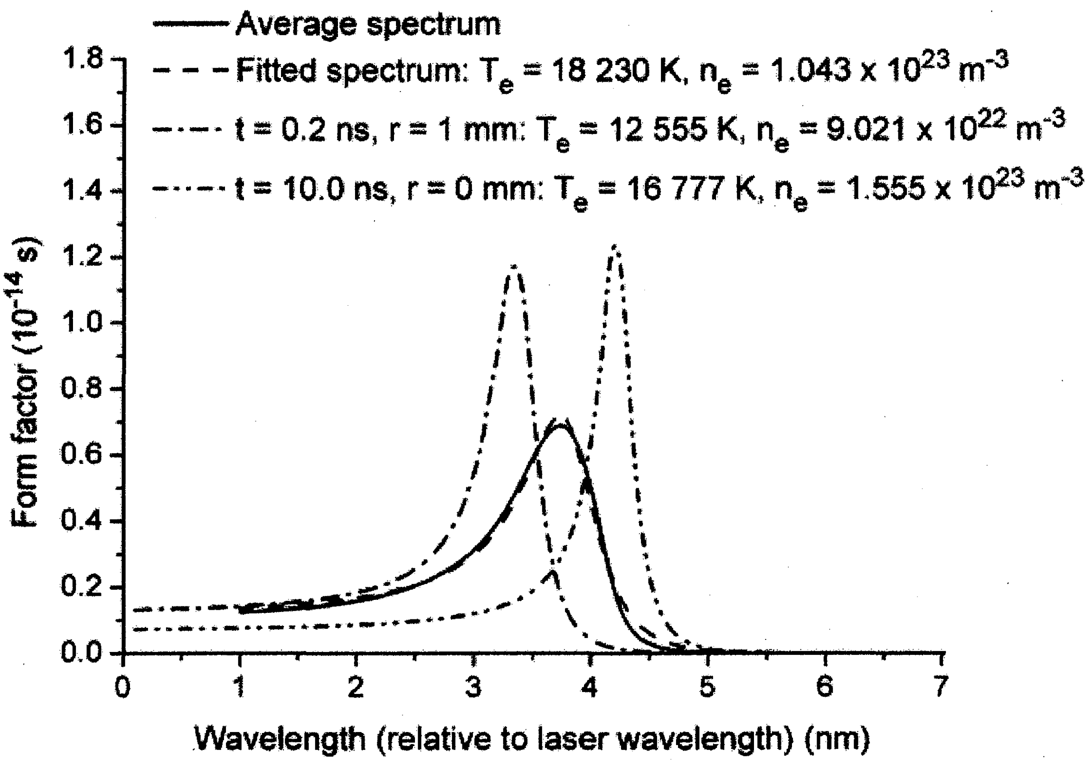

Fig. 8 Average Thomson spectrum calculated for expanded laser beam measurement of a plasma jet (pulse energy = 400 mJ, pulse length = 10 ns, beam radius = 1 mm, initial central electron temperature = 14000 K), and the least-squares best fit spectrum. Also shown are spectra for the electron temperatures and densities present at two times and positions during the laser pulse.

file is axisymmetric. The results are nonetheless expected to be reasonably representative of those for a two-dimensional simulation.) The central electron temperature was calculated to reach 17680 K for a laser pulse energy of 400 mJ, and 16130 K for a pulse energy of 200 mJ. The respective average electron temperatures, calculated as in section 3 (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 14670 K and 13940 K.

As noted in section 4, 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 Thomson spectrum, are shown in **figure 8**.

The electron temperature derived by this method was 18230 K for a pulse energy of 400 mJ, and 17620 K for a pulse energy of 200 mJ. The electron density was 1.04×10^{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 15000 K for a plasma in LTE) when the electron density is below its maximum of around 2×10^{23} m^{-3}, since as shown in figure 7, the spectral position of the Thomson peak depends strongly on the electron density.

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 lineshape. These electron temperatures and densities are comparable to the values of 18000 K and 1.17×10^{23} m^{-3}, and 20000 K and 0.68×10^{23} m^{-3}, respectively, reported in the papers by Gregori et al.[19,20]. 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.

6. Conclusions

A number of flaws in previous measurements of electron temperature by Thomson scattering in thermal plasmas have been demonstrated. Two of these flaws arise from the electron heating that occurs due to absorption of the laser energy.

The first such flaw is that the spectral distribution of the scattered radiation is a spatial average over the cross-sectional area of the laser beam and a time average over the duration of the laser pulse. The "electron temperature" derived from this average scattered signal is a complicated function of the electron temperatures present within the cross-sectional area of the laser beam during the laser pulse. It has been shown here that, for the fully-ionised plasmas present near the centre of welding arcs, this 'electron temperature' corresponds roughly to a simple spatial and time average of the electron temperatures present. This is nevertheless a significant source of error even in such fully-ionised plasmas. For partially-ionised plasmas, such as those present in plasma jets or in the fringes of welding arcs, the measured 'electron temperature' can be significantly greater than the temperature anywhere in the scattering region.

A second problem is 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. The dependence of the absorption of laser energy, and the cooling of the heated electrons by thermal conduction, by elastic and inelastic collisions with heavy particles, and by radiation, must all be considered. We have used a one-dimensional fluid dynamic model of the electron heating and cooling to show that these effects are substantial, and that electron temperatures are 2000 to 6000 K lower than those given by the linear extrapolation. The corrected electron temperatures are comparable with ion and excitation temperatures.

Finally, it has been demonstrated that the use of an expanded or defocused laser beam to decrease the heating of electrons can also lead to inaccurate values of electron temperatures. The steep temperature and density gradients in plasmas, and the large laser beam cross-section, mean that light is scattered from regions at a range of temperatures. The "electron temperature" derived from the average scattered signal has been shown, at least for the partially-ionised plasmas present in plasma jets, to be substantially greater than the temperature anywhere within the laser beam cross-section.

It is concluded that Thomson-scattering measurements of electron temperature in thermal plasmas have significantly overestimated the electron temperature, and do not provide reliable evidence for significant deviations from LTE.

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