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# Determination of Energy-Loss Factors for Slow Electrons in Hot Gases*

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The energy-loss factor for slow electrons in hot gases is determined by a new method that employs a high-frequency (2.45 GHz) electric field to elevate the temperature of the electrons above the temperature of the gas and a Langmuir probe to determine the electron temperature. The electron energy-loss factor $\delta_\kappa$ in a given gas $\kappa$ is then determined by measuring the rate of change of the electron temperature with the high-frequency power used to illuminate the plasma. The determination of $\delta_\kappa$ by this method does not require knowledge of the collision cross sections for momentum transfer. The values of $\delta_\kappa$ obtained by this method are in agreement with theory for monatomic gases (e.g. argon). No previous theoretical or experimental results are available for diatomic gases (e.g., nitrogen) in this range of gas and electron temperatures ($T_g$ from 1700 to 6100°K, $T_e$ from 3260 to 7540°K). The values of $\delta_\kappa$ obtained for nitrogen at elevated gas temperatures are a "reasonable" extrapolation of the room-temperature data available in the literature. Thus it was found that $\delta_{N_2}$ ranges approximately from $3\times10^{-4}$ at a gas temperature of 1700°K to $7\times10^{-4}$ at 5000°K.

UNDER steady-state conditions, in the terminology of Demetriades and Argyropoulos,[1] the energy lost by the electrons per unit volume per unit time in *elastic* collisions with heavy particles $\kappa$ is

$$[R^{(2)}]_{\rm el}=-3kn_e\sum_\kappa(m_e/m_\kappa)(T_e-T_\kappa)\tau_{e,\kappa}^{-1}. \quad (1)$$

The difference between the average internal energy of the electrons and the average internal energy of the heavy component $\kappa$ is $\frac{3}{2}k(T_e-T_\kappa)$. The electron energy-loss factor $\delta_{\kappa,\rm el}$ is the fraction of this energy difference that is lost on the average by an electron in each elastic collision with component $\kappa$. Thus $\delta_{\kappa,\rm el}=2m_e/m_\kappa$.

In the case of inelastic collisions between electrons and heavy particles, accompanied as they are by the excitation of rotational, vibrational, or optical levels and also by dissociation, ionization, or recombination of the heavy particle and/or by "second-order" impacts that result in the transfer of the energy of the excited particle to the incoming electron, we can still write[2] an expression for the average energy transfer between the electron and the heavy particles $\kappa$ in the form

$$[R^{(2)}]_{\rm inel}=-3kn_e\sum_\kappa(m_e/m_\kappa)(T_e-T_\kappa)\lambda_\kappa\tau_{e,\kappa}^{-1}, \quad (2)$$

where $\lambda_\kappa=\delta_\kappa/\delta_{\kappa,\rm el}$ and $\delta_\kappa$ is another characteristic parameter that has the meaning of an average fraction of the energy difference $\frac{3}{2}k(T_e-T_\kappa)$ transferred in *inelastic* collisions between the electron and the heavy particles $\kappa$ within a time $\tau_{e,\kappa}$. In a multicomponent plasma where all the heavy components are at the same temperature $T_\kappa=T_g$, we can write Eq. (2) in the form

$$[R^{(2)}]_{\rm inel}=-\tfrac{3}{2}kn_e\nu_t\delta_{\rm eff}(T_e-T_g), \quad (3)$$

where $\nu_t$ is also defined in Ref. 1 and

$$\delta_{\rm eff}\equiv\nu_t^{-1}\sum_\kappa(2m_e/m_\kappa)\lambda_\kappa\tau_{e,\kappa}^{-1}$$
$$\equiv(1/\nu_t)\sum_\kappa\delta_\kappa\tau_{e,\kappa}^{-1}. \quad (4)$$

It is possible to show[2] that in a high-frequency electric field ($E=E_0\cos\omega t$, $\omega=2\pi f$) the difference between the electron temperature $T_e$ and the gas temperature $T_g$ is given by

$$T_e-T_g=[e^2E_0^2/3k\delta_{\rm eff}m_e(\omega^2+\nu_t^2)](1+\epsilon)\Pi, \quad (5)$$

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[1] S. T. Demetriades and G. S. Argyropoulos, Phys. Fluids **9**, 2136 (1966).

[2] V. L. Ginzburg and A. V. Gurevich, Usp. Fiz. Nauk **70**, 201 (1960) [English transl.: Soviet Phys.—Usp. **3**, 147 (1960)].

where $\epsilon$ is a quantity that is usually much less than unity and $\Pi$ is a quantity usually very close to unity. The effective electron energy-loss factor for all processes and species $\delta_{\text{eff}}$ is usually very small compared to unity and although over a wide range of $T_e$, $\delta_\kappa$ for diatomic molecules may change by a large factor, it remains very nearly constant over narrower ranges of $T_e$ as the electron energy remains below the threshold for exciting the next higher energy absorption mechanism in the molecule. For example,[3] $\delta_{N_2}\approx 3\times 10^{-4}$ at $T=288°\text{K}$ and $T_e$ in the range from 2000° to 5260°K. Therefore in the appropriate range of $\delta_{\text{eff}}$, electron concentration $n_e$, and atom or molecule concentration $n_a$, a measurement of $dT_e/dE_0$ at $\omega^2\gg\nu_t^2$ and constant $\omega$ will enable us to determine $\delta_{\text{eff}}$ from the expression

$$\delta_{\text{eff}}=\frac{2e^2E_0}{3km_e\omega^2}\left(\frac{dT_e}{dE_0}\right)^{-1}=\frac{2e^2}{3km_e\omega^2}\left(\frac{2Z}{A_r}\right)\left(\frac{dT_e}{dP}\right)^{-1}, \quad (6)$$

where $P$ is the power fed into the appropriately constructed and terminated cavity, $Z$ is the impedance of the gap (377 Ω for vacuum), and $A_r$ is the appropriate cross-sectional area of the beam or gap (in our case the area perpendicular to the propagation axis). In a simple gas consisting of one component, $\delta_{\text{eff}}$ is of course equal to the energy loss factor $\delta_\kappa$ of that gas. The quantity $Z/A_r$ can be calculated and/or measured by an experiment with a gas with a known $\delta_\kappa$. Success of this scheme for determining $\delta_\kappa$ for a given gas depends on operation of the experiment within certain constraints. Thus the condition $\omega^2\gg\nu_t^2$ imposes an upper limit on the neutral-particle density $n_a$. The condition $\omega\gg\omega_p\equiv 2\pi f_p$, where $\omega_p$ is the critical plasma frequency given by $f_p=9(n_e)^{1/2}$ in Hz, $n_e$ in electrons/m$^3$, ensures that the high-frequency electric field will penetrate the plasma and imposes an upper limit on the electron concentration. The condition that $2000°\text{K}\gtrsim T_e-T_g\gtrsim 1000°\text{K}$ ensures that the error in measuring $dT_e/dE_0$ will be minimized (since the error in $T_e$ can be kept within ±100°K) and that the influence of $d\delta_{\text{eff}}/dT_e$ is kept small. We can choose the maximum amplitude of the electric field to be smaller than the appropriate breakdown potential for the gases involved,[4] smaller than the critical electric field above which binary theory is questionable, and smaller than the characteristic plasma field $E_p$ above which the electron distribution is no longer Maxwellian. Choice of $n_e/n_a>10^{-6}$ to $10^{-5}$ ensures that the electron distribution remains Maxwellian even at $E_0>E_p$.

Experiments were carried out to measure the electron temperature (in a test cell consisting of a wave-guide section, $A_r=0.1524\text{ m}\times 0.1016\text{ m}$, with a round portion of the narrow wall cut away to accept the plasma stream) as a function of the power input to the cell, in order to obtain $dT_e/dP$ in hot diatomic gases. The operating conditions are: maximum power=85 W, frequency=2.45 GHz, gas temperature=300–6000°K, electron temperature up to 20 000°K, gas pressure 0.1 to 2 Torr, electron density less than the critical number of $7\times 10^{16}$ electrons/m$^3$, electric field=1–10 V/cm. The electron temperature was measured with 0.2 and 1-mm-diam cylindrical Langmuir probes inserted in the test cell using apparatus and techniques similar to those described by Kelly, Nerheim, and Gardner[5] under essentially similar conditions. Under the conditions of the experiment $E_0=(4PZ/A_r)^{1/2}\approx 10^{5/2}P^{1/2}$ V/m, and $E_p\approx(3kT_em_e\delta_{\text{eff}}\omega^2/e^2)^{1/2}\approx 19T_e^{1/2}$ V/m. For this apparatus, assuming $Z=387\ \Omega$, we calculate $\delta_{\text{eff}}=0.287(\Delta P/\Delta T_e)$ with $P$ in watts and $T_e$ in °K. The plasma stream was generated by a Thermal Dynamics Corporation 50-N arcjet provided with a plenum chamber (where other gases could be mixed) and exhausting into a vacuum tank through a supersonic nozzle.

The appropriate gas temperature $T_\kappa$ for Eq. (2) is the temperature that describes the average energy of the molecule or atom and is identical to the static temperature $T$ of the gas only when equilibrium prevails. When this experiment was carried out with argon under conditions such[6] that the electron temperature at the probe with zero applied electric field, $T_{e,E=0}$, was equal to the excitation temperature $T^*$ of the argon atoms [i.e., $T_g=T^*=T_{e,E=0}$ in Eq. (2)], it was found that $\delta_A=4.40\times 10^{-5}$ at $T_{e,E=0}=T^*=1160°\text{K}$ and $\delta_A=8\times 10^{-5}$ at $T_{e,E=0}=T^*=4030°\text{K}$. The magnitude of the high-frequency electric field corresponded to an illumination power $P=2.4$ W. This power was sufficient to raise $T_e$ to 16 800°K (at $T_{e,E=0}=T^*=1160°\text{K}$) and to 12600°K (at $T_{e,E=0}=T^*=4030°\text{K}$) and the Langmuir probe characteristics with or without the electric field were linear over more than two decades. Note that the elastic energy-loss factor for argon is $\delta_{A,\text{el}}=2.7\times 10^{-5}$. The difference between $\delta_{A,\text{el}}$ and $\delta_A$ can be explained on the basis of various inelastic processes (e.g., ionization, radiation, etc., that become more severe as the temperature increases).

When the experiment was carried out with nitrogen under such conditions that, at the probe location, the nitrogen was molecular and the electron temperature with zero applied electric field, $T_{e,E=0}$, was always equal to some excitation temperature $T^*$ of the nitrogen molecule, it was found that the temperature $T_{e,E=0}=T^*$ was always much higher than the static temperature computed by an isentropic expansion from the conditions of the plenum chamber ($p\approx 0.5$ to 1.0 atm and $T_0\approx 1500$–$3500°\text{K}$) to the vacuum tank pressure (0.1–2 mm Hg). In addition, when the vibrational relaxation time was longer than the time of flight of the molecules from the plenum chamber to the probe, the excitation

[3] R. W. Crompton and D. J. Sutton, Proc. Roy. Soc. (London) **A215**, 467 (1952).

[4] A. N. Kontaratos and S. T. Demetriades, Phys. Rev. **137**, A1685 (1965).

[5] A. J. Kelly, N. M. Nerheim, and J. A. Gardner, Am. Inst. Aeron. Astronaut. J. **3** 291 (1966).

[6] W. K. McGregor and L. E. Brewer, Phys. Fluids **9**, 826 (1966).

temperature $T^*$ for the nitrogen molecules at the probe was approximately equal to or higher than the stagnation temperature $T_0$ in the plenum chamber as obtained from an average enthalpy derived from an arcjet energy balance (but always less than the excitation temperature in the arc). Thus in the absence of an electric field, the electron temperature is in equilibrium with the excitation temperature of the molecular nitrogen $T^*$, and we can write $T_{e,E=0}=T^*\gtrsim T_0$. Again, therefore, $T_g=T_{e,E=0}=T^*$ in Eq. (2). The coupling and equilibration of the free-electron and $N_2$ vibrational temperatures under essentially similar conditions (but in the presence of an excess of argon) has also been established by Hurle and Russo.[7]

Typical results of the variation of the measured electron temperature with rf power in nitrogen at 0.9 mm Hg are shown in Table I. For these runs $T_0=$ 3230°K as obtained from an average enthalpy derived from an arcjet energy balance. Typical values of $\delta_{N_2}$ as a function of gas temperature are shown in Table II. The results of five or more runs are averaged for each $T_g$, with typical spreads as in Table I. Note that $\delta_{N_2,\mathrm{el}}=3.9\times10^{-5}$ while Crompton and Sutton[3] give, at $T_g=288$°K, $\delta_{N_2}=4.92\times10^{-4}$ at $T_e=893$°K, $\delta_{N_2}=3.19\times10^{-4}$ at $T_e=3140$°K, $\delta_{N_2}=3.47\times10^{-4}$ at $T_e=5260$°K, and $\delta_{N_2}=8.47\times10^{-4}$ at $T_e=9060$°K.

Typically in these experiments the particle concentrations were $n_e\approx10^{16}$ electrons/m$^3$ or slightly larger, and $n_a\approx10^{22}$ atoms or molecules per m$^3$. The reflected rf power was negligible and there was no observable interaction between the Langmuir probe and the microwave cavity. The ohmic heating power loss $\mathbf{J}\cdot\mathbf{E}=e^2n_e\nu_tE_0^2/(2m_e\omega^2)$, W/m$^3$, was negligible compared to the illumination power per unit volume of plasma.

As far as could be determined, the species concentrations at the probe were not at equilibrium with

TABLE I. Typical electron-temperature measurements as a function of rf power for $N_2$.

| rf power: | 0 W | 4.2 W | 8.4 W | 12.6 W | 16.8 W |
|---|---|---|---|---|---|
| | Electron temperature °K | | | | |
| | 3500 | 4320 | | | |
| | 3490 | 4790 | | | |
| | 3390 | 4540 | | | |
| | | 4590 | 5950 | | |
| | | 4640 | 5710 | | |
| | | | 6110 | 7510 | |
| | 3540 | | | 7340 | |
| | 3410 | | | | 8940 |
| | 3550 | | | | 8680 |
| Averages: | 3480 | 4580 | 5920 | 7340 | 8810 |

[7] I. R. Hurle and A. L. Russo, J. Chem. Phys. **43**, 4434 (1965).

TABLE II. Typical energy-loss factors for $N_2$ as a function of gas temperature.

| Gas temp. °K $T_g=T^*=T_{e,E=0}$ | rf power W | Electron temp. $T_e$ °K (with rf) | Energy-loss factor $\delta_{\mathrm{eff}}$ |
|---|---|---|---|
| 1700 | 2.4 | 4127 | $2.9\times10^{-4}$ |
| 1750 (Air leak) | 4.2 | 3260 | $7.8\times10^{-4}$ |
| 2860 | 2.4 | 3950 | $6.3\times10^{-4}$ |
| 2940 | 2.4 | 3910 | $7.1\times10^{-4}$ |
| 3190 | 0.8 | 3500 | $7.6\times10^{-4}$ |
| 3480 (Air leak) | 4.2 | 4580 | $10.9\times10^{-4}$ |
| 3760 | 2.4 | 4790 | $6.7\times10^{-4}$ |
| 3970 | 0.8 | 4320 | $6.5\times10^{-4}$ |
| 4280 | 2.4 | 5340 | $6.7\times10^{-4}$ |
| 5026 | 2.4 | 6065 | $6.6\times10^{-4}$ |
| 5950 | 2.4 | 6490 | $13.0\times10^{-4}$ |
| 6100 | 2.4 | 7540 | $4.9\times10^{-4}$ |

$T_{e,E=0}=T^*$ but at a much lower temperature.[5] Therefore the values of $\delta_{\mathrm{eff}}$ tabulated in Tables I and II should correspond to $\delta_{N_2}$. However, although "resonances" in $\delta_{N_2}$ with $T_g$ cannot be excluded, it is believed that the variations in the tabulated results are due to impurities in the gas (welder's grade bottled gases, water pumped, with large variations in impurities) and/or leaks in the apparatus. It was observed, for example, that the values of $\delta_{\mathrm{eff}}$ obtained in these experiments changed (a) quite frequently when the exhausted gas cylinders were replaced by new ones, and (b) always when oxygen was deliberately leaked into the gas feed line in small quantities (approximately 0.5%). Air leaks were found in the apparatus sometime after the two series of runs corresponding to $T_g=1750$ and 3480°K (Table II) were carried out. The observed increase of $\delta_{\mathrm{eff}}=\delta_{N_2}$ at $T_g=5950$°K may be due to increased elastic losses due to the rather high electron temperature. The observed decrease of $\delta_{\mathrm{eff}}$ at $T_g=$ 6100°K may be due to an increase of the atom concentration. Whether indeed an increase of 150°K in $T_g$ can change the atom concentration sufficiently to cause the observed shift in the value of $\delta_{\mathrm{eff}}$ is still a matter of conjecture. Air leaks and molecular oxygen impurities would be expected to raise the value of $\delta_{\mathrm{eff}}$.

The fact remains that in this method for determining the electron energy-loss factor (and therefore also the collision cross sections for energy transfer between slow electrons and heavy particles) all important measurements are dc and the energy-loss factor has been uncoupled from (a) the collision frequency, or (b) the drift velocity, the mobility and the diffusion coefficient, and can be measured independently of collision cross sections for momentum transfer and particle densities. Experiments are under way to define the effects of impurities.