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Cooling of an incandescent filament by thermionic emission

Tomasz Durakiewicz, Stanislaw Halas*

Institute of Physics, Maria Curie-Sklodowska University, PL-20031 Lublin, Poland

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Abstract

The lowering of temperature of incandescent tungsten filaments by thermionic emission was investigated both theoretically and experimentally. The effect is significant at tungsten filament temperatures above 2300 K. The influence of this effect on lowering the electron emission current density as well as its significance in mass spectrometry and electron beam evaporation are briefly discussed. Neglecting the effect resulted in lowering of experimentally determined work function to 4.10 eV instead of 4.57 eV for tungsten. Methods of calculation of corrected filament temperature and saturation emission current are presented. (Int J Mass Spectrom 177 (1998) 155–161) © 1998 Elsevier Science B.V.

Keywords: Filament; Temperature distribution; Work function; Thermionic emission; Mass spectrometry; Electron beam evaporation

1. Introduction

Measurement of electron emission current (I_e) is commonly used in various branches of physical sciences, including mass spectrometry, surface sciences, and vacuum technology. The I_e measurement seems to be relatively easy to perform. In numerous experiments, however, large discrepancies between observed and theoretically predicted values of thermoemission current were observed. These differences were assessed to variations in Richardson's constant, A, or to changes in reflection coefficient, patchy work function, or adsorption of molecules on the metal surface [1–4]. Dependence of work function on temperature and the Schottky effect are usually also discussed. In spite of all the phenomena taken into account, the values of absolute emission current density in high temperatures are usually lower than expected. In the present authors' view, omitting the power fraction taken by electrons emitted from the incandescent filament leads to large errors in estimation of filament temperature above 2300 K. Consequently, the values of electron emission current are lower than expected in high filament temperature range.

2. Filament temperature distribution

Let us assume that an electron leaving the surface may be treated as a member of a free electron gas in vacuum, having the kinetic energy, $\frac{3}{2}kT$, and the potential energy, φ. Identifying φ with work function, we obtain total electron energy as follows:

$$E_e = \tfrac{3}{2}kT + \varphi. \quad (1)$$

In the presence of external electric field, the work function value will change due to the Schottky effect.

* Corresponding author. E-mail: dudek@tytan.umcs.lublin.pl

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In the case of electron emission current measurements, external electric field decreases the work function by

$$\Delta\varphi = \sqrt{\frac{eE_0}{4\pi\epsilon_0}} \tag{2}$$

where E_0 is the magnitude of electric field [5], e is electron charge, and ϵ_0 is electromagnetic permeability of vacuum. Therefore, the net power extracted from an isothermic filament by n electrons emitted in time t is

$$P_e = \frac{nE_e}{t} = \frac{I_e}{e}\left(\tfrac{3}{2}kT + \varphi - \Delta\varphi\right) \tag{3}$$

where $I_e = ne/t$ is the total electron emission current.

Let us now consider a filament of length l, cross-section area F, and circumference D. The filament is made of certain material the properties of which are: c is specific heat, μ is density, ρ is specific resistance, λ is heat conductivity, ϵ is total emissivity, φ is work function. Following the procedure of calculation of temperature distribution, which was described in our previous article [6], we formulate first the power balance formula for filament element dx:

$$P_1 = P_2 + P_3 + P_4 + P_5 \tag{4}$$

where P_1 is power dissipated by Joule heating by electric current I to an element dx of the filament, P_2 is power dissipated by thermal radiation, P_3 is power dissipated by heat conductivity, P_4 is power uptaken or released due to finite heat capacity of the element dx, and P_5 is power extracted with electrons from element dx. Power dissipated by heat conductivity of gas is neglected, assuming that all the experiments are performed in high vacuum conditions. Eq. (4) may be written *explicitly* as follows:

$$\begin{aligned} I(t)^2\frac{\rho}{F}dx = {} & Ddx\epsilon\sigma(T^4 - T_A^4) \\ & - Fdx\left(\frac{\partial\lambda}{\partial x}\frac{\partial T}{\partial x} + \lambda\frac{\partial^2 T}{\partial x^2}\right) + \mu Fc\frac{\partial T}{\partial t}dx \\ & + \frac{j_e Ddx}{e}\left(\frac{3}{2}kT + \varphi - \sqrt{\frac{eE_0}{4\pi\epsilon_0}}\right) \end{aligned} \tag{5}$$

where j_e is electron emission current density, calculated from Richardson–Dushmann formula [Eq. (7) below], $\sigma = 5.6705 \times 10^{-8}$ $\mathrm{Wm^{-2}\,K^{-4}}$ is the Stefan-Boltzmann constant, and T_A is ambient temperature. Heating current, $I(t)$, may be set constant to obtain a steady temperature distribution after a certain time of heating.

Eq. (5) is the second-order partial differential equation describing the evolution of temperature distribution along a filament in time. Solution of this equation is in the form $T(x, t)$. Values of ρ, ϵ, λ, and c depend on temperature. Boundary conditions are determined by ambient temperature, T_A, and temperature of the filament ends, T_0. Filament voltage may be of any given waveform. A detailed discussion and evaluation of Eq. (5) without term P_5, as well as appropriate physical data for calculations, may be found in [6]. Simplified form of this equation and faster algorithm may be used for heating by constant currents [7].

3. Cooling of filament by electron emission

If electrons are not collected by anode (electron collector), electrons in metal are in thermodynamic equilibrium with a space charge cloud around the filament and the term P_5 may be assumed to be equal to zero, because only a negligible number of electrons possess enough kinetic energy to leave the space charge potential well. When a positive electron acceleration voltage between filament and collector, U_e, is applied, the electron emission current I_e begins to rise. The dependence of I_e on U_e below the saturation current is described by the Langmuir's formula [8]

$$I_e = PU_e^{3/2} \tag{6}$$

where P is perveance, a characteristic value dependent on geometry of a given filament-collector system, and selected filament temperature. The saturation current I_e^{sat} may be found from a Richardson–Dushmann equation

$$\frac{I_e^{\mathrm{sat}}}{S} = AT^2\exp\left(-\frac{\varphi}{kT}\right) \tag{7}$$

and gives the maximum electron emission current from a surface S of material having work function φ and temperature T, assuming that no electrons are reflected by the metal-vacuum barrier (reflection coefficient $\bar{r} = 0$). A is the Richardson constant $\sqrt{A} = 4\pi emk^2/h^3$, where m is electron mass, k is Boltzmann's constant, and h is Planck's constant. Experimentally, the value of I_e^{sat} is found by plotting I_e against $\sqrt{U_e}$. By linear regression applied to the plateau above saturation the I_e^{sat} is found as extrapolated I_e value at $U_e = 0$.

Because it is not the purpose of this article to discuss the Schottky plots of I_e as a function of U_e, we shall take $I_e = I_e^{sat}$ in further theoretical considerations. We therefore consider only the optimum electron emission cooling conditions. The term $d\varphi/dT$, the magnitude of which is of the order of 10^{-5} eV/K [2], is neglected in calculations, if not stated otherwise.

4. Experimental setup

Assuming constant value of the electron acceleration voltage, U_e, and applied constant filament heating voltage, U_f, in a well recognized Richardson setup for determination of work function, electrons collected by the so-called Richardson's collector, placed in a certain distance from the filament center, do not actually come from the very center. Electric field distribution between the electron collectors and filament is substantially disturbed by filament voltage U_f. Therefore, the trajectories of electrons are not straight, and most of electrons that comprise electron emission current come from areas off the filament center, depending on U_f direction.

Because the filament has its own heat capacity, it is expected intuitively that modulation of filament temperature drops below the significant level for sufficiently high frequencies of U_f. Recent calculations of thermal properties of filaments heated by series of electric pulses [6], based on solving Eq. (5) without term P_5, confirm this fact, and allow to find the temperature modulation for a given filament geometry, material, and both supply voltage waveform and

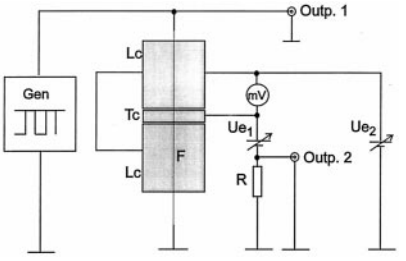

Fig. 1. Schematic diagram of the circuit for electron emission measurements by pulsed heating of filament. Gen is square-wave power generator, Lc are large collectors, Tc is tiny collector, Ue_1 and Ue_2 are electron acceleration voltages, mV is millivoltmeter, $Outp_1$ and $Outp_2$ are outputs for measurement of filament voltage and electron emission signal, connected to digital oscilloscope by screened cable. mV is used to set precisely equal electron acceleration voltages on Tc and Lc collectors. Working pressure was below 10^{-6} Pa.

frequency. Therefore, it is reasonable to heat the filament by a series of squarelike electric pulses and measure the electron emission current only in the periods of time when $U_f = 0$, i.e. when electric field is not disturbed by filament voltage. This may be obtained either by (i) applying appropriate variable potential to the filament or to the electron collector in order to cut off the I_e current during heating, or by (ii) numerical rejection of data collected at that time.

Whatever method of data collection is chosen, one has to determine the filament temperature somehow. The filament is invisible, because most usually the collectors surround it completely. Temperature may be measured pyrometrically as a function of voltage prior to the experiment, without the collectors. One may also use an auxiliary filament, being connected in series with the investigated filament of the same size, and check the auxiliary filament temperature [1,2]. In both cases, cooling of filament by electron emission current is a drawback resulting in lowering the filament temperature.

Measurements were performed for filament A (56 mm length, 0.2 mm diameter) by use of experimental circuit shown in Fig. 1. The U_f amplitude was -7.2 V, frequency 830 Hz. Results of I_e measurements were collected by DSO 28264/200 MHz digital oscilloscope (Link Instruments, Inc., Fairfield, NJ) and stored in memory. The I_e values collected during

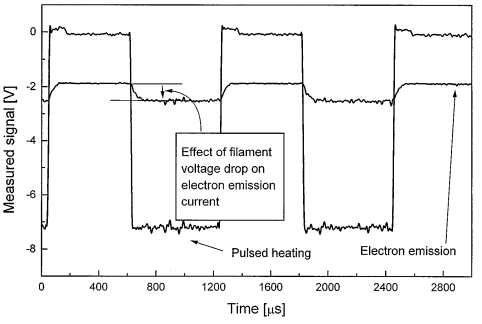

Fig. 2. A sample record of filament voltage and electron emission current at tiny collector, taken by means of DSO 28264/200 MHz digital oscilloscope.

heating periods were rejected to avoid filament voltage drop influence on electron emission. As it may be seen from Fig. 2, the relative difference between total electron current and this measured for $U_f = 0$ is above 20%, only 5% of which comes from a 5 K temperature modulation. Temperature modulation should theoretically diminish below 1 K at frequencies >2 kHz. Measurements in the frequency range up to 3.5 kHz confirmed this prediction.

5. Results

Two tungsten filaments of different sizes were used in calculations based on solving Eq. (5) by finite differences method. The first filament, A, was long enough to have a temperature plateau, spanning almost one third of the total length. The second filament, B (14 mm length, 0.2 mm diameter), not investigated experimentally, was short and revealed no temperature plateau. In both cases the Richardson's collector was subjected to collect electrons from the central 10% of filament's length. Temperature and saturated electron emission current densities calculated for both filaments are shown in Figs. 3 and 4, respectively. The mean temperature and total electron emission current of central 10% of filaments A and B as function of root mean square (RMS) of applied U_f voltage is presented in Figs. 5 and 6, respectively. The Schottky lowering of work function was neglected, because only the saturation current was of interest.

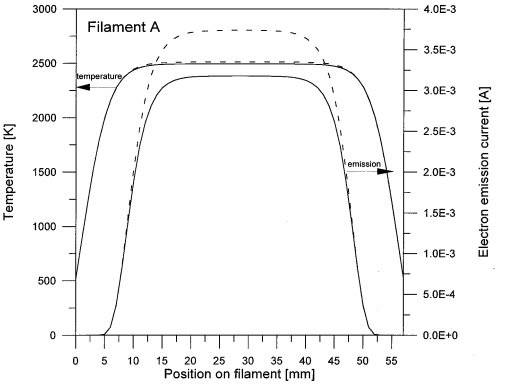

Fig. 3. Mean temperature and I_e distribution along the tungsten filament (A) 56 mm long, 0.2 mm in diameter. The U_f amplitude was −7.2 V, frequency 830 Hz. Dashed lines show overestimated values, whereas solid lines are calculated with filament cooling effect.

The Richardson plot of ln (I_e/T^2) against $1/T$ is shown in Fig. 7. Measurements of I_e were performed for filament A. The U_f amplitude was −7.2 V, frequency 830 Hz, the same values taken for calculations. The values of saturation current were found for each temperature from Schottky plots. The dashed line in Fig. 7 was obtained by least-squares method for saturation current plotted against reciprocal of temperature calculated without filament cooling effect. Crosses and solid line represent the values of

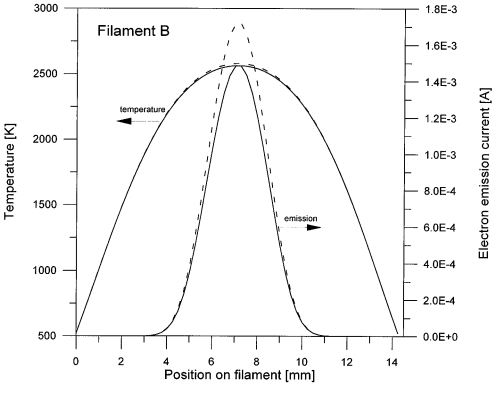

Fig. 4. Mean temperature and I_e distribution along the tungsten filament (B) 14 mm long, 0.2 mm in diameter. The U_f amplitude was −1.85 V, frequency 830 Hz. Dashed lines show overestimated values, whereas solid lines are calculated with filament cooling effect.

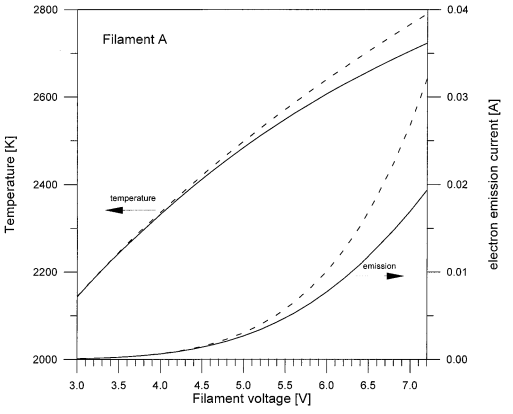

Fig. 5. Mean temperature of central 10% length and total electron emission current of central 10% length of filament (A) as function of RMS of applied U_f voltage. Dashed lines represent calculations performed without filament cooling effect. Solid lines represent values lowered by electron emission.

ln (I_e/T^2) for saturated electron emission current corrected for cooling, plotted against corrected temperatures. Slope of the line (divided by factor 11 600 K) is work function. The value of work function obtained from corrected results, $\varphi = 4.57 \pm 0.21$ eV, is in accordance with accepted value for polycrystalline tungsten (4.54 eV), whereas the value $\varphi_{app} = 4.10 \pm 0.20$ eV obtained from rough data is lower by more than two standard errors.

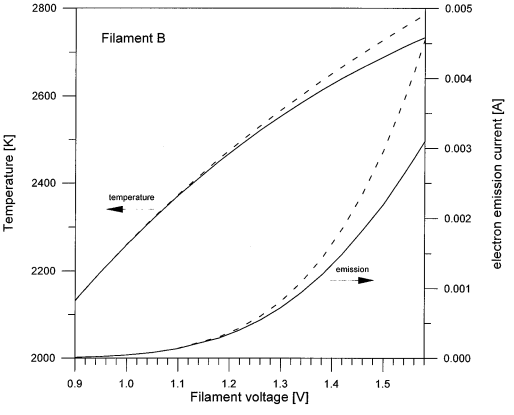

Fig. 6. Mean temperature of central 10% length and total electron emission current of central 10% length of filament (B) as function of RMS of applied U_f voltage. Dashed lines represent calculations performed without filament cooling effect. Solid lines represent values lowered by electron emission.

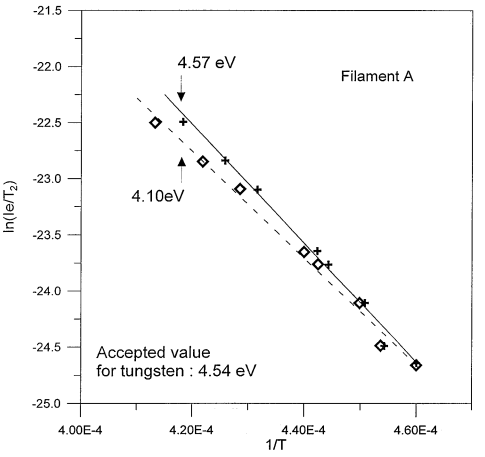

Fig. 7. The Richardson's plot for filament (A). Points approximated by the dashed line represent I_e measurements recalculated by apparent filament temperature values obtained on the basis of Eq. (5) without filament cooling effect. Solid line and crosses represent I_e measurements recalculated for temperature lowered by electron emission.

Effect of cooling in case of electron beam evaporation has been considered theoretically. In such experiments it is crucial to know the power characteristics, namely, the ratio of evaporation power $P_{ev} = I_e U_e$, where U_e is anode voltage, to power P_f delivered to the filament. P_1 stands for P_f in Eq. (4).

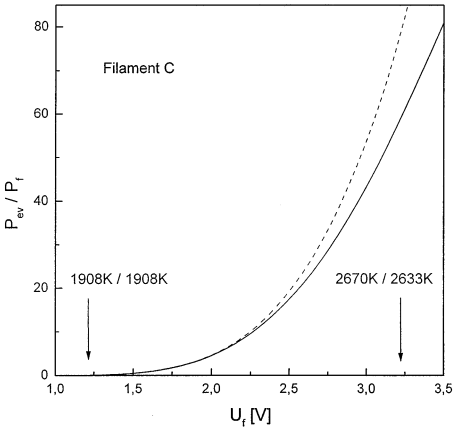

Fig. 8. Ratio of evaporation power, P_e, to power P_f delivered to the filament as a function of filament voltage. Filament C, made of tungsten, 1 mm diameter, 70 mm length. Dashed line shows overestimated values, whereas solid line is calculated with filament cooling effect.

The ratio P_{ev}/P_f is plotted in Fig. 8 against filament voltage corresponding to the filament temperature range 1900–2700 K. U_e was taken after Donkov [9] as 6 kV. Because the magnitude of electric field is large enough to cause a significant Schottky lowering of work function, the 5 cm distance between filament and anode was assumed, and $\Delta\varphi$ was calculated. This resulted in lowering of work function by 0.13 eV. Calculations were performed for massive tungsten filament, C, 1 mm in diameter, 70 mm length, heated by constant current.

6. Discussion

Temperature of tungsten filaments emitting saturated electron current is generally overestimated at high temperatures. The difference $\Delta T = T_{\text{calculated}} - T_{\text{true}}$ becomes significant above 2300 K. For the investigated filaments A, B, and C, the ΔT value at 2600 K was 33, 22, and 37, respectively. It has been calculated that the values of electron emission currents emitted at temperatures 2400 and 2600 K are approximately 7% and 25% lower, respectively, than calculated without term P_5 in Eq. (5).

This effect is especially important in work function determination by thermionic emission method. Residual gases present in the vacuum chamber are adsorbed by tungsten surface. Adsorbed molecules, like oxygen or hydrogen, substantially influence the work function of substrate tungsten, and may be removed only by heating the filament in ultrahigh vacuum. It is therefore desirable to perform measurements in high temperatures [10]. As it may be seen from Fig. 7, this procedure leads to large errors if temperature is estimated without the cooling effect of electron emission.

Electron emission by incandescent filaments is commonly used in gas ion sources for mass spectrometers. The value of ion current (I_i) depends on the ionization cross section and electron emission current (I_e). Let us consider the effect of temperature overestimation on the ion beam. Because the change in energy of electrons due to change in filament temperature is negligible, the ionization cross section may be assumed constant, and the dependence of I_i on I_e is almost linear. The instantaneous time constant of temperature changes, τ, is an important factor that has to be taken into account in design of the electron emission stabilizers. It was shown [6] that the value of τ depends not only on filament temperature, but also on the position along filament. The midpoint of the filament is especially important, because the majority of electrons are emitted from the central part of the filament. In temperatures above 2300 K the value of τ in the midpoint begins to decrease rapidly. This change of operating conditions is a drawback in commonly used electron emission controllers with negative feedback loop, because there is usually no possibility of adjusting the time constant.

Underestimation of filament temperature in case of high electron emission current density, as it is in electron beam evaporators, is significant and must be considered in the control process. Power taken from filament by thermionic emission may decrease the evaporation power by 20% for filament temperatures above 2500 K (see Fig. 8). It therefore seems reasonable to consider increasing the acceleration voltage, U_e, to limits achievable for given apparatus rather than filament temperature to obtain higher evaporation power.

7. Conclusion

Cooling the incandescent tungsten filaments by thermionic emission should not be neglected in calculations or experiments dealing with temperatures above 2300 K. This effect can result in up to 30% overestimation of thermionic emission current from tungsten in high temperatures. For filament materials with low work function, like thoriated tungsten, LaB_6 or Ir–Ce, cooling effect is significant in much lower temperatures (e.g. 20% of thermionic emission overestimation for thoriated tungsten at 2000 K). Similarly, for filaments made of pure Re or Ir, the cooling effect may safely be neglected up to 2600–2700 K. The corrected value of filament temperature may be calculated by use of formula (5), for filaments heated by constant or alternate currents of any waveform.

Cooling effect was found experimentally to be

significant in measurements of work function of tungsten by thermionic emission method, causing 10% decrease in apparent work function value.

It is recommended to include the I_e cooling term in design of electron emission current stabilizers for gas ion sources [11,12], in power supplies for electron beam evaporators [9] and other devices that make use of electron emitting filaments.

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