Thermionic Emission

Synopsis:
Investigate thermionic emission for electrons emitted into vacuum from a heated cathode as a function of temperature and applied electric field and match to various theoretical behaviors, including: Stefan-Boltzman law, Child's law (space-charge), Richardson law (Arhenius behavior).

Background Reading:
Melissinos pp. 65-78 (thermionic emission). New edition does not have this – so see the copied handout instead – borrow and return. This handout contains pertinent dimensions for the vacuum tube (filament and anode). Preston and Dietz pp. 141-147 (thermionic emission); 152-161 (pyrometry)

Skills:
Basic electronics (Ohm's law), switching power supply, optical pyrometer.

Precautions:
The circuit to be used is shown in Fig.1. Note that the vacuum tube used in this experiment, the GE FP-400, is an antique and difficult to replace. The filament current ***must not exceed 2.5 A.***

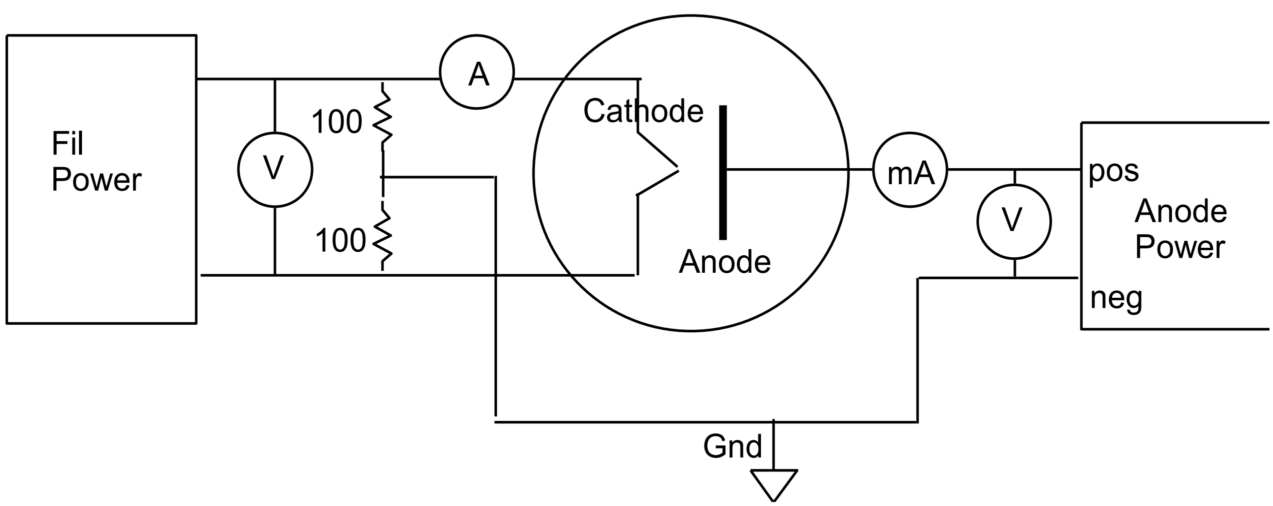

Figure 1. Wiring diagram for the thermionic emission experiment.

Part A: Temperature determination and Stefan-Boltzman law

The total power P radiated by a body in thermal equilibrium at temperature T is given by the Stefan-Boltzmann (SB) law:

$$P = \varepsilon A \sigma T^4, \qquad \text{Eq 1}$$

where ε is the total emissivity, A is the surface area of the emitter, T is the temperature (in Kelvin!) and σ is the SB constant, $\sigma = 5.68 \times 10^{-8}\ \mathrm{W/m^2K^4}$.

1. Connect the circuit shown in Fig. 1. Ask the instructor verify the circuit before turning it on. Turn all knobs to zero, then turn the power switch(es) to on. Note the funky range buttons on the DVMs. Adjust the filament current to 2.0 A. You should see the tube filament (not your circuit wires) glowing.
2. Position the tube and pyrometer for proper viewing: The hole in the anode must be pointing toward the pyro and the pyro must, of course, be carefully aligned to see the light. First find the right location for your eyeball wrt the eyepiece (must be at the "exit pupil" of the optics) by focusing the internal filament. Next focus the filament with the top focus ring (Distance). Then find the glowing filament by panning horiz and vertical until you see it. Finally, adjust the object focus by moving the tube toward/away from the pyro as needed. The filament should appear as a thin vertical line. The focus should be at approx 30 cm. Turn the pyrometer temperature knob until the pyrometer line brightness matches the filament brightness. When these match, the filament image will blend perfectly with the object image, hence the name "disappearing filament" pyrometer. Be sure to use the appropriate scale/filter setting on the front of the pyro. Estimate the uncertainty by turning the dial back and forth and noting "by feel" the range that is clearly too high/low. Each person in the group must learn to take readings.
3. Record T_{pyro} vs filament power (current and volts) for a wide range of current, say 1.0-2.5Amps (do not exceed 2.5A).

Analysis:

1. The pyrometer readings must be corrected for emissivity. When the filament disappears, you have matched the light intensity of target and filament in the visible red region (near 0.65microns). The pyro output dial assumes a perfect black body (ε=1). The object is hotter than it appears, because the grey body emits/absorbs less than perfect (ε=1). Find the true temp using the appended table.
2. Explore the SB law using two fits: First, find an average value for ε(T) over the T range, using the uncorrected T values and assuming that the value of the exponent, n, in T^n, n=4. Secondly, find a best value for n, using the corrected values for T with the implied values for ε(T). For a power law fit, we would normally use a log-log plot to linearize the fit. But the dynamic range of the data makes this impractical. Instead, you can simply use a "power law" fit in Logger Pro.

Part B: Thermionic emission

The emission current density J depends on two variables: accelerating voltage V_a and temperature T. Thus, we have J(V, T). These data are to be compared with Child's law and the Richardson-Dushman equation, as described in Melissinos. See in particular the 3-variable X-Y plot in Fig. 3.14.

Procedure:

Measure I_{emiss} vs V_{anode} for a set of I_{fil} (hence, temperatures). You may use the earlier calibration of filament current vs T. Take data in the range 1.7 to 2.5 step 0.1 Amps, using V_a steps such that the space-charge-limited and saturation asymptotes are both apparent. In particular, run V_a out to the max value for every curve. You might use a variable voltage step size to efficiently map the curve. See the sample data in Melissinos.

Analysis:

There is no analytic expression for the full J(V,T) behavior. The "theory" functions apply only in their respective asymptotic limits You will need to manipulate your data appropriately to obtain "linearized" plots and confine your attention to the separate asymptotic regions.

1. Choose one I(V,T) curve that best represents Child's law. Find the power law exponent and a value for e/m from this curve (fitting Meliss eq 2.4c).
2. Find the saturation current density at zero field, J_0, for all the I (V,T) curves. This requires extrapolating to zero the shape of the curve in the (near)-saturation regime. You can simply fit to Melissinos eq 2.3b using an appropriate range of data. Note that E is proportional to V for any geometry (plane or cylinder).
3. Find a value of work function for tungsten based on the T-dependence of the saturation current (Richardson Equation, Melissinos eq 2.2).

Questions:

1. Explain the function of the two 100 ohm resistors in the filament circuit. Hint: consider the energy of electrons leaving each end of the filament.
2. The ends of the tube filament are cooler than the center (which you measure with the pyro). This could be considered as an "effective" length for the filament, which is shorter than the physical length. Briefly describe how this would affect the measured value for each parameter ε, A, σ and n in the SB law.

Pyrometer correction table for tungsten, from CRC handbook. Columns of particular interest are "Temp-K" (true temperature), and "Total emissivity" (as used in SB law), and "Brightness Temp 0.65u" (as matched by eye in the pyro).

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Tungsten

Temp. °K	Normal brightness new candles per cm^2	Spectral emissivity		Color emissivity	Total emissivity	Brightness temp. 0.65μ	Color temp.
		0.65μ	0.467μ				
300	....	0.472	0.505	.....	0.032		
400	....	.....	.....	.....	.042		
500	....	.....	.....	.....	.053		
600	....	.....	.....	.....	.064		
700	....	.....	.....	.....	.076		
800	....	.....	.....	.....	.088		
900	....	.....	.....	.....	.101		
1000	0.0001	.458	.486	.395	.114	966	1007
1100	0.001	.456	.484	.392	.128	1059	1108
1200	0.006	.454	.482	.390	.143	1151	1210
1300	0.029	.452	.480	.387	.158	1242	1312
1400	0.11	.450	.478	.385	.175	1332	1414
1500	0.33	.448	.476	.382	.192	1422	1516
1600	0.92	.446	.475	.380	.207	1511	1619
1700	2.3	.444	.473	.377	.222	1599	1722
1800	5.1	.442	.472	.374	.236	1687	1825
1900	10.4	.440	.470	.371	.249	1774	1928
2000	20.0	.438	.469	.368	.260	1861	2032
2100	36	.436	.467	.365	.270	1946	2136
2200	61	.434	.466	.362	.279	2031	2241
2300	101	.432	.464	.359	.288	2115	2345
2400	157	430	.463	.356	.296	2198	2451
2500	240	.428	.462	.353	.303	2280	2556
2600	350	.426	.460	.349	.311	2362	2662
2700	500	.424	.459	.346	.318	2443	2769
2800	690	.422	.458	.343	.323	2523	2876
2900	950	.420	.456	.340	.329	2602	2984
3000	1260	.418	.455	.336	.334	2681	3092
3100	1650	.416	.454	.333	.337	2759	3200
3200	2100	.414	.452	.330	.341	2837	3310
3300	2700	.412	.451	.326	.344	2913	3420
3400	3400	.410	.450	.323	.348	2989	3530
3500	4200	.408	.449	.320	.351	3063	3642
3600	5200	.406	.447	.317	.354	3137	3754