Analytical Derivation of Radiant Energy Heat Load on Web Based Polymer Films

Quinn D. Risch

Abstract

A quick good estimate of the blackbody heat load from evaporative metalization on a web based polymer film is derived. Starting from basic principles and building to approximations the result is a formula that is useful to anyone trying to optimize a chamber design.

A major concern in web based metalization processes is the heat load on the film. Knowing the heat load helps determine various factors of the vacuum chamber process such as line speed, chiller sizing, etc. Typically the heat loads are empirical estimates used within the industry and there is no good analytic estimate used. This paper is a quick derivation and estimate of the most challenging portion of the calculation for heat load: radiant heat from evaporative metalization.

The heat load on a web based film from thermal evaporation of aluminum (or any metal) is a result of two terms: physical heat transfer of the metal depositing and the radiance of the evaporation source

$$J/A = Radiance\,term + Metal\,condensation$$

Where J/A is Joules per square meter

The heat load from condensation is a constant term with respect to the thickness, τ, or Optical Density (OD) of the metal and can be almost trivially calculated. For this reason only the more complex derivation of the heat load due to the blackbody radiation of the evaporation boats will be calculated. Therefore,

$$J/A = Radiance\ term\ \ ;\ \ Radiance\,term = R_a\, t_{ex}$$

Where R_a is radiance (Watts/m^2) and t_{ex} is the exposure time

The Stefan-Boltzmann Law gives radiance, R_a, of an object as:

$$R_a = \sigma \varepsilon T^4 \qquad (1)$$

R_a is Watts per square meter, σ is the Stefan-Boltzmann constant, ε is the emissivity of the radiating object and T is the temperature in Kelvin.

The evaporation boats are not uniformly and completely covered by the metal[1] and therefore the energy hitting the film is

$$J/A = \frac{\sigma\, T^4\, (\varepsilon_r SA_r)\, t_{ex}}{SA_f} = \frac{\sigma\, T^4\, (\varepsilon_b SA_b + \varepsilon_m SA_m)\, t_{ex}}{SA_f} \qquad (2)$$

Where SA_r is the surface area[2] of the object radiating energy, SA_f is the surface area being impinged by the radiation at any one instant (typically $SA_f >> SA_r$) and the subscripts b and m are referring to the evaporation boat that is partial covered by the evaporating metal.

The time of exposure, t_{ex}, is related to the line speed of the film, v, and the length of the path that is exposed to the thermal radiation, L_P (assume uniform illumination from the evaporation boats[3])

$$t_{ex} = \frac{L_P}{v} \quad (3) \ ; \ SA_f = w_f L_P \quad (4) \quad \rightarrow$$

$$\frac{\sigma\, T^4\, (\varepsilon_b SA_b + \varepsilon_m SA_m)}{w_f L_P} \left(\frac{L_P}{v}\right) = \frac{\sigma\, T^4\, (\varepsilon_b SA_b + \varepsilon_m SA_m)}{w_f v} = J/A \qquad (5)$$

Where w_f is the width of the film being impinged by the radiation

Temperature, T, is a variable dependent on line speed and desired thickness of the metal to be deposited. T can be found by equating the resultant metal thickness on the film to the flux, Γ, of metal leaving the evaporation boats.

$$m\Gamma \geqslant \delta_{solid\ metal}\, w_d\, \tau\, v \quad \rightarrow \quad m\Gamma = E\ \delta_{solid\ metal}\, w_d\, \tau\, v \qquad (6)$$

Where E is an efficiency factor between 0 and 1 (because not all the evaporated metal ends up on the film), m is molecular mass of the metal, δ is the density of the metal on the film, τ is the thickness of the metal on the film, w_d is the width of the depositing metal and v is the line speed of the metal.

According to basic ideal gas laws the particle flux can be used to get mass per second of the metal evaporating, Q

$$\Gamma = N\left(\frac{kT}{2\pi m}\right)^{1/2} \quad (7) \ ; \quad PV = NkT \quad \rightarrow \quad m\Gamma = Q = P\left(\frac{m}{2\pi kT}\right)^{1/2} \qquad (8)$$

1 The temperature is not uniform on an evaporation boat either, however it is close to uniform and for the purposes of this derivation will be ignored

2 SA_r should be limited to only the top surface of the evaporation boat thus ignoring reflected energy sourced from the underside of the evaporation boat

3 Assuming uniform illumination of the film will overestimate the heat load. One might more accurately take SA_f to be the effective surface area illuminated. For this derivation it is convenient to neglect the $1/r^2$ law.

Where Q is the mass per second, P V = N k T is the ideal gas law and k is the Boltzmann constant.

The pressure in equation 8 is the vapor pressure of the evaporating metal. The vapor pressure can be estimated using the Clausius-Clapeyron equation.

$$P_v \approx e^{C - L/RT} \qquad (9)$$

Where C is a constant specific to the metal, L is the latent heat of vaporization for the metal[4], R is the gas constant and T is the temperature of the metal

Substituting equation 9 into equation 8 with some slight rearranging results in

$$Q \approx \frac{e^{(C - L/RT)}}{T^{1/2}} \left(\frac{m}{2\pi k}\right)^{1/2} \qquad (10)$$

The temperatures of interest for most typical vacuum metal evaporation processes are far from 0 K and can be typically estimated in the range of 1000 – 2000 C (1273.15 to 2273.15 K). In this range of temperatures $T^{-1/2}$ is essentially a constant and can be approximated as the first term of its Taylor series, $1773.15^{-1/2}$ or roughly 0.0237 [5].

$$Q \approx e^{(C - L/RT)} (0.0237) \left(\frac{m}{2\pi k}\right)^{1/2} \qquad (11)$$

By substituting equation 11 into equation 6 one can solve for T

$$Q = m\Gamma = E\,\delta_{solid\,metal}\, w_d\, \tau\, v \;\rightarrow\; e^{(C - L/RT)} (0.0237) \left(\frac{m}{2\pi k}\right)^{1/2} = E\,\delta\, w_d\, \tau\, v \;\rightarrow$$

$$e^{(C - L/RT)} = \left(\frac{1}{0.0237}\right)\left(\frac{2\pi k}{m}\right)^{1/2} v\, w_d\, \tau\, \delta\, E \;\rightarrow\; (C - L/RT) = \ln\left(\left(\frac{1}{0.0237}\right)\left(\frac{2\pi k}{m}\right)^{1/2} v\, w_d\, \tau\, \delta\, E \right) = Z$$

$$\rightarrow\; T = \left(\frac{1}{R(C - Z)}\right) \qquad (12)$$

Now T is solved for (approximately). Substituting equation 12 into equation 5 one solves for the energy deposition per area onto the film and its approximate dependance to line speed and thickness.

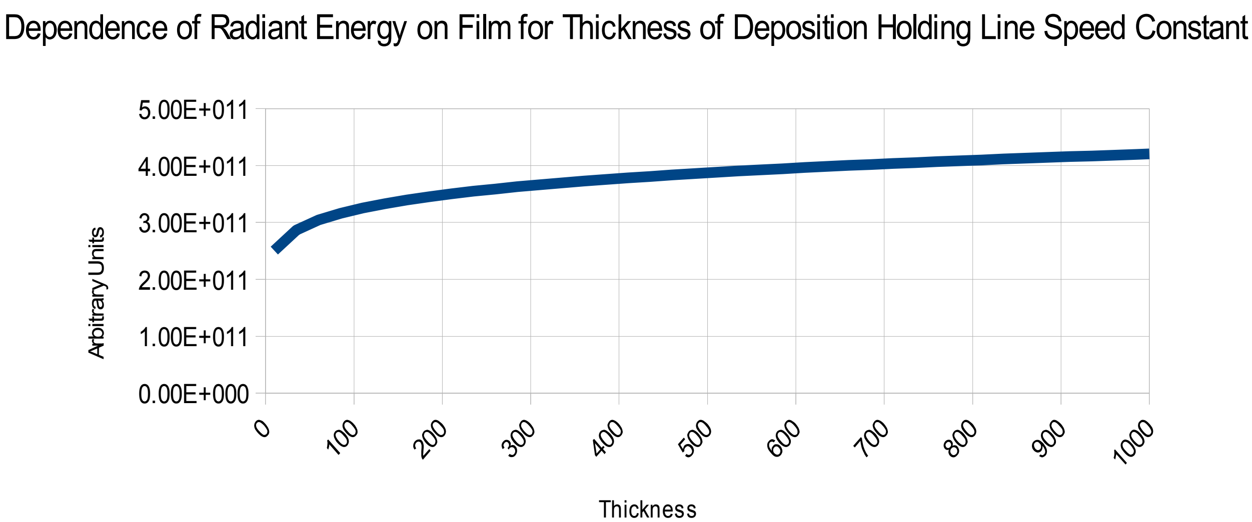
$$J/A = \frac{\sigma\, T^4\, (\varepsilon_b SA_b + \varepsilon_m SA_m)}{w_f\, v} = \frac{\sigma\, (\varepsilon_b SA_b + \varepsilon_m SA_m)}{w_f\, v} \left(\frac{1}{R(C - Z)}\right)^4 \;\rightarrow$$

$$\frac{\sigma\, (\varepsilon_b SA_b + \varepsilon_m SA_m)}{w_f\, v} \left(\frac{1}{\left(C - \ln\left(\left(\frac{1}{0.0237}\right)\left(\frac{2\pi k}{m}\right)^{1/2} v\, w_d\, \tau\, \delta\, E \right) \right)} \right)^4 = J/A \qquad (13)$$

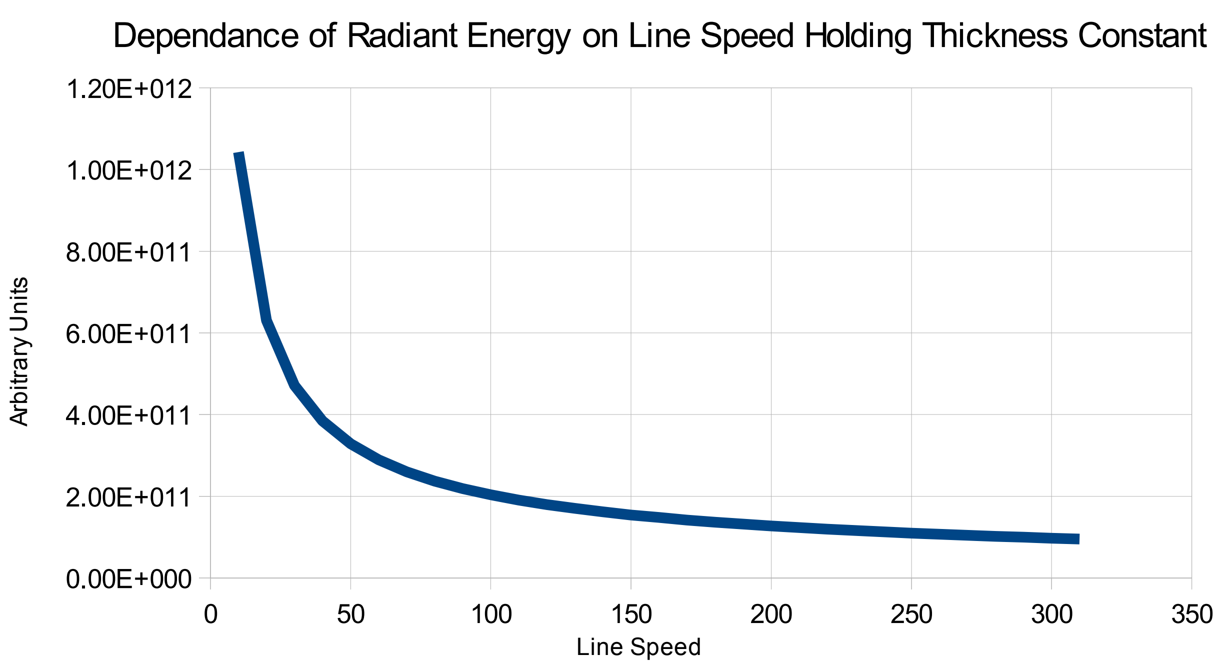
4 Trouton's rule estimates the latent heat of vaporization to be roughly 85 – 88 J K^{-1} mol^{-1} for most elements

5 This is a somewhat crude approximation for the entire range of temperatures quoted giving almost 19% error at the extreme low end of the range. If more accuracy is required the point about which the Taylor series is approximated should be chosen close to the operating temperature of the process. A range of ± 400 C at 1500 C gives an error of only 6%.

Plotting equation 13 with arbitrary numbers can give a general sense of the dependency of the radiant energy load on web based polymer films. As a sanity check one sees that while holding line speed constant if the thickness is increased the thermal load (from radiant energy) increases (which might not be apparent from the complexity of equation 13).



However, maybe unexpectedly, when plotting equation 13 for line speed while holding the thickness constant one sees that the radiant heat load decreases very rapidly with increasing line speed.



Summary

When trying to estimate the heat load on a web based polymer film there are several approximations that need be made for analytical purposes which prove to be justified and very enlightening. Interestingly it is found that when metalizing a polymer film the process should try to operate at maximum line speed in order to minimize the radiant heat load. Operating at maximum line speed has other challenges, but at whatever thickness and line speed that is chosen an accurate estimate of the radiant heat load can be made using equation 13.