FR9601094

CEA-CONF--12210

POWER BALANCE EQUATION IN ELECTRON BEAM EVAPORATION PROCESS

L.BLUMENFELD and SOUBBARAMAYER, DCC/DPE, CEA-CEN SACLAY
91191 GIF SUR YVETTE Cedex, FRANCE

1- INTRODUCTION

In the electron beam evaporation process (SCHILLER et al.) the total power P of the gun is used, for a part P_{vap} to generate the vapor stream and for the rest to cover three main power losses P_{conv}, P_{ebs} and P_{rad} due respectively to three parasite phenomena : turbulent thermal convection in the molten pool, electron back scattering and heat radiation from the vapor emitting surface. It results in a four component power balance equation :

$$P = P_{vap} + P_{conv} + P_{ebs} + P_{rad} \qquad (1)$$

The aim of the paper is to solve Eq(1) . We start by making the list of the scaling laws governing each of the four terms in the rhs of the Eq (1) . The scaling law for the power loss P_{conv} due to the turbulent thermal convection in the molten pool has been derived empirically by Blumenfeld and Soubbaramayer from experiments carried out in the French CEA (Antoni et al.) by evaporating cerium with a 5 KW axisymmetric electron gun. The formulas for the three other terms P_{vap} , P_{ebs} and P_{rad} are drawn from the current literature. Eq (1) is then solved by the standard iteration method. The input data are the physico chemical constants of the evaporant and the two characteristics of the electron beam (i.e the total power(KW) and the power density(KW/cm^2)). The iteration variable is the peak temperature on the melt surface. The output of our calculations yields four important informations on the process: Temperature on the melt surface, vapor flow rate (g/h), power balance chart and cratering of the melt surface. To illustrate the method, we compute the evaporation of Aluminium with a 5 KW axisymmetric gun working in steady state mode. The results are presented in Figures 1 and 2 and Table 1 .

2- SCALING LAWS

The scaling laws for the four power components in the RHS of Eq(1) and for the depth of the crater on melt surface are summarized herebelow:

$$P_{vap} = \Delta H \int_0^{r_T} D \, 2\pi \, r \, dr \qquad D = 0.09 \, (M/T)^{1/2} \, P_{sat}$$

D, g/s/cm^2 M, g T, K P_{sat}, mm Hg

$$\log_{10} P_{sat} = A \, T^{-1} + B \log_{10} T + C \, T + D \, T^2 + E$$

The coefficients A, B , C , D and E are drawn from :
Honig,R.E. & Kramer, D.A. 1970, Vapor pressure data for the solid and liquid elements, in the book " Physicochemical measurements in metal research, ed. Rapp,R.A., vol IV Part 1, pp505-531, Interscience.
The component P_{conv} is introduced through 3 nondimensional numbers

$$Ra = (2 \, g \, \alpha \, r_q^2 \, P_{conv} / \pi \lambda \nu \kappa) \qquad Ma = (2 \, \gamma_T \, P_{conv} / \pi \lambda \mu \kappa)$$

$$Nu = (2 \, P_{conv} / \pi \lambda \, r_q \, \Delta T_m)$$

$$Nu = 0.15 \, Ra^{0.3} + 0.00015 \, Ma \, Ra^{-0.3} \exp \left[0.075 \, p_0 / (\rho \gamma g)^{1/2} \right] - \Delta Nu$$

$$p_0 = p_{sat} (T_F + \Delta T_m)$$

$$\Delta Nu = (0.15 \, Ra^{0.3} - 1) \left[1 + 5.854 \, (Ra^{2/3} \, Ha^{-2})^{1.36} \right]^{-0.695}$$

$$Ha = (\sigma_{el} / \mu)^{1/2} \, B \, r_q$$

$$P_{ebs} = P \, R \qquad P_{rad} = \int_0^{r_T} \varepsilon \sigma T^4 \, 2\pi \, r \, dr$$

$$h_c = p_0 \, r_T^2 \, / \, (\rho \, g \, r_T^2 + 16 \gamma)$$

Comments

1- The last equation was derived from measurements of melt surface distortion made in CEA-experiments of cerium evaporation with a 5 KW gun. The equation works until the cratering has a regular shape , but does not account for more complex phenomena like the Key-hole formation and spattering, which occur for high power density.

2- The validity of the scaling law for P_{conv} is restricted to liquid metals having a Prandtl number close to 0.02 .

3- The preceding set of scaling laws is pertinent to electron beam working in steady state mode, but does not cover the SWEEP MODE. This latter mode with a proper frequency yields (according to Schiller's experimental results on Aluminium evaporation) an efficiency higher by a factor 10 to 35.

3- RESULTS

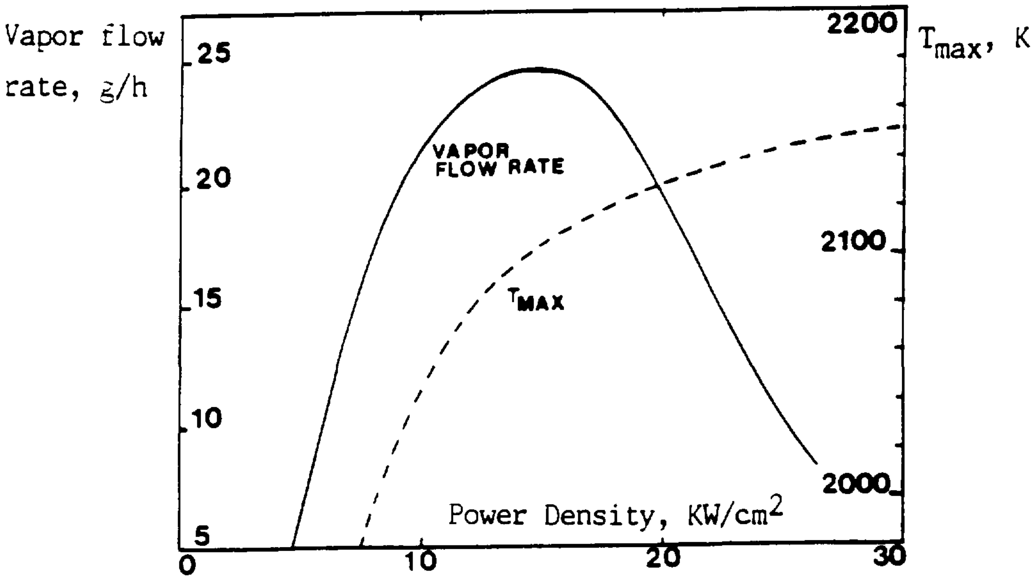

Fig 1 : Evaporation of Aluminium with a 5KW electron beam.

------- Peak temperature on the melt surface : with increasing power density, the temperature reaches a plateau.

——— Vapor flow rate: it passes by a maximum and the maximum calculated (24.5 g/h) is in very good agreement with the experimental result (24 g/h) of SCHILLER et al.

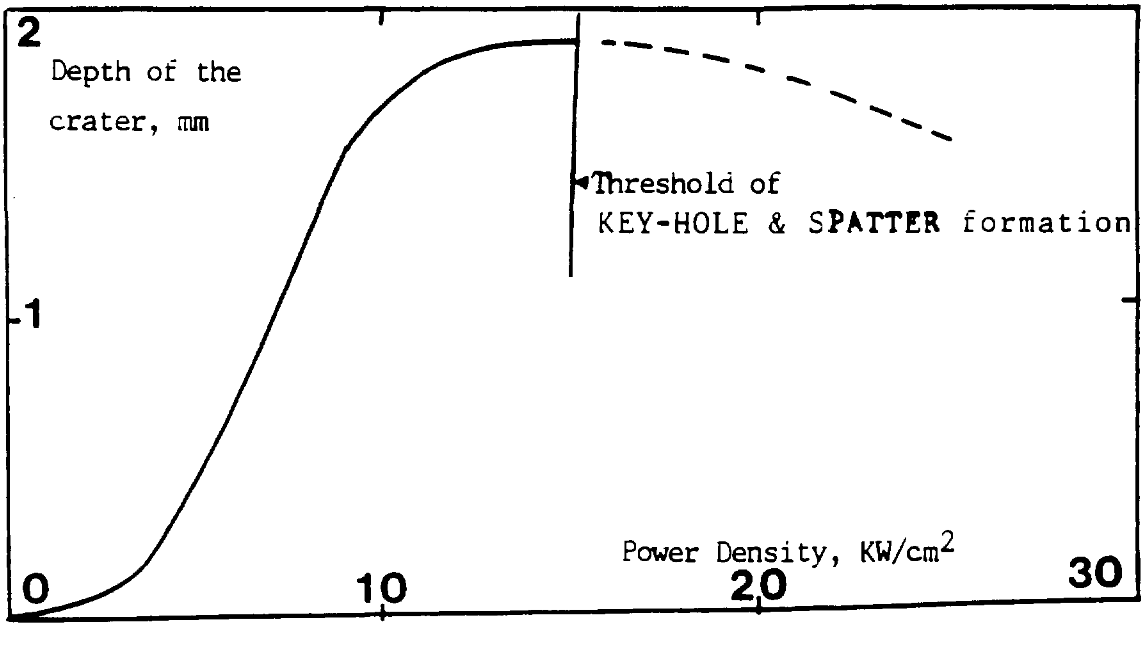

Fig 2 : Evaporation of Aluminium with a 5KW electron beam. Depth of the crater on the melt surface.

TABLE 1 : Power balance chart at the maximum of Fig 1

Power used for evaporation	1.7 %
Power lost in :	
* Radiation	0.3 %
* Back scattering of e^-	15. %
* Heat conduction	12. %
* Heat convection	71. %

4- EFFECT OF A MAGNETIC FIELD

The last section is devoted to the influence of an applied magnetic field on the evaporation rate. In Charlottesville Workshop (1992) , Couairon and Soubbaramayer have shown that an applied magnetic field decelerates the convective motion of the melt, very significantly in the volume of the pool, but much less on the upper free surface. As a consequence, a magnetic field reduces the power loss P_{conv} due to the thermal convection (more precisely the part of P_{conv} due to buyoancy). We give an approximate scaling law for this reduction, based on experiments with molten Gallium published by OKADO and OZOE. The resulting increase in the evaporation rate depends upon the evaporant, the electron beam and the intensity of the magnetic field. For illustration, an example of computation is presented in the case of a small gun of 5 KW evaporating cerium. A magnetic field of 0.5 to 1. Tesla increases the rate of evaporation by a factor 2 to 3 (Fig3)

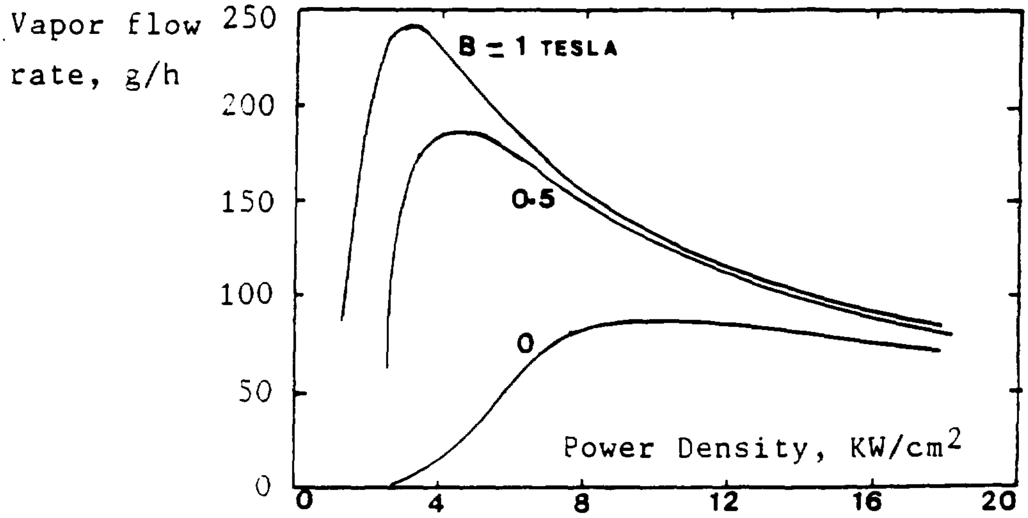

Fig 3 : Evaporation of Cerium with a 5 KW electron beam. Influence of a magnetic field on the vapor flow rate.

References

Antoni B., Bertrand G., Le Guyadec E., Lemaire P., Maury J.& Ravoire J Cerium evaporation from a Electron Beam Source, Proc. of NURETH 6, Grenoble, France 1993 pp 1471-1479

Blumenfeld L. & Soubbaramayer, Combined effect of buoyancy and of interfacial phenomena on the heat transfer coefficient at the melt surface of a EB evaporator, To be published in the Proc. of the 10 th Int.Heat Transfer Conf., Brighton, UK 1994

Couairon A. & Soubbaramayer, Hydrodynamics of molten metals with convection damping effects, Proc. of the Third Workshop on Separation phenomena in liquids and gases, Charlottesville, Virginia USA 1992 pp 99-114

Okada K. & Ozoe H., Experimental heat transfer rates of natural convection of molten Gallium suppressed under an external magnetic field in either the X, Y, or Z direction,J.of heat transfer, vol 114, 107-114 Feb 1992

Schiller S., Heisig U., Panzer S., Electron Beam Technology, John Wiley 1982

Nomenclature

B	Magnetic field
D	Vapor flow rate per unit area
g	gravitational acceleration
Ha	Hartmann number
h_c	Depth of the crater on melt surface
M	Molar mass of the metal
Ma	Marangoni number
Nu	Nusselt number
p_{sat}	Vapor saturation pressure
r	Radial coordinate
r_q	Beam spot radius
r_T	Melt radius ($r_T = 4/3\ r_q$)
R	Electron backscattering coefficient
Ra	Rayleigh number
T	Temperature on the melt surface ($T = T_F + \Delta T_m (1 - r^2/r_T^2))$
T_F	Melting temperature
α	coefficient of the cubic expansion
γ	Surface tension
γ_T	Temperature coefficient of the surface tension
ΔH	Enthalpy of evaporation
ΔNu	Variation of the Nusselt number due to magnetic field
ΔT_m	Peak value of ($T - T_F$)
ε	Emissivity in heat radiation law
κ	Thermal diffusivity
λ	Thermal conductivity
μ	Dynamic viscosity
ν	Kinematic viscosity
ρ	Liquid mass density
σ	Stefan constant
σ_{el}	Electrical conductivity