

THE ROLE OF A GAS PHASE IN THE EVAPORATION PROCESS OF VOLATILE COMPONENTS OF THE METAL BATH

Received – Prispjelo: 2013-05-21
Accepted – Prihvaćeno: 2013-10-30
Preliminary Note – Prethodno priopćenje

In the paper, the role of the gas phase in the process of evaporation of metal bath volatile components, considering mass transfer, is presented.

Keywords: gas phase, evaporation, kinetics, melting, mass transfer coefficient

INTRODUCTION

The development of production technologies with respect to modern construction metallic materials is mainly based on procedures performed at low pressures. This refers to both vacuum induction melting (VIM) and vacuum arc remelting (VAR) technologies. Vacuum treatment ensures production of metals and their alloys that demonstrate higher purity as well as lack of solved gases and many other metallic contaminants. The latter effect is possible due to evaporation of contaminants, whose equilibrium vapour pressures are higher compared to the matrix metal, from the bath.

In the paper, the role of the gas phase in the process of evaporation of metal bath volatile components, considering mass transfer, is presented.

KINETICS OF EVAPORATION

It is known that in the process of liquid metal alloy component evaporation, there are three essential stages [1]:

- Transfer of the evaporating component mass from the body of the liquid metal phase to the interface – stage I.
- A surface reaction, i.e. the evaporation process itself on the liquid metal-gaseous phase interface – stage II.
- Transfer of the evaporating component mass from the interface to the core of the gaseous phase – stage III.

Factors that can markedly affect the evaporation rate are as follows [2-4]:

- temperature
- pressure in the smelting system
- alloy composition

- composition of the gaseous phase over the bath
- hydrodynamics of the smelting system.

The overall mass transfer coefficient of the evaporating component, k_i , is determined with the use of the following equation:

$$\frac{1}{k_i} = \frac{1}{\beta^l} + \frac{1}{\phi k^e} + \frac{RT}{\phi \beta^g} \quad (1)$$

where:

$$\phi = \frac{p_m^0 \cdot \gamma_i \cdot M_m}{\rho_m} \quad (2)$$

and:

- T – temperature,
- R – gas constant,
- β^l – mass transfer coefficient of metal in the liquid phase (metal bath),
- k^e – metal evaporation rate constant
- β^g – mass transfer coefficient of metal in the gaseous phase,
- M_m – molar mass of the basic bath component,
- ρ_m – density of the basic bath component,
- γ_i – activity coefficient of the evaporating component in the liquid alloy,
- p_m^0 – equilibrium vapour pressure of the basic bath component.

The rate of the above evaporation process is determined by its slowest stage. As demonstrated in many studies, stages that limit the evaporation rate are mostly: mass transfer in the gaseous phase and mass transfer in the liquid phase. Diffusion control, related to the mass transfer in the liquid phase, is most commonly observed for low pressures < 10 Pa. For higher pressures above 100 Pa, the process is mainly controlled by diffusion in the gaseous phase. In Table 1, sample results of experiments on evaporation of various alloy components and stages that determine these processes are presented.

MASS TRANSFER IN THE GASEOUS PHASE

While analysing mass transfer in the gaseous phase, it should be noted that for normal pressure, very fre-

Łabaj, G. Siwiec, J. L. Blacha – Silesian University of Technology, Faculty of Materials Engineering and Metallurgy, Katowice, Poland
R. Burdzik – Silesian University of Technology, Faculty of Transport, Katowice, Poland

Table 1 Values of the overall mass transfer coefficient t for evaporation processes with various types of rate control [1,5-8]

Matrix metal /evaporating metal	Pressure / Pa	Temperature / K	$k_i \cdot 10^6$ / $m \cdot s^{-1}$
Cu/Pb ^{a)}	40,0	1 423	7,1
	40,0	1 523	16,6
	13,3	1 423	8,0
	13,3	1 523	22,2
Cu/Pb ^{b)}	8	1 73	474,72
		1 473	82,14
		1 523	90,08
		1 523	96,99
Ti/Mn ^{c)}	10	1 973	153,3
		1 973	176,0
		2 023	205,1
		2 023	208,4
Ti/Al ^{d)}	1 000	1 973	10,7
	100		15,4
	50		17,5
	10		17,8
Fe/Cu ^{e)}	0,06	1 898	41,2
		1 898	38,5
		1 923	47,4
		1 923	45,8
		1 973	47,8
Cu/Pb ^{f)}	101 325	1 473	0,34
		1 523	0,56
		1 573	0,75
		1 623	1,07

^{a)} Diffusion control – gaseous phase [1, 3]
^{b)} Diffusion control – gaseous and liquid phases [4]
^{c)} Diffusion control – liquid phase [5]
^{d)} Kinetic control [6]
^{e)} Diffusion control – liquid phase [7]
^{f)} Diffusion control – gaseous phase [8]

quent collisions of particles that detach from the evaporation surface are observed, and their free path length is about 10^{-10} m. Gradual pressure reduction in the system is accompanied by a considerably longer free path, which is described by the following equation:

$$\lambda_0 = 0,315 \cdot 10^{-3} \frac{1}{d_{0(nm)}^2} \frac{T}{P_{(Pa)}} \quad (3)$$

where:

d_0 – gas particle diameter, nm

P – gas pressure, Pa

λ_0 – mean free path, m

The mean free path of a gas particle in a two-component mixture is determined as follows:

$$\lambda_{01} = \frac{4\sqrt{2}}{\left(1 + \frac{\lambda_{02}}{\lambda_{01}}\right)^2} \sqrt{1 + \frac{M_{01}}{M_{02}}} \lambda_{02} \quad (4)$$

where:

λ_{02} – mean free path of the main gas (concentration: n_2),

λ_{01} – mean free path of the evaporating component (also for n_2),

M_{01}, M_{02} – molar masses of, respectively, the evaporating component and the main gas.

When the particles of one gas are much smaller than the particles of the other gas (i.e. when $M_{01} > M_{02}$ and $d_{02} < d_{01}$), equation (4) can be simplified and:

$$\lambda_{01} = 5,6 \cdot \lambda_{02} \quad (5)$$

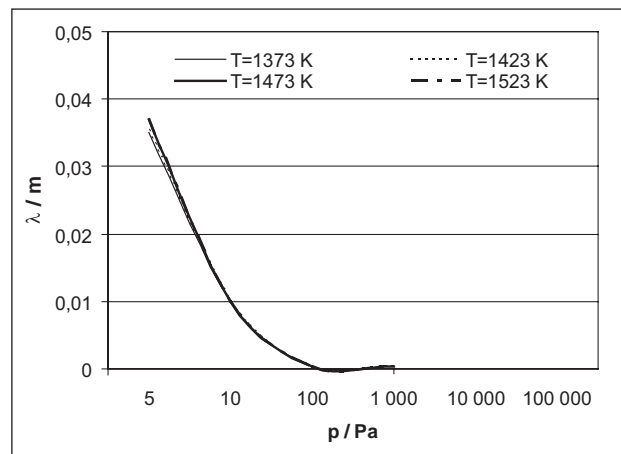


Figure 1 Mean free path of lead vapours versus pressure

In Figure 1, mean free paths of gaseous lead particles in a lead-helium mixture, calculated by means of equation (5) for lead evaporation from the Cu-Pb alloy, are presented. The calculation results are illustrated in Figure 1 and show that the determined λ_0 values for pressures lower than 10 Pa are between ten and twenty centimetres, which means that for diameters of melting pots used in the smelting systems, the melting pot geometry can markedly affect the rate of the analysed process. This has been demonstrated in e.g. studies conducted by Bellot who investigated the role of gaseous phase in the process of chromium evaporation from inductively stirred liquid steel [9].

Under high vacuum, when the condition that the value of the mean free path is much larger than the parameters of the vacuum area geometry (the melting pot diameter or the distance from the condensation surface) is met, so-called free evaporation occurs. Here, the rate of gas particles depends not on their mutual collisions but on the collision with other surfaces in the vacuum area [10].

The vapour flow with respect to the metal that is transferred into the gaseous phase, is determined by the following equation [9]:

$$N_i = \left(\frac{D_{i-g}}{RT\delta_x} + \frac{v^*}{RT} \right) \cdot p_{is} \quad (6)$$

where:

p_{is} – equilibrium pressure of the bath evaporating component vapours

δ_x – thickness of the hypothetical boundary layer on the gaseous phase side

D_{i-g} – vapour diffusivity with respect to metal that evaporates in the gaseous phase.

In this equation, two possible mechanisms of mass transfer in the gaseous phase are taken into account, i.e. molecular diffusion through the boundary layer (the first stage) and convective flow (the second stage). The local gas velocity, v^* , can be determined as follows:

$$v_g^* = \frac{RT}{P_{og}} \sum N_i \quad (7)$$

where:

$\sum N_i$ – a sum of all gaseous phase component flows.

When equations (6) and (7) are applied, the following is obtained:

$$N_i^g = \left(\frac{D_{i-g}}{RT\delta_x} + \frac{\sum N_i}{p_{og}} \right) p_{is} \quad (8)$$

where:

$$\frac{\sum N_i}{p_{og}} + \frac{D_{i-g}}{RT\delta_x} = \beta_g \quad (9)$$

When the following condition is met:

$$\frac{\sum N_i RT\delta_x p_{og}}{D_{i-g}} < 0,2 \quad (10)$$

equation (9) is:

$$\frac{D_{i-g}}{RT\delta_x} = \beta_g \quad (1)$$

According to Harris [11], when the value of equation (10) is larger than 2, diffusion transfer in the gaseous phase is negligible compared to the convective transfer, and the equation that determines the mass transfer coefficient in the gaseous phase is as follows:

$$\frac{\sum N_i}{p_{og}} = \beta_g \quad (12)$$

DETERMINATION OF THE HYPOTHETICAL BOUNDARY LAYER THICKNESS

As mentioned above, the boundary layer thickness, δ_x , is difficult to estimate for most hydrodynamic systems in metallurgical devices. The only process where the boundary layer thickness on the gaseous phase side can be determined is liquid metal barbotage with gases [12, 13]. This parameter mainly depends on the overall pressure in the system.

Before determination of the boundary layer thickness based on the experimental data regarding lead elimination from the Cu-Pb and blister Cu alloys, the value of the left expression of equation (10) was calculated. For all experiments, the following condition was met:

$$\frac{\sum N_i RT\delta_x}{D_{pb}^o} < 0,2 \quad (13)$$

This means that for the analysed evaporation rate determination, equation (14) can be applied. Using this equation and the experimentally determined values of the overall mass transfer coefficient as well as the β_l and k_e values, determined by means of equations, values of the hypothetical boundary layer (δ_x) thickness were estimated. The δ_x value was determined by means of equation [14]:

$$\delta_x = 5,18 \cdot 10^{-7} T - \frac{0,82627}{p} + 6,29 \cdot 10^{-4} \cdot \frac{T}{p} \quad (14)$$

In Figure 2, the δ_x and λ_0 values, determined by means of equations (5) and (14), are compared. Equation (14) can be used for determination of the mass transfer coefficient in the liquid phase in the case of metal bath volatile component evaporation in an induction furnace or other crucible furnaces.

SUMMARY

In the paper, mass transfer in the gaseous phase as the stage of volatile metal bath component evaporation

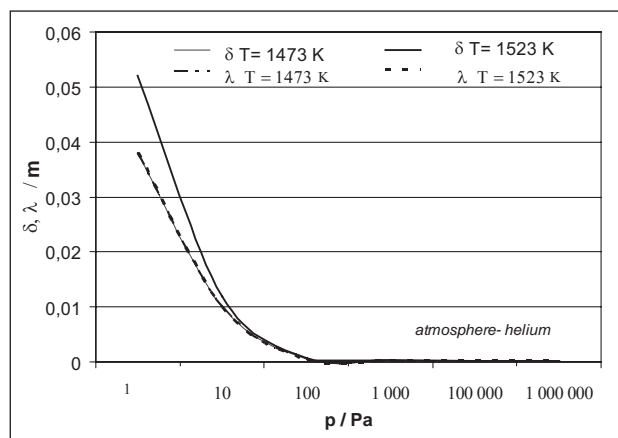


Figure 2 Mean free path of lead vapours in helium and the boundary layer thickness versus pressure (Cu-Pb alloy, T 1 473 K and 1 523 K)

is discussed. The equations for estimation of the mass transfer coefficient (β_g) are presented. Based on the own experimental results, the equation that determines the hypothetical boundary layer thickness for the analysed transfer process is proposed. It can be used for determination of the mass transfer coefficient in the liquid phase in the case of metal bath volatile component evaporation in an induction furnace or other crucible furnaces.

Acknowledgements

The study was conducted under the Research Project No. N N508 589439, financed by the Ministry of Science and Higher Education – Poland.

REFERENCES

- [1] E. Ozberk, R. Guthrie: Transactions of the Institution of Mining and Metallurgy 94 (1985), 146-157.
- [2] L. Blacha, J. Łabaj: Metalurgija 51 (2012), 4, 529-533.
- [3] R. G. Ward: Journal of the Iron and Steel Inst. 201 (1963), 920-923.
- [4] C. Kolmasiak: Metalurgija 51 (2012), 3, 317-320.
- [5] E. Ozberk, R. Guthrie: Metallurgical Transactions B 17 (1986), 1, 87-103.
- [6] L. Blacha: Archives of Metallurgy 48 (2003), 1, 105-127.
- [7] L. Blacha, R. Burdzik, A. Smalcerz, T. Matuła T.: Archives of Metallurgy and Materials, 58 (2013), 1, 197-201.
- [8] G. Siwiec: Archives of Metallurgy and Materials 57 (2012), 4, 951-956.
- [9] J. P. Bellot, M. Ritchie, A. Mitchell, D. Ablitzer: ISIJ International 41 (2001), 7, 696-705.
- [10] K. Ono, R. Suzuki: J. Mass Spectrom. Soc. Jpn. 47 (1999), 1, 38-41.
- [11] R. L. Harris: Vacuum refining of molten steel, PhD thesis, McGill University (1980).
- [12] B. Oleksiak, G. Siwiec: Metalurgija 51 (2012), 1, 25-27.
- [13] B. Oleksiak: Metalurgija 48 (2009), 2, 87-90.

Note: Nowak P. is responsible for English language, Katowice, Poland