



Temperature impact on copper evaporation from liquid iron

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ABSTRACT

Purpose: The purpose of the studies the results of which are being discussed was to determine the temperature impact on the rate of copper removal from liquid steel under the conditions of reduced pressure. In the present article, the authors have provided the activation energy values established for the process studied which enabled them to find out which of the constituent stages of the copper evaporation process is the determinant one.

Design/methodology/approach: The studies of the copper evaporation from liquid iron were conducted using an induction furnace. Based on the results obtained for the change in the copper concentration in liquid bath, the value of the overall copper mass transfer coefficient was estimated. The studies were conducted under the pressures of 0.06 Pa and 101 Pa respectively within the range of temperatures of 1923-1998 K.

Findings: The activation energy values estimated based on the mass transfer coefficient values established came to 52 kJmol⁻¹ and 154 kJmol⁻¹ for the pressures of 0.06 Pa and 101 Pa correspondingly. The values obtained for a pressure below 2 Pa were of the same order of magnitude as the activation energy values established for diffusion in liquid metal alloys based on experimental data.

Practical implications: Increasing the share of demolition scrap in the charge material for steel smelting by application of the EAF process creates a hazard of the liquid metal contamination with copper. The results obtained may provide to introduce corrections into the process parameters in order to intensify the copper removal process.

Originality/value: The literature of the subject lacks discussion of the results of kinetic studies of copper evaporation from liquid steel under the conditions of reduced pressure from the perspective of the temperature impact on this process. The analysis undertaken in the study in question implied that, at low pressures, the copper evaporation process is determined by the phenomenon of mass transfer in the liquid phase.

Keywords: Copper; Steel; Evaporation; Scrap; Refining; Overall mass transfer coefficient

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PROPERTIES

1. Introduction

A considerable decrease in the input of home scrap leads to a necessity of using increased amounts of demolition scrap, which may constitute one of the possible sources of the steel impurities, in the metallurgical processes. The foregoing mainly results from the fact that the said scrap may contain steel components combined with other materials the occurrence of which in the metallic charge is considered detrimental. Such a group of impurities includes non-ferrous metals (copper, tin, lead, zinc, bismuth, etc.) originating from metallic coatings, varnish or components of electrotechnical devices. When one deals with impurities easily removed in the metallurgical process, the increase of their content in the charge material does not pose a serious problem. It is otherwise when the charge material contains increased contents of non-ferrous metals the removal of which in the steel smelting process is particularly difficult. An example of such an impurity may be copper. High content of copper in scrap is to a considerable extent reflected by this metal's content in, for instance, steels manufactured by application of the EAF technology. Due to the fact that copper forms low-melting eutectic compounds with iron, that are released during solidification at the grain boundary, it is possible that, on high content of the problematic metal, the hot steel becomes brittle. It was indeed the negative influence of copper on the properties of steel that has led to the necessity of undertaking studies concerning the possible options of removing it from liquid steel alloys. This paper provides an analysis of the results of studies concerning the impact of temperature on the process of copper removal from liquid iron by evaporation.

2. Test method

The studies consisted in examining a synthetic Fe-Cu alloys obtained by melting of the ARMCO iron together with grade M00B oxygen-free copper in a protective gas atmosphere. The Cu content in the alloy examined came to 0.509% by weight.

All tests were conducted using the VIM 20-50 vacuum furnace manufactured by SECO-WARWICK. The furnace in question (Fig. 1) featured state-of-the-art technological solutions applied in industrial vacuum devices. They included an inductor tilt electric drive, a control panel (Panel View) operated to manage the process and adjust its parameters, a resistance heater for the ingot mould, an alloy additives feeding system and a sampling mechanism. The basic furnace parameters have been summarised in Table 1.

Table 1.
Basic parameters of the VIM 20-50 furnace

Maximum power rating	75 kW
Maximum vacuum	0.01 Pa
Pumping system	mechanical pump Roots rotary pump diffusion pump
Maximum operating temperature	2073 K
Maximum melting pot capacity	10-20 kg
Maximum ingot mould temperature	1173 K

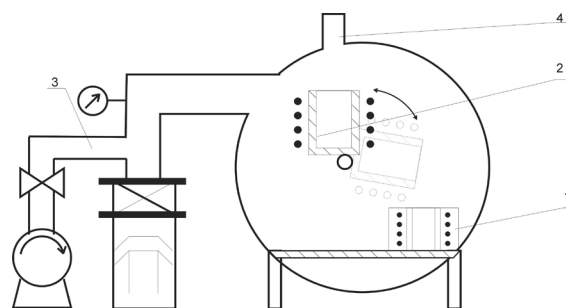


Fig. 1. VIM 20-50 furnace diagram: 1 - ingot mould with a preheating option, 2 - induction coil featuring electric drive enabling rotation of the melting pot, 3 - system of vacuum pumps, 4 - adding and sampling mechanism

The tests were conducted under the following pressures in the system: 0.06 Pa and 101 Pa respectively within the range of temperatures of 1923-1998 K.

3. Test results

The parameter determining the possibility of evaporating the metallic alloy liquid component is referred to as a volatility ratio. For a two-component alloy, it is determined according to Olette based on the following dependence:

$$\Phi = \left(\gamma_i \cdot \frac{p_i^0}{p_A^0} \right) \cdot \left(\frac{M_A}{M_i} \right)^{0.5} \quad (1)$$

where:

γ_i - activity coefficient for evaporating component "i" in the liquid solution,

M_A , M_i - molar masses of primary component „A” and evaporating component “i”,

p_i^0 , p_A^0 - vapour pressure over pure component “A” and “i”.

The process of component “i” evaporation is possible if the following condition is satisfied:

$$\Phi > 1 \quad (2)$$

As proved in one of the previous analyses [1], in the case of liquid Fe-Cu alloys, for the alloys used in the studies, Olette's condition determining the possibility of copper evaporation from the alloys in question is satisfied. The foregoing has been illustrated with the data provided in Fig. 2.

In order to determine the value of the overall copper mass transfer coefficient for the evaporation process analysed, the following dependence was applied:

$$\frac{dC_{Cu}}{dt} = k_{Cu} \cdot \frac{F}{V} \cdot C_{Cu} \quad (3)$$

which assumed the following notation in the integral form:

$$\int_0^t \frac{dC_{Cu}}{C_{Cu}} = -k_{Cu} \cdot \frac{F}{V} \int_0^t dt \quad (4)$$

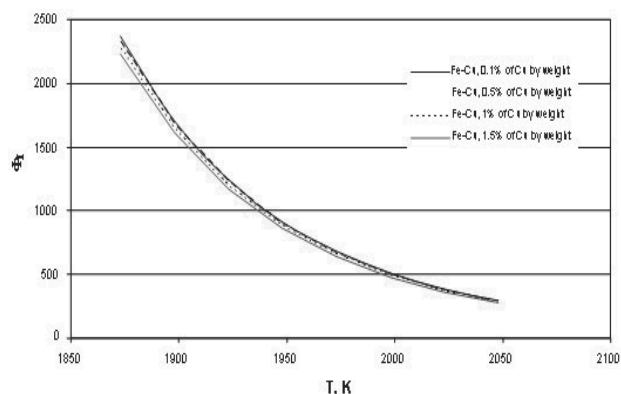


Fig. 2. Change of volatility ratio for copper vapours depending on its content in the liquid iron and temperature [1]

Having integrated dependence (3), one receives the following:

$$2,303 \log \frac{C_{Cu}^t}{C_{Cu}^o} = -k_{Cu} \cdot \frac{F}{V} (t - t_o) \quad (5)$$

where:

F - evaporation areas (interfacial areas), m^2 ,

V - liquid metal volume, m^3 ,

$(t-t_o)$ - process duration time, s.

The overall mass transfer coefficient values established based on dependence (5) have been collated in Table 2.

4. Analysis of the study results

As aforementioned, the studies to determine the impact of temperature on the copper evaporation rate were conducted in a vacuum induction furnace for the measuring system pressure of 0.06 and 101 Pa respectively. The temperature was altered within the range of 1923-1998 K. In order to determine the temperature impact on the overall mass transfer coefficient for the process analysed, the following form of the Arrhenius equation was applied:

$$\ln k_{Cu} = -\frac{E_A}{RT} \quad (6)$$

where:

E_A - process activation energy, $J \text{ mol}^{-1}$.

The apparent activation energy for copper calculated based on equation (6) and the applicable values of mass transfer coefficient came to 52 kJmol^{-1} for the pressure of 0.06 Pa and 154 kJmol^{-1} for the pressure of 101 Pa. The values obtained for a pressure below 1 Pa were of the same order of magnitude as the activation energy values established for diffusion in liquid metal alloys based on experimental data. This confirms the general conclusion that, within the range of low pressures, the process of metal evaporation from liquid alloys is determined by mass penetration in the liquid phase [2-6]. Table 3 provides a collation of sample diffusion activation energy values for selected metals.

Table 2.

Overall mass transfer coefficient values for the process of vacuum remelting of Fe-Cu alloys

Initial Cu content in alloy, % wt.	Temp., K	Pressure, Pa	k_{Cu} , $m \text{ s}^{-1}$
0.509	1923	101	$8.95 \cdot 10^{-06}$
0.509	1923	101	$8.63 \cdot 10^{-06}$
0.509	1923	101	$8.39 \cdot 10^{-06}$
0.509	1923	101	$8.41 \cdot 10^{-06}$
0.509	1923	0.06	$4.78 \cdot 10^{-05}$
0.509	1923	0.06	$4.95 \cdot 10^{-05}$
0.509	1898	0.06	$4.12 \cdot 10^{-05}$
0.509	1898	0.06	$3.85 \cdot 10^{-05}$
0.509	1923	0.06	$4.58 \cdot 10^{-05}$
0.509	1923	0.06	$4.74 \cdot 10^{-05}$
0.509	1923	0.06	$4.58 \cdot 10^{-05}$
0.509	1923	0.06	$4.65 \cdot 10^{-05}$
0.509	1948	0.06	$4.73 \cdot 10^{-05}$
0.509	1948	0.06	$4.65 \cdot 10^{-05}$
0.509	1948	101	$8.93 \cdot 10^{-05}$
0.509	1948	101	$9.05 \cdot 10^{-05}$
0.509	1973	0.06	$4.78 \cdot 10^{-05}$
0.509	1973	0.06	$4.95 \cdot 10^{-05}$
0.509	1973	101	$1.07 \cdot 10^{-05}$
0.509	1973	101	$1.05 \cdot 10^{-05}$
0.509	1998	0.06	$5.09 \cdot 10^{-05}$
0.509	1998	0.06	$5.24 \cdot 10^{-05}$
0.509	1998	101	$1.23 \cdot 10^{-05}$
0.509	1998	101	$1.17 \cdot 10^{-05}$

Table 3.

Values of the metal diffusion activation energy for liquid copper and iron

Metallic alloy matrix	Diffusing metal	Diffusion activation energy, kJmol^{-1}	Ref.
Cu	Fe	12.3	[7]
Cu	Co	11.3	[7]
Cu	Ag	8.5	[7]
Cu	Au	5.7	[7]
Ag	Cu	10	[8]
Ag	Au	7.6	[8]
Fe	Al	81	[9]
Fe	Cr	16	[10]
Fe	Mn	17	[10]
Fe	Ni	24	[10]
Fe	V	24	[10]
Fe	Co	7	[10]
Fe	Mo	10	[10]

Figure 3 illustrates the dependence between mass transfer coefficient and temperature for the Fe-Cu alloy obtained based on equation (6).

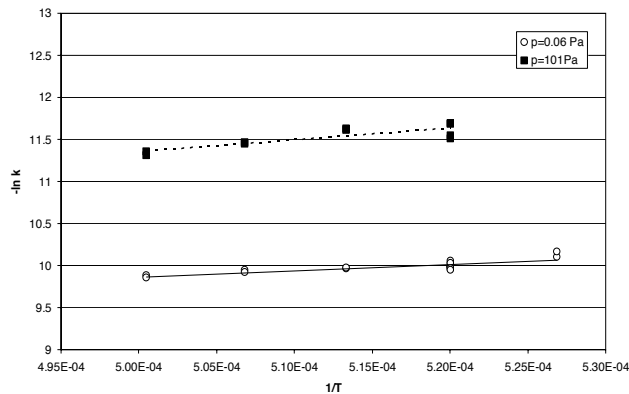


Fig. 3. Temperature impact on the value of the copper mass transfer coefficient in the evaporation process

5. Conclusions

The apparent activation energy value obtained for the process of copper evaporation from liquid iron, which came to 52 kJmol^{-1} for the pressure of 0.06 Pa, is of the same order of magnitude as the activation energy values established for diffusion in liquid metal alloys based on experimental data. This confirms the general conclusion that, within the range of pressures below 10 Pa, the process of metal evaporation from liquid alloys is mainly determined by mass transfer in the liquid phase. For the

pressures exceeding 100 Pa, the process control is of a mixed nature and the evaporation process activation energy values are considerably higher.

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