TRANSPORT OF OXYGEN AND CARBON DISSOLVED IN MOLTEN IRON TO AND FROM AN INDUCTION PLASMA

A.Lacour and A.Accary
Laboratoire de Métallurgie,Université de Clermont II
17 ter rue Paul Collomp,63000 Clermont Ferrand.

ABSTRACT

The study shows that,in the liquid phase,the transport phenomenon can be described by the same formalism as for diffusion in still liquid iron,replacing the diffusion coefficient D by a "transport coefficient" k_c larger than D because of the convective stirring of the metal. The "transport factor" $\beta=k_c/D$ has been calculated for Oxygen and Carbon dissolved in liquid iron and shown to be a measure of the contribution of convection to transport.

1. INTRODUCTION

In the following experiment we will study the exchanges which take place betwween melted iron and an Argon Hydrogen induction plasma. These exchanges will be discussed in the sequential order :

1-the evaporation of iron
2-the Oxygen exchanges
3-the Carbon exchanges.

Samples from 3 - 5 grams of plasma are taken and placed on the top of a cooled sole (Figure 1).

2. THE EVAPORATION OF IRON

We have established /ref.1/ a thermodynamic model based on the following hypothesis :

(A) Only the plasma contained in a vertical cylinder,the base is the sample,is considered;
(B) The plasma gases mix completely and instantly with the vaporous iron at the superficial temperature of the sample.
(C) The elimination of the gas mixture is complete and instantaneous.

On these assumption we have based the calculation of a " mass trans--fer rate " Γ which is the ratio of the amount of iron evaporated at a temperature as evaluated by weight loss of the sample and the same thermodynamically calculated from the measured temperature and the known constants for iron.
If the assumptions are realized, Γ must be equal to 1 /ref.2/.
Figure 2 shows that it is acceptable for samples up to three grams in our experimental set up.

We have then calculated the coefficient of heat transport λ' such as $q = \lambda' dT/dx$ with dT/dx being the thermal gradient in the stu--died metal and q the amount of heat flowing through the unit ti--mes at the abscissa x,and the "factor of convection" $\eta = \lambda'/\lambda$, λ being the thermal conductibility of the metal at a temperature to which λ' has been measured according to the following hypothesis

(a) λ' is uniform and constant throughout the sample
(b) the sample can be described as a thickdisc,heated uni--formly on top and cooled uniformly underneath.

In our experimental conditions (power of the high frequency gene--rator,form of the apparatus,gasflow rates and size of the iron samples),the factor of convection to be used is equal to 6. Treated in the same conditions /ref.2/ samples of chromium,chromium -iron,and HastalloyC are also found to have the same factor convec--tion. We also notice that this factor has the same value as the NUSSELT'S number determined by DWYER /ref.3/ for the laminary flow of extreme pure metals liquid. This,in our eyes seems to validate the hypotheses posed,and in particular,it offers the possibility to describe with the aid of the proposed coefficient of heat transport,the influence of the convection on the exchanges of mass between the melted metal and the plasma.

3. MASS TRANSFER OF THE OXYGEN AND CARBON TO THE LIQUID IRON.

In order to study the transfer of oxygen and carbon between a plasma and a liquid iron,we need to use very pure samples of iron, around three grams and containing less than 5 ppm of carbon and oxygen. We melt then without argon-hydrogen(8%) plasma;then,we introduce either oxygen or methane to the plasma.In the former we obtain oxydation which becomes evident by the change in form of the droplets. In the latter, we obtain carburation resulting from the decomposition of methane.

If ϕ is the flow of oxygen or carbon through a cylinder whose diameter is equal to the one of the sample,and ϕ' the one of oxy--gen or carbon which penetrates the iron, the " mass transfer rate " Γ of oxygen or carbon would be :

$$\Gamma = \frac{\phi'}{\phi} = \frac{\Delta m}{\phi M \Delta t} \qquad [1]$$

Δm being the mass of oxygen or carbon,with the molecular mass M is introduced into the liquid iron during the reaction period Δt. According to the thermodynamic model for the evaporation of iron and according to the hypothesis (A)

$$\phi = \alpha \frac{A T_O}{A_O T} \phi_O \qquad [2]$$

Where ϕ_O is the oxygen or methane flow upon introduction to the among of the furnace

α their " disassociation rate "

A_O section of the tubular furnace equal to 5,7 cm^2

A section of the sample of the mass m_O and of the spcific mass ρ which is equal to $\pi(3m_O/2\pi\rho)^{2/3}$

T_O temperature of the gases when put in the furnace

T temperature of the liquid metal surface

The mass transfer rate is:

$$\Gamma = 0,9 \; \frac{m_o^{1/3}}{M} \; T \; \frac{\Delta m/m_o}{\alpha\phi_o \Delta t} \qquad [3]$$

In diagram 3 we have drawn the experimenta curve having given the variation of mass $\Delta m/m_o$ of the samples in terms of reaction time Δt. Up to three minutes,we can state the quantities of penetrating oxygen or carbon in the liquid iron is in proportion to the length of the treatment period.
For oxygen there exists,as shown by MAKAHURA /ref.4/ and COFIGUI and al /ref.5/,a limiting value for oxygen due to the rapid cooling of the sample. At solidification,the liquid oxide with a composi--tion similar to Fe_2O_3 leads to mixture of Magnetite and Wüstite.

Finally,if for α equal 2 the mass transfer rate Γ of oxygen is equal to 1;the condensed carbon rate $\alpha\Gamma$ (figure 4)increases with the rate of introduced methane.
Also,if we take into account the work completed of the pyrolysis of methane in argon hydrogen plasma by AMOUROUX /ref.6/ and BESOMBES VAIHLE /ref.7/,and if we will conclude that only carbon produced by the disassociation of methane in the plasma and non-recombinable is absorbed by the liquid metal,our thermodynamic model is also valid and Γ equal 1.

4. TRANSPORT OF OXYGEN IN LIQUID IRON

If in liquid iron there is oxygen,then analogically in heat trans--port,we have to determine a transport factor β which multiplied by the coefficient of the diffusion of oxygen in the liquid metal D will be equal to the coefficient of the oxygen transport k_C so that

$$\phi = k_C \frac{dC}{dx}$$

In the instance that oxygen is eliminated from the liquid iron,to a plasma of argon containing 8% hydrogen,we propose the following hypotheses which complete the ones used to calculate heat transport hypotheses (A),(B),(C):

(a) k_C is uniform and constant for the entire sample ;
(b) the sample can be compared to a thick disc with its height (h) equal to its thickness ;
(c) initially,oxygen spreads uniformly in the volume of the disc;
(d) the concentration of atmospheric oxygen is zero or at least negligible.

The oxygen concentration in the liquid iron is verfied by FICK's equation:

$$\frac{\partial C}{\partial t} = k_C \frac{\partial^2 C}{\partial x^2} \qquad [4]$$

where x is the calculated distance between the surface of exchange and the plasma.
The initial conditions and our given limits listed below will permit us to obtain the oxygen concentration C(x,t) at any time and anywhere within the sample and the average concentration C(e,t) on a sharing with a "e" thickness.
We have now complete,five oxygen transport tests in a argon hydrogen (8%) plasma (Table I).

The samples contained initially 500ppm to 85ppm of oxygen. We verify in the table (column4) that the mass transfer rate Γ is inferior to 0,1 which verifies hypothesis (d) and that (column 8) k_c is in accordance with the average value : $5 \pm 1,5.10^{-4} cm^2 s^{-1}$. We can thus state that the value of the transport factor β lies between 6-8 and that with scrupulous measurements, we can see that it is equal to the one for the factor of thermal convection η . It is now a question of finding a term expressing the contribution of the convection to transport of matter.

5. TRANSPORT OF CARBON IN LIQUID IRON

Let us now consider the carbon transport outside of the carburation of samples of liquid iron by a plasma containing hydrogen and methane. By applying the preceeding formalism to carbon, we learn that at any given moment and anywhere within the sample x we can establish the carbon concentrations. The carbon concentration in the liquid iron are verfied by FICK's equation $\frac{\partial C}{\partial t} = k_c \frac{\partial^2 C}{\partial x^2}$ with the hypothesis (A) (B) (C), (a) (b) and

(c'): Initially the carbon concentration in the liquid iron is least negligible (5 ppm);

(d'): the carbon concentration in the plasma is given with the relation [2] .

Four tests of carburation for the duration of 10 seconds were effected with various percentages of methane (Table II). With the same given moment, with the concentration of upper part x_1 and lower part x_2 of the sample, and with the average carbon concen- -tration C_a given by relation [3], we can deduce the coefficient k_c. We can state that the coefficient of transport is in line with the average value $(5 \pm 1) 10^{-3} cm^2 s^{-1}$. The transport factor β of carbon in liquid iron found to be 7 ± 2 and within the limiting uncertainties of one test, equals the oxygen transport factor and the convection factor η . It represents the contribution of convection to the transport of matter in our samples.

6. CONCLUSION

Whether it be a question of heat or mass transport, the influence of the convections can be described, into the apparatus that we have used, by a multiple term which it is necessary to join the coeffi- -cient of conductibility or of diffusion in an immobile state. This term in experimental condition is equal to 6 .

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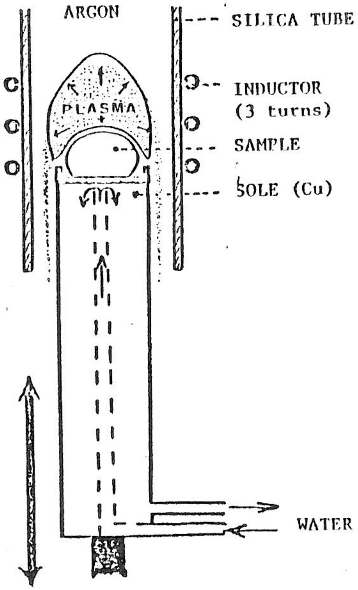

Figure 1 : Sample place into the induction plasma furnace.

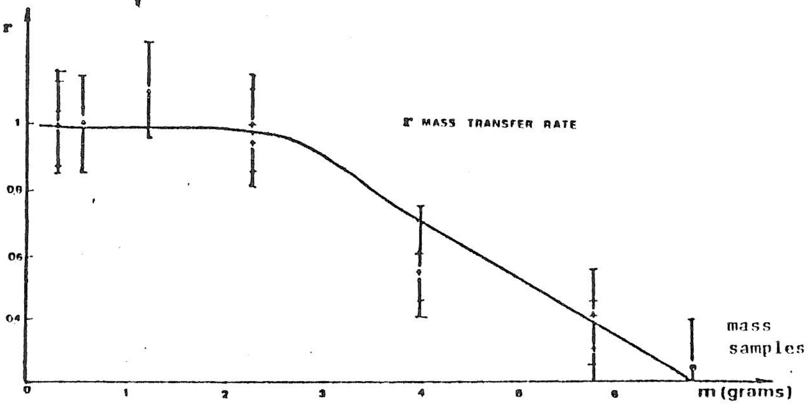

Figure 2 : Evaporation of iron to an induction plasma argon-hydrogene

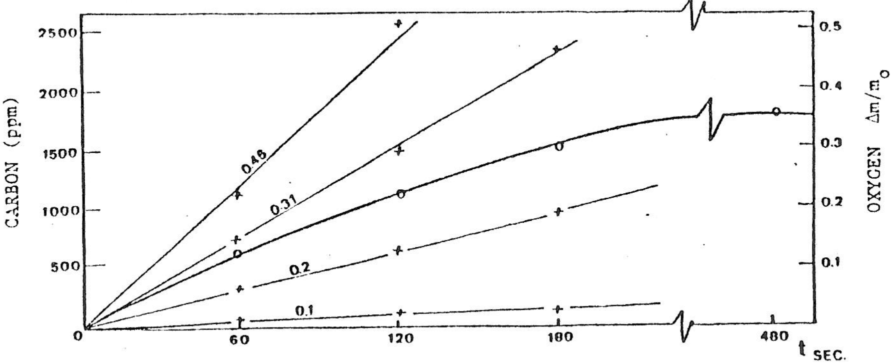

Figure 3 : Mass transfer of the oxygen and the carbon from an induction plasma to the liquid iron.

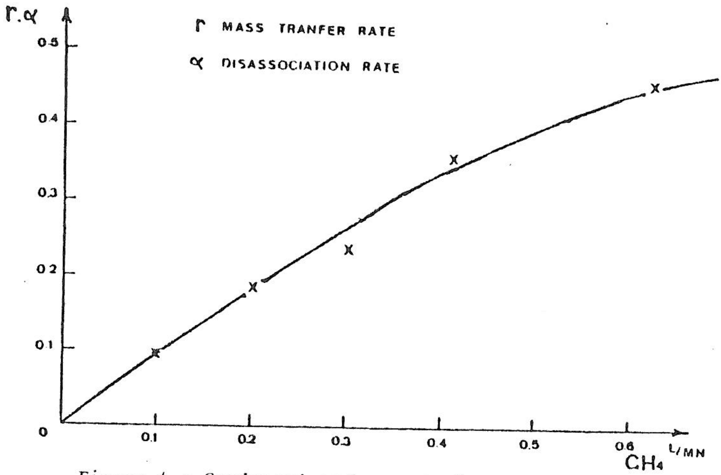

Figure 4 : Condensed carbon rate from argon-hydrogen methane induction plasma to liquid iron.

Test	Sample height h (mm)	Reduction time t (mn)	Transfer rate r	Oxygen concentration before C	after C(e.t)	C_a	Transport coefficient k_c	δk_c
1	4.7	1	0.1	500	200	325	6	1.5
2	5.3	1	0.1	300	85	192	6	1.5
3	5.4	5	0.08	250	18	90	6,5	1.5
4	4.7	5	0.08	121	14	51	4	1
5	5.3	5	0.08	85	9	36	5	1

Table I : Oxygen elimination from the samples of melted iron without plasma

Methane ϕ ($l \cdot mn^{-1}$)	Hydrogen (%)	Carbon concentrations (ppm) C_c(x=1mm)	C_c(x=4mm)	C_c^i(x=2,5mm)	C_a	αr	transport coefficient $k_c \cdot 10^{+3} cm^2 s^{-1}$
0,20	7,3	26	12	21	25	0,18	5
0,31	6,5	122	50	70	68	0,28	6
0,41	6	284	87	165	130	0,37	5
0,62	5	560	125	350	220	0,45	4

Table II: Carburation of the samples of melted iron by an argon plasma containing hydrogen and methane.