Optimization of a Channel-type Reactor for Continuous Steelmaking with Water–Oil–Air Models

Klaus KOCH, Ralf BRUCKHAUS,¹⁾ Elizabeta KORTE,²⁾ Christian ROTH and Jan FALKUS

Institut für Eisenhüttenkunde und Gießereiwesen, Technische Universität Clausthal, Robert-Koch-Str. 42, D-38678 Clausthal-Zellerfeld, Germany. 1) Formerly Technische Universität Clausthal. Now at AG der Dillinger Hüttenwerke, Germany. 2) Formerly Technische Universität Clausthal. Now at Saarstahl AG, Germany.

(Received on July 9, 1993; accepted in final form on November 19, 1993)

Investigations of channel-type reactors are of importance not only for the development of continuous steelmaking processes but also for the pretreatment of pig iron and posttreatment of crude steel. By means of residence time measurements and light section analysis, a channel-type reactor model specially designed for experiments with two (water–air, water–oil) and three phases (water–oil–air) has been developed. Special emphasis was thereby placed on the prevalence of piston flow during top-blowing with several lances in order to increase the area of reaction by emulsification at the interface between the two liquid phases.

In the first experiments the flows of the liquid phases (water, oil) were optimized. Caprylic acid was used to simulate the mass transfer of tramp elements from the pig iron into the slag. The mass transfer was measured through conductivity, transferring the experience of discontinuous experiments to those which were conducted continuously. The different phase contacts: permanent, reverse transitoric (water is flowing continuously along permanent remaining oil layer) and countercurrent, were investigated in a channel-type reactor concerning the effect of mass transfer.

KEY WORDS: continuous steelmaking; channel-type reactor; cold models; water–oil–air experiments; fluid flow; backmixing; mass transfer; reverse transitoric phase contact; countercurrent phase contact.

1. Introduction

During recent years the individual reaction of decarburization has been steadily gaining importance in converter steel metallurgy at the expense of refining reactions for the other companion elements, *i.e.* silicon, manganese, sulfur and phosphorus. The content of the gas-forming carbon in pig iron has remained constant at around 4%, whereas the total content of all other slag-forming companion elements has decreased below 0.5% in individual cases. This trend effectively implies a low-slag operation.

In principle, three possibilities exist for decreasing the content of the associated slag-forming elements: the appropriate selection of starting materials, modifications in blast furnace operation, and suitable treatment of the pig iron between the blast furnace and steel plant.

Between the blast furnace and continuous casting facility, the individual conversion processes are normally conducted discontinuously and are thus temporally separated, while with a continuous method of operation the conversion processes are only spatially separated. A continuous operation method allows an easier optimization of the processes. The significance of a continuous method of operation in steelmaking as well as pig iron pretreatment and crude steel posttreatment is not only seen in the temporally optimized use of the refining units but also in the secondary units.

In the literature there are already a number of proposed processes for continuous steelmaking.¹⁾ Many of these have been already realized and tested in pilot plants. These processes can be separated into three main groups: channel refining, cascade refining and dispersion refining. The last main group includes both spraying and foam refining. The experiments in this work were initially performed with the channel type reactor. For the accelerating of the mass transfer the emulsification effect was used.

Besides an optimal phase contact, the characteristic residence times of the participating phases are decisive for the efficiency of a continuously operating reactor. All regions of the bath should exhibit approximately equal residence times, since the process efficiency would be impaired, for instance, by underdecarburized and overdecarburized volume fractions. In the axial direction of metal flow, which is the first reactor dimension, the reactor should approximate the ideal tubular reactor without backmixing. Along the vertical and horizontal axes, which represent the second and third reactor dimensions, thorough mixing resembling that in a vessel should ensure rapid mass transfer to the blowing trough.

2. Experimental Setup

The objective of the present study is the determination of the optimal flow behavior and the optimal mass

- 1: plexiglass channel length $l = 780$ mm, width $w = 70$ mm, height $h = 90$ mm
- 2: entrance zone
- 3: reactor zone $l = 650$ mm, $w = 70$ mm, $h = 90$ mm
- 4: exit zone $l = 130$ mm, $w = 70$ mm, $h = 90$ mm, water volume $= 0.2$ l
- 5: solution supply container volume $V = 10$ l
- 6: metering pump
- 7: entrance pipe diameter $d = 10$ mm
- 8: measurement probe in 4
- 9: signal amplifier and personal computer for data storage
- 10: oil dam
- 11: oil metering pump
- 12: oil distributor $w = 55$ mm, $h = 2$ mm
- 13: oil exit channels
- 14: blowing lances $d = 3$ mm
- 15: rotameter
- 16: fine pressure regulator
- 17: oil supply container $V = 1$ l

Fig. 1. Schematic drawing of the experimental system for the investigation of the flow conditions and mass transfer using continuous operation methods.

Table 1. Survey of test parameters.

Water	$\dot{V} = 5.0$ to 13.0 (ml/s)
without oil	$V = 1.229$ or 1.456 (cm ³); $h = 2.7$ or 3.2 (cm)
with 300 ml oil	$V = 1.456$ (cm ³); $h = 3.2$ (cm)
with 600 ml oil	$V = 1.229$ (cm ³); $h = 2.7$ (cm)
Oil	$\dot{V} = 1.0$ to 2.3 (ml/s)
	$V = 300$ (ml); $h = 0.8$ cm
	$V = 600$ (ml); $h = 1.6$ cm
Air	$\dot{V} = 2.2$ (l/s); without emulsification
	$\dot{V} = 2.4$ (l/s); emulsification limit
	$\dot{V} = 3.2$ (l/s); oil spraying limit

transfer for the liquid phases in a continuously operating channel reactor by means of laboratory scale investigations on water-oil-air models. The general experimental setup²⁾ is illustrated in **Fig. 1** and **Table 1**.

The core piece of the apparatus is a plexiglass channel (1). A storage container (5) serves for the preparation and supply of the tracer-containing water solution. A metering pump (6) introduces a regulated quantity of solution through a tube (7), into the channel. In one type of experiment a caprylic acid tracer (concentration: 0.5 ml in 1 l H_2O) was added to the water using a step function procedure, while in the other type a NaCl solution (concentration: 250 g in 1 l H_2O) was added to the water

using a Dirac delta function procedure. A measurement probe (8), which was connected to a signal processor and personal computer, was used to determine the electrical conductivity of the fluid exiting the reactor. In order to carry out investigations of the countercurrent phase contact, a second metering pump (11) was available for the continuous introduction of oil during the experiment. The top-blowing of air onto the trough region through the use of lances (14) results in emulsification and stirring of the reactor contents. The space x between all lances is equidistant along the whole channel-type reactor (z lances with 100 mm distance from the nozzles to the bath surface) and has to be calculated as $x = 650/(z + 1)$ (mm).

The flow behavior of the reactor bath was also investigated with help of light section analysis^{3,4)} and described qualitatively. From these investigations it is possible to determine the flow patterns in the bath, as well as the blowing trough geometry, during top-blowing with the lances.

With this apparatus the flow behavior and mass transfer could be investigated for reverse transitoric phase contact as well as phase contact in countercurrent flow with or without enhanced bath stirring and emulsification through the top-blowing of air. A compilation of the experimental groups are shown in **Fig. 2**, which presents the experiments in a table form.

The individual experimental parameters were optimized in a stepwise manner as the complexity of the systems increases from A I to B III. From the large number of experiments carried out, only a few of the characteristics will be discussed in the following section.

3. Fluid Flow Experiments

3.1. Water Experiments

Firstly, single-phase experiments²⁾ were carried out using water as the model fluid in order to study the residence time behavior of the channel (experimental group A I in **Fig. 2**). Investigations to smooth the erratic, badly reproducible flow behavior (**Fig. 3a**) were carried out. Although all of the experiments were performed with constant experimental parameters, a high degree of deviation of the results was seen. Through optimization of the various experimental parameters, such as water flow rate, shape and position of the entrance tube, the residence time spectrum is significantly smoothed with good reproducibility (**Fig. 3b**).

3.2. Water-Oil Experiments with Reverse Transitoric Phase Contact

As seen in **Fig. 4**, a pronounced smoothing of the residence time spectra (also with fully identical experimental parameters for all individual experiments) was achieved through the addition of oil²⁾ (experimental group A II in **Fig. 2**). The top layer of oil has partially the same effect as the bottom and the walls of the reactor. The flow of water is more similar to a piston flow. In **Fig. 5**, the y -axis is the Bodenstein number,^{5,6)} Bd , which can be determined²⁾ from the behavior of the residence time spectra curve. The Bodenstein number is a measure of the quality of the desired piston flow in direction of

Group numbers	Graphic symbol	Mode of operation		Phases			Phase contact		Tracer		Input signal	
		discont.	cont.	water	oil	air	permanent	rev. trans. countercurrent	NaCl	caprylic acid	Dirac delta	step function
A fluid flow												
A I			X	X					X ^a	X ^b	X ^a	X ^b
A II			X	X	X			X	X		X	
A III			X	X		X			X		X	
A IV		X		X	X	X	X					
B mass transfer and fluid flow												
B I		X		X	X	X	X			X		
B II			X	X	X	X		X		X		X
B III			X	X	X	X		X		X		X

Fig. 2. Schematic compilation of the experimental groups for the optimization of the flow and mass transfer.

the reactor channel axis and is defined as the ratio of mass transport through piston flow to mass transport through turbulent backmixing in the axial direction or as

$$Bd = \frac{u \cdot l}{D_{ax}} \dots\dots\dots (1)$$

where, u : velocity of piston flow,
 l : reactor length,
 D_{ax} : axial dispersion coefficient.

With the addition of an oil layer over the water, a reduction of the deviation in the residence time spectra and also a rise in the Bodenstein number with increasing water flow rate are seen in this figure. In addition, the effect of the solution entrance tube position in the oil or solution layer is demonstrated.

3.3. Water-Air Experiments

Even more consistent curves were obtained from the experimental groups A III (water-air experiments^{3,4}) in Fig. 2). For all six spectra shown in Fig. 6 the impulse of the air blowing from the lances creates a strong stirring effect and, with that, the desired smoothing of the flow behavior through the reactor length (the primary dimension). Furthermore, the maximum lies around the

rather high value of 1.7, which is desired in order to obtain the required uniformity of the reaction products. Likewise, the desired strong mixing in the second and third channel dimensions is reached through the cellular structure of the channel contents, which is again stabilized through the many vortices under an individual lance. The air was always top-blown through the lances (with cylindrical nozzles) at the spraying limit of water.

The dependence of the Bodenstein number on the lance number is depicted in Fig. 7. Even with the discontinuities and deviation of the curve taken into account, a correlation can be established between secondary and primary vortices⁷⁾ and theoretical considerations concerning the geometry of the blowing trough. For a small lance number, up to 5, only unstable flow patterns can arise in the reactor bath. When the lance number is increased, a stable flow pattern forms which is affected only by primary vortices. A further increase in the lance number results in deformation of the primary vortices in a collision zone. Beyond a lance number of 14, the formation of a longitudinal vortex is theoretically possible. In every case where a collision zone was observed, the Bodenstein number remained roughly constant (a plateau) as the lance number was increased. Plateau I

Fig. 3. Residence time spectra for the single-phase case. (Only water; NaCl tracer; Dirac delta function.)
 a) without optimized flow conditions; $\bar{t} = 339$ s
 b) with optimized flow conditions; $\bar{t} = 461$ s

Fig. 4. Residence time spectra for the two-phase case without mass transfer. (Water-oil; reverse transitory phase contact; NaCl tracer; Dirac delta function; $\bar{t} = 286$ s.)

occurs in the collision zone of the secondary vortices, plateau II in the collision zone of the primary vortices, and plateau III in the confluence zone of the longitudinal vortex. A high degree of deviation was observed at the end of each plateau which is ascribed to unstable flow in the reactor bath.

The influence of many other parameters has also been investigated,³⁾ first of all the top-blowing conditions with the parameters lance distance and blowing rate and secondly the channel geometry with the bath depth and flow rate.

4. Mass Transfer and Fluid Flow Investigations

The experiments presented up to now have concentrated exclusively on the optimization of the flow patterns. Now the mass transfer from the water phase

Fig. 5. Dependence of the Bodenstein number on water flow rate and entrance position. (Without mass transfer; water-oil; reverse transitory phase contact; NaCl tracer; Dirac delta function.)

Fig. 6. Residence time spectra recorded under identical experimental conditions during top-blowing with 15 equidistant lances; $\bar{t} = 300$ s. (Without mass transfer; water-air; at the water spraying limit; NaCl tracer; Dirac delta function.)

Fig. 7. Measured variation of the Bodenstein number with increasing number of lances z and indication of scattering width. (Without mass transfer; water-air; at the water spraying limit; NaCl tracer; Dirac delta function.)

into the oil phase will be taken into consideration. Later on, the mass transfer in the gas phase, simulating the decarburization reaction, will also be looked into.

4.1. Additional Experiments with Permanent Phase Contact

In this chapter, experimental groups BI and AIV (from Fig. 2) will be discussed. These experiments²⁾ are easier to investigate in discontinuous reactor vessels (cylindrical, $d=240$ mm) because of the complex experimental setup that would be required in a channel reactor. The results from discontinuous and continuous operating reactors are comparable because the flow behavior in a discontinuous vessel corresponds to that of a continuous reactor in the second and third reactor dimensions.

The investigations of mass transfer between two immiscible phases (BI in Fig. 2) were carried out by the addition of a tracer that is soluble in both phases. In the case of water-oil-air experiments with mass transfer, caprylic acid was used. From the reduction of the tracer concentration in solution phase, conclusions can be drawn on the size of the mass transfer coefficients, rate constants, and distribution values.

The continuous determination of the tracer content was achieved through conductivity measurements so there is no need to use chemical analysis to determine the tracer concentration. In order to reduce errors from varying water quality, only deionized water was used. From all the experimental results, it can be concluded that the reaction is of 1st order. Without the top-blowing of air, it takes several days in order to reach equilibrium.

In this and the following experimental group, at least two critical blowing rates can be detected, namely the critical oil spraying limit and the critical emulsification limit. The latter limit corresponds to the spraying of water droplets into the oil phase.

The mass transfer coefficient β lies around $2.13 \cdot 10^{-4}$ (m/s), derived from^{2,6,8)}:

$$\frac{C_i}{C_0} = \frac{1 + \eta^* \cdot Y \cdot e^{-(1 + 1/(\eta^* \cdot Y)) \cdot \beta \cdot (A/V) \cdot t_i}}{1 + \eta^* \cdot Y} \quad \dots\dots\dots(2)$$

where, c_i : measured concentration at time t_i ,
 t_i : measured residence time,
 c_0 : measured start concentration,
 A : area,
 V : volume,

$$\eta^* = \frac{(X)^*}{[X]^*} \quad \dots\dots\dots(3)$$

η^* : physical-chemical distribution coefficient,
 $(X)^*$: equilibrium concentration in slag phase,
 $[X]^*$: equilibrium concentration in metal phase,

$$Y = \frac{S}{M} \quad \dots\dots\dots(4)$$

S : slag mass,
 M : metal mass.

A value for the physical-chemical distribution coefficient η^* of 71 was determined.

In the second supplemental experimental group (AIV in Fig. 2), water-oil-air experiments, the formation of flow patterns in the two phases as well as the emulsification conditions were investigated. At a definite

Fig. 8. Schematic representation of the flow conditions below the spraying limit of the oil. (Water-oil-air; discontinuous operation method; permanent phase contact.)

blowing rate the first small solution droplets in the oil can be seen-especially in the primary vortices. The amount of droplets remains almost constant over time with a constant blowing rate. This process, where water droplets are sprayed into the oil phase, corresponds to emulsification limit mentioned earlier.

It is very remarkable that under the special conditions of the three-phase case the flow patterns in the water underneath the blowing trough are directed downwards (Fig. 8), while in the two-phase water-air case the water flows upwards. Of course, this interesting effect is coupled to a specific oil-layer thickness. In the emulsification tests presented schematically in Fig. 8, the thickness of the oil layer h_{oil} is 15 mm. Constant parameters are: $d_{H_2O} = 240$ mm, $h_{H_2O} = 120$ mm and $d_{nozzle} = 3$ mm. Variable are the blowing conditions: $\dot{V}_{air} = 12$ to 28 l/min and the lance distance from the surface (40 to 120 mm).

4.2. Water-Oil-Air Experiments with Reverse Transitory Phase Contact

For these experiment groups (BII in Fig. 2) with a now continuous operation,²⁾ just as with the next experimental group, eight equidistantly arranged lances at a height of 10 cm above the bath were used. This arrangement was chosen on the basis of the already mentioned stepwise optimization of the flow behavior in the channel. The volume of the oil layer was in each case constant 0.6 dm^3 . (Corresponding experiments with 0.3 dm^3 oil led to almost similar results.)

The mass transfer is highly dependent on the chosen blowing rate. The most favorable value was determined in each case under emulsification conditions at the oil spraying limit, which still lies beyond the emulsification limit. The maximal reduction in the tracer concentration was around 21 %, for a relatively short channel (650 mm) by the previous given geometry. This was reached with the lowest water flow rate Fig. 9.

In step function operation the response curves usually gather around $t/\bar{t} = 1$ (see Ref. 9)). In opposite to this fact the curves in Fig. 9 (test group BII and also BIII in the next chapter) shift to larger values. The Levenspiel model is mainly valid for single phase systems. In this publication a three phase system with an additional mass

Fig. 9. Representation of the normalized concentration c/c_0 over the normalized time $t/\bar{t}$ for various solution flow rates. (With mass transfer; at the oil spraying limit; water-oil-air; reverse transitory phase contact; caprylic acid tracer; step function.)

transport between the both liquid phases is investigated. Levenspiel has described the problem of additional mass transfer.⁹⁾ In this case the caprylic acid dissolves partially in the oil phase and does not reach the measuring probe. At the beginning this transition, caused by the concentration difference, is rather large. That is the reason why the tracer signal arrives later at the measuring probe. For the physically determined flowing question it means a shifting of the zero to longer times t , involved in the formula of the normalized residence time

$$\Theta = \frac{t}{\bar{t}} \quad \dots\dots\dots (5)$$

where, t : time,

$\bar{t}$: calculated, average residence time.

The average residence time $\bar{t}$ is calculated by

$$\bar{t} = \frac{V_{H_2O}}{\dot{V}_{H_2O}} \quad \dots\dots\dots (6)$$

where, V_{H_2O} : water volume,

$\dot{V}_{H_2O}$: flow rate of water.

With this it is impossible to take the described, additional effect of mass transfer into account. Another shifting to the right (larger Θ -values) is caused by low $\dot{V}_{H_2O}$ values in Fig. 9. The same effect can be seen with the variation of $\dot{V}_{oil}$ in the following chapter in the case of countercurrent phase contact. These phenomena could be taken into consideration by the determination of the measured average residence time, that had to be recorded in an additional, parallel test group. Altogether, for this complex further tests and considerations are necessary.

The results for all tests in this experimental group are shown in Fig. 10 for differing emulsification conditions. It can be seen that the ΔC values obtained, and with that the mass transfer, are highly dependent on the chosen blowing rate. The greatest reduction in the tracer concentration, with values between 0.11 and 0.21 (corresponding to 11 and 21 %), was reached by blowing at the oil spraying limit (SL). This diminishes with decreasing blowing rate to now only 6 to 12 % at the emulsification limit (EL). The smallest difference, approximately 1 to 4 %, was obtained for the experiment

Fig. 10. Dependence of the dimensionless concentration difference, ΔC , on the solution flow rate for various emulsification conditions. (Water-oil-air; reverse transitory phase contact; caprylic acid tracer; step function.)

Fig. 11. Dependence of the normalized concentration on the normalized time for variable solution flow rate. (Water-oil-air; at the oil spraying limit; counter-current; caprylic acid tracer; step function; oil flow rate constant 1, 0 ml/s.)

without emulsification (WE) but still with stirring by the top-blown air.

When every group is inspected, further statements are possible. It can be seen that with a constant blowing rate the mass transfer increases with decreasing solution flow rate. This can be explained through the proportionally increasing residence time of the solution.

4.3. Water-Oil-Air Experiments with Countercurrent Phase Contact

For countercurrent phase contact²⁾ (experiment group B III in Fig. 2) the reduction of the tracer content lies around 18 %, as shown in Fig. 11, with a thin oil layer (0.3 dm³ of oil in the reactor). It can be determined for the chosen experimental conditions that the mass transfer for reverse transitory phase contact is in the same range as that for countercurrent phase contact. The corresponding values are adjusted in each case for the lower oil flow rate.²⁾ Next to the influence of the solution and the oil residence time in the reactor, the emulsification conditions are the most important factor in achieving the highest possible mass transfer.

The dependence of the concentration difference, ΔC , on the solution flow rate and oil flow rate for the countercurrent experiment is shown in Fig. 12 with top-blowing at the oil spraying limit (SL). The drawn-in

Fig. 12. Dependence of the dimensionless concentration difference, ΔC , on the solution and oil flow rates. (Water-oil-air; at the oil spraying limit; counter-current; caprylic acid tracer; step function.)

lines limit the region of the individual experimental results. From the scatter of the points only tendencies can be detected and no exact conclusions can be drawn. It is highly probable that, because of the emulsification conditions at the oil spraying limit, the best mass transfer can be again achieved with low solution flow rates and also low oil flow rates. This can be attributed, as with reverse transitoric phase contact, to the increased residence time of the solution and additionally, in the countercurrent case, to the increased residence time of the oil.

The experimental results make possible, parallel to the evaluation of the mass transfer value, the simultaneous determination of the Bodenstein number, which contains information about the flow behavior of the solution phase.²⁾ The values obtained are clearly between 4 and 10. These agree within an order of magnitude with previous determined values (see the case with 8 lances in Fig. 7).

5. Concluding Remarks

In this study it was attempted to obtain quantitative results in a stepwise manner toward the development of continuous operation methods for the various cases of phase contact in the complex system "water-oil-air". The experiments are related to the optimization of not only the flow behavior but also the mass transfer between the water and oil phases. Of interest are the following points:

In the single-phase case with flowing water in the channel, very irreproducible results and a very erratic course of the residence time spectra were obtained

because of the wall friction, etc. This should be of importance in practice for the transport of molten metal in channels.

A stabilization of the flow behavior is possible through three types of measures.

- Optimization of the channel parameters, such as channel and entrance geometries as well as water flow rate.
- Addition of a permanent overlaying oil phase with smoothing influences.
- Top-blowing of air through lances, in order to achieve a stirring effect with a cascade behavior and little backmixing. This is the most important measure.

In the three-phase case, which has the greatest practical importance, the emulsification plays a significant role in the mass transport. Through suitable optimization measures, such as increasing the length of the channel as well as changing the water, oil and air flow rates, relatively high Bodenstein numbers and better mass transport can be achieved with phase contact in countercurrent flow.

Acknowledgement

This research work was financially supported by the Deutsche Forschungsgemeinschaft, which is gratefully acknowledged.

REFERENCES

- 1) W. Domröse, K. Koch and E. Steinmetz: *Stahl Eisen*, **96** (1976) No. 21, 993.
- 2) R. Bruckhaus: Kaltmodelluntersuchungen zum Strömungsverhalten und Stoffübergang bei kontinuierlichen Rinnenreaktoren mit Metall-Schlacke-Phasenkontakt, Dr.-Ing.-Diss., Techn. Univ. Clausthal, (1992).*
- 3) E. Korte: Wasser-Luft-Modelluntersuchungen zur Optimierung von Rinnenreaktoren für die kontinuierliche Entkohlung von Fe-C-Schmelzen beim Sauerstoffaufblasen, Dr.-Ing.-Diss., Techn. Univ. Clausthal, (1989).*
- 4) K. Koch, E. Steinmetz, J. Lamut and E. Korte: Proc. Sixth Int. Iron and Steel Cong., Vol. 1, ISIJ, Tokyo, (1990), 386.
- 5) Gmelin-Durrer: Metallurgie des Eisens, 4. Auflage, Bd. 6, Theorie der Stahlerzeugung 2, Springer-Verlag, Berlin-Heidelberg-New York, (1978).
- 6) F. Oeters: Metallurgie der Stahlherstellung, Springer-Verlag, Berlin, (1989).
- 7) K. Koch, R. Bruckhaus and J. Falkus: Proc. Sixth Int. Iron and Steel Cong., Vol. 3, ISIJ, Tokyo, (1990), 94.
- 8) E. Steinmetz: *Arch. Eisenhüttenwes.*, **39** (1968), 421.
- 9) O. Levenspiel: Chemical Reaction Engineering, 2nd Ed., John Wiley and Sons, Inc., New York, London, Sidney, Toronto, (1972).

* available at: University Library Clausthal, Technical University Clausthal, D-38678 Clausthal-Zellerfeld, Germany.