Effect of blowing parameters on bath mixing efficiency during basic oxygen furnace steelmaking process

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Abstract
Basic Oxygen Furnace (BOF) steelmaking is the main method for steelmaking production, mixing efficiency of BOF vessel would greatly affect the uniformity of chemical composition and temperature in molten steel. Therefore, this paper conducted the effect of blowing parameters on bath mixing efficiency during BOF steelmaking process. Through measuring the mixing time of steel bath in BOF vessel, the effect of different blowing parameters was studied. Based on analysis of variance for the experimental results, the influence degree on mixing efficiency by different blowing parameters was acquired, and the optimized combination of blowing parameters was obtained. Moreover, the mixing index which indicated the mixing degree of steel bath in BOF vessel was proposed in this study, and an apparent nonlinear relation was acquired after determining relationship between the mixing index and blowing parameters. The optimal blowing parameters were applied to an 80 t industrial BOF vessel in a special steel plant, the end point carbon and oxygen equilibrium was decreased from 0.0032 to 0.0026, endpoint phosphorus and total Fe content in slag were reduced by 0.0012% and 2.21%, respectively. The mixing index and results presented in this work could be helpful to improve mixing efficiency in commercial BOF vessels.

Keywords
basic oxygen furnace, blowing parameters, influence degree, mixing index

1 | INTRODUCTION

BOF (Basic Oxygen Furnace) steelmaking is the main method for steelmaking process. According to statistical data, the crude steel produced by BOF accounted for 70.8% of the global steel production in 2018.1 During BOF steelmaking process, top blowing oxygen jet and bottom blowing gas are promoted to produce a homogeneous distribution of components and temperature in the melt.2,3 The removal rate of carbon and phosphorus content of the liquid iron are mostly controlled by the intensity of bath mixing during BOF steelmaking process, and a high mixing efficiency is favorable for decarburization, lowering FeO content of slag and oxygen content of liquid steel.4-6 Therefore, comprehensive study on the mixing behavior of steel bath is helpful to clarify the effect of different blowing parameters on mixing efficiency and optimize the blowing parameters.

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In the past decades, various physical models have been designed to investigate the mixing behavior of steel bath for BOF steelmaking process. Among these experiments, the mixing time (the time required to homogenize the liquid bath) was applied to evaluate the mixing effect of different blowing parameters under top blowing, bottom blowing, and top-bottom combined blowing.

Cao et al. studied the interaction between top blown jet and molten steel, and the mixing effect of top blown parameters through a cold model experiment. The results showed that lower and higher cavity shape index (a dimensionless factor to demonstrate the cavity shape related to cavity depth and cavity width) may lead to longer mixing time in steelmaking process. Ajmani et al. carried out the mixing study for the 130 t LD converter at Tata Steel using a 1:6 scale perspex model, the effect of increasing the number of bottom tuyeres, there location and configurations on bath mixing was investigated. Singh et al. investigated the mixing behavior with different bottom tuyere configurations in a 1:6 scale down model, they found that the mixing time became a minimum at a pitch circle diameter (PCD) of 0.5 with only bottom blowing. Olivares et al. carried out water modeling in 1:8 scale down model. They reported that the mixing time decreased when bottom gas flow rate, bath height, and number of tuyeres were increased. Nakanishi et al. conducted the water model experiments to clarify mixing rate of molten steel under different bottom gas flowrate and number of tuyeres. They found that the increase of bottom gas flowrate would realize a better mixing, and a simple relationship between the mixing time, bottom gas flowrate, and number of tuyeres was obtained. Quiyoom et al. investigated the gas-induced liquid-phase mixing in a 1:6 scaled-down BOF vessel for different bottom tuyere configurations. It was found that the mixing time was minimum when the eight bottom tuyeres were placed at the PCD of 0.5. Lai et al. studied influence of bottom tuyere configuration on bath stirring by measuring bath mixing time, and the results showed that asymmetric bottom tuyere configurations had shorter bath mixing time than symmetric bottom tuyere configurations.

In previous studies, the effect of single blowing parameters (such as top lance height, bottom gas flowrate, number of tuyeres and so on) on bath mixing was considered. Chou et al. investigated the effect of gas flowrate on the mixing between molten iron and molten slag with a transparent water model, the mass transfer rate was used to evaluate the mixing efficiency. Li et al. proposed the concept of bath mixing degree (bath mixing degree represented the stirring intensity and uniformity degree of molten bath) to describe the effect of oxygen lance height on BOF bath mixing. However, much less attention had been paid to the integrated stirring effect of combined blowing parameters and accurate evaluation of bath mixing degree during BOF steelmaking process.

In this study, the stirring characteristics and influence degree on mixing efficiency by different blowing parameters were studied in a scaled-down BOF vessel. Meanwhile, the mixing index which indicated bath mixing degree of BOF vessel was proposed to optimize the blowing parameters for BOF steelmaking.

2 EXPERIMENTAL APPARATUSES AND PROCEDURE

This study was carried out in a 1/6th scaled BOF vessel made of Plexiglas. The schematic diagram of the experimental apparatus was shown in Figure 1. Compressed air was injected to the top lance and bottom nozzles to simulate the top blowing and bottom blowing. In order to maintain the density and viscosity ratio of water to slag phase, vegetable oil was selected as slag layer for water model experiment.

Bottom blowing plays an important role in BOF bath mixing and is affected by several parameters such as nozzle configuration, number of nozzles, bottom gas flowrate and so on. Normally, symmetric and asymmetric nozzle configurations would generate different distribution of bottom plumes, various bottom gas flowrate would cause different stirring energy in liquid bath. The mixing performance usually changes with different nozzle configurations and blowing parameters. Singh and Quiyoom investigated the effect of bottom tuyere configurations on bath mixing time, they found that the mixing time was minimum at a PCD of 0.5. Lai concluded that asymmetric bottom tuyere configurations had shorter bath mixing time than symmetric bottom tuyere configurations. Based on above consideration, four kinds of bottom nozzle configurations, including actual configuration and three tested configuration that nozzles were placed at the circumference of 0.5D, 0.6D, and 0.7D (D is the diameter of the bath), were surveyed in this study, which was shown in Figure 2.

In order to maintain the dynamic similarity between scaled-down model and industrial BOF vessel, the modified Froude number ($F_{rn}$) and blowing number ($N_{b}$) were considered in this study, which were shown as Equations (1) and (2).

\[
F_{rn} = F_{ri} \frac{u_i^2 \rho_{gm}}{g h_m (\rho_{lm} - \rho_{gm})} = \frac{u_i^2 \rho_{gi}}{g h_i (\rho_{li} - \rho_{gi})}
\]
FIGURE 1  Schematic diagram of water model experiment

FIGURE 2  Typical bottom nozzle configurations for this study
where \( u \) is velocity at nozzle jet, m/s; \( h \) is lance height, m; \( \rho_g \) and \( \rho_l \) are density of gas and liquid phases, kg/m\(^3\); \( g \) is gravitational constant, m/s\(^2\); subscript \( m \) is for scaled-down model; and \( i \) is for industrial BOF; \( U_g \) is critical gas velocity, m/s; \( \sigma \) is surface tension, N/m. Based on the similarity theory and experimental conditions, the experimental parameters for scaled-down model and industrial BOF were listed in Table 1.

In order to clarify the bath mixing efficiency for BOF vessel, the mixing time was measured by two electrical conductivity probes using saturated KCl solution.\(^{33}\) Fifty milliliters of saturated KCl solution was injected into the bath through a pipe which was placed just above the vessel mouth. As shown in Figure 3, the mixing time was defined when instantaneous conductivity was within \( \pm 5\% \) of the final conductivity in the bath. Modeling of the same blowing parameters was repeated for three times, and mean value of the tested time was selected for the mixing time.

### Table 1

| Parameter                        | Prototype | Model |
|----------------------------------|-----------|-------|
| Diameter of the bath [mm]        | 4020      | 670   |
| Height of the bath [mm]          | 1271      | 212   |
| Height of converter shaft [mm]   | 3200      | 533   |
| Number of nozzles of oxygen lance| 4         | 4, 5  |
| Nozzle angle, \( \theta \) [°]   | 12        | 12    |
| Diameter of nozzle throat [mm]   | 34.3      | 5.73  |
| Lance height, \( h \) [mm]       | 950–1550  | 71.88–171.88 |
| Top gas flowrate, \( Q_t \) [Nm\(^3\)/h] | 14,000–17,000 | 69.08–83.88 |
| Bottom gas flowrate, \( Q_b \) [Nm\(^3\)/h] | 40–100 | 0.22–0.54 |
| Number of bottom nozzles         | 4         | 4     |
| Density of liquid slag [kg/m\(^3\)] | 3490      | 890   |
| Viscosity of liquid slag [Pa s]  | 0.3       | 0.1   |
| Thickness of slag layer [mm]     | 150       | 20    |

### Figure 3

Measuring of the bath mixing time with two electrical conductivity probes.
With the aim to determine the influence degree on mixing efficiency by different blowing parameters and obtain the optimal blowing parameters for BOF steelmaking process, a scheme of orthogonal test, which included five factors and multilevel, was conducted in this study. The parameters for orthogonal test were listed in Table 2.

### 3 | RESULTS AND DISCUSSION

#### 3.1 | Influence degree on mixing efficiency by different blowing parameters

The mixing time induced by different blowing parameters (such as lance height, top gas flowrate, bottom nozzle configurations, and so on) was measured through physical modeling of BOF vessel in this paper, which was listed in Table S1. Figure 4 presented the effects of different parameters on mixing time.

As it was depicted in Figure 4, with the increase of top lance height, the mixing time gradually increased. Especially when top lance height changed from 71.88 mm to 171.88 mm, the mixing time showed an obvious increase from 28 to 40 s. The reason can be analyzed that the effective stirring energy of top blown gas rapidly decreased with the increase of lance height. Moreover, with the gradual increase of bottom gas flowrate (changed from 217.2 to 544.8 L/h), the stirring energy of bottom gas bubble would augment correspondingly, and the mixing time of steel bath decreased from 40 to 30 s, which was revealed in Figure 4. Furthermore, the tested bottom nozzle configuration b displayed a better mixing effect among the four configurations, which was presented in Figure 4. The reason was analyzed that symmetrical and concentrating distribution of bottom gas would promote the circular flow of steel bath, and enhance the mixing of liquid bath.

As a type of inferential statistics method, analysis of variance would permit examination of several variables at the same time for purposes of determining whether a significant relationship exists between them. With the aim to illustrate the influence degree on mixing efficiency by different blowing parameters, analysis of variance for the experimental results was conducted. As it was depicted in Table 3, mean squared error expressed the degree of data dispersion, a larger mean squared error showed a greater data dispersion. The value of F-test and confidence level determined whether a
significant relationship existed between the mixing time and blowing parameters, normally a larger $F$-test and smaller confidence level revealed that a more significant relationship existed. Based on above analysis, the influence of lance height on mixing time was the most significant, and the effect of other parameters (such as bottom nozzle configuration, top gas flowrate, and bottom gas flowrate) on mixing time was also obvious. According to the influence degree on mixing efficiency, the blowing parameters were ordered by lance height, bottom nozzle configuration, top gas flowrate, bottom gas flowrate and number of lance nozzles.

In order to achieve a preferable mixing efficiency, the optimal combination of blowing parameters was investigated according to statistical analyses of the experimental results, which was depicted in Table 4. Taking lance height for example, the mean mixing time was minimum when lance height was level 1. Therefore, the optimal combination of blowing parameters for this study was A1B1C2D2E4.

Specifically when the lance height was 71.88 mm (950 mm for an 80 t industrial BOF), the top gas flowrate was 69.08 m$^3$/h (14,000 Nm$^3$/h for an 80 t industrial BOF), the number of lance nozzles was five, the bottom nozzle configuration was b, the bottom gas flowrate was 544.8 L/h (100 Nm$^3$/h for an 80 t industrial BOF), a preferable mixing efficiency was acquired. Figure 5 compared the effect of different combination of blowing parameters on mixing time, and the detailed blowing parameters were listed in Table 5.

As shown in Figure 5, when the optimal scheme was adopted, the mixing time of BOF vessel was the least (24 s) among all the five experimental schemes in this study. Therefore, the optimal combination of blowing parameters obtained in this study could provide good reference for the mixing efficiency of commercial BOF vessels.
### 3.2 Relation between mixing index and blowing parameters

According to the experimental results, the effect of different blowing parameters on mixing time was investigated, and the mixing index which signified the stirring intensity and uniformity degree of steel bath in BOF vessel was put forward in this paper. Li\(^2\)\(^8\) assumed that the relation between bath mixing degree and oxygen lance height was linear, and the bath mixing degree was proposed, which could be defined as Equation (3).

\[
\eta = \alpha (h_0 - h)
\]  

where \(\eta\) was bath mixing degree (the value changed from 0% to 100%); \(\alpha\) was the constant coefficient, m\(^{-1}\); \(h_0\) was the lance height when bath mixing degree was 0, m; \(h\) was the real-time lance height, m.

However, the mixing degree of steel bath in BOF vessel was an integrated function of blowing parameters (such as lance height, top gas flowrate, bottom gas flowrate) and blowing time, the bath mixing degree \(\eta\) was revised and the mixing index \(\lambda\) was proposed in this paper. It was found that there was an obviously relationship between the mixing index \(\lambda\), lance height, top gas flowrate, bottom gas flowrate, and blowing time when the bottom nozzle configuration was fixed. Equation (4) showed the expression of mixing index, and Figure 6 displayed the relation between the mixing index and blowing parameters based on different bottom nozzle configurations.

\[
\lambda = (a \cdot t + b) \cdot \left( \frac{h_{\text{min}}}{h} \cdot \frac{Q_t}{Q_{t_{\text{max}}} \cdot Q_{b_{\text{max}}}} \right)
\]  

where \(\lambda\) was the mixing index (the value changed from 0% to 100%, when the mixing index was 100%, it indicated that the BOF vessel was completely mixed); \(a\) was constant coefficient, s\(^{-1}\); \(b\) was constant; \(t\) was the blowing time, s; \(h_{\text{min}}\) was the minimum lance height of oxygen lance descend, m; \(h\) was the real-time lance height, m; \(Q_{t_{\text{max}}}\) was the maximum top gas flowrate that oxygen lance could supply, Nm\(^3\)/h; \(Q_t\) was the real-time top gas flowrate, Nm\(^3\)/h; \(Q_{b_{\text{max}}}\) was the maximum bottom gas flowrate that bottom nozzles could blow, Nm\(^3\)/h; \(Q_b\) was the real-time bottom gas flowrate, Nm\(^3\)/h.

As can be seen from Figure 6, an apparent nonlinear relation between the mixing index, lance height, top gas flowrate, bottom gas flowrate, and blowing time was acquired under four kinds of bottom nozzle configurations. Therefore, the mixing index could be applied to evaluate the mixing degree of steel bath in BOF vessel under different blowing parameters, and provide a good reference for optimization of blowing parameters during BOF steelmaking process.

### 3.3 Application to industrial process

This study analyzed the effect of different blowing parameters on bath mixing efficiency. Eventually, the optimal combination of blowing parameters for an 80 t industrial BOF vessel was obtained: bottom nozzle configuration was b, top lance height was 950 mm, top gas flowrate was 14,000 Nm\(^3\)/h, five nozzles lance, and bottom gas flowrate was 100 Nm\(^3\)/h. Furthermore, the optimal blowing parameters were preliminarily applied to an 80 t BOF in a special steel plant. As it was depicted in Table 6, the initial composition of charged materials (such as hot metal, scrap, slagging materials, and so on) was not significantly different for the heats with and without optimal blowing parameters. Ultimately, some technical efficiency was acquired, which was shown in Table 7.
FIGURE 6  Relationship between the mixing index and blowing parameters based on different bottom nozzle configurations: (A) bottom nozzle configuration a; (B) bottom nozzle configuration b; (C) bottom nozzle configuration c; (D) bottom nozzle configuration d

TABLE 6  Composition of charged hot metal with and without optimal blowing parameters

| Composition | \(\omega (C)/\%\) | \(\omega (Si)/\%\) | \(\omega (Mn)/\%\) | \(\omega (P)/\%\) | \(\omega (S)/\%\) |
|-------------|------------------|------------------|------------------|------------------|------------------|
| Without optimal parameters | 4.2–4.5 | 0.45–0.65 | 0.38–0.49 | 0.095–0.115 | 0.023–0.035 |
| With optimal parameters | 4.2–4.5 | 0.48–0.63 | 0.41–0.50 | 0.092–0.113 | 0.025–0.035 |

TABLE 7  End point composition and temperature with different blowing parameters

| Blowing parameters | Mean values of 100 heats spring steel |
|--------------------|-------------------------------------|
|                    | [%C] [%O] | \(\omega (Mn)/\%\) | \(\omega (P)/\%\) | \(\omega (TFe)/\%\) | \(T/^\circ C\) |
| Before optimization | 0.0032   | 0.136  | 0.0143 | 16.48 | 1648 |
| After optimization  | 0.0026   | 0.152  | 0.0131 | 14.27 | 1644 |

As it was depicted in Table 7, the control of end point composition and temperature of molten steel was improved with application of optimal blowing parameters. Specifically, the end-point carbon and oxygen equilibrium was decreased from 0.0032 to 0.0026; end-point manganese content was increased by 0.016%; end-point phosphorus content, total Fe content in slag and end-point temperature were reduced by 0.0012%, 2.21% and 4\(^\circ\)C, respectively.
4 | CONCLUSIONS

The effect of different blowing parameters on bath mixing efficiency was studied in this paper. Through analysis of variance for the experimental results, the influence degree on mixing efficiency was ordered by top lance height, bottom nozzle configuration, top gas flow rate, bottom gas flow rate, and number of lance nozzles. The mixing index which signified the stirring intensity and uniformity degree of steel bath in BOF vessel was proposed, an apparent nonlinear relationship between the mixing index, lance height, top gas flow rate, bottom gas flow rate, and blowing time was revealed.

The optimal blowing parameters were obtained and applied to an industrial BOF vessel, obvious technical efficiency was achieved. This study could provide some reference to achieve a better mixing efficiency for BOF steelmaking process. Future studies would seek to evaluate the bath mixing efficiency with mixing index and optimize the blowing parameters for different BOF vessels.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

1. Basson E. Steel Statistical Yearbook 2018. Brussels, Belgium: Word Steel Association; 2018.

2. Cecca C, Barella S, Mapelli C, et al. Thermal and chemical analysis of massive use of hot briquetted iron inside basic oxygen furnace. J Iron Steel Res Int. 2017;24:901.

3. Cao LL, Wang YN, Liu Q, Feng XM. Physical and mathematical modeling of multiphase flows in a converter. ISIJ Int. 2018;58:573-584.

4. Chu KY, Chen HH, Lai PH, et al. The effects of bottom blowing gas flow rate distribution during the steelmaking converter process on mixing efficiency. Metall Mater Trans B. 2016;47:948-962.

5. De VL, Bellemans I, Vercruyssen C, Verbeken K. Basic Oxygen Furnace: assessment of recent physicochemical models. Metall Mater Trans B. 2019;50:2647.

6. Kadrolkar A, Dogan C. The decarburization kinetics of metal droplets in emulsion zone. Metall Mater Trans B. 2019;50:2912-2929.

7. Asahara N, Naiko K, Kitagawa I, Matsu M, Kumakura M, Iwasaki M. Fundamental study on interaction between top blown jet and liquid Bath. Steel Res Int. 2011;82:587-594.

8. Cao LL, Liu Q, Wang Z, Li N. Interaction behaviour between top blown jet and molten steel during BOF steelmaking process. Ironmak Steelmak. 2018;45:239-248.

9. Ajmani SK, Chatterjee A. Cold model study of mixing and mass transfer in LD converters at Tata Steel. Ironmak Steelmak. 1996;23:335.

10. Sato S, Ando M, Okada J, Ueda Y, Iguchi M. Prediction of plunging depth induced by top Lance gas blowing onto a low-melting-point metal bath. ISIJ Int. 2020;60:1675-1683.

11. Tago Y, Higuchi Y. Fluid flow analysis of jets from nozzles in top blown process. ISIJ Int. 2003;43:209-215.

12. Singh V, Kumar J, Bhanu C, Ajmani SK, Dash SK. Optimisation of the bottom Tuyeres configuration for the BOF vessel using physical and mathematical modelling. ISIJ Int. 2007;47:1605-1612.

13. Olivares O, Elias A, Sanchez R, Cruz MD, Morales RD. Physical and mathematical models of gas-liquid fluid dynamics in LD converters. Steel Res. 2002;73:44-51.

14. Ballal NB, Ghosh A. A water model study of bottom-blown oxygen steelmaking processes. Metall Mater Trans B. 1981;12:525-534.

15. Wu WJ, Yu HX, Wang XH, Li HB, Liu K. Optimization on bottom blowing system of a 210 t converter. J Iron Steel Res Int. 2015;22:80-86.
16. Nakanishi K, Kato Y, Nozaki T, Emi T. Cold model study on the mixing rates of slag and metal bath in Q-BOP. *Tetsu-to-Hagane*. 2009;66:1307.
17. Quiyoom A, Golani R, Singh V, Buwa V. Effect of differential flow schemes on gas-liquid flow and liquid phase mixing in a Basic Oxygen Furnace. *Chem Eng Sci*. 2017;170:777.
18. Li WF, Zhu R, Dong K, et al. Physical simulation and industrial testing of bottom-blown O2-CaO converter for steelmaking process. *Metall Mater Trans B*. 2020;51:1060-1069.
19. Choudhary SK, Ajmani SK. Evaluation of bottom stirring system in BOF steelmaking vessel using cold model study and thermodynamic analysis. *ISIJ Int*. 2006;46:1171-1176.
20. Quiyoom A, Ajmani SK, Buwa V. Optimization of bottom tuyere configuration for basic oxygen furnace steelmaking through experiments and CFD simulations. *Chem Eng Sci*. 2018;346:127-142.
21. Lai ZY, Xie Z, Zhong LC. Influence of bottom Tuyere configuration on Bath stirring in a top and bottom combined blown converter. *ISIJ Int*. 2008;48:793-798.
22. Silveira CO, Ribeiro MA, Salgado RS, et al. *Proceedings of the Iron & Steel Technology Conference*. Pittsburgh, PA: AIST; 2019:979.
23. Han C, Shen M, Yang C. Water model study on effect of process parameters on top and bottom combined blowing of 120 t BOF and application. *SPE Steel*. 2017;38:1.
24. Li MM, Li L, Li Q, Zou ZS. Modeling of mixing behavior in a combined blowing steelmaking converter with a filter-based Euler–Lagrange model. *JOM*. 2018;70:2051-2058.
25. Maia BT, Imagawa RK, Petrucelli AC, Tavares RP. Effect of blow parameters in the jet penetration by physical model of BOF converter. *J Mater Res Technol*. 2014;3:244.
26. Chen M, Liao GF, Li GQ, Yuan G, Xiao ZH, Su FG. Water model study on a 210 t top-bottom combined blown converter. *Chin J Proc Engine*. 2011;11:36.
27. Chou JM, Chuang MC, Yeh MH, et al. Effects of process conditions on mixing between molten iron and slag in smelting reduction vessel via water model study. *Ironmak Steelmak*. 2003;30:195-202.
28. Li GH, Wang B, Liu Q, et al. A process model for BOF process based on bath mixing degree. *Int J Miner Metall Mater*. 2010;17:715-722.
29. Sabah S, Brooks G. Splash distribution in oxygen steelmaking. *Metall Mater Trans B*. 2015;46:863-872.
30. Li MM, Li Q, Kuang SB, Zou ZS. Determination of cavity dimensions induced by impingement of gas jets onto a liquid bath. *Metall Mater Trans B*. 2016;47:116-126.
31. Li Q, Li MM, Kuang SB, Zou ZS. Numerical simulation of the interaction between supersonic oxygen jets and molten slag–metal Bath in steelmaking BOF process. *Metall Mater Trans B*. 2015;46:1494-1509.
32. Sabah S, Brooks G. Splashing in oxygen steelmaking. *ISIJ Int*. 2014;54:836-844.
33. Chen C, Jonsson LT, Tilliander A, Cheng GG, Jonsson PG. A mathematical modeling study of the influence of small amounts of KCl solution tracers on mixing in water and residence time distribution of tracers in a continuous flow reactor-metallurgical tundish. *Chem Eng Sci*. 2015;137:914-937.

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