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STUDY OF THE USE OF SYNTHETIC NATURAL GAS(SNG) INTO CHARCOAL MINI BLAST FURNACE BY THE FOUR FLUID MODEL[1]

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Abstract

In the Brazilian domestic market, the synthetic natural gas(SNG) has been available for large consumers. Initially the SNG has been considered to be used at facilities on the semi integrated mini mills based on electric furnace. However to study new possibilities of use of SNG on the ironmaking industries is important and can be an alternative to expensive installations of pulverized coals. Theoretically the injection of synthetic gas on the tyueres of small blast furnace based on biomass can enhance the competitiveness of the hot green pig iron production due to its possibility of considerable decrease of the granular charcoal consumption, increase in productivity and enhancement of combustion in the raceway in addition to the decrease of specific CO_2 emissions. This model treats the blast furnace as a multi-phase reactor and four phases are considered simultaneously: gas, lump solids (raw iron ore, sinter, pellets and granular charcoal), hot metal and molten slag. The model is based on conservation equations for mass, momentum, energy and chemical species numerically solved based on the finite volume method. The SNG has high amount of H_2 and strongly effects the inner conditions of the reactor and only a comprehensive model with detailed chemical reaction rates can properly predict the inner conditions of the process and hence furnish useful information to design smooth operational conditions. The simulation results indicated that smooth operations up to 25 Nm^3/tof pig iron can be considered with increase on the productivity up to 58%.

Keywords: Synthetic natural gas(SNG); Modeling;Biomass; Mini blast furnace.

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1INTRODUCTION

In the present status of technological development the technology to produce hot metal in the steel industry is based on the blast furnace-BOF processes route using coke and pulverized coal as reducing agent. However, this route is recognized as intensive energy consuming and demands high quality of raw materials such as lump coke and sinter. In the integrated route of crude steel production the blast furnace is responsible of around 70% of total energy input and about 60% of the total cost of pig iron production in this process is due to the reducing agent consumed in the blast furnace as lump coke or pulverized coal injected through the tuyeres. Therefore, tremendous efforts have been made in order to reduce the reducing agent rate of the blast furnace, or at least, replace the coke consumption by less precious materials injected through the blast furnace tuyere.(1-6) Based on this perspective, the replacement of fossil reducing agent by biomass is the spot light of this technology, since replace the reducing agent by a renewable resource with environmental benefits that can be obtained by capturing CO_2 from the atmosphere in a relatively short cycle (about 7 years), if one considers the charcoal produced by forestation. Therefore, it is a competitive technology for producing hot metal, especially for region where the climate is favorable to the plantation of biomass and will demand to increase steel production by constructing new blast furnaces in near future. The combustion rate of charcoal is quite high compared with those of coal and coke.(4-8)When pulverized charcoal is injected into the raceway, it combusts first and furnishes heat and CO_2 which is used for gasification of the pulverized coal by solution loss reaction in addition to partial and full combustion directly with the oxygen. Composition of charcoal is quite different from that of coal usually injected into the blast furnace.(4-6) The charcoal used in this study has very low ash, sulfur and silica content, however, volatile matter is usually higher, as shown in Table 1. The gas produced due to gasification reaction within the raceway has higher hydrogen content and lower ignition temperature is needed(around 700 ^{o}C). In addition, the technology for injection of pulverized coal already get maturity and several blast furnaces over the world have been continuously operated with pulverized coal rates around 200 kg/thm. However, there is clear limitation for further increases in the injection rates of pulverized coal mainly due to the gas and particles flows in the lower part of the furnace and unburned coal or ash that can remain in the raceway, which could deteriorates the permeability of this region leading to unstable operation. In the same hand, the pulverized charcoal injection technology applied for small blast furnaces based on granular charcoal has entered in a stage of high technological development.(2-4)The injection technology of gaseous fuel has proven the beneficial effects due to low ignition temperature and high combustibility. The synthetic natural gas(SNG) has high amount of hydrogen and its combustibility is very high compared with pulverized coal. Therefore, this study is focused on the simultaneous injection of pulverized charcoal and synthetic natural gas(SNG) on a compact blast furnace aiming at contributing to clarify the in-furnace phenomena and show the feasibility of simultaneous injection. Several authors have addressed the multiple injections of carbonaceous materials into the blast furnace by theoretical and experimental analysis.(1,4-9)However, only detailed mathematical model based on fundamental phenomena is expected to fully considers the important aspects of simultaneous injection. In this paper a mathematical model of the blast furnace is proposed to simulate the blast furnace operation with simultaneous injection of pulverized charcoal and synthetic natural gas(SNG). The present model uses similar approach as those presented by Yagi,(10) Austin, Nogami and Yagi(11,12) and Castro, Nogami and Yagi,(13,14) which applied multiphase theory to describe the motion, energy and chemical species of each phase inside the furnace. Although some hybrid models based on DEM(Discrete Element Method) have been discussed,(15-20) the multiphase theory is considered suitable and accurate enough to describe the actual operation of the blast furnace.

Table 1 Properties of the raw materials used in this study

(Mass %)	Granular charcoal	Pulverized Charcoal(PCH)
C(fixed)	72.2	70.83
Volatile matter	22.5	25.80
Humidity	2.1	0.01
SiO_2	1.61	1.10
Al_2O_3	0.15	0.11
CaO	1.10	1.58
S	0.001	0.0022
$P(P_2O_5)$	0.01	0.170
$K(K_2O)$	0.32	0.40
Ash	3.20	2.96
Volatile mater		
C	75.3	72.00
N	6.50	7.35
H	14.4	16.50
O	3.75	4.15
Average particle diameter(μm)	-	120
True density(kg/m^3)	1345	1150
Particle porosity(-)	0.65	0.85
Pore tortuosity (-)	0.7	0.9
Thermal conductivity(W/mK)	0.6	0.6
Calorific value (kJ/kg)	31274	30162

Synthetic natural gas(SNG) (%vol)

propane	n-butane	isobutane	propene	trans-butene -2	isobutene	Cis-butene 2	others
31.8	28.2	13.2	12.8	4.4	3.8	2.8	3.0

Iron bearing sources sinter+slaggingagent(%)

Fe_2O_3	FeO	SiO_2	Al_2O_3	CaO	MnO	MgO	H_2O
82.6	3.2	4.9	1.2	4.8	0.2	1.6	1.5

Therefore, the continuum approach is a better tool to evaluate the performance of the whole blast furnace process under multiple injection operation.(10-15,20-22)Therefore, in the present study a detailed model able to take into account particular phenomena and mechanism of simultaneous injection of pulverized charcoal and synthetic natural gas is used. Thus, this model aims to address new features of the simultaneous injection and to investigate new operation possibilities, which could contribute to lower reducing agent consumption and suggest new environmentally cleaner process operation techniques.

2MODEL APPROACH

The mathematical model is three-dimensional and analyses the packed bed region within the blast furnace, from the slag surface in the hearth up to the burden surface in the throat. Five-phases are treated: gas(includes SNG species), lump solids(granular charcoal, sinter, pellets, lumpore), hot metal, slag andpulverized charcoal. All phases are treated simultaneously due to mutual interactions. Thus, the governing equations of all phases, that form a large set of strongly coupled non-linear equations, are solved simultaneously. In this model, conservation equations of motion, energy and chemical species are considered and coupled with chemical reactions and physical properties. For the sake of simplicity, all the conservation equations are represented in a compact form, as in Equation(1).

$$\frac{\partial\left(\varepsilon_i \rho_i \phi_i\right)}{\partial t} + \mathrm{div}\left(\varepsilon_i \rho_i \vec{V}_i \phi_i\right) = \mathrm{div}\left(\varepsilon_i \Gamma_{\phi_i}\, \mathrm{grad}\, \phi_i\right) + S_{\phi_i} \qquad (1)$$

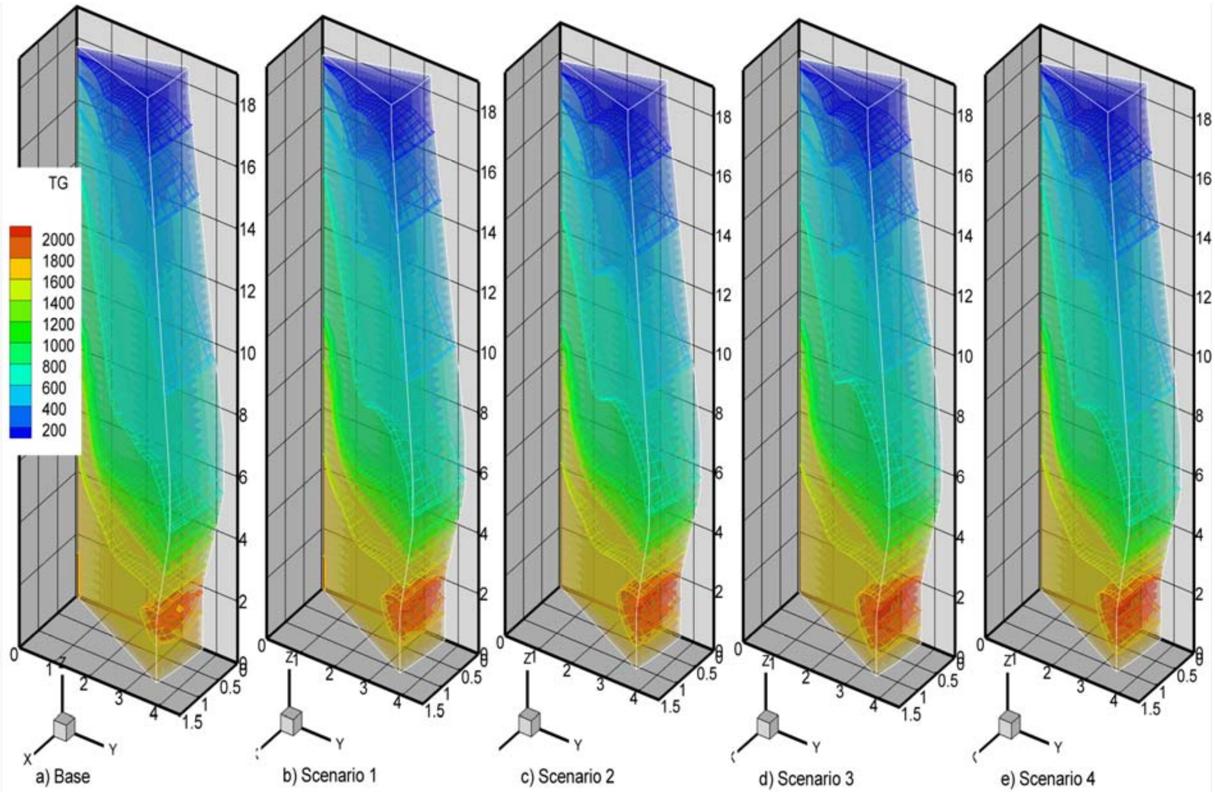
In this equation, ϕ is the dependent variable, expressing the component velocities for the phase momentum equations, the enthalpy for the phase energy equations and the chemical species for the phase continuity equations, *i*represents the phase being considered or the chemical species ofeach phase. ε and ρ are phase volume fraction and density, respectively. V and t are phase velocity field and time, respectively. Γ_{ϕ_i} is the effective transfer coefficient which represents effective dynamic viscosity in the momentum equations, effective thermal conductivity in the energy equations and effective diffusion coefficient of the chemical species in the materials equation of each phase. The source terms(S_ϕ) are due to inter-phase interactions that canappear through chemical reactions, surface interactions and external force.(10-22)The source terms in the conservation equations take into account chemical reactions, phase transformations, momentum exchange, external force and so on. The continuity and species conservation equations have mass sources due to chemical reactions and phase transformations. Enthalpy sources arise from inter-phase heat transfer, heat of reaction and sensible heat accompanied with mass transfer due to chemical reactions and phase transformations. The formulations for the phase interactions and chemical reactions have been published in previous reports.(9-15)This model considers the pulverized charcoal injected through a separated lance into the raceway channel. The charcoal injected through the blast furnace tuyeres is mixed with the gas stream and, in contact with oxygen, combusts partially and the volatile matter evolves in the interior of the raceway and finally almostcomplete combustion in the raceway is achieved. The unburned pulverized coal or ash continues to reacts and meltdown when particle temperature is higher than the melting temperature. The chemical reaction models for pulverized charcoal and coal used in this study have similar rate expressions, however, the parameters of reactivity and inner particle structure are quite different, which gives high difference in reaction rates.(6) The boundary conditions were applied on the boundary of the computational domain limited at the bottom by the slag surface, at the top by the burden surface and by thelateral walls. At the top, the gas phase is assumed as fully developed flow while solid inflow is modeled assuming no gradient velocity, with the inflow rate given by solid mass consumption due to chemical reactions and melting. At the tuyere inlet of blast, additional oxygen and pulverized coal are given by their inflow rates. The blast flow rate are fixed and pulverized coal and charcoal are iteratively calculated to reach the aimed pulverized coal and charcoal injection rates, which are specified at the beginning of the iterative calculation. The blast temperature are specified as a fixed value throughout the calculation. At the side wall, momentum and mass fluxesacross the wall are assumed null while heat transfer is allowed by setting an overall heat transfer coefficient. For the gas velocity it is assumed null values perpendicular and tangential to the furnace wall. The solid tangential velocity on the wall surface assumes coulomb attrition law with a specified coefficient of 0.3 and the normal force is calculated using the local solid pressure. The burden distribution is determined by the relative volume fractions of the inlet solids and their average diameter. The numerical method used to solve the transport equations is based on the finite volume method (FVM) formulated for a general non-orthogonal coordinate system.(23) The numerical mesh is constructed based on a body fitted coordinate system which allows accurate description of the blast furnace wall shape.(23) To solve the governing (momentum)equations of continuous phases the SIMPLE(Semi-Implicit Method for Pressure-Linked Equations) algorithm is applied on a staggered grid for covariant projections of the velocities and the numerical coefficients of the discretized equations are determined by using the power low scheme.(23-25)

3RESULTS AND DISCUSSIONS

In this section, the model is applied to investigate new operational conditions with higher injection rates of pulverized charcoal(PCH) and synthetic natural gas(SNG) in order to compare with a base case considering only injection of pulverized charcoal. In the calculation procedure the oxygen injection and the granular charcoal charged are adjusted aiming at obtaining stable operation of the blast furnace. For all cases the oxygen enrichment is adjusted to maintain the thermal condition of the lower part of the blast furnace which guarantee smooth operation compatible with the base case. The scenarios were selected according to simultaneously increasing the gas rate injection and productivity. The operational parameters calculated in these simulations are presented in Table 2. As can be observed the productivity of the compact blast furnace process can be largely increased (about 58%) for the scenarios analyzed. The raceway temperatures are increased due to the high combustibility of the synthetic natural gas and larger release of heat compared with pulverized charcoal and coal, since the SNG is composed of hydrocarbons of longer chains, as shown in Table 1. It is observed also that the blast rate could be decreased by replacing air with oxygen and as consequence, the total blast rate was decreased for all cases analyzed. The total amount of carbon consumed by solution loss reaction taking place on the granular charcoal and pulverized charcoal increased for all conditions. This behavior is explained by the higher concentration of the CO_2 gas in lower region of the furnace due to the combustion of the SNG injected. For all cases the hot metal saturation in carbon was achieved and the silicon content is dependent of the lower blast furnace conditions with a general trend showing increased with temperature of the raceway but decreasing for the highest productivity observed. The specific carbon emissions increased as a general trend but for the highest productivity recovered to the base case level, however, it is important to point out that most of the carbon emissions are renewed source based on biomass plantation which confer to these operations to be classified as clean technology and depending on the synthetic gas(SNG) prices can be used as flexible operation symbiotically implemented with the charcoal technology.

Table 2:Operational parameters calculated by the model

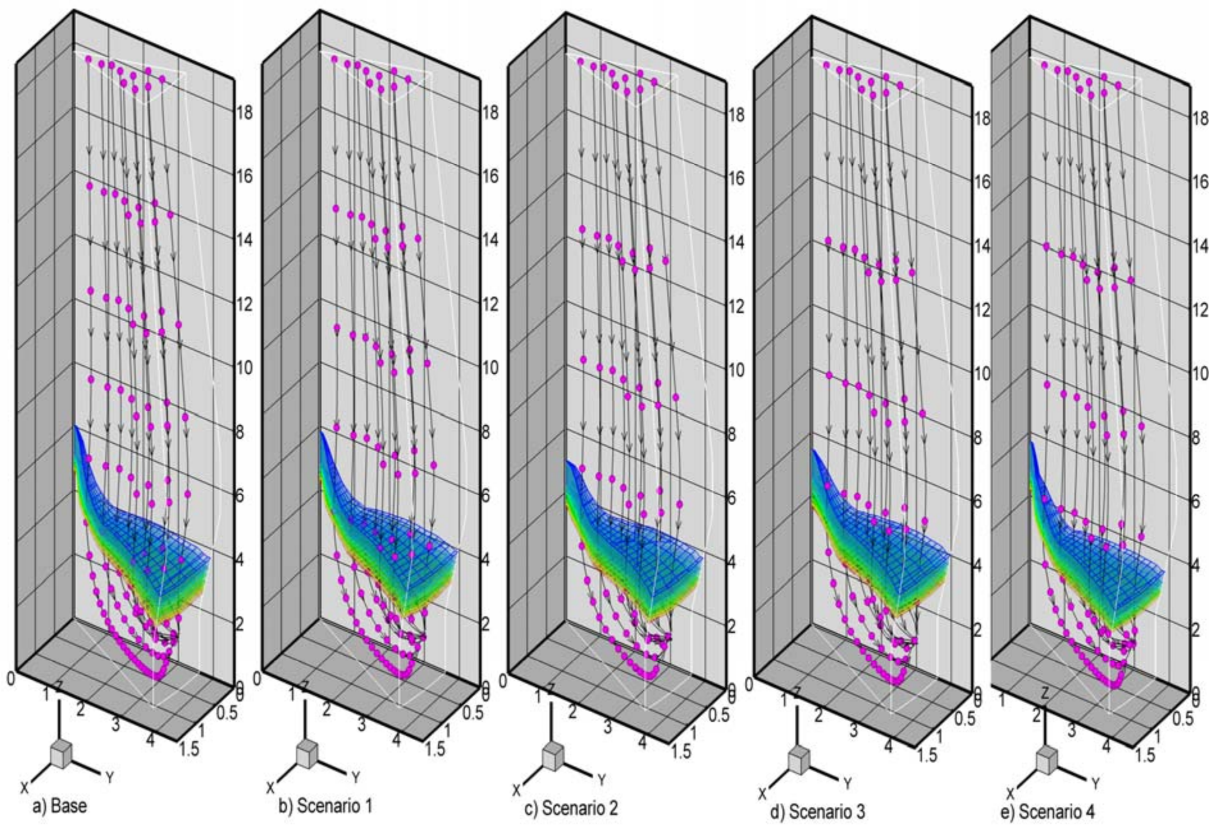
	Base	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Productivity (thm/day/m^3 Working vol.)	3.19	3.84	4.28	4.72	5.05
Production(t/day)	2602.7	3132.5	3501.7	3852.8	4126.4
Oxygen enrichment (Nm^3/thm) (input)	39.4	109.7	132.8	149.6	138.8
Blast(Nm^3/thm) (input)	814.7	676.9	606.1	551.4	513.7
Total blast(Nm^3/thm) (input)	854.6	802.5	753.8	726.9	676.6
Blast temperature(input)	1100	1100	1100	1100	1100
Raceway temperature (^oC)	2130	2338	2435	2503	2473
Si	0.44	0.48	0.45	0.48	0.30
C	4.79	4.79	4.79	4.79	4.79
Slag rate (kg/thm)	205.6	203.5	203.9	201.8	205.8
CaO/SiO_2	1.01	1.09	1.10	1.13	1.11
CaO	37.8	38.3	38.5	38.5	38.1
MgO	14.1	16.2	16.2	17.3	17.5
Al_2O_3	10.5	10.1	9.9	9.7	9.8
Off gas (Nm^3/thm)	1483.3	1478.9	1443.8	1420.6	1716.2
$CO_2/(CO+CO_2)$	31.1	30.5	28.6	31.0	32.1
Granular charcoal (kg/thm)	399.1	398.3	415.1	379.6	358.6
PCH (kg/thm)	134.1	133.9	134.1	134.3	133.8
SNG rate (Nm^3/thm)	0	15.9	14.9	25.8	24.2
Granular charcoal solution loss (kg C/thm)	33.1	38.4	42.3	43.7	51.7
PCH solution loss (kg C/thm)	55.7	55.7	55.1	56.7	54.2
Carbon emission (kg C/thm)	410.2	431.8	444.5	429.8	410.3



a) Base b) Scenario 1 c) Scenario 2 d) Scenario 3 e) Scenario 4

Figure 2 Inner temperature distributions pattern for the scenarios analyzed

Figure 2 shows the gas temperature patterns of the synthetic natural gas injection compared with the base case. As can be observed, the lower part of the compact blast furnace increased the temperature for the scenarios simulated and enhanced the heat transfer in this region although the upper part of the reactor remains almost unchanged . The solid motion and cohesive zone shape are important parameters for assure feasible operation conditions of the blast furnace. Thus, Figure 3(a) - 3(e) shows the descending solid pattern and cohesive zone shapes for the scenarios simulated. As can be pointed out, as the simultaneous injection was increased the cohesive zones slightly moved down. This behavior is attributed to the increase of the productivity combined with the heat transfer in this region due to the increase in the gas velocity. As can be observed, the scenario 4 restores the positioning and shape of the cohesive zone compared with the base case but with very high productivity, indicating that it is possible to attain high productivity with low granular charcoal consumption and high rates of SNG injection with oxygen. Therefore, among the scenarios analyzed, the scenario 4 was considered the best candidate to operate with simultaneous injection of pulverized charcoal and synthetic natural gas(SNG) with compatible specific carbon emissions and inner temperature and solid flow patterns.



a) Base b) Scenario 1 c) Scenario 2 d) Scenario 3 e) Scenario 4

Figure 3 Solid flow patterns and cohesive zone shapes for the scenarios analyzed

4 CONCLUSIONS

In this study a five-phase mathematical model of the blast furnace has been presented, which can simulate the blast furnace operation under simultaneous injection of synthetic natural gas(SNG) and pulverized charcoal. The model considers multiphase interactions for momentum, energy and chemical species coupled with the rates of chemical reactions. The model was applied to investigate feasible scenarios of simultaneous injections and high productivity for the compact blast furnace. The model results indicated that combined injection of pulverized charcoal and synthetic natural gas can be smoothly carried out with effective increase in the productivity of the actual furnace(about 58%).

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REFERENCES

1 A. Babich, S. Yaroshevskii, A. Formoso, A. Cores, L. Garcia and V. Nozdrachev, *ISIJ Int*., 39 (1999), No. 3, 229.
2 J. A. Castro, A. J. Silva, H. Nogami and J. Yagi: Tecnologia em Metalurgia, Materiais e Mineração, 1(2004), No. 2, 59.
3 A.W.S. Baltazar, J.A. Castro and A.J. Silva: Estudos Tecnologicos em Engenharia, 2(2006), No 2, 65.

4 J. G. M. S. Machado1, E. Osorio, A. C. F. Vilela, A. Babich, D. Senk and H. W. Gudenau: Steel Research Int., 81(2010), No 1, 9.
5 P.S. Assis, W.B. Martins and C.B. Vieira: REM-Revista da Escola de Minas, 56(2003), No 4, 281.
6 J. A. Castro, Y. A.J. Silva, Y. Sazaki and J. Yagi: ISIJ Int. 51 (2011), No 5, 748.
7 J.A. Castro, A.W.S. Baltazar and A.J. Silva: WIT Trans. Eng. Sci. , 50(2005), No 1, 207.
8 A. Babich, D. Senk and M. Fernandez: ISIJ Int. 50 (2010), No 1, 81.
9 J.A. Castro and A. W. S. Baltazar: *TMM-Tecnologia em Metalurgia e Materiais e Mineração*, 6,(2009), No. 1, 13.
10 J. Yagi: ISIJ Int., 33(1993), No. 6, 619.
11 P. R. Austin, H. Nogami and J. Yagi: ISIJ Int., 37(1997), No. 5, 458
12 P. R. Austin, H. Nogami and J. Yagi: ISIJ Int., 37(1997), No. 8, 748.
13 J. A. Castro, H. Nogami and J. Yagi: ISIJ Int. 40 (2000), No. 7, 637.
14 J. A. Castro, H. Nogami and J. Yagi: ISIJ Int. 41 (2001), No. 1, 18.
15 X.F. Dong, A.B. Yu, S.J. Chew and P.Zulli: Metallurgical and Materials Transactions B, 41B(2010), No. 2, 330.
16 S. Ueda, S. Natsui, H. Nogami, J. Yagi and T. Ariyama: ISIJ Int., 50(2010), No 7, 914.
17 Z. Zhou, H. Zhu, A. Yu, B. Wright, D. Pinson and P. Zulli: ISIJ Int., 45(2005), No. 12, 1828.
18 A.T.Adema, Y. Yang and R.Boom: ISIJ Int., 50(2010), No 7, 954.
19 Z. Zhou, H. Zhu, A. Yu, B. Wright, D. Pinson and P. Zulli: Powder Technology 208(2011), No. 1, 72.
20 X.F. Dong, A.B. Yu, J. Yagi and P. Zulli: ISIJ Int., 47(2007), No. 11, 1553.
21 J. A. Castro, H. Nogami and J. Yagi: ISIJ Int. 42 (2002), No. 11, 1203.
22 J. A. Castro, H. Nogami and J. Yagi: ISIJ Int. 42 (2002), No.1, 44.
23 M.C. Melaen: Numerical Heat Transfer, B, 21(1992), No. 1, 1.
24 S. V. Patankar and D. B. Spalding: Int. J. Heat Mass Transfer, 15(1972), No. 1, 1787.
25 K. C. Karki and S. V. Patankar: Numer. Heat Transfer, B, 14 (1988), No. 3, 295.