COLD TESTINGS OF A WINDOWED FLUIDIZED BED REACTOR USING QUARTZ SAND FOR SOLAR GASIFICATION OF COKE

N. Gokon[1,] *, T. Tanabe[2], H. S. Cho[1], T. Hatamachi[2], T. Kodama[3]

[1] Center for Transdisciplinary Research, Niigata University, 8050 Ikarashi 2-nocho, Nishi-ku, Niigata 950-2181, Japan

[2] Graduate School of Science and Technology, Niigata University, 8050 Ikarashi 2-nocho, Nishi-ku, Niigata 950-2181, Japan

[3] Department of Chemistry & Chemical Engineering, Faculty of Engineering, Niigata University, 8050 Ikarashi 2-nocho, Nishi-ku, Niigata 950-2181, Japan

Abstract

A windowed fluidized bed reactor prototype was studied and developed for solar thermochemical gasification of coal cokes with steam and CO_2. The windowed fluidized bed reactor is assumed to be combined with a newly developed beam-down optics. Recently, quartz sand was employed as a chemically-inert bed material for the fluidized bed and worked as a thermal transfer/storage medium inside the reactor for coke gasification under direct light irradiation. In order to design a laboratory-scale prototype windowed fluidized-bed containing of quartz sand and coke particles, the reactor model of fluidized bed was made from a transparent acrylic resin to allow us to observe a fluidizing particle through the sidewall of the reactor body; a branching tube is equipped with the sidewall of the reactor to continuously supply coal-coke particles from a screw feeder. In the present study, in order to evaluate fluidization performance of coal-cokes, the pressure loss between the inlet and outlet gases was examined, and descending coal-coke particles on the sidewall of the reactor was observed in the reactor model. The moving velocity and distance of descending particles from the top to bottom of fluidized bed were measured by the visual observation of the tracer particles on outside wall of reactor model.

Keywords: *Solar thermochemical gasification, Coal-cokes, Fluidized bed reactor, Cold testing*

1. Introduction

Coal gasification using CO_2 or steam as an oxidant is a highly endothermic process at high-temperature, and is used to produce solar-hybrid syngas (solar-fuel) composed of a mixture of hydrogen and carbon monoxide. Solar gasification is a promising key technology for thermochemical conversion, which can produce clean gaseous fuels from solid carbonous material by using high-temperature solar heat [1-6]. The greatest advantage of solar-driven gasification is the storage of a significant fraction of solar energy as the chemical energy of the synthesized fuel molecules, and the fuels can reduce the net CO_2 emissions to the environment and conserve fossil fuels.

$$CH_n(\text{coal}) + H_2O(l) = CO + (1+n/2)H_2 \qquad \Delta H_{298K} = 175 \text{ kJ/mol} \qquad (1)$$

$$CH_n(\text{coal}) + CO_2 = 2CO + n/2H_2 \qquad \Delta H_{298K} = 172\text{kJ/mol} \qquad (2)$$

The calorific value of coal or carbon feed can theoretically be upgraded by about 45% when the process heat required to drive the reactions (1) and (2) is provided by concentrated solar radiation. Syngas derived from solar energy can be thermochemically converted to hydrogen via water–gas shift reaction; to liquid hydrocarbon fuels such as diesel, kerosene, and gasoline via Fischer–Tropsch synthesis; or directly used as a combustion fuel for power generation.

The present authors in Niigata University study a windowed reactor prototype using fluidized bed of coal cokes particles, and have proposed to combine the windowed solar chemical reactor, such as a solar gasifier, with a newly developed solar reflective tower or beam-down optics [7-10]. Recently, quartz sand was employed as a chemically-inert bed material for the fluidized bed and as a thermal transfer/storage medium inside the reactor for coke gasification under direct light irradiation. In order to design a laboratory-scale $30kW_{th}$ prototype windowed fluidized-bed containing of quartz sand and coke particles, the reactor model of fluidized bed was made from a transparent acrylic resin to allow us to observe a fluidizing particle through the sidewall of the reactor body; a branching tube was equipped with the sidewall of the reactor to continuously supply coal-coke particles from a screw feeder [11].

doi:10.18086/swc.2015.04.24 Available at http://proceedings.ises.org

In the present study, in order to evaluate fluidization performances of coal-cokes, the pressure loss between the inlet and outlet gases was examined, and descending coal-coke particles on the sidewall of the reactor was observed in the reactor model. The moving velocity and distance of descending particles from the top to bottom of fluidized bed were measured by the visual observation of the particles on outside wall of reactor model.

2. Experimental procedure

2.1. Preparation of quartz sand as a bed material

Quartz sand was purchased from Japan Pure Chemical Co., Ltd. The quartz sand was sieved using mesh screens into four particle size ranges: 100–200 μm, 200–300 μm, 300–500 μm, and 500–700 μm; the quartz sand of 300–500 μm size was used as the chemically inert bed material for investigation. Real and bulk densities of quartz sand at 25 °C are 2.6 g cm^{-3} and 1.3 g cm^{-3}, respectively. The loading amount of quartz sand was 2000 g. The layer height/layer diameter ratio (L/D ratio) was 1.17.

2.2. Fluidized-bed reactor cold model (FBCM)

Fig. 1 shows schematic view of a fluidized bed reactor cold model (FBCM) with a transparent quartz window at its top. The reactor model of laboratory-scale prototype windowed fluidized-bed containing of quartz sand and coke particles was fabricated. The FBCM was made from a transparent acrylic resin to allow us to observe a fluidizing particle through the sidewall of the reactor body; a branching tube was equipped with the sidewall of the reactor in order to continuously supply coal-coke particles from a screw feeder. In the present study, an orifice type distributor was newly designed in order to enhance an internal circulation of fluidizing particle; a number of pores were densely arranged in a center of the distributor, while pores were sparsely located in a circumference of the distributor [11].

Fig. 2 shows photographs of the FBCM. A windowed fluidized-bed reactor can prevent direct contact, ensuring an interspacing gap between the coal-coke particles and window. It assumed that concentrated solar radiation passes downward through the window and directly heats the FBCM of fluidizing particles. A draft tube is located at the center of the fluidized particle bed inside the reactor, and is possible to remove itself in order to evaluate the impact on internal circulation of quartz sand. For the internally-circulating fluidized bed (ICFB) with draft tube, inlet gas (air in this study) is allowed to flow into the draft tube and annulus region between the internal tube and reactor wall. In this reactor design, it is expected that the fluidizing particles are always transported upward in the draft tube and move downward in the annulus region. This forced circulation pattern will enable solar energy to be transferred from the top to the bottom of the fluidized particle bed; the bed temperature remains high and homogeneous, thus preventing localized overheating of some areas within the bed. Therefore, by directly heating the bed, the solar gasification will occur in the fluidized bed inside the reactor.

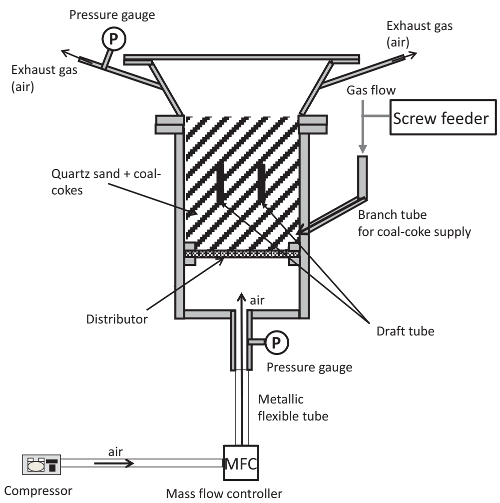

Figure 1 Experimental set-up for fluidization performances of mixture of the coal-coke and quartz sand using the reactor model of fluidized bed reactor.

Figure 2 Photograph of experimental system using fluifdized bed reactor conbined with screw feeder for coal-coke supply.

2.3. Fluidization performance testing using the designed reactor model of fluidized bed reactor

Fluidization performances of mixture of the coal-coke and quartz sand using the reactor model of fluidized bed reactor were examined in this study. The quartz sand of 300-500 μm size was selected and used for testing in the series of experiment. 40 g of coke particles were mixed with 2000 g of quartz sand, and the mixture was loaded in the fluidized bed region of the reactor tube. The static bed heights were 140 mm before fluidization. The air flow into the bottom of reactor was controlled by mass-flow controller; the gas stream was passed through the distributor; the internally circulating fluidized bed was formed inside the reactor resulting in the fluidization of mixture of coal-coke and quartz sand. The air could be flowed at volumetric gas velocities of 0-100 N $dm^3 \cdot min^{-1}$ (superficial gas velocities of 0-0.147 $m \cdot s^{-1}$) to examine the fluidization performances of mixture of the coal-coke and quartz sand. The gas pressures at gas inlet and outlet were measured by using pressure gauge, respectively. In addition, the descending cokes and sand particles on the sidewall of the reactor were observed in the reactor model. The moving velocity and distance of descending particles from the top to bottom of fluidized bed were measured by the visual observation of the particles on outside wall of reactor model. From the fluidization performances, the impacts of internal circulation of mixture of coal-coke particle and quartz sand on the fluidization state in the fluidized bed reactor are evaluated.

3. Results and Discussion

A windowed reactor model of fluidized bed reactor designed for solar coke gasification using quartz sand as a bed material was used in the series of experiments. The reactor model was used for the fluidization performance testing of mixture of coal-coke and quartz sand in this study. Figure 3 shows relationship between pressure loss of fluidized bed and gas velocity in the reactor model of fluidized bed reactor with/without draft tube. Figure 3 (a) is the results for use of internally circulating fluidized bed with draft tube, while Figure 3 (b) exhibits the results for use of fluidized bed without draft tube. As seen in Figure 3 (a), the values for U_{mf} and pressure loss for the fluidized bed reactor with the draft tube (U_{mf} = 0.071 m s^{-1}, and pressure loss of 1.67 kPa) were almost the same with those for that without draft tube (U_{mf} = 0.077 m s^{-1}, and pressure loss of 1.63 kPa) (Fig. 3 (b)). This result means that draft tube in the reactor did not impact on the gas velocity and pressure required for making fluidization. Namely, the draft tube did not facilitate a formation of fluidized bed at boundary region between fixed bed and fluidized bed. However, in a higher gas velocity region than the value for U_{mf}, a pressure loss for the fluidized bed with draft tube slightly decreased with increasing gas velocity; a pressure loss for that without draft tube is almost constant although increasing gas velocity. This result for lowering pressure loss indicates that the orifice type distributor enhances an internal circulation of mixture of coal-coke and quartz sand; in addition, the presence of draft tube embedded in the fluidized bed forms a coordinate internal circulation of bed particles in the reactor. This tendency appeared similarly at the previous results of the batch-type fluidization testing for use in a mixture of coal-coke and quartz sand without screw feeder [11]. This result for decreasing pressure loss indicates that a draft tube have a potential to enhances a fluidization of mixture of coal-coke and quartz sand in a reactor. The effectiveness of draft tube appears prominently in higher gas velocity than the U_{mf} value (U_{mf} = 0.071 $m \cdot s^{-1}$).

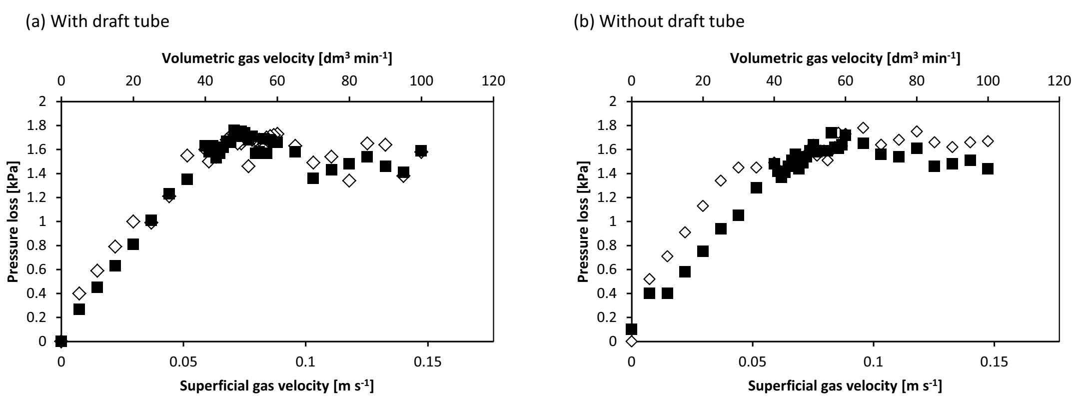

Figure 3 Relationship between pressure loss of fluidized bed and superficial gas velocity in the designed reactor model of fluidized bed (a) with or (b) without draft tube. A mixture of quartz sand and coal coke particles are used as a fluidization medium in the reactor model. The open plot is the results for increasing gas velocity, and the closed plot is the result for decreasing gas velocity in the figures.

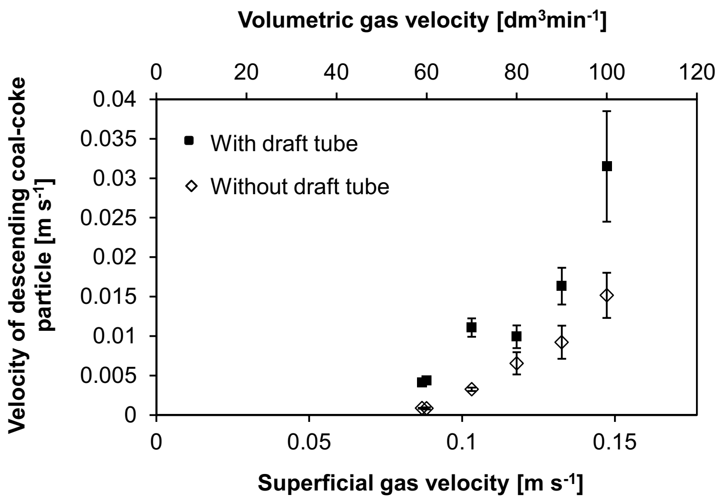

Figure 4 Relationship between descending coal-coke particle of fluidized bed and superficial gas velocity in the designed reactor model of fluidized bed reactor with/without draft tube. The descending particles were observed at a position of 35 mm below height from the bed surface.

A velocity of descending particle are measured at different bed height, the results are shown in Figure 4-6. The result observed at a position of 35 mm below height from the bed surface appears in Figure 4. The mixture of quartz sand and coal coke particles was fluidized in the reactor model, and coal-coke was observed as a descending particle. The open plot is the result for without draft tube, and the closed plot is the result for with draft tube in the figures. A velocity of descending particle increases with increasing gas velocity for fluidized bed reactor with and without draft tube. The velocity of coal-cokes at the bed layer (0.25H, H = bed height) is 1.5-5.1 times higher in the fluidized bed with draft tube than that without draft tube in a wide range of superficial gas velocity U = 0.088-0.147 $m{\cdot}s^{-1}$. This means that the use of draft tube dominantly enhances the mobility of coal-cokes at higher gas velocities than U_{mf}. The tendency for increasing velocity of descending coal-coke particle was obviously observed in comparison to the only use of quartz sand [11]. These results shown in Figure 4 mean that coal-coke is descended at a fast velocity on the outer wall of the reactor tube in the fluidized bed in comparison to the quartz sand; the use of draft tube enhances the velocity of descending coal-coke in a mixture bed of coal-coke and quartz sand at a wide gas velocity range.

The results for velocity of descending particle at further deep depth of the fluidized bed are shown in Figure 5. The velocity of descending coal-coke particle was measured at a position of 55 mm below height from the bed surface. The velocity of coal-cokes is 1.9-7.5 times higher in the fluidized bed with draft tube than that without draft tube in a wide range of superficial gas velocity U = 0.088-0.147 $m{\cdot}s^{-1}$. The result indicates that the velocity of descending coal-coke was decreased with the deep layer (0.4H) of the fluidized bed with and without draft tube, but coal-coke in the fluidized bed with draft tube could be moving down relatively faster than that without draft tube as the bed layer was increasing depth. On the other hand, the velocity of descending quartz sand was also decreased with the deep layer, but the velocity of quartz sand in the fluidized bed with draft tube was 2 times higher than that without draft tube in a range of U = 0.088-0.147 $m{\cdot}s^{-1}$[11]. This means that coal-coke particle can be subject to influence by using draft tube.

Figure 6 show the results for the velocity of descending coal-coke particle at the middle layer (0.46H, H = bed height) of the fluidized bed. The velocity of descending particle was measured at the position of 65 mm below height from the bed surface. The velocity of coal-cokes is 2.4-7.5 times higher in the fluidized bed with draft tube than that without draft tube in a wide range of superficial gas velocity U = 0.088-0.147 $m{\cdot}s^{-1}$. As seen in Figure 4-6, a difference of velocity of coal-coke particle between fluidized bed with and without draft tube remains at high gas velocity although the bed layer is deeper. The results for velocity of descending coal-coke particle means that an internally-circulating fluidized bed with draft tube enhances velocity of descending coal-coke particle at bed layer for the surface to middle depth (0.46H) in the velocity range of U = 0.088-0.147 $m{\cdot}s^{-1}$.

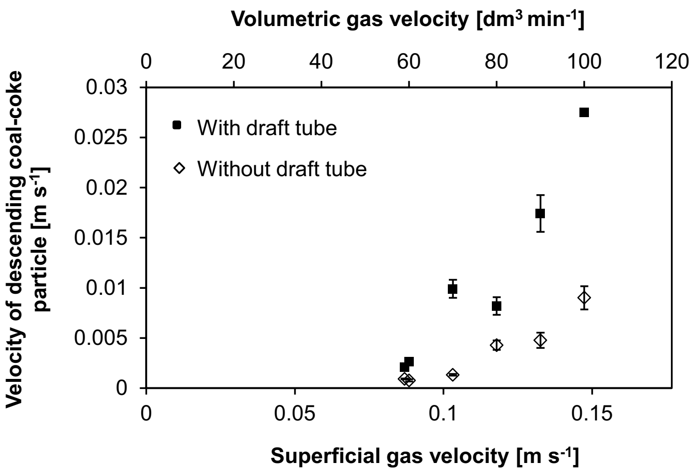

Figure 5 Relationship between descending coal-coke particle of fluidized bed and superficial gas velocity in the designed reactor model of fluidized bed reactor with/without draft tube. The descending particles were observed at a position of 55 mm below height from the bed surface.

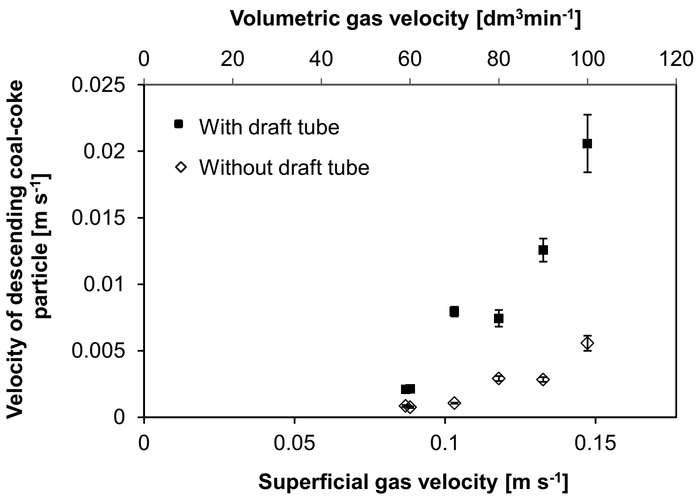

Figure 6 Relationship between descending coal-coke particle of fluidized bed and superficial gas velocity in the designed reactor model of fluidized bed reactor with/without draft tube. The descending particles were observed at a position of 65 mm below height from the bed surface.

Table 1 Moving distance of descending coal-coke particles in the fluidized bed reactor with/without draft tube on the sidewall of reactor.

Volumetric gas velocity [dm^3 min^{-1}]	Superficial gas velocity [m s^{-1}]	With draft tube			Without draft tube		
		Branch tube [dm^3 min^{-1}]		*Moving distance of descending particles [mm]	Branch tube [dm^3 min^{-1}]		*Moving distance of descending particles [mm]
		Volumetric gas velocity [dm^3 min^{-1}]	Superficial gas velocity [m s^{-1}]		Volumetric gas velocity [dm^3 min^{-1}]	Superficial gas velocity [m s^{-1}]	
59	0.087	2.9	0.0043	80(±4)	3.4	0.0050	70(±6)
60	0.088	2.2	0.0032	78(±5)	3.0	0.0044	72(±5)
70	0.10	2.5	0.0037	82(±3)	2.0	0.0029	75(±3)
80	0.12	1.9	0.0028	85(±3)	2.1	0.0031	78(±4)
90	0.13	1.6	0.0024	91(±4)	1.7	0.0025	80(±2)
100	0.15	1.6	0.0024	95(±5)	1.6	0.0024	88(±2)

* Moving distance : moving distance from fluidized surface to bottom

A moving depth of descending coal-coke particle on the sidewall of the reactor is observed in a range of U = 0.088-0.147 m·s^{-1}.The results are listed in Table 1. The moving depth of descending particle was measured from the surface of fluidized bed to the disappearance height (the particle is moving towards the center of fluidized bed) on the sidewall of reactor. The branch tube is used to feed coal-coke particle into the fluidized bed of quartz sand by gas passing, and the volumetric and superficial gas velocities for the branch tube are listed in Table 1. In the case of the fluidized bed with draft tube, coal-coke particle is moved down to 80 mm depth (0.57H) at U = 0.087 m·s^{-1}. The moving distance increases with increasing gas velocity. The muximum distance of 95 mm (0.68H) at U = 0.15 m·s^{-1} is almost corresponded to a lower surface of draft tube. The results indicate that draft tube has a functional role in conveying a descending particle at deeper layer along the sidewall of the reactor. On the other hand, in the case of the fluidized bed without draft tube, the moving distances are 70 mm (0.5H) and 88 mm (0.63H) at U = 0.087 and 0.15 m·s^{-1}, respectively. The moving distance increases with increasing with gas velocity, however, the moving distance in the fluidized bed with draft tube is superior to that without draft tube in a range of U = 0.087-0.15 m·s^{-1}. The results for the moving distance indicates that an internally-circulating fluidized bed with draft tube have a potential to move a fluidizing particle downward on sidewall of the reactor as well as upwards moving in the center region of the fluidized bed. Furthermore, as seen in Table 1, it is striking that the gas velocities passed through the branch tube are relatively lower for the internal-circulation with draft tube than the conventional fluidized bed without draft tube. The results for gas velocities in the branch tube means that coal-coke particles feeded through the branch tube can be easily to enter into an internally-circulating fluidized bed of quartz sand with draft tube in comparison to a fluidized bed without draft tube. One of the reasons will be due to high mobility (moving distance at deeper layer and moving velocity along the sidewall) of coal-coke particles in an internally-circulating fluidized bed with draft tube.

In the next step, based on the results in this study, a laboratory-scale prototype windowed fluidized-bed of quartz sand and coke particles feeded by screw-feeder will be fabricated and tested for coal-coke gasification under continuous supply of coal-coke conditions by concentrated Xe-beam or solar radiation.

4. Summary

A laboratory-scale prototype windowed fluidized-bed containing of quartz sand and coke particles was designed and, the reactor model of fluidized bed was made from a transparent acrylic resin to allow us to observe a fluidizing particle through the sidewall of the reactor body; a branching tube was equipped with the sidewall of the reactor to continuously supply coal-coke particles from a screw feeder. The fluidization performances of coal-cokes, the pressure loss between the inlet and outlet gases was examined, and descending coal-coke particles on the sidewall of the reactor was observed in the reactor model.

This result for decreasing pressure loss indicates that a draft tube have a potential to enhances a fluidization of mixture of coal-coke and quartz sand in a reactor. The effectiveness of draft tube appeared prominently in higher gas velocity than the U_{mf} value (U_{mf} = 0.071 m·s^{-1}). As seen in Figure 4-6, a difference of velocity of coal-coke particle between fluidized bed with and without draft tube remained at high gas velocity although the bed layer was deeper. The results for velocity of descending coal-coke particle means that an internally-circulating fluidized bed with draft tube enhances velocity of descending coal-coke particle at bed layer for the surface to middle depth (0.46H) in the velocity range of U = 0.088-0.147 m·s^{-1}. The results for the moving distance indicates that an internally-circulating fluidized bed with draft tube have a potential to move a fluidizing particle downward on sidewall of the reactor as well as upwards moving in the center region of the fluidized bed. Furthermore, as seen in Table 1, it is striking that the gas velocities passed through the branch tube are relatively lower for the internal-circulation with draft tube than the conventional fluidized bed without draft tube. The results for gas velocities in the branch tube means that coal-coke particles feeded through the branch tube can be easily to enter into an internally-circulating fluidized bed of quartz sand with draft tube in comparison to a fluidized bed without draft tube. If the behaviour of coal-coke particles is done at high-temperature, gasification performances of gasification rate will be expected under the continuous supply of coal-coke particles feeded through the branch tube.

5. References

1. D. W. Gregg, R. W. Taylor, J. H. Campbell, J. R. Taylor, A. Cotton, Solar Energy 25, 353–364 (1980).

2. R. Taylor, R. Berjoan, J. Coutures, Solar Energy 30 [6], 513–525 (1983).

3. A. Z'Graggen, P. Haueter, G. Maag, A. Vidal, M. Romero, A. Steinfeld, International Journal of Hydrogen Energy 32, 992−996 (2007).

4. A. Z'Graggen, P. Haueter, G. Maag, M. Romero, A. Steinfeld, International Journal of Hydrogen Energy 33, 679−684 (2008).

5. A. Z'Graggen, A. Steinfeld, International Journal of Hydrogen Energy 33, 5484–5492 (2008).

6. P. von Zedtwitz, A. Steinfeld, Industrial & Engineering Chemistry Research 44, 3852–3861 (2005).

7. T. Kodama, N. Gokon, S. Enomoto, S. Itoh, T. Hatamachi, ASME Journal of Solar Energy Engineering132[4], 041004-1-6 (2010).

8. N. Gokon, R. Ono, T. Hatamachi, L. Liuyun, H.-J. Kim, T. Kodama, International Journal of Hydrogen Energy 37[17], 12128-12137 (2012).

9. N. Gokon, T. Izawa, T. Abe, T. Kodama, International Journal of Hydrogen Energy 39, 11082-11093 (2014).

10. N. Gokon, T. Izawa, T. Kodama, Energy 79, 264-272 (2015).

11. N. Gokon, T. Tanabe, T. Shimizu, T. Kodama, Cold Test with a Benchtop Set-up for Fluidized Bed Reactor Using Quartz Sand to Simulate Gasification of Coal Cokes by Concentrated Solar Radiation, SolarPACES 2015, Cape Town, South Africa, 2015.