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THE GAS FLOW IN THE LOOP SEALS OF A DUAL CIRCULATING FLUIDIZED BED: Splitting of the fluidizing agent and gas leakage through the loop seals

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ABSTRACT

A cold flow model of a 120kW CLC reactor system is used to investigate the splitting of the fluidizing gas of the loop seals and to measure the leakage through the loop seals from the air reactor to the fuel reactor. The cold flow model is fluidized with nitrogen, air is used as tracer gas. The pressure difference between the reactors is varied during the experiment. The splitting of the fluidizing agent shows a dependency on the solids circulation rate. A gas leakage is only observed at low solids circulation rates and high pressure differences.

INTRODUCTION

The dual circulating fluidized bed system (DCFB)

The DCFB system as described by Pröll et al (1) is used as chemical looping combustion (CLC) reactor. It has a high potential for inherent CO_2 separation. CLC is a fuel conversion technology where oxygen is selectively transported from the so called air reactor (AR) to the so called fuel reactor (FR) by means of circulating solids. It is possible to produce almost pure CO_2, which is easily accessible for CCS. Any nitrogen leakage from the air reactor to the fuel reactor has a negative effect on the carbon capture efficiency and should be kept as low as possible.

Loop seals

The loop seals are critical components in the DCFB but also in a common circulating fluidized bed (CFB). As mentioned by Basu and Butler (2) the loop seal is not yet fully understood. Kumar Chandel and Alappat (3) report on the effect of different circulation rates on gas bypassing in a loop seal like device in a recirculating fluidized bed. Basu and Butler (2) further describe the influence of the loop seal design on the functionality of the loop seal and identify it as a critical part in a CFB. They also mention, that the circulation rate influences the splitting of gas steams in the loop seal and describe the mixing of the gas in the downcomer with the fluidizing agent in the loop seal. They mention that with increasing solids flux in the downcomer the amount of gas mixed into the loop seal increases. This rises the gas leaking through the loop seal.

EXPERIMENTAL

Experimental Set-up

The cold flow model used in this work has been designed and built for the fluid dynamic analysis of a 120 kW chemical looping pilot plant for gaseous fuels as described in the work of Pröll et al (4). The model is a 3:1 scale of the hot unit. The dimensions are based on data of the pilot plant and meet the scaling criteria of Glicksman et al (5).

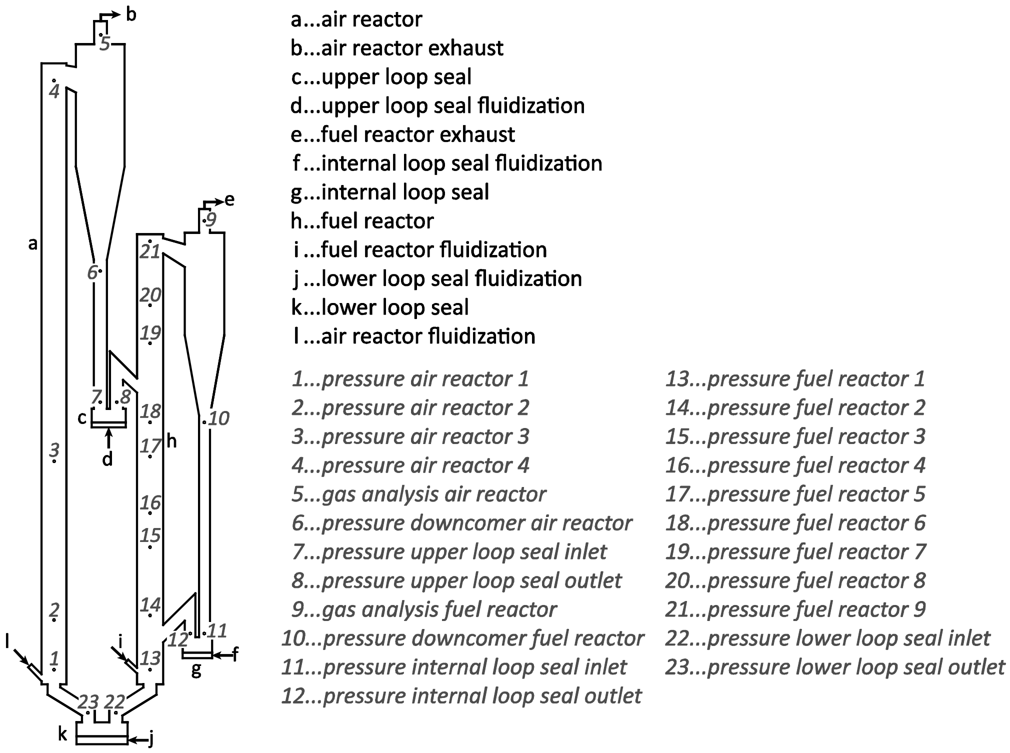

Figure 1: Scheme of the cold flow model with main parts (a-l) and all measuring points (1-23)

The configuration of the cold flow model is shown in Figure 1. Also all the pressure measuring points are indicated. Positions 5 and 9 in Figure 1 show the points where the oxygen is measured. Detailed description of the cold flow model can be found in Pröll et al (4). The fluid dynamic parameters of the hot unit and the cold flow model are listed in Table 1. The materials and fluidization conditions are selected to best fulfill the fluid dynamic similarity. Nitrogen is the main fluidizing medium for all operating points. Compressed air is the tracer gas used for the investigations as described below. Either the upper loop seal or the lower loop seal (positions f and d in Figure 1) is fluidized with air to measure the splitting of the loop seal fluidization. During the leakage measurement the air reactor is fluidized with air and all the other system is fluidized with nitrogen. All flows are adjusted with valves and measured with rotameters. Bed material is a bronze powder. The particle properties are listed in Table 1.

Table 1: Fluid dynamic parameters of the cold flow model (H...hot unit, C...cold flow model

Parameter	Unit	AR_H	FR_H	AR_C	FR_C
η_G	Pa·s	$4.70\cdot10^{-05}$	$4.10\cdot10^{-05}$	$1.81\cdot10^{-05}$	$1.81\cdot10^{-05}$
ρ_G	$kg\cdot m^{-3}$	0.316	0.288	1.20	1.20
U	$m\cdot s^{-1}$	7.32	2.08	4.25	1.21
ρ_P	$kg\cdot m^{-3}$	3200	3200	8730	8730
d_P	µm	161	161	68	68
Ψ	-	0.99	0.99	1	1
D	mm	150	159	50	54

Particles that are not separated in the cyclones leave them with the gas stream. Downstream filters are installed in both gas ducts to separate these fines without mixing the gas streams. Pressure is recorded as shown in Figure 1.

Experimental Procedure

In the first test runs the splitting of the fluidization of the loop seals is determined. This effect is represented by the splitting factor S_{uLS} for the upper loop seal and S_{lLS} for the lower loop seal. A splitting factor of one means: all of the gas fed into the loop seal fluidization leaves on the air reactor side. In case of the determination of the splitting of the lower loop seal fluidization both reactors and the loops seals except the lower loop seal are fluidized with nitrogen. The lower loop seal is fluidized with air. The oxygen in the air is used as tracer to determine the split of the loop seal fluidization. The oxygen concentration is measured in the fuel reactor outlet and in the air reactor outlet (positions b and e in Figure 1), using a Rosemount NGA2000 (0 - 5 vol% O_2). To investigate the dependency of the pressure difference between the reactors ($\Delta P_{AR/FR}$) valves are installed after the cyclone separators to adjust the pressure difference. In this study the behavior under 5 different $\Delta P_{AR/FR}$ values is investigated. The air reactor fluidization is increased stepwise from 10 Nm^3/h to 30 Nm^3/h. The other parameters, fluidization of the loop seals and the fuel reactor, are kept constant. All operating parameters are shown in Table 2.

To measure the splitting of the upper loop seal fluidization the same procedure as before is used. All loop seals are fluidized with nitrogen except the upper loop seal which is fluidized with air. The same pressure differences between the reactors are set and the air reactor fluidization is varied in the same way as shown in Table 2.

The gas leakage is measured by fluidizing the air reactor with air and the rest of the system with nitrogen. The oxygen is measured in the fuel reactor. The variation of parameters is the same as for the measurement of the splitting of the loop seal fluidizations.

Table 2: Operating parameters

Parameter	Unit					
$\Delta P_{AR/FR}$	mbar	5	12	21	30	33
$\dot{V}_{AR}$	$Nm^3 \cdot h^{-1}$	10	15	20	30	
$\dot{V}_{FR}$	$Nm^3 \cdot h^{-1}$	7				
$\dot{V}_{uLS}$	$Nm^3 \cdot h^{-1}$	1				
$\dot{V}_{lLS}$	$Nm^3 \cdot h^{-1}$	1				
$\dot{V}_{iLS}$	$Nm^3 \cdot h^{-1}$	1				

To determine the splitting of the loop seal fluidization and the leakage a model is established to describe each measurement condition. For each setup the oxygen concentration in both the air reactor and the fuel reactor is calculated. The equations used, reflect the oxygen balance of each reactor under the different measurement conditions (splitting of the upper loop seal, the lower loop seal and the leakage). The parameters for the splitting of the loop seal fluidization and the leakage are calculated by means of least squares method. The model equations are shown below.

Measurement of the upper loop seal split:

$$\frac{\dot{V}_{uLS} \cdot (1 - S_{uLS}) \cdot \chi_{O_2,air}}{\dot{V}_{FR} + \dot{V}_{uLS} \cdot (1 - S_{uLS}) + \dot{V}_{lLS} \cdot (1 - S_{lLS}) + \dot{V}_{leak} + \dot{V}_{iLS}} = \chi_{O_2,FR} \quad \text{Eq. 1}$$

$$\frac{\dot{V}_{uLS} \cdot S_{uLS} \cdot \chi_{O_2,air}}{\dot{V}_{AR} + \dot{V}_{uLS} \cdot S_{uLS} + \dot{V}_{lLS} \cdot S_{lLS} - \dot{V}_{leak}} = \chi_{O_2,AR} \quad \text{Eq. 2}$$

Measurement of the lower loop seal split:

$$\frac{\dot{V}_{lLS} \cdot (1 - S_{lLS}) \cdot \chi_{O_2,air}}{\dot{V}_{FR} + \dot{V}_{uLS} \cdot (1 - S_{uLS}) + \dot{V}_{lLS} \cdot (1 - S_{lLS}) + \dot{V}_{leak} + \dot{V}_{iLS}} = \chi_{O_2,FR} \quad \text{Eq. 3}$$

$$\frac{\dot{V}_{lLS} \cdot S_{lLS} \cdot \chi_{O_2,air}}{\dot{V}_{AR} + \dot{V}_{uLS} \cdot S_{uLS} + \dot{V}_{lLS} \cdot S_{lLS} - \dot{V}_{leak}} = \chi_{O_2,AR} \quad \text{Eq. 4}$$

Measurement of the leakage:

$$\frac{\dot{V}_{AR} \cdot \chi_{O_2,air}}{\dot{V}_{AR} + \dot{V}_{uLS} \cdot S_{uLS} + \dot{V}_{lLS} \cdot S_{lLS} - \dot{V}_{leak}} = \chi_{O_2,AR} \quad \text{Eq. 5}$$

$$\frac{\dot{V}_{leak} \cdot \chi_{O_2,AR}}{\dot{V}_{FR} + \dot{V}_{uLS} \cdot (1 - S_{uLS}) + \dot{V}_{lLS} \cdot (1 - S_{lLS}) + \dot{V}_{leak} + \dot{V}_{iLS}} = \chi_{O_2,FR} \quad \text{Eq. 6}$$

RESULTS AND DISCUSSION

Figure 2 depicts the different pressure profiles of the operating points investigated during the whole campaign. To keep the complexity of the diagrams low, only the fuel reactor profile of the $\Delta P_{AR/FR}$ = 5 mbar case is shown, since the fuel reactor conditions have not been varied during the experiment. The air reactor profiles and the upper loop seal profiles are shown for each pressure difference.

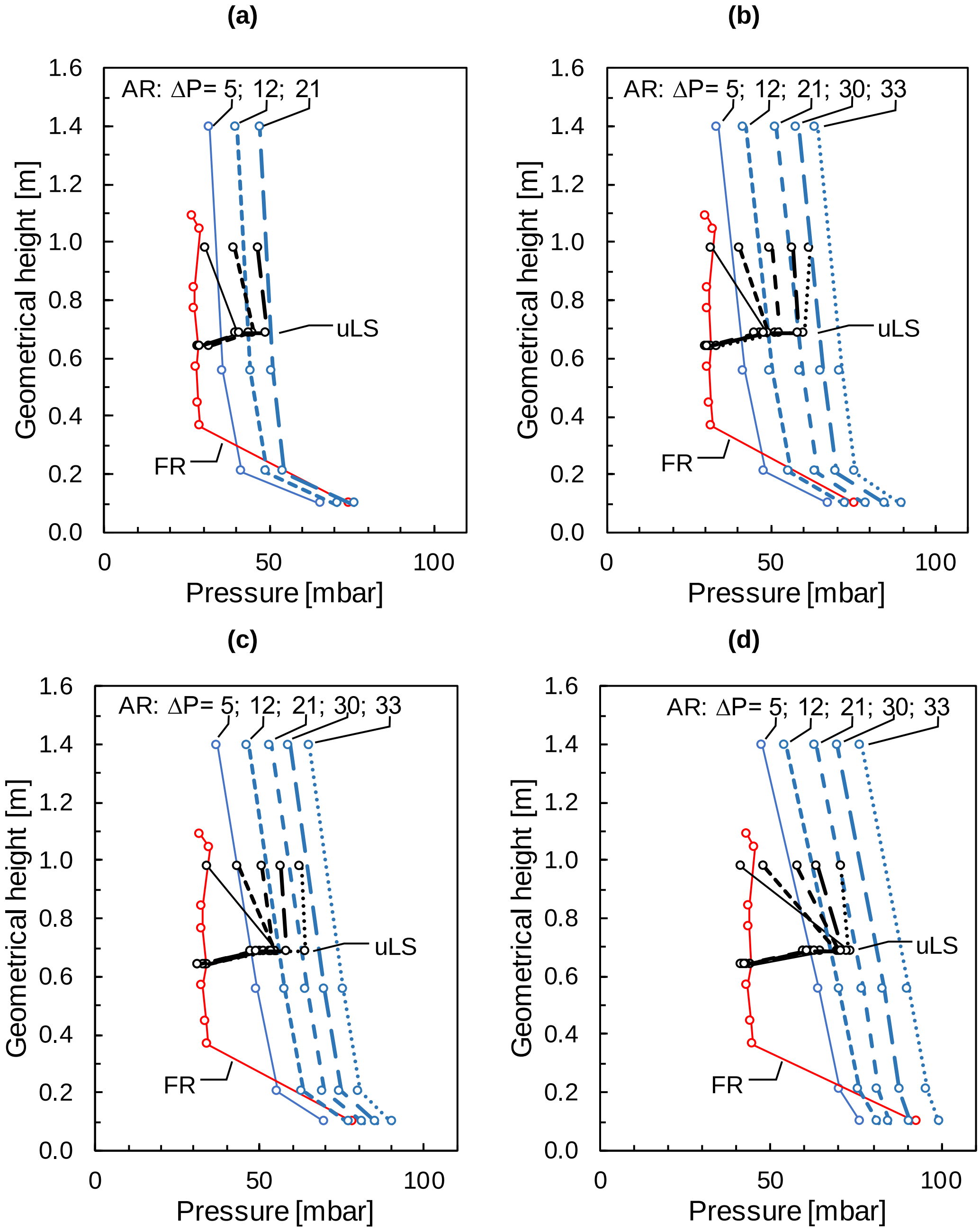

Figure 2: Pressure profiles for different air reactor fluidizations: 10 Nm³/h in (a), 15 Nm³/h in (b), 20 Nm³/h in (c) and 30 Nm³/h in (d). Parameter in diagrams: Pressure difference.

Split of loop seal fluidization

The split of the loop seal fluidization is shown in Figure 3 for the upper and the lower loop seal, represented by the corresponding splitting factors S_{lLS} for the lower loop seal and S_{uLS} for the upper loop seal. In a wide range of pressure differences between the two reactors the split of both, the upper and the lower loop seal, is only dependent on the fluidization of the air reactor. As described by Pröll et al (4) the global solids circulation is mainly corresponding on the air reactor fluidization, so the split is also a function of the global solids circulation rate. Only under conditions of high pressure difference and low solids circulation the split of the fluidizing gas changes.

In the case of the lower loop seal the gas split changes significantly for a pressure difference of 33 mbar and a fluidization of the air reactor of 15 Nm^3/h. For all other operating points more than half of the gas is directed to the air reactor but in this case almost 60 percent of the gas leaving the loop seal on the fuel reactor side. The upper loop seal seems to be more sensitive on the pressure drop than the lower loop seal since the change in the gas splitting behavior starts at a lower pressure difference of 30 mbar.

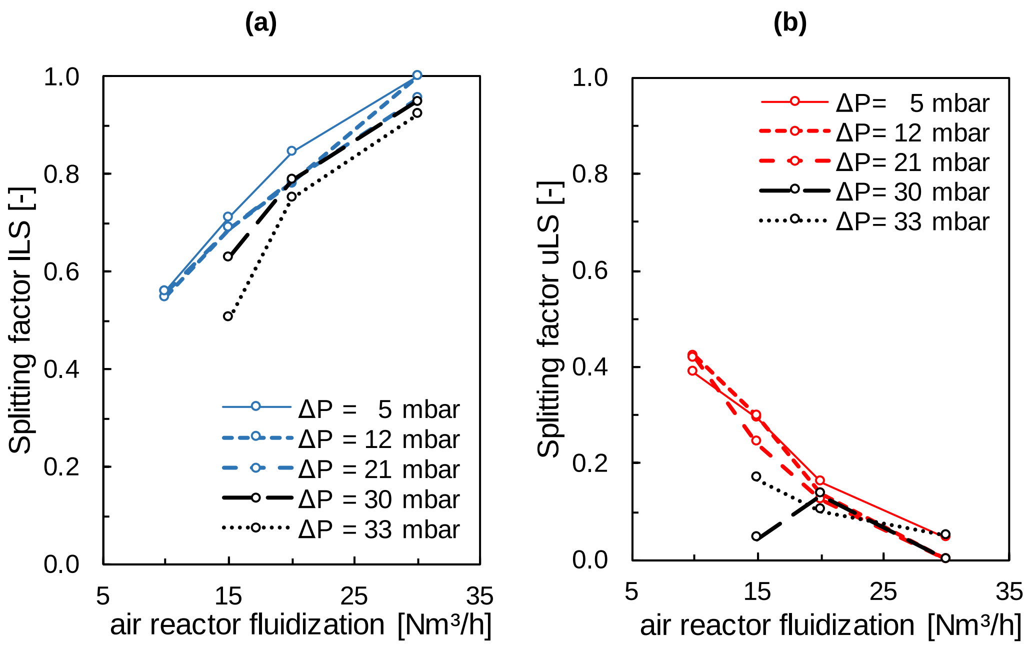

Figure 3: Splitting factors of the loop seal fluidization for the lower loop seal (a) and the upper loop seal (b)

Leakage from the air reactor to the fuel reactor

In Figure 4 the leakage is illustrated as a function of the air reactor fluidization and for different pressure differences between the reactors. For conditions of low solids circulation and high pressure difference between the reactors a significant amount of the air reactor atmosphere leaks to the fuel reactor. With increasing solids circulation the gas leakage vanishes also under these conditions. To identify the location of the leakage, either the upper loop seal or the lower loop seal, a purge gas stream is injected in the air reactor downcomer (position 7 in Figure 1). The leakage decreases with increasing purge gas flow. This indicates that the leakage is located in the upper loop seal. But the method of purging is not an ideal workaround to avoid the leakage, since the cyclone separation efficiency decreases dramatically.

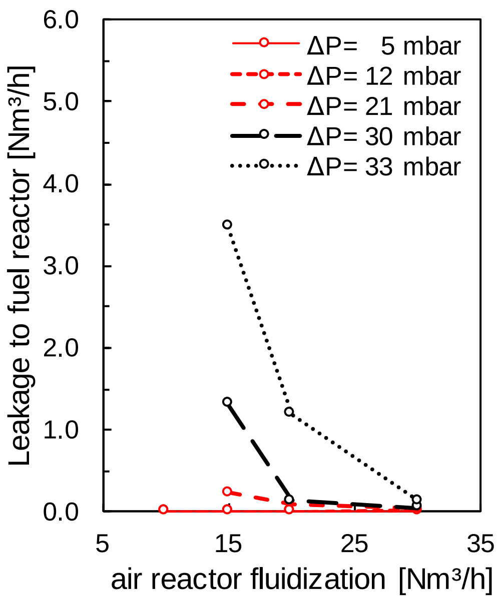

Figure 4: Leakage from the air reactor to the fuel reactor

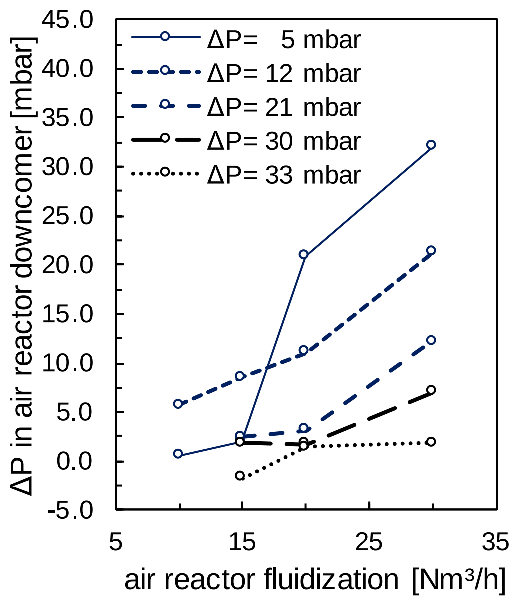

Figure 5: Pressure drop in the air reactor downcomer

To understand the behavior of the upper loop seal in the cold flow model, Figure **5** depicts the pressure drop over the air reactor downcomer, which is a measure for the bed height in the downcomer. For operating conditions with a significant gas leakage to the fuel reactor almost no bed material is in the downcomer to allow proper operation of the loop seal. This behavior does not reflect the observations in the 120kW unit where the gas leakage increases with solids circulation and the downcomer is always filled with material. In the cold flow model the leakage is a product of poor filling of the loop seal with particles, maybe caused by a too shallow loop seal.

CONCLUSION

The splitting of the loop seals is described for a defined operating area. The change of the gas paths in the loop seals follows the change of solids circulation and is also a function of the pressure difference between the reactors. With increasing solids circulation the major part of the gas from the lower loop seal flows to the air reactor and almost all of the gas in the upper loop seal leaves in fuel reactor direction. The leakage behaves different than in the hot pilot plant, but it is also a problem of the upper loop seal. In the cold flow model gas leakage is only a problem under following conditions: low solids circulation rates and high pressure ddifference between the reactors. In the hot pilot plant the leakage increases with solids circulation, which goes along with the findings of Li et al (6). Purging in the air reactor downcomer reduces the leakage but influences negatively the air reactor cyclone. To show that this is a real workaround to reduce the leakage further investigations will be necessary.

NOTATION

η_G Gas dynamic viscosity... [Pa·s]
ρ_P Particle density............. [kg/m^3]
ρ_G Gas density.................... [kg/m^3]
$\chi_{O_2,air}$ Oxygen concentration in the air......................... [vol%]
$\chi_{O_2,FR}$ Oxygen concentration in the fuel reactor.......... [vol%]
$\chi_{O_2,AR}$ Oxygen concentration in the air reactor............ [vol%]
Ψ Particle sphericity...........[-]
D Inner reactor diameter... [mm]
d_P Mean particle diameter.. [µm]
$\Delta P_{AR/FR}$ Pressure difference between air reactor and fuel reactor.................... [mbar]
S_{uLS} Splitting factor upper loop seal........................ [-]
S_{lLS} Splitting factor lower loop seal........................ [-]
U Superficial gas velocity.. [m/s]
$\dot{V}_{uLS}$ Volume flow to the upper loop seal..................... [Nm^3/h]
$\dot{V}_{leak}$ Volume flow of the gas leakage from air reactor to fuel reactor................ [Nm^3/h]
$\dot{V}_{lLS}$ Volume flow to the lower loop seal........................ [Nm^3/h]
$\dot{V}_{iLS}$ Volume flow to the internal loop seal........................ [Nm^3/h]
$\dot{V}_{FR}$ Volume flow to the fuel reactor.................... [Nm^3/h]
$\dot{V}_{AR}$ Volume flow to the air reactor...................... [Nm^3/h]

REFERENCES

(1) T. Pröll, P. Kolbitsch, J. Bolhàr-Nordenkampf, H. Hofbauer, A novel dual circulating fluidized bed system for chemical looping processes, AIChE J. 55 (2009) 3255–3266.

(2) P. Basu, J. Butler, Studies on the operation of loop-seal in circulating fluidized bed boilers, Applied Energy 86 (2009) 1723–1731.

(3) M. Kumar Chandel, B.J. Alappat, Pressure drop and gas bypassing in recirculating fluidized beds, Chemical Engineering Science 61 (2006) 1489–1499.

(4) T. Pröll, K. Rupanovits, P. Kolbitsch, J. Bolhàr-Nordenkampf, H. Hofbauer, Cold Flow Model Study on a Dual Circulating Fluidized Bed (DCFB) System for Chemical Looping Processes, Chemical Engineering & Technology 32 (2009) 418-424.

(5) L.R. Glicksman, M. Hyre, K. Woloshun, Simplified scaling relationships for fluidized beds, Powder Technology 77 (1993) 177–199.

(6) Y. Li, Y. Lu, F. Wang, K. Han, W. Mi, X. Chen, P. Wang, Behavior of gas-solid flow in the downcomer of a circulating fluidized bed reactor with a V-valve, Powder Technology 91 (1997) 11–16.