CHEMICAL ENGINEERING TRANSACTIONS

VOL. 45, 2015

A publication of
AIDIC
The Italian Association
of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216 DOI: 10.3303/CET1545149

Modelling of Flow Behaviour at Downer and Riser in Triple Bed Circulating Fluidized Bed Using Equivalent Circuit

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To obtain high power generation efficiency, an advanced integrated coal gasification combined cycle (A-IGCC) based on exergy recuperation concept that recycles waste heat from gas turbine to steam gasification of coal is being developed in our laboratory. This system uses a triple bed circulating fluidized bed for coal gasification. The proposed triple bed circulating fluidized bed is a very complex system. For stable operation and to gain control over the system, a model of the flow behaviour in the circulating fluidized bed is necessary. A novel method for analyzing the systems using a simple model of the flow behaviour inside of circulating fluidized bed is proposed in this research. We found the analogy between flow behaviour of fluidized bed and equivalent circuit with correlations of pressure to voltage, solid mass flux to electric current and hydraulic resistance to electric resistance. Based on these analogies, flow behaviour in the fluidized bed can be modelled simply. By using this model, the dynamic characteristics of the pressure response at downer and riser when the sold mass flux has been changed were examined. According to these investigations, this proposed method proved to be a promising method for analyzing the systems when designing a circulating fluidized bed.

1. Introduction

Integrated Gasification Combined Cycle plants (IGCC) are efficient power generation systems of low pollutants emissions compared to other thermal coal technologies. IGCC plants are not yet a commercial technology widely used all around the world due to their high investment cost and the need to decrease the greenhouse gas emissions (Sofia et al., 2013). To obtain high power generation efficiency, an advanced integrated coal gasification combined cycle (A-IGCC) system based on exergy recuperation concept that recycles waste heat from gas turbine to steam gasification of coal is developing in our laboratory. This system consists of a triple bed circulating fluidized bed for coal gasification. The proposed triple bed circulating fluidized bed is a very complex system. For stable operation and controlling of the system, a model of the flow behaviour in the circulating fluidized bed is necessary.

Equivalent circuit approach has been widely used in electric fields. Equivalent circuit is a concise expression for the system characteristics. This is a useful method to analyze complex systems composed of several subsystems or parts, such like an integrated circuit. It is possible to analyze the system by combination of each subsystem equivalent circuits. Equivalent circuits have also been applied for analyzing fluidic devices (Turowski et al., 2011). This approach is to translate fluidic device behavior into a collection of elemental electric devices such as resistors, capacitors, and inductors (Lam et al., 2006). It is possible for engineers who design these fluidic devices to use a generic circuit simulator such as ‘SPICE’ (Chatterjee et al., 2005). Integrated fluidic devices which looks like IC (Oh et al., 2012) and LSI (Thorsen et al., 2002) are able to simulate. Moreover, it enables one to simulate circuits including the sensing and driving units (Takao et al., 2011).

A novel method for using a simple model for analyzing the flow behaviour inside a circulating fluidized bed is proposed in this research. This paper describes an equivalent circuit for circulating fluidized bed (CFB) based on a type of behaviour model for expressing electric element within circuit simulation, so as to

Please cite this article as: Ishizuka M., Mizuno H., Kotani Y., Kansha Y., Tsutsumi A., 2015, Modeling of flow behavior at downer and riser in triple bed circulating fluidized bed using equivalent circuit, Chemical Engineering Transactions, 45, 889-894 DOI:10.3303/CET1545149

simulate their flow behaviour easily. For controlling the fluidized bed flow, an equivalent circuit expression of the flow behaviour in a fluidized bed will be effective. In this work, a new approach has been proposed for converting the circulating fluidized bed system composed of downer and riser to equivalent circuit expression. This approach consists of substitution of unit equivalent elements for fluidized bed. We applied RLC circuit as equivalent circuit of downer and riser. With this approach, in order to estimate the circuit element property, the flow property of downer and riser in triple bed circulating fluidized bed were measured experimentally.

2. Similarity between an electrical circuit and the flow characteristics fluidized bed

2.1 Equivalent circuit modelling

The modelling was carried out assuming the similarity between an electric circuit based and a microfluidic circuit. The electrical circuit and the electrical characteristics are analogous to the flow properties of the fluidized bed. We assumed pressure difference and the potential difference as the driving force, electrons and particles as a carrier and solid mass flux as current. Based on these assumptions, we get the following relation with the flow characteristics due to the similarity of the electrical circuit. A flow resistance is defined as (2) based on the analogy with Ohm's law (1). Definition of the inertance of the fluidized bed (4) is defined from analogy of the inductance definition of the electrical circuit (3). Definition of compliance (6) is obtained from the definition of capacitance (5).

$$V(t) = 40e^{-x}(1+x) \tag{1}$$

$$P = FsRa \tag{2}$$

$$V = L\frac{dI}{dt} \tag{3}$$

$$P = Ma\frac{dFs}{dt} \tag{4}$$

$$I = C\frac{dV}{dt} \tag{5}$$

$$Fs = Ca\frac{dP}{dt} \tag{6}$$

Through these relations, similarity between the electrical characteristics of the electrical circuit and the flow characteristics of fluidized bed can be obtained and are shown in Table 1. In the case of forming an electrical circuit, it is necessary to satisfy the law of Kirchhoff's current law and voltage law. This is to balance the material and energy in the circuit exactly. Storing kinetic energy of the particles in a fluidized bed is assumed as energy storage of coil in the electrical circuit. The accumulation of energy due to changes in particle concentration in a fluidized bed is assumed as energy storage of capacitor in the electrical circuit. It should be noted that in this study it is assumed that the volume of the fluidized bed will not be changed.

Table 1: Analogy between flow behaviour of fluidized bed and electric circuit

Fluidizations			Electronics		
Particles			Electrons		
Solid mass flux	Fs	($kg \cdot s^{-1}$)	Current	I	(A)
Pressure drop	P	(Pa)	Voltage drop	V	(V)
Resistance	Ra	($Pa \cdot s \cdot kg^{-1}$)	Resistance	R	($\Omega = V \cdot A^{-1}$)
Capacitance	Ca	($kg \cdot Pa^{-1}$)	Capacitance	C	($F = A \cdot s \cdot V^{-1}$)
Inertia	Ma	($Pa \cdot s^2 \cdot kg^{-1}$)	Inductance	L	($H = V \cdot s \cdot A^{-1}$)

Assuming that a downer/riser is like a fluid consisting of particle, it can be modelled as an equivalent circuit by connections of resistance R, reactance L, capacitance C, as shown in Figure 2. In this circuit, each element of R, L, C describes the parameter of the system. This equivalent circuit is the same as electro wiring equivalent circuit. It satisfies the Kirchhoff's voltage law and also satisfies the Kirchhoff's current law.

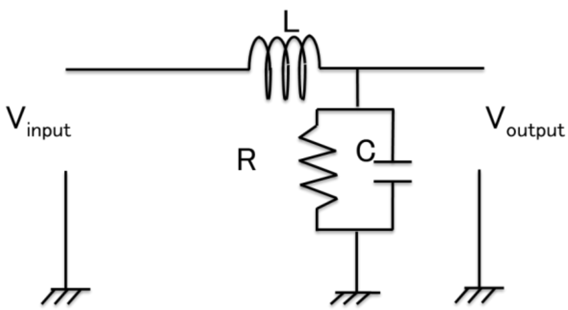

Figure 2: Equivalent circuit model of the downer/riser flow

2.2 Step response of the equivalent circuit

To determine the parameters of the resistor, the capacitor and the inductor on the equivalent circuit, we evaluated the output voltage when the input voltage is changed in step. We calculated the output voltage change using the “SPICE” program. We gave a constant voltage E to the equivalent circuit as input voltage so that the circuit reaches a steady state with constant current flow I. There is no voltage change in inductance due to the constant current. According to the Ohm’s law (1), voltage drop is proportional to the current generated in the resistor R. When the input voltage changes as a function of time, the current flow in the circuit also varies as a function of time. Changes in voltage at the capacitance are also function of time. When the input voltage changes, voltage drop is proportional to the current that is generated in the resistor R. The inductance tries to prevent the current change and delays the change in current functions. In addition, the capacitance prevents the voltage changes. It is possible to determine the resister property of equivalent circuit by experimental results of a constant circulating condition results in a circulating fluidized bed. However, a step or pulse response experimental results are required to determine the parameters of the capacitor and the inductor of the equivalent circuit. In this study, the step response experiment was introduced to our triple bed circulating fluidized bed. This experiment results allows us to obtain an equivalent result that gives a step change in particle concentration at the entrance of the downer, and the variation as the results for the pressure difference in the downer.

3. Experiment

3.1 Circulating fluidized bed

Step response experiment of downer and riser were carried out using a circulating fluidized bed cold model (Guan et al., 2010). Figure 3 is a schematic diagram of the TBCFB (Triple Bed Circulating Fluidized Bed) cold model. The model comprises a riser (0.05 m I.D. × 6.0 m height), a downer (0.05 m I.D. × 1.3 m height), a gas–solid separator, and a bubbling fluidized bed (BFB, 0.37 m × 0.08 m ×1.06 m). Pressure measurement taps were placed in the inlet and outlet part of downer/riser. The distance between the two taps in downer is 1.2 m and in riser is 6.0 m. A distributor to the top of the downer inlet is installed to pass the air from the air supply port of a distributor to downer as downward flow. Supply control to downer particles was performed by a butterfly valve at the top of the distributor. Gas-solid separator was installed for the purpose of separation of gas and particles at downer exit. The density and average particle size of the sand particles used in the cold model were 2,600 kgm^{-3} and 83 micrometres (minimum fluidization velocity (Umf) = 0.0058 ms^{-1}).

3.2 Experimental Procedure

The operation condition of riser gas superficial velocity (Ugr) was 6 ms^{-1} and downer gas superficial velocity (Ugd) was varied from 0 to 3 ms^{-1}. Initially, we formed a stable particle circulating. As a step input, we have to stop the supply of particles to close the butterfly valve for downer experiment, stopping the gas supply to the BFB for riser experiment. The pressure fluctuation in the downer was measured when the valve is closed at $t_d = 0$, and in the riser when the gas was cut off at $t_r = 0$. The pressure measurement was recorded to PC at a sampling rate of 50 Hz using a data logger (CONTEC, AIO-163202FX-USB), controller (Keyence, AP-V41A) and pressure sensor (Keyence, VP-48).

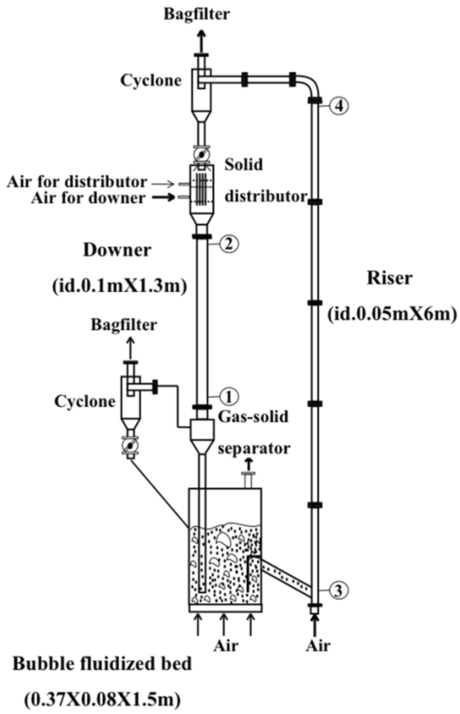

Figure 3: Experimental setup of step response

4. Results and Discussion

4.1 Step response of downer and riser

Figure 4 shows the results of the measured pressure difference when particle circulation was observed by changing Ugd from 0 to 3 ms^{-1}. The particle feed to downer was stopped when t = 0 s. There was a dead time after outage. Subsequently, the downer pressure reduced gradually. Assuming spherical particles and free-fall in downer, the terminal velocity is estimated from bulk density 2,600 kgm^{-3} and particle size 80 micrometers. The average time of the particles pass through the distance between the pressure taps in downer was 2.4 s. This result was reasonable, considering that the pressure difference variation is obtained by the particles in the downer and the distributor. In this experiment, delay of response to the step input was provided by the retention of the particles in the distributor and downer. Because the solid mass flux of this circulating fluidized system depends on the Ugr velocity, the solid mass flux in this experimental condition was constant. Pressure difference during steady state operation in different Ugd was due to the difference of the particle hold-up in the downer. Increasing the Ugd reduced the particle holdup in the downer, hence the pressure difference had decreased when Ugd was increasing. Pressure difference decreases with increasing Ugd.

A step response of the riser experiment was performed on condition of Ugr = 6 ms^{-1} and Ugd = 2 ms^{-1} (Figure 5). The BFB fluidized gas supply was stopped when t = 0 s. A short dead time was observed, and then the riser pressure difference was reduced. The timespan pressure variation could be observed in riser was longer than that in downer. This difference in timespan was cause by back mixing of particle in riser and downer. Mixing is often done in riser, but less in our triple bed circulating fluidized bed system downer.

4.2 Step response of the equivalent circuit

We performed step response of the downer equivalent circuit model expressed in a RLC circuit by SPICE processing system. The results calculated by the SPICE processing system is depict on Figure 6. The dotted lines are the results obtained from the model and the lighter lines are experimental values for reference. Step response of differential pressure fluctuations and transient characteristics calculated from the equivalent circuit model of downer shows a similar trend to Figure 4. Hence, it can be seen that the equivalent circuit model is able to express the response characteristics of the pressure step response of downer.

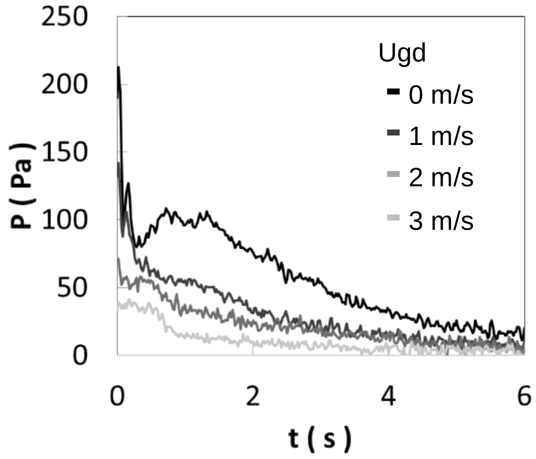

Figure 4: Representative result of pressure profile in downer Ugr = 6 m/s, Ugd - 0 m/s , -1 m/s, -2 m/s, -3 m/s

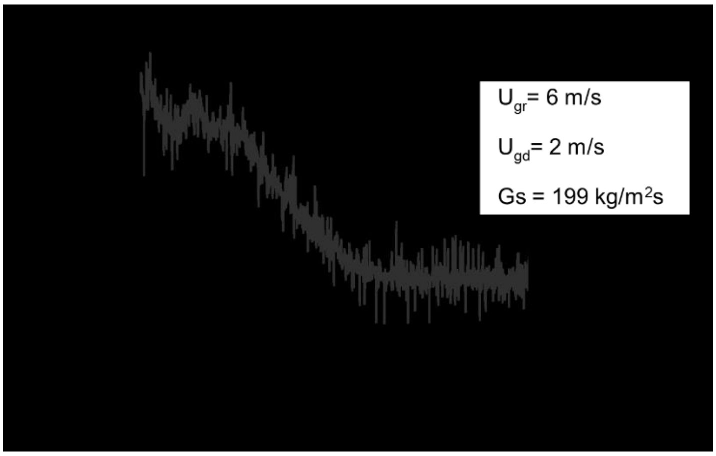

Figure 5: Representative result of pressure profile in riser Ugr = 6 m/s, Ugd = 2m/s

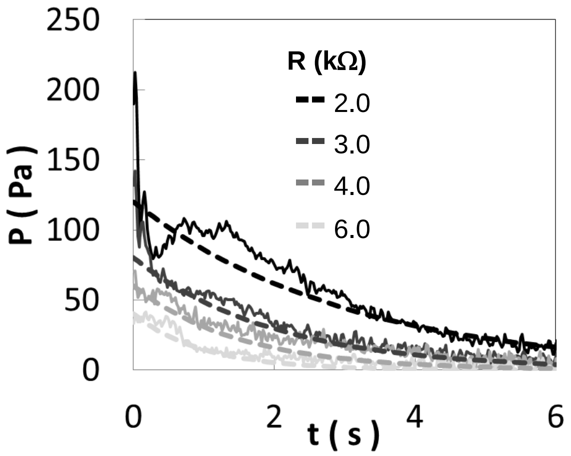

Figure 6: Representative result of step response calculated by SPICE C = 0.5 mF, L = 1.0 mH, - R = 2.0 kΩ, -3.0 kΩ, -4.0 kΩ, - 6.0 kΩ

5. Conclusions

We proposed to make a model of the flow behaviour in a fluidized bed by an equivalent circuit model consisting of an electrical circuit based on the similarity between electronics and fluidics. It was seen that the flow behaviour of the fluidized bed has some analogies with electric circuits such as pressure to voltage, solid mass flux to electric current. By assuming voltage and pressure, solid mass flux and current are equal, we have modelled the flow properties of the downer by equivalent circuit in the lumped parameter system include capacitor, resistor and coil. To estimate the element properties of an equivalent circuit model, a step response experiment of downer and riser was performed using triple bed circulating fluidized bed.

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