Spouting Enhancement by Addition of Small Quantities of Liquid to Large-Particle Gas-Spouted Beds

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1. Introduction

In fluidized beds we have previously reported(1) that there are circumstances where fluidizing particles by a gas can be promoted by adding small quantities of liquid (typically 10 vol% of total bed volume), contrary to most conventional gas-solid fluidized beds where addition of liquid causes immobilization. The liquid-assisted system provides superior heat and mass transfer compared to conventional fluidized beds, and therefore the some industrial application may be possible. We have identified the mechanism of fluidization enhancement(1) and have shown the heat transfer characteristics(2). In the present work we also investigate the whether there are circumstances where liquid addition can also assist gas-spouted beds.

Several previous groups have studied the properties of three-phase (gas-liquid-solid) spouted beds(e.g. 3,4). There has been some work(5,6,7) which suggests the possibility of spouting enhancement by liquid addition. In particular, Patel et al.(5) indicated that the minimum spouting velocity decreases with addition of liquid. They commented briefly on this finding, but their discussion focused on bed stability, and there was no more direct discussion of spouting enhancement by addition of liquids.

This paper focuses on spouting enhancement by addition of liquid. First we present observations of what happens when liquid is added to a gas-spouted bed and compare them with previous observations regarding liquid-assisted fluidized beds. While overall enhancement occurs in both cases, the distribution of the added liquid over the cross-section of the bed is quite different in the two cases. In spouted beds, the liquid gathers only in a restricted region around the gas spout, contrary to fluidized beds, where it is spread over the entire cross-section. Thus, the mechanism of enhancement of bed mobilization is different in the two cases. The mode of enhancement is therefore considered in relation to the hydrodynamics in the bed, pressure profiles and the nature of the spout-annulus interface.

2. Experimental Equipment and Methods

The experimental set-up is shown in Fig 1. The spouting column was a transparent acrylic half cylinder of inside diameter 180 mm and 1000 mm height. The orifice (a half-cylinder hole) used to introduce spouting air was 30 mm in diameter. The bed materials were uniform polystyrene particles (6 ± 0.1 mm spheres and 3.2 mm cylinders (mean size: ϕ3.2 x 3.2 mm, ρ_s =1010 kg/m^3) and spherical glass beads (mean dia. 2.1 mm, ρ_s =2450 kg/m^3). The added liquid was tap water.

Experiments were carried out for L_o (static bed height) / D (bed diameter) = 1.5. Each experiment started after addition of a small quantity of water to a gas-spouted bed. The water content, α, is defined as :

$$\alpha = V_{wtr} / V_{B.blk} \quad \text{..............} \quad (1)$$

where V_{wtr} = added volume of water, $V_{B.blk}$ = dry bed bulk volume.

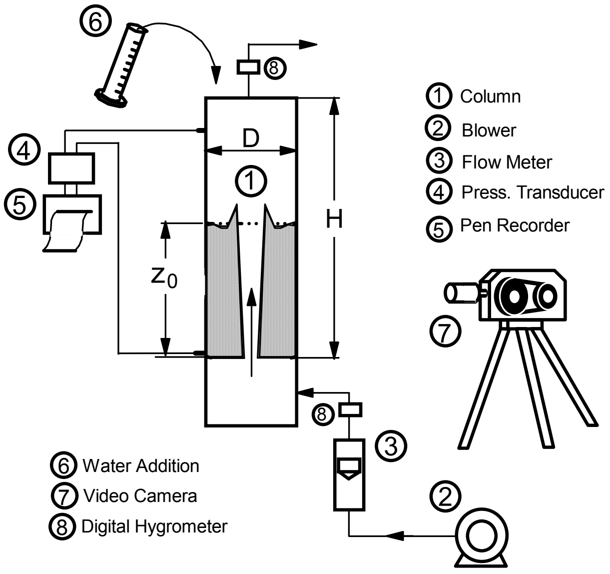
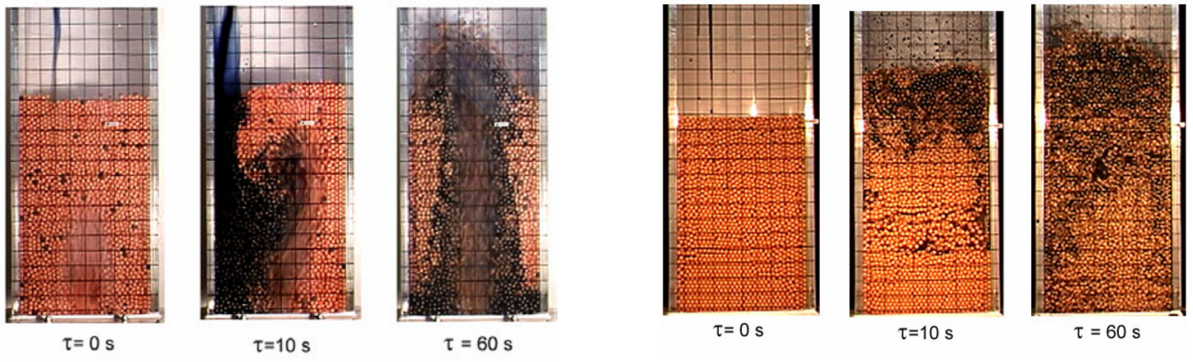


Fig 1 Experimental set-up

3. Results and Discussion

3-1: General Characteristics

(1) Spouting enhancement: The change in the nature of the spouting when water was added to the bed of polystyrene particles (6 mm diameter, density close to that of water) is shown in Fig 2-a. The corresponding change for fluidization is also shown for comparison. Once water (α = 0.1) was added to the dry bed, e.g. at the minimum spouting velocity, the behavior changed immediately to intense spouting, in spite of there being no change in air flow rate. After about one minute the behavior the spouted bed reached a steady state. While overall enhancement occurred in the spouted bed as for the fluidized bed, the distribution of the added liquid over the cross-section of the bed was quite different in the two cases. Focusing on liquid distribution, Fig 2-b shows that the liquid gathers only in a restricted region around the air-spout in the spouted bed, contrary to fluidized beds where it spreads over the entire cross-section of the column.

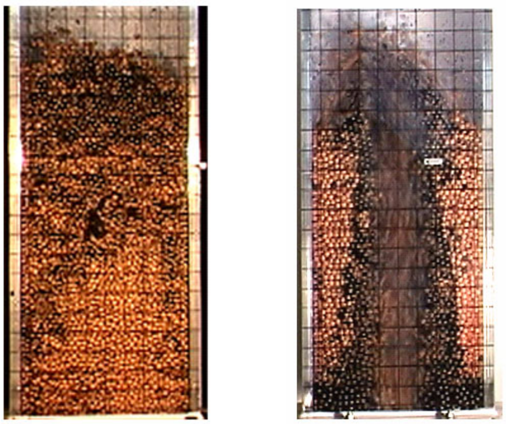


(Spouted Bed) **(Fluidized Bed)**

Fig2-a Transitions of bed situation after addition of 10 vol% colored water at minimum spouting (fluidization) velocity to dry beds

The mechanism of fluidization enhancement was identified in our previous work$^{(1)}$ with the aid of the "Modified Liquid-Perturbed Gas Model"$^{(8)}$. In this model, the interstitial gas velocity is increased because of the reduction of open area for gas flow due to the presence of the liquid and the formation of solid-liquid aggregates in the bed; fluidization is then promoted. Only when certain conditions for particles and added liquids are satisfied will the fluidization enhancement occur.

On the other hand, for a spouted bed, the added liquid (colored water) is not uniformly spread. Instead it is locally concentrated. Therefore, the mechanism for spouting enhancement should be quite different from what we found previously for fluidized beds. This unique phenomenon (liquid concentration and promotion of particle motion) has also been confirmed for other operating conditions, covering a range as in the previous fluidization work. In these experiments, even for other means of supplying the liquid (e.g. liquid supplied around the periphery of the column rather than pouring onto the fountain), enhancement of spouting and concentration of the liquid at the spout/annulus interface were observed.



Fluidization: Uniformly Spread

Spouting: Locally Concentrated

Fig2-b Liquid distribution in beds (10vol %) at the minimum spouting (fluidization) velocity.

(2) Effect of water addition on minimum spouting velocity, U_{ms}: In conventional gas-fluidized or gas-spouted beds of sand, catalyst or glass beads, for example, the amount of water added could lead to immobilization due to liquid bridges between particles whose strengths are affected by viscous and surface tension forces.

The promotion of spouting observed with large light particles is related to buoyancy caused by the liquid and inter-particle forces affected by the particle size and the wettability of the solid by the liquid. A ΔP_B - U diagrams for a dry spouted bed with and without draft tube are shown in Fig5. The ascending and descending gas-velocity lines show hysteresis. The descending line is selected for determination of the minimum spouting velocity, U_{ms}. The ΔP_B - U diagrams for different liquid content, α, are shown in Fig 3 for 6 mm polystyrene particle. U_{ms} values for different cases are presented in Table 1. In the spouted bed, the trend is similar to that for fluidized beds. The minimum spouting velocity decreased with increasing liquid content, α , e.g. decreasing by about 25% for α=0.1 compared with dry bed (α=0). This means that particle motion is promoted more at the same gas flow rate when liquid is added.

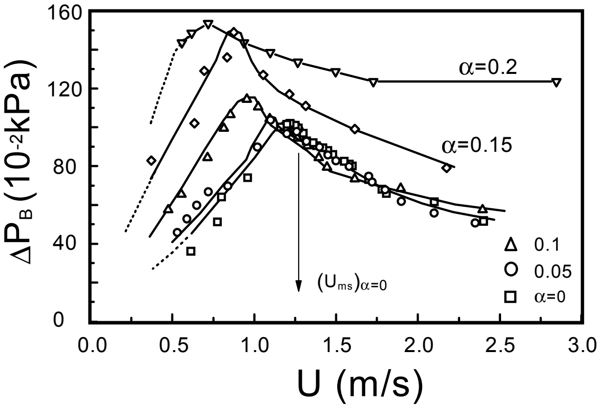


Fig3 ΔP_B - U diagram for decreasing gas velocity for several liquid contents α.

Table 1 Minimum spouting velocity U_{ms} (m/s)

	$\alpha = 0$	0.05	0.1	0.15	0.2
U_{ms}	1.3	1.1	1.0	0.9	0.8
U_{mf} *)	1.45	1.05	0.89	-	0.63

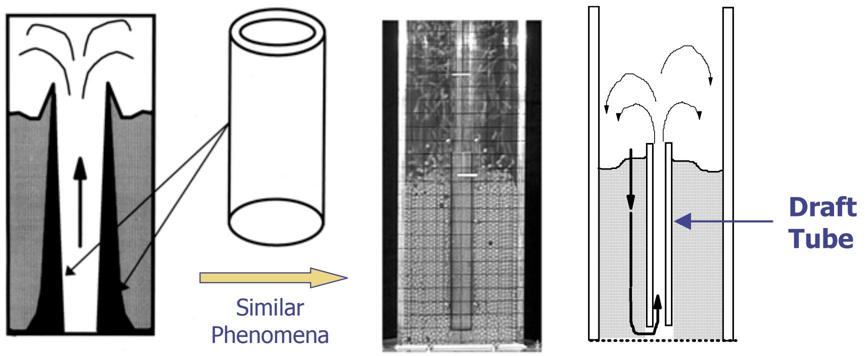
*) minimum fluidization velocity in 180mm dia. column (1)

The conditions (particle size, density, wettability) for the enhancement of spouting was also confirmed. The similar results as fluidized bed was obtained. The degree of the enhancement was good for a 6mm PLST-bed by water addition , not so good but still showed spouting enhancement for a 3.2mm PLST-bed and poor mobilization for a 2.1mm glass beads-bed.

3-2: Mechanism of spouting enhancement

(1) Analogy with Draft-Tube Spouting: Our previous model for fluidization enhancement was based on the "Modified Liquid-Perturbed Gas Model"[(8)]. In this model, the interstitial gas velocity is increased because of the reduction of open area available for gas flow due to presence of the liquid and the formation of solid-liquid aggregates in the bed, thereby promoting fluidization. In the spouted bed case, on the other hand, the added liquid never spreads uniformly over the column cross-section. Instead it concentrates locally around the air-spout as shown in Fig.2-b. This means that a different explanation for the enhancement is required for spouted beds.

Assumption: Concentrated liquid around the air spout acts like a solid draft tube (quasi-draft-tube).



Liquid-Added Spouted Bed **Dry Bed with Installed Draft-Tube**

Fig.4 Schematic diagram showing the modeling of spouting enhancement

Here we propose the following "quasi-draft-tube model" as shown in Fig.4, in which the added liquid collects around the gas spout at the spout/annulus interface and then acts rather like a solid draft tube (Fig. 2-b). Therefore the entering air does not fan out into the annulus, in particular around the region of the bottom of gas-spout, as in conventional spouted beds. Instead it retains a higher velocity in the spout, resulting in spouting enhancement.

(2) Spouting by draft-tube insertion:

Previous work[(9)] has shown that spouting can be enhanced by the addition of an impermeable draft tube. To compare our liquid-enhanced spouted bed with a dry bed with draft tube, an experiment was carried out in a dry bed in which a half-draft tube of inner diameter 30 mm, the same as the diameter of the air-inlet hole, was installed on the front wall at 30 mm above the flat-base in a half-column bed. It was confirmed that spouting was enhanced by the draft tube (Fig.4). At the same time, U_{ms} decreased to 45% (Fig. 5 – descending velocity line) or 60% (Fig. 5 – ascending

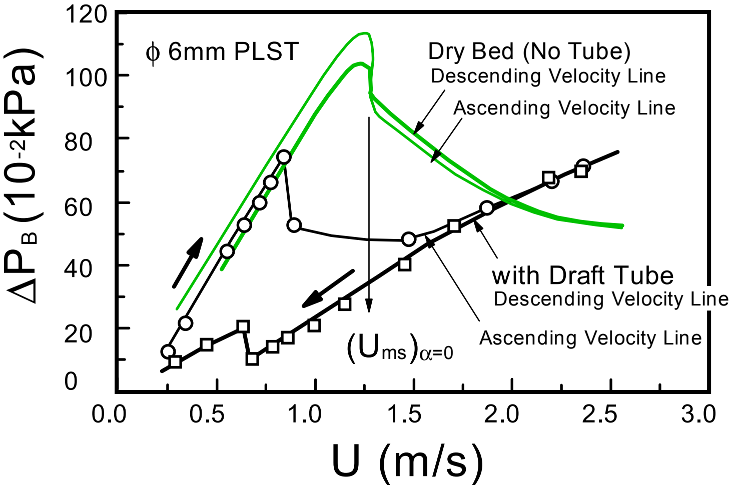


Fig.5 ΔP_B-U diagram for spouted bed with and without draft-tube velocity line) of the dry bed U_{ms} value without a draft tube. The profile of the ΔP_B-U curve was similar to solid-draft-tube results in a spouted bed of relatively small glass beads (mean diameter ~ 1.3 mm) reported by Ishikura et al.(10). An important result to note here is that the pressure drop through the whole bed (after U_{ms}) increases with increasing gas velocity due to friction loss in the draft tube, and the profile does not show the decreasing curve.

(3) Measurement of static pressure distribution: To show the validity of the above "quasi-draft-tube model ", static pressure distributions in three types of bed were measured. In this experiment, the static pressure on the inner flat wall surface of the half-column was measured. Liquid droplets or a liquid layer involved in wetted beds sometimes hindered measurement of the pressure. Therefore a special improved pressure sensor (Fig.6) was used, derived from a diaphragm-type precision differential pressure sensor (Kyowa Co; DP-400, Max 400 mm H_2O), modified by enlarging the pressure inlet and by drilling a drain tap to release liquid.

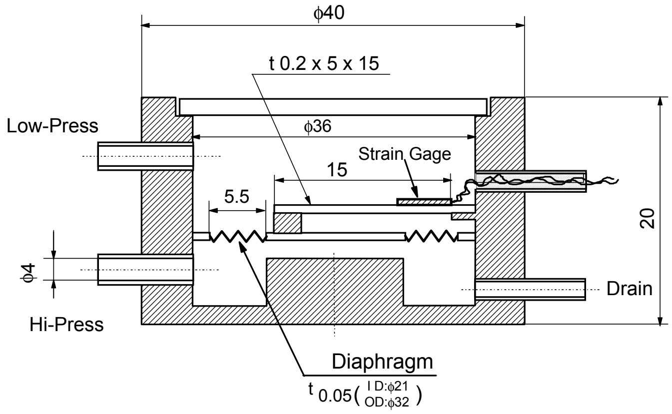


Fig.6 Improved pressure sensor for multiphase flow

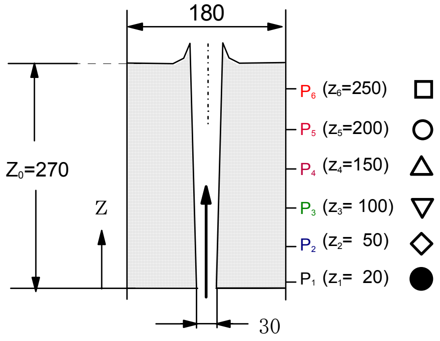


Fig.7 Locations of static pressure measurements
(Symbols correspond to Fig.8)

Fig. 7 shows the placement of the pressure taps on the flat wall of the column. Fig. 8 plots the static pressure distributions from bottom to top of the bed for three cases: a dry spouted bed, a wetted spouted bed and a dry bed with draft-tube. The upper figures show the pressure distribution

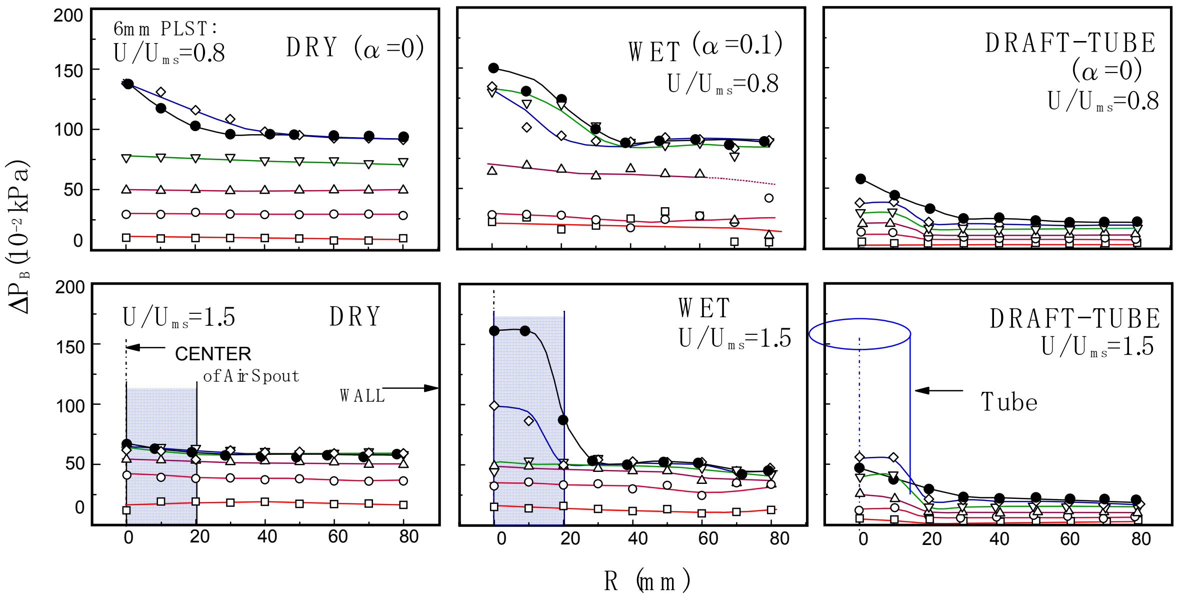


Fig.8 Static pressure distribution on front flat plate (half-column) in three types of beds, in a dry spouted bed, wet bed and in a dry bed with draft-tube.
Upper figures for fixed bed (U/U_{ms}=0.8) and lower figures for spouted bed (U/U_{ms}=1.5)

for a fixed bed condition ($U/U_{ms}=0.8$), whereas the lower figures correspond to spouting ($U/U_{ms}=1.5$). The lower figures (at spouted bed condition) indicate clearly that the pressure distribution for the wetted spouted bed is very similar to that for a dry bed with draft-tube, although the pressure distribution for the conventional dry spouted bed differs from that of the other two beds. An interesting feature is the reverse pressure gradient around the air-spout, as shown in Fig.9. This pressure gradient probably acts as a driving force for gathering the added liquid into the interface region between the air-spout and annulus, because the liquid can move easily with large-light poorly wettable particles as water droplets in a dynamic suspension.

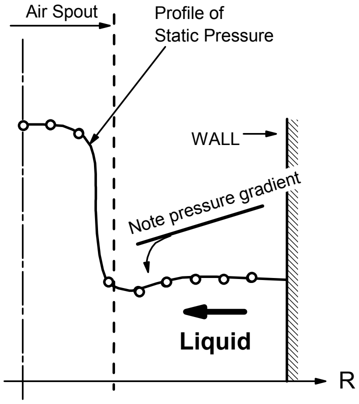


Fig.9 Schematic diagram for pressure distribution

One more interesting finding from the figures is that there are some inversions in the pressure values near the spout-annulus interface for the case of the dry fixed bed and high-velocity dry beds with draft-tube. These data were reproducible and the validity of the base spouted bed data is confirmed by comparing with conventional dry spouted bed results reported by Yokogawa (11). The upset in the bed with draft-tube probably depended on the low pressure due to the high inlet velocity region at the entrance of the draft-tube and the high pressure of the particle suspension in the bottom region of the draft tube.

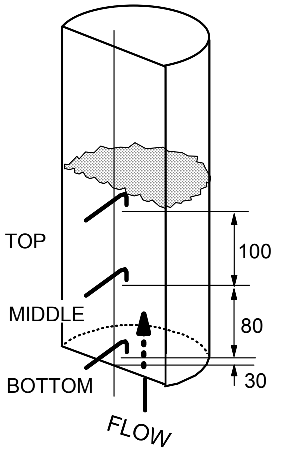


Fig.10 Configuration for measuring velocity

(4) Effect of liquid addition on air-spout: In order to obtain more evidence for the validity of the "quasi-draft-tube-model", the air velocity in the core of the air-spout was measured before and after adding liquid to the bed. The core velocity of the air-spout was measured at 10 mm intervals from the flat wall surface in the spout (diameter of air-spout ~40 mm) at three heights – bottom, middle and top of the column (Fig. 10).

The 3 mm diameter Pitot tube (total pressure tube and the wall static pressure) were used to determine the velocity. The changes of the core velocity in the spout before and after adding water are shown in Figs. 11a to c. It is clear that the air-spout velocity at the bottom position increased upon addition of water. No change of

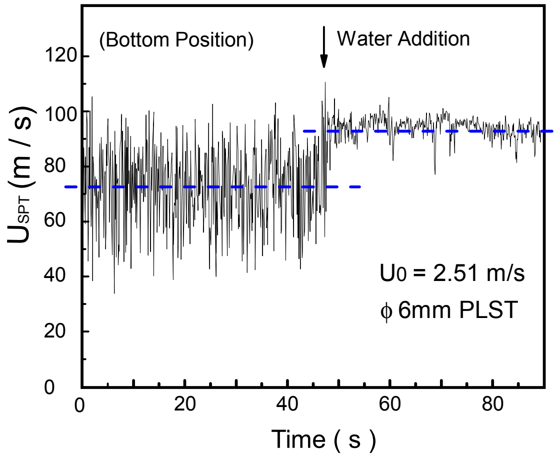


Fig.11-a Change of air velocity of air-spout (at bottom position)

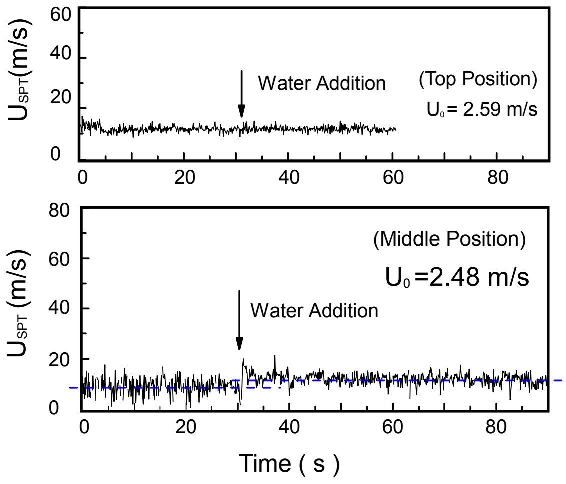


Fig.11-b Change of air velocity for middle position (lower Fig.)
Fig.11-c: for top position(upper Fig.)

velocity was observed in the region above about half-way up the spout. A small increase was observed, however, at lower heights. The velocity at the bottom position changed from about 70 to 90 m/s when the water was added, and the latter velocity is similar to that if the full air flow is through the spout.

(5) Concluding remarks for this section: The experiment with the draft-tube indicates that the particle motion is enhanced by a draft-tube. Comparison of static pressure distributions within the three types of bed, it shows that the wetted spouted bed and the dry bed with draft-tube behave in similar manners. The pressure profiles of these two beds are very similar.

From the measurement of air-spout velocity, it can be said that the air flow rate into the spout is increased by the concentration of liquid from the air inlet to the middle of the bed around the spout. This suggests that the added liquid forms a solid-like tube, enhancing the flow field around the air inlet, and that the bed mobilization is thus significantly promoted. These findings support the above assumption of a "quasi-draft-tube-model". From the VCR observations, the cross-sectional area of the air-spout changed very little over the entire height of the spout when the water was added. Therefore more air flows up the core of the liquid-assisted bed, in particular around the bottom region of the spout, whereas the efflux of air from spout to annulus occurs over the whole gas-spout region in the dry spouted bed without a draft tube. The differences in the profiles of the ΔP_B-U curves support this trend (compare dry bed curves, with and without draft tube, in Fig5).

Further discussion based on hydrodynamics is needed in the future, with special attention to the inversions of pressure near the inlet of the draft-tube.

4.Conclusion

When liquid is added to a gas-spouted bed of relatively large non-wettable particles, with a liquid density similar to the particle density, the liquid addition can cause a dramatic increase in the extent of spouting. While this phenomenon is qualitatively similar to liquid-assisted fluidization(1), the distribution of the added liquid over the cross-section of the bed is quite different in the two cases. In spouted beds, the liquid gathers only in a restricted region around the gas spout. These findings are explained by bed hydrodynamics. Concentration of liquid around the spout/annulus interface converts this interface to an impermeable or slightly permeable draft tube, enhancing spouting by causing a higher gas velocity up the spout.

References

(1) Y, Nagahashi, D.H. Lee, J.R. Grace, N. Epstein, A.Yokogawa and Y. Asako, Enhancement of Large-Particle Gas-Fluidization by Adding Liquid. AIChE Journal, **49** (2003), 675-681.

(2) Y. Nagahashi, J. R. Grace, Y. Asako, N.Epstein, D.H.Lee and A. Yokogawa, Effect of Liquid Addition on Heat Transfer in Gas-Fluidized Beds of Large Light Particles, Journal of Process Mechanical Engineering (Proc. Instn. Mech. Engrs., Part E), Vol.**217** (2003), 279-286.

(3) D.V. Vukovic, F.K. Zdanski, G.V. Vunjak and Z.B. Grbavcic, Pressure Drop, Bed Expansion and Liquid Holdup in a Three Phase Spouted Bed Contactor, Can. J. Chem. Eng., **52** (1974) 180-184.

(4) L.S. Fan, S.J. Hwang and A. Matsuura, Hydrodynamic Behaviour of a Draft-Tube Gas-Liquid-Solid Spouted Bed, Chem. Eng. Sci., **39** (1984) 1677-1688.

(5) K. Patel, J. Bridgwater, C.G.J. Baker and T. Schneider, Spouting Behavior of Wet Solids, Proc. 5th Int. Drying Symposium, **1** (1986) 421-425.

(6) T. Schneider and J. Bridgwater, The Stability of Wet Spouted Beds, Drying Technology, **11 (2)** (1993), 277-301.

(7) M.F.D. Medeiros, S.C.S.Roca, O.L.S. Aisina, C.E.M. Jeronimo, U.K.L. Medeiros and A.L.M.L. da Mata, Drying of Pulps of Tropical Fruits in Spouted Bed: Effect of Composition on Dryer Performance, Drying Technology, **20** (2002), 855-881.

(8) J.P. Zhang, N. Epstein and J.R. Grace, Minimum Fluidization Velocities for Gas-Liquid-Solid Three-Phase Systems, Powder Technol., **100** (1998) 113-118.

(9) J.R. Muir, F. Berruti and L.A. Behie, Solids circulation in Spouted and Spout-Fluid Beds with Draft-Tubes, Chem. Eng. Commun., **88** (1990) 153-171.

(10) T. Ishikura, H. Nagashima and M. Ide, Hydrodynamics of a Spouted Bed with a Porous Draft Tube Containing a Small Amount of Finer Particles, Powder Technology, **131** (2003), 56-65.

(11) A.Yokogawa, The Study on the Characteristics of Spouting of Spouted Beds, Doctoral Thesis, Osaka University, (1971).