STUDIES ON GAS HOLD-UP IN GAS-LIQUID SPOUTED VESSEL

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In a gas-liquid spouted vessel, where power is supplied from a pump to water and gas is introduced at a nozzle attached at the bottom of the vessel, gas bubbles are finely broken at the nozzle and dispersed to the vessel. Gas hold-up in the gas-liquid spouted vessel rapidly increases with increasing liquid flow rate and easily exceeds twice the gas hold-up in the aerated tower of the same gas flow rate with no liquid flow, though co-current liquid flow gives zero or negative effect on gas hold-up in the aerated tower. Effect of liquid flow rate, gas flow rate, nozzle to vessel diameter ratio and nozzle length on effective spouting of gas bubbles were studied experimentally. Ways are also considered to scale up the gas-liquid spouted vessel.

It was already reported by the present authors that the liquid-phase spouted vessel is effective in fluidizing or dissolving coarse or heavy solid particles due to action of water jet concentrated at the nozzle and strong turbulence in the vessel. It was also reported in those papers that introduction of gas to the nozzle of the solid-liquid spouted vessel gave preferable effect on particle movement and mass transfer from solid particles, though introduction of gas into the three-phase fluidized bed gave reduction of bed height.

The mixing vessel is mostly used for gas absorption, and various types of mixing techniques for accomplishing intimate contact between liquid and gas bubbles have been developed. However, application of the mixing vessel is limited to relative low gas rates as decrease of average density around the impeller causes lowering of impeller power which is necessary to break and disperse gas bubbles.

In the case of the gas-liquid spouted vessel, power is supplied from a pump to water and gas is broken at the nozzle attached at the bottom of the vessel and is dispersed into the vessel as stated below.

In this paper gas hold-up observed in the gas-liquid spouted vessel is reported.

1 Experimental Apparatus

The schematic diagram of the gas-liquid spouted vessel is shown in Fig. 1. Liquid was recirculated from the overflow through the pump and gas was introduced from a compressor or a bomb to the nozzle attached at the bottom of the vessel, as shown in Fig. 1. Various dimensions of the spouted vessel and other reactors used in this experiment are shown in Table 1.

As experimental liquid, tap water, NaCl solutions or glycerin-water solutions were used. Liquid flow rates in this study were 0 to 60 lit/min. Gas flow rate was also varied from 5 to 120 lit/min.

2 Experimental Method

The average gas hold-up in the vessel and the local gas hold-up at various sections in the vessel were
measured using the static pressure change observed at various points of the vessel.

3 Result and Discussion

As the part of power supply is separated from the part of bubble breaking and liquid is concentrated at the nozzle as a high speed jet in the case of the spouted vessel, liquid energy from a pump is effectively used to break gas bubbles in the nozzle and to disperse from the nozzle outlet into the turbulent spouted section where mixing is vigorous, and approximates perfect mixing as stated in the previous paper13).

Effect of liquid flow rate, gas flow rate and nozzle diameter on gas hold-up in the gas-liquid spouted vessel is shown in Figs. 2 and 3. It is clear from these figures that the gas hold-up in the gas-liquid spouted vessel increases rapidly with increasing liquid flow rate and that it easily exceeds twice the gas hold-up observed in the aerated tower using a single nozzle sparger of the same gas flow rate. The gas hold-up in the aerated tower using a single-nozzle sparger can be known from these two figures as the gas-liquid spouted vessel with zero liquid flow rate means an aerated tower using a single-nozzle sparger.

It was reported by Akita that above a certain gas flow rate (about 100 m/hr in superficial velocity) phenomena in the aerated tower were not affected by type of gas sparger14). Rapid increase of gas hold-up with increase of co-current liquid flow rate is one of the characteristics observed in the gas-liquid spouted vessel. On the contrary, in the case of a co-current aerated tower, gas hold-up decreases slightly with increasing liquid flow rate as reported by Kato15) and Inoue16).

It was also observed in this study that mixing time for the gas-liquid spouted vessel decreased with increasing liquid flow rate, though almost no effect of liquid flow rate on mixing time for the aerated tower was reported by many authors1,20).

These differences of effect of liquid flow rate on mixing time or gas hold-up may be explained by effective utilization of liquid energy as a high speed jet from the nozzle in the spouted vessel, whereas liquid energy is dispersed over the cross-sectional area in the case of the aerated tower.

Difference of conditions of bubble dispersion is clearly known from pictures shown in Fig. 4. Small broken bubbles are finely dispersed in the gas-liquid spouted vessel, though large bubbles are scattered in the aerated tower using a single nozzle sparger.

It should be also mentioned here that introduction of gas to a point just above the nozzle exit of the spouted vessel has no effect on bubble breaking and the condition of bubble dispersion in the vessel is almost the same as that of the aerated tower using a single-nozzle sparger.

Accordingly, it can be stated that spouting of high-speed gas-liquid two-phase flow from a nozzle dominates the phenomena in the gas-liquid spouted vessel. However, study of behaviour of two-phase gas-liquid flow in a nozzle has not received the attention of many investigators, and only the pressure
As shown by solid lines in Fig. 5, gas hold-up in the gas-liquid spouted vessel is approximated by the following equations within the range of this experiment for 15-cm inner-diameter vessels.

\[
H_g = H_{g0} \quad (L \leq L_c) \\
H_g = H_{g0}(1 + K \log(L/L_c)) \quad (L \geq L_c)
\]

where \( L \) and \( H_g \) represent liquid flow rate and gas hold-up in the vessel, respectively. \( L_c \) and \( K \) mean critical liquid flow rate for gas spouting and gas spouting coefficient.

\[
H_{g0} = \frac{1}{1 - H_{g0}} \cdot 0.2 \left( \frac{gD^2 \rho_L \gamma}{\pi gD^3} \right)^{1/3} \left( \frac{U_g}{\sqrt{gD}} \right)^{1/3}
\]

(3)

For water of which temperature is between 10°C to 60°C, the following equation obtained in this experiment can be used as an approximation of Eq. (3).

\[
H_{g0} = 1.56 \times 10^{-3} U_g^{0.8} \quad (20 \leq U_g \leq 400)
\]

(4)

Effect of gas flow rate on \( L_c \) and \( KH_{g0} \) is shown in Figs. 6 and 7. It is clear from Fig. 5 that \( L_c \) increases a little with increasing gas flow rate. It means that more liquid energy is required to break and disperse gas bubbles of larger gas flow rate at the nozzle. It is also known from Fig. 6 that the nozzle diameter has almost no effect on \( L_c \). As a result \( L_c \) can be represented as follows using superficial velocity:

\[
U_{c0} = 18.1 U_g^{1/3} d_n^{1/3}
\]

(5)

\( KH_{g0} \), which represents increasing rate of gas hold-up in the gas-liquid spouted vessel, increases in proportion to the gas flow rate and becomes almost constant when the gas flow rate exceeds 50 lit/min, 4.72 cm/sec in superficial gas flow rate, as shown in Fig. 7. It is also known from Fig. 7 that \( KH_{g0} \) is almost inversely proportional to nozzle diameter in the range of this experiment.

recovery of a two-phase flow from a diffuser were studied by several authors\(^3\,7\,8\,23\). Therefore, the nature of nozzle performance with two-phase flow is not well established.
Using superficial velocity

\[ KH_{g0} = 2.35 \times 10^{-3} U_g d_n^{-1} \quad (0 \leq U_g \leq 170) \]  
\[ KH_{g0} = 0.4 d_n^{-1} \quad (U_g \geq 170) \]

It is confirmed in this experiment that the same correlative equations from Eq. (1)–Eq. (7) are applicable to 6 to 20 cm diameter vessels keeping geometric similarity. It is observed in this study that the ratio of nozzle diameter to vessel diameter should be smaller than 0.2 to get good dispersion of bubbles, though too small nozzle diameter gives larger pressure drop at the nozzle and causes cavitation because the sonic velocity becomes very low in the gas-liquid mixture. The present authors chose 0.1 as a standard of nozzle-to-vessel diameter ratio which gives the ratio of one hundred for superficial liquid velocity in the nozzle to that in the vessel.

According to Govier or Bergles, limit of the bubbly flow regime is at about 0.25 in gas volume flow-rate ratio and two-phase flow condition in a pipe changes from bubbly flow to churn turbulent, annular or slug flow with increasing gas volume flow-rate ratio. But even in the case of the gas volume flow-rate ratio when churn-turbulent, annular or slug flow is produced, initial flow condition soon after the introduction of gas to liquid is bubbly flow condition. Accordingly, even in the case of high gas volume flow-rate ratio, good dispersion of bubbles is obtained and high gas hold-up is attained in the gas-liquid spouted vessel as shown in Figs. 2, 3 and 5.

The effect of nozzle length on gas breaking phenomena was examined by using specially arranged easily exchangeable nozzles as shown in Fig. 8 where the nozzle was inserted into the vessel. The gas hold-up measured for the vessel as shown in Fig. 8 showed the same values as the ordinary gas-liquid spouted vessel as shown in Fig. 1 within the nozzle length tested in this experiment.

When the nozzle is too long, bubble dispersing is not done effectively, as annular or slug flow is developed approaching the nozzle exit to give low gas hold-up in the vessel. This effect can be seen from the curve (2) in Fig. 8, where gas is introduced 150 cm below the nozzle inlet. Effective gas breaking also cannot be obtained when the nozzle is too short, as shown in Fig. 8. It is known from this experiment that nozzle length should be larger than nozzle diameter to get good spouting of gas liquid mixture into the spouted vessel.

In Fig. 9 change of local gas hold-up in the gas-liquid spouted vessel is shown. The local gas hold-up in the turbulent spouted section is much larger than that measured in the calm uniform flow section existing above the turbulent spouted section where plug-flow mixing is approximated. It can be properly assumed from Fig. 9 that coalescence of gas bubbles in the calm uniform flow section is not notable because the local gas hold-up in all sections in the calm uniform flow section are almost identical, as shown by curve (3) in this figure.

When NaCl solutions or glycerin solutions are used as liquid in place of water, gas hold-up in the gas-liquid spouted vessel increases greatly, as shown in Fig. 10. The gas hold-up in the spouted vessel increases by 10% or 30% by using NaCl or glycerin.
solutions, respectively, in place of water. However, increase of gas hold-up in the aerated tower with a single nozzle sparger is almost half of that observed for the spouted vessel. This difference may be due to the difference of the gas-breaking mechanism. As bubbles are easily coalesced in the overflow of the gas-liquid spouted vessel even when solution of surface active materials as NaCl salt or glycerin is used as liquid, the gas-liquid spouted vessel may be applicable for flotation or fermentation.

As the gas hold-up around the impeller is much higher than the average gas hold-up in the mixing vessel\(^1\), increase of gas flow rate may have a negative effect on phenomena in the aerated mixing vessel, because the reduced torque due to high gas hold-up around the impeller cannot disperse air bubbles effectively. This effect was experimentally observed for gas absorption\(^4,11\) and heat transfer from the vessel wall\(^12\). As shown in Fig. 11, gas hold-up in a three-phase fluidized bed is lower than that observed in an aerated tower, though the particle diameter forming a fluidized bed has considerable effect on gas hold-up\(^19\).

According to reports on gas hold-up in a three-phase fluidized bed by Østergaard\(^18,19\) or Sherrard\(^21\), dispersion of gas bubbles is not good and reduction of bed height occurs due to the clear water rising up rapidly behind large bubbles, even though rather high superficial liquid velocity is required to fluidize solid particles.

As the gas-liquid spouted vessel gives a large capacity coefficient in gas absorption at comparatively low gas flow rate and low power requirement due to large gas hold-up and finely dispersed bubbles in the vessel, as stated elsewhere by the present authors\(^16,17\), it may have a great possibility as a reactor for gas absorption.

In any event to solve problems in the gas-liquid spouted vessel, it is necessary to clarify the phenomena of gas-liquid two-phase flow spouting from the nozzle to the large container.

### 4 Conclusions

1) In the gas-liquid spouted vessel where power is supplied from a pump to water and gas is introduced at the nozzle attached at the bottom of the vessel, gas bubbles are finely broken at the nozzle and dispersed to the vessel. Gas hold-up in the gas-liquid spouted vessel rapidly increases with increasing liquid flow rate and easily exceeds twice the gas hold-up in the aerated tower with a single nozzle sparger of the same gas flow rate.

Correlative equations for gas hold-up in the gas-liquid spouted vessel are also obtained for the air-water system.

2) Gas hold-up in the turbulent spouted section is much larger than the average value in the vessel, and coalescence of gas bubbles in the calm uniform flow section is not notable because local gas hold-up in all sections of the calm uniform flow section are almost identical.

3) The ratio of nozzle diameter to vessel diameter should be smaller than 0.2 to get good spouting, but too small ratio gives a large pressure drop at the nozzle. Ratio of 0.1 was chosen as the standard in this experiment. The nozzle length should be larger than nozzle diameter to get good spouting.

### Nomenclature

\( D = \) vessel diameter [cm]

\( d_n = \) nozzle diameter [cm]

\( d_p = \) particle diameter [cm]

\( G = \) gas flow rate [lit/min]
\( H_g \) = gas hold-up in gas-liquid spouted vessel
\( H_{gr} \) = gas hold-up in aerated tower
\( H_v \) = vessel height
\( h_g \) = local gas hold-up
\( K \) = gas spouting coefficient
\( L \) = liquid flow rate
\( L_c \) = critical liquid flow rate for gas spouting
\( L_n \) = nozzle length
\( U \) = superficial velocity in the vessel
\( u \) = superficial velocity in the vessel
\( \theta \) = cone angle of the spouted vessel

Literature Cited