Refereed Proceedings

The 12th International Conference on Fluidization - New Horizons in Fluidization Engineering

Engineering Conferences International *Year* 2007

Effect of the Gas-to-Liquid Ratio on the Performance of Nozzles Injecting Gas-Atomized Liquid into a Fluidized Bed

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EFFECT OF THE GAS-TO-LIQUID RATIO ON THE PERFORMANCE OF NOZZLES INJECTING GAS-ATOMIZED LIQUID INTO A FLUIDIZED BED

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ABSTRACT

A novel experimental technique using triboelectric and temperature measurements was developed to assess the performance of nozzles injecting gas-atomized liquid into a gas-solid fluidized bed. The effect of varying the gas-to-liquid mass ratio on the nozzle performance was investigated.

INTRODUCTION

In many industrial applications, such as fluid coking, fluid catalytic cracking, and gas-phase polymerization, liquids are injected into fluidized beds of solid particles. A key objective is to ensure rapid and uniform distribution of the liquid feed on fluidized solid particles, which minimizes the formation of undesired agglomerates, improves operability, and maximizes the yield and quality of valuable products. Ideally, the liquid fed to the fluidized-bed reactor should uniformly contact the largest possible amount of bed solids by forming a thin liquid film on individual solid particles (1). Extensive studies (2, 3, 4), however, have shown that, under realistic process conditions, as soon as liquid is injected into the reactor via gas-assisted nozzles, liquid-solid agglomerates are formed, hindering the progress of endothermic cracking reactions. For example, Knapper et al. (4) employed a sophisticated tracer technique to quantitatively assess liquid-solid contact in a fluid coking pilot plant. They showed that only a small fraction of the fluidized particles was contacted by the injected liquid, its magnitude depending upon the injection-nozzle technology used.

Further studies are therefore required to gain a deeper knowledge of how the nozzle technology and the operating conditions affect the quality of the interaction between liquid jets and a fluidized bed. To date, however, most of the available experimental techniques are not suitable for scale-up studies of jet-bed interaction, and are too time-consuming for the systematic screening of nozzles. A new, rapid and easily scalable method was, therefore, developed (5). It uses the electrical signal generated by a triboelectric probe to define a performance index for nozzles injecting gas-atomized water into an air-fluidized bed of glass beads. The triboelectric probe used for this study was a stainless steel tube whose outer surface was exposed to collisions with fluidized bed particles. Because wetted particles produce a much stronger signal than dry particles, the probe signal is a direct function of the overall bed wetted area. For example, with a poor nozzle, a large fraction of the injected liquid would be trapped within agglomerates, and the bed particles coming in contact with the probe would be relatively dry, resulting in a weaker signal. Further information on the use of triboelectric probes for measuring the solids wetted area in a gas-solid fluid bed can be found elsewhere (6, 7).

The objective of this study was to provide insight into the effect of the air-to-liquid ratio (*ALR*) on the contact between injected liquid and fluidized solid particles. These results were related to the nozzle open-air spraying performance, as determined with a laser-photocell arrangement and high-speed videos.

EXPERIMENTAL

Experimental set-up and materials

The gas-solid fluidized bed employed in this work is shown in Figure 1. The bed solids were glass beads having a Sauter-mean diameter of 171 μm, and an apparent particle density of 2500 kg/m^3. The fluid bed was 2.8 m tall, and had a rectangular cross-section of 0.15 m by 1.22 m. For all the experiments, the static bed height was maintained constant at 0.85 m, which corresponded to a bed mass of 236 kg, and the superficial gas velocity was kept at 0.4 m/s to yield a fully bubbling fluidization bed. A humidity and temperature meter (EXTECH Instruments 4465CF) monitored the fluidization air humidity. The air relative humidity was constant at approximately 5 %.

Experiments were conducted by injecting water into the fluidized bed via an air-atomization nozzle. The liquid injection system was comprised of a premixer were gas and liquid were separately introduced, and a nozzle whose internal geometry was characterized by a converging-diverging-converging section. This spray nozzle design has been patented for use in industrial fluid cokers (8). The nozzle was mounted horizontally about 0.6 m above the distributor grid, and had an inner tip diameter of 0.001588 m. Liquid was supplied to the nozzle at constant mass flow rate from an air-pressurized tank, and the mass flow rate of atomization air was controlled with sonic nozzles.

The horizontal triboelectric tube was installed 0.18 m above the distributor grid (Figure 1). It consisted of a stainless steel tube having an outer diameter of 9 mm, and a length of 55 cm. It was connected to the ground through a micro-ammeter connected to a data acquisition system, and recorded at a sampling rate of 1000 Hz.

The bed temperature was measured at a rate of 1 Hz by four thermocouples installed at the locations shown in Figure 1, and penetrating 2 cm into the bed.

Figure 2 illustrates the laser-photocell arrangement used to characterize the atomization characteristics of the spray nozzle in open air. It measured the attenuation of a laser beam directed perpendicularly to the axis of the gas-liquid spray. The laser beam had an approximate diameter of 2 mm, and intersected the gas-liquid jet 9 mm downstream of the nozzle tip on its longitudinal axis. The photocell signal was acquired at a frequency of 4000 Hz. The attenuation of the laser beam is proportional to the liquid/gas interface intercepted along its path.

High-speed videos of the open-air gas-liquid spray were recorded with a high-speed video camera (Redlake Imaging Corporation, Motionscope Model PCI 500) with a resolution of 320 x 280 pixels at a rate of 500 fps. For each tested condition, the video was taken for approximately 8 s.

Experimental method for assessing nozzle performance within the fluidized bed

In order to examine the effect of changing the nozzle *ALR* on the interaction between injected liquid and fluidized bed, two independent nozzle performance indices were introduced: the Nozzle Performance Index *NPI*, which is derived from the triboelectric signal, and the Temperature Index, *TI*, which is based on temperature measurements.

The *NPI* provides a direct indication of how well the injected liquid coats the bed particles. The triboelectric signal is generated by the numerous collisions of wetted fluidized particles and agglomerates on the triboelectric tube, and is therefore proportional to the bed wetted surface area (6, 7). The *NPI* was obtained by normalizing the signal resulting from a specific nozzle injection by a reference signal generated by premixing a fraction of bed solids with liquid in an external mixing device. As a result, an *NPI* equal to 1 would indicate that the spray nozzle performed as efficiently as the external premixer, whereas an *NPI* of 0 would correspond to a complete segregation of the injected liquid within agglomerates.

The Temperature Index, *TI*, quantifies the variations in bed temperature produced by imperfect distribution of the sprayed liquid on the solid particles. For a liquid distribution poorer than that of the external premixer (reference case), the difference between the temperature readings provided by the four thermocouples would be larger, and *TI* would have a value smaller than 1.

A more detailed description of the experimental method is available elsewhere [5].

RESULTS AND DISCUSSION

All the experiments were conducted using the same spray nozzle. For the fluidized bed experiments, the nozzle was operated at a liquid mass flow rate of 30 g/s, while varying the *ALR* within the range from 0 to 1.5 wt%, and at 24 g/s with the *ALR* varied between 0 and 3 wt%. The liquid-solid contact was assessed by means of the two nozzle performance indices (*NPI* and *TI*). For each injection condition, three to six experimental runs were conducted.

Figure 3 shows that, for all the examined injection conditions, the average values of the index obtained from triboelectric measurements, *NPI*, and the temperature-based index, *TI*, were in remarkably close agreement.

Figure 4a shows the effect of the *ALR* on the jet-bed interaction when the nozzle was operated at 24 g/s of liquid flow rate. The points indicate the average *NPI* resulting from duplicate experiments, and the error bars show the 95% confidence interval associated with each value. The results clearly show that increasing the *ALR* between 0 and approximately 1.5 wt% was beneficial to the liquid-solid contact. However, for ALR > 1.5 – 2 wt%, the NPI exhibited a nearly constant value. It can also be noticed that, in the ALR range between 0 and 1.5 wt%, increasing the liquid mass flow rate by 20 %, from 24 to 30 g/s, did not have any substantial effect on the two nozzle performance indices (Figure 4b).

Several attempts were made to correlate the nozzle performance with parameters characterizing the gas-liquid flow through the nozzle, such as tip pressure, energy input to the nozzle, and sonic velocity at the nozzle tip (9). However, none of them could be satisfactorily correlated to the liquid-solid contact. An indirect, yet effective correlation was found between the experimentally determined nozzle performance index, NPI, and an empirical parameter, f, which is a function of the *ALR* and the gas voidage at the nozzle tip (volumetric fraction occupied by the gas phase), α:

$$f = \frac{1}{\alpha}\sqrt{\frac{ALR}{1+ALR}} \tag{1}$$

The gas voidage at the nozzle tip was estimated by treating the gas-liquid flow as a strictly homogeneous mixture (no-slip assumption) according to Eq. (2):

$$\alpha = \frac{Q_G}{Q_G + Q_L} = \frac{1}{1+\frac{Q_L}{Q_G}} = \frac{1}{1+\frac{\rho_G}{\rho_L}\frac{100}{ALR}} \tag{2}$$

where Q_G and Q_L indicate the volumetric flow rates of gas and liquid respectively, and ρ_G and ρ_L the corresponding densities.

The equation of state for the gas phase provided the gas density as a function of the tip pressure, which was predicted by means of a model that has been validated against extensive experimental data (10).

It should be noted that the gas voidage, α, is a function of the *ALR*, the liquid density, and the gas density, which in turn depends upon the tip pressure. For a nozzle of given size and internal geometry supplied with air and water, the tip pressure depends only on liquid flow rate, and *ALR*. The function *f*, and hence the *NPI*, depend only on the nozzle operating conditions (liquid flow rate, and *ALR*).

Figure 5b illustrates the effect of increasing the *ALR* on the function *f* at three liquid flow rates. It suggests that doubling the liquid flow rate (from 24 g/s to 48 g/s) would considerably enhance the nozzle performance. Of course, doubling the liquid flow rate would also greatly increase the nozzle pressure drop. At the same time, at higher liquid flow rates, the critical *ALR* beyond which the *ALR* effect dissipates is lower.

In order to gain a deeper understanding as to why increasing the *ALR* became gradually less beneficial at higher *ALR*s, the nozzle atomization performance in open air was characterized by measuring the attenuation of a laser beam intersecting the gas-liquid jet very close to the nozzle tip. The open-air tests were conducted at a liquid flow rate of 24 g/s by covering a range of *ALR* between 0.4 and 3 wt%. The signal attenuation, a, was defined as the difference between the value of the undisturbed signal and the average of the signal calculated over a 5-second period of steady-state spraying. Assuming that the attenuation of the laser beam, a, is proportional to the number of droplets intercepted, and that the generated droplets are equal-size spheres of diameter d_d, the following equation can be derived (9):

$$a \propto \frac{1}{{d_d}^3}\frac{d}{1+\frac{ALR}{100}\frac{\rho_L}{\rho_G}} = \frac{1}{{d_d}^3}\cdot R \tag{3}$$

Image analysis of the high-speed videos of the open-air sprays provided the time-averaged value of the gas-liquid jet width, d, from which the ratio R in Eq. (3) can be evaluated for every tested *ALR* (Table 1). As the *ALR* was increased, despite the decrease in R, the attenuation of the photocell signal increased (Table 1). This suggests that the increase of the attenuation for increasing *ALR* must be attributed to a larger gas-liquid interface area, i.e. smaller liquid droplets. As shown by Eq. (3), the ratio of R to the measured attenuation, a, is proportional to the droplet volume ($\pi d_d^3/6$). Interestingly, changes in the R/a ratio with increasing *ALR* were satisfactorily correlated to the nozzle performance index, *NPI* (9). This result suggests that proper *ALR*, leading to a finer liquid atomization in a gaseous environment, can also enhance the liquid-solid contact within a fluidized bed.

Furthermore, the time-averaged value of the expansion angle of the gas-liquid spray, θ_{ext}, was estimated from image analysis of the high-speed videos when the nozzle was operated at 24 g/s of liquid with the *ALR* ranging from 0.4 to 3 wt%. The spray profile was obtained for each video frame, and θ_{ext} was calculated as the slope of the linear fitting of the time-averaged spray profile, assuming angular symmetry (Figure 2). The fluidized-bed expansion angles were estimated for different *ALR*s assuming a constant proportionality between open-air and fluidized-bed angles (Table 2). For every *ALR*, the estimated jet expansion angle was used as input to a model (11) that predicts the gas-solids entrainment rate into the jet over a distance of 1 cm from the nozzle tip. A good correlation was found between the mass flow rate of gas and solids entrained into the jet and the nozzle performance index, *NPI* (9). This finding suggests that the higher nozzle performance at higher *ALR* could be explained by the higher rate of solids entrainment into the spray cavity resulting from the larger jet expansion angle.

In conclusion, at higher *ALR*, finer liquid atomization promotes a more uniform coating of the solid particles, while the higher rate of entrained solids resulting from the larger jet expansion angle offers fast renewal of the bed solids within the jet cavity, and hence enhances the liquid-solid contact. Further experiments with different nozzle geometries will establish the relative importance of finer droplets and enhanced solids entrainment.

CONCLUSION

This study investigated the effect of varying the air-to-liquid ratio (*ALR*) on the performance of a gas-atomized spray nozzle. The nozzle performance was assessed both for injections into a gas-solid fluidized bed and for open-air sprays.

Increasing the *ALR* was beneficial below a critical *ALR* (1.5 - 2 wt%). As the *ALR* was further increased, benefits to the nozzle performance became progressively smaller. A satisfactory correlation was established between the data generated by the fluidized-bed experiments and a simple parameter that is function of *ALR* and gas voidage at the nozzle tip.

Both the spray atomization performance and the gas-solids entrainment into the jet derived from the spray expansion angle showed a similar behavior as the *ALR* was increased, and could be successfully correlated to the nozzle performance index.

NOMENCLATURE

a	attenuation of the photocell signal (V)
ALR	gas-to-liquid ratio (wt %)
d	width of the gas-liquid spray (mm)
d_d	droplet diameter (m)
f	correlation parameter (-)
NPI	Nozzle Performance Index (-)

Q_G, Q_L gas-liquid volumetric flow rate (m^3/s)
R auxiliary parameter defined by Eq. (3)
TI Temperature based Nozzle Performance Index (-)

Greek letters

α gas voidage (-)
ρ_G, ρ_L gas-liquid density (kg/m^3)
θ_{ext} expansion angle of the gas-liquid jet in the fluidized bed (degrees)
θ_{int} expansion angle of the gas-liquid spray in open air (degrees)

REFERENCES

[1] M. Gray, *Upgrading of petroleum residues and heavy oils*, Marcel Dekker Inc., New York, 1994.
[2] P. K. House, M. Saberian, C. Briens, F. Berruti, E. Chan, *Injection of a liquid spray into a fluidized bed: particle-liquid mixing and impact on fluid coker yields*, Ind. Eng. Chem. Res. 43 (2003) 5663-5669.
[3] S. Bruhns, J. Werther, *An investigation of the mechanism of liquid injection into fluidized beds*, AIChE J. 51 (2005) 766-775.
[4] B. A. Knapper, M. R. Gray, E. W. Chan, R. Mikula, *Measurement of efficiency of distribution of liquid feed in a gas-solid fluidized bed reactor*, Int. J. Chem. React. Eng. 1 (2003) A35.
[5] F. Portoghese, F. Berruti, C. Briens, E. Chan, *Novel triboelectric method for characterizing the performance of nozzles injecting gas-atomized liquid into a fluidized bed*, submitted for publication to Chem. Eng. Process. (2006).
[6] F. Portoghese, F. Berruti, C. Briens, *Use of triboelectric probes for on-line monitoring of liquid concentration in wet gas-solid fluidized beds*, Chem. Eng. Sci. 60 (2005) 6043-6048.
[7] F. Portoghese, F. Berruti, C. Briens, *Continuous on-line measurement of solid moisture content during fluidized bed drying using triboelectric probes*, Powder Technol. (2006), accepted for publication.
[8] E. W. Chan, T. E. Base, R. D. Kennett, D. A. Emberley, K. Jonasson, T. W. McCracken, A. J. Bennett, CA Patent 2224615, 1997.
[9] F. Portoghese, L. Ferrante, F. Berruti, C. Briens, E. Chan, *Effect of injection-nozzle operating parameters on the interaction between a gas-liquid jet and a gas-solid fluidized bed*, submitted for publication to Powder Technol. (2006).
[10] P. House, C. Briens, F. Berruti, E. Chan, *Predicting the pressure drop of internally mixed atomization nozzles*, submitted to Int. J. Chem. React. Eng. (2006).
[11] S. Ariyapadi, F. Berruti, C. Briens, P. Griffith, C. Hulet, *Modeling the injection of gas-liquid jets into fluidized beds of fine particles*, Can. J. Chem. Eng. 81 (2003) 891-899.

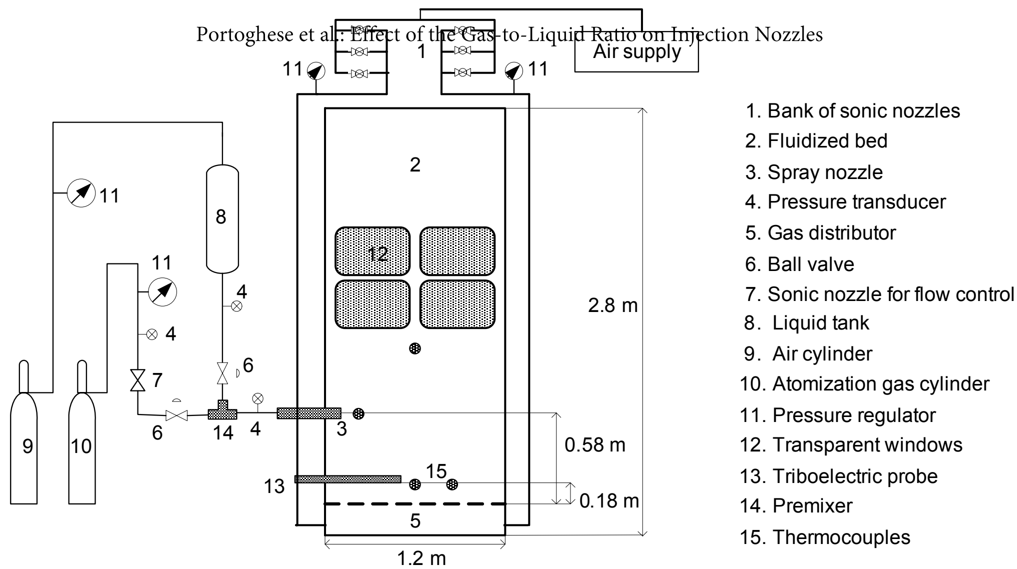

Figure 1. Schematic diagram of the fluidized bed apparatus.

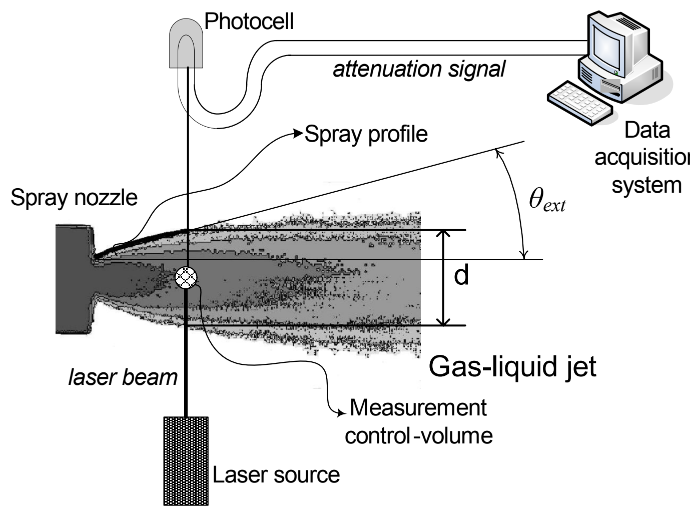

Figure 2. Schematic diagram of the laser-photocell arrangement.

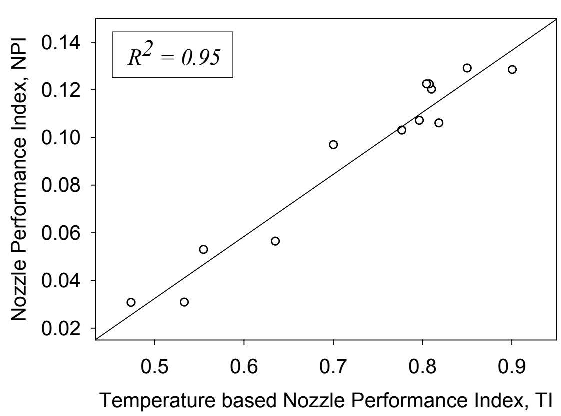

Figure 3. Correlation between the Nozzle Performance Index, *NPI*, and the Temperature based Nozzle Performance Index, *TI*.

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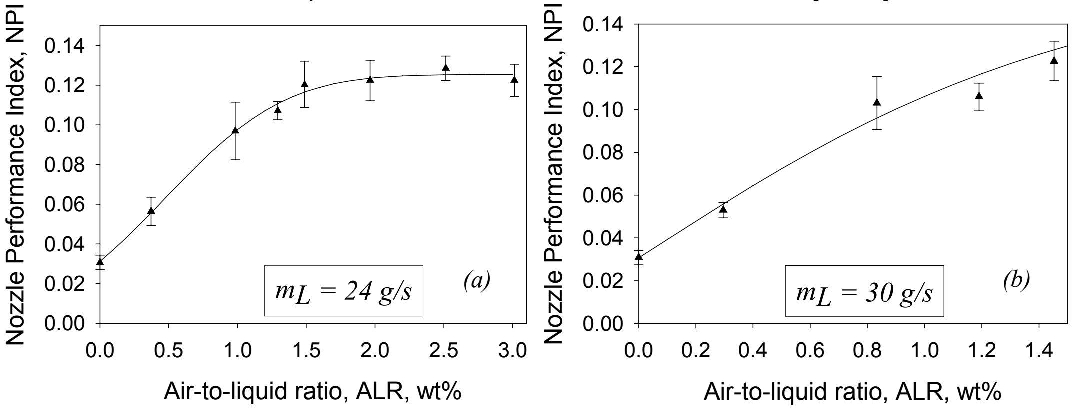

Figure 4. Effect of *ALR* on the Nozzle Performance Index, *NPI*, for two liquid flow rates: (*a*) m_L = 24 g/s; (*b*) m_L = 30 g/s.

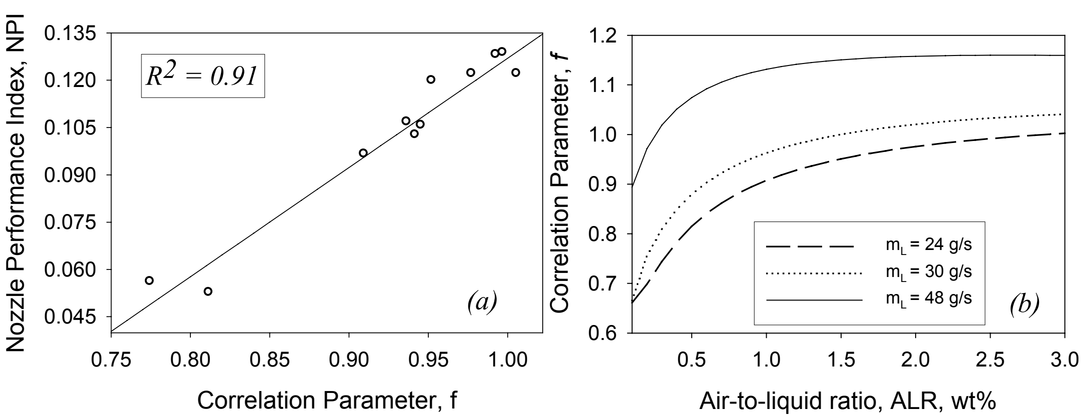

Figure 5. (*a*) Correlation between the Nozzle Performance Index, *NPI*, and the function *f*; (*b*) Predicted effect of varying the *ALR* at different liquid flow rates.

Table 1. Open-air spray width, *d*, for the tested *ALR*s.

ALR, wt%	0.4	1	1.5	2	3
d, mm	3.26	5.73	7.01	7.78	8.16
R, mm	0.78	0.64	0.54	0.46	0.33
a, V	0.22	0.42	0.53	0.57	0.61

Table 2. Open-air spray expansion angles, θ_{ext}, and estimated fluidized-bed expansion angles, θ_{int}.

ALR, wt%	0.4	1	1.5	2	3
θ_{ext}, º	3.6	8.6	12.65	13.5	14.25
θ_{int}, º	2.28	5.44	8	8.54	9.01