CHAPTER 4
RESULTS AND DISCUSSION

4.1 Flow regimes in airlift contactors

The effective operation of airlift contactor particularly in biochemical applications depends significantly on the flow regime in the contactors. One of the reasons for this is because the behavior of bubbles in the system varies according to the flow regime. Figure 4.1.1 illustrates the flow regime in the gas-liquid contactor as a function of superficial gas velocity. It can be seen that as the gas throughput increases, the fraction of gas in the contactor increases and this leads to a smaller contacting area between gas and liquid. In view of biochemical applications, the ideal system would be those that have the largest surface area between gas and liquid which will facilitate the mass transfer rate and, hence, the growth of microorganisms. Therefore the most suitable flow regime for this purpose would be either bubbly or churn flow regimes. In bubbly flow regime, gas bubbles flow uniformly in the system. The size of bubble is the smallest, and according to Wongsuchoto et al. (2002), bubble size in this flow regime ranged between 0.5 - 6 mm. It might be desirable to operate the system closer to churn flow regime as this flow regime often provides more turbulent condition which also enhances the mass transfer between gas and liquid. However, the size of bubble will be larger than that obtained from the bubbly flow condition. Bubbles in the system with this flow regime often have "cap" shape and move at high velocity.

This experiment was conducted to investigate the flow regime of the contactor with sea water instead of fresh water. It was unfortunate that bubbles formed in sea water always had small size and stayed closed to each other like a swarm, which made the measurement for bubble size difficult. Hence, for the sake of simplicity, the flow regime in this system was divided into two main categories. The first category was when the gas throughput was small. In this regime, only bubbles in riser were observed and the liquid velocity was not adequate for dragging the bubbles down the downcomer and this is called "No gas entrainment regime". As the gas velocity become higher more bubbles were dragged down the downcomer and the presence of bubbles in the downcomer became apparent, this regime is called "Gas entrainment regime" (See Figure 4.1.2).

Note that the range of superficial gas velocity employed in this work was controlled so as not to operate the contactor above the churn condition.

Let us define "critical superficial gas velocity" or "$u_{sg,c}$" as the velocity when the flow regime in the contactor changed form "without gas entrainment" to with "gas entrainment" regimes. The operation of different ALCs could then be summarized as follows:

A_d/A_r	$u_{sg,c}$ (cm/s) (water and sw15)	$u_{sg,c}$ (cm/s) (sw30 and sw45)
16.55	-	28.5
2.61	2.7	2.7
1.79	2.1	2.1
1.21	1.7	1.7

This experiment was carried out the ALCs with A_d/A_r of 16.55, 2.61, 1.79, and 1.21, when the salinity level varied from 0, 15, 30, 45 ppt. From visual observation, the critical gas velocities for the cases with air-water and air-sea water systems were found to be in the same range, except for the ALC with A_d/A_r of 16.55 where no gas entrainment was observed at all for the whole range of u_{sg} examined in this work. As bubbles in air-sea water system was observed to be smaller (detail in the next section), it was anticipated that the critical gas velocity in this system be smaller. This was because the presence of bubbles in the downcomer occurred only when the liquid velocity exceeded the terminal velocity of gas bubbles and small bubbles have smaller terminal velocity. Hence, it should be easier for the bubbles in air-seawater to move down into the downcomer. However, this was only apparent in the system with A_d/A_r of 16.55. It was believed that this unexpected results took place as the equipment did not allow fine adjustment gas velocity and the critical velocity might have lied within the velocity range that could not be manipulated.

4.2 Hydrodynamics in airlift contactors

Hydrodynamics is important in the design of airlift contactors as it controls the behavior of the system both in fluid dynamics and in mass transfer. Hydrodynamic parameters include gas holdups, liquid velocity and bubble characteristics. Gas holdup is the gas fraction in the system and in the ALC system, gas holdups are not uniformed but vary according to the location. Generally, there are three major gas holdups i.e. gas hold ups in overall, riser, and in downcomer. Liquid velocity is one of important hydrodynamic parameters which are generally controlled by the gas velocity (in batch system). Liquid velocity in the ALC also depends significantly on the location in the system. Often, there are two types of liquid velocity in the ALC, that is riser and downcomer liquid velocities. These two velocities must be related by the mass conservation law:

$$v_r A_r (1-\varepsilon_r) = v_d A_d (1-\varepsilon_d) \tag{4.1}$$

where, v_r riser liquid velocity (cm/s)

v_d downcomer liquid velocity (cm/s)

ε_r riser gas holdup (-)

ε_d downcomer gas holdup (-)

A_r riser cross sectional area (cm^2)

A_d downcomer cross sectional area (cm^2)

This research investigated the effect of salinity (0-45 ppt), ratio of downcomer to riser cross sectional areas (design parameter), and gas velocity (operating parameter) on these hydrodynamic parameters.

4.2.1 Gas holdup

4.2.1.1 Effect of salinity on gas holdup

Salinity changes the physical properties of liquid phase (See Appendix B) resulting in the varying bubble size. Bubble diameter is known to be controlled by the surface tension and the interaction between each bubble. Some might be more detail by considering also gas holdup in the gas-liquid separator section. In this work, however, gas holdup in the gas-liquid separator (the top part above the draft tube) was not taken into account. This was because this section only possessed small fraction of the entire volume of the contactor. Hence, the gas holdups of concerns in this work only included that in riser and downcomer, and overall gas holdup was the sum of these two holdups where the relationship between these gas holdups can be expressed as:

$$(1-\varepsilon_T)V_T = (1-\varepsilon_r)V_r + (1-\varepsilon_d)V_d \tag{4.2}$$

$$V_T = V_r + V_d \tag{4.3}$$

where, ε_T total gas holdup (-)

ε_r riser gas holdup (-)

ε_d downcomer gas holdup (-)

V_T total volume (cm^3)

Vr riser volume (cm^3)

V_d downcomer volume (cm^3)

Salinity was reported to increase the surface tension in water and therefore bubble size in sea water was expected to be larger than those in fresh water. Additional experiments were carried out to investigate the effect of salinity on bubble size. A small bubble column was operated with the same sparger as used in the ALC and the pictures were captured from this small system to facilitate the observation for bubble diameter. The results as shown in Figure 4.2.1 indicated that, surprisingly, increasing salinity in water led to a decreasing bubble size. This might occur due to the effect of hinder coalescence in the sea water. *(Prince, 1990)* Although liquid with higher surface tension could theoretically accommodate larger bubbles, high surface tension also prevents bubbles from coalescing. As the sparger employed in this work generated small bubbles, these bubbles tended not to coalesce and therefore systems with sea water (sw15, sw30, and sw45) were found to have small bubbles with similar size at 0.5-1.5 mm, whereas the system with tap water had a slightly larger bubble at 1.7-2.0 mm (Figure 4.2.1)

Figures 4.2.2 - 4.2.5 are a series of experimental results on gas holdups. In these figures, "w" represents "water" whereas sw represents "sea water". The number after "sw" indicates the level of salinity which is 15, 30 and 45 part per thousand (ppt), respectively. It is clear from these plots that the overall and downcomer gas holdups increased with increasing salinity level.

4.2.1.2 Effect of gas velocity on gas holdup

The overall, downcomer and riser gas holdups gradually increased with an increase in superficial gas velocity because increasing superficial gas velocity meant that more gas flow was added into the system at the same ratio of downcomer to riser cross sectional area. Thus, there was more gas content in the column and this was reflected in the higher gas holdup. Moreover, Wongsuchoto (2002) reported that high gas flow rate would lead to a higher level of bubble breakage (in air-water system). As small bubbles move at a slower speed than large bubbles, bubble breakage led to a higher contact time of gas bubbles and liquid in the system at any specific time. To put it more simply, higher gas throughputs in ALCs led to smaller bubble size and this resulted in longer residence time of bubbles in the system. This was one of the reasons why larger gas holdup was observed in the ALCs at high u_{sg}. At a very high u_{sg}, the gas holdup seemed to reach a constant level (as obvious with the system with A_d/A_r = 16.55). As the density of bubbles because significantly high, bubble coalescence played an important role in the system and the flow pattern started to enter the slug regime where the bubble size was extremely large (perhaps close to the diameter of riser). In this condition, gas content in the system did not notably vary with gas flow.

4.2.1.3 Effect of ratio of downcomer to riser areas on gas holdup

The ratio between downcomer and riser cross sectional areas (A_d/A_r) of the ALC is among one of the most important design parameters. This parameter is known to have marked influence on the behavior of the ALC. Often, larger riser or smaller A_d/A_r should result in more gas fraction (or gas holdup) in the contactor. In this work, this statement was re-confirmed. The experiment in fresh tap water was carried out and the results are displayed in Figure 4.2.6. In this figure (and in the following figures too), the notations DT1 to DT4 stand for the ALC with A_d/A_r of 16.55 (DT1), 2.61 (DT2), 1.79 (DT3), and 1.21 (DT4). Overall and downcomer gas holdups were found to increase as A_d/A_r decreases. In other words, the highest gas holdup was obtained in the system with A_d/A_r of 1.21 and the lowest with A_d/A_r of 16.55. Riser gas holdup, however, did not follow the same trend. It should be reminded that the comparison between ALCs was done at the same u_{sg} and u_{sg} was measured with respect to the riser cross sectional area. Therefore, although the various ALCs were with different A_d/A_r, the flow of gas in riser was at the same velocity. Hence, the gas holdup in the riser was anticipated to be within a similar range. Figures 4.2.6 - 4.2.9 illustrates that this statement was somewhat reliable as the gas holdup in the four ALCs were more or less in the same range.

4.2.2 Liquid velocity

4.2.2.1 Effect of salinity on liquid velocity

Liquid velocity is one of the important hydrodynamics parameters. In the batch system, liquid velocity is induced by the momentum/energy transfer from the gas bubbles in the system. Liquid velocity is also naturally induced from the difference between the fluid densities in riser and downcomer. The properties of liquid phase should have a significant role in regulating the liquid velocity in the system. In this case, salinity in sea water alters the surface tension and density of the liquid, and this was shown to have influenced bubble size and gas holdups in the system. Therefore it was expected that liquid velocity would change with liquid properties. The effect of design and operating parameters in the system with sea water might not be the same as in the air-water system. This aspect of sea water and liquid velocity was investigated in this section.

In air-sea water system, as bubble size was smaller than that in air-water system and since small bubbles move at lower speed than large bubble, it was expected that liquid velocity in the air-sea water be smaller than in air water system. However, the result demonstrated very scattering data and the effect of salinity on the liquid velocity was not clear and could not be concluded at this point.

4.2.2.2 Effect of gas velocity on liquid velocity

Increasing gas velocity means adding more gas into the system. This is also equivalent to adding more energy into the system. Therefore, with more energy/momentum transfer from gas to liquid, an increase in liquid velocity was obtained as shown in Figures 4.2.10 - 4.2.17. Interestingly, liquid velocity in riser was found to linearly increase with superficial gas velocity whilst downcomer liquid velocity seemed not to be significantly affected. This should not be possible as downcomer liquid velocity should follow riser liquid velocity to satisfy the mass conservation principle. To verify this result, a simple calculation was made to check the existence of mass conservation between riser and downcomer. According to the mass conservation principle, the mass or volume flow of liquid in riser must be equal to that in downcomer or:

$$Q_{Lr} = Q_{Ld} \qquad (4.4)$$

or

$$v_r(1-\varepsilon_r)A_r = v_d(1-\varepsilon_d)A_d \qquad (4.5)$$

Figures 4.2.10-4.2.17 demonstrates the comparison between the volume flows in riser and downcomer at various levels of salinity and different A_d/A_r. It was clear that the volume flow in downcomer was always lower than that in riser. The liquid velocity measured by the color tracer technique could only represent the velocity of the portion of liquid moving downwards. The fraction of area of downcomer for this liquid portion was smaller than the total area and therefore the calculation in Eq (4.4) was not accurate. Similarly, when riser became large, there must exist local liquid circulation in riser and the calculation of liquid flow in riser in Eq.(4.5) was over estimated. More experiment must be carried out to identify this local liquid circulation in this ALC system. Information provided in Wongsuchoto (2002) should be consulted for this additional experiment.

4.2.2.3 Effect of ratio of downcomer area to riser area on liquid velocity

The ratio of riser and downcomer cross sectional areas is an important factor defining liquid velocity. Figures 4.2.14 to 4.2.17 illustrate the effect of A_d/A_r on liquid velocity. In these figures, DT1 represents the system with A_d/A_r of 16.55, DT2, A_d/A_r = 2.61, DT3, A_d/A_r =1.79, DT4, A_d/Ar =1.21. Large A_d/A_r meant that the cross sectional area of riser was small in composition with that of downcomer. In this case, bubbles became were dense and there was more interaction between gas bubbles which might lead to bubble coalescence. As a result, a larger bubble size was obtained. This large bubble moved at higher velocity and therefore induced a faster liquid velocity. In the system with small A_d/A_r, on the other hand, less bubble interactions in the riser caused less bubble coalescence and therefore bubble size remained unaltered and small. Consequently, less liquid velocity was observed.

4.3 Overall gas-liquid mass transfer in airlift contactors

Gas-liquid mass transfer is generally critical for the design of bioreactors. This mass transfer depends on several parameters which could be expressed in terms of mass transfer coefficient (k_L), mass transfer area (A) and the concentration difference driving force (ΔC):

$$Q_{O_2} = k_L A \Delta C \tag{4.6}$$

where Q_{O2} oxygen transfer rate (g/s)

k_L mass transfer coefficient (cm/s)

A interfacial gas-liquid mass transfer area (cm^2)

ΔC concentration difference driving force (g/cm^3)

ΔC usually cannot be manipulated as this depends on the equilibrium in the gas-liquid and the consumption rate (by micro organism in bioreactors). It is general to focus on the mass transfer coefficient and area in the design and control of such system. However, problems always lie at the determination of mass transfer area, and therefore the overall volumetric mass transfer coefficient (k_La) was introduced

$$Q_{O_2} = k_L a (C_L^* - C_L) V \tag{4.7}$$

where: a is the specific area or the mass transfer per unit volume of the dispersion and k_La can be measured using the dynamic method (Wongsuchoto, 2002). In this method, it was assumed that the system was homogeneous. However, the ALCs employed in this work might not fit with this experiment. Hence, the measurement for dissolved oxygen (DO) in the contactor was performed at several locations to check for its consistency. The results indicated that local k_La at various location in the contactor varied within ±10 %. This small variation suggested that the dynamic method could well be used in this system.

4.3.1 Effect of salinity on overall volumetric gas-liquid mass transfer coefficient

Figures 4.3.1 - 4.3.4 illustrate that k_La was higher with the sea water in the liquid. This could be described as the effects of the increases in both specific area and the overall volumetric mass transfer coefficient.

Sections 4.2.1.1 and 4.2.2.1 indicated that salinity affected liquid properties as shown in Table B-1(Appendix B). Specifically speaking, surface tension and viscosity increased when salinity increased and this condition could accommodate larger bubble. However, the bubble in sea water system was found to be smaller than fresh water and this was attributed to the hinder coalescence of component in sea water. Salinity was found to increase gas holdup in the system. The bubble size was also small with the addition of salinity. Hence, the system with sea water should have high mass transfer area.

From visual observation, some bubbles were spherical in shape and some were ellipsoidal, so the equivalent size of bubbles (d_B) must be calculated where:

$$d_B = \left(p^2 q\right)^{1/3} \tag{4.8}$$

where d_B the equivalent size of bubble (mm)

p the width size of bubble (mm)

q the height size of bubble (mm)

Interfacial gas-liquid mass transfer per volume can be calculated from:

$$\text{area of bubble} = 4\pi\left(\frac{d_B}{2}\right)^2 \tag{4.9}$$

and the total mass transfer area is:

$$A_b = N_b\left(4\pi\left(\frac{d_B}{2}\right)^2\right) \tag{4.10}$$

where N_b is the number of bubbles in the system.

Hence, the interfacial gas-liquid mass transfer area per volume, a, can be calculated from:

$$a = \frac{N_b}{V}\left(4\pi\left(\frac{d_B}{2}\right)^2\right) \tag{4.11}$$

since

$$\varepsilon = \frac{V_b}{V} \tag{4.12}$$

where V_b bubble volume (cm^3)

V system volume (cm^3)

Substituting V_b by the total volume of each bubble into Eq. (4.12) leads to:

$$\varepsilon = \frac{\frac{4}{3}\pi\left(\frac{d_B}{2}\right)^3 N_b}{V} \tag{4.13}$$

Rearranging Eq. (4.13) to calculate N_b/V:

$$\frac{N_b}{V} = \frac{\varepsilon}{\frac{4}{3}\pi\left(\frac{d_B}{2}\right)^3} \tag{4.14}$$

Substituting N_b/V from Eq.(4.14) into Eq. (4.11) gives:

$$a = \frac{6\varepsilon}{d_B} \tag{4.15}$$

As the bubble size and gas holdup changed with salinity level, "*a*" in the ALC at various salinity levels (information from DT3) could be summarized as follows:

u_{sg} (cm/s)	d_B (mm)				ε(–)				a (1/mm)			
	w	sw15	sw30	sw45	w	sw15	sw30	sw45	w	sw15	sw30	sw45
2.1	4.00	1.10	0.20	1.27	0.03	0.03	0.03	0.04	0.04	0.18	0.20	0.19
3.1	4.89	1.60	0.14	1.26	0.04	0.05	0.05	0.05	0.05	0.18	0.14	0.26
4.7	4.95	3.63	0.12	3.36	0.06	0.07	0.07	0.07	0.07	0.11	0.12	0.13
6.2	3.00	3.39	0.13	3.33	0.07	0.08	0.08	0.08	0.14	0.13	0.13	0.15
8.0	4.04	3.09	0.17	2.92	0.07	0.08	0.09	0.09	0.11	0.16	0.17	0.18
9.6	4.82	2.78	0.21	2.26	0.09	0.09	0.10	0.10	0.11	0.19	0.21	0.27
12.0	3.75	2.62	0.26	2.17	0.10	0.10	0.11	0.11	0.16	0.23	0.26	0.30

Next, the mass transfer coefficient, *k*, in the ALC system with sea water was compared to that with water. It is generally known that "*k*" is a function of Sherwood number (Sh), Reynolds number (Re) and Schmidt number (Sc) where:

$$Sh \; \alpha \; Re\, Sc \tag{4.16}$$

or:

$$\frac{k_L d}{D} = c\left(\frac{\rho v d}{\mu}\right)^a \left(\frac{\mu}{\rho D}\right)^b \tag{4.17}$$

where *a, b,* and *c* are empirical constants.

Hence, the relationship between "*k*" and other liquid/bubble properties could be summarized as:

$$k_L \; \alpha \; \left(\frac{\rho}{\mu}\right)^{a-b} \frac{1}{d^{1-a}} \tag{4.18}$$

where d_b bubble diameter (m)

ρ density (kg/m^3)

μ viscosity (cp)

D diffusivity of gas or solute in liquid (m^{2}s^{-1})

v velocity (ms^{-1})

"a" and "b" were reported to vary between 0.3-0.6 (Wongsuchoto, 2002) depending on the flow condition in the reactor.

As "ρ" of water and sea water did vary significantly with the lowest of 997 kg/m^3 and the highest of 1047 kg/m^3, the effect of the variation in ρ to k_L was assumed to be negligible. Similarly, "μ" varied only in a narrow range with a span only from 0.95(water) to 0.99(sw45) cp. Hence, the influence of μ on k_L should be negligible. Therefore k_L should depend solely on $1/d^{\{1-a\}}$ where a smaller d would result in a higher k_L. It was expected then that k_L in sea water system was higher than k_L in water system. Thus, theoretically, k_La in the air-sea water system should be higher than that in the air-water system as both "a" and "k_L" were supposed to be higher with salinity level. However, experiments revealed that this was not the case. In A_d/A_r of 16.55, the results shows the highest k_La was found in the ALC with sw45 but in many other cases, k_La at sw 45 was no longer the highest not to mention those cases where k_La of air-water system was higher than that of sw45. This might be because the flow condition in the sea water system was not as rigorous as that in the water system. As the bubbles in water were larger than those in sea water, a more turbulent condition was usually observed in the ALC. This meant that the analysis using Eq.(4.18) was not accurate as "a" and "b" for water and sea water should not be the same. To characterize this flow condition, additional experiment must be carried out to have a better statistical evaluation of such correlation. This is remained here as a recommendation for future work.

4.3.2 Effect of gas velocity on overall volumetric gas-liquid mass transfer coefficient

The effect of gas velocity on overall volumetric gas-liquid mass transfer coefficient is illustrated in Figures 4.3.1 to 4.3.8. The result shows that k_La increased with an increase in superficial gas velocity. However, there seemed to be a region where these was a drop in k_La. This often occurred at u_{sg} of approx. 5-8 cm/s.(except the case with A_d/A_r of 16.55 where a drop in k_La was not observed). This phenomenon corresponded well with the time profile of riser gas holdup in Figures 4.2.i. At approximately the same range of superficial gas velocity, a drop in riser gas holdup was also apparent. The actual reason for this drop could not be explained at the time of this experiment but it was expected to be due to the change in the flow regime in the contactor. At low gas throughput, the system should be in the bubbly flow regime where there was a well distribution of small air bubbles throughout the contactor. Bubbles size was small as coalescence was prohibited due to high surface tension. As more gas was added into the system, the contactor entered a turbulence or churn turbulence regime where bubble coalescence became more significant. This increased the bubble size, and consequently, the speed of gas bubbles in the system increased which led to a drop in the riser gas holdup. The result suggested that k_La varied significantly with riser gas holdup and not with overall or downcomer gas holdups as no drops in these gas holdups were observed clearly from the experiment. It is possible, therefore, to conclude that most of the mass transfer took place in riser. Considering a comparison between Figures 4.2.i(C) and Figures 4.3.i, this conclusion became more apparent. In short, the variation in k_La in the ALCs with various salinity levels followed the trends of riser gas holdup quite closely.

4.3.3 Effect of ratio of downcomer area to riser area on overall volumetric gas-liquid mass transfer coefficient

In large riser ALC (small A_d/A_r), bubble dispersed in liquid phase without coalescence, thus, there was more interfacial gas-liquid area for mass transfer. On the other hand, small riser promoted more bubble coalescence which led to a smaller mass transfer area. Also in the ALCs with small A_r, less gas was supplied to the system at the same superficial gas velocity. Therefore the comparison based on the same superficial gas velocity would result in a lower mass transfer coefficient. This was illustrated in Figures 4.3.5-4.3.8 where a reduction in k_La was obtained in the ALCs with larger A_d/A_r.

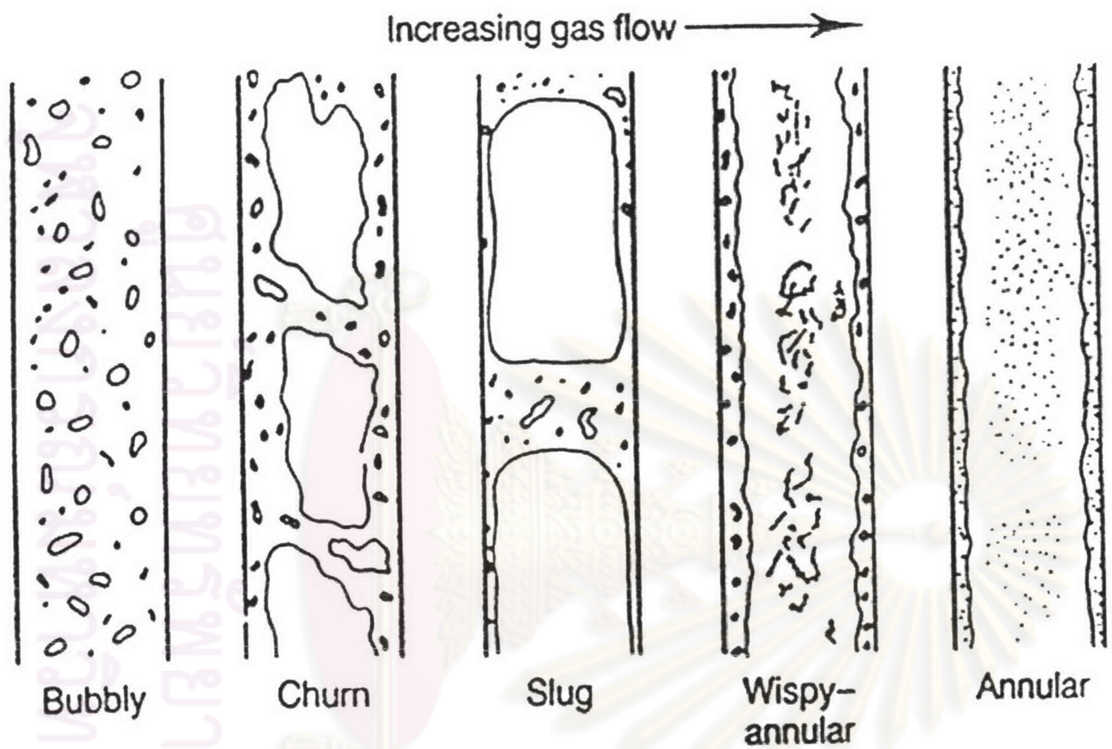
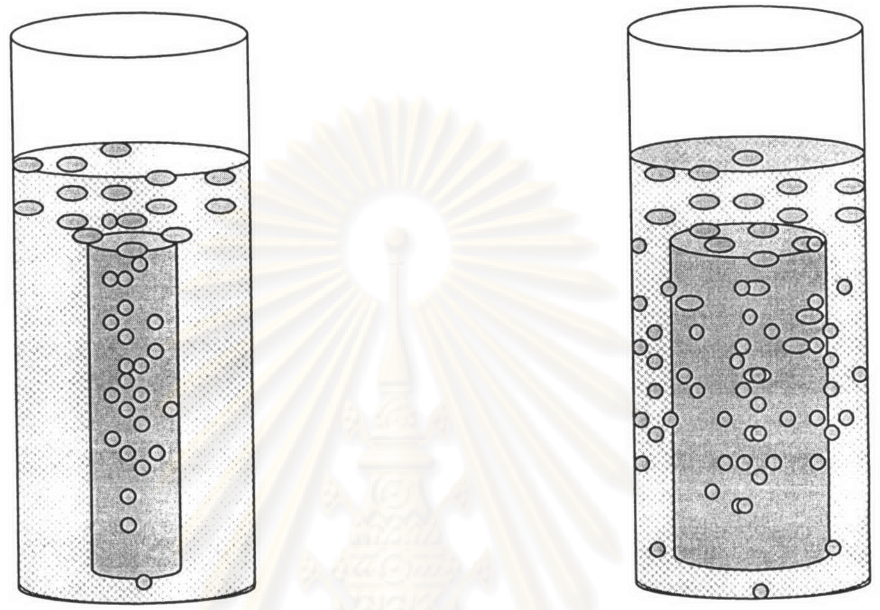
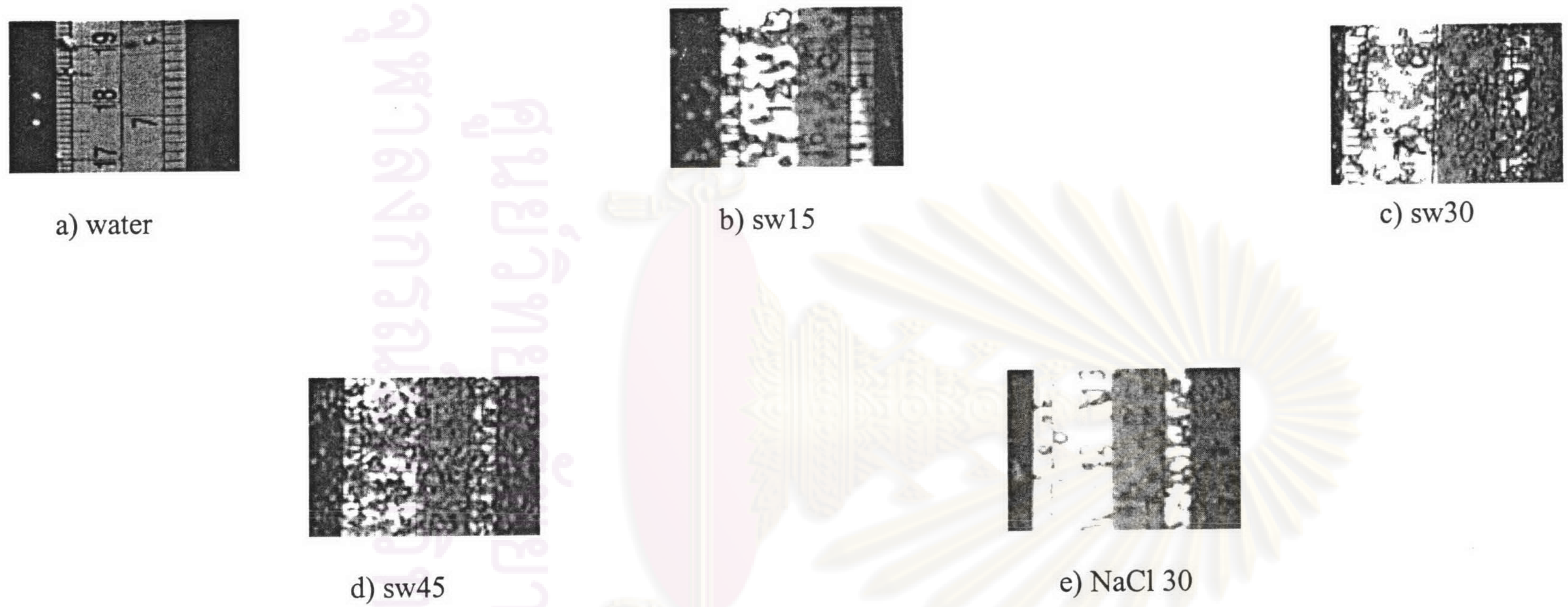


Figure 4.1.1 Flow regimes in vertical direction with increasing gas flow rate



(a) (b)

Figure 4.1.2 Flow regimes (a) No gas entrainment (b) Gas entrainment



a) water b) sw15 c) sw30 d) sw45 e) NaCl 30

Figure 4.2.1 Comparison of bubble size with various liquids

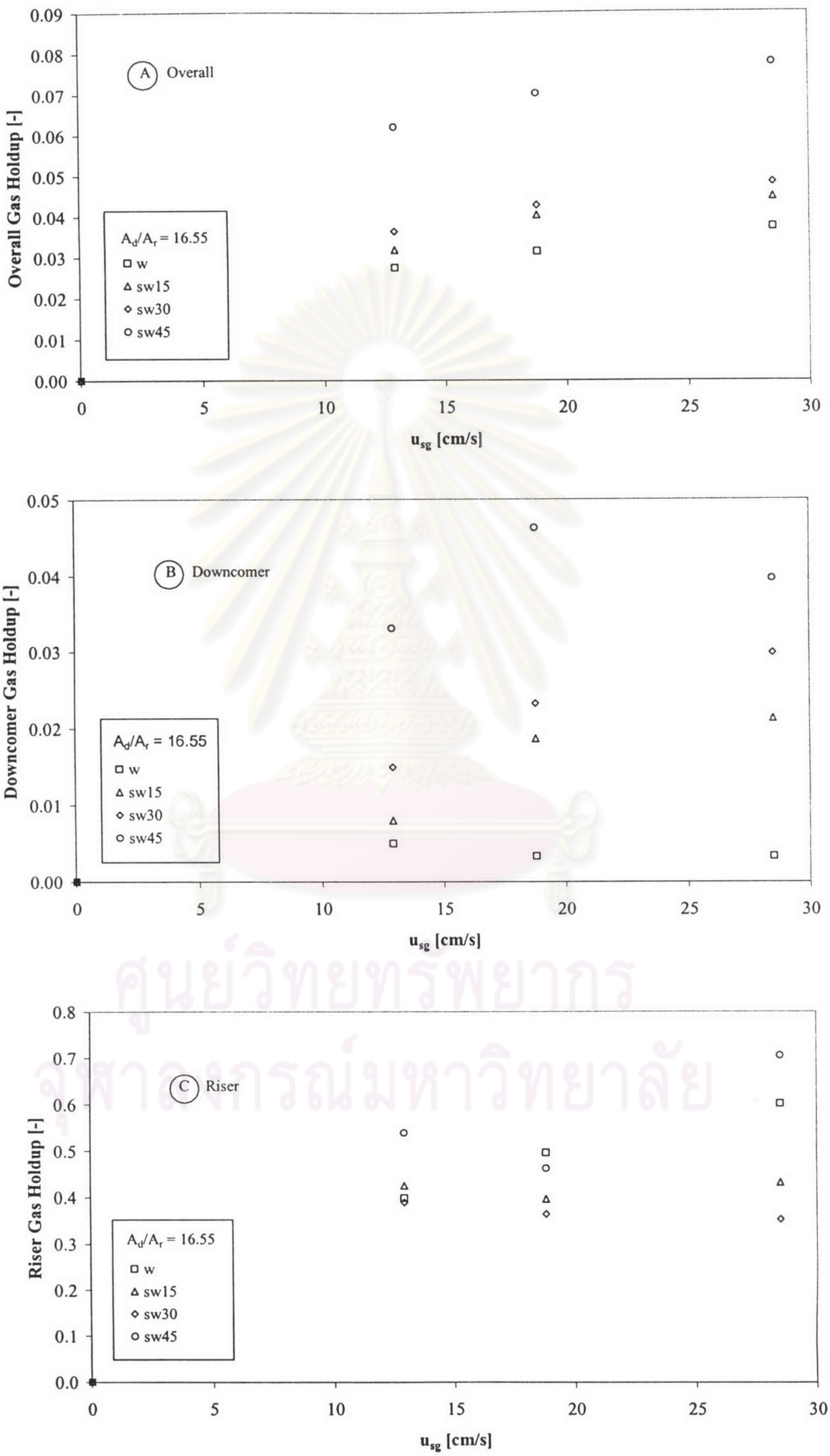


Figure 4.2.2 Effect of salinity on gas holdups in ALC with A_d/A_r of 16.55

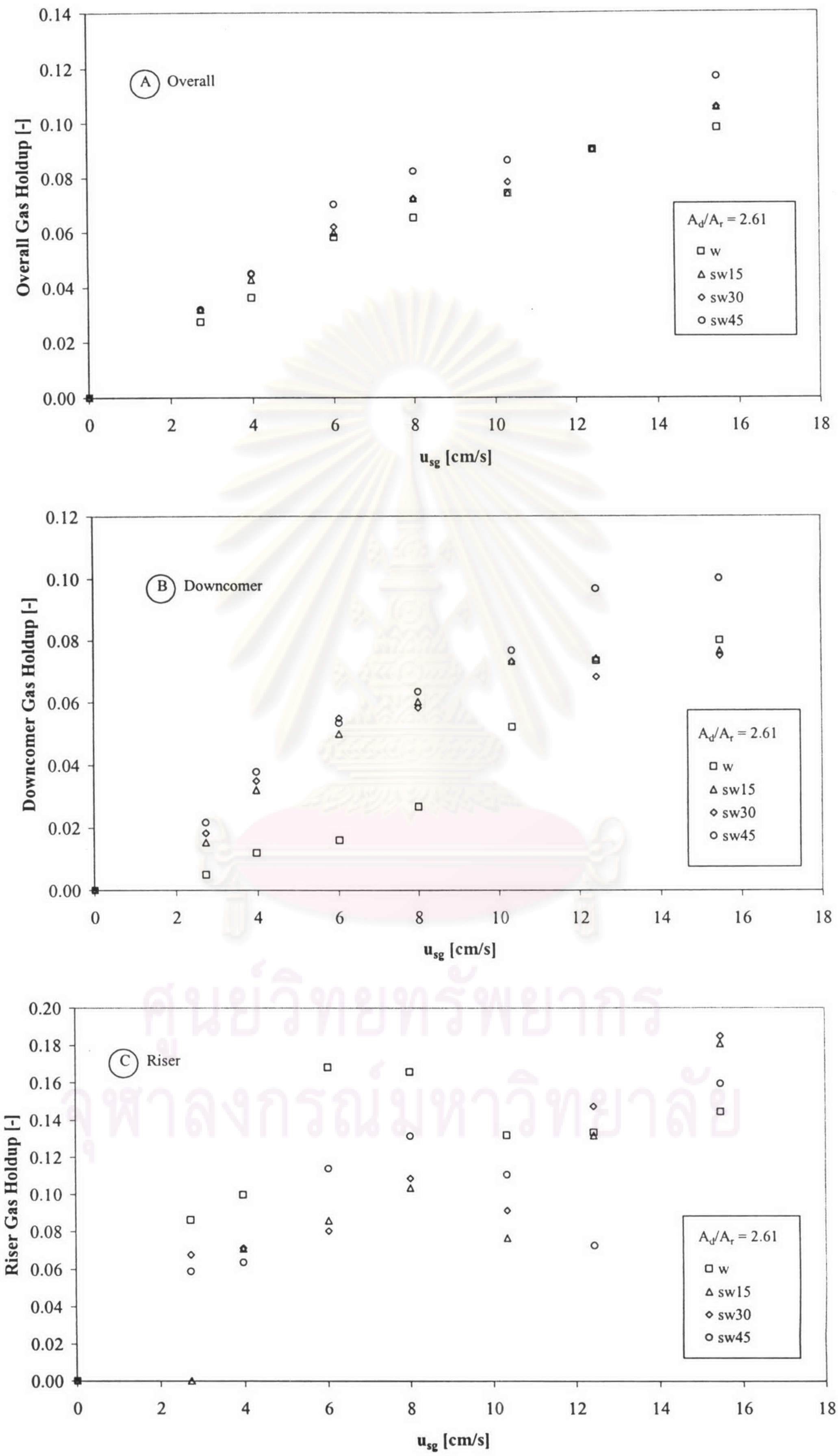


Figure 4.2.3 Effect of salinity on gas holdups in ALC with A_d/A_r of 2.61

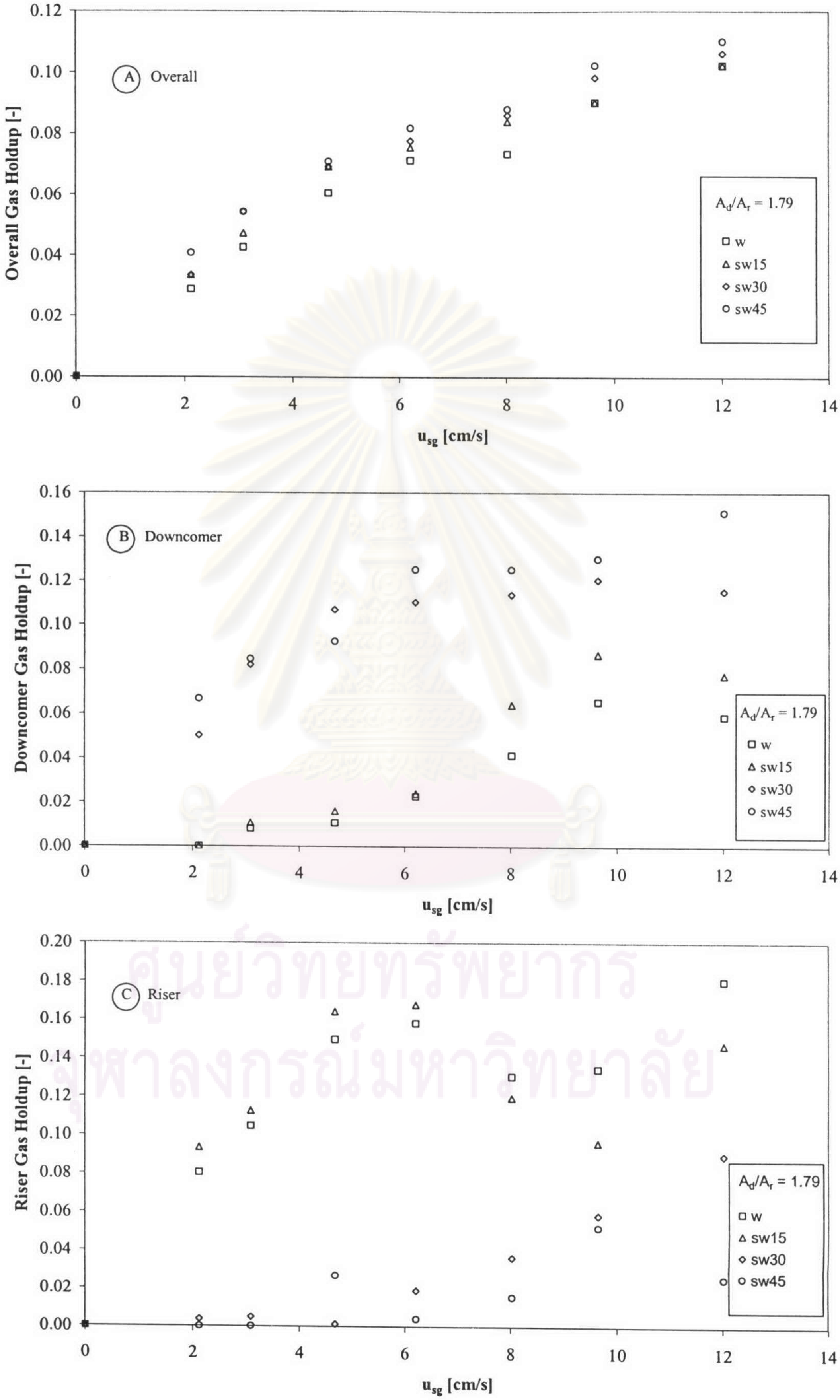


Figure 4.2.4 Effect of salinity on gas holdups in ALC with A_d/A_r of 1.79

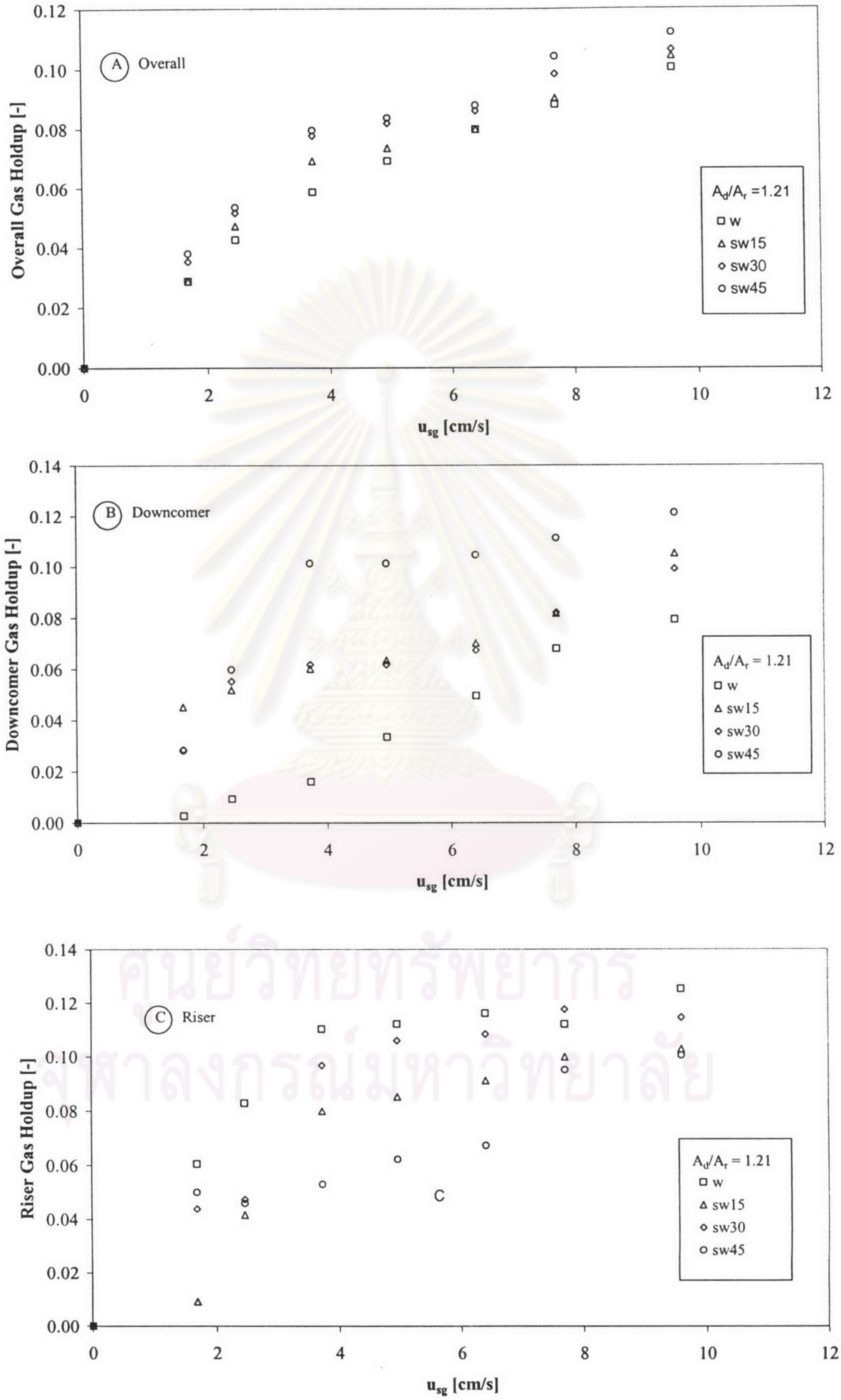


Figure 4.2.5 Effect of salinity on gas holdups in ALC with A_d/A_r of 1.21

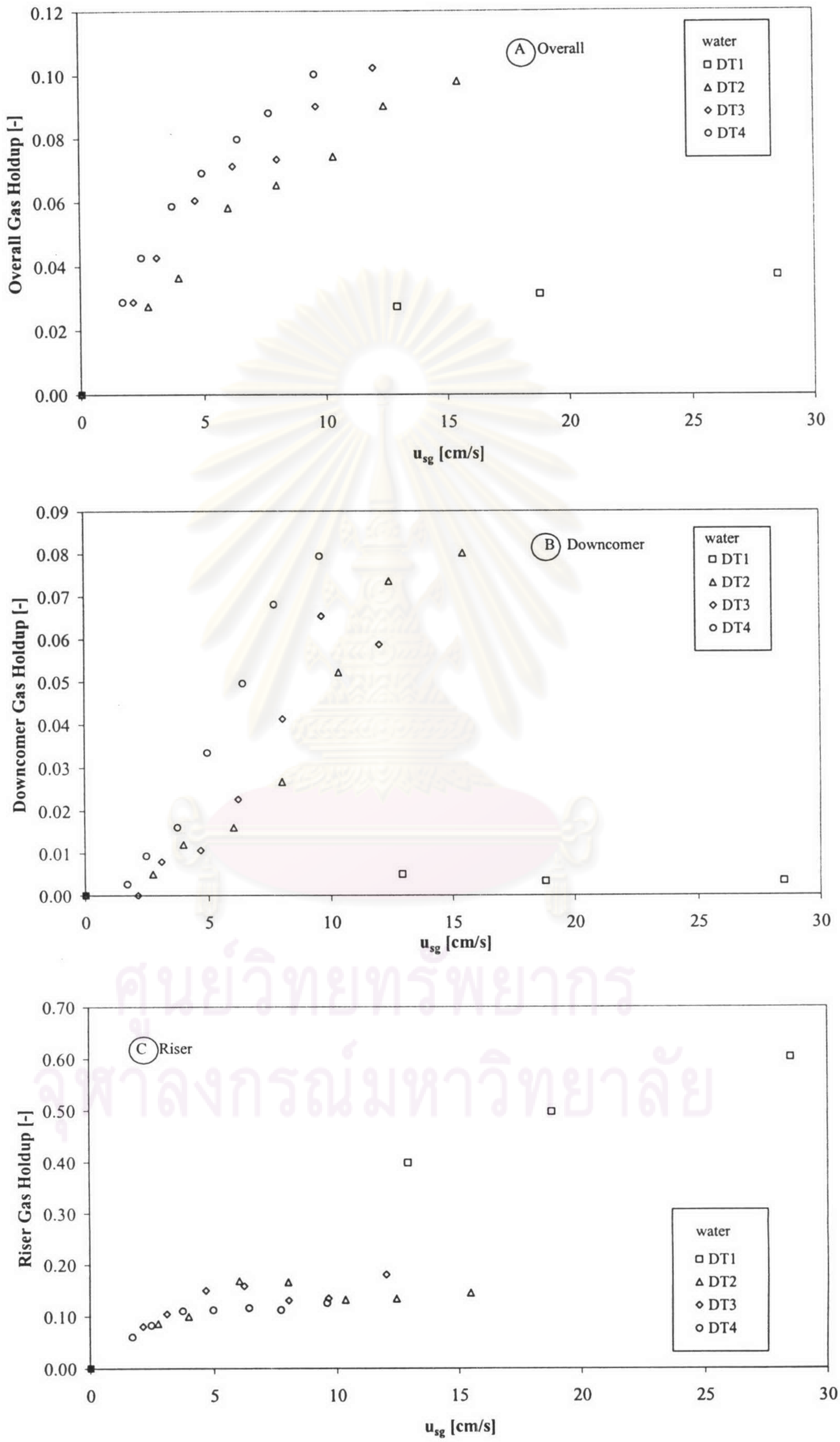


Figure 4.2.6 Effect of A_d/A_r on gas holdups in ALC with water

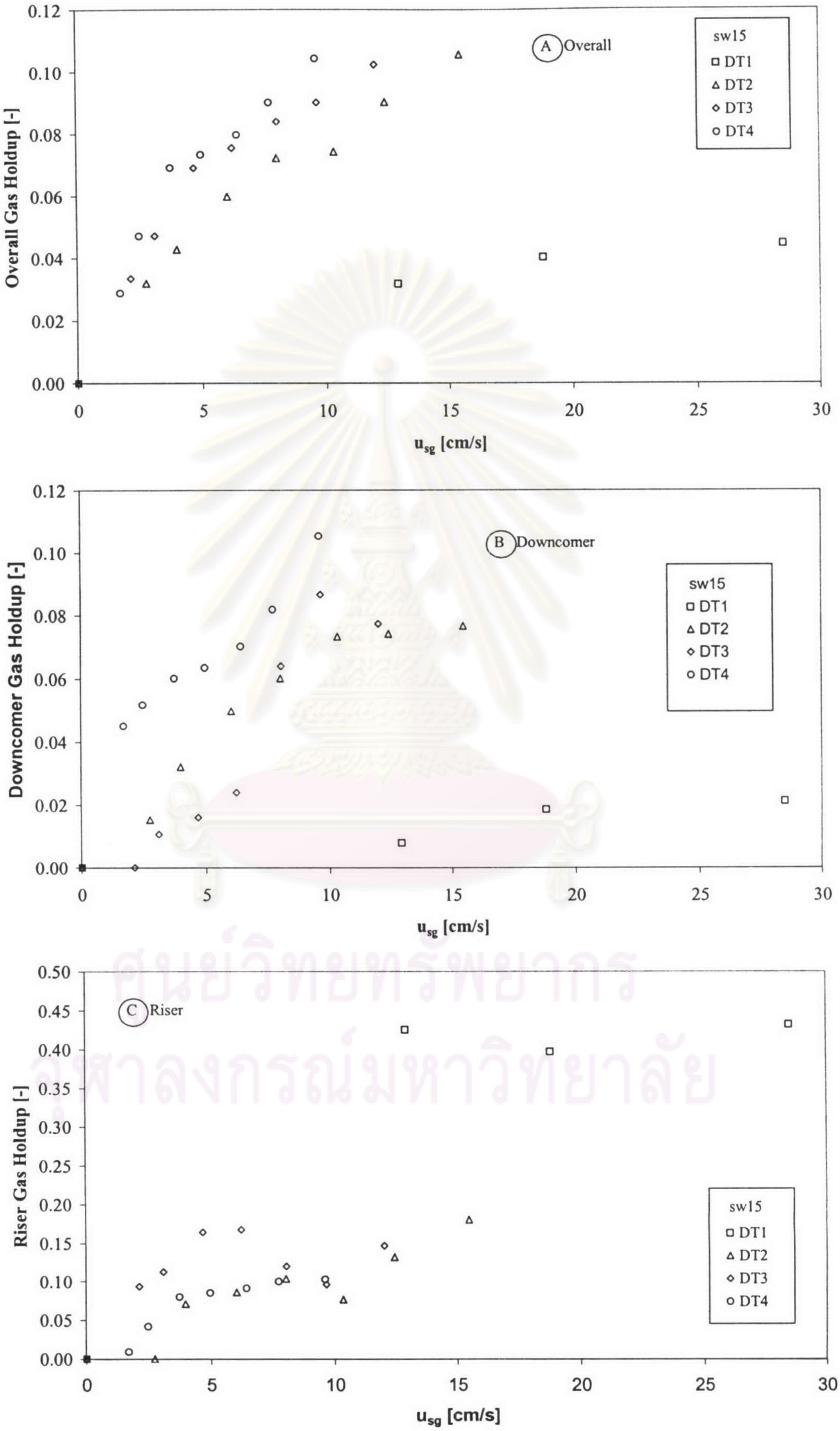


Figure 4.2.7 Effect of A_d/A_r on gas holdups in ALC with sw15

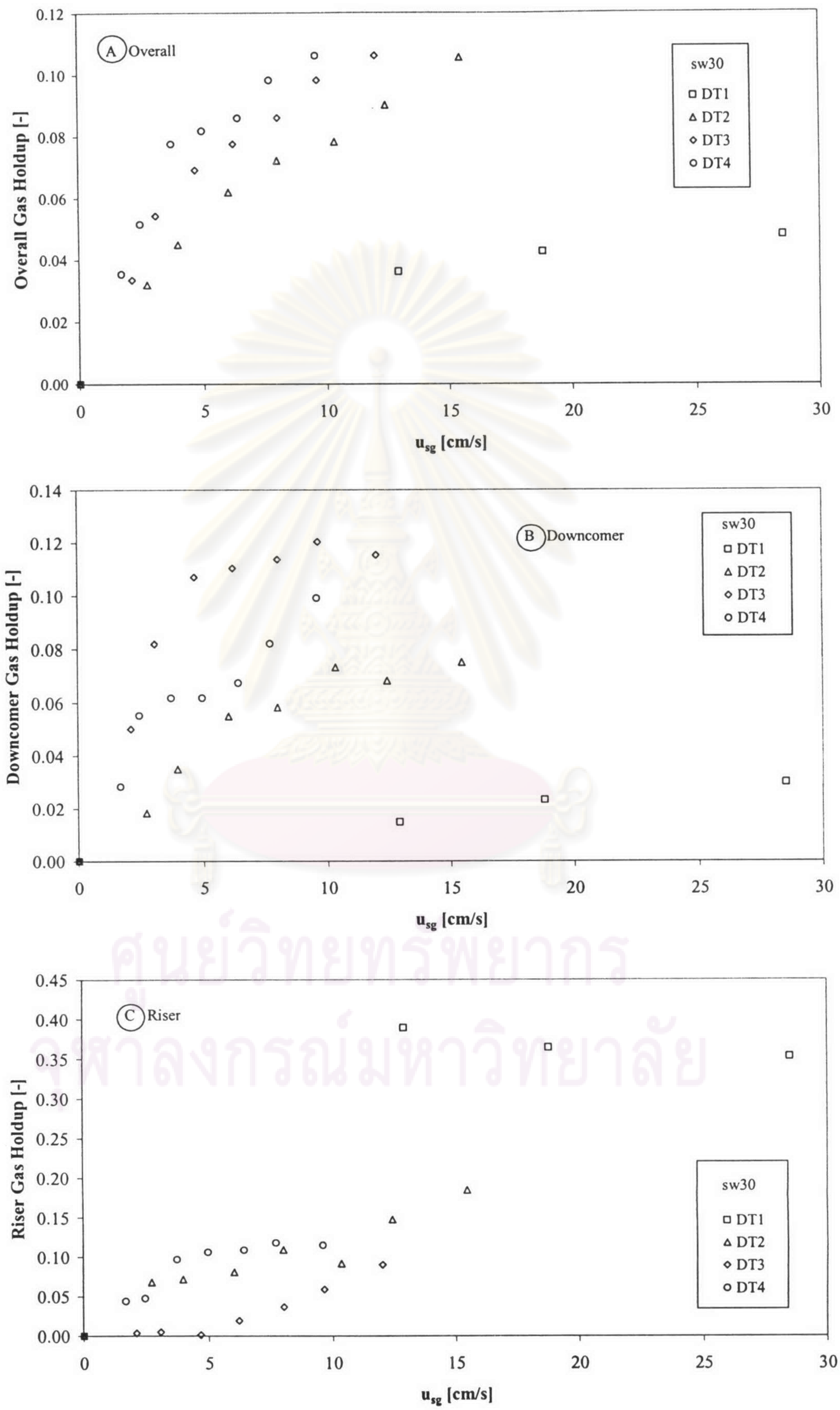


Figure 4.2.8 Effect of A_d/A_r on gas holdups in ALC with sw30

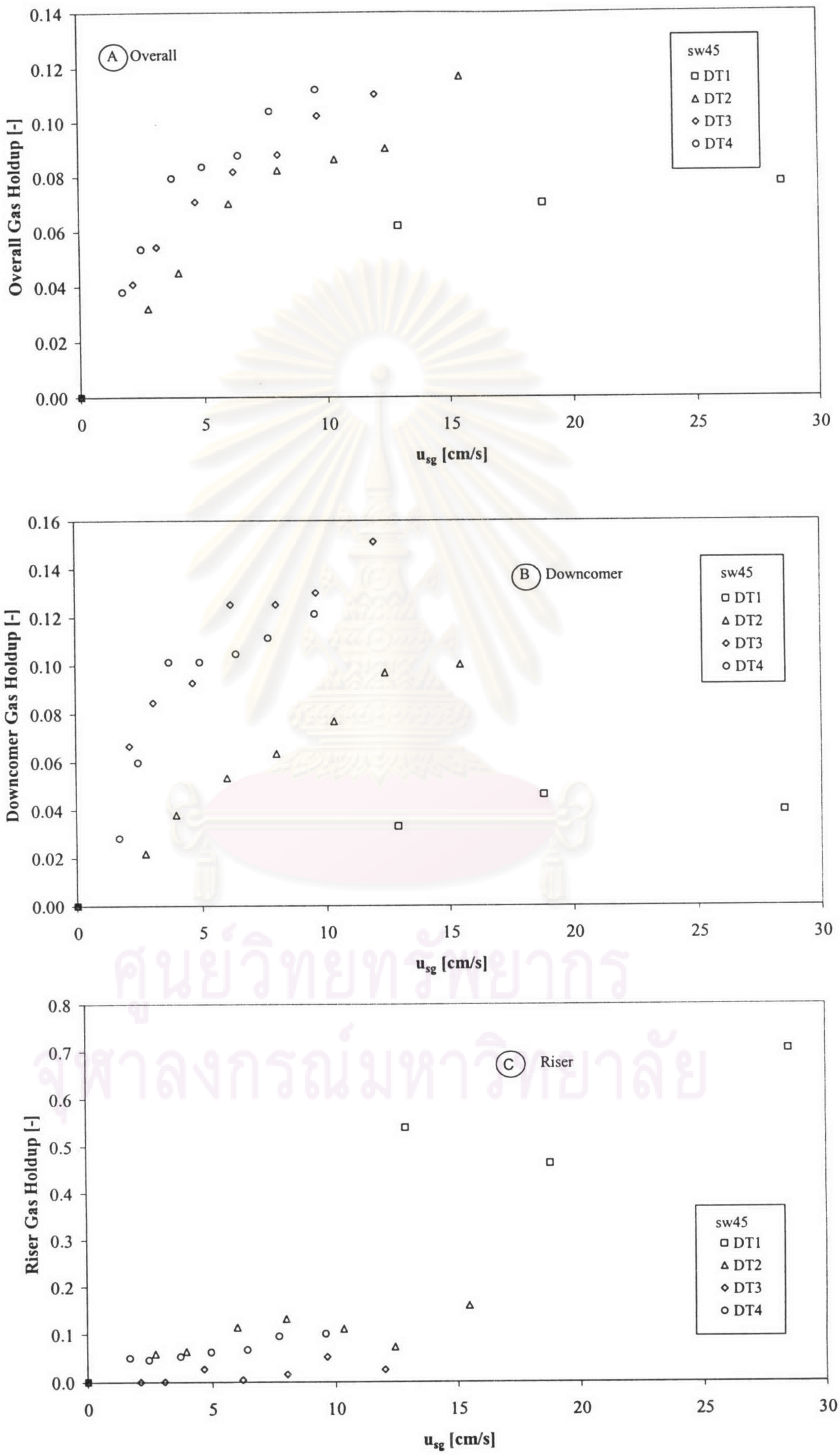


Figure 4.2.9 Effect of A_d/A_r on gas holdups in ALC with sw45

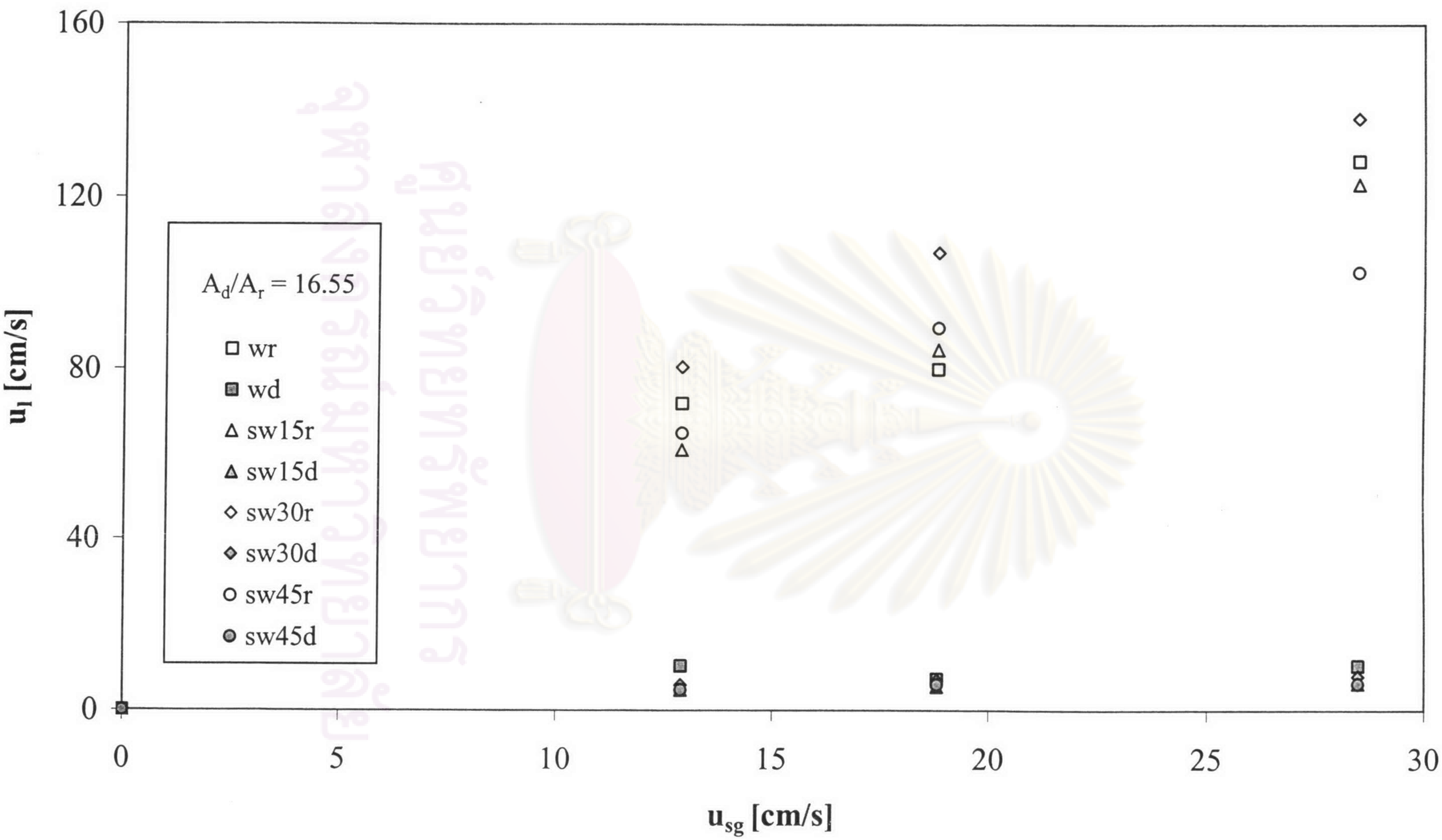


Figure 4.2.10 Effect of salinity on liquids velocity in ALC with A_d/A_r of 16.55

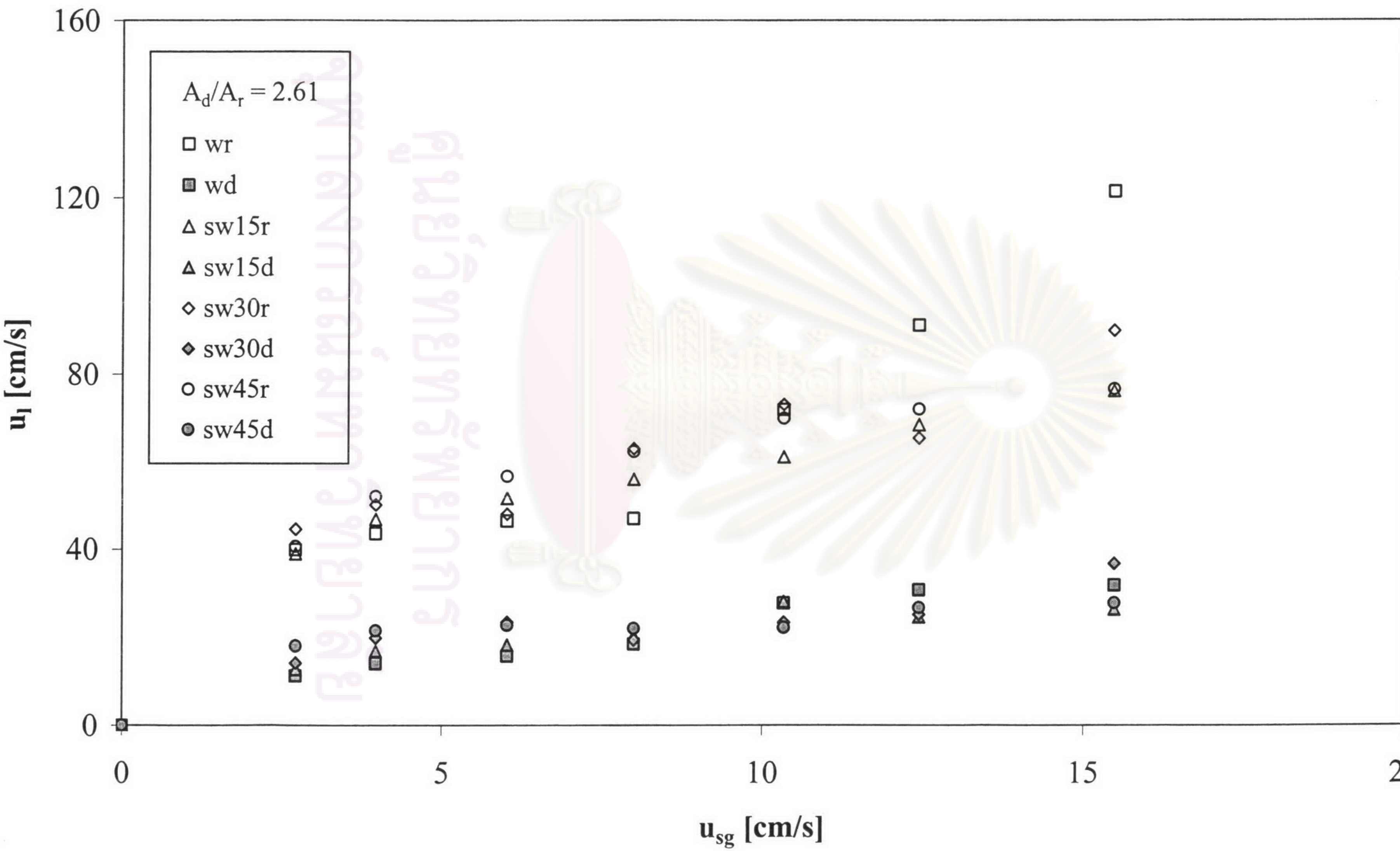


Figure 4.2.11 Effect of salinity on liquids velocity in ALC with A_d/A_r of 2.61

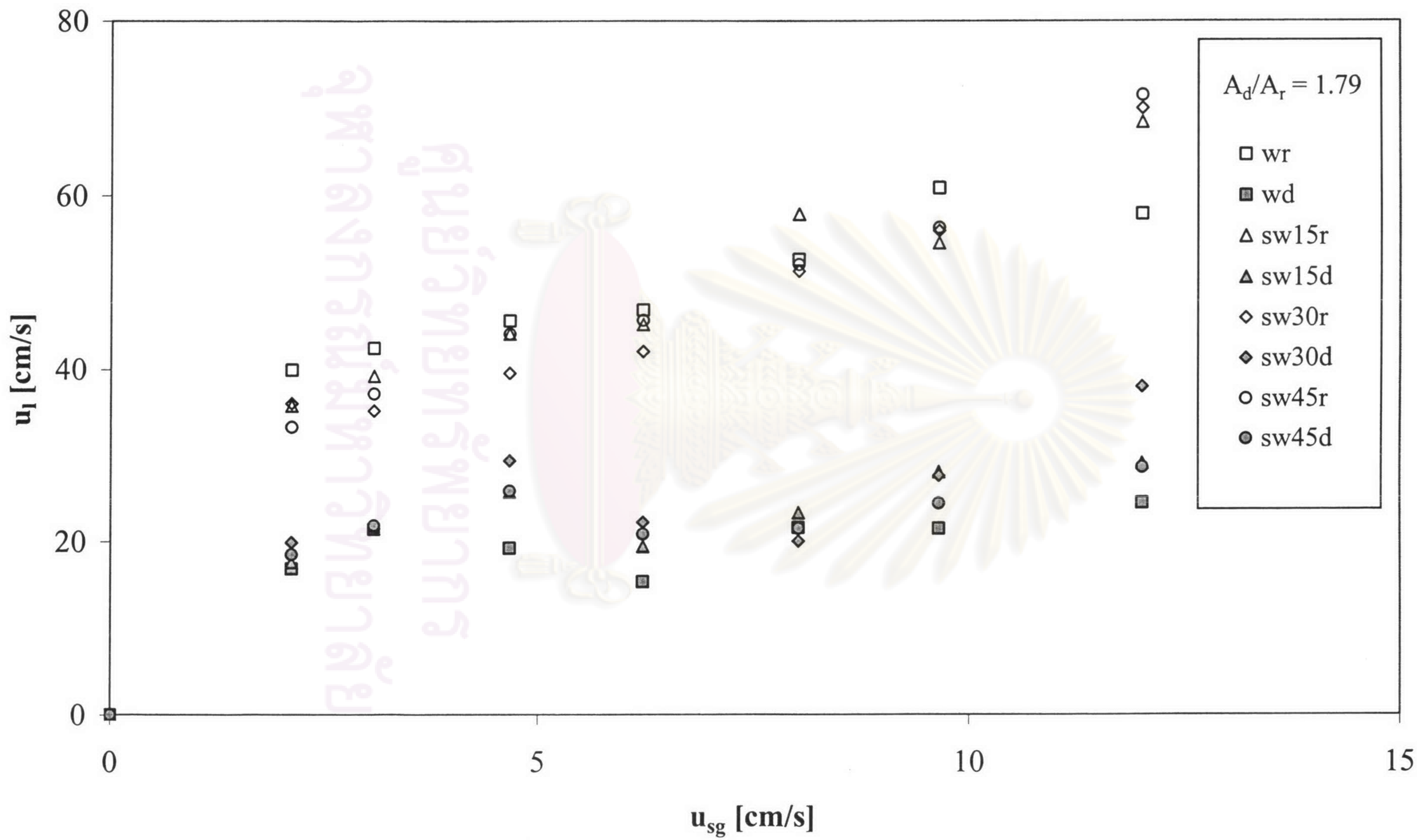


Figure 4.2.12 Effect of salinity on liquids velocity in ALC with A_d/A_r of 1.79

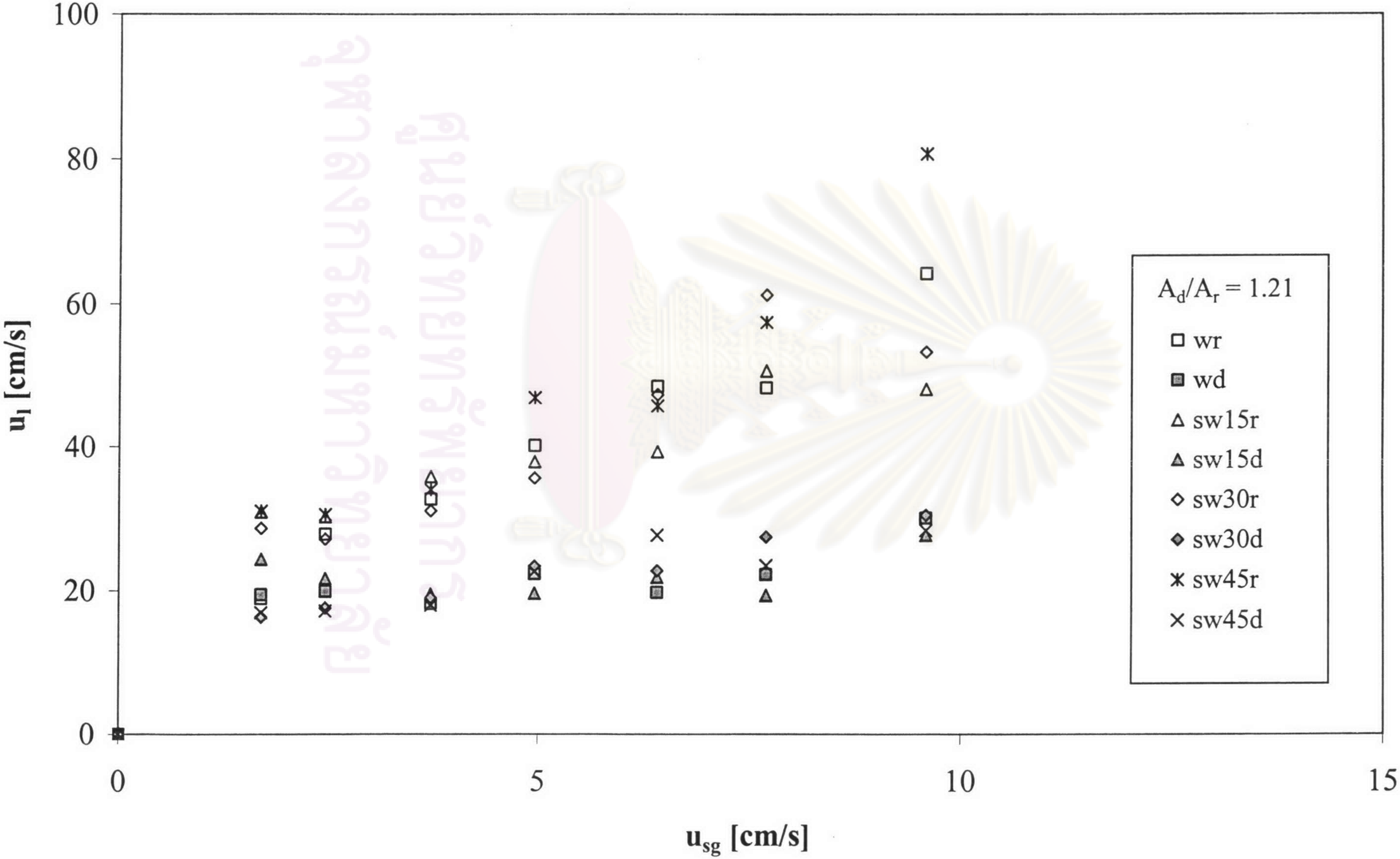


Figure 4.2.13 Effect of salinity on liquids velocity in ALC with A_d/A_r of 1.21

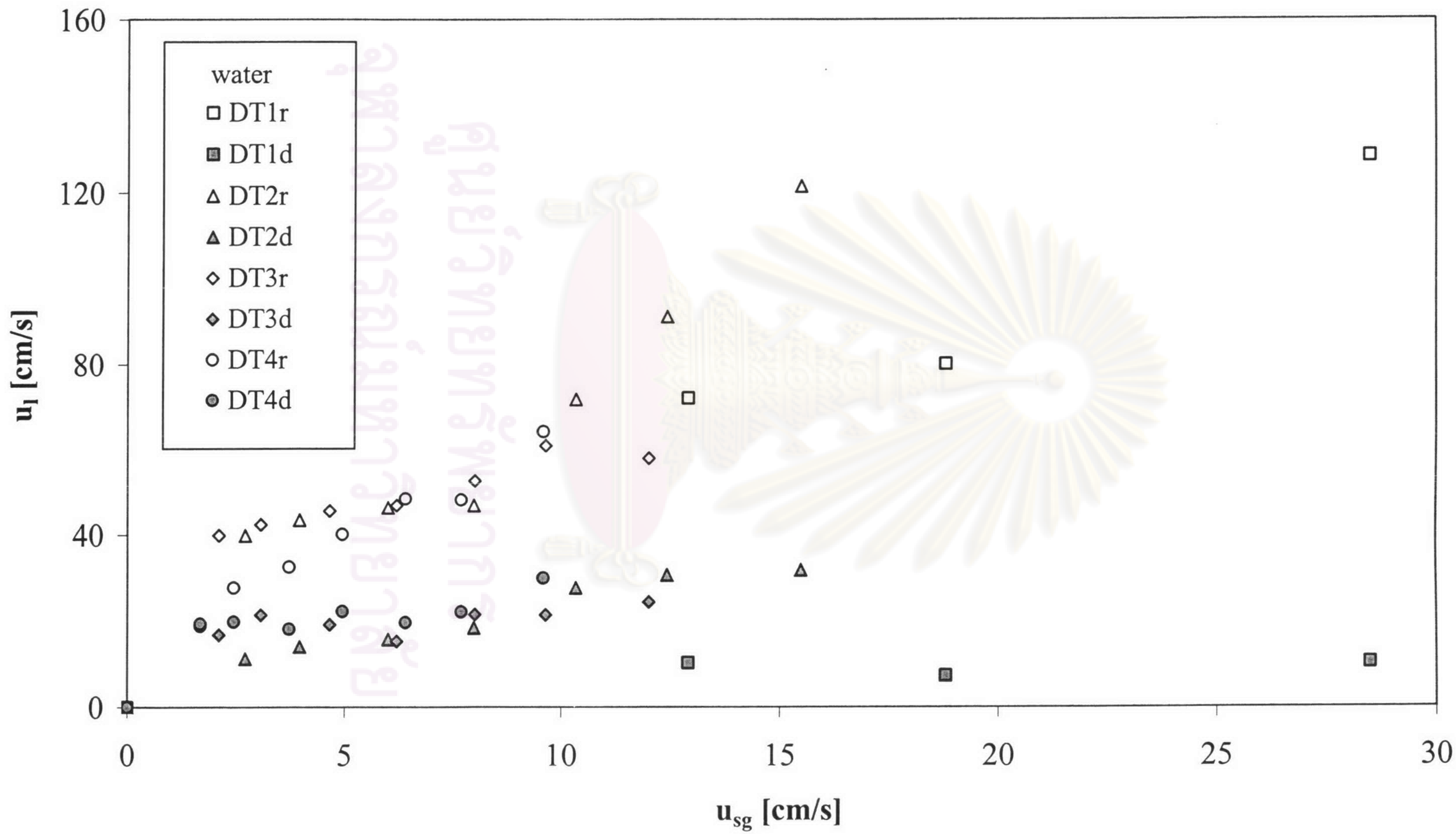


Figure 4.2.14 Effect of A_d/A_r on water velocity in ALC

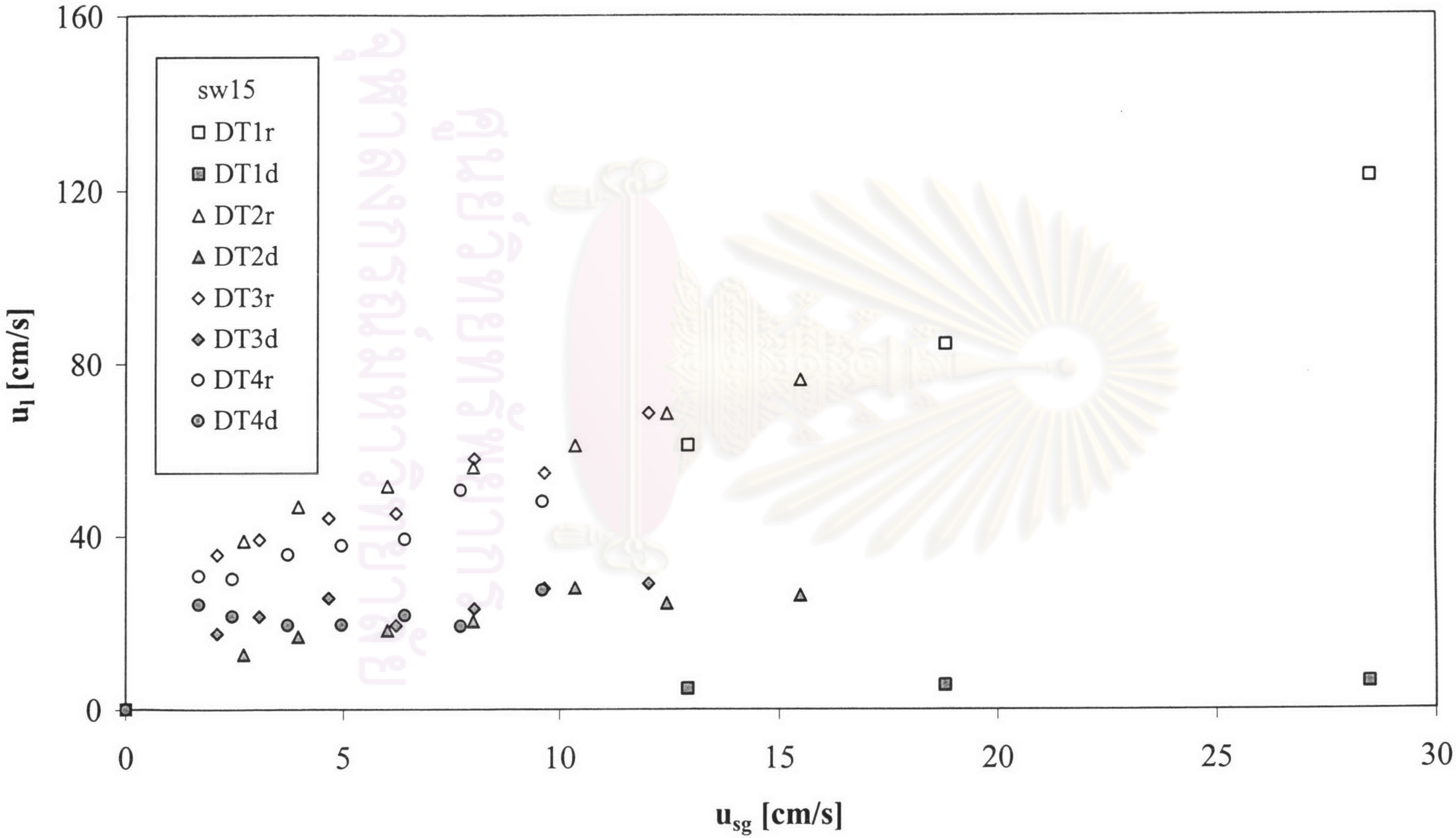


Figure 4.2.15 Effect of A_d/A_r on sw15 velocity in ALC

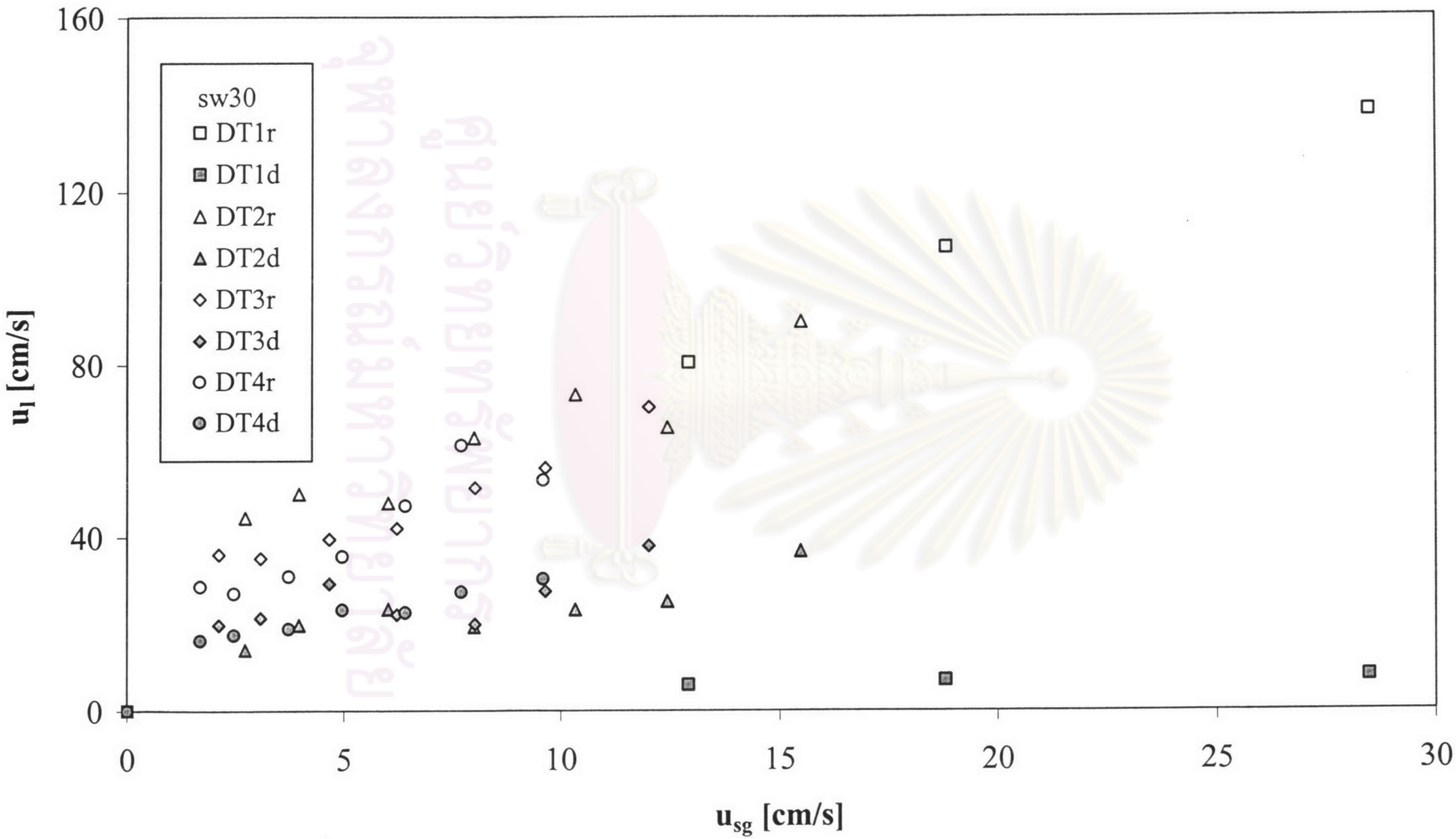


Figure 4.2.16 Effect of A_d/A_r on sw30 velocity in ALC

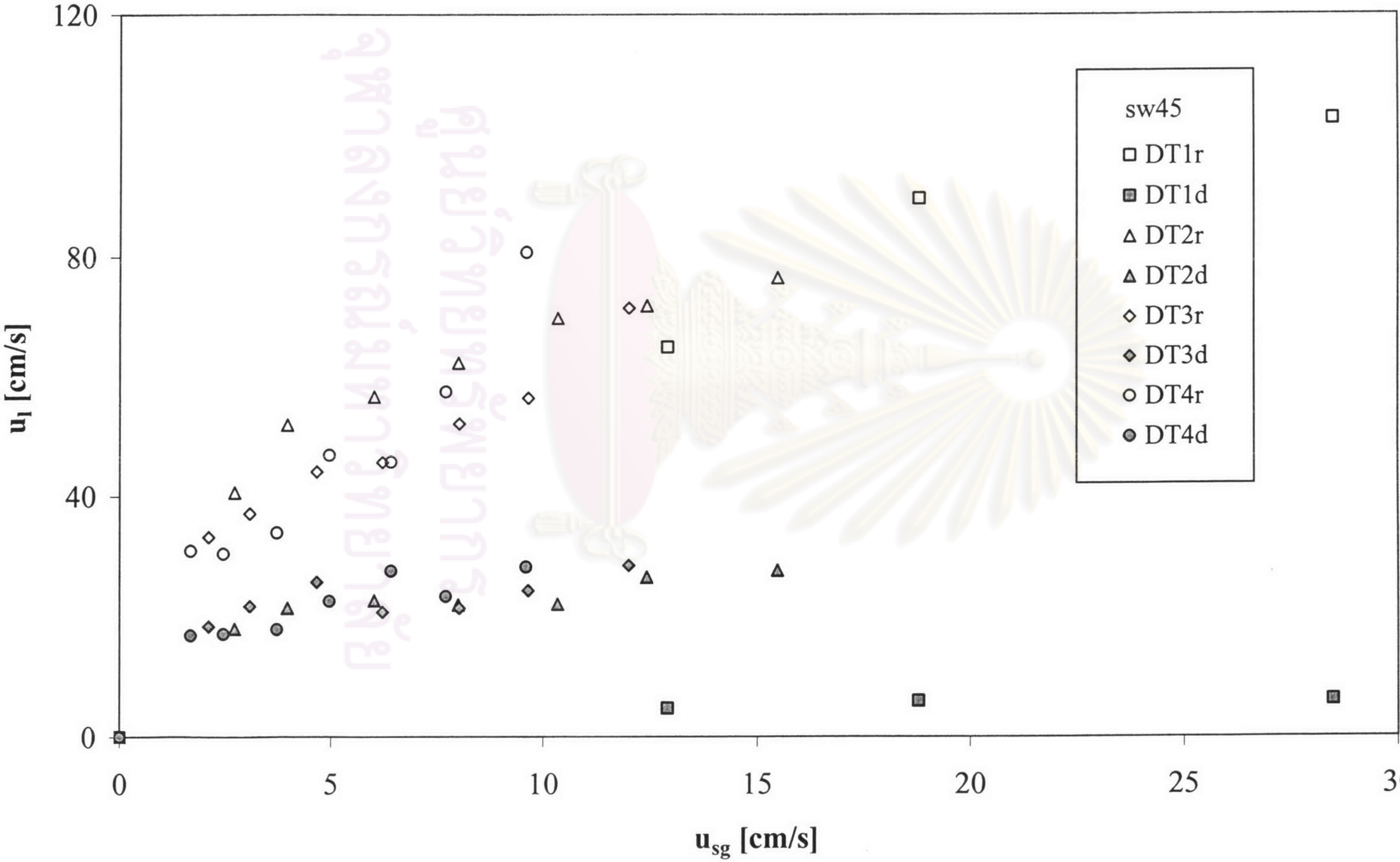


Figure 4.2.17 Effect of A_d/A_r on sw45 velocity in ALC

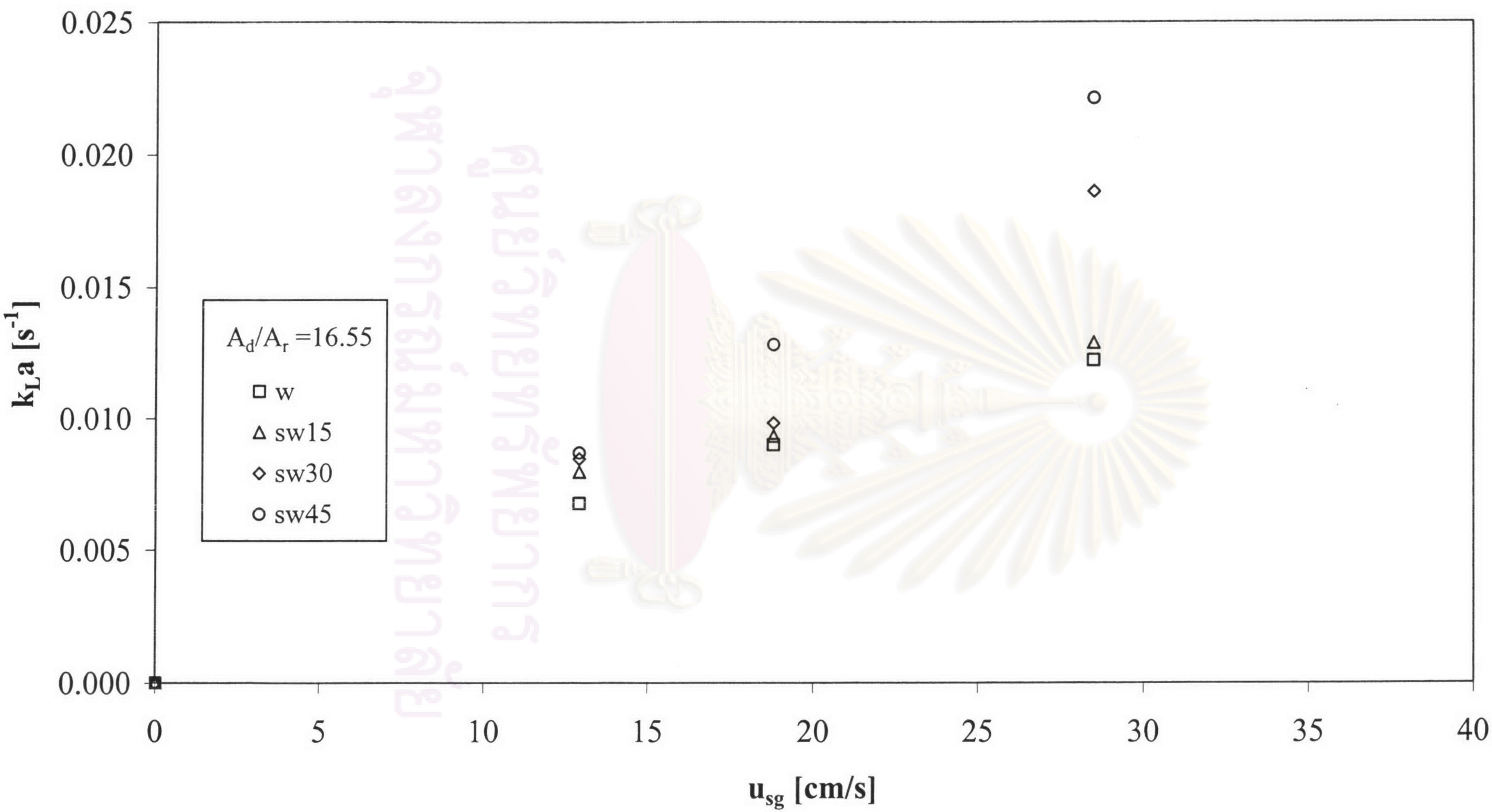


Figure 4.3.1 Effect of salinity on k_La in ALC with A_d/A_r of 16.55

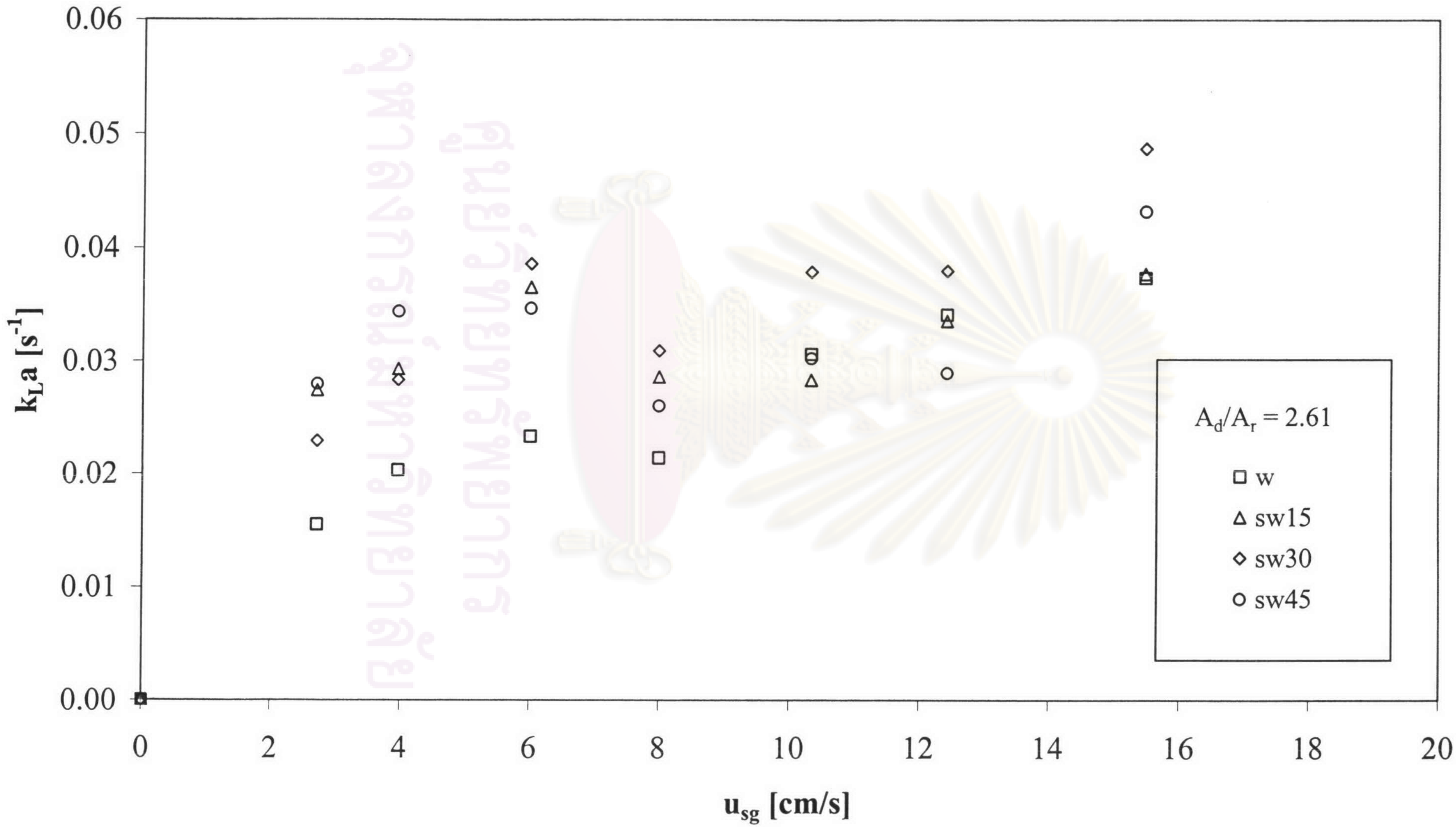


Figure 4.3.2 Effect of salinity on k_La in ALC with A_d/A_r of 2.61

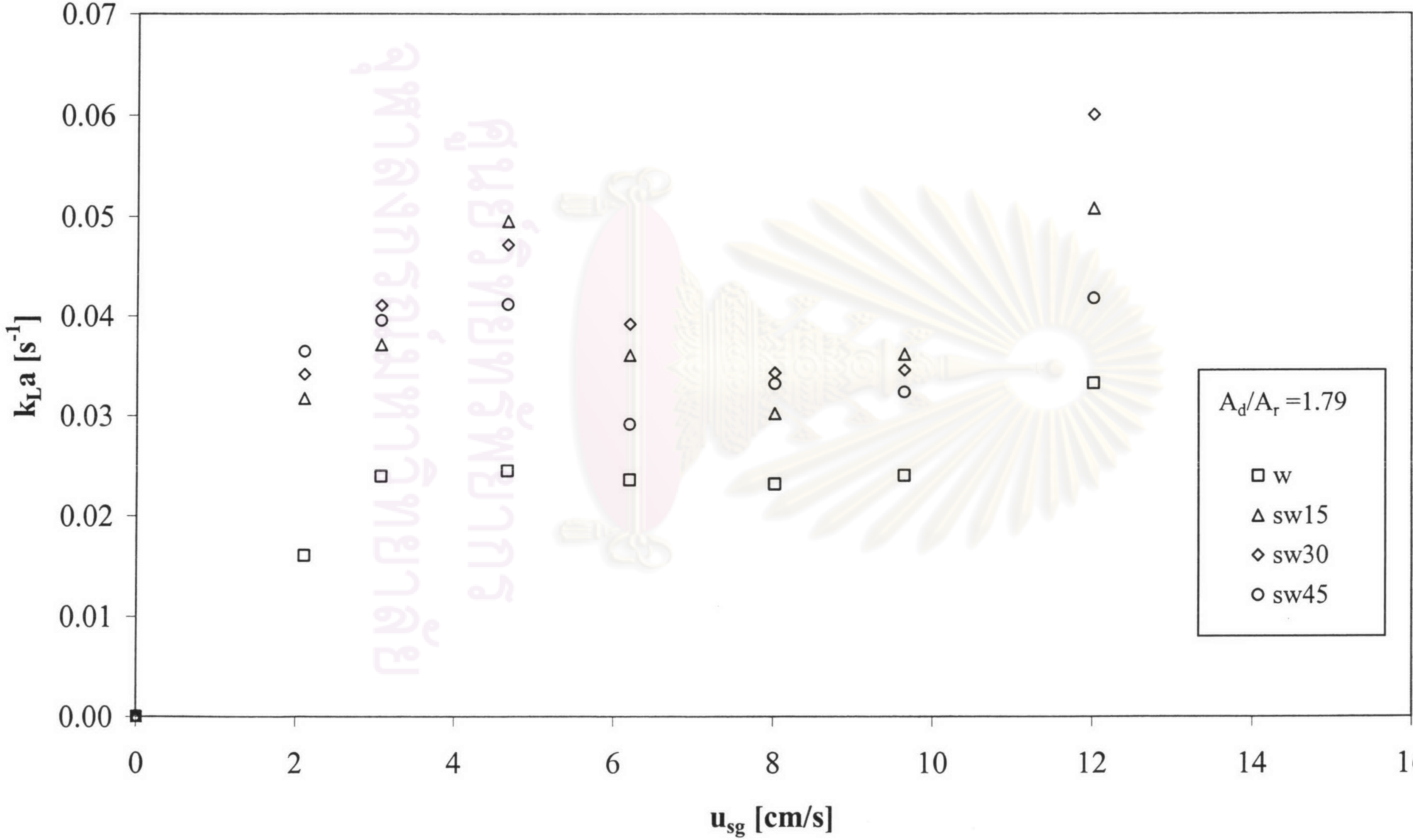


Figure 4.3.3 Effect of salinity on k_La in ALC with A_d/A_r of 1.79

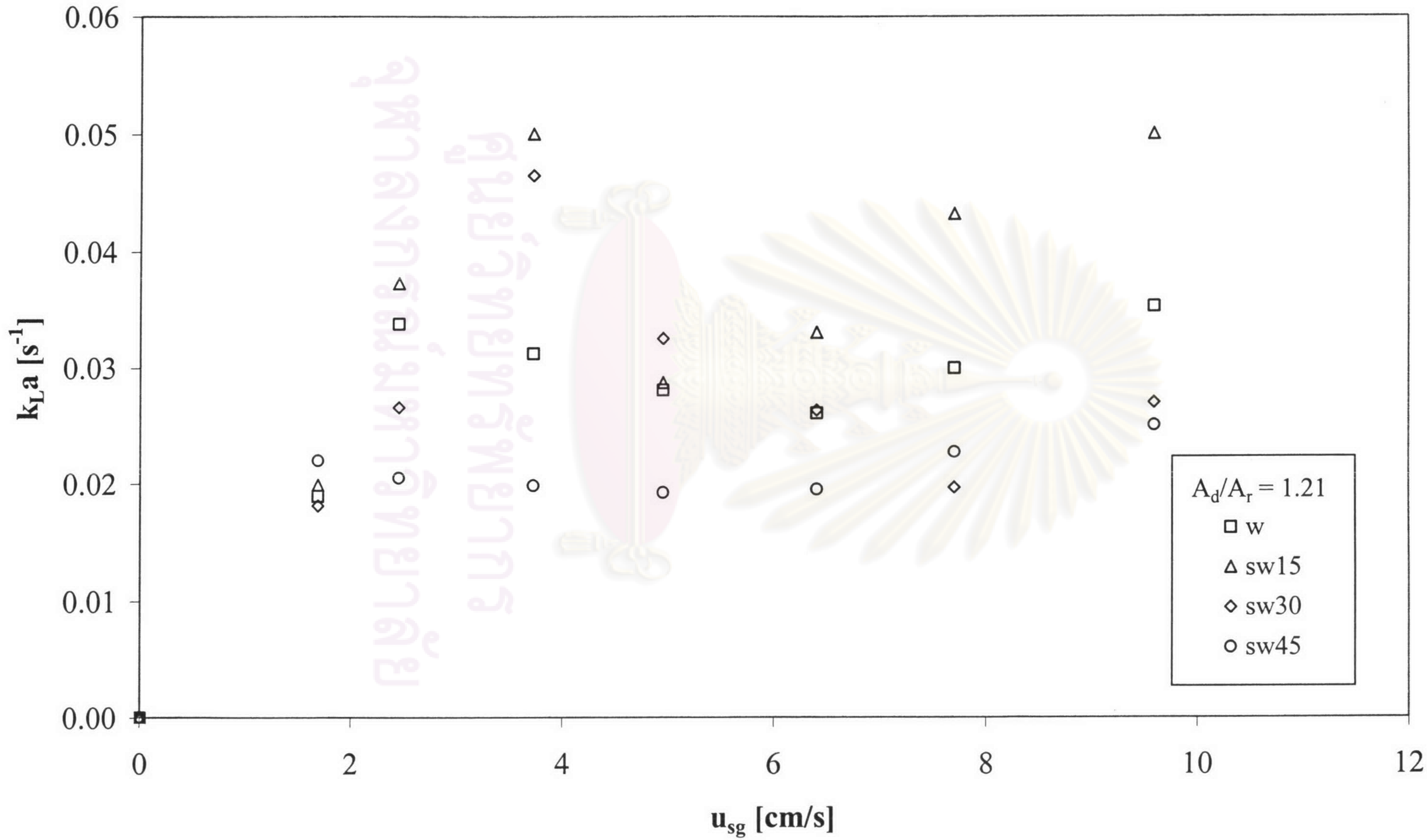


Figure 4.3.4 Effect of salinity on k_La in ALC with A_d/A_r of 1.21

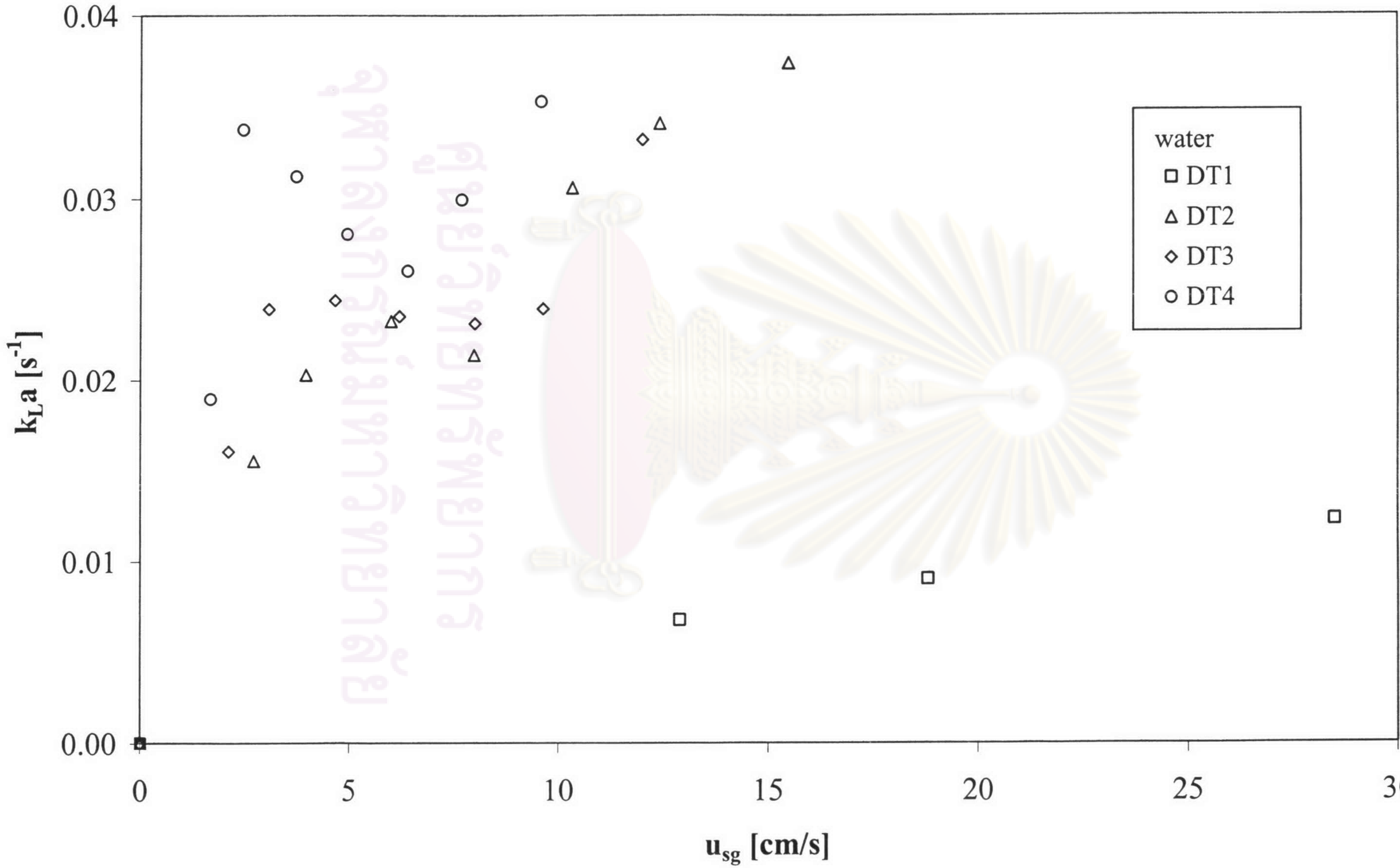


Figure 4.3.5 Effect of A_d/A_r on k_La in ALC with water

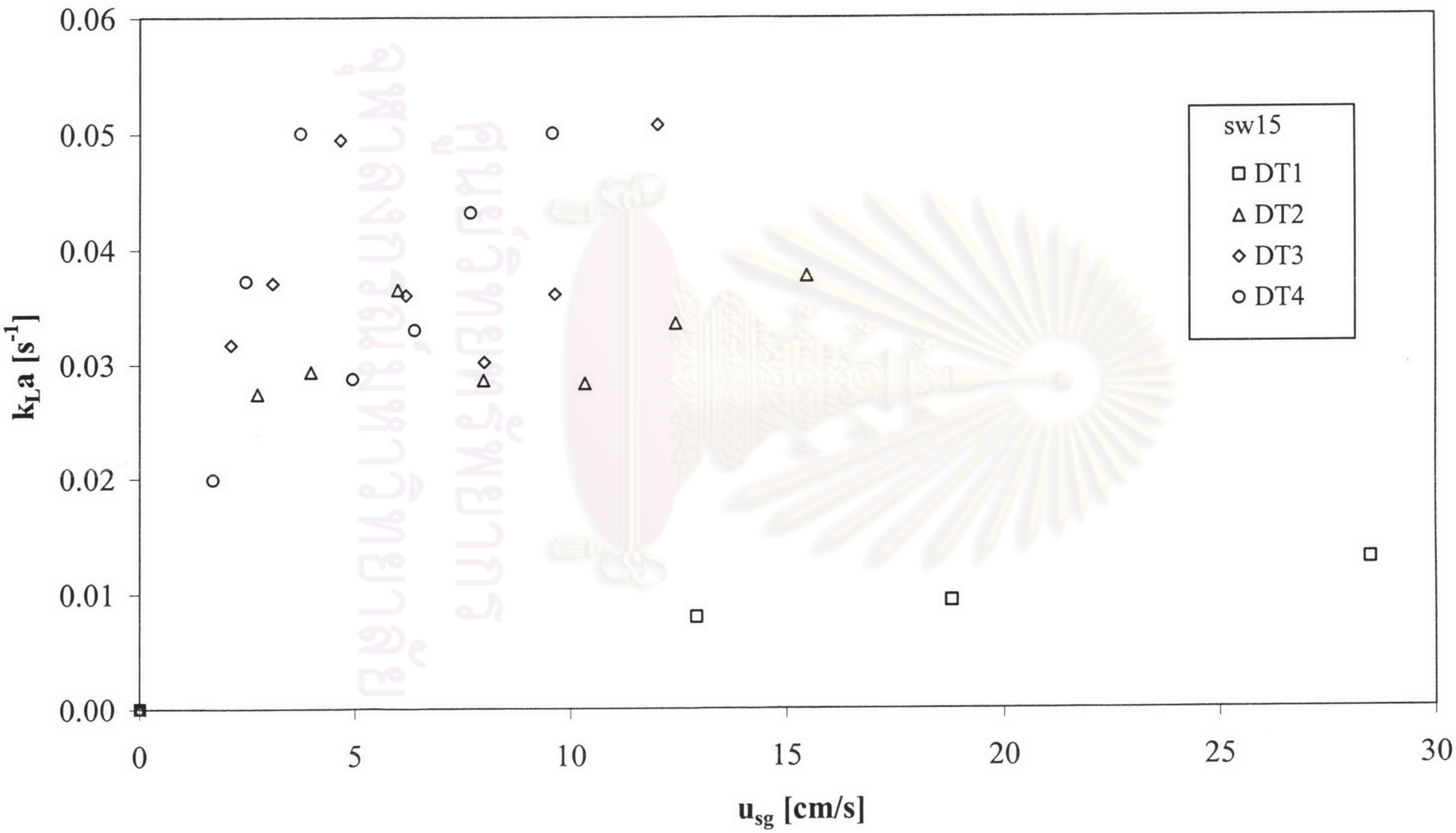


Figure 4.3.6 Effect of A_d/A_r on k_La in ALC with sw15

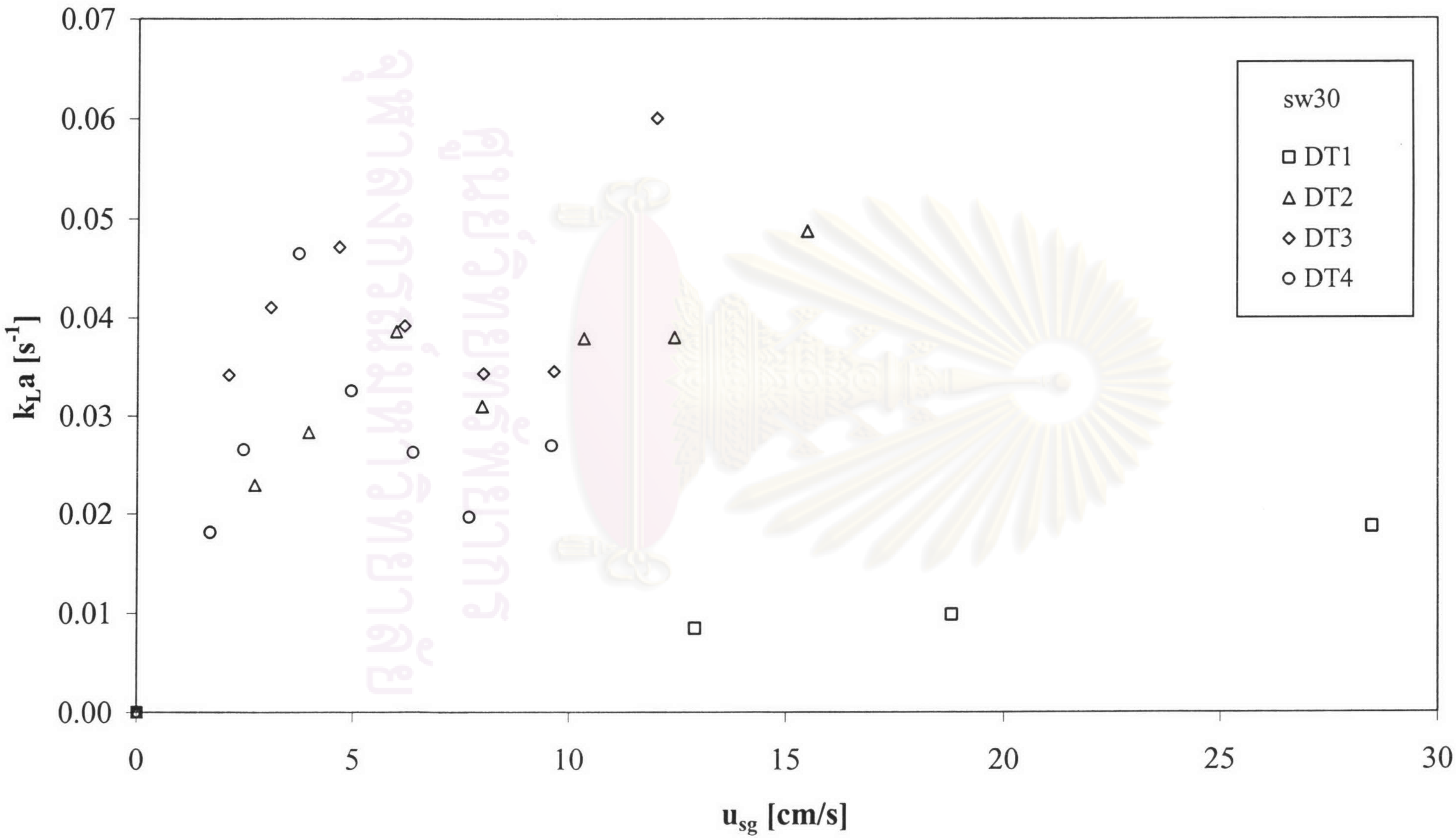


Figure 4.3.7 Effect of A_d/A_r on k_La in ALC with sw30

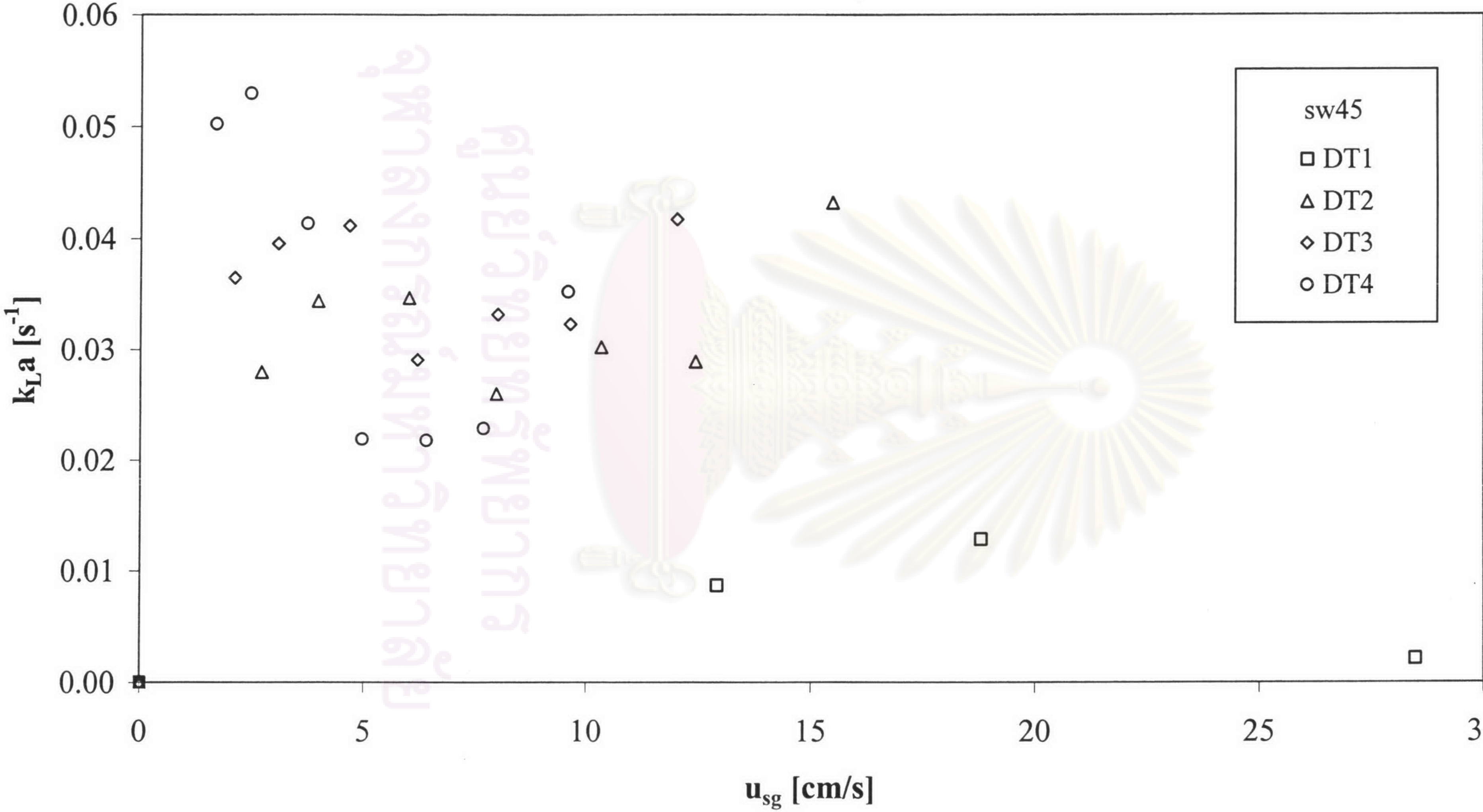


Figure 4.3.8 Effect of A_d/A_r on k_La in ALC with sw45