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Predicting the Minimum Fluidization Velocity of Algal Biomass Bed

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Abstract: -The minimum fluidizationvelocity (U_{mf})is an important hydrodynamics parameter in the design of fluidized bed reactor. This paper aims to predict the minimum fluidization velocity of liquid-solid (algal biomass) reactor. The experimental work was carried out in glass column of 1 m height and 7.7 cm inside diameter. The minimum fluidization velocities of beds were found to be 2.27 and 3.64 mm/s for algal mesh sizes of 0.4-0.6 and 0.6-1 mm diameters, respectively. It was found that the minimum fluidization velocitywas not affected by the variation of bed weight, but it was a function of the particles diameter. The results showed that the experimental U_{mf} is greater than the calculated value. This may be attributable to the following: the equations of calculation U_{mf} were based on the homogenous bed and spherical particles; the calculated $U_{mf}$was not take into consideration the friction between the fluid and the wall of column.

Keywords: -*Fluidized bed; Algae; Fluidization velocity; Particles*

I. INTRODUCTION

Fluidized beds have been used widely by chemical industry, pharmaceutical industry, food industry, wastewater treatment and recovery of different substance (Park et al., 1999).Fluidized beds are common and important reactors in process engineering due to their better characteristics concerning the uniformity of the temperature, concentration, and avoid the formation of dead zones and clogging (Fu and Liu, 2007).As well as, fluidized bed reactor offers high available surface area, since there is no contact between particles, and intimate contact of the entire surface with the wastewater(Sulaymon et al., 2013).

Thetermfluidization is used to describe the condition of fully suspended particles. Liquids or gases are passed upwards at certain velocity through a bed of solid particles, at this velocity the pressure drop across the bed counter balances the force of gravity on the particles and further increase in velocity achieve fluidization at a minimum fluidization velocity. Fluidization quality is closely related to the intrinsic properties of particles, e.g. particle density, particle size and size distribution, and also their surface characteristics (Richardson, 2002; Asif, 2012).

Several studies pointed that the first challenge of designing and operation a fluidized bed reactor is finding the minimum fluidization velocity (U_{mf}).The U_{mf} is a crucial hydrodynamics parameter of fluidized beds as it marks the transition at which the behavior of an initially packed bed of solids changes into a fluidized bed. Therefore, its accurate specification is indispensable for a successful initial design, subsequent scale-up, and operation of the reactors or any other contacting devices based on the fluidized bed technology. Industrial practice on fluidized beds usually involves the fluidization of solids over a wide range of particle sizes and/or systems with two or more components. In these cases, each particle fraction or each solid species has its own minimum fluidization velocity(Ngian, 1980).When a fluid flows slowly upwards through a bed of very fine particles the flow is streamline and linear relation exists between pressure gradient and flow rate. If the pressure drop (ΔP) across the whole bed is plotted against fluid velocity (u_c) using logarithmic coordinates as shown in the Fig. (1), a linear relation is again obtained up to the point where expansion of the bed starts to take place (A), although the slope of the curve then gradually diminishes as the bed expands and its porosity increases. As the velocity is further increased, the pressure drop passes through a maximum value (B), then falls slightly and attains an approximately constant value that is independent of the fluid velocity (CD). If the fluid velocity is reduced again, the bed contracts until it reaches the condition where the particles are just resting on one another (E). The bed voidage then has the maximum stable value which can occur for a fixed bed of the particles. If the velocity is further decreased, the structure of the bed then remains unaffected provided that the bed is not subjected to vibration. The pressure drop (EF) across this reformed fixed bed at any fluid velocity is then less than that before fluidization. If the velocity is now increased again, it might be expected that the curve (FE) would be retraced and that the slope would suddenly change from 1 to 0 at the fluidizing point. This condition is difficult to reproduce, however, because the bed tends to become consolidated again unless it is completely free from vibration. In the absence of channeling, it is the shape and size of the particles that determine both the maximum porosity and the pressure drop across a given height of fluidized bed of a given depth. In an ideal fluidized bed the pressure drop corresponding to ECD is equal to the buoyant weight of particles per unit area. In practice, it may deviate appreciably from this value as a result of channeling and the effect of particle-wall friction. Point B lies above CD because the frictional forces between the particles have to be overcome before bed rearrangement can take place. In a fluidized bed, the total frictional force on the particles must equal the effective weight of the bed. Thus, the pressure drop across the bed is given by:

$\Delta P = (\rho_s - \rho_l)(1-\varepsilon).g.h$………….. (1)

Where, ρ_s and $\rho_l$are the particles andfluid densities (kg/m^3), respectively. εis the void fraction, g is the gravitational acceleration (9.81 m/s^2), and h is bed height.

Eq.(1) applies from the initial expansion of the bed until transport of solids takes place (Richardson, 2002).

Ngian and Martin (1980)studied the bed expansion behavior of liquid fluidized beds of char particles coated with attached microbial growth of denitrifying mixed bacteria. They concluded that the correlations recommended by Richardson-Zaki for homogenous spheres are satisfactory for the estimation n of small particles (0.61 mm dia.), for the larger support particles (1.55 mm dia.) the predicted U_i values was found to be 30 to 70% below the experimentally values.

Tsibranska and Hristova(2010) studied the behavior of activated carbon in a fluidized bed for removal of Pb^{2+}, Cu^{2+}, Cd^{2+} and Zn^{2+} ions from aqueous solution. This work presented complete theoretical equations of bed expansion, minimum fluidization velocity, external mass transfer coefficient and mass balance equations for fluidized bed reactor.

Sulaymon et al., (2010)studied the hydrodynamic characteristics of three-phase fluidized beds. The experimental work of fluidized beds system was carried out in QVF glass column of 10.6 cm in dia. and 2 m height. Activated carbon with diameter 0.25 -0.75mm and density 770 kg/m^3 was used as a solid phase. The minimum liquid flow rate required to fluidize a bed of particles was determined from the change in the bed dynamic pressure drop behavior that occurs as the bed changes from a fixed bed to a fluidized bed. It was found that the minimum fluidization velocity increases with increase in particle size.

Wang et al., (2011) studied the removal of emulsified oil from water by inverse fluidization of hydrophobic silica aerogels (nanogel). The hydrodynamics characteristics of the nanogel granules of different size ranges are studied by measuring the pressure drop and bed expansion as a function of superficial water velocity. The minimum fluidization velocity was measured experimentally by plotting the pressure drop against the superficial fluid velocity. The results showed that the major factors which affect the oil removal efficiency and capacity are the size of nanogel granules, bed height, and fluidization velocity.

In recent years, there has been a significant increase in the studies concerning algae as biosorbents for metal removal due to their binding ability, availability and low cost(2003). In this study, the algae were used as a solid media in the liquid-solid fluidized bed reactor. This material was widespread used in the biosorption process of various materials. Therefore, the objectives of this work are: (i) to characterize the physical properties of algal biomass such as density, specific surface area and bed void fraction. (ii) to study some of the hydrodynamics properties such as $U_{mf}$of algal biomass in the fluidized bed reactor.

II. EXPERIMENTAL WORKS AND MATERIALS

2.1 Materials

Mixture of green (Chlorophyta) and blue-green (Cyanophyta) algae were used in this study as a bed material. Large quantities of algae have been observed their spreading along the artificial irrigation canal in Baghdad University. This canal feed by water from the Tigris River. For this study, algae were collected from the selected location of this canal in April and September 2011. Approximately greater than 5 kg of fresh algae was collected at each month. Sample of 0.5 kg of collected algae at each month were analyses for their genus and species and percentage weight by using microscope. These analyses were achieved according to the standard methods (APHA, 2005) in laboratories of Iraqi Ministry of Sciences and Technology/Water Treatment Directory. The results showed that there are five species were dominated in these two samples, Oscillatoriaprinceps alga was the highest percentage, these results were listed in table (1).

The collected algae were washed several times with tap water and distilled water to remove impurities and salts. The algal biomass was sun-dried and then dried in oven at 50 °C for 48 h. The dried algal biomass was shredded, ground to powder and sieved. Mesh sizes of 0.4-0.6 and 0.6-1 mm ofparticle diameters were used.The biomass particle size distribution was determined using a set of standard sieves. Since the algal biomass could swell in water, therefore the biomass was initially soaked in water and then wet sieved. Particles density, surface area and void fraction were measured and listed in table(2),these parameters are so important in the characterization of fluidized bed.Fig.(2)shows two pictures of powdered algal biomass particles.

2.2 Experiments

Fig. (3)shows a schematic diagram of fluidized bed reactor used in the experiments of this work. Experiments were carried out in a 7.5 cm inner diameter and 1 m high glass column, stainless steel distributer of 5mm thickness with 0.2 mm holes diameter was installed at the bottom of the reactor to distribute an influent flow smoothly. The flow rate of water was adjusted using calibrated flow meter. A U-tube manometer was connected to the reactor to observe the pressure drop along the bed at each flow meter reading, the manometer has an inside diameter of 5 mm and length of 50 cm. The manometer liquid is carbon tetrachloride (CCl_4) with ρ_l=1590 kg/m^3. The bed heights were read visually.In addition, all the experiments were carried out at room temperature.

A typical experimental runs are described as follows. First, the pressure drop across the empty column was measured at different water flow rates in order to obtain a correlation that can be used to determine the pressure drop of the fluidized bed alone; this was done by subtracting the empty column pressure drop from the total fluidized bed pressure drop. Then known weight of the algal biomass particles to be fluidized was loaded into the fluidization columnand then vigorously agitated with water in order to arrange particles and break down any internal structure. After that the bed left to settle down, and then the water flow rate increased gradually from 0 to 100 l/h. At each flow meter readings the pressure drop and bed height were measured.The static pressure before the column was kept constant to ensure consistent readings. The algal biomass particles were fluidized by increasing the flow until the drag force on the particles balances the buoyant force.

III. RESULTS AND DISCUSSION

3.1 Bed Expansion

It is important to establish the relationship between the superficial liquid velocity (U) and the bed voidage (ε) (Ngian, 1980).An accurate description of the bed void fraction is an important prerequisite for determining various hydrodynamic aspects of the fluidized bed including the minimum fluidization velocity of fluidized bed (Nidal et al., 2001).For homogeneous particles in a liquid fluidized bed, it is generally accepted that the most convenient expression to relate U to ε is the Richardson-Zaki equation (Richardson, 2002):

$U/U_i=\varepsilon^n$………………………….. (2)

Where Uis the superficial fluid velocity, $U_i$is the settling velocity of a particle at infinite dilution, and n is constant. The index n is a function of Reynolds number at terminal velocity (Re_t) as follows:

$n=4.65+20d/D$ ($Re_t<0.2$) ………….(3)

$n=(4.4+18d/D)Re_t^{-0.03}$ ($0.2<Re_t<1$) ……… (4)

$n=(4.4+18d/D)Re_t^{-0.1}$ ($1<Re_t<200$) ……..(5)

$n=4.4Re_t^{-0.1}$ ($200< Re_t<500$)……(6)

$n=2.4$ ($Re_t>500$) ……..(7)

where, d is the particle diameter; D is the bed diameter.

The settling velocity at infinite dilution (U_i) and the terminal velocity (U_t) are related by:

$log\, U_i = log\, U_t - \frac{d}{D}$…………………..(8)

$Re_t = \frac{U_t.d.\rho_l}{\mu_l}$…………………….(9)

$U_t = \frac{g.d^2.(\rho_s-\rho_l)}{18.\mu}\, \mathrm{Re_p} < 0.2$….(10)

$U_t=\frac{0.153.g^{0.71}.d^{1.14}.(\rho_s-\rho_l)^{0.71}}{\rho_l^{0.29}.\mu^{0.43}}\, \mathrm{Re_p} > 0.2$……(11)

Where,$\rho_s$and $\rho_l$are the densities of the particle and fluid, respectively; μ is the viscosity of the fluid, and Re_p is the particle Reynolds number.

Fig. (4)shows the voidage against superficial velocity of 0.4-0.6 mm particles diameter. The correlation obtained from this figure is (U in mm/s):

$U=15.24\, \varepsilon^{3.675}$……………… (12)

In addition, the bed voidage can be found experimentally by subtracting the volume of the particles (V_p) from the total volume of the fluidized bed (V_b). Hence, the voidage of the fluidized bed is:

$\varepsilon=\frac{V_\varepsilon}{V_b}=\frac{V_b-V_p}{V_b}=1-\frac{V_p}{V_b}=1-\frac{m_p}{\rho_s.V_b}=1-\frac{m_p}{\rho_s.A.h_{mf}}$….. (13)

where, V_ε is void volume, m_p is the mass of particles (kg), A is the cross sectional area of the bed (0.0044 m^2), h_{mf} is the bed height (m).

The bed voidage of fluidized algal biomass was found experimentally using Eq.(13) and compared with theoretical value that calculated using Eq.(2).Table (3) shows the calculated values of (n), experimental and theoretical voidage (ε). As seen in table, the values of calculated voidage are lower than experimental values. This may be due to the fact that the Richardson-Zakiequation is based on the homogenous and spherical particles shape in liquid fluidized bed.

3.2Minimum Fluidization Velocity

The U_{mf} was determined experimentally by measuring the pressure drop across the bed of algal particles, and then compared with the calculated value. Two mesh sizes of particles were used in this study ranging from 0.4-0.6 mm and 0.6-1 mm diameter. The weight of algal biomass that used for each particles diameter range were 30, 50, 70, 100, and 150 g. Fig. (5)shows the pressure drops across the bed against the superficial fluid velocity in logarithmic scale for 30 and 70 g of algal biomass bed. This graph is used to obtain the minimum fluidization velocity (U_{mf}), as well as to show the pressure drop rises linearly below minimum fluidization in the packed bed region and then plateaus above minimum fluidization. The U_{mf}can be read from the sharp change in the pressure drop across the fixed bed region. The pressure drop was found to be less for the smaller particles (Fig.5) compared with the larger particles, and the fluidized bed height was double the initial static bed for all algal biomass weights.

Several correlations were proposed for prediction of the minimum fluidization velocity. The most important one was Ergun equation (Tsibranska and Hristova, 2010). Equation (14) is a simplified form of Ergun equation. Ergun equation may be applied when the flow regime at the incipient fluidization which is outside the range of Carman-Kozeny equation applicability.

$$Ga = 150\left(\frac{1-\varepsilon}{\varepsilon^3}\right)Re + \left(\frac{1.75}{\varepsilon^3}\right)Re^2 \quad \text{.... (14)}$$

$$Ga = \frac{d^3\rho_l(\rho_s-\rho_l)g}{\mu^2} \quad \text{....... (15)}$$

$$U_{mf} = \frac{\mu}{d.\rho_l}Re \quad \text{........ (16)}$$

Where, Ga is the Galileo number.

The value of void fraction mentioned in Eq.(14) was determined from the Richardson-Zaki correlation (Eq.(2)). It is important to note that the Ergun equation contains terms with third order dependence on the bed void fraction. As a result, even a small error in the bed void fraction can lead to a significantly higher error in the prediction of the pressure drop.

Table (4) shows the minimum fluidization velocity, plateau pressure drop (ΔP) and fluidized bed height (h_{mf}) of two different particles size.It can be seen that the U_{mf} is not a function to the weight of bed but it is a function to the particles diameter. It was found that the experimental U_{mf} greater than the calculated value. This may be attributable to the following: the equations of calculation U_{mf} were based on the homogenous, spherical particles; the calculated U_{mf}do not takes into consideration the friction between the fluid and the wall of column. These results are in a good agreement with (Sulaymon, 2013).

IV.CONCLUSION

In this study, the minimum fluidization velocity of algal biomass beds was found experimentally and then compared with the calculated value that obtained using Ergun equation. The experimental minimum fluidization velocities were found to be 2.27 and 3.64 mm/s for mesh sizes of 0.4-0.6 and 0.6-1 mm particles diameters, respectively.On the other hand,the results showed that the experimental U_{mf} was greater than the calculated value. This can be attributed to that Ergun equation suppose homogenous bed and spherical particles.The pressure drop is found to be less for the smaller particles than for the larger bed particles and the fluidized bed height is double the initial static bed for all algal biomass weights.

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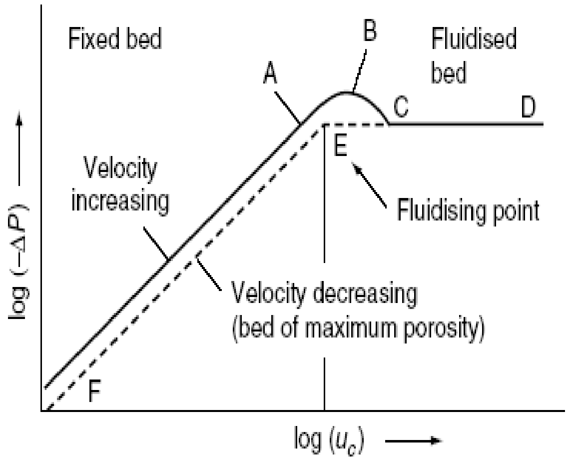

Fig. 1 Pressure drop across fixed and fluidized beds (Richardson, 2002)

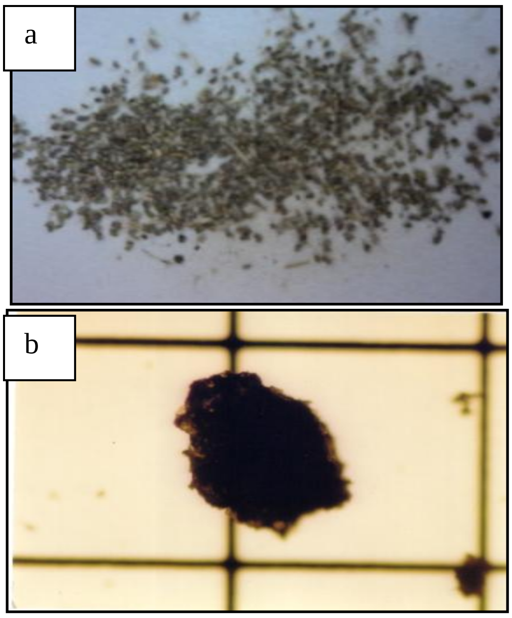

Fig. 2 Two plots pictures of, a: 0.6-0.4 mm diameter of powdered algal biomass, and b: Microscopic picture of one particle of 0.4-0.6 mm dia. alga biomass (mesh size:1x1 mm^2)

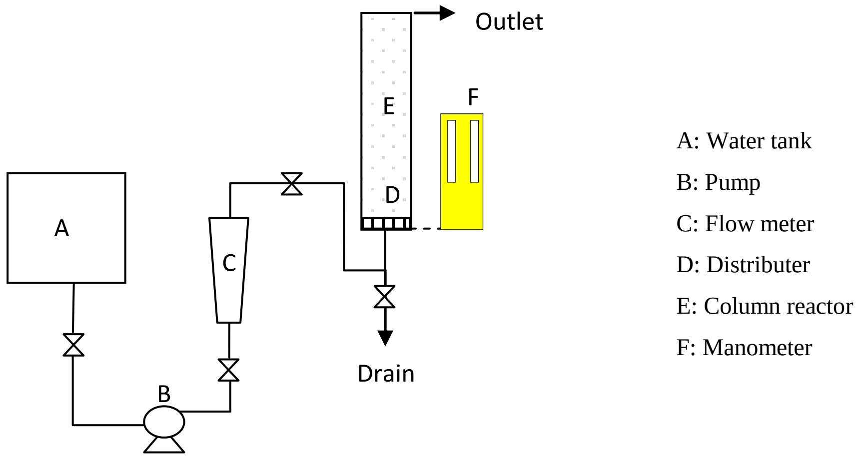

Fig. 3 Schematic diagram of fluidization experimental setup

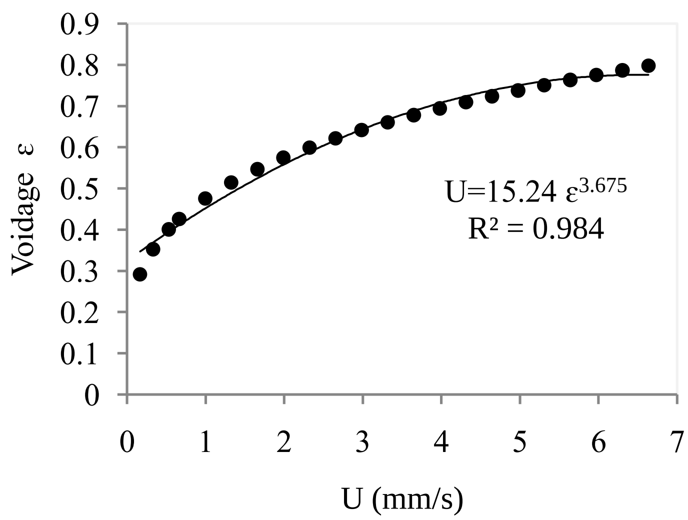

Fig. 4 Relationship between voidage and superficial velocity of 0.4-0.6 mm particles diameter

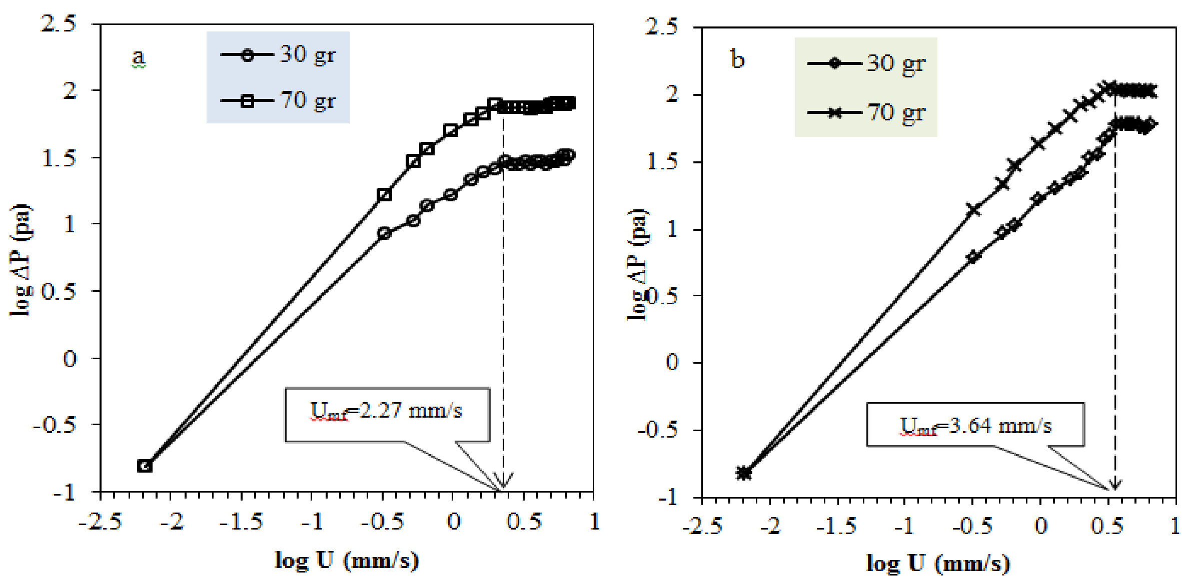

Fig. 5 Pressure drop vs. superficial fluid velocity in algal bed, a: 0.4-0.6 mm and b: 0.6-1 mm particle diameter

Table (1) Division, genus, species and weighting percentage of collected algae

Division	Genus and Species	Percentage	
		June/ 2011	September/ 2011
Cyanophyta	Oscillatoriaprinceps	88 %	91 %
Chlorophyta	Spirogyra aequinoctialis	5 %	3 %
Cyanophyta	Oscillatoriasubbrevis	2 %	2 %
Cyanophyta	Oscillatoriaformosa	3 %	1 %
Chlorophyta	Mougetasp	1 %	2 %
others	---	1 %	1 %

Table (2) Physical properties of algal biomass particles

	Particle diameter (mm)	
	0.4-0.6	0.6-1
Bulk density(kg/m^3)	474	400
Real density (kg/m^3)	1120	1120
Surface area (m^2/g)	1.88	1.65
Particle porosity (--)	0.713	0.77
Static bed void fraction (--)	0.577	0.642

Table (3) Theoretical and experimental voidage for two particle size ranges and at $U=U_{mf}$

Particle size (mm)	U_i (m/s)	index (n)	Calculated ε Eq.(2)	Experimental ε Eq.(13)
0.4-0.6	0.015	3.69	0.61	0.75
0.6-1	0.017	3.53	0.65	0.83

Table (4) U_{mf}, ΔP and h_{mf} of two different size particles

Particle size (mm)	Mass (g)	Static height (cm)	ΔP (pa)	h_{mf} (cm)	Calculated U_{mf} (mm/s)	Experimental U_{mf} (mm/s)
0.4-0.6	30	1.5	32.9	3	2.21	2.27
	50	2.5	56.3	5		
	70	3.5	65.5	7		
	100	5	80.1	10		
	150	7.5	112	15		
0.6-1	30	1.8	50.6	3.6	3.11	3.64
	50	3	66.1	6		
	70	4.2	89.9	8.4		
	100	6	103.3	12		
	150	9	124.8	18		