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INVESTIGATION OF THE HYDRODYNAMIC FACTORS EFFECTS AND QUANTIFICATION OF FINES FLOCCULATION USING COFACTOR-POLYETHYLENE OXIDE: A METHODOLOGY TO PRODUCE THE REQUIRED FLOC SIZE AND ESTIMATE THE COST

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ABSTRACT

The small particles in most industrial applications are flocculated to the required size. The fines flocculation using the cofactor (CF)-polyethylene oxide (PEO) is conventionally used in papermaking. In this work, we have investigated the effects of the hydrodynamic process factors: the stirring rate, the shear rate, Reynolds number and the effective shear rate on fines flocculation. Floc size and flocculation rate constant were the main important parameters have been investigated to get the required size and the flocculation speed that economize and reduce the operation cost. For more, we used the methodology proposed in previous work that characterized flocculation process and found the required floc size and flocculation speed from the hydrodynamic process factors. For more, we investigated the stirring intensity $(G_p\,\tau)$ along with the floc size (A), where (G_p) is the process shear rate and (τ) is the characteristic time of flocculation. The dimensionless $G_p\,\tau$ value quantifies the micro characteristics and the interactions among the fines with time. At low values of G_p, results show high values of $G_p\,\tau$ and longer characteristic time τ that indicate high operation cost. At high values of G_p, results show a decrease in $G_p\,\tau$ value, which oscillates in between 720 and 543 and indicates a decrease in the operation cost.

KEYWORDS: Polyethylene oxide, Cofactor, Flocculation, Shear rate, Floc Size, Rate Constant, Stirring Intensity, Quantification.

INTRODUCTION

Fines flocculation is one of the most important processes in papermaking since fines comprises more than 50.5% of the pulp (Abdallah, Mohammad. R., 2002). Retention of the fines in paper sheet economizes the manufacturing process and prevents blockage in units (van de Ven T. G. M., 1993). To maintain this retention, flocculation of the fines, colloids and other existing particles are essential. The cofactor (CF)- polyethylene oxide (PEO), the dual retention aid is the most conventionally used in papermaking as the neutral PEO does not incorporate with the other ions (Pelton, R.H., et. al., 1980; Pelton, R.H., et. al., 1981). Neither CF nor PEO adsorb on fibers, fines and most fillers, but their combination adsorbs form the large stiffen CF-PEO complex and adsorb (Carignan. A, et.al., 1998). The CF induces bridging in between these particles causing them to flocculate (van de Ven, T.G.M., and Alince, B., 1996). The PEO coils were recommended to be prepared in entangled coils state of a size (δ) larger than the size of the electrostatic repulsion layer (K^{-1}) to overcome repulsion and adsorb on the surfaces (Kratochvil. D, et. al., 1999). When CF adsorbs on PEO, the resulting CF-PEO complex expands into larger size (δ_x) and adsorbs on the surfaces. The CF-PEO induced bridging takes place when the two conditions are satisfied on surfaces; the $\delta_x > 2\kappa^{-1}$ and the polymer coverage $\theta(<1)$ (De Witt, J.A., and van de Ven, T.G.M., 1992). The PEO entanglements were found to dissociate by the effect of the process shear rate (G_p), which also affects to dissociate the attachments in the floc, breaking the floc and enhances deflocculation (Abdallah Qasaimeh, M.R.,, 2011). Flocculation process and retention never happen without mixing or shearing in flocculation vessel. Number of factors in flocculation process have primary effects on flocculation parameters and resulted floc specifications. In literature, flocculation of the fines using the cofactor (CF)- polyethylene oxide (PEO) retention aid system continued as the main topic of some of our research work (Dr. Mohammad Raji Abdallah Qasaimeh, 10, 11, 2024; Dr. Mohammad Raji Abdallah Qasaimeh, 10, 5, 2024; Mohammad Raji Abdallah Qasaimeh, 2022; Abdallah Qasaimeh, M.R., et. al., 2011; Abdallah Qasaimeh, M. R., et. al., 2014), and of some other works (Carignan, A., et. al., 1998; van de Ven, T.G.M., 1997: van de Ven, T.G.M., et. al., 2004), where some affective factors and parameters were found. First we studied the effect of the cofactor addition with PEO as a dual system, investigated the CF-PEO induced bridging, and found it to enhance flocculation several times the asymmetric bridging where PEO was used alone (Abdallah, Mohammad. R., 2002; Abdallah Qasaimeh, M.R., 2011). In other work, deflocculation phenomena appeared in both asymmetric bridging and CF-PEO induced bridging (Carignan, A. et al. 1998; van de Ven, T.G.M. 1994), while in our work (Abdallah, Mohammad. R., 2002; Dr. Mohammad Raji Abdallah Qasaimeh, 10, 5, 2024); Mohammad Raji Abdallah Qasaimeh, 2022) we attributed its cause to parameters in PEO (Abdallah Qasaimeh, M.R., 2011). One factor we studied in flocculation process was the effect of CF concentration (C), in a wide range; we found out number of the flocculation parameters and the rate constants (Dr. Mohammad Raji Abdallah Qasaimeh, 10, 5, 2024); Mohammad Raji Abdallah Qasaimeh, 2022). The second factor was the consistency of the fines (C_{fn}), the number of particles in a unit volume, through which we studied the verification of flocculation process with smoluchowski (Smoluchowski, M., 1917) and Longmuir equation (Abdallah, Mohammad. R., 2002). We have also studied the effect of the changes in C_{fn} , the optimum value of C_{fn}, and its affective parameters (Dr. Mohammad Raji Abdallah Qasaimeh, 10, 11, 2024). The third factor was the process shear rate (G_p), which creates stresses and eddies in case of turbulence causing the particles to collide, and based on this Smoluchowski proposed his isotherm (Smoluchowski, M., 1917). When these collisions are successful to attach with an efficiency, a floc is formed and this attachment was studied to verify Longmuir equation (Abdallah, Mohammad. R., 2002). According to Longmuir, the flocculation rate $r_f \ (=r_{att} - r_{\det})$ is a resultant of the attachment rate (r_{att}) and the opposing detachment rate $(r_{\det})$. Workers and mill operators directed their works to enhance r_{att} and reduce $r_{\det}$ (Abdallah, Mohammad. R. 2002). At initial flocculation flocs are not yet initiated and particle attachments are the dominants for no detachment, thus resulting the maximum rate, which decreases with time to become zero at equilibrium. The attachment rate r_{att} in Longmuir equation was modeled based on the rate constant (k_0) defined by Smoluchowski isotherm. The k_0 was the rate of collision between two spherical particles of radii a_1 and a_2 subjected to a process shear rate (G_p) expressed as $k_0 = \frac{4}{3} G_p \left(a_1 + a_2\right)^3$ (Smoluchowski, M., 1917). For the case that particles are identical having same radius (a) as in homoflocculation, the rate constant becomes $k_0 = \frac{16}{3} G_p a^3$ (Abdallah, Mohammad. R. 2002; Petlicki, J. and van de Ven, T.G.M. 1992). When the particles are rod like shape (e.g a fiber), having an axis ratio $a/b >> 1$ (a being half the length, b radius of the cross section), the Smoluchowski's theory was modified to $k_0 = \frac{4}{3} G \left(a + a_c\right)\left(b + a_c\right)^2$ (Petlicki, J. and van de Ven, T.G.M. 1992). For a suspension having a consistency C_{fn}, the number of particles in a unit volume and based on Smoluchowski isotherm, the successful collisions attach in a unit volume unit time (the flocculation rate) will be $r_f = r_{att} = -k_{att} C_{fn}^2 = -\eta\, k_o C_{fn}^2$. Here the (k_{att}) is the attachment rate constant, which becomes $k_{att} (=\eta\, k_o) = \frac{4}{3} \eta\, G_p \left(a_1 + a_2\right)^3$ in case of heteroflocculation and $k_{att} (\eta\, k_o) = \frac{16}{3} \eta\, G_p\, a^3$ in case of homoflocculation, where (η) is the flocculation efficiency. The efficiency η denotes the ratio of the collisions leading to successful attachments to the total performed collisions (Abdallah, Mohammad. R. 2002; van de Ven, T.G.M., and Mason, S.G., 1981). In other hand, after floc initiation in flocculation, detachments among the resulting flocs occur with the detachment rate $r_{\det} (=-k_{\det} C_F)$, where C_F is the number of flocs in a unit volume, and $k_{\det}$ is the detachment rate constant usually a function of G_p, temperature (T) and bond strength (Varenners, S. and van de Ven, T.G.M. 1987; Abdallah, Mohammad. R. 2002). This discussion shows the primary role of the process shear rate G_p in particle flocculation, which also applies in fines flocculation (Abdallah Qasaimeh, M. R., et. al., 2014; van de Ven, T.G.M., 1989). Interactions among the particles and created by the hydrodynamic forces cause flocculation. Wide range of these interactions subjected to simple shear operate between small particles (e.g. fillers) and spheroids (e.g. fibers) prevents the small particles to approach the large ones into distances where the colloidal forces become important. Similar effects are expected in papermaking suspensions, resulting in very low efficiencies for the deposition of fillers or fines on fibers (van de Ven, T.G.M., 1989). For more, the G_p has some other effects rather than particle flocculation such as dispersion, floc breakage, deflocculation, disentanglement of the PEO entanglement, and dissociation of the CF-PEO complex. One indicator to these effects by G_p was the decrease in flocculation rate (r_f) and floc size (A) with the increase in stirring rate G_p (Abdallah Qasaimeh, M. R. et al. 2014). Further indicators reported in literature was the formation of fiber flocs after a reduction in G_p (Jacquelin, G. 1968; Bjorkman 2003). Dispersion of large particles into smaller sizes and floc breakage occurred by the effect of high G_p and at definite values of G_p, the fibers eroded from fiber floc surfaces (Healy, T. W. and La Mer, V.K. 1964; Spicer, T.P. and Pratsinis, S. E. 1996) and the floc splitted into two (Klomogorov, A. N. 1949; Higashitani, K.

et. al. 1989). Furthermore, the induced attachments between the fibers with cationic starch were broken by the continued agitation and formed dispersed suspension (Roberts, J. C. et al. 1986; Roberts, J. C., et. al., 1987). For more, the detachment of the forming flocs also occurs during flocculation process. The particles attached by the adsorption forces and interactions by G_p also detach by the effect of G_p, which after equilibrium enhances deflocculation (Abdallah Qasaimeh, M.R. 2011; Mohammad Raji Abdallah Qasaimeh, 2022).

Referred to the reviewed results in literature, and for the importance of the shear rate role to fix the floc size, the importance of the required particle size on product quality, and to economize flocculation process cost, our proposal in this work was to investigate and analyze the role of the process shear rate G_p on flocculation process and resulted flocs characteristics.

EXPERIMENTATION

MATERIALS

In this work, we have used the same materials we used in previous works (Abdallah, Mohammad. R. 2002; Abdallah Qasaimeh, M.R. 2011;Abdallah Qasaimeh, M.R. et al., 2011; van de Ven, T.G.M. et al. 2004), but with different conditions based on the factors to be studied. The material to be flocculated was the fines abstracted from number of pulps, taken from Masson Maclaren Mill (Canada). These pulps were disintegrated and washed to remove the fibers and other colloids before use. The retention aid was the dual CF and PEO system. The PEO used was the neutral PEO of a 7 million molecular weight (Flocc 999). The CF used was the negative phenol material (Interac 1323). Both the PEO and the CF were supplied by I.Q.U.I.P Inc, (Canada).

Experimental Setup

The set up (Fig. 1) is the one used in previous works (Abdallah, Mohammad. R. 2002; Abdallah Qasaimeh, M.R. 2011; Abdallah Qasaimeh, M.R. et al. 2011; van de Ven, T.G.M. et al. 2004) with conditions and fixed parameters that fulfill the study of the objective of this work. Half liter of fines suspension were prepared at consistency $C (= (0.1\%)$ in 1 liter capacity beaker as flocculation vessel. The fines were mixed by a paddle of 6 cm length centered in the beaker at stirring rate (N rpm) that induces the process shear rate G_p to maintain the homogeneous suspension at steady state 1. The fines were circulated at constant stream rate via a transparent tube by a peristaltic pulp at a constant tube shear rate G_t. The stream passed the Photometric

Dispersion Analyzer (PDA) photocell to measure the flocculation intensity as ratio reading (R), the measure of floc size. The cofactor (0.25 mg/g fines) was first added followed with PEO addition (0.12 mg/g fines). After PEO addition, the reading R increased with time showing flocculation and reaching maximum at equilibrium (steady state 2). The experiment was repeated keeping all variables constants but at different stirring rate N to study the effect of the process shear rate on fines flocculation.

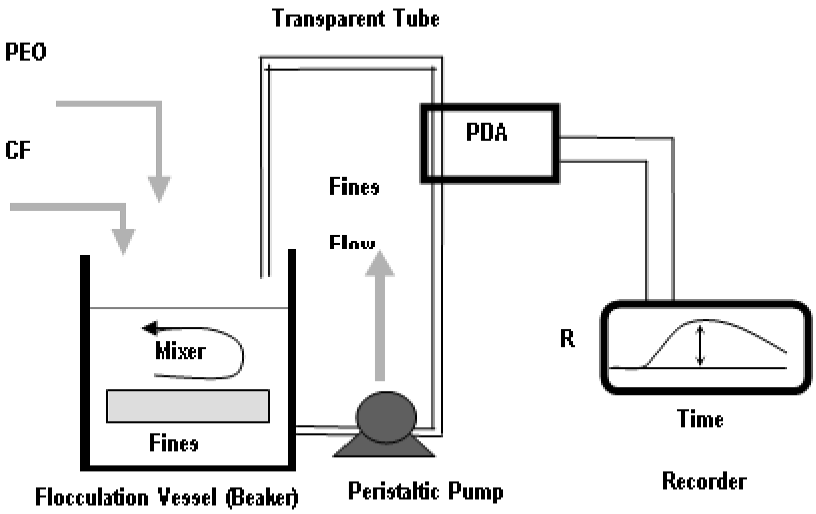

Fig. 1: Experimental Set up of Fines flocculation.

Flocculation and Deflocculation Intensity Readings

The output ratio signal of PDA, the ratio reading R, is the ratio of the alternating to the direct voltages in the PDA circuit loops. It was taken as the vertical distance the pen of the recorder moved within the time (t) in arbitrary units (A.U.). The reading R at time t denotes the size (A) of the particle (Gregory, J. 1984; Rank Brothers Ltd.). The larger the particle, the larger the reading R, which started after PEO addition showing flocculation. The recorder plots the reading R versus the time t (Fig. 2), where the maximum R indicates the maximum floc

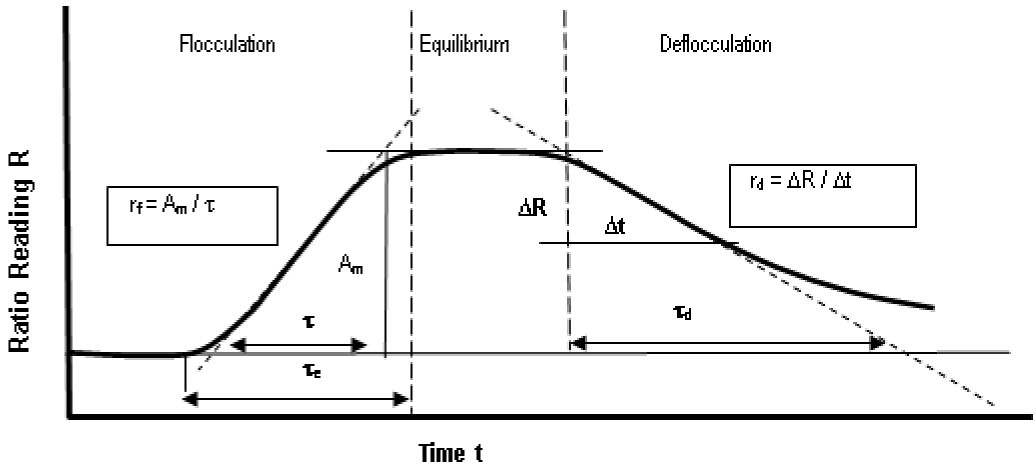

Fig. 2: Flocculation and Deflocculation Intensity Readings.

size (A_m). The initial rate of flocculation r_f $(= A_m / \tau)$ in A.U. is the slope of the curve at initial flocculation (Abdallah, Mohammad. R. 2002). The characteristic time of flocculation (τ) that indicates flocculation speed is the time needed to maintain A_m at initial rate r_f (Abdallah, Mohammad. R. 2002). Flocculation time expended to reach equilibrium is the equilibrium time (τ_e). As deflocculation occurred after equilibrium, the slope of the curve at initial deflocculation is the initial rate of deflocculation (r_d). The time needed to drop the reading R to initial value at rate r_d is the characteristic time of deflocculation (τ_d) that indicates deflocculation speed (Abdallah Qasaimeh, M.R. 2011). In this work, the flocculation rate constant was taken using k_f $(= 1/\tau)$ (Dr. Mohammad Raji Abdallah Qasaimeh, 10, 5, 2024; Mohammad Raji Abdallah Qasaimeh, 2022).

RESULTS AND DISCUSSION

Number of flocculation experiments (Table 1) were performed at different stirring rates N (rpm). The important flocculation parameters (Fig. 3): the flocculation amplitude (floc size), the flocculation rate, and characteristic time of flocculation were determined and plotted.

Table 1: The practical stirring rate N (rpm) with the corresponding shear rate G_p (s^{-1}).

Experiment	1	2	3	4	5	6	7	8	9	10	11
N (rpm)	70	100	132	180	206	241	303	356	460	552	688
G_p (s^{-1})	11.7	16.7	22	30	34	40	51	59	77	92	115

Results (Fig. 3) show the variations of these parameters with stirring rate N. With the increase in stirring rate N, the floc size A increased, reached maximum at $N = 206$ (rpm) and then started to decrease significantly at high stirring rates N. This result is in agreement with other work in literature as follow. In floc formation and during coagulation and removing humic acid, the stirring condition showed a remarkable effect on floc growth and structure. Gentle stirring resulted in larger floc, while intense stirring accelerated the floc breakage causing the final floc size to reduce. In fast stirring, the floc growth in the early coagulation stage was enhanced, but the capacity of the primary aggregates to grow into larger flocs was reduced (Junjie Yu. et. al. 2022). In microalgal harvesting using coagulation separation, an appropriate shear rate (9 s^{-1}) produced more desirable microalgal flocs (in terms of size and compactness) than higher or lower shear rates (Haiyang Zhang. et. al. 2019).

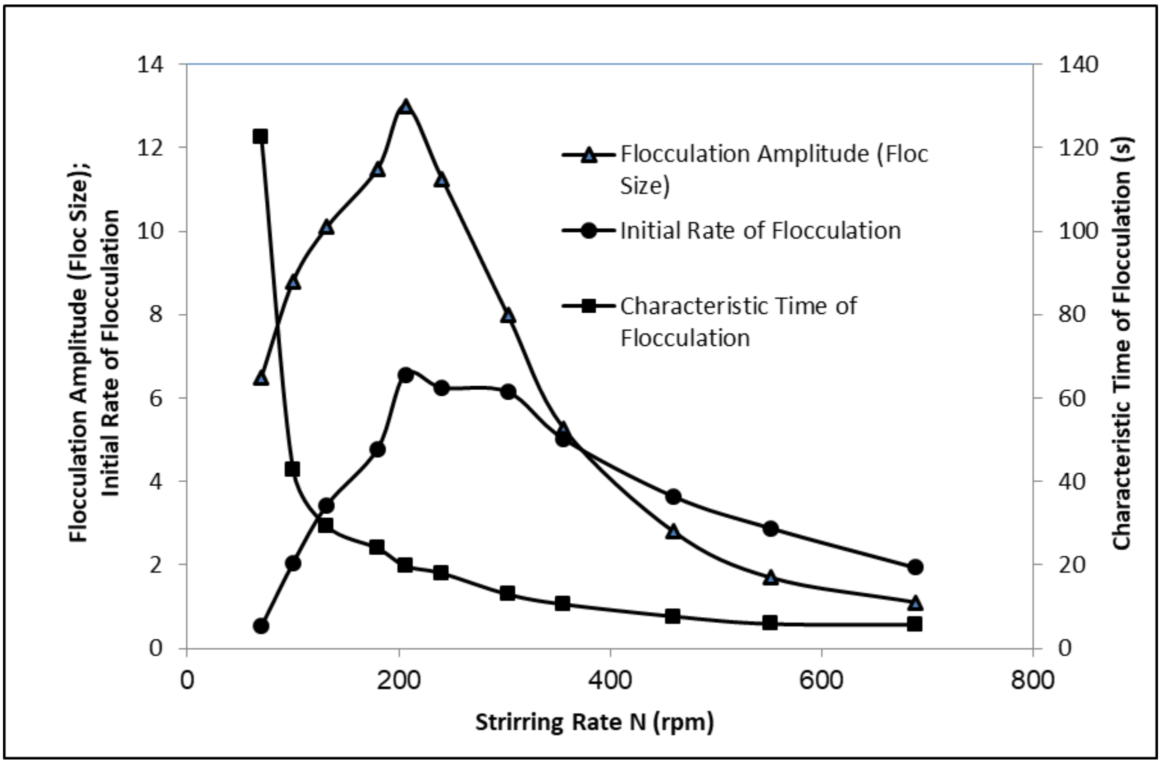

Fig. 3: Flocculation amplitude, rate and characteristic time as functions of stirring rate.

Similarly to floc size A, the flocculation rate r_f in this work (Fig. 3) has shown the same behavior. In other hand, the characteristic time of flocculation τ decreased drastically at low stirring rates N and started to plateau at high stirring rates $N > 460$ (rpm). One important parameter has identified the flocculation kinetics is the flocculation rate constant k_f $(= 1/\tau)$ that expressed the speed of flocculation process. As the wanted size of the floc is determined and selected, the speed of flocculation is needed also at the lowest cost of the operation. For

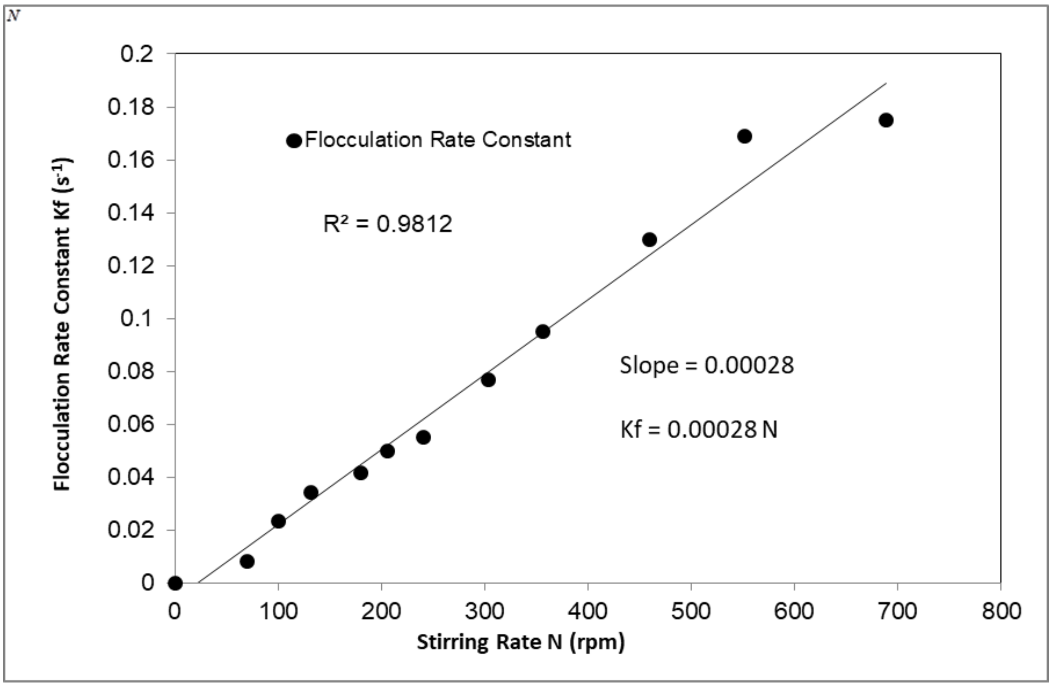

Fig. 4: Flocculation rate constant k_f as a function of stirring rate N.

this, we have plotted (Fig. 4) flocculation rate constant k_f versus the stirring rate N, and a proportional relation between k_f and N is shown. This relation is shown strongly linear with $R^2 = 0.9812$, and taking the best fit of data, the slope (S) is found to be $S = 0.00028$ that maintains the following linear relation: $k_f\ (= 0.00028\, N)$, where k_f is in seconds (s) and N is in (rpm). Since most processes occur in flow systems and the process shear rate G_p runs the process in the form of stirring rate N, we have studied the hydrodynamic factors in flocculation process and found the values of the process shear rate G_p, the Reynolds number (Re) and the effective shear rate (G_{eff}) for each experiment. The need to find out these factors become essential to analyze the flocculation process. The values of these factors usually found using the hydrodynamic laws and plot their values (Fig. 5) versus the stirring rates N. The shear rate values (Table 1) are estimated using $G_p = k\, N$, where $k = 10$ and N in (rpm) (Coulson and Richardson's, Sixth edition), converting the N (rpm) from minutes into (rps) in seconds. The Reynolds number $\mathrm{Re}\,(= \dfrac{N\, D^2\, \rho}{\mu})$ is estimated, where (D) is the diameter of the paddle, and (ρ) and (μ) are the density and the viscosity of the suspension respectively. Estimation of G_{eff} is done by using $G_{eff} = G_p \ \mathrm{Re}^{0.5}$ (Petlicki, J. and van de Ven, T.G.M., 1992). The diameter of the paddle used was $D = 6\ cm$. As the fines suspensions have the same consistency $C_{fn}\ (=0.1\%)$, the properties of these suspension do not have valuable deviations from that of water. In estimation of Re, we used $\rho(=1\frac{gm}{cm^3})$ and $\mu(=1\ c.poise)$, and then we found the hydrodynamic values of G_{eff}. The G_p, Re, and G_{eff}

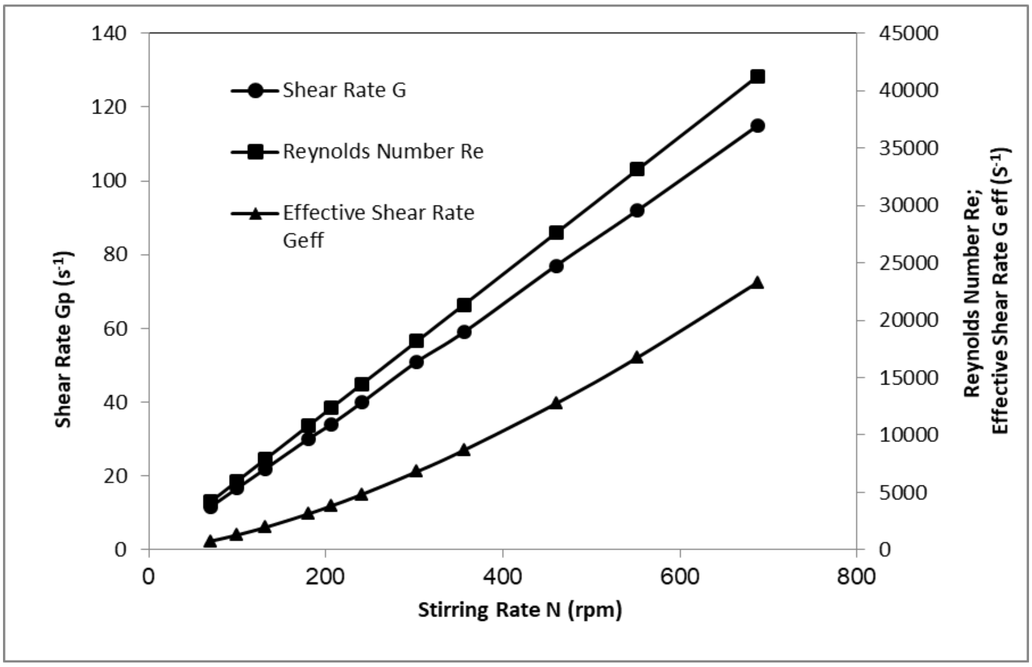

Fig. 5: Shear rate, Reynolds number and effective shear rate as functions of stirring rate.

were then plotted (Fig. 5) versus the stirring rate N. These hydrodynamic factors in flocculation process have significant effects on the flocculation parameters and floc characteristics. Analysis of these factors effects on flocculation rate constant k_f and on floc size A have been taken into consideration, since both k_f and A are important parameters in flocculation process. One destination in fines flocculation is the size of fines floc A that should fulfill the permeability, opacity, and apparent density of the paper sheet (Brecht, W., and Klemm, K., 1953). The second destination is the speed of flocculation to produce the required floc size in minimum operating time that reduces the manufacture cost. For this, we have proposed a methodology to fulfill these two destinations using the values of the hydrodynamic factors in flocculation process. In this methodology, the selection of the required floc size can be through plotting the values of the hydrodynamic factors in vertical coordinate (Fig. 6) versus the values of the floc size in horizontal coordinate. Results are shown at low, medium, and high ranges of the shear rates (Table 2), but not same limits. The variations of the floc sizes with G_p (Table 2) are compared with the variations of floc sizes in

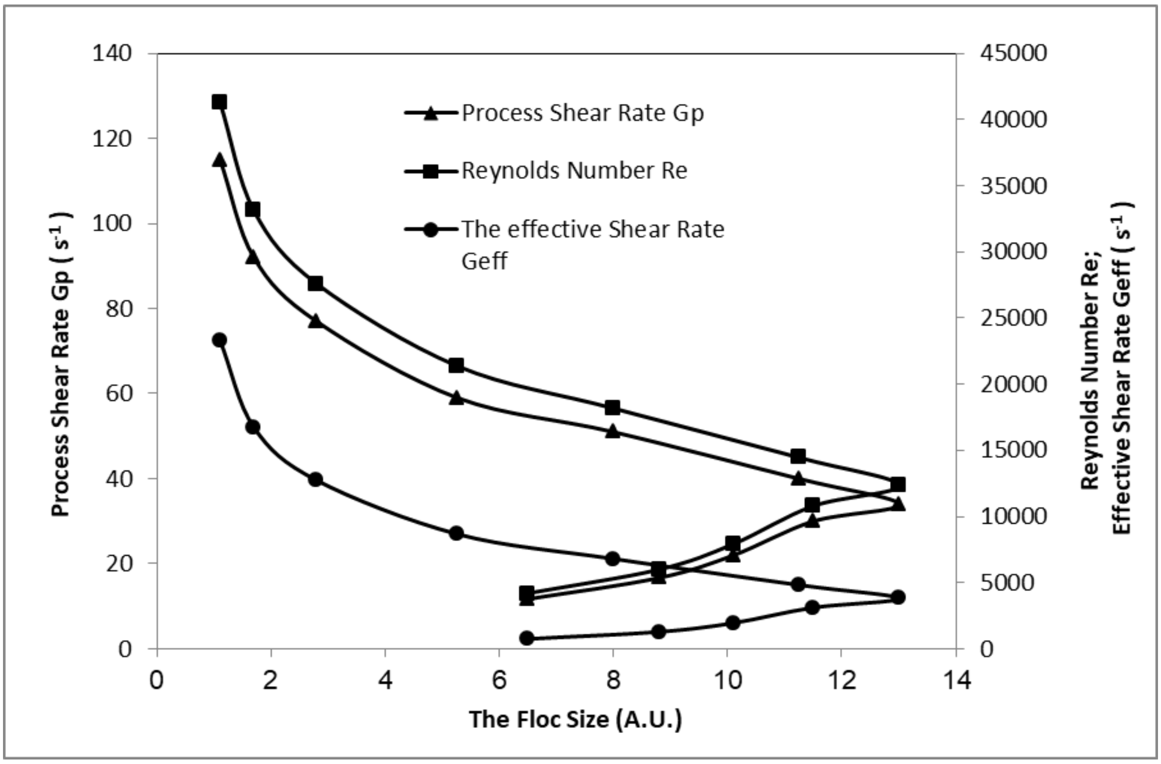

Fig. 6: Shear rate, Reynolds number and effective shear rate versus Floc size.

other works; the Zhenbei Wang, et. al., (2018) and the Teresa Serra et. al., (2008). Not same limits logically happen and can be attributed to the differences in the processes nature such as particle types, retention aids, and other process factors. This comparison shows an agreement in the shear rate effects on the sizes of the resulted flocs in the flocculation of the particles. To explain the methodology to select the required floc size from figure 6, we follow the following steps. First, let the floc size of fines in industry is the required maximum size ($A = 13\,AU.$) , then flocculation process can be operated at $G_p = 34\,s^{-1}$, $\mathrm{Re} = 12360$.

Table 2: Comparison of the floc size variations at low, medium, and high shear rates of this work with two other works in literature.

Literature Work	Low Shear Rate	Medium Shear Rate	High Shear Rate
Zhenbei Wang, et. al.	At $11 < G_p < 30\,s^{-1}$ Micro-flocs with	$30 < G_p < 55\,s^{-1}$ Size decreased from 13.61 μm to 10.91 μm	$55\,s^{-1} < G_p$ Sizes decreased to 1.85 -1.89 μm.

	larger size		
Teresa Serra, et. al.	At $G_p < 20\ s^{-1}$ Mean particle diameter increased with G_p	$20 < G_p < 30\ s^{-1}$ Producing the largest flocs	$30 < G_p$ Floc breakage, reduction of maximum floc sizes
This work	At $G_p = 6.5 s^{-1}$ The size is $A = 11.7\ AU.$	At $G_p = 34 s^{-1}$ Maximum size is $A = 13\ AU.$	At $G_p = 115 s^{-1}$ The size is $A = 1.1\ AU.$

$G_{eff} = 3818 s^{-1}$. Second, let the floc size is required small at ($A = 6.5\ AU.$), then flocculation process can be through two choices. One is at $G_p = 11.7 s^{-1}$, $\mathrm{Re} = 4200$, and $G_{eff} = 756 s^{-1}$. Two is at $G_p = 55 s^{-1}$, $\mathrm{Re} = 20000$, and $G_{eff} = 7740 s^{-1}$. Third, let the floc size of fines is required very small say ($A = 1.1\ AU.$), then the flocculation process can be operated at $G_p = 115 s^{-1}$, $\mathrm{Re} = 41280$, $G_{eff} = 23302 s^{-1}$. To fulfill the second destination, where the required size of fines floc is to be produced in minimum operating time that reduces the operating cost, we have plotted the flocculation rate constant k_f in the horizontal coordinate

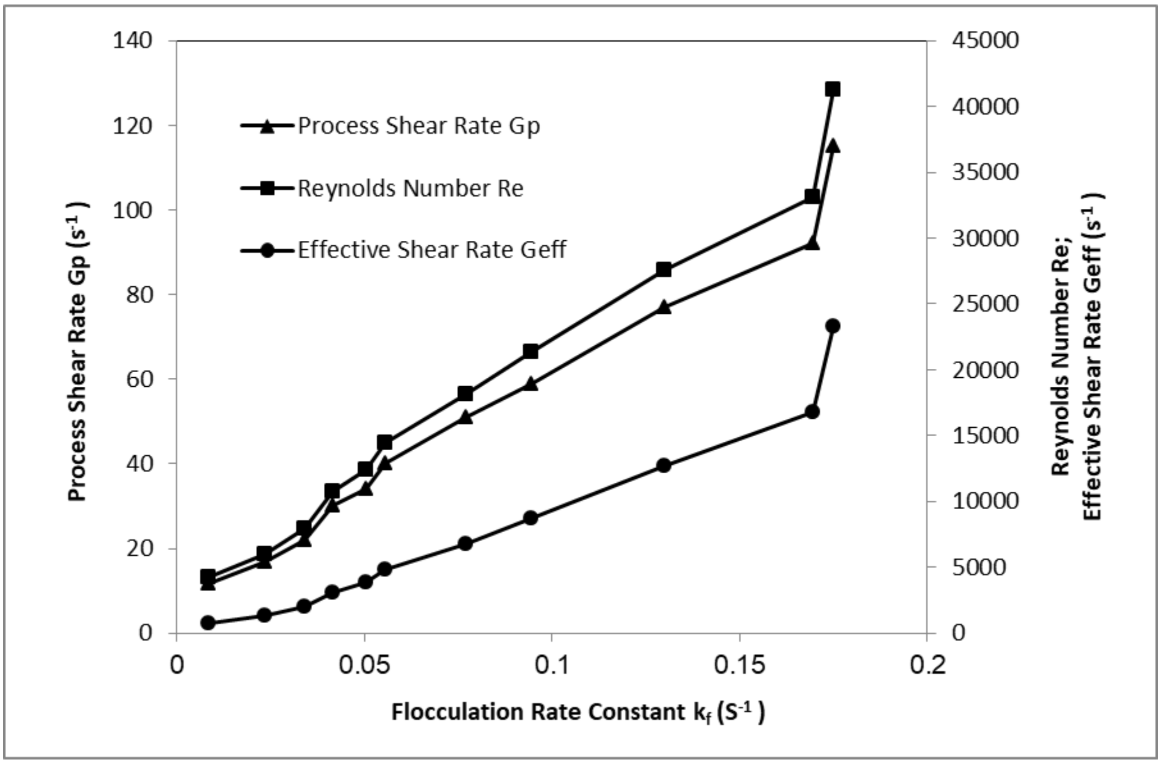

Fig. 7: Shear rate, Reynolds number and effective shear rate as functions of flocculation rate constant.

(Fig. 7) with the hydrodynamic factors in the vertical coordinates. Results (Fig. 7) show direct proportionality between the process shear rate G_p, Reynolds number Re, and effective shear rate G_{eff}, and the flocculation rate constant k_f. This means that with the increase in G_p (the increase in Re and in G_{eff}), the flocculation speed will increase, thus minimizing the operation cost. This direct proportionality (Fig. 7) of the k_f with G_p, Re, and G_{eff} means that flocculation rate constant k_f can represent the role of the hydrodynamic factors in

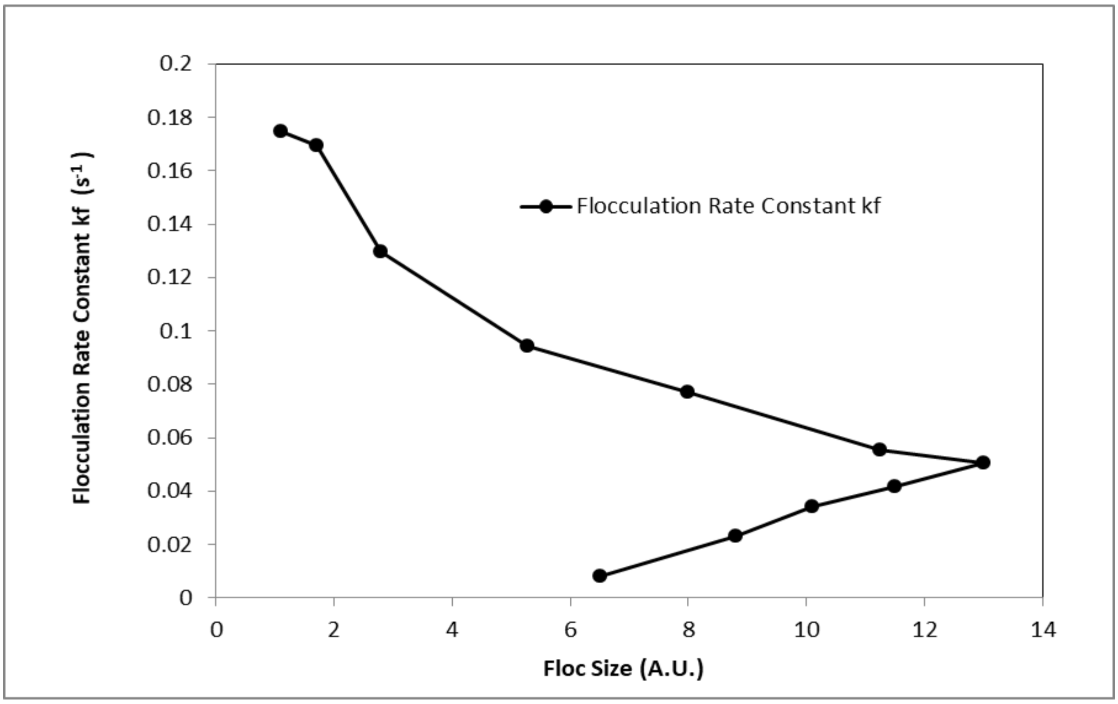

Fig. 8: Flocculation rate constant as functions of floc size of fines.

flocculation process. For this, we have plotted k_f in vertical coordinate (Fig. 8) with the floc size A in horizontal coordinate. The two destinations are now combined (Fig. 8) as follow. Step one, we select the required floc size A and then select the flocculation rate constant k_f (the flocculation speed). Step two, we fix the k_f at the horizontal coordinate (Fig. 7) and run flocculation process at the corresponding values of G_p, Re, and G_{eff}. For more explanation, let the required floc size is $A = 10.1$ (A.U.), then from figure 8 we get two values: the $k_{f1} = 0.0341 s^{-1}$ and the $k_{f2} = 0.0626 s^{-1}$. Using figure 7 at k_{f1} and k_{f2}, we operate the flocculation process at the corresponding values of G_p, Re, and G_{eff} selecting the better one. In case of flocculation in a reactor vessel, we need to operate a mixer at the stirring rate that produces the required floc size. The values of k_{f1} and k_{f2} are located on the vertical coordinate of figure 4 and then the corresponding required stirring rates N is chosen. Since higher the G_p is higher the N, the Re, and G_{eff}, but of lower τ or lower the operation time (t). Taking the value of τ for the time t $(t=\tau)$, and find out the dimensionless mixing intensity $(G_p\, t)$ (Dong Hyun Kim., et. al., 2023) to quantify the mixing characteristics. The G_p is responsible on the micro deformation occurring by the flow or the mixer stresses in the suspension that mostly resulting in flocculation, settling, and dispersion. Now, the $G_p\, t$ is the quantification of these changes in time t. Taking $t=\tau$, the $G_p\, t$ will quantify the fast effect of the micro deformation, since τ is the time needed to proceed flocculation at initial rate, mainly, the flocculation of fines using CF-PEO is very fast. Now $G_p\, t$ will magnify the micro characteristics or interactions (e.g. attachments, detachments, settling) among fines with time. Since one of the main affective factors in flocculation is the G_p, so we have plotted G_p (Fig. 9) versus the $G_p\, t$ and floc size A as a macro measurement. Analyzing the $G_p\, t$ effect, results show that $G_p\, t$ has high values at low values of G_p ($N<100$ rpm) with small floc sizes A. This behavior indicates that some of the fines do not flocculate and most probably they settle before flocculation (Dong Hyun Kim., et. al., 2023), and since the state takes long time, it indicates large operation cost of flocculation, and higher is the cost with a decrease

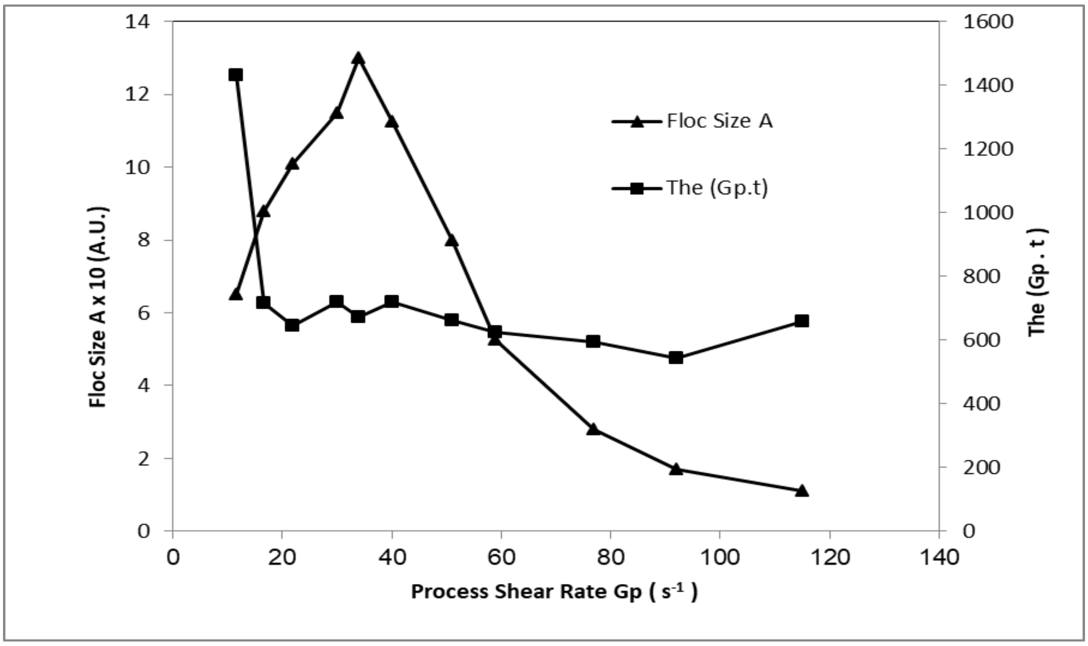

Fig. 9: The floc size A and the $G_p\, t$ as a function of the process shear rate G_p.

in G_p. At higher G_p values, the $G_p t$ values oscillate in a narrow range in between the 720 and 543 and has a tendency to decrease with the increase in G_p, where τ decreases showing faster interactions with lower cost range. For the floc size, the increase in floc size from $A = 8.8$ (A.U.) to the maximum $A = 13$ (A.U.) occurs in between $G_p = 16.7\,s^{-1}$ and $G_p = 34\ s^{-1}$, while $G_p t$ remains oscillating between 543 to 720. In the period at $G_p > 34\ s^{-1}$ the floc size decreases to the minimum $A = 1.1$ (A.U.), while $G_p t$ remains oscillating in between 543 to 720. This discussion leads to say that the low process shear rate G_p (low N) consumes more cost in flocculation process, while at high shearing after the maintenance of the maximum floc size, the floc size decreases with slow decrease in the operation cost. As a conclusion, Now we recommend to operate flocculation at the stirring (shearing) rates that produces the required floc size using the proposed methodology whatever is the G_p, except the low values of G_p for high cost, since $G_p t$ oscillates in between the same narrow range.

CONCLUSION

We have studied the role of the hydrodynamic process factors in flocculation process. We investigated flocculation experiment at different stirring rates and found the effects of these stirring rates on the flocculation parameters such as floc size, flocculation rate and characteristic time of flocculation. In hydrodynamic view, we analyzed the stirring rate effect into the shear rate, Reynolds number and the effective shear rate. In flocculation process view, we analyzed floc size and flocculation rate constant. We proposed a methodology to select the required floc size and find out the flocculation rate constant to fix the speed of flocculation process. The values of the shear rate, Reynolds number and effective shear rate are found from flocculation rate constant to maintain flocculation process at the necessary hydrodynamic factors that produce the required floc size, and flocculation speed and cost.

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