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USING ON-LINE TURBIDIMETER MONITORING TECHNIQUE IN EVALUATING ALGAL SUSPENSION REMOVAL

In this study, an on-line Nephelopmetric turbidimeter connecting to a data acquisition unit was used to monitor the algal flocs formation at various velocity gradient (or mixing energy, G in s^{-1}) values. The results indicated that the standard deviations (SD) of the turbidities during the flocculation (slow mixing) period provide more information than the floc size. In addition, this on-line monitoring technique can be a simple and effective indicator to obtain an optimal G value for a flocculation process.

1. INTRODUCTION

Water-borne algae may be single or multiple cellular plants. With sufficient sunlight and nutrients, they multiply rapidly and secrete odour and colour in the water. When surface water containing high concentration of algae is used as a source of drinking water, the quality of drinking water will be affected greatly [1], [2]. Most water treatment plants depend on chemical coagulation or flocculation process for removing the majority of waterborne algae to reduce the loading to the subsequent unit processes and operations [3]–[6]. Thus, coagulation is an important operation unit; its efficiency affects the subsequent sedimentation and filtration. In a water treatment plant, the selection and the dosage control of coagulants depend generally on the results from jar tests. Improper coagulant and dosages may lead to a useless operation and increase the quantity of chemical sludge, and therefore result in an ineffective removal of waterborne algae. Additionally, the G value is the most important

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of many physical and chemical parameters (e.g. velocity gradient (G), mixing time (t), and the type and shape of mixers, etc.) in affecting the efficiency of floc growth in the coagulation process [7], [8]. With a fixed G value, the mixing time (t) may be changed to improve efficiency [9], [11]. Thus, the value of Gt is another important parameter used in water treatment plants for adjusting mixing intensity. The value of Gt indicates the input of energy for coagulation. The use of aluminium salts generally requires higher and wider range of Gt values than the use of ferric salts for effective flocculation [12]. YOSHIHIKO et al. [13] proposed that the G value has a significant influence on reducing the number of original particles during flocculation. MHAISALKAR et al. [14] studied the influence of the G value on the residual turbidity of water samples whose original turbidity levels were different and which were coagulated with various coagulants. They reported that insufficient mixing intensities did not agglomerate small particles effectively. The G value also has been shown to significantly affect the final floc size and structure, and the rate of flocculation [15]–[17]. Some studies presented in literature can provide a comprehensive understanding of the relationship between G values and the size of the flocs based on monitoring with a Photometric Dispersion Analyzer (PDA) [18]–[19]. However, the PDA is not a commonly used instrument in water treatment plants. In this study, the jar test using polyaluminium chloride (PACl) to flocculate the algal suspension prepared in our laboratory was continuously monitored with an on-line Nephelopmetric turbidimeter. In our previous study [20], an on-line monitoring technique was found to demonstrate well a linear relationship between the square root of floc sizes and the standard deviations (SD) of the measured turbidity fluctuation. Therefore, the goal of the study was to investigate floc formation under various G values of both rapid and slow mixing to obtain the optimal conditions for floc formation.

2. EXPERIMENTAL EQUIPMENT AND METHODS

2.1. CULTIVATING THE ALGAL SUSPENSION

The freshwater *Chlorella* sp., a round single-celled green alga with an average diameter of 4 μm (varying from 2 to 8 μm), was used in this study. It is a predominant species found in domestic eutrophic lakes. The *Chlorella* sp. was obtained from the Taiwan Fishery Research Institute, Tung-Kong Branch, and a cultivation method [20] was used to prepare the algal suspension in laboratory. The cultivation solution using an inorganic medium was prepared according to the formula proposed by WALNE [21].

2.2. PREPARATION OF PACl COAGULANTS

For the preparation of the PACl coagulant with a 1.5 basicity (B, $B=OH^-/Al^{3+}$), 30 ml 0.5 M NaOH solution were added using a peristaltic pump at flow rates of 0.05 ml/min into 70 ml 0.143 M $AlCl_3$ solution.

2.3. JAR TEST

Figure 1 shows the schematic diagram of the jar test apparatus and the on-line Nephelometric turbidimeter (WTW model MIQ/C1184) attachment [20]; the jar test was made with covered black opaque acrylic containers instead of the traditional jar test flasks. A hole was drilled in the cover for adding chemicals. One litre of the prepared 10-NTU synthetic algae sample was placed in the acrylic flask. The coagulation study was done with 1-litre raw water samples containing 10-NTU *Chlorella* sp. suspension to be coagulated using 1.1×10^{-4} M (Al) of PACl. The content was rapidly mixed for 60 seconds with G values maintained at 10 s^{-1}, 50 s^{-1}, 100 s^{-1}, 200 s^{-1}, 300 s^{-1} and 400 s^{-1} followed by slow mixing for 10 minutes with G values maintained at 0 s^{-1}, 10 s^{-1}, 20 s^{-1}, 30 s^{-1} and 50 s^{-1}, and then it was allowed to settle. The Nephelopmetric turbidimeter (WTW model MIQ/C1184) connecting to a data acquisition unit (YOKOGAWA model FX-106-0-2) developed by CHENG et al. [20] was used to measure and record the turbidity data for every second and instantaneously appeared on a computer monitor. The curves of turbidity versus time were plotted from the data of turbidity using Microsoft EXCEL. All turbidity data collected during the slow mixing period were grouped every 120 seconds. The values of standard deviation (SD) for each group consisting of 120 data points were plotted versus time. All coagulation studies were conducted using PACl, which is currently the most commonly used coagulant in water treatment plants.

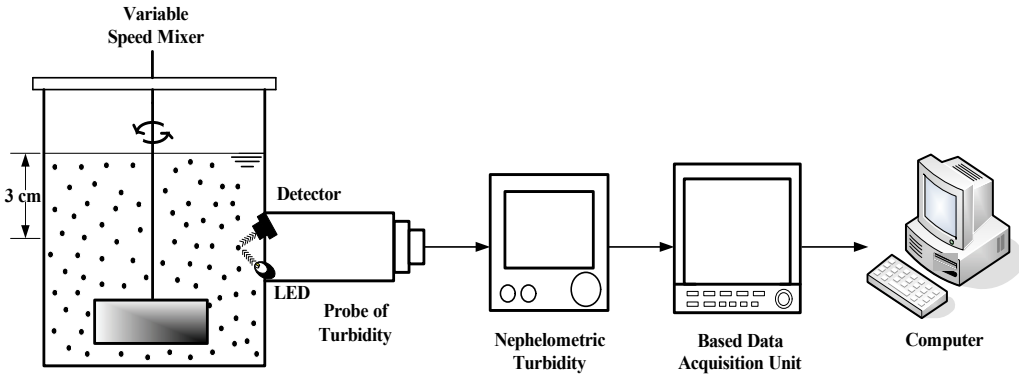

Fig. 1. Schematic diagram of the Nephelometric turbidimeter set-up for the jar test [20]

3. RESULTS AND DISCUSSION

It has been known that the velocity gradient (G) is the most important parameter affecting the flocculation efficiency. We searched for the optimal G value for flocculating the algal suspension using PACl as the coagulant by performing the coagulation

at various G values. The rapid mixing G value was fixed at 100 s^{-1} for 60 seconds followed by slow mixing at 20 s^{-1}, 30 s^{-1} and 50 s^{-1} for 10 minutes. Variations of Nephelopmetric turbidity units (NTU) are shown in figure 2. For the settling of the flocs, the slow mixing at 20 s^{-1} was better than the 30 s^{-1}, and the 30 s^{-1} was better than the 50 s^{-1}. This indicates that under similar mixing rates, the smaller the slow mixing G values, the better the floc settleability. During the flocculation period shown in figure 2, the fluctuation of turbidity data can also indicate the condition of particles agglomeration into flocs. Our previous study [20] indicated that the size of the flocs was proportional to the amplitude of turbidity fluctuations in the coagulation process; the standard deviation (SD) of the turbidity data was found to be directly related to the size of the flocs. The turbidity monitoring results (figure 2) showed that when the samples were flocculated at higher G values in the process of slow mixing they had relatively smaller turbidity fluctuation than that at lower G values. The largest amplitude of turbidity fluctuation was observed at slow mixing 20 s^{-1} and led to relatively large flocs, and then a better sedimentation in a shorter settling time. Also, when the turbidity data collected during the flocculation were grouped every 120 seconds and

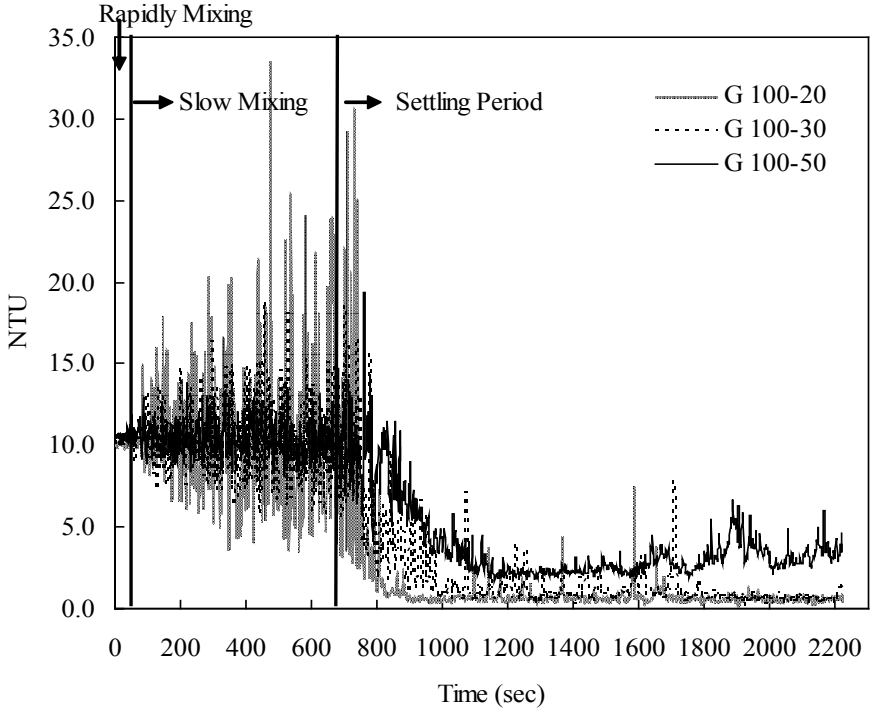

Fig. 2. The changes of turbidity per second for samples coagulated using 1.1×10^{-4} M PACl, rapid mixing at G value of 100 s^{-1} for 60 seconds; slow mixing at G values of 20 s^{-1}, 30 s^{-1}, and 50 s^{-1} for 10 min

the turbidity SD for each group (120 values) was plotted versus time (figure 3), the turbidity SD increased initially and became steady under same *G* values. This indicated that the flocs gradually grew in size during the flocculation period. The SD of turbidities were in the order of 20 s^{-1} > 30 s^{-1} > 50 s^{-1}, they also proved to be similar in floc size and settling ability (figure 3). Further, samples subject to slow mixing at 20 s^{-1} and 30 s^{-1} did not show much difference in the final residual turbidity (figure 2). When the traditional jar test was used to determine the flocculation efficiency by observing the final residual turbidity in the supernatant, the conditions at 20 s^{-1} and 30 s^{-1} were considered to bring about the same flocculation efficiency, however, the condition is more efficient at 20 s^{-1} than at 30 s^{-1} in producing larger flocs. The above observation demonstrates that the method of on-line monitoring supernatant turbidity with a Nephelopmetric turbidimeter is more reliable in determining the floc size and also in providing more floc growth data for analysis.

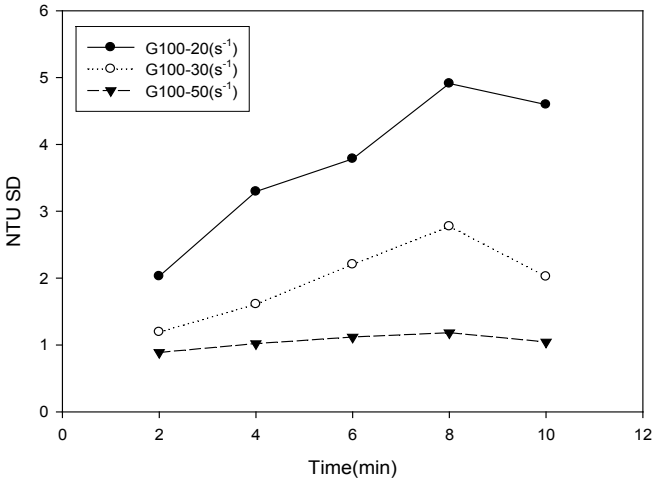

Fig. 3. Relationship between the SD of turbidities and slow mixing times (rapid mixing at *G* value of 100 s^{-1} for 60 seconds; slow mixing at *G* values of 20 s^{-1}, 30 s^{-1} and 50 s^{-1} for 10 min; coagulant dose of 1.1×10^{-4} M PACl)

Subsequently, the *G* value was changed by subjecting the samples to rapid mixing at 100 s^{-1}, 200 s^{-1}, 300 s^{-1} and 400 s^{-1} for 60 seconds followed by slow mixing at 20 s^{-1} for 10 min. As shown in figure 4, the smaller rapid mixing *G* value resulted in a greater SD variation of the turbidity. Conversely, mixing with a greater *G* value appeared to cause the destruction of the flocs and poor settling [22]. The phenomenon was more obvious when using higher *G* values for slow mixing. As shown in figure 5, all samples subject to slow mixing at 50 s^{-1} for 10 minutes after they had been rapidly mixed at 100 s^{-1}, 200 s^{-1}, 300 s^{-1}, or 400 s^{-1} for 60 seconds exhibited poor floc formation evidenced by the turbidity SD of the supernatant during slow mixing. Except for the sample flocculated at 100 s^{-1}, the fact that all other samples had turbidity SD val-

ues below 1 indicated that the flocculation efficiency was significantly influenced by the mixing speed of both rapid and slow mixing.

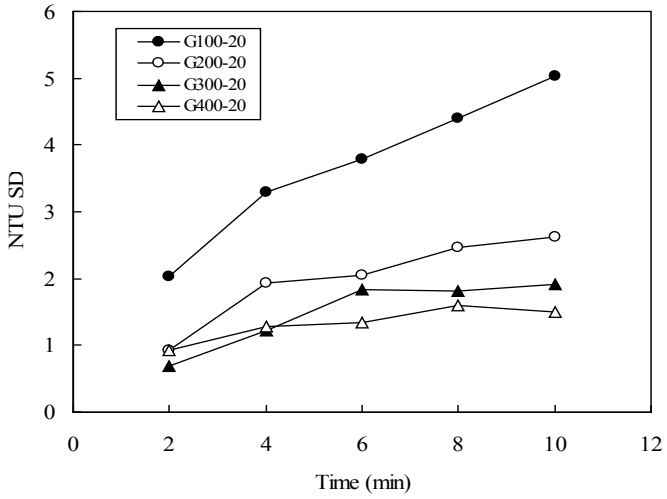

Fig. 4. Relationship between the SD of turbidities and slow mixing times (rapid mixing at G values of 100 s^{-1}, 200 s^{-1}, 300 s^{-1}, and 400 s^{-1} for 60 seconds; slow mixing at G value of 20 s^{-1} for 10 min; coagulant dose of 1.1×10^{-4} M PACl)

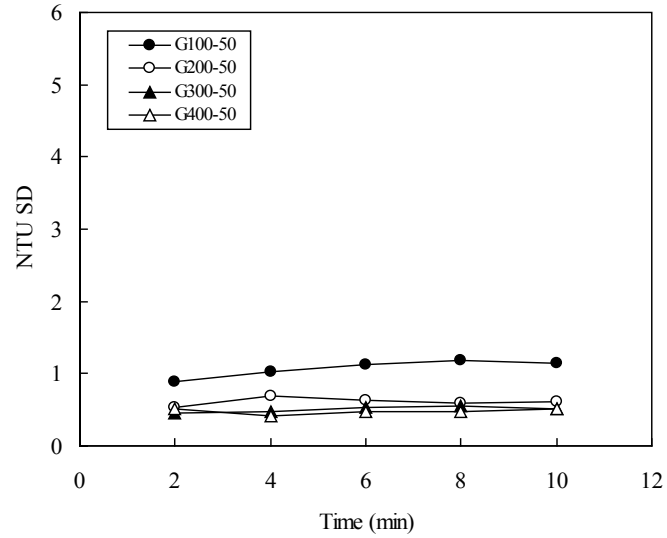

Fig. 5. Relationship between the SD of turbidities and slow mixing times (rapid mixing at G values of 100 s^{-1}, 200 s^{-1}, 300 s^{-1}, and 400 s^{-1} for 60 seconds; slow mixing at G value of 50 s^{-1} for 10 min; coagulant dose of 1.1×10^{-4} M PACl)

Without the addition of coagulant, slow mixing at 20 s^{-1}, 30 s^{-1} and 50 s^{-1} did not cause the algal suspension to agglomerate effectively, thus, the turbidity SD values did not show much variation. As shown in figure 6, all turbidity SD values were between 0.20 and 0.25 indicating that the above observed variations of turbidity SD were contributed to the interaction between coagulant and algal suspensions leading to the formation of large flocs.

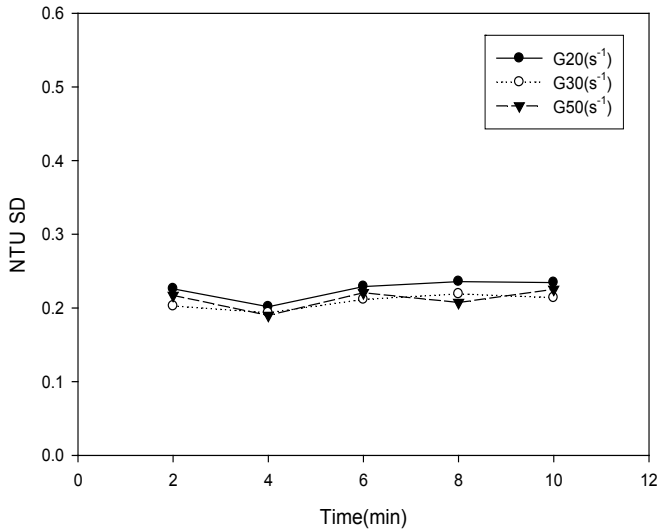

Fig. 6. The turbidity SD for 3 uncoagulated samples, slow mixing at *G* value of 20 s^{-1}, 30 s^{-1} and 50 s^{-1} for 10 minutes, respectively

As discussed above, slow mixing intensity led to effective floc formation. Hence, several studies were carried out with samples treated with rapid mixing at 100 s^{-1} for 60 seconds, followed by slow mixing at reduced *G* values of 0 s^{-1}, 10 s^{-1}, 20 s^{-1}, 30 s^{-1}, and 50 s^{-1} for 10 minutes. As shown in figure 7, without slow mixing (at 0 s^{-1}), flocs were formed after stopping the rapid mixing for 4 min, and the turbidity SD also began to change. With *G* at 0 s^{-1}, the slow mixing operation was actually eliminated so that the quiescent condition after the end of the rapid mixing period allowed the algal flocs to settle immediately. After 4 minutes, the water at 3 cm below surface became clear without measurable turbidity, therefore there were no data for calculating the turbidity SD. The results also showed that the floc formation in samples without slow mixing was not as efficient as samples subject to slow mixing at 10 s^{-1} and 20 s^{-1}, but it is better than that at 30 s^{-1}. The sample subject to rapid mixing at 100 s^{-1} for 60 seconds and slow mixing at 10 s^{-1} for 10 min revealed the best floc formation (figure 7). When slow mixing *G* values were increased, the turbidity SD decreased and floc formation deteriorated. Hence, decreasing the slow mixing intensities led to better floc formations, but the step of slow mixing cannot be eliminated, otherwise the floc

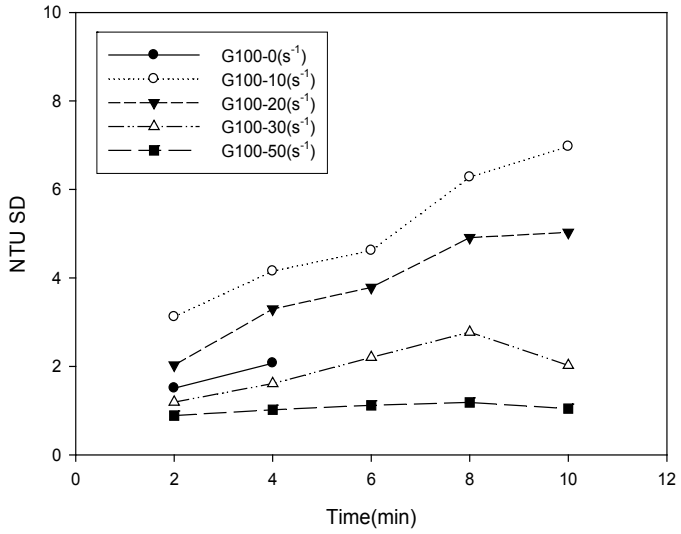

Fig. 7. Relationship between the SD of turbidities and slow mixing times (rapid mixing at G value of 100 s^{-1} for 60 seconds and slow mixing at G values of 0 s^{-1}, 10 s^{-1}, 20 s^{-1}, 30 s^{-1} or 50 s^{-1} for 10 min; coagulant dose of 1.1×10^{-4} M PACl)

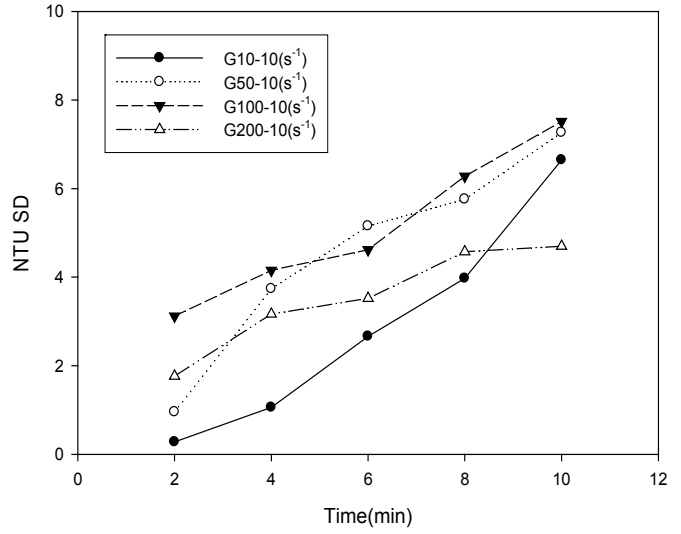

Fig. 8. Relationship between the SD of turbidities and slow mixing times (rapid mixing at G values of 0 s^{-1}, 50 s^{-1}, 100 s^{-1}, or 200 s^{-1} for 60 seconds and slow mixing at G value of 10 s^{-1} for 10 min; coagulant dose of 1.1×10^{-4} M PACl)

will be deteriorated. Thus, the optimal G value at 10 s^{-1} was used as the optimum level for slow mixing coupled with various rapid mixing G values at 10 s^{-1}, 50 s^{-1}, 100 s^{-1},

formation and 200 s^{-1} for 60 seconds in jar tests. As is shown in figure 8, the rapid mixing intensities slower than 10 s^{-1} did not lead to satisfactory turbidity, SD indicated a poor mixing between algal solids and the coagulant, thus the floc formation was unsatisfactory. Although the final turbidity SD reached 6.65, it was still worse than the turbidity SD at 50 s^{-1} and 100 s^{-1}. In short, too high or too low rapid mixing *G* values adversely affected the flocculation of algal suspension; only the optimal *G* value led to the best flocculation efficiency. Using the Nephelopmetric turbidimeter devised in the lab provided prompt and accurate information about turbidity for selecting the optimal flocculation conditions.

These studies on the optimal *G* value revealed the relationship between turbidity SD and floc formation for samples subject to various slow mixing intensities. Larger flocs settled better with less turbidity left in the supernatant. The final residual turbidities after the sedimentation for samples subjected to rapid mixing at 100 s^{-1} for 60 seconds followed by slow mixing at 10 s^{-1}, 20 s^{-1}, 30 s^{-1} and 50 s^{-1} for 10 min and settling under undisturbed conditions for 1 hour are shown in figure 9. A greater turbidity SD resulted in lower final turbidity after all flocs in the suspension settled. Hence, the on-line monitoring of turbidity during the slow mixing period allowed the calculation of turbidity SD, which appeared to be a reliable factor for determining flocculation efficiency.

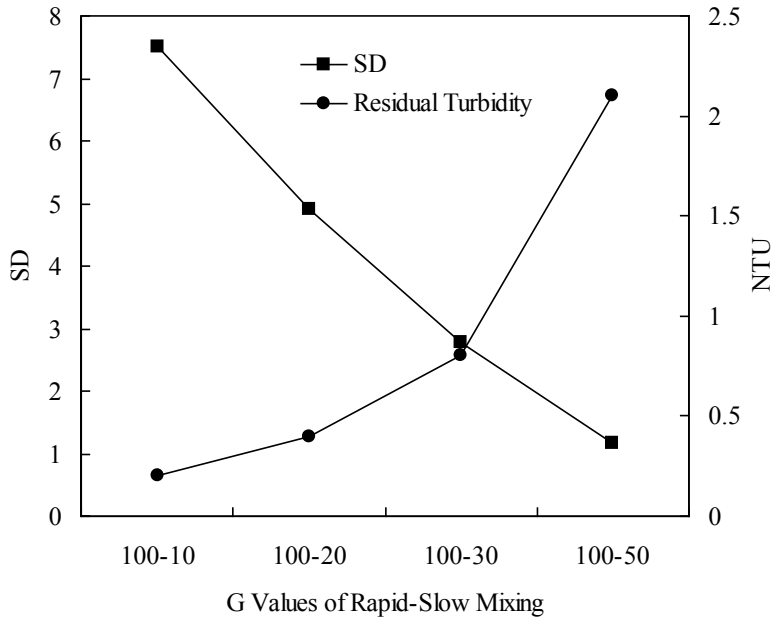

Fig. 9. Relationship between rapid-slow mixing *G* values and the final residual turbidities of the flocculation samples

4. CONCLUSIONS

The continuous on-line turbidity monitoring using the Nephelopmetric turbidimeter device provides more accurate flocculation data in jar tests. The relationship between the standard deviation (SD) of measured turbidities and the resulting floc sizes assisted in understanding the influence of various conditions on the floc agglomeration and subsequent sedimentation. The result indicated that the values of *G* for both rapid and slow mixing operations will greatly influence the treatment of *Chlorella*-containing water. In addition, successful removal of the *Chlorella* suspension in water requires a rapid mixing at appropriate *G* values, so the coagulant can be thoroughly mixed with the algal particles. Avoiding excessive rapid and slow mixing operations assures a satisfied efficiency for the subsequent floc formation and sedimentation.

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