Enhanced Solid–Liquid Separation of Coal-Contaminated Wastewater Using a Reflux Lamella Settler

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Abstract

A systematic study was conducted to demonstrate enhanced sedimentation of low-density coal particles from wastewater in a newly designed settling vessel consisting of two inclined sections, termed the Reflux Lamella Settler (RLS). The RLS is a modified settling vessel consisting of inclined sections. Inclined sections are incorporated to provide a large settling area for solid particles, thereby enhancing settling rates compared to conventional settling tanks/vessels. Two RLS were designed and fabricated: one was a small lab-scale piece of equipment, and the other was relatively large and designated the prototype RLS for experiments. The first set of experiments was performed on the lab-scale RLS and a vertical settling column, which were filled with a solution of water and coal particles. The solid particles settled at a higher rate in the RLS due to the presence of inclined sections and reached a maximum solid concentration of 0.63 (v/v) at the base. In contrast, the vertical settling column achieved a maximum solid concentration of 0.43(v/v), demonstrating relatively slow settling of solid particles. In addition, experiments were conducted on the prototype RLS to examine the settling of solid particles at a larger scale under batch process conditions and the applicability of the equipment for high flow rates. A sample comprising 1 kg of coal particles of size 0.25 mm (250 microns) and 12 kg of water was placed in the prototype RLS, and results were obtained. A maximum solid volume fraction of 0.63 (v/v) was achieved in the prototype RLS and 0.15 (v/v) in the dilute region, values that were almost identical to those in the lab-scale unit. This shows that the RLS could be used to handle a large amount of wastewater. The coloured PVC particles were used to validate particle movement within the RLS. It showed that, after entering the RLS, these particles quickly settled on the inclined surface and slid downwards. The car wash sample was used treated in the RLS, which showed that it takes 90 minutes to settle the solid particles, resulting in a reduction in turbidity from 233 to 30 NTU during that time.

Keywords: Boycott effect, Flux, Hindered settling, Inclined channels, Total Suspended Solids,

1. Introduction

Wastewater treatment and recycling in mineral processing and associated industries are becoming a core issue for ongoing sustainability. In wastewater treatment, sedimentation is an essential primary technique for the efficient removal of suspended particles, silt, sludge, and other contaminants from the liquid [1, 2]. In sedimentation, gravity is the primary force that causes solid-liquid separation, for which settling tanks and/or thickeners are used. In settling tanks, solid particles settle to the bottom and are removed in the underflow from the base, while relatively clear water overflows from the top.

Nevertheless, managing wastewater/solid-liquid mixtures is a complex process due to the settling characteristics and rheological properties of the various types of solid particles present. For instance, settling of fine particles less than 1 mm in size, such as coal in coal processing, organic waste, plastic materials, silt, and sand in wastewater, is a very slow process [3] and requires longer settling times. To handle the high flow rates of these particles, the settling tanks must be very large, resulting in increased size and number, which makes them more expensive. Various techniques have been used to enhance the settling of solid particles, including coagulation, flocculation, and improvements to settling tank design. Subsequently, one of the most important methods of enhancing the settling rate of solid particles is the incorporation of inclined channels in sedimentation tanks [4, 5]. The concept of enhanced settling in inclined channels was first proposed by Boycott in 1920 [5]. The author, Boycott, in 1920 observed that blood corpuscles settled rapidly in an inclined tube, contrary to a vertical tube, and termed this phenomenon the *Boycott Effect* [5]. According to the Boycott Effect [5], inclined channels/plates provide a large effective settling area for solid particles, due to which particles settle at a relatively high rate. Similarly, Devis and Acrivos [3] demonstrated in their experiments that solid particles settle faster in an inclined channel than in a vertical column [5, 6]. According to PNK theory, the enhanced settling rate, S_t, in an inclined channel is given by Davis & Acrivos [3],

$$S_t = u_t z \left(\frac{L}{z} \sin\theta + \cos\theta \right) \qquad (1)$$

where, u_t is the terminal settling velocity, z is the channel width perpendicular to the channel surface,
L is the channel length and θ is the inclination angle of the channel.

$\left(\frac{L}{z} \right) \sin\theta$, a factor, enhances the velocity of the interface.

which can be further increased by increasing the aspect ratio $\frac{L}{z}$ for a given angle of inclination [3, 6].

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For instance, consider the settling of solid particle species in a vertical and an inclined channel. As the particles settle in the channel, the suspension segregates into three distinct layers Figure 1(a, b). The first layer on the surface of the inclined channel (Figure 1a) contains a higher concentration of solid particles and is called the sediment. Moving vertically, the second layer contains a relatively lower concentration of solid particles and is termed the dilute zone. The top layer represents the clarified water that forms after the solid particles settle in the inclined channel [3, 6]. During a continuous process, the solid particles, after forming sediment, slide downwards into the underflow, whereas clear water overflows [6, 7]. A similar phenomenon occurs in the vertical channel (Figure 1a); however, the settling area in the vertical channel is much smaller than that in the inclined channel, as shown geometrically in Figure 1(a, b).
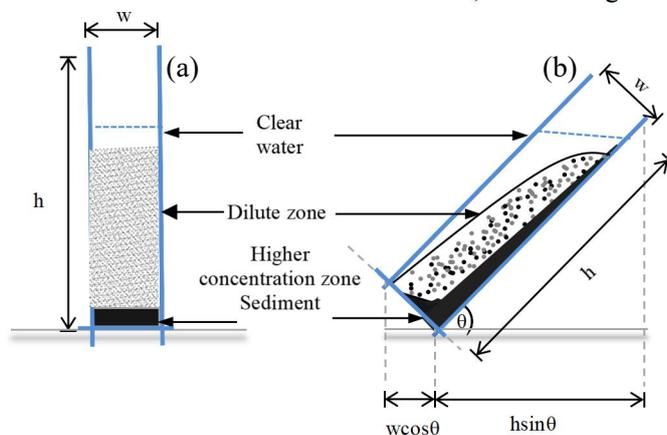

Figure 1(a, b): Settling of solid particles in a vertical and inclined channel

The inclined channels, due to their enhanced sedimentation and high capacity per unit volume, are incorporated into settling tanks to configure low-footprint settlers known as lamella settlers [6-8]. Lamella settlers are gravitational solid-liquid separators that may vary in design but generally comprise parallel inclined channels/sections within a vessel. The compact design of the lamella settler provides a relatively high surface area and throughput, making it a cost-effective method for increasing the solids settling rate [6, 7, 9].

Forsell and Hedstrom [10] studied, for the first time, the application of lamella settlers in water treatment processes. The authors showed that lamella settlers require shorter retention times than conventional settlers, due to the large sedimentation surface area they provide, which depends on the channel angle and spacing. Poh [11] showed experimentally that laminar flow conditions in inclined channels are more effective than turbulent flow for reducing the conveyance of coarser particles to the overflow. Adelman et al. [12] studied the effect of inclined channel spacing on sedimentation. They discussed lamella settlers with an inclined channel spacing of 50 to 300 mm; however, for narrow spacing, there was not much literature available. They used a 25 mm inclined channel spacing in their experimental work and observed that the particles' settling velocity in the inclined section was lower than the fluid velocity. This phenomenon prevented the particles from settling onto the plates and sliding down the channel. They also observed that the velocity difference increased as the plate spacing was further reduced to 15 mm and concluded that large spacing in inclined channels is suitable for sedimentation processes; however, further investigation is required into the properties of solid particles (size, shape, and density) and fluid velocity before finalizing the channel spacing [12]. Recognizing the importance of lamella settlers, they are frequently preferred over traditional vertical settlers due to their ability to handle high flow rates and occupy less footprint in wastewater treatment processes [9, 11].

In this research work, a newly designed lamella settler, comprising two inclined sections and a vertical section in the middle, termed the Reflux Lamella Settler (RLS), has been developed and used to investigate the settling of low-density solid particles. The results for sediment formation, dilute zone length, and clear water height in the RLS have been recorded and compared with corresponding results from a vertical settling tank.

2.0. Materials and Methods

2.1. Experimental Design

A newly designed laboratory-scale experimental unit, the Reflux Lamella Settler (RLS; Figure 2a), was fabricated in the lab. The lab-scale RLS consisted of two inclined sections, each at 70º, and a vertical section in the middle. The length of the upper inclined section was 17 cm, the vertical section was 20 cm, and the lower inclined section was 15 cm. The internal diameter of the lab scale RLS was 4.8 cm, and the external diameter was 5.2 cm. These dimensions were selected because a vertical vessel of similar dimensions was available in the lab (Figure 2b). The only difference between the two vessels/equipment was that one had inclined sections, while the other was straight, termed the conventional vertical column, as shown in Figure 2(a, b).

Figure 2(a, b): (a) Lab scale Reflux Lamella Settler, (b) Lab scale vertical settling column

Similarly, a prototype RLS was designed, fabricated, and utilized to study a large volume of wastewater. Original and schematic diagrams of the prototype RLS are presented in the Figure (3). In the prototype RLS, the lengths of the upper inclined section, vertical section, and lower inclined section were set at 30, 16, and 23 cm, respectively. The inclined sections were tilted at 70º. The cross-sectional area of RLS was 225 cm², with a total water capacity of 13 litres. The prototype RLS was fabricated to handle relatively large volumes of wastewater and scaled up to almost twice the size of the lab-scale RLS. Furthermore, the size was kept within the available space so that it could be displayed as a bench apparatus and handle approximately 10-15 litres of wastewater.
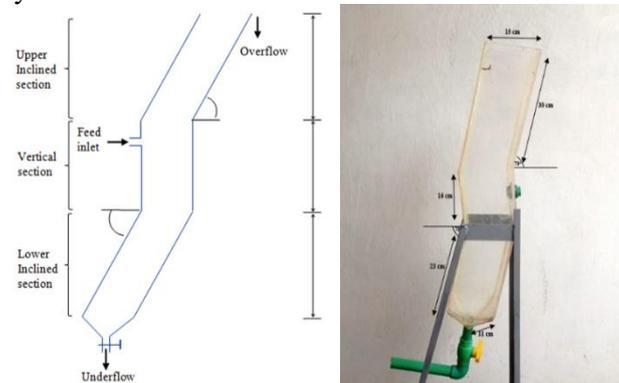

Figure 3: Schematic and original diagrams of the large Reflux Lamella Settler

The presence of two inclined sections was intended to enhance sedimentation. The inclined section at the base served as a high classification zone, enhancing the initial settling of solid particles. The second inclined section at the upper end of the equipment provided an extra settling zone for those solid particles that tended to escape from the lower section with the fluid. In the second inclined section, these particles had another chance to settle and slide back towards the lower section of the equipment. The middle section was provided to ensure uniform distribution of feed/slurry.

2.2. Sample Preparation

Coal (1200-1400 kg/m³); samples were prepared in the size range 0.25-0.50 mm. Coarse coal particles were first crushed in the lab using a lab-scale jaw crusher, through which solid particles were reduced to a size range of 6 mm. The crushed particles were further reduced to a finer size using a lab-scale grinder, i.e., a hammer mill. The ground coal product consisted of particles in a different size range. After sieve analysis, coal particles in the size range 0.25 and 0.50 mm (+0.25-0.50 mm) were retained on the sieves of mesh number 60 and 35, repectively, were collected and utilized for the experimental study.

The first set of experiments was performed on the lab-scale reflux lamella settler (RLS) and a vertical settling column, for which two samples were prepared: 20 gm of 0.25 mm coal particles were manually mixed with 822 gm of water in a container. Similarly, second sample was prepared by mixing 0.50 mm coal particles with water for lab-scale RLS experiments.

Correspondingly, for the second set of experiments in the prototype RLS, two samples were prepared by mixing 0.25 mm coal particles with water. The third study was conducted to evaluate the performance of the prototype RLS, including its ability to handle fine particles and its potential for use as a primary treatment device on a commercial basis. For this, wastewater samples were collected from different carwash stations operating in Peshawar city, as part of our previously published work by Syed et al. [9], in which a wastewater treatment unit was designed and proposed for commercial purposes. In this study, turbidity tests were performed to examine the settling of solid particles in the RLS.

Furthermore, a short study was conducted to illustrate the settling of coloured PVC particles (density 1400 kg/m³) on the inclined surface in the prototype RLS. The PVC particles were selected to represent coal particles because PVC has a density of 1400 kg/m³, similar to that of coal.

3.0. Results and Discussion

3.1. Comparison of lab-scale RLS and conventional vertical settling column

Experiments were performed on the lab-scale RLS and a vertical settling column. In the first experiment, a 2% solution containing 20 g of coal particles with a size of 0.25 mm (fine particles) was prepared. The experiments were carried out for 1 hour at ambient temperature (25 ºC) under batch process conditions.

Figure 4(a, b) demonstrates the coal solution filled in the RLS and the vertical vessel at the start of the experiment. In comparison, Figure (c, d) shows the coal particles sliding down from the upper inclined section of the RLS. Figure (e, f) shows particles settled at the base of RLS and the vertical settling column.
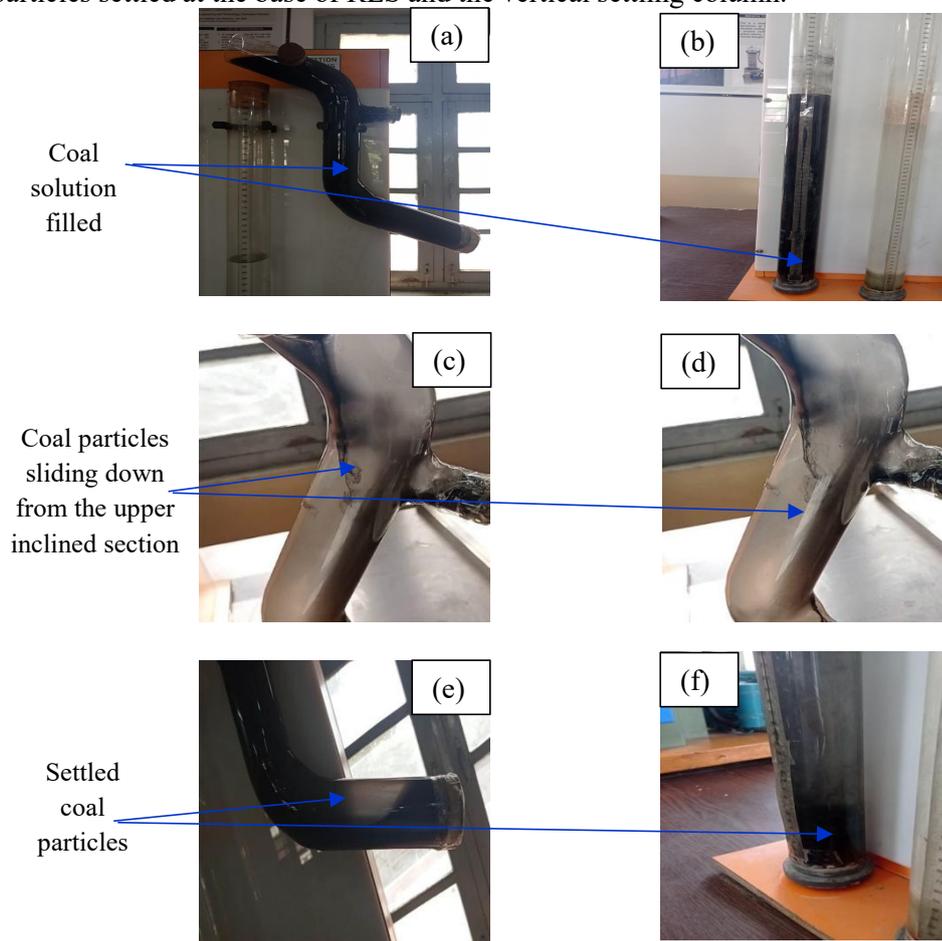

Figure 4(a, b, c, d, e, f): Settling of coal particles in the RLS and vertical settling column

Figure 5 shows the experimental results of the change in height of the clear-water zone over time due to particle settling. The results show that a clear water zone began to form in both equipment/columns as the sedimentation process progressed. After the first 10 minutes, a clear water zone began to form due to the settling of solid particles. The height of the clear water zone from the top was 5 cm in the RLS, whereas in the vertical settling column, the height of the clear water zone was 1 cm. Similarly, after 30 and 50 minutes, the height of the clear water zone increased to 27 and 40 cm, respectively, and further increased to 43 cm after 60 minutes in the RLS. Whereas, in the vertical settling column, the settling rate of solid particles was relatively slow as after 30 minutes the height of clear water zone was 15 cm and reached to a maximum value of 36 cm in 60 minutes. The results illustrate that the settling rate was relatively higher in the RLS compared to the vertical settling column.
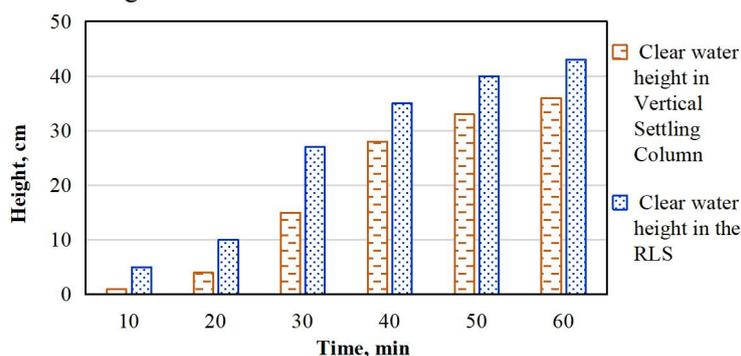

Figure 5: Clear water height versus time for coal particles

A comparison of the change in the solid volume fraction with height in the RLS and the vertical settling column is shown in Figure 6, which displays two zones: a high-solid concentration zone near the base and a dilute zone above it. In the RLS, the solid volume fraction reached a maximum of 0.63 (v/v) at the base after 60 minutes. The high solid volume fraction indicated that the maximum solids settled at a higher rate due to inclined sections within the given period, forming a sediment. Similarly, the dilute zone had a solid volume fraction of 0.15 (v/v), indicating that the solids concentration was low, as the maximum solids settled at the base. Three experiments were carried out on the RLS to observe any change in the readings. Figure 6 shows three profiles with 15% error bars for the RLS results and illustrates that the results from the three experimental runs were almost identical.

Similarly, the analysis of the vertical settling column shows that the solid volume fraction reached to a maximum concentration of of 0.43 in 60 minutes due to a slower settling rate. While the solid volume fraction in the dilute zone was 0.31, it was reasonably higher than that in the RLS. A higher solid volume fraction indicated that the particles were suspended and settling more slowly in the vertical settling column. The results for the vertical settling column are shown with error bars for three different runs in Figure 6. The results differ slightly from each other, however, they fall within the 15% difference range.
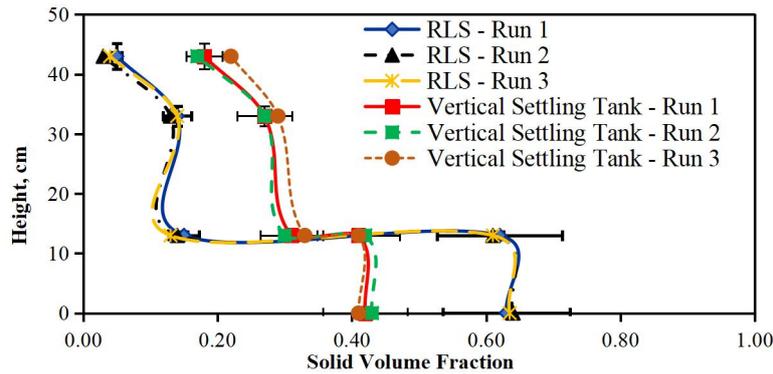

Figure 6: Solid Volume Fraction versus Height for coal particles of size 0.25 mm

A comparison of the results of the change in heights of the clear water zone, dilute zone, and sediment in the lab-scale RLS and vertical settling column (Figure 7). In Experiment 2, the RLS and the vertical settling column were filled with a 40% solution of 0.50 mm coal particles. After 32 minutes, three distinct zones of different heights were observed in the RLS, with the clear water zone at 4.5 cm, the dilute zone at 4.7 cm, and the sediment zone at 11.5 cm. The results show that the maximum solid particles settled at the base of the RLS, resulting in a higher sediment zone height. The height of clear water zone in the vertical settling column was 4.3 cm, the dilute zone was 13 cm, and the sediment zone was 3 cm. The maximum height of the dilute zone, i.e. 13 cm, in the vertical settling column, depicted that the solid particles were in suspension and settling slowly.
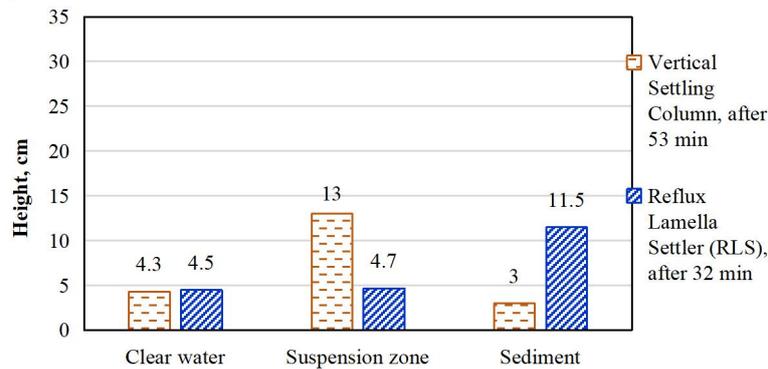

Figure 7: Comparison of the heights of clear water, suspension zone, and sediment in the RLS and vertical settling column

3.2. Prototype Reflux Lamella Settler

The prototype RLS was used to study the settling of solid particles at a relatively large scale under batch process conditions. A sample was prepared by mixing 1 kg of coal particles of size 0.25 mm (250 microns) with 12 kg of water. The sample was filled in the prototype RLS, and the experiments were performed for 1.5 hours. Figure 8 shows the settling of particles in the prototype RLS.

Figure 8: Settling of coal particles in the prototype RLS

Solid volume fraction versus height in the prototype RLS for three experimental runs under batch process conditions (Figure 9). The results depict two distinct zones: a high-solid-concentration zone near the base and a dilute zone above it, analogous to the lab-scale RLS results. The solid volume fraction reached a maximum of 0.62 (v/v), indicating that the solids settled to the base of the equipment within the given time. Similarly, the dilute zone had a solid volume fraction ranging from 0.085 to 0.14 (v/v), indicating a low concentration of solids. Figure 9 shows three profiles of solid volume fraction with error bars representing a 15% difference and demonstrates results that are almost identical across the three experimental runs.

The study on the prototype RLS showed that the equipment's behaviour was almost identical to that of the lab-scale unit. The equipment successfully handled a relatively large amount of water with solids. The channel spacing was kept at 15 cm (150 mm) as according to the literature [12]. Narrow space channels, however, could cause clogging problems in settling tanks/vessels, as reported in the literature [12]. Furthermore, to study the throughput advantage of the equipment, experiments under continuous process conditions may be performed, which will be a future part of this research.
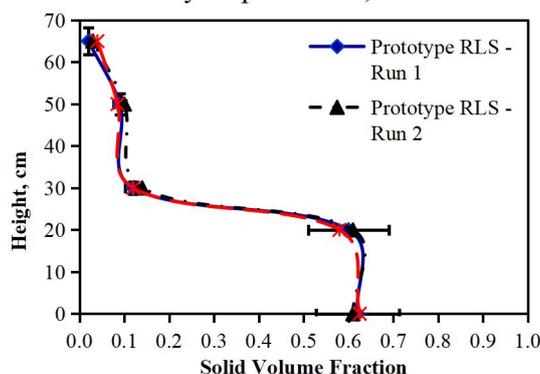

Figure 9: Solid Volume Fraction versus Height for coal particles of size 0.25 mm in the Prototype RLS

3.3. Turbidity test of carwash wastewater in the Prototype RLS

A carwash wastewater sample was placed in the prototype RLS, and its initial and final turbidity was recorded. This experiment was performed to examine the prototype RLS's ability to handle fine particles in carwash wastewater, including silt and soil. Wastewater samples were collected from a local carwash station, and their turbidity was checked before sedimentation in the prototype RLS, which was 233 NTU (Nephelometric Turbidity Unit). The carwash wastewater was held in the prototype RLS for 90 mins, and turbidity was measured every 30 minutes. Table 1 shows the turbidity test results of the carwash wastewater sample. After the first 30 mins of sedimentation, the turbidity reduced to 184 NTU. Similarly, after 60 mins, the turbidity reduced to 148 NTU, and after 90 mins, it significantly reduced to 30 NTU. The turbidity tests showed that the fine solid particles present in the wastewater settled in the prototype RLS, yielding relatively clearer water at the top. The results depict that the prototype RLS is an effective piece of equipment for handling fine particles.

Table 1: Turbidity of the carwash wastewater sample

S. No.	Carwash Service Station Name	Time in (minutes)	Turbidity (NTU)
1	Zahed Jamal Carwash	0	233
		30	184
		60	148
		90	30

3.4. Settling of PVC particles in the Prototype Reflux Lamella Settler

An investigation related to the settling of coloured PVC particles (density 1400 kg/m³) was carried out in the prototype RLS. The particles were coloured to observe their movement within the RLS. The coloured PVC particles were dropped in the prototype RLS from the top. It was observed that the particles, after entering the RLS, settled rapidly on the upward-facing wall of the inclined section and slid down towards the bottom. The settling of a single particle has been shown in Figure 10(a-e) with a blue circle on it. The particle, after entering, quickly settled on the inclined section and slid downwards. Similarly, in Figure 10(f-g), the settling behaviour of some other particles has been shown. After

entering the RLS, these particles settled on the surface of the inclined section, slid on it, and moved downwards to reach the lower section (base) of the RLS.
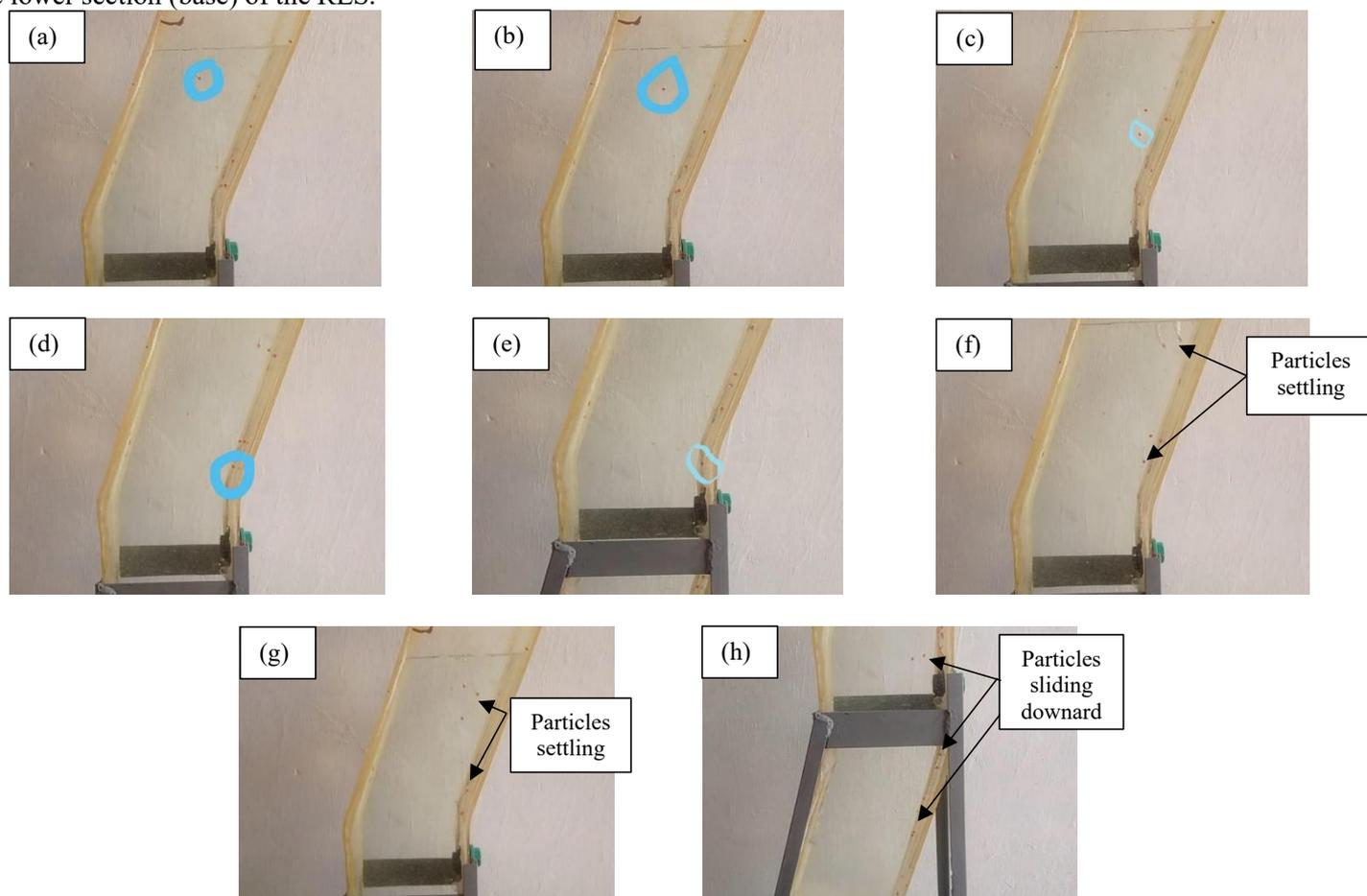

Figure 10(a-h): Settling behaviour of PVC particles in the prototype Reflux Lamella Settler

The prototype RLS was designed for continuous operation, with solid particles settling more quickly, and to handle high flow rates due to its large capacity area. Moreover, its design requires less space. Studying the throughput advantage or yield of the equipment under continuous process conditions could be a future part of this research work.

Conclusion

The study established the efficiency of the newly developed Reflux Lamella Settler (RLS) for enhanced sedimentation of coal particles and other suspended solids from wastewater. Both lab-scale and prototype experiments confirmed that the inclined design of the RLS significantly improved settling performance compared to a conventional vertical settling column, achieving a higher solid concentration of 0.63 (v/v) at the base versus 0.43 (v/v) in the vertical column. Prototype trials using coal-water mixtures produced results similar to those of the RLS, confirming its scalability and suitability for handling larger wastewater volumes. Also, treatment of carwash wastewater resulted in a substantial reduction in turbidity from 233 NTU to 30 NTU within 90 minutes, demonstrating its efficiency in removing fine, low-density particles, such as silt and soil. Observations using PVC tracer particles further confirmed rapid settling along the inclined sections, validating the mechanism of enhanced separation. Overall, the findings establish the RLS as an efficient and scalable technology for improving solid–liquid separation and treating coal-contaminated and similar industrial wastewaters.

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Author's contribution:

Naveedul Hasan Syed; Article writing as first author, experiment design, proof reading

Naseer Ahmed Khan; Corresponding author, experiment evaluation, proof reading

Saira Bano;   Formatting, Proof reading

Faisal Khan;   Experiments performed

Iqra Qazi;   Formatting, proof reading

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