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DESIGN AND IMPLEMENTATION OF A LOW COST OPTICAL BASED PAINT VISCOSITY CONTROL DEVICE

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Abstract. In this study, a full-scale prototype of a water-based printer's paint viscosity control device was proposed and conducted. Specifically, a novel approach of low-cost paint viscosity determination by exploiting the optical sensing method was proposed and a full-scale prototype was developed to exhibit the proposed concept. The feasibility of the proposed device was demonstrated by measuring the accuracy, setpoint control deviation and estimating its development cost. An accuracy of 1.5 cSt and a standard deviation of 1 cSt were recorded by comparing the measured viscosity data with the Zahn cup measuring method. The viscosity control results at a setpoint value of 40 cSt gave a variation of 0.8 cSt. The convergence time from initial 45 cSt to 40 cSt viscosity was 10 minutes. The developed cost was excessively competitive and was only one-fifth of the comparable commercial products. Furthermore, the device had solid and lightweight features, making it straightforward for portable applications.

Keywords: optical-based sensing, water-based paint, viscosity control, low cost instrumentation.

Classification numbers: 5.1.1, 5.2.2.

1. INTRODUCTION

Viscosity is a physical quantity that characterizes the resistance due to intrinsic friction between molecules when they slide on each other. This friction becomes conspicuous when moving one layer of liquid to another. Therefore, the viscosity is associated with the capability to function the processes of pumping, transporting liquids, glues in piping systems, and the processes of spraying and evaporation of fuels in the combustion chamber. There are two categories of viscosity including (1) Dynamic viscosity (Pas or cps) known as absolute viscosity and (2) Kinematic viscosity (cSt: Centistokes) being the ratio between dynamic viscosity and its density [1].

Viscosity is measured by two methods, namely dynamic method and kinetic method. The kinematic approach is carried out by passing a viscous liquid through a standard tube at a temperature of 40 - 100 degrees Celsius with the unit of measurement being centiStokes (sCt = mm^2/s). Meanwhile, the dynamic method is a measure of slipping one oil over another with the unit being centiPoise (cP = mPa.s). This is the method that has been applied to the Brookfield viscometer.

Viscosity is a significant factor in the food, petrochemical, paint, ink, and coating industries. Specifically, establishing the exact viscosity index or viscosity parameters is critical to the success of the product. Owing to its essential applications, there are considerable related research and commercial products. Specifically, regarding the food industry, Kaur *et al*. presented an investigation on the effect of the processing method on tomato juice viscosity [2]. Naumov *et al*. [3] investigated the effect of liquid food viscosity on the load characteristics of single-screw pumps. Matthew *et al*. [4] conducted a food viscosity assessment to determine the effect on bite acceptance with lip closure on the spoon for a high- and low-preferred food at high, medium, and low viscosity. Secondly, viscosity in petrochemicals equivalently catches considerable interest. Xu *et al*. [5] introduced a method to process high-viscosity petrochemical wastewater. Finally, the viscosity of paint, ink, and coating materials significantly affects the product quality. Consequently, many research projects have been carried out. For example, Wicaksono and Puriyanto [6] introduced a PLC-based controller to control online paint viscosity; Lawrence *et al*. [7] utilized extracts of Bryophyllum Pinnatum to evaluate paint viscosity against bacterial species. Rava *et al*. [8] investigated the correlation between paint viscosity and adhesive penetration and deposition. Gao *et al*. [9] presented the influence of ink viscosity on the quality of ink-jet printed polyester. In another attempt, Magdy Kader [10] studied the impact of ink viscosity on the enhancement of rotogravure optical print quality. Mahajan and Bandyopadhyay [11] explored the relationship of ink viscosity and printability in the offset lithography process on paperboard used in packaging. For the coating industry, in [12], the thermal behavior of the PEG/MP-coated viscose fabric was investigated and in [13], Kukkamo and Laari demonstrated the importance of rheology and viscosity in paper and board coating.

Regarding the commercial product for viscosity control, the first representative product is from Saint Clair SYSTEMS. This system comprises a MP2000A viscosity controller and a MXBOC viscosity sensor [14]. This system was deployed to automatically control the viscosity of liquids combined with an M2000 controller and a viscosity sensor. The viscosity sensor is mounted on the tank at a depth of 7 to 26 inches and operated under atmospheric pressure. Additionally, the MXBOC can measure viscosities from 0.1 to 100,00 cps. The second commercial representative product was developed by Pamark, VC-1 Viscosity Controller [15]. This system was exploited to control the viscosity of printer ink. The manufacturer stated that the VC-01 has the function of continuously monitoring the viscosity of ink inside the ink cup. If the viscosity is outside the set value, the solvent will be automatically complemented without any operator intervention or production interruption.

The automatic viscosity control machine provides high processing speed, continuous viscosity control, therefore, ensuring the printing quality. It is observed that the aforementioned commercial products’ functionalities capture very well the demands of the printing industry. However, the implementation cost is relatively expensive due to their convoluted structure and sensing technology. Consequently, in this study, the optical sensing approach is introduced. Specifically, an optical sensor was utilized for counting the paint drops to establish the corresponding viscosity. This is a novel approach to viscosity measurement to meet the requirements of low cost, favorable accuracy and stability, ease of added solvent automation, and water-based paint. This approach was inspired by the conventional paint viscosity measurement method, the so-called Zahn Cup methodology, where a standard cup with a small open hole at the bottom is deployed to generate continuous drops. Estimating the flowing time gives the corresponding viscosity value. It is evident that the proposed approach of utilizing optical based sensing has not been applied to viscometers on the commercial market nor in previous studies. The reason behind this may be that the performance of the mechanical-photonic principle is not as good as that of the electro-mechanical principle. However, the application of the proposed approach in the printer's paint viscosity setpoint control is satisfactory.

2. SYSTEM DESIGN

2.1. Proposed concept design

The novel design concept is presented in Figure 1. In this design, a hydraulic pump is utilized to continuously pump the measured paint from a roll-to-roll printer’s paint tank to supply to the cup and assure that the cup is always full of paint. The overflow paint is drained back to the printer's paint tank via the draining gate. A tiny open hole at the bottom of the cup creates the drops which get through the optical sensing case to get back to the printer's paint reservoir. The optical sensor sends the drop counting results to the controller for processing. The drop's velocity is converted to the corresponding viscosity value by the controller. The converted values are compared to the desired setpoint. If the monitored viscosity is greater than the setpoint, the solvent solenoid valve is excited to release the solvent to the printer's paint tank that consequently decreases the paint viscosity and vice versa.

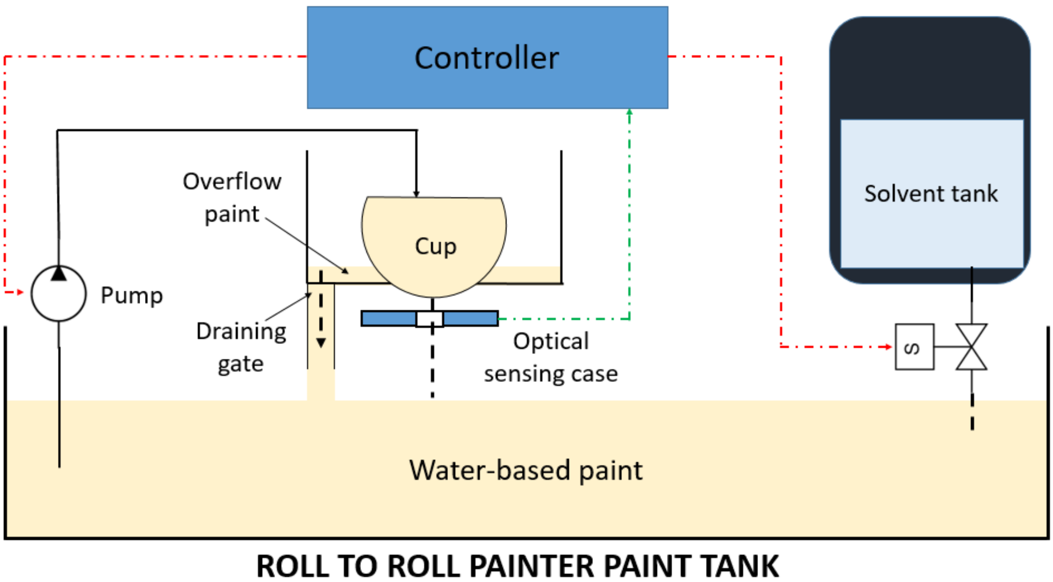


Figure 1. Conceptual design.

2.2. Hardware design

In order to realize the proposed concept, the device structure consisting of (1) supporting frame, (2) cover, (3) paint measurement box, (4) sensor case, and (5) reservoir was designed and shown in Figure 2.

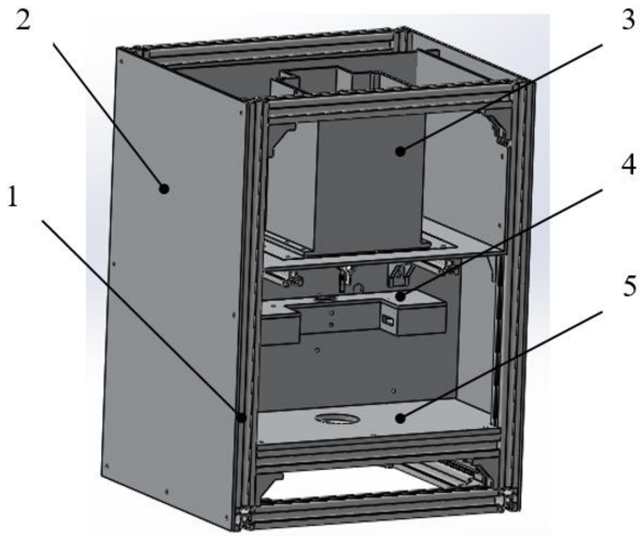
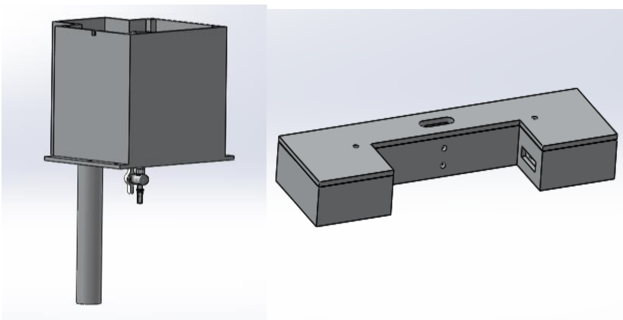


Figure 2. Device structure design.

As aforementioned, the proposed device utilizes the method of drop counting to establish the viscosity of the paint. Consequently, a burette experiment tube attached to a 3D printed plastic box was applied to generate the paint drops. Paint was pumped from the printer's paint tank to the paint measurement box (Figure 3.a) by a peristaltic pump. The over-flow paint was drained back to the printer's paint tank through a 20 mm diameter plastic tube. An optical sensor was utilized to count the paint drops. A sensor case made from 3D printed plastic was exploited to insulate the sensor from surrounding influences during operation (Figure 3.b).



a) *b)*

Figure 3. a) Paint measurement box and b) sensor case.

2.3. Controller design

Figure 4 demonstrates the controller design's diagram. It comprises (1) Arduino microcontroller unit, (2) LCD, (3) keypad, (4) pump motor and motor driver, (5) optical sensor, (6) solvent control solenoid valve and its driver, and (7) solenoid driving circuit board.

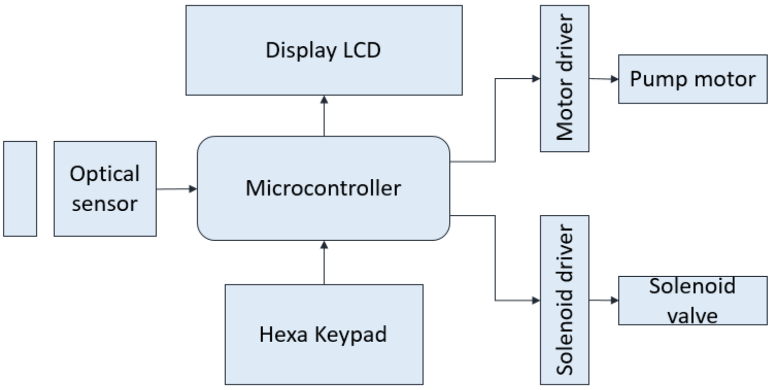


Figure 4. Schematic diagram.

3. EXPERIMENTAL SETUP

3.1. Device prototype

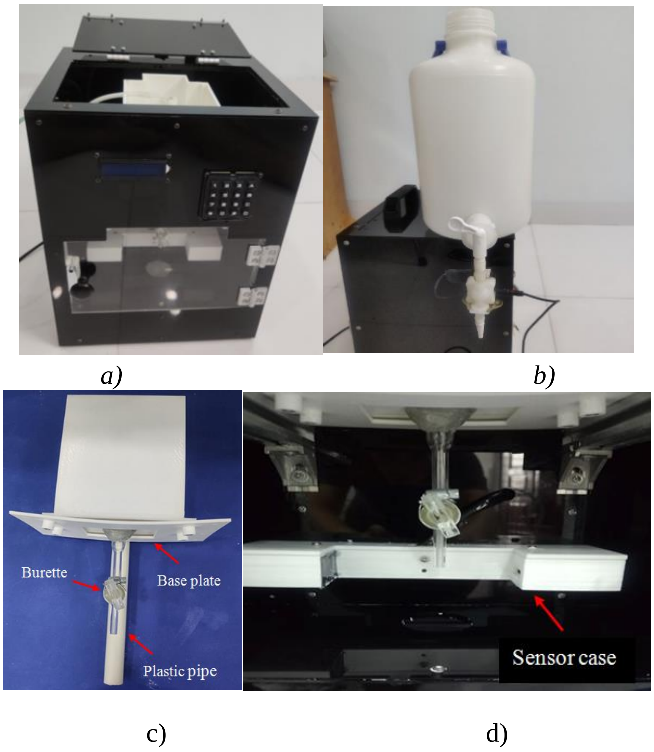


Figure 5. a) Full scale prototype, b) Solvent supply container with controlled valve, c) Paint viscosity measurement box, and d) Optical sensor case.

The full-scale prototype was conducted and presented in Figure 5. The Figure consists of (a) full-scale prototype, (b) solvent supply container with controlled valve, (c) paint viscosity measurement box, and (d) optical sensor case.

3.2 Experimental setup

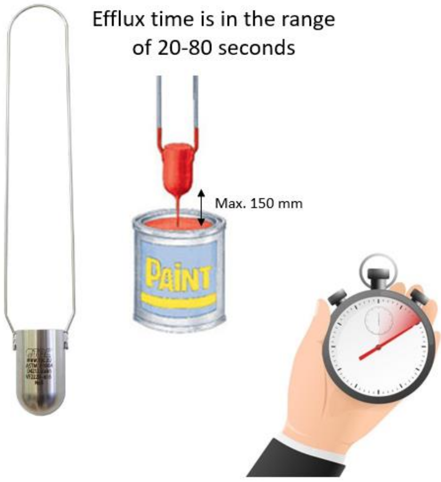


Figure 6. Paint viscosity measurement utilizing Zahn cup setup.

The first experimental setup is for measuring the viscosity utilizing the Zahn cup. The obtained results were subsequently applied to compose the relationship between the drop velocity and kinematic viscosity and verify the measured results of the proposed device. Figure 6 presents the experimental setup to determine viscosity by a Zahn cup, where the following steps were carried out:

Step 1: Clean the standard cup with an appropriate solvent, before and after use.

Step 2: Choose an appropriate cup with the sample to be tested. Note that the sample's efflux time is in the range of 20 - 80 seconds. If outside this range, adopt another applicable cup.

Step 3: Dip the cup in the sample for 1-5 minutes, leaving the cup to balance the heat between the medium and the sample. Lift the cup vertically from the sample surface. Keep the cup upright and not exceeding 150 mm above the surface of the sample. Time is recorded from the first to the last drop from the cup. The efflux time is converted to the corresponding kinematic viscosity value utilizing the following associated equations.

- Zahn Cup #1: $\nu = 1.1(t - 29)$ (1)
- Zahn Cup #2: $\nu = 3.5(t - 14)$ (2)
- Zahn Cup #3: $\nu = 11.7(t - 7.5)$ (3)
- Zahn Cup #4: $\nu = 14.8(t - 5)$ (4)
- Zahn Cup #5: $\nu = 23t$ (5)

Where t is the efflux time in second and ν is the kinematic viscosity in centistokes (cSt).

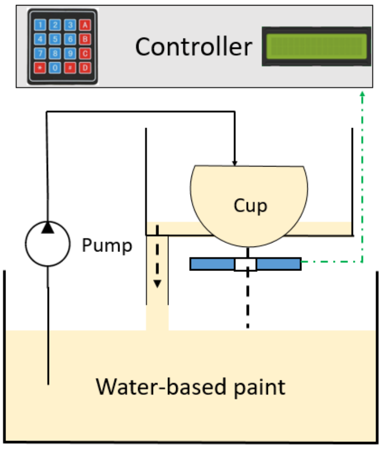


Figure 7. Device viscosity measurement setup.

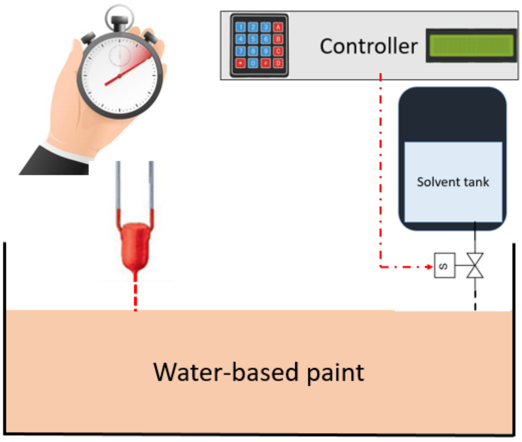


Figure 8. Complemented solvent amount definition setup.

Figure 7 demonstrates the second experimental setup to validate the device operation, define the device's characteristic line, and acquire the device precision. After determining the viscosity of the paint with the Zahn cup, the same paint sample was applied to the machine. The resulting drop velocities correspond to the viscosity results conducted by the Zahn cup method. The correlating results were then utilized to resolve the device characteristic lines and formula. This experimental setup was also deployed to characterize the accuracy and standard deviation of the machine. Specifically, the device's accuracy was acquired by comparing the measured results obtained from the device with the Zahn cup method.

The third experimental setup depicted in Figure 8 was exploited to designate the required added solvent volume. Water-based paint with a viscosity of 56 cSt corresponding to an efflux time of 30 s was deployed. The proposed device was programmed to control the solenoid valve to provide the controllable solvent amount to the paint tank. The associated variation of the paint's viscosity was measured and recorded. Finally, a statistical regression was conducted to draw the correlation between the amount of solvent to be provided and the expected viscosity level. The regression formula was eventually implemented into the whole system's control program.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Device characteristic lines and formula

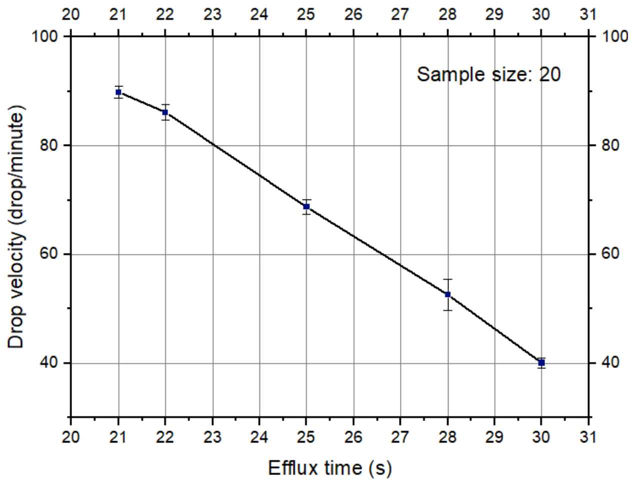


Figure 9. Efflux time versus drop velocity characteristic.

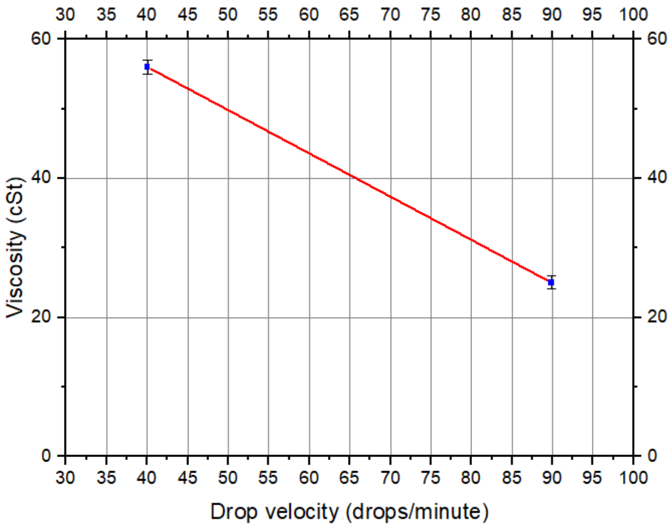


Figure 10. Drop velocity versus viscosity characteristic.

Figure 9 presents the efflux time versus drop velocity characteristic of the device. This graph demonstrates the correlation between the referenced viscosity measured by the Zahn cup and the paint droplet velocities counted by the machine. Taking the linear regression and converting the efflux time to the corresponding viscosity value yields the relationship between the drop velocity and kinematic viscosity. The result is illustrated in Figure 10.

Applying the relationship in Figure 10, the correlation between viscosity and velocity was obtained and expressed by the following formula:

$$\nu = (-0.62).V + 80.8 \tag{6}$$

where: ν is viscosity (cSt) and V is drop velocity (drops/minute). It is noted that the proposed measurement method was inspired from the Zahn cup manual measurement, however the suggested method utilizes the drop velocity (i.e. V) instead of using efflux time (t) (as shown in Equations (1-5)) to define the viscosity. Furthermore, the use of the drop velocity variable also serves the purpose of continuous measurement.

4.2 Device accuracy

Since the water-based paint viscosity is sensitive to environmental temperature, which in turn influences the experimental results. Specifically, the paint sample used at times has distinctive viscosity values due to water evaporation. Consequently, vegetable glycerin oil was utilized in the device accuracy definition experiments owing to its two advantages. First, it is unaffected by environmental temperature, and second, it is easily soluble in water to vary its viscosity.

The rapeseed oil with a constant viscosity parameter of 34.26 cSt at 40 °C [16] was used. This tested sample was applied for both the Zahn cup and the proposed device. After 20 measurements with the Zahn cup at room temperature, the result of efflux time is 29 s which corresponds to the Centistroke viscosity of 53 cSt. Afterward, the rapeseed oil was measured by the device with the same replication. The results in Figure 11 show that the maximum discrepancy is around 4.5 cSt and the standard deviation is around 1 cSt.

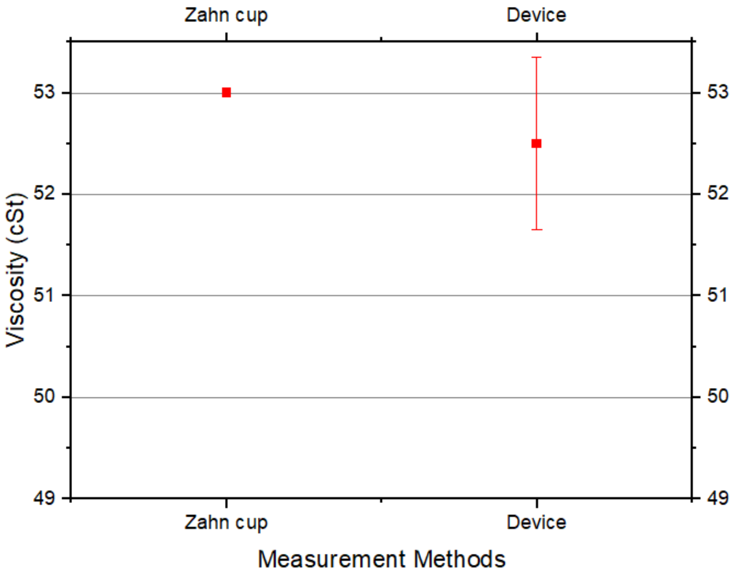


Figure 11. Device error analysis results.

Figure 12 presents the experimental data of added solvent amount versus paint viscosity. This data was afterward used to estimate the added solvent amount when operating in the autonomous mode. Specifically, a setpoint of paint viscosity is configured and the device automatically controls the added solvent to maintain the desired viscosity.

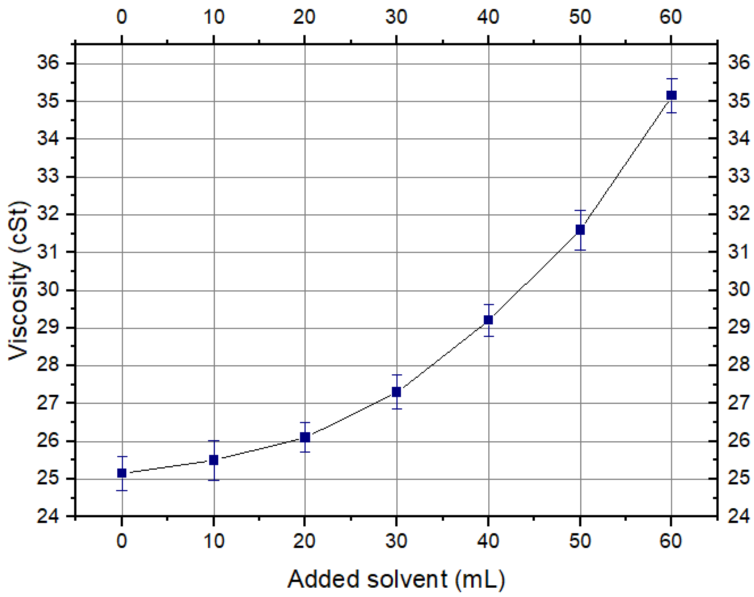


Figure 12. Added solvent amount versus paint viscosity.

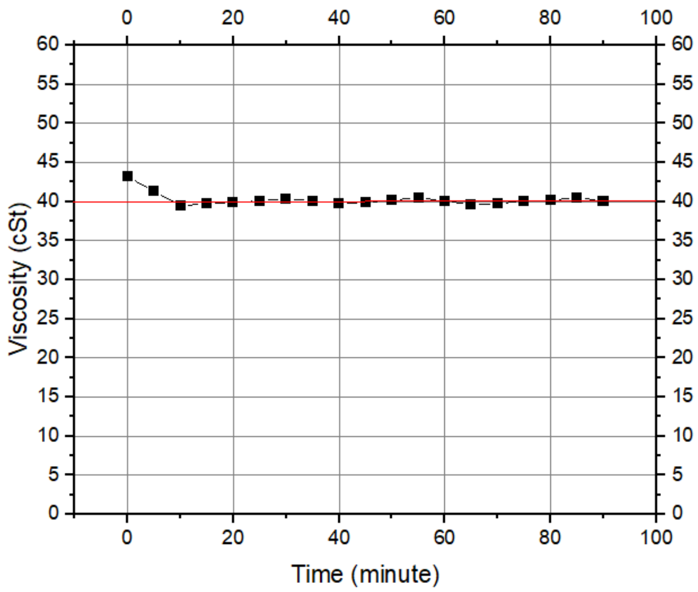


Figure 13. Viscosity control result.

Figure 13 shows the viscosity control results when applied the proposed device to the roll-to-roll water-based printer system. The control setpoint was set to 40 cSt. The results demonstrated that the variation is around 0.8 cSt. A 10-minute convergence time from initial 45 cSt to 40 cSt viscosity was recorded. This variation and the convergence time are due to the long uniform dilution time. This can be improved by increasing the number of solvent valves distributed uniformly over the printer's paint tank.

5. CONCLUSION

In this study, a novel approach to the low-cost water-based paint viscosity control system applied in the roll-to-roll printing industry was proposed. A full-scale prototype of the proposed device was conducted to verify the feasibility. An accuracy of 1.5 cSt and a standard deviation of around 1 cSt were recorded. The proposed device's specifications are presented in Table 1. These results are satisfactory for viscosity setpoint control. Specifically, the viscosity control results at a setpoint value of 40 cSt gave a variation of 0.8 cSt. The convergence time from initial 45 cSt to 40 cSt viscosity was 10 minutes. Furthermore, the device had solid and lightweight characteristics that made it easy for portable purposes. The development cost was competitive and was one-fifth of commercial products.

Table 1. Proposed device's specifications.

Features	Specification
Dimensions	300 (w) × 250 (d) × 380 (h) mm^3
Net weight	3.5 kg
Measuring range	0-100 cSt
Accuracy	~ 1.5 cSt
Standard deviation	~ 1.0 cSt
Developed cost	~ 5 millions VND

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CRediT authorship contribution statement. Thi-Thu-Hien Pham: Methodology, Investigation. Quoc-Hung Phan: Formal analysis. Duy-Anh Nguyen: Formal analysis, Investigation. Ngoc-Bich Le: Methodology, Funding acquisition, Supervision.

Declaration of competing interest. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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