A review on the design and development of turbidimeter

ARTICLE · JANUARY 2015

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A review on the design and development of turbidimeter

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Abstract

Purpose – This paper aims to present a review of the design and development of the turbidimeter for measuring the turbidity level in water. Monitoring the turbidity level of water is important because it is related to public health.

Design/methodology/approach – A precise and reliable turbidimeter can provide vital data that reveals the water condition level. Several turbidimeter units are discussed briefly. Three types of turbidimeter design – single beam, ratio and modulated four beams – are elaborated with some illustrations of the design concept. Various improvements and innovations for upgrading turbidimeter design are also discussed.

Findings – This paper elaborated on a new method of estimating the water turbidity level in water samples using an optical tomography system based on the independent component analysis method. The results showed that a tomography-based turbidimeter can measure slight changes in the level of turbidity when the volume of contaminants is changed slightly. The turbidimeter can also provide a profile of the distribution of the turbidity in the water sample.

Originality/value – A turbidimeter based on the optical tomography concept can be a valuable tool in determining the level of pollution in rivers, sea, etc.

Keywords Optical fibre, Light scattering, Turbidimeter, Turbidity measurement, Water quality

Paper type Literature review

1. Introduction

Water constitutes 70 per cent of the earth's surface and is definitely the most valuable natural resource we have (Orebiyi and Awomeso, 2008). The dehydration problem can lead to kidney and heart disease, cause headache and reduce the physical performance of humans (Popkin and Rosenberg, 2010). In addition to drinking, water is used to wash, clean and cook. Water also makes a large contribution to the industry where it is used to generate electricity in power plants and is used for transporting people and goods.

The water pollution issue surrounding the world has increased concern among many people. Water pollution can be described as the contamination of water resources by the presenting of sewage, germs and toxic chemicals (Iqbal *et al.*, 2013). Human activities are the biggest contributors to water pollution (Chen *et al.*, 2007).

The water quality level can be determined by observing the level of turbid water. The level of turbid water changes due to the existence of suspended particles, organic matter and chemicals (Verma and Prachi, 2012; Mylvaganam *et al.*, 1998). The easiest way to estimate the turbidity level is by evaluating the colour of a water sample because colour is relatively easy to measure as compared to dissolved organic matter (Christian and Sheng, 2003). Turbidity measurements are widely used in the water treatment industry. The sensor that is used to measure the turbidity level is called a turbidimeter (Omar and Matjafri, 2009). The presence of particles causes the light to be scattered from the straight line and reduces the light intensity (Ródenas-Torralba *et al.*, 2007). The existence of coloured particles or contaminated water can absorb the light energy and this effect can be used to design a precise turbidimeter. A turbidimeter is also widely utilized in the food and beverage industry to control the quality of products (Fleet and Siebert, 2005) and determine the rehydration of dairy powder (Gaiani *et al.*, 2009).

2. Turbidimeter units

A long time ago, the turbidity level was measured using a Jackson Turbidity Unit (JTU). This unit is based on the Jackson Candle method, where it observes the reduction of light intensity in a column of water. The turbidity level depends on how much volume of water has to be added to the column to reduce the intensity of the candlelight (Muer, 1911). JTU units are no longer used nowadays because turbid water cannot be measured with fewer than 25 JTUs (Myre and Shaw, 2006).

Nowadays, a turbidimeter uses the Nephelometric Turbidity Unit (NTU) as the unit of measurement. The international level of turbid water for domestic use is standardized between 5 and 25 NTU (Gasim *et al.*, 2006). Formazin Turbidity Units (FTUs) are another unit of turbidity measurement. The FTU works with a nonspecific or nondescript measurement angle, which differs from the NTU.

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35/1 (2015) 98–105

[DOI 10.1108/SR-01-2014-604]

The authors wish to acknowledge the assistance of the Ministry of Higher Education, Malaysia, and Universiti Teknologi Malaysia under the GUP Research Vote 08J73 for providing the funds and resources for carrying out this research.

The NTU works on 90° of angle measurement. The FTU is not recommended for use because the US Environmental Protection Agency has made a rule that a turbidimeter is required to be designed based on 90° of angle measurement (Basic Turbidimeter Design and Concept, 1999).

The other parameter that is used to measure the turbidity level is total suspended solids (TSS). The unit for TSS is milligram per litre of pure water (mg/l). Research conducted by Lewis *et al.* (2002) and Hannouche *et al.* (2011) determined the relationship between the TSS unit and the NTU unit. Holliday *et al.* (2003) and Baker *et al.* (2001) suggested a related equation between these two units, which can be described as:

$$NTU = a(TSS)^b \tag{1}$$

where a is the regression-estimated coefficient and b is approximately equal to 1 for all particles.

3. Turbidimeter design

Various researches have been carried out to improve the accuracy and reliability of the turbidimeter. Tai *et al.* (2012) developed a smart turbidimeter for measuring the turbidity level in a distributed measurement system and the turbidimeter is reliable for investigating the quality level of water at a temperature range between 0 and 40°C. This section discusses the design of a light beam for a turbidimeter where it consists of a single-beam design, a ratio design and a modulated four-beam design.

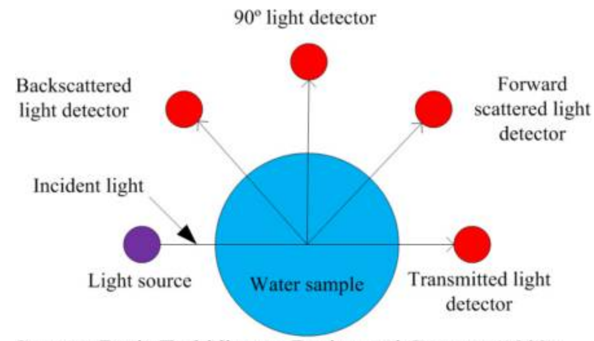
3.1 Single-beam design

The single-beam design is the simplest turbidimeter design. The design consists of a light source and a detector. Two categories of single-beam turbidimeter can be described: an absorptiometer and a nephelometer. An absorptiometer measures the absorption of light, whereas a nephelometer measures scattering light at an angle of 90° from the light projection (Fernandez *et al.*, 2000; Lambrou *et al.*, 2010). A research using a nephelometer can be seen in Ranasinghe and Ariyaratne (2012), where they inspect the water purification in Sri Lanka. In addition, Ibrahim *et al.* (2013) successfully applied the light absorption concept to measure the turbidity level of water, while investigation using both concepts of light absorption and scattering was carried out by Bilro *et al.* (2010) and Postolache *et al.* (2002).

3.2 Ratio design

The ratio design of a turbidimeter has two extra detectors which are installed between a transmitted light detector and a 90° light detector, as shown in Figure 1. The first detector is known as the "forward scattered light detector". The other detector is known as the "backscattered light detector", which is placed between the light source and the 90° light detector for detecting the backscattering light. This design has advantages when it measures the turbidity level in coloured samples, as transmitted light and scattered light are the most affected elements (Basic Turbidimeter Design and Concept, 1999).

Figure 1 Ratio turbidimeter



Source: Basic Turbidimeter Design and Concept (1999)

3.3 Modulated four-beam design

Garcia *et al.* (2007) and Postolache *et al.* (2007) used the four-beam turbidimeter design to measure the turbidity level. This design consists of two light sources and two light detectors, as shown in Figure 2(a and b). The transmitting and scattering light principles are used for this design, where the measurement process is divided into two stages. The first stage is operated by turning on light source 1 and turning off light source 2, as illustrated in Figure 2(a). At this stage, detectors 1 and 2 are functional to take measurement values from the angle of 90° scattered light and transmitted light, respectively. The second stage is when light source 2 is turned on and light source 1 is turned off, as shown in Figure 2(b).

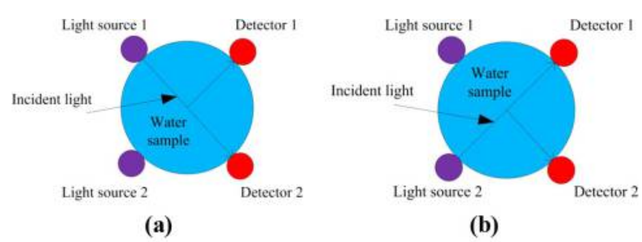
4. Improvement of the design of the turbidimeter

Innovative improvement of the turbidimeter is vital to get accurate measurement results. This section is divided into two subsections. The first subsection discusses the use of optical fibre as a medium for light transmission, and the second subsection discusses the several light colours for a pair of sensors in a turbidimeter.

4.1 Optical fibre

Optical fibre has been widely used for monitoring particle concentration and particle sizing measurement (Tran *et al.*, 2006). In the field of process tomography, researches conducted by Ibrahim *et al.* (2002), Yan *et al.* (2005), Md Yunus (2005) and Abdul Rahim *et al.* (2005) utilized optical fibre for imaging and identifying various flow patterns and boundaries. In another research area, Garcia *et al.* (2007),

Figure 2 (a) First stage of measurement and (b) Second stage of measurement



Source: Garcia *et al.* (2007)

Bilro *et al.* (2010) and Prerana *et al.* (2012) proposed the design of a turbidimeter using optical fibre. Aiestaran *et al.* (2009) applied optical fibre to measure the volume and turbidity of low-viscosity fluid. Niskanen *et al.* (2006) successfully designed a multifunction spectrophotometer for the determination of optical properties, which enabled them to control the observation of transmission, reflection and light scattering from a liquid sample.

Optical fibre is widely chosen for designing turbidimeters, as it acts as a light transmission medium between water samples and the receiver circuit. Optical fibre provides water protection to electronic circuits because it can be placed under water (Garcia *et al.*, 2007). The other advantage is that optical fibre brings flexibility to a turbidimeter. By using optical fibre, measurement can be carried out easily either for long-distance measurement or in a narrow area (Garcia *et al.*, 2007). A turbidimeter using optical fibre is not restricted to a single probe. A research conducted by Prerana *et al.* (2012) proposed an optical bundle probe for investigating the light scattering effect, where the turbidity sensor was tested in a water sample. A bundle probe means one or more fibres are used for emitting light from the source and the remaining fibres are used for receiving the light reflected/scattered from the water sample (Papaioannou *et al.*, 2003).

4.2 Several colours of transmitting and receiving light

The colour of light plays an important role in the accuracy of a turbidimeter. This is because light wavelength depends on the colour of light. The light emitter for a turbidimeter can be a bulb, laser or light-emitting diode (LED). An LED is usually selected as an emitter because it has a small size, low cost and several lights' wavelength number (Erickson, 1997). This section will discuss the design of a light pair system, which comprises a visible light pair system and an invisible light pair system.

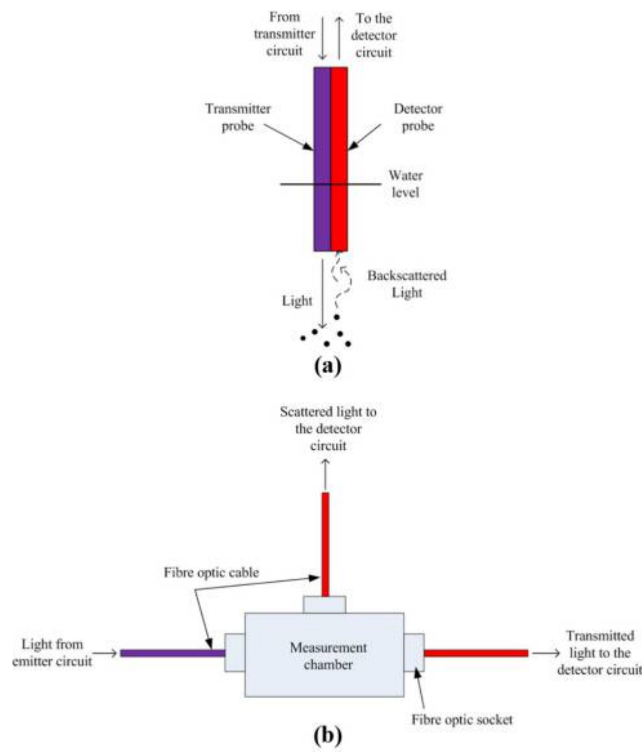
4.2.1 Visible light pair system

An experiment for a visible light pair system was carried out by Omar and Matjafri (2009), Ebie *et al.* (2006), Chang and Wu (2013) and Park *et al.* (2013) to investigate the turbidity level. Omar and Matjafri (2009) used three different modes of measurement configuration: backscattering, transmittance (0° scattering) and 90° scattering. The apparatus setup is illustrated in Figure 3(a and b). Two systems were used, which consisted of a blue LED and blue photodiode (blue system) and a red LED and red photodiode (red system). In terms of correlation coefficient and root mean square error, the blue system has a better result than the red system for the backscattering experiment. On the other hand, the red system shows a better result for the transmittance and 90° scattering experiment.

4.2.2 Invisible light pair system

Invisible light has an upper peak wavelength of not more than 750 nm, and such light cannot be seen by the eye. Conversely, visible light has a wavelength range between 380 and 750 nm. This characteristic of light is essential to obtain an accurate analysis and it helps to ensure that the receivers detect light from invisible light only, and not the visible light from the surroundings, such as a laboratory lamp. Orwin and Smart (2005) utilized an infrared LED, which acts as an invisible light source and a photodiode to monitor the suspended sediment. In their design, both light source and photodiode have a peak wavelength of 880 nm.

Figure 3 (a) Backscattered light measurement and (b) transmittance and 90° light measurement



Source: Omar and Matjafri (2009)

Research conducted by Ródenas-Torralba *et al.* (2007) and Aiestaran *et al.* (2009) tested visible light and invisible light for measuring the turbidity of water. Aiestaran *et al.* (2009) performed the experiment using red (660 nm) and green (530 nm) LED colours for visible light. For invisible light, an infrared LED (880 nm) was utilized. The highest voltage loss occurred when the red LED was tested in black dye, followed by in blue and red dye. For the green LED and infrared LED measurement test, voltage losses were still high with black dye, followed by red and blue dye. From the experiments, the best result can be seen when the infrared LED was tested in blue dye due to lower voltage losses. The result proved that by using infrared light, the precision of a turbidity sensor is high as the light detector detects the light from the infrared LED only and excludes light from the surroundings, such as lamps and sunlight.

5. Estimation of the turbidity level using an optical tomography system

An optical tomography system can estimate the turbidity level of water. The word "tomography" is a combination of Greek words, with "tomos" meaning "slice" and "graph" meaning "image" (Williams and Beck, 1995). In other words, tomography can be defined as a process of getting a slice of a picture. A tomography system consists of several sensors that are located externally around the pipeline to determine the internal condition without disturbing the process flow (Ibrahim *et al.*, 2012). Many turbidity sensors are designed as a point sensor, which means the sensor has to collect or be placed in a water sample to measure the turbidity level. However, this sensor is not appropriate in an industrial flow process because it cannot measure directly from the pipe and will disturb the flow process. Hence, a new design for predicting the water turbidity level is proposed using a noninvasive technique based on the use of the independent component analysis (ICA) method. In this design, 18 infrared transmitters and 18 receivers are used as sensor pairs (Mohd Khairi *et al.*, 2013).

5.1 Results for pure water and contaminated water

This section is divided into two parts – pure water and contaminated water. The experiment starts by investigating the turbidity level for pure water. The experiment continues for contaminated water, where several volumes of green food colour ingredients are used to contaminate the pure water.

5.1.1 Pure water

Three litres of pure water are poured into a cylindrical vertical pipe until the water level is above the sensor placement. In this case, no colour ingredient is added to the water sample to maintain the originality of the water. The pipe is mapped onto 18 × 18 pixels. An ICA algorithm is utilized to get the *K* value. The result of the overall *K* value is converted into a concentration profile by using the LabVIEW software for displaying the concentration profile of the water turbidity level. The experimental setup for pure water in the vertical pipe and the concentration profile can be seen in Figure 4(a and b), respectively. The value of *K* for pure water became the reference value for comparison with the contaminated water.

5.1.2 Contaminated water

In this experiment, a sample of 3 litres of pure water is polluted by adding several volumes of green food colour ingredients. The colouring, in various volumes of 5, 15, 25 and 35 ml, is added to the vertical pipe using a syringe. The condition of the water after undergoing the contaminating process is tabulated in Figure 5 together with the results of the concentration profiles.

5.2 Discussion of results

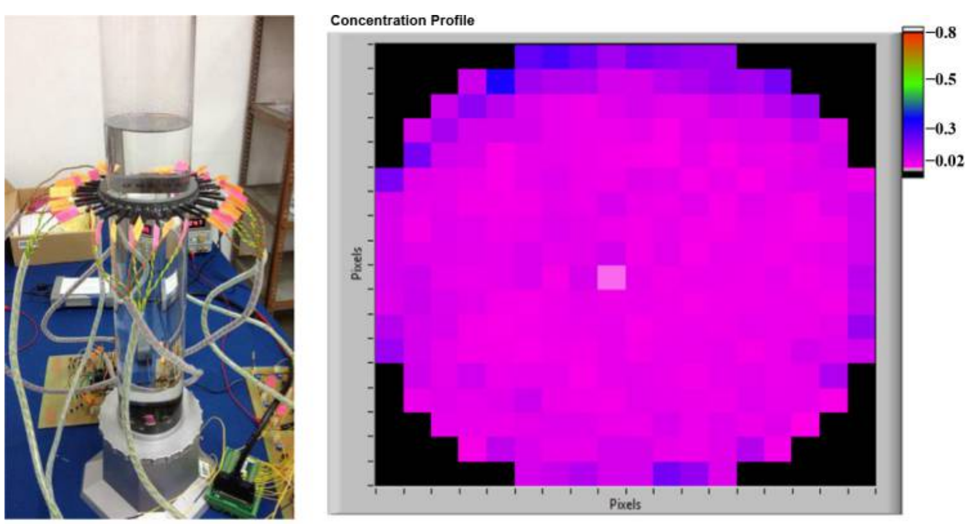
From the concentration profile in Figure 4(b), it can be seen that the pixel value located near the pipe's border is higher than the pixel value near the middle of the pipe. This is because all light receivers from RX1 to RX18 are located close to the border. Hence, most of the lights have a tendency to cross the pixels, which are located near the pipe's surface. Although the average value has been taken, the pixel value near that location is still high compared to other locations.

In clean water, light can be transmitted directly without any interruption, except in water where light is attenuated. The turbidity level in the water can be predicted by analysing the *exp(-αl)* value because the parameter is included in the attenuation coefficient (α) value. The clean water has a lower *K* value than the contaminated water. This is due to the fact that light experiences less attenuation in clean water and does not affect much of the reference value α in the water medium.

The pixels are randomly picked and the selected pixels are {5,5}, {10,10}, {8,14}, {12,6} and {14,13}, as illustrated by the green circles in Figure 6. Table I shows the *K* value of the pixels corresponding to the various volumes of colour ingredients that were added to the clean water. The sample of contaminated water is prepared by adding several volumes of colour ingredient starting from 5 ml, and followed by 15, 25 and 35 ml. The water sample is clean water when the colour ingredient volume is 0 ml.

In Table I, each pixel shows the same behaviour whereby the *K* value is the highest when 35 ml of colour ingredient is mixed with water. Despite some pixels showing a reduced *K* value when the volume is increased, the ending point at 35 ml is still higher than the other volumes. The *K* value for unclean water is seen to be higher than that of clean water for almost all pixels. By looking at the concentration profile results, the pixels' colours have shown varying colours from pure water to the highest level of unclean water. The change of colour looks

Figure 4 (a) Pipe containing pure water and (b) the concentration profile of pure water



(a) (b)

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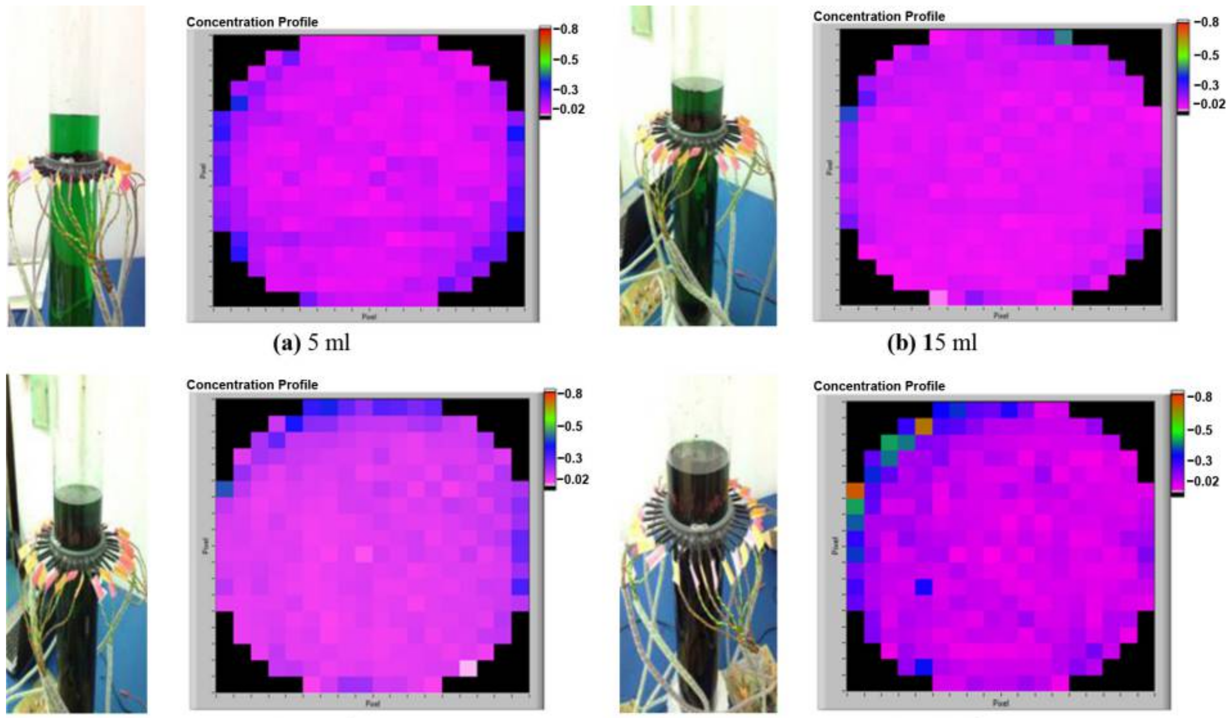
Figure 5 The water condition and concentration profile after being supplemented with different volumes of green colouring



(a) 5 ml **(b)** 15 ml **(c)** 25 ml **(d)** 15 ml

Figure 6 The location of selected pixels is marked by green circles

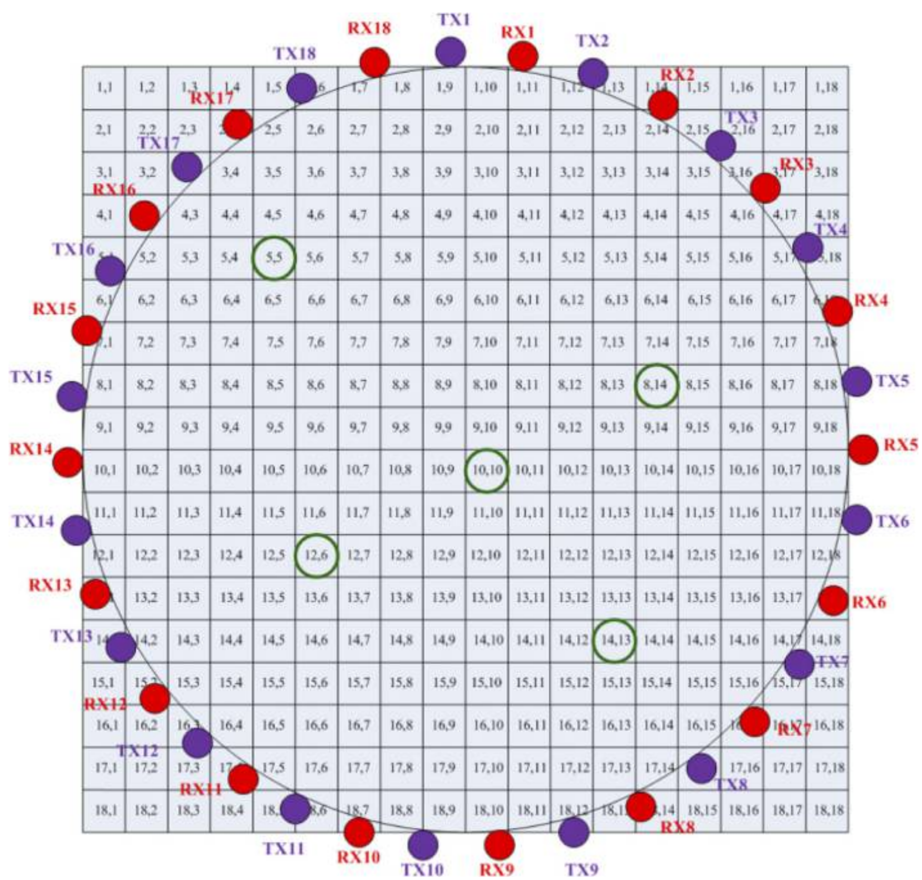


Table I The *K* value corresponding to the added volume of colour ingredient

Volume of colour ingredient (ml)	*K* value Pixel {5,5}	Pixel {10,10}	Pixel {8,14}	Pixel {12,6}	Pixel {14,13}
0	0.029	0.046	0.045	0.035	0.046
5	0.056	0.056	0.035	0.047	0.045
15	0.071	0.061	0.050	0.028	0.050
25	0.079	0.066	0.062	0.037	0.053
35	0.135	0.070	0.063	0.055	0.070

significant if we compare the concentration profiles of 0 and 35 ml of colour ingredient. Further investigation regarding the variation of *K* value is carried out by evaluating the five pixels from the pipe.

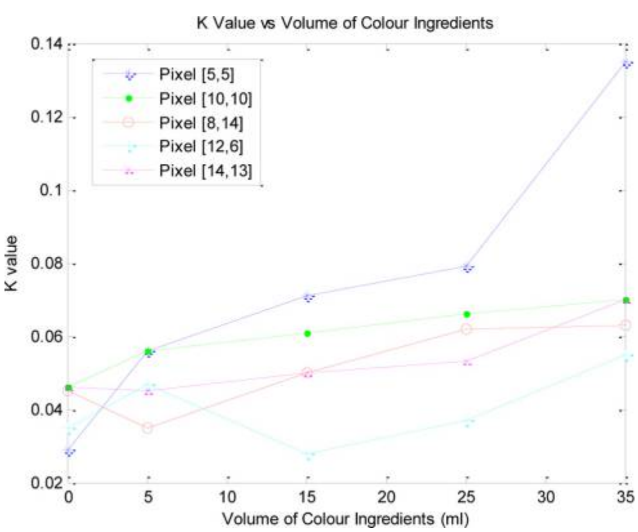
Data in Table I are plotted in the form of a graph, as shown in Figure 7. The increasing value of *K* in the contaminated water is due to light experiencing more absorption when it is traversed in dark water. In addition, the light energy is more attenuated when light is transmitted in contaminated water. Hence, the attenuation coefficient (α) for water becomes low and results in the *K* value increasing when α is reduced.

The results show that a tomography-based turbidimeter can measure slight changes in the level of turbidity when the volume of colour ingredients is changed slightly. This type of turbidimeter can also provide a profile of the distribution of the turbidity in the water sample. An example of how this turbidimeter can be applied is the measurement of the quality of a soft drink. The quality of water is extremely important to the success of a soft drink. Contaminants can degrade taste and colour. Hence, this type of a turbidimeter can provide information on the quality of water to ensure that it complies with regulations concerning consumer health and safety.

6. Conclusion

This paper provides a review of the various designs and developments of the turbidimeter. The overview began with an introduction to the unit of turbidity measurement, followed by several turbidimeter designs. Modifications to the turbidimeter have proven that it can obtain precise and reliable measurement results. A turbidimeter based on the optical tomography concept can be a valuable tool in determining the level of pollution in rivers, sea, etc.

Figure 7 The graph of *K* versus volume of colour ingredients



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