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Article

A Study of Object Transparency Via Charge-Coupled Device Mathematical Modelling Assessment

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Abstract— **This research discusses an application of Couple-Charge Device (CCD) linear sensor and laser diode in an optical tomography (OPT) system. Tomography is a system that could capture a cross-sectional image based on sensor data scattered across the periphery of the examining device in the non-invasive and non-intrusive framework. This project focuses on quantifying the level of object transparency based on CCD and mathematical modelling assessment. The objective of this project is to investigate the light refraction, reflection and absorption effect on object transparency. The study will include a discussion on the light parameters and its mathematical expression. The voltage output measured by CCD defines the degree of intensity of light obtained after penetrating through different object transparency. In conclusion, this research has successfully proved the potential of CCD in OPT configuration to detect different size diameters of a targeted transparent object, which is an air bubble in non-flowing crystal-clear liquid.**

Keywords— **Charge-Coupled Device (CCD); optical tomography; object transparency; LabVIEW programming.**

I. INTRODUCTION

Charge-Coupled Device (CCD) is an integrated light-sensitive circuit that stores and displays information. In order to prevent any serious damage that may occur in a system, the monitoring process of steam bubbling production is essential for the engineers. The percentage of gas in the fluid solution, the flow rate of gas, the presence and absence of gaseous liquids, the shape and diameters of gases are important details for process controls. CCD is used as the mechanism tool to deal with this issue together with the tomography process. Tomography is a tool for capturing a cross-sectional image based on sensor data scattered around the visualization system's periphery [1]. In detail, optical tomography is one of the non-invasive and non-intrusive tomography approaches. It is a non-hazardous tomography system to monitor multiphase flow processes [2].

The primary goal of this analysis is to examine the level of object transparency based on CCD through mathematical modelling evaluation. To achieve this goal, one important objective will be conducted – to generate the mathematical modelling from the investigation of light in the optical tomography system, which includes the investigation of the light refraction, reflection and absorption effect on object transparency. The voltage output measured by CCD represents the level of light intensity received after penetrating through different objects. As a result, this research proves the capability of CCD to detect the different size of object transparency that will eventually result in different values of output voltage.

II. LITERATURE REVIEW

CCD is a sensor that is sensitive to light intensity. It will convert the light intensity into voltage signals. This study involves three types of light characteristics; light absorption, reflection, and scattering. By going through a particular type of medium, light is attenuated. In the optical path, the density of an object gave attenuation exponentially to the output of the light based on Beer-Lambert Law shown in equations (1) and (2).

$$I_{out} = I_{in} e^{-\propto x} \tag{1}$$

$$\ln\left(\frac{I_{in}}{I_{out}}\right) = \propto x \tag{2}$$

From equation 2, α is the linear attenuation vector, and x is the distance traversed by the beam of light. From the ray sum of the coefficients of linear attenuation distributed along the path inside the target, the real logarithm of the intensity-to-transmit intensity factor incident is obtained. The losses of energy arise as light travels in the form of light reflectance across an interface. Reflectance, defined by the symbol R and shown in equation (3), is the ratio of light reflected on each surface.

$$R = \left[\frac{n_1 - n_i}{n_1 + n_i}\right]^2 \quad (3)$$

Where n_1 is a transmitted refractive index and n_i is an incidence refractive index.

Below are the equations that are involved when light penetrated from air to Perspex (equation (4)) and from water to glass surfaces (equation (5)).

For air-perspex interface:

$$R = \left[\frac{1.5-1}{1.5+1}\right]^2 = 0.04 \; or \; 4\% \quad (4)$$

For water-glass interface:

$$R = \left[\frac{1.5-1.33}{1.5+1.33}\right]^2 = 0.0036 \; or \; 0.36\% \quad (5)$$

The R value is the minimum surface reflection and occurs on plane surfaces where the surface is normal to the light ray. This represents a greater fraction of ray reflection as the incident ray angle of incidence increases. The amount of light that the particle transmits is decreased by these reflective effects [3]. Based on Hecht E, the diffraction phenomena occurred when an opaque object located between a screen and a light source produces a bright and dark shadowy area. In Figure 1, the diffraction effect is known as Fresnel or Near-field diffraction due to the position – either the panel or the light source is near to the blockage or obstruction. Besides, there was Fraunhofer or Far-field diffraction whenever the source of light or the panel is distant from the blockage.

In a case where the particle or the targeted object is near to the linear CCD sensor (the length between the object and the sensor is 71 mm), the diffraction effect in the optical tomography method is expected to be primarily Fresnel diffraction. The diffraction effect is closely connected to the obstruction 's height. The effects of diffraction will be minimal if the particle size or obstruction is very high relative to the light source wavelength x. The diffraction effects become more prominent as the obstruction size decreased.

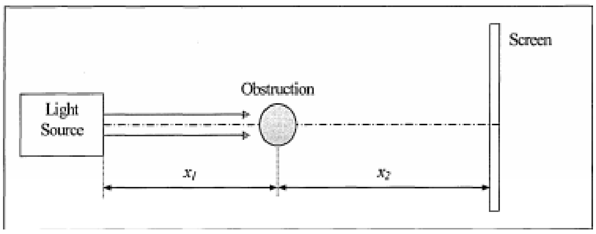

Figure 1. A light strikes an obstruction [4]

Each object has a degree of transparency in this universe. Based on its opacity, the transparency of the material will determine the capacity of light to pass through it. The intensity of light is mainly attributed to the CCD output voltage [4]. Once the beam is distorted by a compact object, the subsequent fringe pattern on the picture shows the diffraction effect, as shown in Figure 2 to Figure 4. Figure 4 shows that there are some light 'softens' at the edge of the shadow, even though a compact or opaque object acts as the barrier [4].

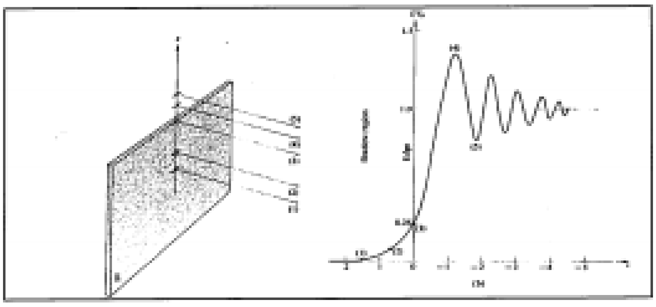

Figure 2. The opaque screen and the intensity distribution

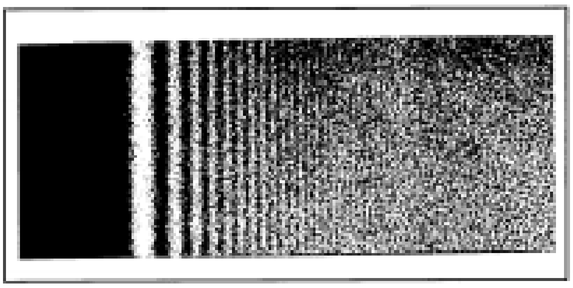

Figure 3. The fringe patterns

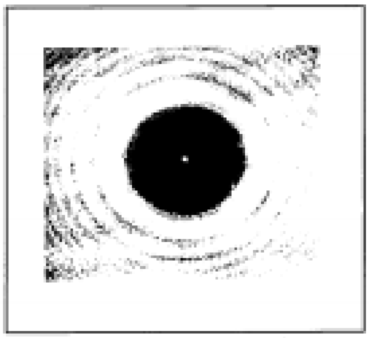

Figure 4. The shadow pattern cast by a Vs-inch diameter rod

The term transparency in optics is the property of letting light pass through something. It is a translucent material if some light can be seen through an object, but some details of the image are lost. Frosted glass, paper and some types of amber are examples of translucent materials. The word optical clarity is the ability to allow light to pass through something. This position-sensitive detector will assess where the sensor is struck by light [5]. In essence, imaging capture systems consist of an optoelectronic sensor and a device that converts digital code to an analogue form of signal. As a spatially uniform array, the sensor is a matrix of modelled small cells. The cell is a light-sensitive microscopic device that can generate electrical impulses pertaining to light incidents of different intensities. This sensor is sensitive to the light intensity but not to the colours, despite its photosensitivity. It is crucial to implement the optical filters to differentiate the three main colours, which are the red, green and blue in a selected pixel sensor. Instinctively, as in the human vision, three spectral bands (red, green, and blue) formalize the scene.

CCD sensor (Figure 5) has high affectability and exactness, high signal rates, a wide unique range and uses low power consumption. The basic principle of CCD is to measure the light ray dimension acquired by its sensors that are created using semiconductor components. Thus, CCD is accepted to have the option to distinguish hazy items as it were. This is on the basis that the light that reaches their surface may imitate or absorb hazy posts. The existence and location of the object will be determined by the last measure of light power obtained by the CCD. These developments demonstrate that CCD has a high affectability to distinguish dull spots [6].

In different investigations, researchers explore the utilization of CCD linear sensors in an optical tomographic instrumentation framework implemented to estimate particles. Four CCD linear sensors are mounted around an octagonal flow pipe for a four-projection system. Optical tomography is commonly used both in manufacturing and medical industries [7]. There are several factors that make this form of tomography the best device for non-invasive and non-intrusive sensors. It is resistant to electrical interference and noise and consists of hard field sensors with high resolution. In estimating an object, the fundamental concept of the optical tomography system depends on its source of waves and radiation.

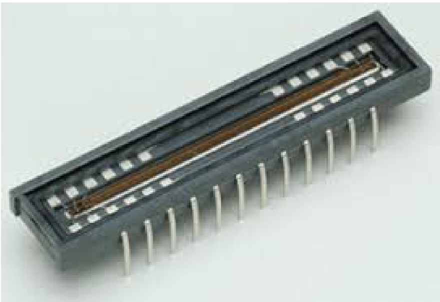

Figure 5. CCD Linear Array Sensor

The OPT system's primary idea is to observe the radiation force and wave generated within the midst of the intersection of the deliberate material. Additionally, the OPT system works to break down the structure and formation of objects. In fact, optical tomography sensors are recognized as opto-electronic sensors. There are three sections that constitute the basic construction of an optical tomography application: equipment (hardware), the application for collecting information (DAQ system) and programming. The block diagram of an optical diagram is shown in Figure 6 [8].

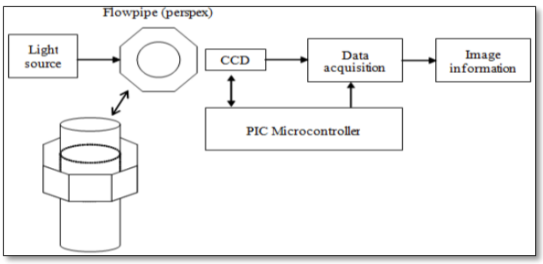

Figure 6: A block diagram of the optical tomography system

III. METHODOLOGY

Figure 7 illustrated the light travel and passed through three distinct instruments, which are the air, perspex and water. It can be observed that two modes of mathematical expression are involved in this simulation. There are;

a. Light attenuation due to absorption.
b. Light reflectance

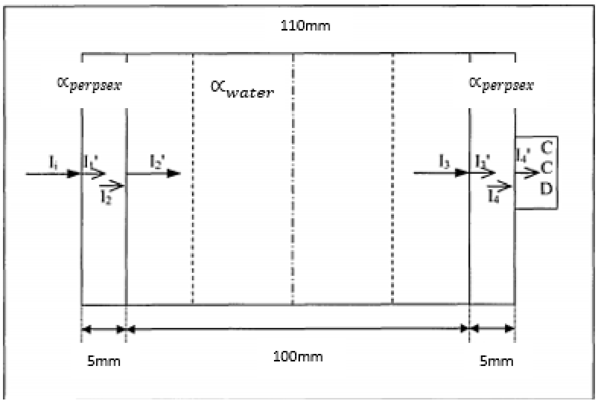

Figure 7. Side view of the overall measurement section

As light passes through different density of medium, the Beer-Lambert Law declared the amount of light strength or its intensity would be attenuated by multiplying it to the exponential attenuation as in equation 6. In equation 6, x represents the distance of light transverse. The alpha is a constant in this project that represents bubble air with a coefficient value of 1.0 and x is the manipulates value.

$$I_{out} = I_{in} e^{-\alpha x} \quad (6)$$

When light passes through the different medium or go through any object, the energy of photo (light) will be decreased, and thus, light reflectance occurred as in equation (7) and (8).

$$I_{Final\ reflection1} = I_{initial} - \left[I_{initial} \left(\frac{n_2 - n_1}{n_2 + n_1} \right)^2 \right] \quad (7)$$

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1} \right)^2 \quad (8)$$

Where R , n_1 and n_2 corresponds *t*o reflection ration, transmitted refractive index and incidence refractive index respectively. In order to generate mathematical expression, both this light attenuation due to absorption and light reflectance are combined to calculate the transparency of the object via the CCD tomography method. Equation 9 to 27 shows the mathematical expression steps involved when there is an air bubble in the pipeline system full of water.

In this quantifying object transparency experiment, the study was further observed with the selection of air bubbles as the subject. The $n_{air\ bubble}$ which represents the air bubble's refractive index, was assumed to be [9]. Figure 8 is the modelled light striking the air bubble, which acts as the static object in the centre of the flow pipe. The diameter of the air bubble will be varied, which are 1mm, 3mm and 5mm.

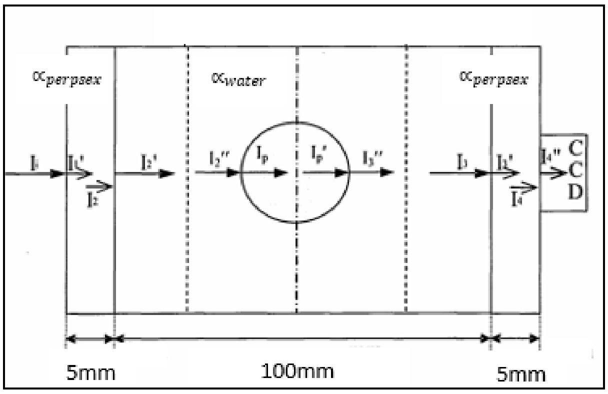

Figure 8. The light striking a static object in the middle of the pipe

Mathematical equation for calculating where there is an air bubble (1 mm)

Firstly, as the source of light entered the flow pipe, I_i (light intensity) is reduced due to the reflection at the air/perspex interface

$$I_1' = I_i - I_{reflection1} = I_i - \left[I_i\left(\frac{n_{perspex}-n_{air}}{n_{perspex}+n_{air}}\right)^2\right]$$

$$I_1' = I_i - \left[I_i\left(\frac{1.5-1}{1.5+1}\right)^2\right] = 0.96I_i \quad (9)$$

Light is then absorbed in travelling through perspex

$I_2 = I_1' e^{-(\propto_{perspex} x 5mm)}$ where the $\propto_{perspex}$ is 0.003mm^{-1} and the glass length, X = 5mm

$$I_2 = I_1' e^{-(0.003mm^{-1}x5mm)} = 0.9851I_1' \quad (10)$$

Substitute equation 9 into 10 results into equation 11, which is

$$I_2 = 0.9851\,(0.96I_i)$$

$$I_2 = 0.9457I_i \quad (11)$$

I_2 is further reduced at the Perspex/water interface and becomes I_2' ;

$$I_2' = I_2 - I_{reflection2} = I_2 - \left[I_2\left(\frac{n_{water}-n_{perspex}}{n_{water}+n_{perspex}}\right)^2\right]$$

$$I_2' = I_2 - \left[I_2\left(\frac{1.33-1.5}{1.33+1.5}\right)^2\right] = 0.9964I_2 \quad (12)$$

Then, substitute equation 11 into 12 results into equation 13, which is;

$$I_2' = 0.9964\,(0.9457I_i)$$

$$I_2' = 0.9423I_i \quad (13)$$

The calculation below is the equation for the calculation of the light absorption in the length of the water, x of the 1 mm air bubble diameter measurement.

$$x = \frac{100mm - 1mm}{2} = 49.5mm. \quad (14)$$

I_2' transverse the cell being attenuated by water α = 0.00287mm^{-1}

$I_2'' = I_2' e^{-(\propto_{water} x 49.5mm)}$ where water length, X = 49.5mm

$$I_2'' = I_2' e^{-(0.00287mm^{-1}x49.5mm)} = 0.8676I_2' \quad (14)$$

Substitute equation 13 into equation 14, hence it becomes equation 15;

$$I_2'' = 0.8175I_i \quad (15)$$

Next is the water-to-air bubble calculation (1 mm). I_p is the light intensity value due to the reflectance phase being conducted.

I_p is diminished due to the water-air bubble interface, therefore it becomes;

$$I_p = I_2'' - I_{reflection3} = I_2'' - \left[I_2''\left(\frac{n_{air\ bubble}-n_{water}}{n_{air\ bubble}+n_{water}}\right)^2\right]$$

$$I_p = I_2'' - \left[I_2''\left(\frac{1-1.33}{1+1.33}\right)^2\right] = 0.9799I_2'' \quad (16)$$

Replace equation 15 into equation 16. Hence, the parameter of I_2'' is replaced with $0.8175I_i$ and the value of I_p as in equation 17;

$$I_p = 0.8011I_i \quad (17)$$

Since the object of interest is an air bubble, no light absorption phenomena occurred within the next phase. Thus, the process continues due to the distortion of light reflectance in 1mm size of the air bubble. The calculation from the air bubble (1mm) to water. I_p' is the intensity value of light due to reflectance process.

$$I_p' = I_p - I_{reflection3} = I_p - \left[I_p\left(\frac{n_{water}-n_{air\ bubble}}{n_{water}+n_{air\ bubble}}\right)^2\right]$$

$$I_p' = I_p - \left[I_p\left(\frac{1.33-1}{1.33+1}\right)^2\right] = 0.9799I_p \quad (18)$$

Substitute equation 17 into 18, therefore equation 19 becomes;

$$I_p' = 0.7850I_i \quad (19)$$

I_p' is further attenuated by water length 49.5mm where $\propto_{water}$ = 0.00287mm^{-1}

$$I_3'' = I_p' e^{-(\propto_{water} x 49.5mm)}$$

$$I_3'' = I_p' e^{-(0.00287mm^{-1}x49.5mm)} = 0.8676I_p' \quad (20)$$

Substitute equation 19 into 20, hence it becomes;

$$I_3'' = 0.6811I_i \quad (21)$$

As light passes through from water to perspex, the intensity value of I_4' is the intensity value of light due to the reflectance process.

$$I_3 = I_3'' - I_{reflection4} = I_3'' - \left[I_3''\left(\frac{n_{perspex}-n_{water}}{n_{perspex}+n_{water}}\right)^2\right]$$

$$I_3 = I_3'' - \left[I_3''\left(\frac{1.5-1.3}{1.5+1.3}\right)^2\right] = 0.9949I_3'' \quad (22)$$

Substitute equation 21 into 22, then it becomes equation 23;

$$I_3 = 0.6776 I_i \qquad (23)$$

As light crossing through the Perspex-glass phase, light absorption occurred.
$I_3' = I_3 e^{-(\propto_{perspex} x5mm)}$ where the $\propto_{perspex}$ is $0.003mm^{-1}$ and the glass length, X = 5mm

$$I_3' = I_3 e^{-(0.003mm^{-1} x5mm)} = 0.9851 I_3 \qquad (24)$$

Substitute equation 23 into 24, therefore it becomes;

$$I_3' = 0.6675 I_i \qquad (25)$$

As light passes through from water to Perspex, the intensity value of I_4 is the intensity value of light due to the reflectance process.

$$I_4 = I_3' - I_{reflection5} = I_3' - \left[I_3'\left(\frac{n_{air} - n_{perspex\ glass}}{n_{air} + n_{perspex\ glass}}\right)^2\right]$$

$$I_4 = I_3' - \left[I_3'\left(\frac{1-1.5}{1+1.5}\right)^2\right] = 0.96 I_3' \qquad (26)$$

Replace equation 25 to equation 26, hence it becomes equation 27;

$$I_4 = 0.6408 I_i \qquad (27)$$

As in equation 17, there is no light absorption in the air bubble, thus producing the final light intensity mathematical expression as in equation 27.
The procedure of equation 14 to 27 is repeated with 3mm and 5mm size of air bubble diameter.

IV. DISCUSSION

Table 1 below shows the result obtained from the theoretical mathematical calculation when there is an air bubble with a 1mm diameter, an air bubble with a 3mm diameter and a 5mm diameter. The output voltage of the CCD is theoretically determined using the formula:

$$Voltage_{CCD} = (1 - I_4') * 5 \qquad (28)$$

From the CCD Sony ILX551A datasheet, the final light intensity equation is then multiplied to 5 based on the maximum voltage output of this optoelectronic sensor [10]. The relationship between the bubble size, the value of its final light intensity, and the calculated output voltage of the CCD is shown in the table below.

TABLE 1.
RELATIONSHIP OF BUBBLE SIZE AND VOLTAGE OF CCD

Diameter of air bubble (mm)	Distance of light transverse (mm)	Value of final light intensity I_4'	Voltage of CCD (V)
1	49.5	$0.6418 I_i$	1.79
3	48.5	$0.6453 I_i$	1.77
5	47.5	$0.6492 I_i$	1.75

Therefore, as the light intensity increases, the air bubble also increases in size. The graph below shows that the light intensity (air bubble size) is inversely proportional to the Linear Sensor of the Charge Coupled System (CCD). A decreasing value of the CCD voltage output is created by the increase in light intensity.

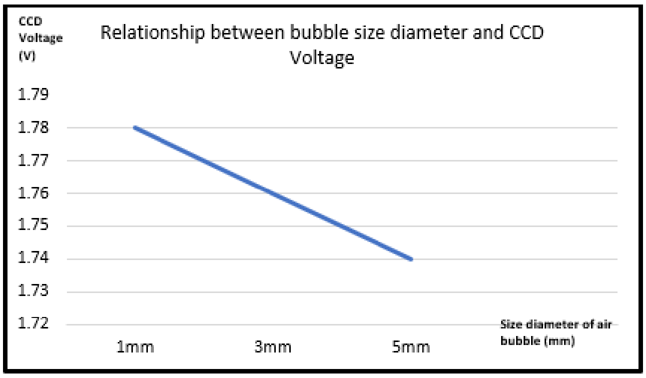

Figure 9. Graph plotted CCD voltage value versus the bubble size

IV. CONCLUSIONS

In this study, the relationship between the diameter of an air bubble, light intensity, and voltage of CCD is measured through mathematical expression identification. In conclusion, it is proven from the theoretical calculation that as the light intensity increases, the voltage of CCD also increases.

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