

Effect of Square and Triangular Mini-Channel Cross-Section on Infrared Transceiver Signal Characteristics during Bubble and Slug Two-Phase Flows

Abstract

Multiphase flows occur in many naturally occurring processes and Industrial applications. A comprehensive understanding of multiphase flow behavior in mini and microchannels is critical, as these channels are widely used in microthrusters, heat exchangers, petrochemical industries, and mini and microreactors. In the present work, two phase adiabatic flow experiments are carried out in a square channel with sides of 2.0 mm and a thickness of 0.0 mm. The behavior of an infrared transceiver sensor during two phase flows of slug and bubble in a square channel is reported in the study. A numerical model is developed in COMSOL Multiphysics to compare the effects of flow regimes on the behavior of the IR transceiver signal in a square and a triangular channel of equivalent cross-sectional area. The results indicate that the IR sensor is sensitive to the test section cross-section and the flow regime geometry. Fluid density and viscosity are of secondary importance compared to the medium's refractive index for an IR Transceiver.

Keywords: Two-phase flows, mini channels, IR sensor, Image processing, COMSOL

1. Introduction

Multiphase flow is a type of fluid flow in which same or different phases of fluids, flow together. Two-phase flow involves two phases: gas/liquid, solid/liquid, or solid/gas. Gas/Liquid two-phase flows are observed in the tubes of condensers and evaporators in power plants, refrigeration, and air conditioning circuits, in the atomization of fuel, and in heat pipes used for various cooling applications. The heat and mass transfer characteristics of multiphase fluids depend upon flow regimes such as bubble, slug, stratified, and annular flows in these

tubes. The design of slug catchers in the petrochemical industry requires a thorough understanding of the flow regimes in pipelines carrying crude oil. Multiple studies have reported characterizing multiphase flow regimes using high-speed cameras and various types of sensors.

Many studies have been reported in the literature on two-phase flows in circular cross sections. However, limited work has been reported for two-phase flows inside square and triangular channels. Unlike circular channels, both square and triangular channels have a flat surface and can have a uniform surface area contact for the flowing two phase fluids. Jian et al. [1] observed two-phase gas-liquid flow in a square mini channel with a permeable wall on one side. The surface characteristics of different permeable walls and their effects on pressure drop were detailed. The pore density and roughness of the permeable wall governed the two-phase pressure drop, as gas venting through the porous surface reduced the frictional resistance to the liquid phase; this shows that, unlike a plain solid wall, the wall material and microtexture of a channel can directly alter two-phase flow characteristics. Vasileiadou et al. [2] studied the flow boiling behavior of an ethanol/water mixture in a mini-square channel. It was found that adding ethanol (5%) to water increased the heat transfer coefficient compared to pure components. Balkrishna and Sameer [3] studied laminar heat transfer in a mini-square channel using infrared thermography. Yafei et al. [4] studied two-phase flows in microchannels of triangular cross-sections and determined the capillary pressure required for two-phase flow to initiate. Hamed and Saeid [5] conducted experiments and simulations of the side weir in subcritical flow in triangular channels. The surface jump for various Froude numbers at the end of the quarter of the weir length was reported. Gan et al. [6] measured the two-phase pressure drop of acetone in a triangular silicon microchannel and developed a correlation. The proposed correlation could predict the experimental data with a mean absolute error of 12.6%.

Various works on sensors developed for two phase flow characterization have been reported. Marco et al. [9] proposed a novel capacitive sensing configuration to estimate the area fraction occupied by each fluid in oil-conductive water two-phase flow. Horst et al. [10] studied bubble, slug and annular two-phase flow in tight lattice subchannels. Cold-neutron tomography experiments were carried out in non-adiabatic subchannel during a refrigerant flow in a heavy water circuit to determine steady-state dryout. Different configurations of capacitive sensors were used by Reis and Cunha [11] to measure volumetric concentration during two-phase flows. The volumetric concentration was measured using a double-ring capacitor configuration. A dual-plane electrical resistance tomography (ERT) and a multi-electrode conductance sensor was used by Shi et al. [12] to analyze oil-water two-phase flow in a horizontal pipe. It was found that the multi-electrode conductance sensor measure the phase fraction of an oil-water two-phase mixture satisfactorily. Thorn et al. [13] used tomography to measure the flow rate in multiphase flow. Electrodes were positioned on the outer surface of the tube along the circumference to create the electric field. Arun et al. [14] developed a novel technique for identifying a two-phase flow regime using an IR sensor and the volume-of-fluids method. Mithran and Venkatesan [15] studied the effects of IR transceiver orientation on gas/liquid two-phase flow regimes, and the transmittance and refractive behavior of IR rays on bubbly and slug flows in circular channels. A pair of IR transceivers was used by Mithran and Venkatesan [16] for volumetric reconstruction of two phase flow regimes. A recent work of Sowndarya and Venkatesan [17] demonstrated the real-time reconstruction of a slug regime using collimated IR transceivers.

The works detailed above report on various studies conducted on sensors developed for two-phase flow characterization. Sensors with electrical signal outputs are desired, especially in the petrochemical and process industries, since a feedback-based control system for decision-making (actuation/deactivation) can be designed for specific applications. Except for Refs. [18]

– [10], separate signal-processing circuits are required in the mentioned sensors. The complexities introduced during signal processing can be eliminated using a simple, cost-effective method such as an IR transceiver setup to measure two-phase flows. Limited work has recently been reported using the IR transceiver setup to study the two-phase flow behavior. This work analyzes two-phase gas-liquid flow with a carrier fluid of varying viscosity using a designed Infrared transceiver circuit in a square channel. The IR signal data obtained is compared with high-speed photographs processed with an image processing technique using MATLAB. A numerical model is developed in COMSOL Multiphysics to analyze the behavior of IR rays passing through slug and bubble regimes in square and triangular channels with equivalent cross sections. The numerical results of the triangular and square channels are compared. The results of air-water, air-olive oil, and air-methanol two phase flows are studied in the two different geometries. Unlike the earlier IR-transceiver studies of Refs. [11]-[10], which were restricted to a single circular or square test-section geometry, the present work is the first to couple a simple, low-cost IR transceiver circuit with a ray-optics COMSOL model to isolate and quantify the individual effects of test-section cross-sectional shape (square versus triangular) and carrier-fluid properties (viscosity, density and refractive index) on the transmitted IR signal for both bubble and slug regimes. This combined experimental-numerical framework, and the resulting design guideline that the refractive index and cross-sectional geometry of the medium govern the IR transceiver response while density and viscosity play only a secondary role, constitute the key novelty of this study.

2. Experimental setup

Fig. 1 details the experimental layout. The test section is a square channel made of borosilicate glass with a length of 60 mm, sides of 20 mm, and a thickness of 0.5 mm. The setup used is the one as detailed in Ref. [11]. The IR transceiver is positioned 20 mm downstream of the T-junction, i.e., more than 12 hydraulic diameters from the inlet. For the laminar flow rates used

in this study ($Re < 200$), the hydrodynamic entry length estimated from $L_h \approx 0.05 \cdot Re \cdot Dh$ remains below 6 mm, so the flow is expected to be fully developed well before reaching the measurement plane, and the reported IR signal corresponds to a fully developed two-phase flow regime rather than an entrance-dominated structure. Syringe pumps are used with an integrated controller to regulate flow rate (E-spin SPK101 single-channel) and to pump water and compress air into the test section. The two fluids are mixed using a T-section with a 2 mm diameter, and the resulting mixture is then connected to the square channel in the horizontal direction. The two-phase air and olive oil flow is also supplied using a similar method. The IR transmitter and receiver are in line, facing each other at 90° to the test section. The present study uses an IR33A infrared LED with a 6mm diameter as a source of IR rays. PD33-B silicon pin diode of 6mm diameter with 80° view angle is used to sense the Infrared rays in this study.

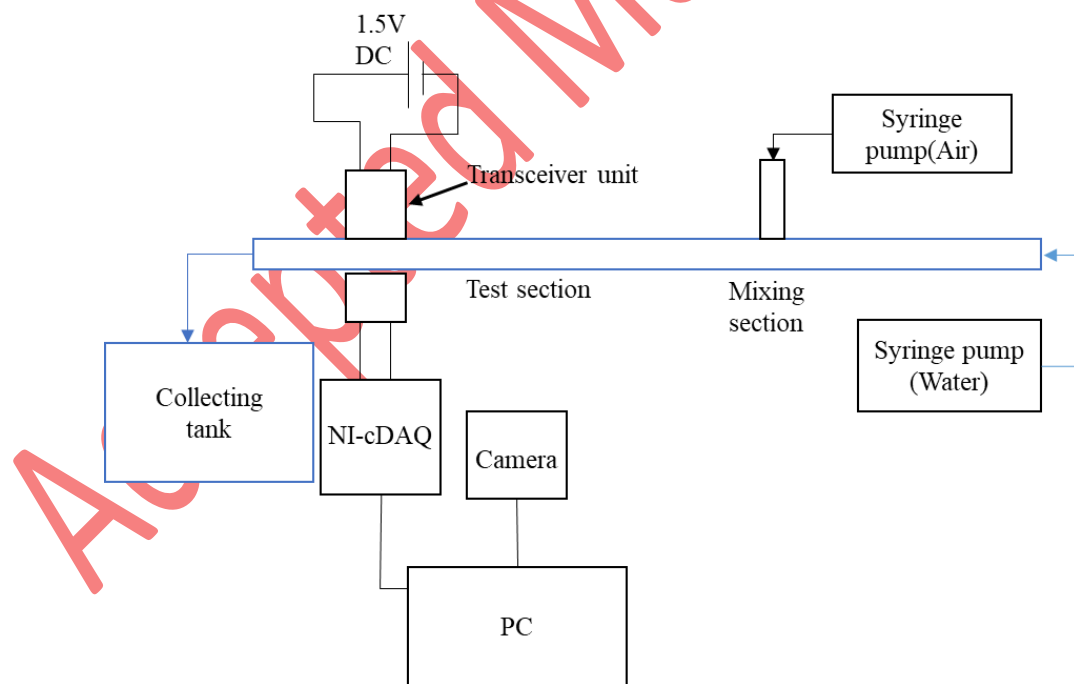


Fig 1. Schematic diagram of the Experimental setup

The sensors used have the exact dimensions stated in the technical data sheets for the LED and Photodiode [17, 18]. For the reader, the two phase flow is from right to left. A high-speed

color camera (PROMON 200) along with a Navitar zoom 3000 lens captures videos of the high speed two-phase regimes in the test section. The high speed system can capture images at 3000 fps, and the frame rate can be adjusted based on the required resolution. AOS Promon Studio v3.1.2 software is used for frame by frame analysis of the captured high-speed video. The current generated by the IR photodiode is measured with an NI 9203 module connected to the NI-cDAQ 9174 chassis, and the data is recorded using LabVIEW software. The imtoolbox in MATLAB software processes the image and measures the pixel lengths of the regimes. The distance transform method converts pixel lengths to the required dimensions in millimeters, as described by Mithran and Venkatesan [13]. For each frame, the bubble boundary is first segmented from the background using intensity thresholding. The equivalent diameter is calculated in MATLAB as the diameter of a circle with the same cross-sectional area as the segmented bubble. The pixel area is converted to mm² using the distance-transform calibration. Because the bubble is not perfectly spherical, this equivalent diameter is further averaged over the frames spanning the full transit of the bubble (typically 8-10 frames at 3000 fps) to obtain the mean bubble diameter reported in this study, thereby reducing the influence of frame-to-frame shape fluctuations.

2.1 Numerical model

A numerical model similar to the experiment is developed using the COMSOL Multiphysics package. The model is designed with geometries and fluids similar to those used in the experiments. Differential equations (first order) of Snell's law are solved in COMSOL with the ray's position as q , angular frequency ω , and wave vector k . The equation is solved for every single ray in the time domain t to compute the number of photons reaching the receiver. The numerical model is the same as that of Ref. [16], which is validated with experimental results for hydrogen peroxide air two phase flow.

The transport equations solved by the Geometrical Optics module are the ray-tracing (eikonal) form of Hamilton's equations, $dq/dt = \partial\omega/\partial k$ and $dk/dt = -\partial\omega/\partial q$, together with the local dispersion relation $\omega = ck/n(q)$. Here $n(q)$ is the space-dependent refractive index field assigned to each domain (air, borosilicate glass, and the working liquid) from the phase distribution measured in the experiments. At every interface, Snell's law and the Fresnel equations govern the refraction angle and the splitting of ray power into refracted and reflected components. The IR source is modeled as a cone of rays with a half-angle of 30° , matching the LED datasheet beam divergence, and the receiver is modeled as a deposit boundary that records the fraction of the emitted ray's incident on it.

3. Results & discussions

The results obtained through experiments and the numerical model are discussed in the forthcoming sections. Section 3.1 explains the single-phase results obtained through the developed numerical model. Section 3.2 details the experiments and the numerical model of IR ray irradiation behavior under changes in the test section's cross-sectional shape (square and triangular). Section 3.3 details the variation in IR ray behavior as fluids of varying viscosity and density flow through a channel of varying cross-section.

3.1 Single-phase results in square and triangular geometries

The regime's refractive index and geometry are the predominant factors in the IR ray's irradiation behavior. A change in the shape of the regime alters the direction of photon refraction. Thus, the shape and size of the medium through which the IR rays travel must be considered when designing an IR transceiver.

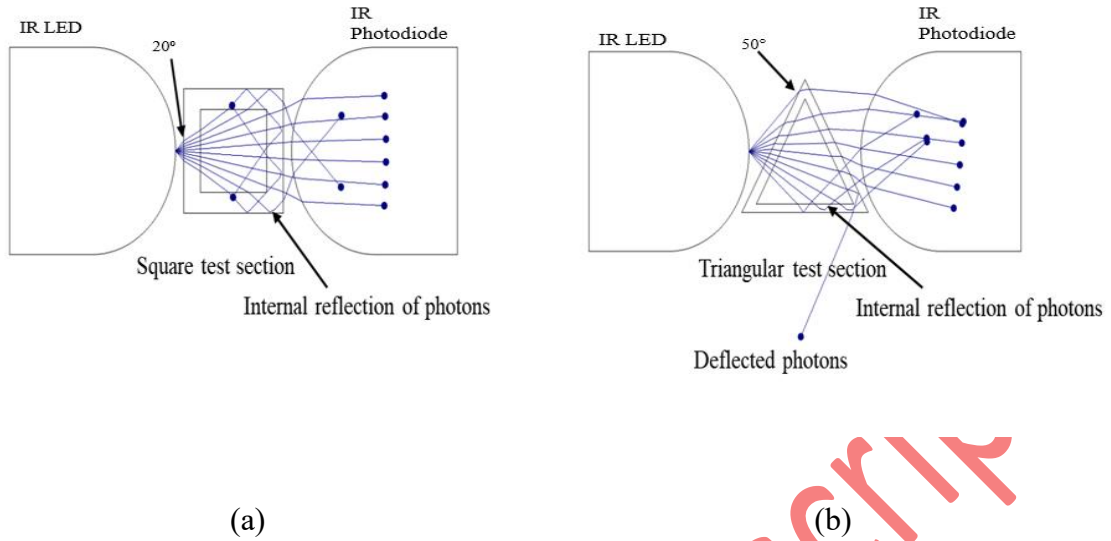


Fig 7. Interaction behavior of IR rays for single-phase flow in (a) square test section, (b) triangular test section

A triangular and square channel of equivalent cross-sectional area is modeled to verify the effect of test section cross-section on IR ray behavior. The angle at which the IR rays pass through the medium decides the refraction phenomenon of the rays. The IR rays are released at a viewing angle of 20° degrees (from the datasheet) [19]. The photons from the IR transceiver in the form of a conical volume contact the square test section at an angle of 20° to the normal of the square channel's surface. This can be verified from the alternate interior angle theorem. The IR rays meet the surface of the triangular test section at an angle of 50° , while the IR rays' contact is at 20° for a square channel. This difference in the angle of incidence is significant because it sets the ray closer to (triangular) or farther from (square) the critical angle for total internal reflection at the glass-air/liquid interface. The larger 50° incidence angle in the triangular channel is closer to the critical angle. So a larger fraction of the rays are internally reflected rather than transmitted. This explains why the triangular channel consistently returns a weaker, more scattered signal at the receiver than the square channel does throughout Section 3.3. The interaction of IR rays from the IR LED source with the surfaces of triangular and

square test sections, along with their refraction and internal reflection ray patterns for single-phase flow, is simulated using a 2D COMSOL Multiphysics model. It is shown in Fig. 5. (a) and (b). Only 10° rays are sent, and the pattern received is shown.

The IR rays travel from one medium to another by partially refracting or reflecting through the medium. In the present study, reflected rays are not considered, as only refracted rays reach the photodiode. Some of the rays reach the critical angle to the normal of the medium's surface and get internally reflected. A few rays get deflected from the test section before reaching the photodiode, as shown for the triangular channel in Fig. 5. (b).

The refractive index of a medium does not depend on its shape or size. The speed and wavelength of the photons are affected as they travel through a combination of different shapes and thicknesses of other media. However, the photon frequency remains constant. From the following equations, it can be seen that the refractive index of a medium (n) is the ratio of the speed of a photon in vacuum to its speed in the medium.

$$n = \frac{c}{v} = \frac{f \cdot \lambda}{f \cdot \lambda_m}$$

Where,

n = refractive index of a medium,

c = speed of light in vacuum,

v = speed of light in the medium,

f = frequency of the photon,

λ, λ_m = wavelength of a photon in vacuum and medium

As the speed and wavelength of the ray change while traveling from one medium to another, there is a change in the angle of the refracted ray, which is given by Snell's law.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Where,

n_1, n_2 = refractive index of the first and second medium,

θ_1 = angle of the incident ray,

θ_2 = angle of the refracted ray.

When the incident angle of a ray exceeds the critical angle, the ray undergoes internal reflection within the medium. The condition is that the ratio of the refractive indices of the two media must be less than 1.

$$\sin \theta_c = \frac{n_2}{n_1}$$

Where, θ_c = critical angle of the medium,

n_1, n_2 = refractive index of the first and second medium

Fig. 3. (a) and (b) detail the rays' refraction and internal reflection patterns in a triangular and square channel for single-phase water flow.

3.3 IR irradiation behavior on bubble/slug two phase flow through square and triangular channels

Experiments are done in a square channel at specified superficial air and water velocities. The velocities are chosen from flow regime map published in the literature. The regime dimensions are found out using the image-processing technique, as described in section 3 and Ref. [13].

The test section is placed between the IR transceiver setup. The IR photons from the transmitter reach the receiver after passing through the test section. The photons get scattered as they pass through the two-phase fluids inside the test section that have different refractive indices. The refractive index values of single-phase water, air and borosilicate glass, are 1.33, 1 and 1.5 respectively. The image obtained from high-speed imaging for a bubble regime is shown in Fig. 3.

The signal pattern obtained from the IR transceiver which is recorded in a NI-cDAQ when the bubble passes through the circuit is shown in Fig. 4. The current measured by the IR sensor is 0.88 mA when single phase water flow through the test section. The current value is 0.66 mA for single-phase air. The current variation is recorded when a two phase regime passes through the IR transceiver setup. The bubbles curvature geometry and the air water interface results in the sudden drop and rise in the current values. The bubble's diameter is obtained by image processing the high-speed photograph using MATLAB.

The square channel is of 2 mm side; the bubble formed is tiny and appears spherical. Due to differences in density and gravity, the bubble is on the top of the square channel, with more liquid at the bottom, as shown in Fig. 3. A numerical model is developed that accounts for the thickness of the liquid film. The bubble center is offset by 0.3 mm, equal to the liquid diameter at the center of the test section. This 0.3 mm offset value was obtained directly from the high-speed images. The thickness of the liquid film beneath the bubble in Fig. 3 is 0.3 mm, and buoyancy forces the bubble toward the top wall of the 2 mm-square channel. This measured offset value was incorporated, rather than assuming a concentric bubble, and was necessary for the numerical ray count to match the experimental signal amplitude. The number of rays released from the release point is set at 100. The number of rays reaching the sensor can be directly measured as the percentage of photons received in the selection. The results plotted in Fig. 4 show the total number of rays in the selection area (as a percentage) for a

specific position in the bubble regime. The signal patterns of the experiment and the numerical model are similar, and the work is extended for an equivalent triangular channel. The results obtained are shown in Fig. 4, 5. Due to the mentioned phenomenon, it may be noted that the signal pattern is similar but there are fluctuations in the obtained signal for a triangular channel when compared to a square channel.

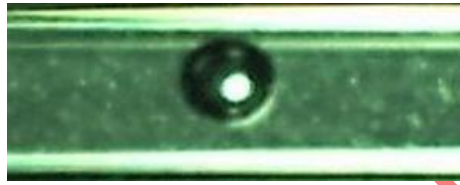


Fig. 3 Bubble regime in a 1 mm square channel

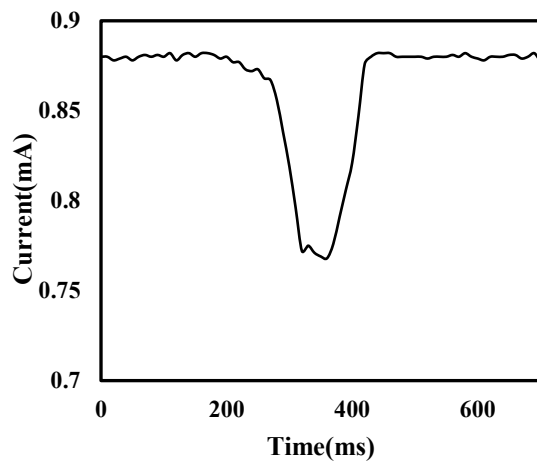


Fig. 4 Experiment - bubble

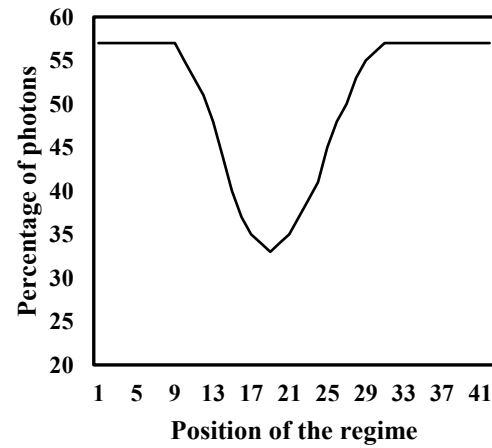


Fig. 5 Numerical model - bubble

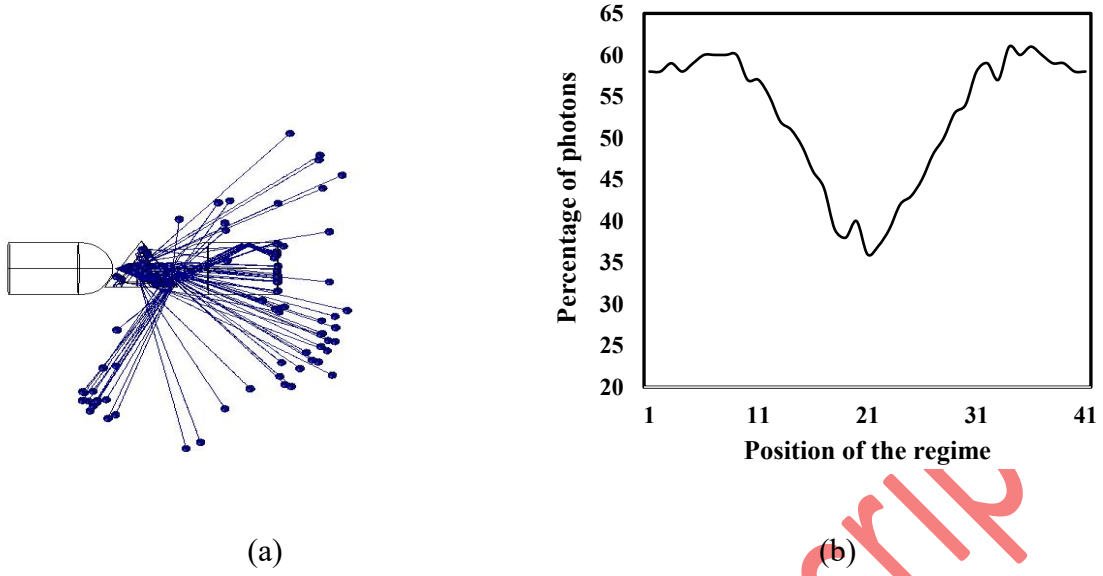


Fig 4, (a) Refraction of IR photons for a bubble in a triangular channel

(b) Signal patterns for a triangular channel

The experimental photograph obtained for a slug regime in a square channel is shown in Fig. 5. The corresponding experimental current-time data recorded from an IR sensor using a NI-cDAQ are shown in Fig. 6, 7. The front and rear portions of the slug have a curvature shape, and due to the air-water interface on the region, the drop and the rise in the current value occur. Except for the front and rear curvatures, the entire area is occupied by air, surrounded by thin liquid films at the top and bottom. This is indicated as a constant signal of a straight-line pattern, as shown in Fig. 6, 7.

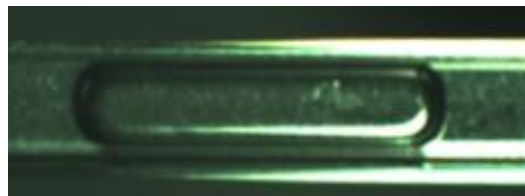


Fig 5. Slug regime in a 3 mm square channel

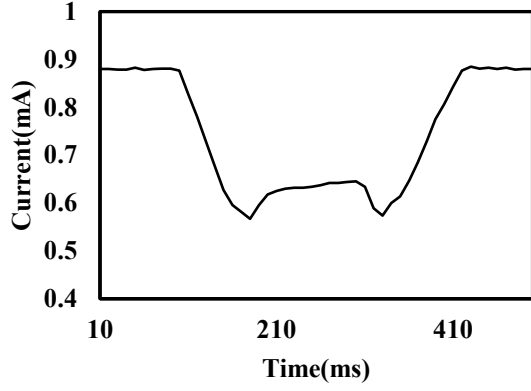


Fig 6.1. Slug regime – Experiments

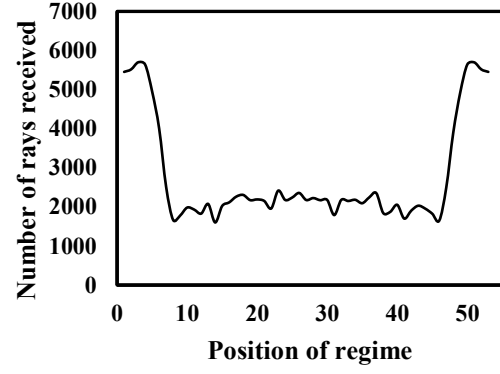


Fig 6.2. Slug regime – Numerical

The dimensions of the slug obtained from image processing are numerically simulated using COMSOL Multiphysics. The slug flow pattern, which usually occurs in the mini/microchannels, always has a thin liquid film surrounding the regime. The liquid film thickness varies with channel size and flow regime. Hence, the slug regimes considered in the present study are modeled with uniform liquid film thickness. The results obtained in the numerical model is shown in Fig. 6.2. The experimental and numerical plots in Fig. 6.1 & 6.2 detail the pattern obtained for the slug regime in a square channel. The photons are scattered more by the slug than by the bubble, because the bubble regime is small. It can be observed that the magnitude of the current drop at the front and rear ends appears to be equal. Fig. 5 (a) illustrates the refraction of the IR photons in single-phase water, and Fig. 5 (b) explains the refraction of photons while IR rays pass through the front end of the two-phase slug regime inside the square channel. The refraction pattern changes as the two-phase regime replaces the single-phase water, and a current drop may be observed as the photodiode refracts more photons. Some of the photons are scattered in various directions as the rays pass through varying shapes of the slug regime. The individual photons are directed toward the IR receiver, and the corresponding current, in milliamperes, is recorded in the experiment. The difference between these current values is 0.30 mA, which is comparable to that in the bubble regime,

where the current difference is 0.12 mA, as described in Fig. 3. The current amplitude values show that the size of the regime is proportional to the current amplitude value. The results for a triangular channel for the equivalent cross-sectional area and slug dimensions are shown in Fig. 4 (a) and (b). The signal pattern in the plot is similar to that of a square channel, but the drop on the front and rear portions of the slug is not the same in magnitude because of the cross-section of the channel. This asymmetry arises because the front and rear menisci of the slug approach the sloped triangular wall at slightly different local incidence angles as the interface curvature changes direction. Since the triangular channel's 60° angle of incidence is close to the critical angle (Section 3.1), even this small difference in local angle shifts a larger or smaller share of rays past the critical angle for total internal reflection. This will result in an unequal current drop at the front and rear of the slug, an effect that is negligible in the square channel because its 90° incidence angle is well away from the critical angle. The wavering pattern is observed throughout the signal. Compared with the numerical results of the square channel, the wavering occurs only along the length of the slug surrounded by a constant liquid film.

If the signal patterns of a slug flow are compared between a square and a triangular channel, although the magnitude of the received photons in the receiver is the same, the phenomenon is different. In a square channel, due to the rays' conical spreading, many rays are refracted away from the receiver. In a triangular channel, the rays emitted reach the critical angle, are internally reflected, and travel toward the IR LED again.

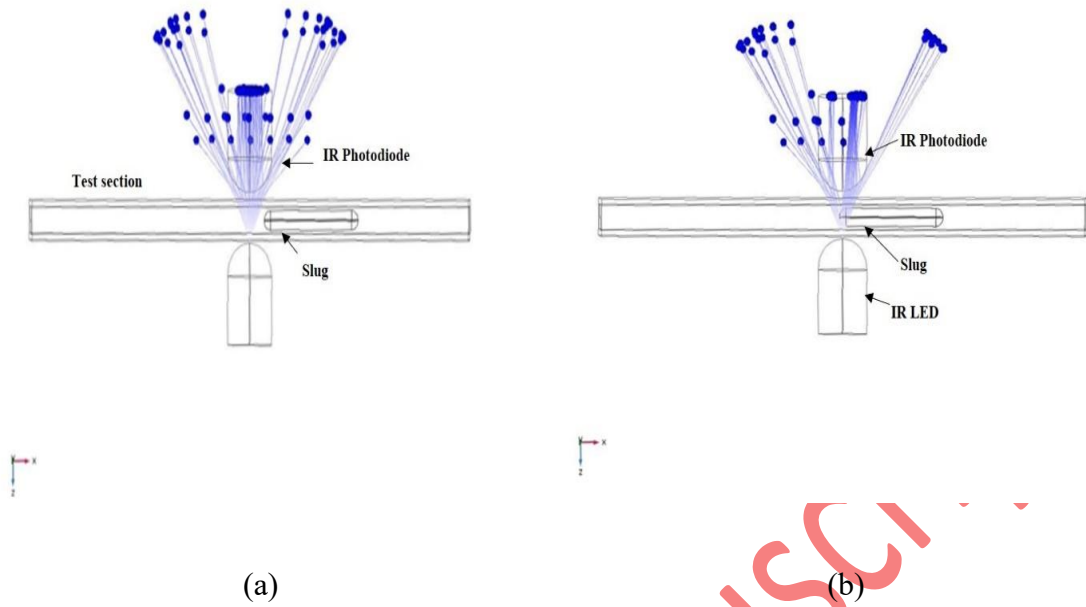


Fig 7. Refraction of IR photons in a square channel (a) single-phase water (b) front end of the slug regime

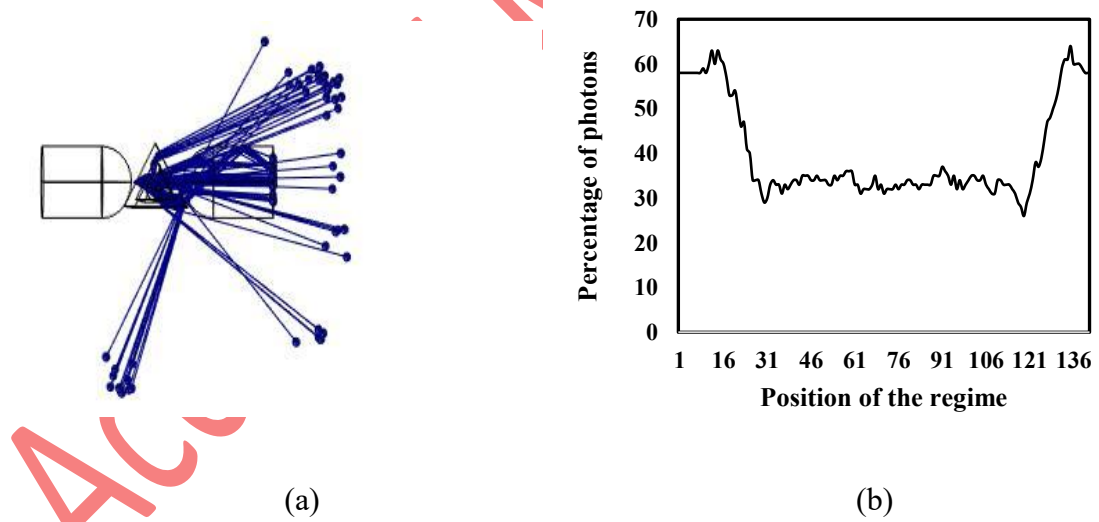


Fig 8. (a) Refraction of IR rays at the center of the slug-triangular channel

(b) Numerical results – Slug – Triangular channel

The receiver's orientation relative to the sensor also plays a significant role in the reception of refracted rays. At the receiver end, a square channel senses more IR rays than a triangular channel, resulting in a clearer signal output. The results show that the regime's refractive index and shape are predominant in the IR ray irradiation behavior. Changes in the shape of the regime affect the direction of photon refraction. Thus, the shape and size of the medium through which the IR rays travel must also be considered when designing an IR transceiver.

3.3 IR irradiation behavior with the change of fluids

The results in section 3.1 indicate that the cross-section of the test section plays a vital role in the signal pattern of an IR transceiver. This section details the effects of fluid properties on the behavior of IR transceivers. Experiments and numerical studies are conducted for air-olive oil two phase flow. Numerical studies are conducted for air-methanol two phase flow. Olive oil is less dense and more viscous than water, but has a higher refractive index. Methanol is less dense and viscous and has the same refractive index as water. The refractive index of a fluid can be functionally related to its density [19]. As density and viscosity are interrelated, Lorentz Lorenz's [20] equation explains that the number of molecules per unit volume (density) and polarizability is proportional to the refractive index of a medium.

$$\frac{n^2 - 1}{n^2 + 2} = \frac{4\pi}{3} N\alpha$$

Where,

n = refractive index,

N = number of molecules per unit volume,

α = mean polarizability

The refractive index of the fluid is not proportional to density. The comparison of the density and refractive index of fluids with densities higher and lower than that of water is shown in Fig. 9. The refractive index of a medium is associated with the density of free electrons and photon interaction to polarize the free electrons of that substance and the wavelength of the photon source.

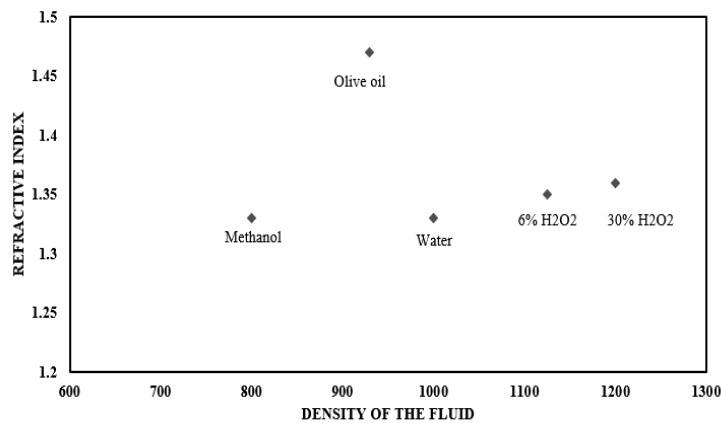


Fig 9. Refractive index Vs. Density of fluids

Since the IR LED wavelength is constant throughout the study, the photon source's wavelength is neglected when calculating the medium's refractive index. The refractive index increases with an increase in the polarization of electrons. Olive oil is more viscous than other fluids. However, viscosity is not directly related to olive oil's refractive index. Viscosity is the resistance to shear force offered during the interaction of molecules. In olive oil, the number of free electrons is high because the available oxygen molecules are abundant, and polarization is high due to a higher electron density than in other fluids. Due to its high polarizability, Olive oil has a refractive index of 1.47, which is closer to that of glass. The bubble and slug regime formed in air-olive oil two-phase during experiments done in a square section is shown in Fig. 10 (a) and (b). Due to the higher viscosity of Olive oil, the regimes formed are not axisymmetric as they advance through the liquid phase. Figures 11 (a) and (b) show the corresponding signal plot from the IR transceiver setup. The bubble regime shown in Fig. 10(a) appears to have a

sharp nose at the front end (F) and a relatively blunt rear end (B). Hence, a sudden spike in the current time plot indicated in (F) & (B) in Fig. 11 (a) is observed.

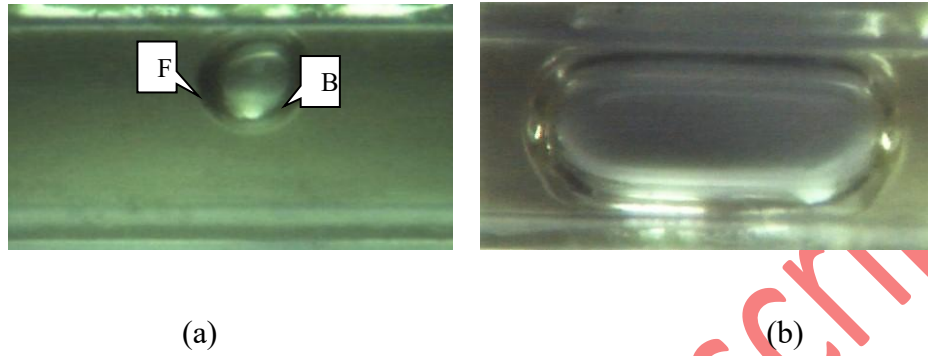


Fig 10. Regimes in air-olive oil two-phase flow (a) bubble (b) slug

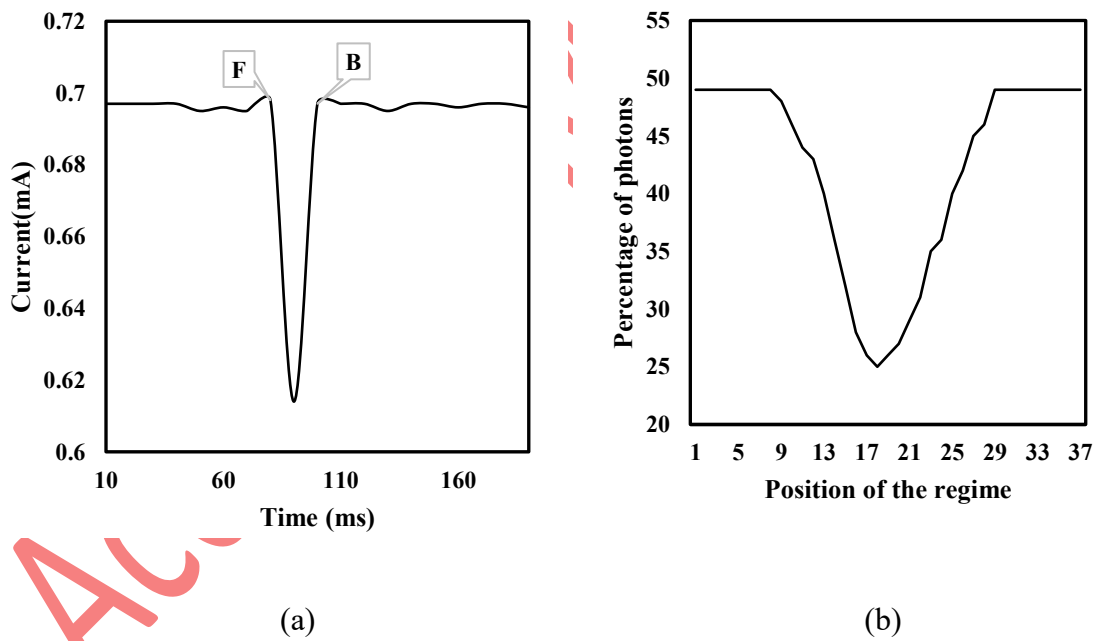


Fig 11. Air-olive oil bubble in a square channel (a) Signal patterns (experiment) (b) Signal patterns (Numerical)

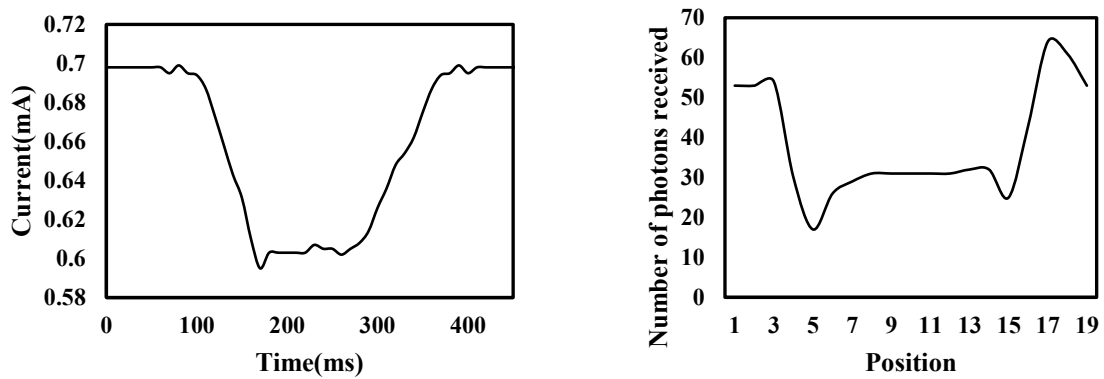


Fig 11. Air-olive oil slug in a square channel (a) Signal patterns (experiment)

(b) Signal patterns (Numerical)

A reduction in signal pattern fluctuations is observed compared to the experimental signal in the air-water two-phase bubble regime. Olive oil is more viscous than water; hence, the interface velocity of a two-phase flow of olive oil will be less than that of water. So, the drop and rise in the signal pattern (experiment) and percentage of rays refracted (numerical) will have a smooth drop compared to air-water two phase flows. Similar signal patterns and changes are observed in the air-olive oil numerical simulation in the triangular channel for slug and bubble flow. As the refractive index of the olive oil is higher than that of water and closer to the refractive index of glass, and due to the triangular shape of the test section, the scattering of the photons is more significant. However, the obtained signal pattern resembles those in the square channel, with reduced amplitude.

Methanol and water differ in density but have the same refractive index of 1.33 [21]. The free electrons in methanol and water are almost equal. Hence, the free electron density is closer for methanol and water, and the refractive index is nearly the same, irrespective of density variation. The signal pattern of the methanol when IR LED rays pass through the air-methanol two phase flow is studied numerically. The dimensions of the slug and bubble regime obtained in the air-water two phase flow are used to model the regime with water replaced with

methanol. The results show that the fluid's density does not affect the refractive index, whereas the polarizability of several electrons does. Though the density varies, the water and the methanol two phase flow with air have similar patterns as visualized in Figs. 4, 6, and 12.

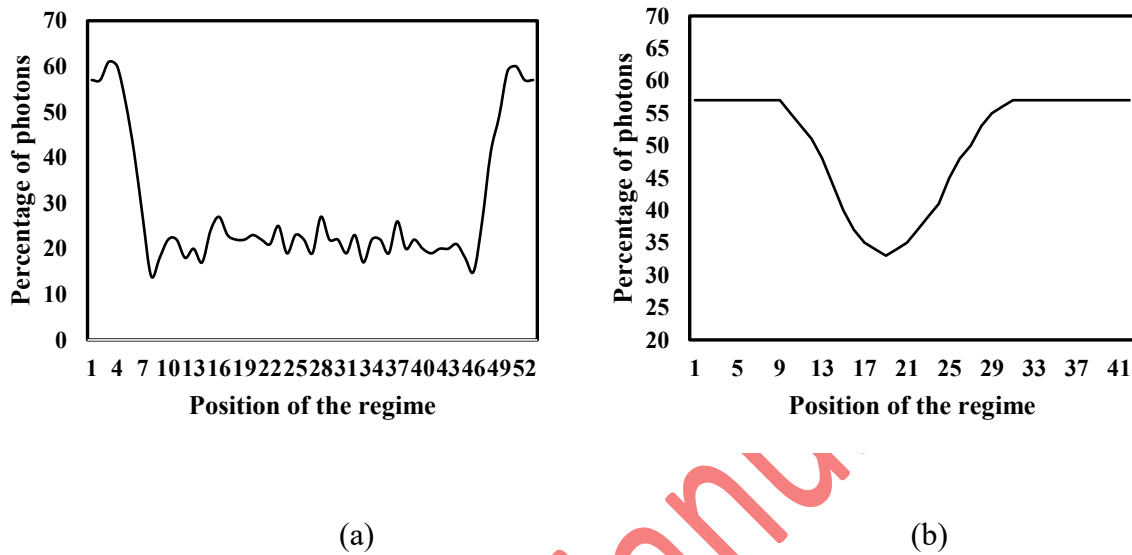


Fig. 12. Air-methanol flow in a square channel (a) slug regime (b) bubble regime.

Air-Methanol is also modeled in the triangular channel, and the plots obtained are similar to those obtained in air-water two phase flows. The dimensions of the slug and bubble obtained during air-water flow are used to model the air-methanol flow. The above results show that IR irradiation behavior depends on the refractive index, the test section cross-section, and the flow regime through which the photons travel. The fluid's density and viscosity are of secondary importance in the design of an IR transceiver circuit.

4. Conclusion

Two phase experiments are performed in a square mini channel and an IR transceiver is used to characterize bubble and slug regimes. The IR transceiver is positioned at 90° to the test section. NI-cDAQ is used to record the time-current history of the IR transceiver setup. A numerical model is developed in COMSOL Multiphysics for the same setup. The results are compared with the Air-Olive oil two-phase flow in the same test section. The experimental and numerical results confirm that differences in the fluid's viscosity and density do not affect the IR irradiation behavior. The fluid's refractive index, as well as the medium's cross-section, influences the infrared rays passing through it. The signal pattern depends on the velocity at which the regime crosses the medium. The above results can be further extended to precisely design IR sensor arrays to reconstruct the volumetric void fraction.

Quantitatively, the single-phase current recorded by the IR sensor was 0.88 mA for water and 0.66 mA for air, and this 0.22 mA baseline difference set the reference scale for all two-phase measurements. In the square channel, the bubble regime produces a current difference of 0.12 mA, while the slug regime produced a larger difference of 0.20 mA, confirming that the magnitude of the current drop increases with the length of the two-phase regime obstructing the IR path. The bubble center was found to be offset by 0.30 mm from the channel mid-plane due to buoyancy, and accounting for this offset was required for the numerical model to match the experimental amplitude. In the triangular channel, the larger 60° angle of ray incidence, compared with 90° for the square channel, moved the rays closer to the critical angle for total internal reflection, and this reduced and de-symmetrized the received signal relative to the square channel for both the bubble and slug regimes. Replacing water with olive oil (refractive index 1.47) or methanol (refractive index 1.33 , same as water) while keeping the regime geometry fixed left the signal pattern essentially unchanged in shape, whereas changing the cross-sectional geometry from square to triangular consistently reduced the received signal

amplitude; this quantitatively confirms that the refractive index and cross-sectional geometry of the medium, rather than its density or viscosity, are the primary design variables governing IR transceiver response in two-phase mini-channel flows.

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