

A study on the flow characteristics of a vertical perforated-pipe distributor in a circular separator

L.H. Ngu, P.L. Law and K.K. Wong

*Department of Civil Engineering, Faculty of Engineering
University of Malaysia, Sarawak*

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Abstract

This study investigates the flow velocity profile of a specially designed vertical perforated-pipe distributor inlet to accommodate a circular separation tank consisting of inclined coalescence frustums to enhance solid-water-oil separation process. The separation system is equipped with an upflow center-feed perforated-pipe distributor inlet to direct flow to the inclined coalescence frustums in an attempt to provide uniform flow pattern. The inlet perforated vertical pipe consists of 12 equal diameter holes positioned at 3 levels, with 4 holes at each level to direct flow towards coalescence frustums at 4 different directions, i.e., 0°, 90°, 180° and 270°. It was demonstrated that flow velocity gradient across the diameter of the separator decreases horizontally with distance from inlet, and depth from water surface. Theoretically calculated vertical perforated-pipe inlet hole velocity, v_{hole} and experimentally measured inlet hole velocity, $v_{hole\ meas}$ were correlated, and found to be $v_{hole} = 2.04 v_{hole\ meas}$ with a correlation coefficient of $R^2 = 0.96$. An empirical mathematical expression for the vertical perforated-pipe inlet hole velocity was established.

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Keywords: Velocity profile, perforated-pipe, distributor inlet, coalescence frustums

1. Introduction

A circular basin equipped with a center-feed upflow inlet design enables wastewater to flow into the system whereby the horizontal velocity, v_h decelerates with distance from inlet as a result of continual increase in surface area (Corbitt, 1989 and Davis, et al., 1991). Deininger et al. (1998, 1996) presented results of a full-scale measurement of flow velocity and solids distribution in a traditional up-flow center-feed inlet for a circular secondary clarifier, and evaluated its flow patterns by using numerical modeling. A two-phase three-dimensional model was applied to gain a better understanding of the observed flow patterns.

Figure 1 illustrates experimental flow patterns of circulating currents within a traditional up-flow centered-feed inlet by Deininger et al. (1996, 1998). The experiment demonstrates that a traditional circular up-flow center-feed inlet would give rise to some fluids bypassing separation zone, and some trapped and circulated around the separation zone. Additionally, Deininger et al. (1998) found that fluids trapped in the separation zone had sufficient retention time for separation process to occur and fluids bypassing the separation zone had less or inadequate retention time for separation process to occur. Full-scale velocity components in radial direction as well as solids distribution showed a satisfactory agreement to the predicted values. Density currents were detected in the deeper zone of clarifiers and Deininger et al. (1996) stressed that these patterns had not been taken into account or adopted in current design procedures. Novel design methods based on the dynamic behavior of flow and density distribution in clarifiers are needed in order to improve the efficiency of wastewater treatment systems.

In this study, an alternative vertical perforated-pipe distributor inlet was specially designed to accommodate a circular separation tank consisting of inclined parallel coalescence frustums to enhance solid-water-oil separation process. The design of the vertical perforated-pipe inlet distributor was based on the principle of Boycott effect whereby the presence of an inclined medium promotes settling of particle, coalescence of oil droplets and increase solid-liquid-oil separation efficiency. A circular tank with a center-feed up-flow inlet equipped with inclined coalescence frustums separation system would enhance separation of wastewaters loaded with excessive amount of oil, grease and suspended solids. Theoretically, a vertical perforated-pipe distributor inlet design would optimize separation process by providing relatively uniform and even fluid flow towards the operating spaces where the frustums of coalescence plates are located.

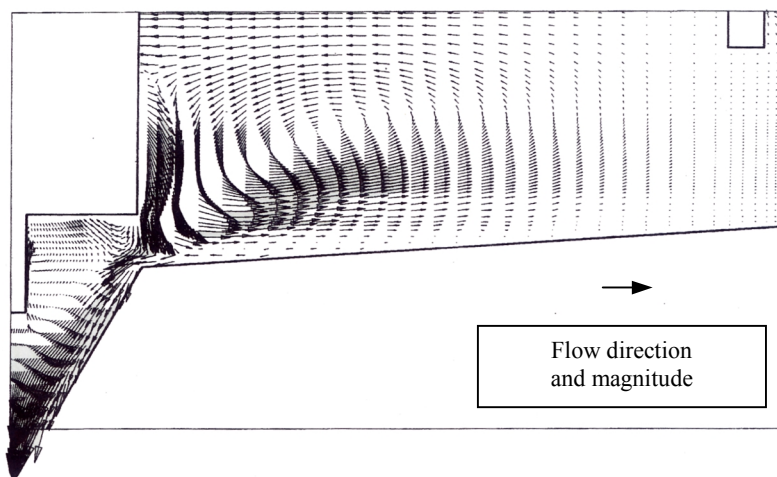


Fig. 1. Flow velocity profile of a circular secondary clarifier with center-feed, coanda tulip with baffles inlet (Deininger et al., 1998)

2. Methodology

2.1 Vertical perforated-pipe distributor inlet design and parameters

To achieve uniform fluid distribution, a vertical perforated-pipe distributor inlet was designed based on theoretical principals of horizontal perforated-pipe distributor inlet by Perry and Green (1997). The module design in Perry and Green (1997) is a horizontal

perforated-pipe distributor with holes of uniform diameter located at constant intervals from each other directing the flow upward as shown in Fig. 2. In the separation tank, the inlet pipe was a vertical pipe consisting of 12 inlet holes of uniform diameter with 4 inlet holes at each of the 3 levels at uniform intervals (5.0 cm) directing fluid flow towards the inclined coalescence frustums at 4 different directions, i.e., at 0° , 90° , 180° and 270° (Fig. 3).

One of the primary differences between a horizontal and the proposed vertical perforated-pipe distributor inlet is that the proposed inlet could create an additional down force by the water volume acting on the flow. However, due to relatively small volumetric flow, the momentum force is extremely small and is neglected in the design considerations. In this perforated-pipe distributor inlet design, Perry and Green design formula and rule were adopted with the assumptions that conditions and rules are applicable to the proposed inlet pipe. Experimental measurements on inlet hole velocities were correlated with calculated design inlet hole velocities to find out the degree of their correlation.

Design of separation tank inlet velocity would be maintained <1.0 m/s as recommended by Corbitt (1989) so as not to produce excessive amount of inlet energy. Inlet pipe of the proposed system was designed as a perforated-pipe or sparger based on the horizontal module designed by Perry and Green (1997) to achieve uniform fluid distribution. Perry and Green horizontal module design is a horizontal perforated-pipe distributor inlet with holes of uniform diameter located at constant intervals directing flow upwards (Fig. 2). In the proposed separation tank, the inlet pipe was a vertical pipe with proposed design of 12 holes of uniform diameter, positioned at 3 levels (5.0 cm intervals), 4 holes at each level to direct flow toward coalescence frustums at 4 different directions, i.e., 0° , 90° , 180° and 270° (Fig. 3).

With the proposed vertical inlet pipe, an additional downward force created by the water volume acts on the flow. Due to its relatively small volume, it would be neglected in the design calculations. In this distributor design, Perry and Green (1997) design formula and rule would be adopted with the assumption that its condition and rule apply to the proposed inlet pipe. Experimental measurements on inlet hole velocities were correlated with calculated design inlet hole velocities in an attempt to establish their correlation.

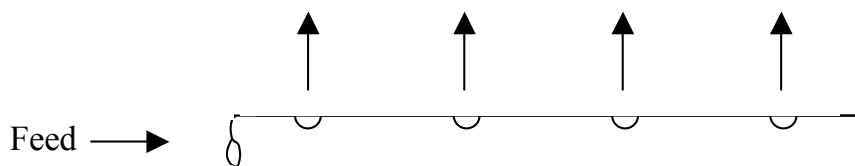


Fig. 2. Horizontal perforated-pipe distributor by Perry & Green (1997)

In turbulent flow, a rough uniform distribution is assumed with a constant friction factor, the combined effect of friction and inertial (momentum) pressure recovery is given by Perry and Green (1997) as

$$\Delta p = \left(\frac{4fL_p}{3D_p} - 2K \right) \frac{\rho v_i^2}{2} \quad (\text{discharge manifolds}) \quad (1)$$

where

Δp	=	net pressure drop over the length of the distributor, Pa	
L_p	=	distributor pipe length, m	
D_p	=	distributor pipe inner diameter, m	
f	=	fanning friction factor	
v_i	=	distributor pipe inlet velocity, m/s	
K	=	1.0 for full momentum recovery 0.5 for negligible viscous losses	} for remaining portion of flow after dividing at a takeoff point

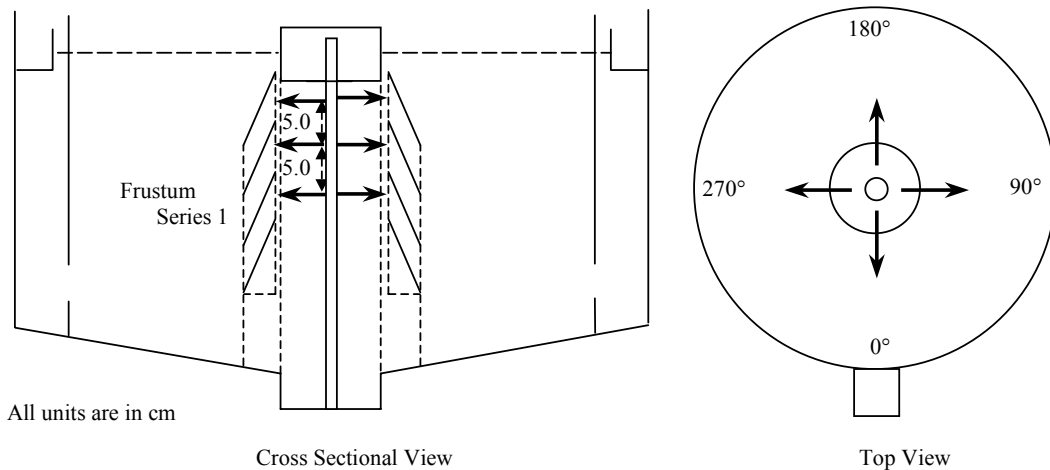


Fig. 3. Vertical Perforated-Pipe Distributor Inlet

To obtain a desirable uniform distribution, the average pressure drop across the inlet holes Δp_{hole} would have to be larger as compared to the pressure variation over the length of pipe Δp . Then, the relative variation in pressure drop across the various inlet holes would be small, and so would be the variation in flow. When the area of an individual inlet hole is small as compared to the cross-sectional area of the pipe, inlet hole pressure drop may be expressed in terms of discharge coefficient C_o (orifice discharge coefficient usually taken as 0.62), and the velocity across the inlet hole v_{hole} as (Perry and Green, 1997)

$$\Delta p_{hole} = \frac{1}{C_o^2} \frac{\rho v_{hole}^2}{2} \quad (2)$$

Provided that C_o is the same for all the inlet holes, the percent mal-distribution, defined as the percentage variation in flow between the first and last inlet holes may be estimated reasonably well for small mal-distribution by (Senegal, 1957)

$$\text{Percent mal-distribution} = 100 \left(1 - \sqrt{\frac{\Delta p_o - |\Delta p|}{\Delta p_o}} \right) \quad (3)$$

Eq. 3 shows that for a 5% mal-distribution, the pressure drop across the inlet holes would be about 10 times the pressure drop over the length of the pipe ($\Delta p_{hole} = 10\Delta p$). For discharge manifolds with $K=0.5$ in Eq. 1, and with $4fL_p/3D_p \ll 1$, the pressure drop across the holes should be 10 times the inlet velocity head, $\rho v_i^2/2$ for 5% mal-distribution. This leads to a simple design equation. Discharge manifolds, $4fL_p/3D_p \ll 1$, 5% mal-distribution:

$$\frac{v_{hole}}{v_i} = \frac{A_c}{A_h} = \sqrt{10} C_o \quad (4)$$

where

$$\begin{aligned} A_c &= \text{pipe cross-sectional area, m}^2 \\ A_h &= \text{total hole area of the distributor, m}^2 \end{aligned}$$

Use of large inlet hole velocity to pipe velocity ratios promotes perpendicular discharge streams. Distributor inlet velocity, v_i is computed by

$$v_i = \frac{Q}{A_c} \quad (5)$$

Separator flow is designed in the laminar flow range, therefore fanning friction factor, f for laminar flow can be obtained from Hagen-Poiseuille equation (McCabe et. al., 1993)

$$f = \frac{16}{N_{Re}}, \quad N_{Re} \leq 2,100 \quad (6)$$

For turbulent flow in smooth tubes, the Blasius equation (Perry and Green, 1997) gives the friction factor for a wide range of Reynolds number.

$$f = \frac{0.079}{N_{Re}^{0.25}}, \quad 4,000 < N_{Re} < 10^5 \quad (7)$$

2.2 Inlet distributor design calculations

Design of the vertical distributor inlet with 12 holes of uniform diameter, 4 holes at each level (Fig. 3), and the distributor inlet pipe criteria and parameters are listed below. The design calculations at different flowrates are shown in Table 1, in addition to illustrating the relationship of inlet hole velocities (Diameter = 3.30 mm) and flowrates. Different inlet hole velocities could be achieved by changing the inlet flowrate, Q . The required inlet velocity at less than 1.0 m/s as stipulated in Table 1 could be achieved at flowrate of less than 1.00×10^{-4} m³/s.

Distributor pipe length, L_p	=	0.15 m
Pipe inner diameter, D_p	=	0.016 m
Pipe cross-sectional area, A_c	=	$2.01 \times 10^{-4} \text{ m}^2$
Water density, ρ	=	1000 kg/m ³
Dynamic viscosity of water, μ	=	0.001 Pa.s
Commercial stainless steel pipe roughness, ε	=	0.002 mm (White, 1999)
ε/D_p	=	0.00125

Table 1. Vertical distributor inlet design calculations at various flowrates

Flowrate, Q m ³ /s	Vel, v_i m/s	N_{Re1}	f_l	N_{Re3}	f_s	f_{ave}	$\frac{4f_{ave}L_p}{3D_p}$	Total hole area, A_h , m ²	One hole area, A_{holes} , m ²	Hole dia, mm	Inlet hole vel, v_{holes} m/s	Average pressure drop across hole, ΔP_{holes} Pa
1.00×10^{-4}	0.497	7955	0.0082	2652	0.0110	0.0096	0.1201	1.03×10^{-4}	8.55×10^{-6}	3.30	0.975	766.21
0.75×10^{-4}	0.373	5966	0.0090	1989	0.0080	0.0085	0.1065	1.03×10^{-4}	8.55×10^{-6}	3.30	0.731	430.99
0.50×10^{-4}	0.249	3977	0.0098	1326	0.0121	0.0109	0.1367	1.03×10^{-4}	8.55×10^{-6}	3.30	0.487	191.55
0.25×10^{-4}	0.124	1989	0.0080	663	0.0241	0.0241	0.2011	1.03×10^{-4}	8.55×10^{-6}	3.30	0.244	47.89

Design total hole area, A_h ($1.03 \times 10^{-4} \text{ m}^2$) was replaced into design Eq.4. [A_c / A_h (1.951) = $\sqrt{10} \text{ Co}$ (1.961)] and was found to satisfy design Eq.4 with a difference of 0.01.

3. Experimental procedure

3.1 Separation tank flow distribution pattern

The separation tank flow distribution pattern was determined by injecting a slug of tracer into the influent and the flow pattern of the colored influent was thus observed. The flow distribution patterns of center feed upflow influent and perforated-pipe up-flow influent were established experimentally. To determine the flow distribution patterns, the experiment was carried out without the series of coalescence frustums in the separation tank. The injection port was fixed to the influent line. The mixing tank was filled with clean water and the water was pumped to the separation tank at the flowrate of $1 \times 10^{-5} \text{ m}^3/\text{s}$. The separation tank was then filled with clean water and 10 ml of blue tracer was injected using a syringe into the influent through the injection port. The colored influent pattern was carefully observed to determine the flow pattern. After determining the flow pattern, the pump was stopped and water from the separation tank was discharged. Experiment was repeated with the perforated-pipe inlet holes covered with tape to determine flow distribution pattern of separation tank with center feed upflow influent.

3.2 Flow velocity profile

Flow velocity profile across separation tank was studied in an attempt to establish the relationship of horizontal velocities, v_h with radius and depth from water surface. Flow velocities were measured using a current flow meter at various points (different radius and depth) in the separator without the coalescence frustums. A current flow meter, Model EA520-268 of ELE Electromagnetic (1998) was used for the purpose. The current flow meter is an electromagnetic flow meter, which uses the Faraday principle to measure the flow of water past a cylindrical sensor. The sensor has its electrodes on the side and the volume of water that is being sensed is a spherical volume around the sensor to a diameter of about 120 mm as shown in Fig. 4. Because of relatively large sensing volume, the cylindrical sensor would not be used in situation where the water boundary [bottom, sides, or surface] is nearer than 40 mm to the sensor.

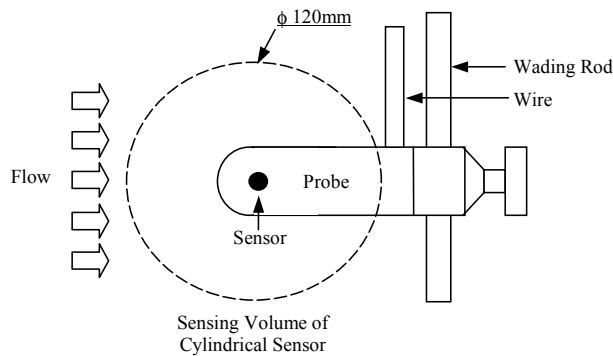


Fig. 4. Cylindrical sensor and its sensing volume (ELE International, 1998)

In this case also, the experiment was carried out without the series of coalescence frustums in the separation tank. Zero calibration of the probe was carried out in still water to determine the current flow meter zero error. Zero error was then deducted from test reading to produce the actual reading. The perforated-pipe inlet holes were covered with tapes to measure the velocity profile of the separation tank with a center feed upflow inlet. The mixing tank was filled with water and the water was pumped to the separation tank at the flowrate of $4.0 \times 10^{-5} \text{ m}^3/\text{s}$. The separation tank was then filled with clean water and the velocities of the fluid were measured at 36 measuring points. Measuring points were set at radius 12.25 cm, 17.25 cm and 22.25 cm where it is 5 cm, 10 cm and 15 cm, respectively from the inlet well, depth of 10 cm, 15 cm and 20 cm where the perforated-pipe holes are located from the water surface at orientation 0° , 90° , 180° and 270° where the inlet flow are directed as shown in Fig. 5. Therefore, there were a total of $[3 \text{ lengths} \times 3 \text{ depths} \times 4 \text{ orientations} = 36 \text{ measuring points}]$. The tapes were removed from the inlet holes, and the fluid velocities at the 36 measuring points were taken to determine the velocity profile of the separation tank with perforated-pipe inlet.

3.3 Correlation of Calculated and Measured Perforated-Pipe Distributor Inlet Hole Velocities (v_{hole})

Correlation between calculated and measured perforated-pipe distributor inlet hole velocities, v_{hole} was conducted to verify and adjust design parameters to actual measured

values. Inlet hole velocity, v_{hole} of the perforated-pipe distributor inlet would be measured using a miniature propeller velocity meter, Model H33 of Armsfield Limited (1995) directly at the opening of the inlet hole instead of the current flow meter. This is due to the large sensing volume of the current flow meter that could not be used in situation where the water boundary is nearer than 40 mm from the sensor, in this case the inlet distributor pipe.

The miniature propeller flow-meter system is designed for measuring very low velocities of conducting fluids; usually water, in open channels. The rotor blades produced linear output of frictional torque over a wide range of velocities. This frictional torque produced a current signal (frequency, Hz) proportional to velocity. In this experiment, the low speed probe would be used and its relationship to flow velocity is given as $v = 0.0056x + 0.0337$ (where v = flow velocity in m/s, and x = reading in Hz).

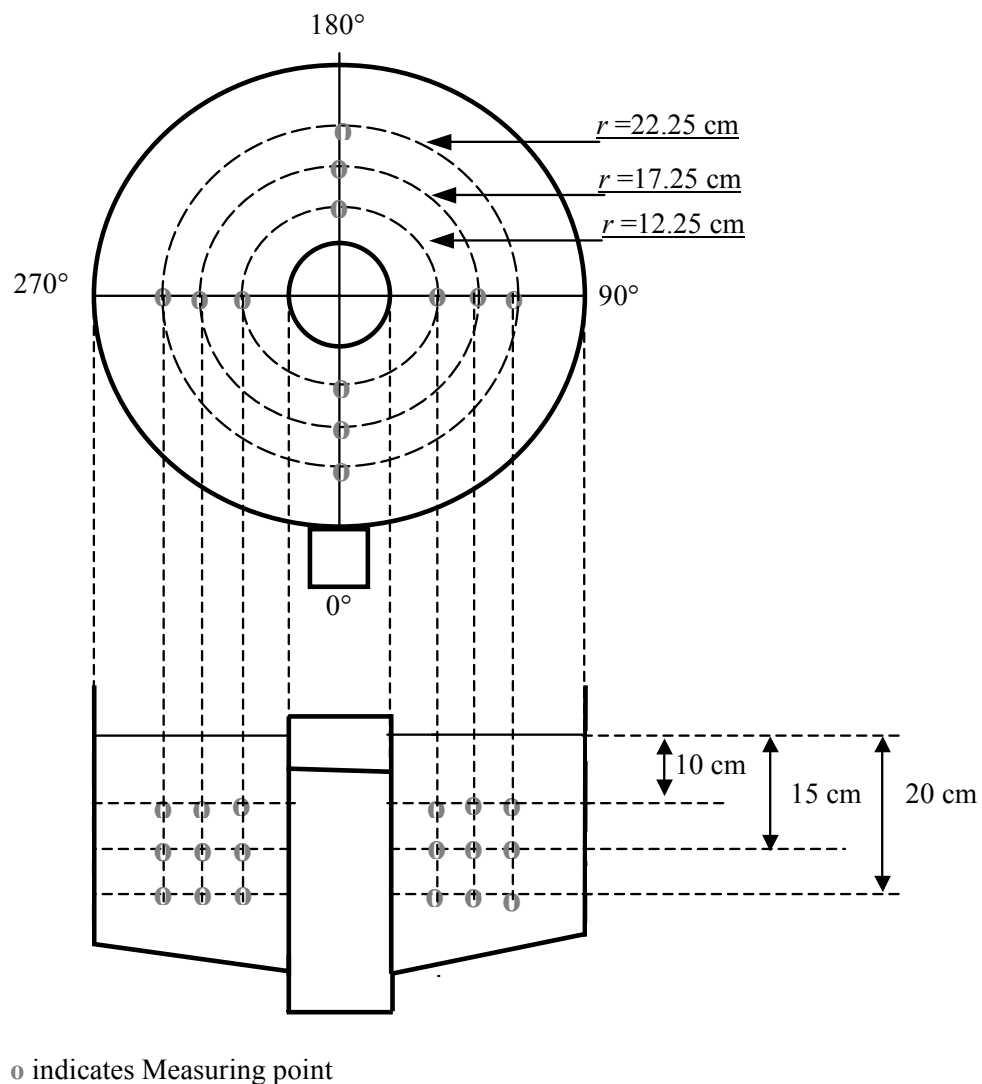


Fig. 5. Measurement points for flow velocity profile

4. Results and discussion

4.1 Separation tank flow distribution pattern

The flow distribution characteristics of the separation system without frustum with a typical upflow center-feed inlet and the designed upflow center-feed perforated pipe distributor inlet are shown in Fig. 6. Figure 6(a) illustrates the fluid flow distribution pattern for a circular separator with a typical upflow center-feed inlet. It was observed that the distribution pattern was similar to the circulating current of the traditional upflow center feed inlet velocity distribution study by Deininger et.al. (1998). Fluid entering the separator was found to flow downwards along tank bottom and some fluid was found to flow out of the separation zone through the flow channel of the outlet baffle. Some fluids were trapped and circulated around the separation zone. That would provide sufficient time for oil droplets to rise to the water surface to be separated. Fluid escaping through the outlet baffle flow channel had less or inadequate retention time for oil droplets to separate from water. Therefore the flow distribution provided different retention time for oil separation and did not fully utilize the coalescence frustums for oil separation. Perforated-pipe distributor inlet provided a direct flow from the inlet hole toward the coalescence frustum as illustrated in Fig. 6(b) and Fig. 7 to optimize separation process utilizing a more uniform and even flow. It was therefore found more favorable.

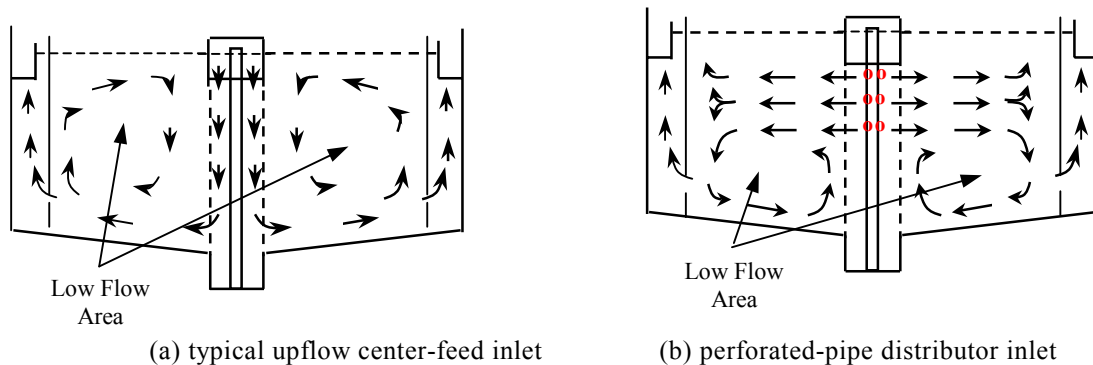


Fig. 6. Fluid flow distribution pattern in the separation tank

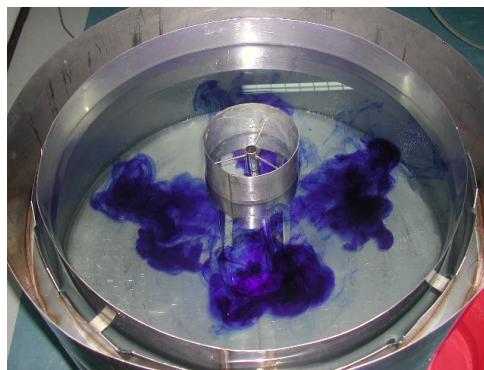


Fig. 7. Flow characteristics of perforated-pipe distributor inlet at 10^{-5} m³/s.

4.2 Velocity flow profile

Figure 8 shows the flow velocity profile across separation tank at different radius and depth with a typical upflow center-feed inlet and design perforated-pipe distributor inlet. For both inlets, horizontal velocity, v_h is indirectly proportional to radius and depth. Flow velocity gradient across the diameter of the separator showed that there was a decrease in horizontal velocity, v_h with an increase of radius from inlet and depth from water surface. The overall horizontal velocity, v_h for the typical center-feed upflow inlet was lower as compared to the v_h of perforated inlet distributor. This was due to different flow distribution pattern where higher v_h for perforated inlet distributor was resulted from direct flow from the pipe towards coalescence frustums where measuring probe was positioned.

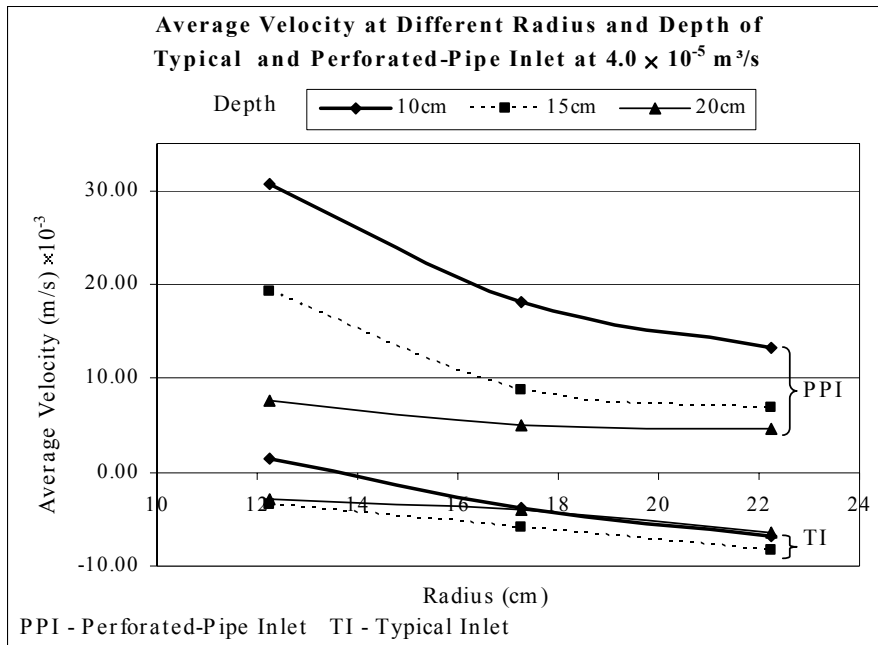


Fig. 8. Typical and vertical perforated-pipe inlet flow velocity profiles

4.3 Correlation between calculated and measured perforated-pipe distributor inlet hole Velocity (v_{hole})

Figure 9 shows the correlation between calculated inlet hole velocity, v_{hole} and measured inlet hole velocity, $v_{hole\ me}$ for the perforated inlet distributor. This relationship can be expressed as $v_{hole} = 2.04 v_{hole\ me}$ with a good correlation coefficient of $R^2=0.96$. Thus, the measured inlet hole velocity, $v_{hole\ me}$ was approximately half (0.5) of calculated inlet hole velocity, v_{hole} . This was probably due to a difference in design conditions as compared to Perry and Green (1997) design module. The proposed pipe orientation and inlet hole location differ from Perry and Green design module, and this affects the values of inlet hole velocities. From the experimentally measured inlet hole velocities values, a new set of inlet hole velocities expression could be derived from Equations 2 and 4. The

inlet hole velocity of this separation system with a vertical inlet orientation could be

written as $v_{hole\ me a} = \sqrt{\frac{4\Delta p_{hole} C_o^2}{\rho}}$ and $\frac{v_{hole\ me a}}{2v_i} = \frac{A_c}{A_h} = \sqrt{10} C_o$.

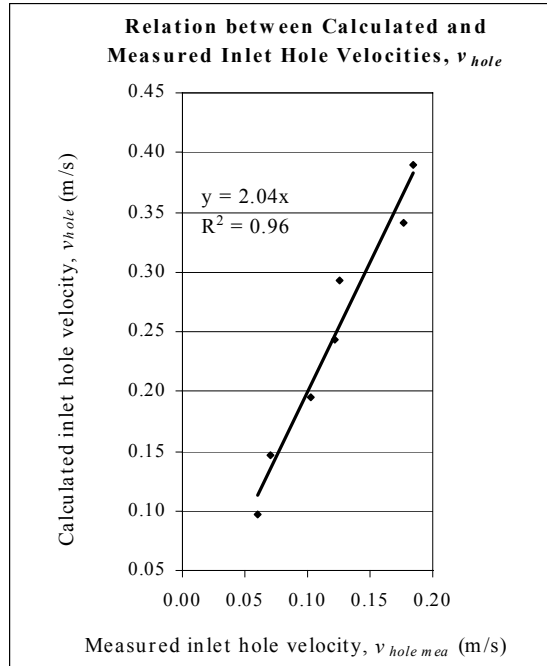


Fig. 9. Correlation between calculated and measured inlet hole velocities

5. Conclusions

In the present investigation, a circular separator with parallel coalescing frustums at multiple angles was designed and its performance in removing physically emulsified and free oils was studied experimentally. From this study, it is concluded that the design perforated-pipe distributor inlet is capable of providing uniform and direct flow to the coalescence frustums. This is shown experimentally through observation of colored influent (blue dye) and the flow velocity profile across separation tank. It is concluded that the horizontal velocity, v_h decreases indirectly and proportionately with an increase in radius and depth or cross sectional area. The relationship of the calculated perforated pipe inlet hole velocity, v_{hole} and measured inlet hole velocity, $v_{hole\ me a}$ is $v_{hole\ cal} = 2.04 v_{hole\ me a}$ with a correlation coefficient of $R^2=0.96$. The deviations of calculated values from measured values could be due to inlet pipe orientation and inlet hole location. For this separation system, the inlet hole velocity whereby the inlet pipe is

arranged in vertical orientation could be expressed as $v_{hole\ me a} = \sqrt{\frac{4\Delta p_{hole} C_o^2}{\rho}}$ and

$$\frac{v_{hole\ me a}}{2v_i} = \frac{A_c}{A_h} = \sqrt{10} C_o.$$

From the present study, further development and research work can be carried out on areas such as (a) development of an inlet flow distribution baffle and study its effect on

separation tank flow distribution (b) study on separation tank flow distribution characteristics and the effect of dead or stagnant spots, currents and hydraulic characteristics to separation tank retention time and efficiency by using tracer studies.

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