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MUTIPHASE OSCILLATORY FLOW IN A BAFFLED TUBE

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RINGKASAN: *Kelakuan hidrodinamik aliran multifasa telah dikaji di dalam sebuah turus sesekat. Sebelum kajian makmal dimulakan, satu simulasi CFD telah dilakukan bagi aliran berayun di dalam turus sesekat. Simulasi yang telah dilakukan menunjukkan pencampuran yang baik diperolehi pada ruang di antara plat sesekat. Aplikasi aliran berayun di dalam turus sesekat bagi pencampuran multifasa dibincangkan di dalam kertas ini. Kajian aliran berayun cecair-pepejal dan gas-cecair-pepejal menunjukkan aliran berayun di dalam turus sesekat mampu mengampaikan butiran pepejal sehingga 20 peratus dari jumlah jisim di dalam turus. Pecahan jisim pepejal yang terampai di dalam turus meningkat dengan peningkatan frekuensi ayunan, kelikatan cecair dan kesan gabungan ayunan dan pembendaliran.*

ABSTRACT: Hydrodynamics behaviour of multiphase oscillatory flow in a baffled tube was investigated. A CFD simulation of an oscillatory liquid flow in a baffled tube is carried out to determine the extent of its mixing capability prior to the actual laboratory work. The results of the CFD simulation show that efficient mixing is achieved in the space between baffles at low oscillatory Reynolds number corresponding to low oscillation frequencies. The application of oscillatory flow in a baffled tube for multiphase mixing is studied in this work. Oscillatory flow in a baffle tube is able to suspend solid up to 20% by weight of the column content. The mass fraction of solid in suspension increases with oscillation velocity and liquid viscosity. The combined effect of oscillatory flow and gas fluidisation on solid suspension is also investigated in this work. The results shows that greater mass fraction of solid is suspended under this condition.

KEYWORDS: oscillatory flow, mixing, baffled tube, gas fluidisation and solid suspension.

INTRODUCTION

Oscillatory flow mixing can be achieved if there is a fully reversing flow around baffle plates which may be produced either by oscillating the fluid or baffle plates. The essential requirement is that sharp edges are presented transverse to the flow. Mechanism of fluid mixing in a baffled tube is illustrated in Figure 1. Flow of the fluid around a baffle plate in one direction produce vortices behind the plate. These vortices take whatever is near the walls of tube with them. Upon reversing the flow direction the vortices formed are pushed into the centre of space between baffle plates while new vortices are formed at the same time, and the cycle is repeated. Formation and disruption of vortices due to the interaction of the fluid and baffle plate provide mixing mechanism in the space between baffle plates.

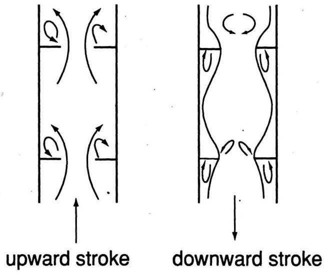


***Figure 1.** Mechanism of fluid mixing in a baffled tube*

Oscillatory flow in a baffled tube can be characterised by two dimensionless groups. The first group is the oscillatory Reynolds number, Re_0, which describes the intensity of oscillation applied to the system,

$$Re_o = \frac{\omega \rho x_0 D}{\mu} \qquad [1]$$

where ω is angular frequency, x_0 is peak amplitude, ρ is liquid density, μ is liquid viscosity and D is column diameter. Efficient mixing can be achieved from oscillatory flow in a baffled tube at Re_0 greater than 150 (Roberts, 1991). Recently Ni and Gough (1997) suggested a modification on the definition of oscillatory Reynolds number to account for variation in the inner diameter of baffle (orifice), D_0, as follows,

$$Re_0 = \frac{\omega \rho x_0 \mathrm{D}}{\mu} \left(\frac{D}{D_0} \right) \qquad [2]$$

where D_0 is the opening diameter. The second group that is used to characterise oscillatory flow is the Strouhal number, St:

$$St = \frac{D_0}{\pi x_0} \qquad [3]$$

where St represents a ratio of orifice diameter to oscillation amplitude. If there is an additional net flow along a device a net flow Reynolds number, Re_n, is also relevant, which gives a measure of intensity of the flow in device. The net flow Reynolds number is expressed as follows

$$Re_n = \frac{\rho D U}{\mu} \qquad [4]$$

with U is the superficial liquid velocity. Brunold *et al.* (1989) showed that baffle spacing of the order of 1.5 tube diameter and constriction ratio of about 60% is optimal to achieve good mixing under oscillatory condition. Mackley (1991) indicated that the wall baffle (orifice) gives the impression of more chaotic flow than central baffle which means that the overall global mixing appears to be greater for the wall baffle than the central baffle.

Investigations carried out on oscillatory flow in baffled tubes show that it can be used to improve available processes or provide an alternative way to improve fluid mixing. Dickens *et al.* (1989) found that axial dispersion in oscillatory flow in periodically baffled reactors is greatly reduced. Mackley *et al.* (1993) showed that particles can be maintained in suspension in vertical baffled columns with oscillatory flow. Howes *et al.* (1991) simulated mixing in a periodically baffled tube and found that at Re_n greater than 100, radial mixing can be enhanced.

In the present work, oscillatory flow in periodically baffled tube is simulated using a computational fluid dynamic software Cosmosm^{TM}/FlowPlus^{TM}. Experimental work was also performed to investigate the hydrodynamics behaviour of multiphase oscillatory flow in a baffled tube.

MATERIALS AND METHODS

CFD Simulation

Oscillatory flow in baffled tubes is simulated (2-D) using a finite element computational fluid dynamic (CFD) software, Cosmosm^{TM}/FlowPlus^{TM}, to determine the parameters which affect the occurrence of vortices and chaotic flow. The simulation was performed on a periodically baffled tube of an internal diameter 50 mm, baffle opening diameter of 13 mm and an inter-baffle distance of 75 mm. Three baffles were used. The oscillating velocity at the entrance of the tube was simulated using a sine function. The simulation was performed for Reynolds number in the range of 314 to 1885 ($314 < Re_o < 1885$) and Strouhal number in the range of 0.026 to 0.079 ($0.026 < St < 0.079$).

Experimental Investigations

The experimental work was conducted in a glass column of 1335 mm height and 50 mm diameter. The column has 18 baffle plates made of stainless steel and connected to the driver by two vertical tie rods. The diameter of the baffle plate is 45 mm and each plate has a central hole of 13 mm diameter. A schematic illustration of the baffle set-up is presented in Figure 2 whilst, Figure 3 shows the schematic diagram of the experimental apparatus used in this work. In all experimental runs, the column was operated at a fixed amplitude of 20 mm.

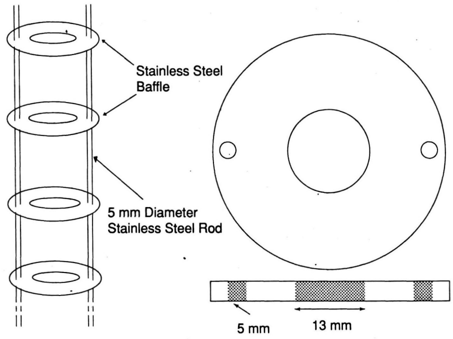
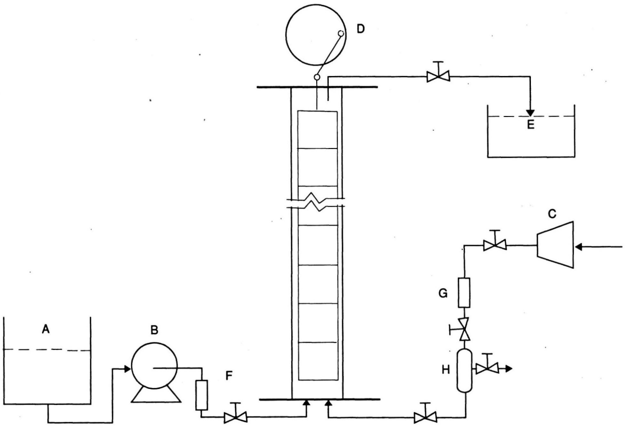


***Figure 2**. Baffle set-up*



A water tank, B water pump, C compressor, D motor and motor drive,
E over flow tank, F water rotameter, G air rotameter, H water drainage

***Figure 3.** Experimental set-up*

Three different solids were used namely, activated carbon, sands and Polyethylene Terepthalate (PET). Water, carboxy methyl cellulose (CMC) solutions, cooking oil and kerosene were used in these experiments to determine the effect of liquid viscosity on solid suspension. A summary of the properties of the solids particles and the liquids used in this investigation is presented in Table 1.

Table 1. Properties of solid particles and liquids used in experimental investigations

No.	Solid	Dia., mm	S.G.	Liquid	Density, ρ gm/cm^3	Viscosity, μ mPa.s	Terminal velocity, V_t mm/s
1	Polyethylene Terepthalate (PET)	3.2	1.37	Water	1.0	1.0	95
		-		CMC	1.0025	30.0	8.5
		-		Kerosene	0.808	0.9	110
		-		Oil	0.825	27.0	10.5
2	Activated Carbon (AC)	1.7	1.8	Water	1.0	1.0	65
		-		CMC	1.0025	30.0	6
		-		Kerosene	0.808	0.9	75
		-		Oil	0.825	27.0	8.5
3	Sand (S)	0.8	2.6	Water	1.0	1.0	
		-		CMC	1.0025	30.0	7
		-		Kerosene	0.808	0.9	
				Oil	0.825	27.0	9.5

Solid particles with known a weight is loaded at the top of the column operated at a fixed oscillation frequency, amplitude and gas flow rates. The oscillation frequency is reduced until the solid particles started to settle by visual inspection. The time for the solids to settle down is noted. In these experiments the gas flow rate was varied from 0.083 l/s to 0.5 l/s, and oscillation frequency was varied from 0.5 to 5.0 rps. The viscosity of the liquid phase is varied from 1 to 35 mPa.s. A summary of the operating parameters used in this investigation is presented in Table 2.

Table 2. Experimental Conditions and Variables

No.	Variable	Symbol	Value
1	Oscillation frequency	f	0.5-4.0 rps
2	Oscillation amplitude	A	20 mm
3	Plate thickness	t	1 mm
4	Gas flow rate	Qg	5-30 l/min
5	Liquid viscosity	μ	1-35 mPa.s

RESULTS AND DISCUSSION

CFD simulation

A typical result obtained from the simulation is presented in Figures 4a and 4b. Velocity in the y-direction shows opposite signs on opposite sides of the inter-baffle region. Velocity in the x-direction shows greater value in the inter-baffle region nearer to the wall showing greater radial mixing. These results also show the vigorous vortices separating from the baffles and causing greater radial mixing.

It can be seen that in the inter baffle regions especially near the baffles, vortices are formed and vigorous radial mixing occurs especially for low Re_o number (Figure 4a). This can clearly be seen from the x-velocity and the y-velocity component especially near the baffle opening. At higher Re_o number (Figure 4b), axial mixing is greater due to the larger amplitude of oscillation which is in the y-direction. Comparing the y-velocity component of Figures 4a and 4b shows that the velocity profile is extended longer in the axial direction at higher Reynolds number.

The result obtained from this simulation showed that efficient mixing can be achieved in the space in between baffles. At a high enough oscillatory Reynolds number, the radial mixing is almost comparable to the axial mixing giving an overall efficient mixing throughout the space in between baffles.

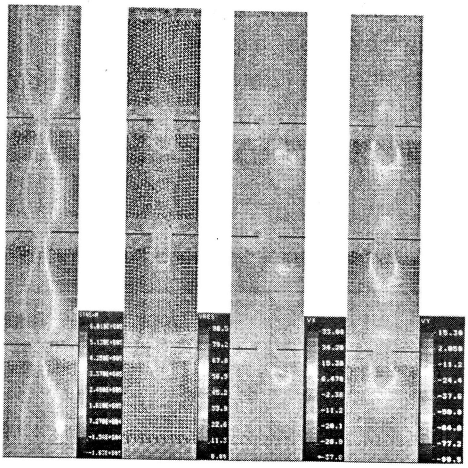


Figure 4a. *Stream function, resultant velocity, velocity in x-direction, and velocity in the y-direction for* $Re_n = 314$ *and St 0.079*

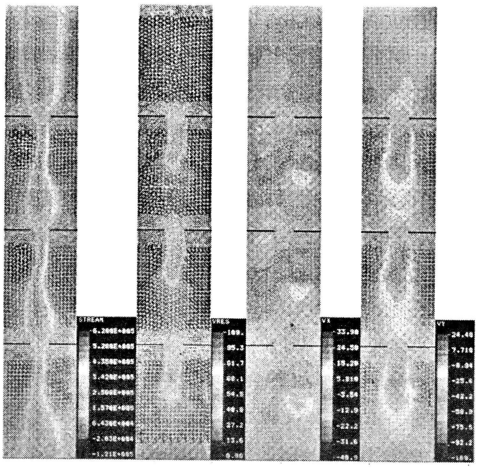


Figure 4b. *Stream function, resultant velocity, velocity in x-direction, and velocity in the y-direction for Re_n = 628 and St 0.053*

Solid Suspension

Solid suspension capability of oscillatory flow in baffled tube was investigated using three solids with different densities. These solids are sand, activated carbon and PET. The result collected for solid suspension in all three liquids are presented in Figure 5. To achieve suspension, the fluid velocity must be higher than the terminal velocity of the particles so that the particles can be lifted up and over the baffle plates. The reduction of particle settling velocities in oscillatory is due to domination of the oscillatory flow over the net flow, where a particle is in stick-slide motion, the periodical upward motion of the fluid increases the fluid drag forces and helps the particle to suspend in liquids. A greater oscillation frequency is required to suspend solid particles with higher density.

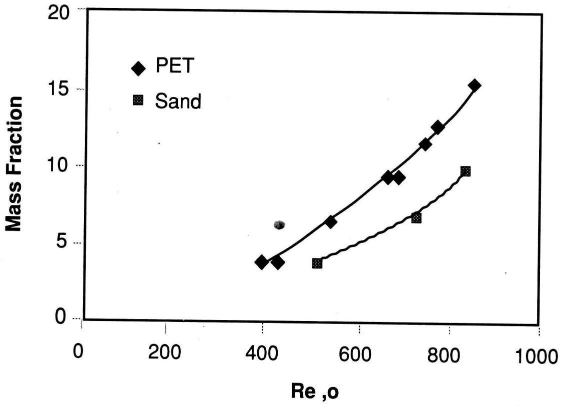


Figure 5. *Solid suspension in oscillatory flow mixing*

A denser solid has a higher terminal velocity, thus requiring a greater upward force to achieve suspension. The mass fraction of PET, the least dense material, in suspension is higher than sand at the same operating conditions as shown by Figure 5. Greater solid suspensions is observed in liquid with higher viscosity. A more viscous liquid gives greater resistance to solid velocity resulting in lower terminal velocity. Greater mass fraction of solid in suspension is observed in CMC solution and cooking oil. The time required for the solid particles to sediment varies with the liquid viscosity. The solid particles remain in suspension longer in liquids with greater viscosity. It is observed that the duration of sedimentation time ranges from 0.75 to 1.5 in water and kerosene and 1.5 to 3.0 hours in CMC and cooking oil.

Fluidisation is now a technique widely used for maintaining particles in suspension within a liquid phase. In this study, the combined effect of flow oscillation d effect of gas fluidisation and oscillation on solid suspension. All of these runs were conducted at the same value of frequency and amplitude. The only variable varied in these runs is the gassing rate. From the result obtained it is shown that greater solid suspension capability is achieved with a combination of gas fluidisation and flow oscillation. The fluidising effect of the gas provides an additional upward force that increased the drag force on the solid. Therefore, greater mass fraction of solid in suspension can be achieved with the combined effects of fluid oscillation and gas fluidisation.

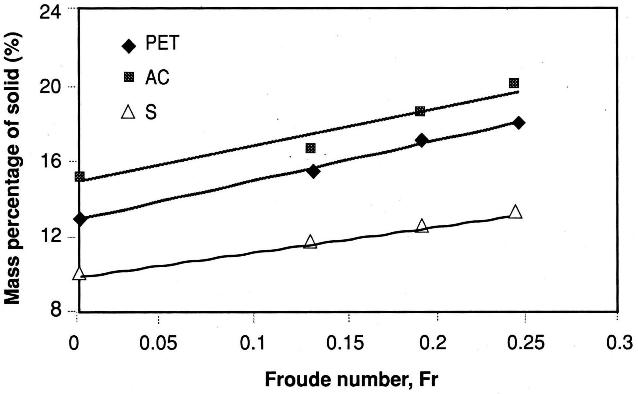


Figure 6. *The combined effect of gas fluidisation and oscillation on solid suspension*

CONCLUSION

The 2-D simulation carried out on an oscillatory liquid flow in a baffled tube showed that efficient mixing can be achieved in the space in between baffles. At a high enough oscillatory Reynolds number, the radial mixing is almost comparable to the axial mixing giving an overall efficient mixing throughout the space in between baffles.

Oscillatory flow in baffled tubes is able to suspend solid particles up to 20 per cent. The combined effect of oscillation and gas fluidisation is able of suspending greater mass fraction of solid as compared to the absence of gas fluidisation. The solid suspension (mass percentage of solid) increases with increasing oscillation frequency, gas fluidisation and liquid viscosity. However, the solid in suspension decreases with increasing specific gravity and terminal velocity of solid particles under the same operating conditions.

NOMENCLATURE

D	Diameter of tube, m
D_o	Inner diameter of baffle (orifice), m
x_o	Centre to peak amplitude of oscillation, m
ρ	Liquid density, kg/m^3
μ	Liquid viscosity, kg/m.s
Re_o	Oscillatory Reynolds number
St	Strauhal number
Fr	Froude number $(Ug/(Dg)^{1/2})$
g	Gravitational acceleration, m^2/s

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