Chapter III

Literature Reviews

Mixing has been studied since 1948, and the foremost studies of mixing were concerned with batch mixing. In that time, many parameters affecting batch mixing system were studied as follows.

Power

In the first age of mixing study quite intended to the study of Power. In 1950, Rushton, Costish and Everett [32] found that the Reynolds Number was the function of dimensionless group and the configuration of the mixing tank. The power curve for the Standard Geometrical Configuration has been experimentally determined by a number of people, Rushton, Costish and Everett [32] in 1950, Bates, Fondy and Corpstein [33] in 1963 and Chapman, Urban and Holland [34] in 1965. A power curve is a plot of ϕ or N_P vs. N_{Re} on log-log coordinates as Fig.3.1. As the Reynolds number increases, the flow changes from viscous to turbulent. For the Standard Configutration the transition is gradual, covering a range from $N_{Re} = 20$ to $N_{Re} = 2000$. The power and flow characteristics remain dependent only on the Reynolds number until $N_{Re} \approx 300$ (segment BC, Figure 3.1). At this point enough energy is being transferred to the liquid for vortexing to begin. The baffles, however, effectively suppress vortexing and the flow remains dependent upon the Reynolds number until $N_{Re} = 10,000$. When flow becomes horizontal (segment DE). Here the flow is independent of both the Froude and Reynolds numbers.

A power curve for unbaffles vessel of an otherwise Standard Configuration is given in Fig.3.2.

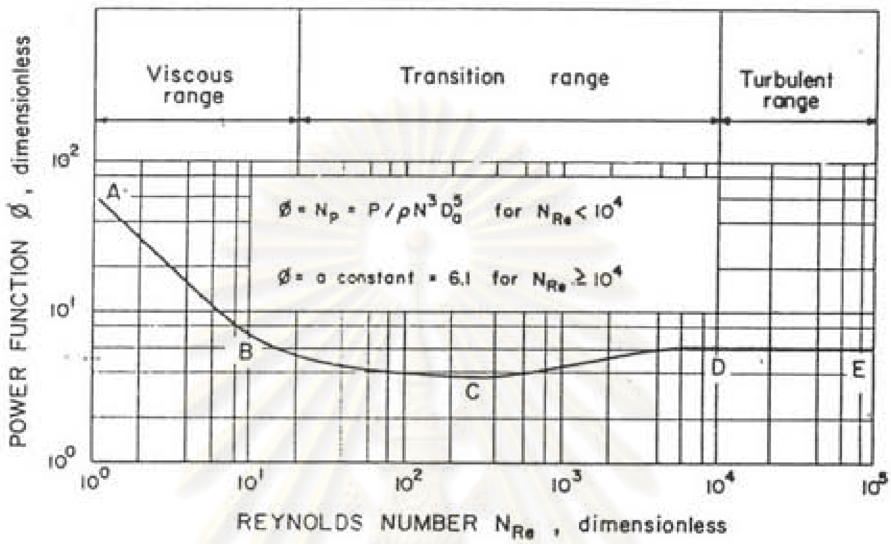

Figure 3.1 Power curve for standard tank configuration

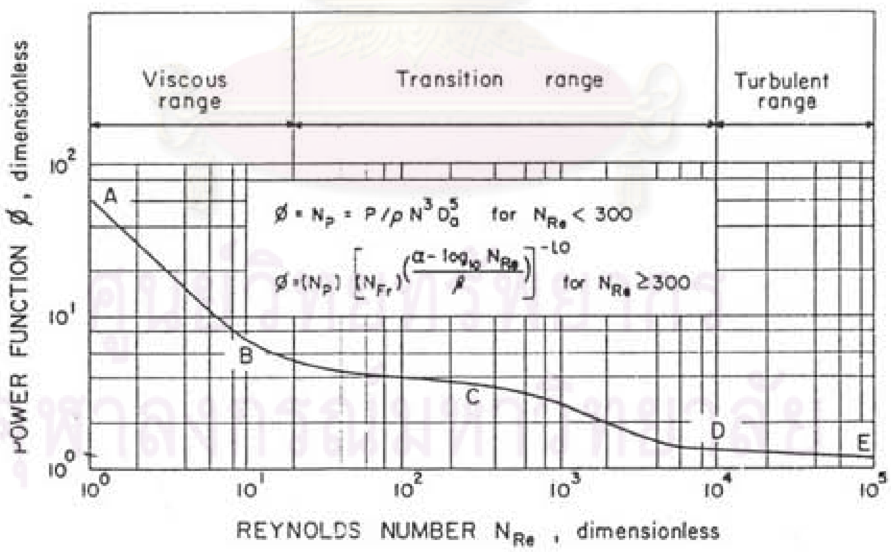

Figure 3.2 Power curve for an unbaffled vessel

From Fig.3.2, The power curves for the baffled and unbaffled systems are identical up to $N_{Re} \approx 300$ when vortexing begins. As vortexing increases, the power falls off sharply, and the power curve assumes a changing negative slope (segment

CD). In fully developed turbulent flow (N_{Re} > 10,000) the slope of the power curve has constant negative value (segment DE).

From the power curve, it was reported that when the Reynolds Number is greater than 10^4, the Power Number is constant at 6.1 so the range of Reynolds Number in mixing operation should not greater than 10^4 because of more energy loss.

Scale-up Method

In 1957, Johnstone and Thring [35] presented the principle of similarity for using in batch mixing scale up method. The principle of similarity is told that in liquid mixing, it is necessary to consider three types of similarity: geometry, kinematic and dynamic.

Two system are said to be geometrical similarity when the ratios of corresponding dimensions in one system are equal to those of the other system. Hence geometrical similarity exists between two pieces of equipment of different sizes when they both have the same shape.

Kinematic similarity exists between two systems of different sizes when not only are they geometrically similar, but the ratios of velocities between corresponding points in each system are the same.

Dynamic similarity exists between two systems when, in addition to being geometrically and kinematically similarity, the ratios of forces between corresponding points in each system are equal.

Impeller

The first mixing impellers were probably simple two-bladed radial paddles. Widely used devices remain variations of the radial pumping impeller. Radial impellers are generally applied to applications requiring the generation of shear in order to produce mass transfer to material dispersion. In recent time, axial-flow impellers have predominated in many flow-controlled processes (mild blending, solid suspension, etc.).

Because of the longevity of the radial-flow devices, a good deal more pumping data are available in the literature. In particular, the Rushton turbine (six-bladed disc turbine) has been documented in several independent studied. The results of nine studies have been analyzed in a consistent form Table 3.1. In view of the different measurement techniques used, the consistency of the results is truly remarkable. Sachs and Rushton, Tennant, Nielson, and Cutter [36, 37, 38, 39] all used streak photography techniques to measure the discharge velocity from the impeller. Cutter also used Kiel probes to cross-checked their results. A three-dimensional pitot tube was used by De Sousa and Pike, Cooper and Wolf, and Kratky *et al.* [40, 41, 42]. Cooper and Wolf cross-checked their results using a hot-wire anemometer in air. The study by Reed *et al.* [43] represents the first published data using a laser velocimeter to measure the flow in a mixing vessel. Reviewing only that work done using a six-bladed impeller, the flow number for a Rushton turbine is reported as 0.75 ± 0.04. several of the authors have measured velocity variations across the centerline of the radial plume. Fig.3.3 is a plot of radial velocity divided by the impeller tip speed as a function of radial position. The total scatter of peak velocities is within ± 15 % of the solid line drawn to represent the mean of the data.

A great deal of information has been published on pumping and power for sundry radial-flow impellers in a wide range of vessel geometries. In some cases, the tanks are baffled; in others, they are baffled. The unverified results for many of these sources are listed in Table 3.2. These results, when used with care, can provide a good basis for design information when comparing different types of impellers.

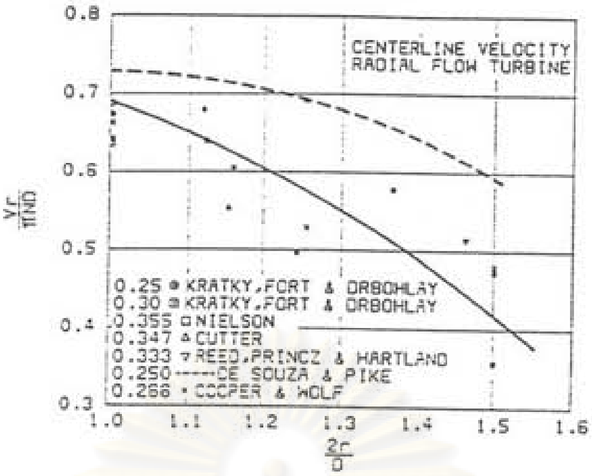

Figure 3.3 Centerline velocities for radial-flow turbines by various investigation

Experimentally determined flow numbers for axial-flow impellers (marine propellers and pitched-bladed turbines) are presented in Table 3.3. Nagata [44] reports a nondimensionalized flow number of 0.43 for a marine propeller. These measurements were taken with a pitot tube on an 11.8-in.-diameter impeller after aligning the probe with the mean flow. Data taken by Cooper and Wolf [41] using a hot-wire anemometer and three-dimensional pitot tubes yield a flow number of 0.53. Although the two results do not indicate the pitch ratio of the impellers, it is presumed that the marine propellers tested had pitch ratios around 1.0. Results which did stipulate a pitch ratio of 1.0 indicate a flow number of 0.40 (work by Rushton and Oldshue [3]). In fact, a series of experiments were conducted on different impellers of various pitch ratios by Rushton and Mack [45], as shown in Table 3-3. The pitch ratios varied from 0.84 to 1.6, producing flow numbers from 0.27 to 0.73. These results were obtained by using a double tank arrangement with an orifice, allowing the impeller to pump from one tank to another tank at a constant head. They indicate an increase in flow number with increasing pitch ratio.

Investigator	Tank diameter	Z/T	C/T	Number baffles	B/T	D	D/T	W/D	Number blades	V_r (πND)	N_Q	Fluid		
Sachs and Rushton	11.50	1.00	0.33	4	0.083	4.00	0.347	0.20	4	0.370	0.704			
Tennant	11.50	1.00	0.33	4	0.083	4.00	0.347	0.20	6	0.460	.54-.88	Water	Sp.Gr.	μ
	11.50	1.00	0.33	4	0.083	4.00	0.347	0.20	6	0.370	.54-.78	45% corn syr	1.19	15
	11.50	1.00	0.33	4	0.083	4.00	0.347	0.20	6	0.524	.54-.97	75% corn syr	1.33	265
Kratky et al.	39.40	1.00	0.30	4	0.100	13.11	0.330	-	6	0.640	0.740			
	39.40	1.00	0.30	4		9.80	0.250	0.20	6	0.670	0.770			
Nielson	11.25	-	0.33	4	0.087	2.00	0.178	0.20	6	0.590	0.570			
				4		4.00	0.355		6	0.630	0.710			
				4					6	0.680	0.700	10 CPS		
				4		7.00	0.622	0.20	6	0.660	1.030			
Cutter	11.50	1.04	0.50	4	0.104	4.00	0.347	0.20	6	0.550	0.730			
Reed et al.	7.56	1.00	0.33	4	0.104	2.56	0.333	0.20	6	0.600	0.730			
DeSouza and Pike	11.5-12.25	1.04	0.33	4	.081-.087	3.00	.245-.260	-	6	0.660	0.840			
			0.50	4		3.00	.245-.261		6	0.660	0.840			
Cooper and Wolf	15.00	1.33	-	4	0.100	4.00	0.267	0.20	6	0.650	0.750	Water		
	15.00	1.33		4	0.100	4.00	0.267	0.20	6	0.690	0.623	Air		
	15.00	1.33		4	0.100	3.00	0.200	0.20	6	0.580	0.726	Water		
	15.00	1.33		4	0.100	3.00	0.200	0.20	6	-	-			
	15.00	1.33		4	0.100	5.00	0.333	0.20	6	0.750	0.840	Water		
	15.00	1.33		4	0.100	5.00	0.333	0.20	6	0.680	0.680	Air		
	15.00	1.33		4	0.100	6.00	0.400	0.20	6	0.760	0.890	Water		
	15.00	1.33		4	0.100	6.00	0.400	0.20	6	0.670	0.770	Air		
Rushton	36.00	1.33	0.44	4	-	6.00	0.167	0.20	4	-	0.600			
									3	-	0.500			

Table 3.1 Pumping data for Rushton turbine from various investigators

Rushton turbine type	Z/T	C/T	Number baffles	B/T	D/T	W/D	Pitch angle	Number blades	N_P	N_Q
Consensus	1.0-1.33	0.3-0.5	4	0.08-0.10	0.2-0.35	0.20		6	-	0.7-0.85
Rushton	1.33	0.44	0	-	0.17	0.20		4	-	0.6-0.7
Rushton	1.33	0.44	4	-	0.17	0.20		3	-	0.50
VHL		0.33	4	0.1	0.33	0.20		4	4.00	0.47
VHL		0.33	4	0.1	0.33	0.20		6	5.00	0.68
Several Muffts		-	-	-	0.33	0.20		6	5.0-5.7	-
Missenard-Quint	1.00	0.33	3	0.1	0.33	0.20		6	6.30	0.75
Moritz	1.00	0.33	4		0.33	0.13		6	2.50	0.51
LIGHTNIN	1.00	0.33	4	0.1	0.33	0.20		6	5.18	-
Nagata	-	-	0	-	0.50	0.20		8	0.93	0.34
Nagata	-	-	0	-	0.50	0.20		16	1.08	0.33
Paddle										
Nagata	1.00	0.50	8	-	0.50	0.20		8	9.50	1.34
Nagata	1.00	0.50	0	-	0.50	0.20		8	0.95	0.34
Nagata	1.00	0.50	2	-	0.50	0.20		2	2.70	0.40
Voncken and Bruxelmane	1.00	1.2-2.0	4	0.1	0.26-0.4	0.25		4	3.30	0.90
Voncken and Uhl	1.00	0.33-0.5	4	0.1	0.33-0.36	0.13		6	2.60	0.40
Voncken	1.00	0.50	4	0.1	0.36	0.18		6	-	0.80
Uhl	1.00	0.33	4	0.1	0.33	0.20		6	4.00	-
Voncken and Uhl	1.00	0.33-0.5	4	0.1	0.33-0.36	0.25		6	5.10	1.30
Pfaudler										
	-	-	0	-	0.50	0.10	50		0.37	0.23
	-	-	2	-	0.50	0.10			0.73	0.29

Table3.2 Flow data for sundry radial-flow impellers

Rushton turbine type	Z/T	C/T	Number baffles	B/T	D/T	W/D	Pitch angle	Number blades	N_P	N_Q
Retreat paddle	1.00	5.00	8				80		2.40	0.66
			8				60		3.80	1.20
			8				0		9.50	1.34
			8				-80		6.20	0.17
			0				80		0.55	0.37
			0				60		0.71	0.43
			0				40		0.88	0.43
			0				0		0.95	0.34

Table 3.2 Flow data for sundry radial-flow impellers (Continued)

Rushton turbine type	Z/T	C/T	Number baffles	B/T	D/T	W/D	Pitch ratio	Number blades	N_P	N_Q
MARINE PROPS										
Missenard-Quint		1.00	3	0.1	0.33		1	3	0.37	0.55
Ekato		1.00	3	0.1	0.33		1	3	0.35	-
Moritz		1.00	4	0.1	0.33		1	3	0.35	0.50
LIGHTNIN		1.00	4	0.1	0.33		1	3	0.32	-
Uhl and Gray		1.00	4	0.1	0.33		-	3	-	0.50
Nagata		-	8	0.1	0.50		-	3	0.60	0.43
Cooper and Wolf			4		0.53		-	3	-	0.53
Rushton and Oldshue			-		-		1	3		0.40
Marr	0.7-1.1	0.4-0.8	3		0.2-0.6		-	3		0.61
Fort et al.	1.0				0.2-0.33		-	3		0.52
Concensus									0.33-0.37	0.40-0.55
Pitch-blade turbine										
Bruxelmane	-	1.00	4	0.1	0.33	0.200	45°	4	1.50	0.75
LIGHTNIN	-	1.00	4	0.1	0.33	0.200	45°	4	1.27	0.79
Missenard-Quint	-	1.00	2	0.1	0.33	0.280	45°	6	4.10	0.87
Ekato	-	0.17-0.34	3	0.1	0.33	0.250	45°	6	2.00	-
Fort et al.	-	1.00	4	0.1	0.33	0.200	45°	6	1.60	0.96
Uhl and Gray	-	1.00	4	0.1	0.33	0.176	45°	6	1.30	-
Nagata	1.0	-	0	-	0.50	0.100	45°	8	0.72	0.31
Nagata	1.0	-	8	0.1	0.50	0.100	45°	8	2.80	0.87
Fort et al.	1.0	-	4	0.1	0.2-0.33	0.200	24°	3	-	0.48
Shaped blades	-	0.50	3	0.1	0.67	DNA	-	3	0.43	0.64

Table 3.3 Experimentally determined flow numbers for axial-flow impellers

Rushton turbine type	Z/T	C/T	Number baffles	B/T	D/T	W/D	Pitch ratio	Number blades	N_P	N_Q
Orange MIG		3 impeller	4	0.1	0.70	-	-	2	0.60	-
		3 impeller	4	0.1	0.80	-	-		0.40	-
		3 impeller	0	-	0.90	-	-		0.20	-
Intermig		3 impeller	3	0.1	0.70	-	-		0.80	-
Missenard-Quint	MIG type	0.50	3	0.1	0.67			2	0.32	0.58
	MIG type		4	0.1	0.71			2	0.30	-
Mixer-TT			3	0.1	0.25-0.50	DNA		3	-	0.96
Mixer-TTM			3	0.1	0.25-0.51	-		3	-	0.37
Mixer-EXP			3	0.1	0.25-0.52	-		3	-	0.47

Table 3.3 Experimentally determined flow numbers for axial-flow impellers (Continued)

						Non-baffled				Baffled			
	d/D	b/D	n_p	α	θ	N_p	N_{qd}	N_p/N_{qd}	$Re \times 10^{-5}$	N_p	N_{qd}	N_p/N_{qd}	$Re \times 10^{-5}$
Paddle	0.513	0.051	8	-	90°	0.81	0.25	3.2	1	4.2	0.66	6.4	0.80
Paddle	0.513	0.103	8	-	90°	0.95	0.34	2.8	1	9.5	1.34	7.1	1.30
Paddle	0.513	0.205	8	-	90°	1.07	0.59	1.8	1	19.1	2.33	8.2	0.80
Paddle	0.308	0.103	8	-	90°	2.17	1.23	1.8	0.37	14.2	2.90	4.9	0.76
Paddle	0.718	0.103	8	-	90°	0.57	0.14	4.0	2	-	-	-	-
Paddle	0.822	0.103	8	-	90°	-	-	-	-	4.6	0.36	16.7	1.00
Retreat Paddle	0.513	0.103	8	80°	90°	0.55	0.37	1.5	1	2.4	0.66	3.6	0.80
Retreat Paddle	0.513	0.103	8	-80°	90°	-	-	-	-	6.2	0.17	36.4	0.80
Brumagin	0.513	0.103	8	70°	90°	0.44	0.34	1.3	1	1.05	0.78	1.3	1.00
Pitched paddle	0.513	0.103	8	-	45°	0.72	0.34	2.3	1	2.8	0.87	3.2	1.30
Pitched paddle	0.513	0.103	2	-	45°	-	-	-	-	2.7	0.40	6.8	1.30

Table 3.4 Discharging performance of various impellers

Another technique used to measure flow was the time of flight of a particle as it was projected through the impeller region. Results obtained by Marr [46] using this method are shown in Table 3.3. For marine propellers ranging from 2 to 5 in. (50 to 130 mm.) in diameter, a flow number of 0.61 was measured.

In the above summary, the measurements presented for marine propellers show nondimensional flow number ranging from 0.27 to 0.73. The variability observed in these measurements certainly could be attributed to testing of propellers with different pitch ratios, along with deficiencies in measurement technique. Table 3.3 also presents measurements for pitched-blade turbines. Nagata published data for an 11.8 in. Impeller operating in a cylindrical tank, both with and without baffles. These measurements were made with a pitot tube. The results indicate a flow number of 0.31 for the case without baffles and a flow number of 0.87 when eight baffles are used. Thus, the use of baffles improved the circulation rate by a factor of 3. The measured power numbers are listed for reference.

The study of impeller effecting the batch mixing system has been investigated widely. Hirsekorn and Miller [47] had examined by using the paddle with the high viscosity liquid and they found that it can work effectively. Weber [48] found that pitched blade turbine can be used more effectively in the system of high viscosity liquid. For the study of the impeller in the low viscosity liquid system, Holland [16] showed the standard configuration of batch mixing system by using flat bladed disc turbine (invented by Rushton) as impeller. This standard configuration are used with low viscosity liquid system. EEUA (Engineering Equipment Users' Association) [49] showed the agitator selection as follows.

Impeller

Propeller (< 2 kg/ms)

Turbine (<50 kg/ms)

Paddle (<1000 kg/ms) — viscosity increases ↓ — speed increases ↑

Anchor

Helical ribbon

Helical screw

Propellers, Turbines, Paddles:
- low – viscosity blending
- dispersing gases in liquids of low viscosity
- liquid / liquid contacting
- suspending solids in low – viscosity liquids

Anchors, Helical ribbons, Helical screw:
- high – viscosity blending

Kneaders:
- blending pastes, rubbers, doughs
- dispersing fine solids in viscous liquids, etc.

Baffle

Another parameter studied was baffles. Lyons [50] found that there is no need to use baffles for vortex protection in the over 600 poise viscosity liquid system and the laminar range system. Bates, Corpstein and fondy [33] found that square, rectangular, or horizontal cylindrical tanks with vertical shaft installation show a swirl damping effect intermediate between baffled and unbaffled cylindrical tank design. The amount of side-wall baffling needed to achieve maximum power has not been explored extensively, but it is common to add two baffle at 180° on the tank wall adjacent to the impeller.

This condition is encountered in continuous flow systems, such as in liquid-liquid extraction. The effects on power are unusual. Flynn and Treybal [51] found that more baffle is required in vessels completely filled with liquid than needed where an air-liquid interface exists, to insure a fully baffled condition. This work was extended by Laity and Treybal [52] who confirmed that a 16.7% baffle width was required to give the same power as a width of 10% tank diameter having a free surface. In addition, Laity and Treybal found a small but measurable effect of flow rate on power number. They obtained an increase in power number linear with the ratio of flow rate to vessel diameter. Above a retention time of 32 sec., doubling the flow rate yielded approximately 14% increase in power.

Mixing Time

In batch mixing study, mixing time (θ_M) was necessary to indicate the efficiency of the system. Due to two typical impellers i.e., circulation flow type and shearing flow type, but neither the circulation nor the shearing actions should be neglected in general. For baffled agitation, Nagata [44] derived the following correlation in the range $\mathrm{Re} \approx 10^4$.

$$\frac{1}{\theta_M} = 0.1\left\{ n\left(\frac{d}{D}\right)^3 N_{qd} + 0.21n\left(\frac{d}{D}\right)\left(\frac{N_P}{N_{qd}}\right)^{1/2} \right\}\left\{1 - e^{-13(d/D)^2}\right\} \quad (3\text{-}1)$$

N_{qd} is the discharge flow number . Therefore $q_d = N_{qd} \cdot nd^3$ is discharge flow rate and the total liquid volume to be circulated is proportional to D^3. Thus $N_{qd}\ n\ (d/D)^3$ is a sort of circulation velocity.

Values of N_{qd} and N_P/N_{qd} vary with the impeller type. Several examples are listed in Table 3.4. these values for the other types of impeller may be estimated by the following equations referring to the table.

Continuous mixing system

In continuous mixing system study, Cholette and Cloutier [53] found that in low speed agitation, or in agitation of high-viscosity liquids, a stagnant corner with a small degree of mixing or a bypass caused by channeling may appear as a result of incomplete mixing. By replacing the non-ideal flow reactor with an appropriate model, the state of mixing in the vessel may be represented. The model proposed by Cholette *et al* shows a fraction of channeling, the volume fraction of complete mixing. The fraction of flow is completely mixed in this domain and another part of it flows into the stagnant zone and then flows back in the complete mixing zone. Takamatsu and Sawada [54] generalized the Cholette model and extended the range of application from low to high viscosity regions using the flow model presented by Yamamoto *et al.* [55]. As shown in Fig.3.4, a stagnant zone A and a complete mixing flow C controls the transition region (2), and complete mixing C, a stagnant zone or a forced vortex zone D and a channeling E is combined in the turbulent region (3). They presented experimental results shown in Fig.3.5 and evaluated the quantitative fractions of volumes of the stagnant zone (V_d), the piston flow (V_p), the complete mixing flow (V_b) and the forced vortex zone (V_k) with change in Reynolds number.

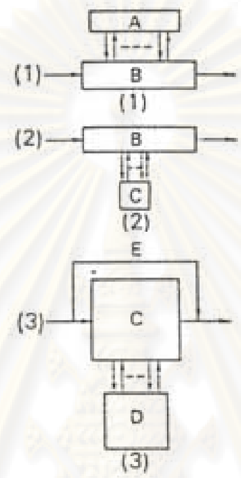

Figure 3.4 Takamatsu and Sawada's model

A: stagnant zone, B: piston flow zone, C: complete mixing flow zone,

D: cylindrically rotating zone, E: channeling flow zone

Inoue *et al.* [56] proposed another flow model in 1863. They divided the vessel volume into four regions and complete mixing was assumed in each individual cell. The discharge flow from the impeller reaches the vessel wall and is divided into an upward and downward flow. Part of the liquid flows back to the impeller passing through the forced vortex zone. These two are assumed to be well mixed by the impeller and the combined flow is discharged again. By measuring the response curve generated from an impulse injected in various positions of the vessel, one can show the mechanism of mixing in the vessel. In 1962, Van de Vusse [57] represented the flow model by assumption that the flow in a vessel is represented by stream lines 1, 2 and 3 shown in Fig.3.6. The feed is injected into stream 1 and an outlet stream is discharged from stream 2. Stream 3 is a circulation flow. The state of mixing along the three paths is replaced by that in continuous stirred tanks in series in n-th stages and the mixing mechanism is represented by their mean delay time of first order and the number of vessels in series. Sato and Taniyama [58] applied this procedure to impellers set in two stages. Otto and Stout [59] used pulse tracer input and the corresponding response curve. From these curves, they obtained a mean or first order moment, a variation or a second order moment and a skew or a third order moment, and proposed a method to represent the state of mixing in the reactor by a mixing index. In 1959, Marr [46] represented an equation for the effluent stream concentration when a pulse concentration disturbance is introduced into the feed stream. A flow within the vessel was assumed as shown in Fig.3.7. The blender in Fig.3.7 mixes the streams, q_F and $(q_I - q_F)$, instantaneously in a region of negligible volume. The distributor was assumed to have the following relationship between the concentration, C_B, entering and C_D, leaving the distributor:

$$\frac{C_D}{C_B} = \frac{1}{(\tau S+1)^2} \quad (3\text{-}2)$$

where $$\tau = V/2(q_I - q_F) \quad (3\text{-}3)$$

when τ = Residence Time

V = Volume of the mixing system

q_I = Internal circulation flow rate (function of DN^3)

q_F = Inlet flow rate

From the study of the continuous mixing system, the models describing the continuous system are diffusion model, continuous stirred tank reaction in series and a model combined with a complete mixing flow and a piston flow.

In addition, many parameters effecting the continuous mixing vessel was studied by Thamtharai [4] in 1992, and he reported that turbine is effective in continuous mixing system.

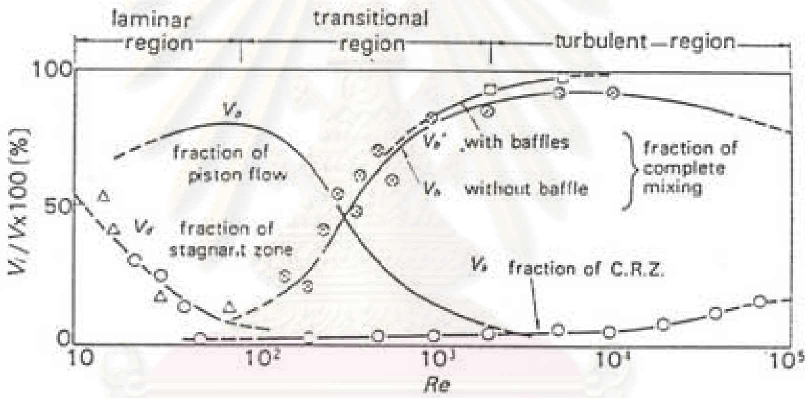

Figure 3.5 Diagram showing the distribution of zones

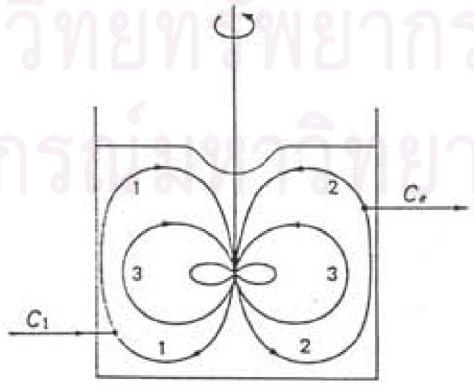

Figure 3.6 Van de Vusse's model

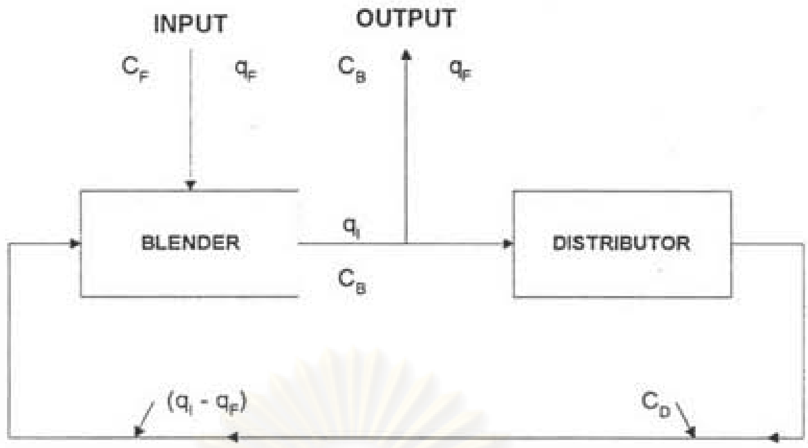

Figure 3.7 Flow diagram for continuous flow through an agitated vessel.

From literature review, parameters affecting batch mixing system have been studied widely and data collected are complete but the study of continuous mixing system are aimed to develop the model. In practice, the parameters affecting continuous system which have been studied may be used readily and this study is to determine other parameters that affect continuous mixing system to make the data more complete.