CHAPTER 5

TWO DIMENSIONAL RICKER MODEL FOR TUBULAR REACTOR

5.1 INTRODUCTION

The theory of residence time distribution generally begins with three assumptions:

- The reactor is at steady-state.
- Transport at the inlet and the outlet takes place only by advection.
- The fluid is incompressible.

The incompressibility assumption is not required, but compressible flows are more difficult to work with and less common in chemical processes.

5.2 MECHANISM OF MOTIONLESS MIXER

Motionless or static mixers are widely known and applied in process technologies for the mixing of liquids, especially for highly viscous materials, and to contact different phases to enhance heat and mass transfer. Producing dispersions in two- and multiphase systems such as emulsions, suspensions, foams, etc., is also the common aim of using motionless mixers. Far less information is known on their behavior, capabilities and applications in bulk solid treatments. Although investigations started more than thirty years ago in this field, research and development is still under way even now. Recent studies

and applications gave evidence on the beneficial features of such devices in powder technology for mixing and other treatment of bulk solids.

Motionless or static mixers are flow-modifying inserts, built into a tube, duct or vessel. These tools do not move themselves, but using the pressure difference or the kinetic and potential energy of the treated materials, create predetermined flow patterns and/or random movements, causing velocity differences and thus relative displacements of various parts of the moving material. In this way, motionless mixers can considerably improve the process to be carried out. In fluids, motionless mixers work efficiently both in turbulent and laminar regions. Splitting, shifting, shearing, rotating, accelerating, decelerating and recombining of different parts of materials are common mechanisms in this respect, both in fluids and bulk solids.

Motionless mixers eliminate the need for mechanical stirrers and therefore have a number of benefits such as no direct motive power, driving motor and electrical connections. The flow of materials (even particulate flow) through them may be induced either by gravity, pressure difference or by utilizing the existing potential or kinetic energy. The space requirement is small, allowing a compact design of equipment in bulk solid treatments. Installation is easy and quick, e.g. by simple replacement of a section of tube or by fixing inserts into a tube or vessel. Set-up and operating costs are much lower than those of mechanical mixers, while maintenance is practically superfluous. Motionless mixers are available in a number of different types, shapes and geometries, made from a great variety of materials. The mixer can therefore easily be matched to process requirements and to the features of the processed materials. Physical properties e.g. flow behavior, particle size, mechanical strength, abrasive effects, safe prescriptions e.g. for food and pharmaceutical industries, can be taken into account by the proper design of mixers. Applications in powder technology are equally feasible in gravity and

pneumatic conveying tubes, in chutes, hoppers and silos, or even in rotating, vibrated or shaken containers. The greatest advantages of motionless mixers in bulk solids treatment are their high performance, continuous operation, energy and manpower savings, minimum space requirement, low maintenance costs, trouble-free operation, easy measurement and control, and improvement of product quality. There are a number of different types of motionless mixers available from a number of manufacturers; most of them are applicable for bulk solids, too. The most widely known types are, e.g. Sulzer SMX and SMF mixers, Ross ISG and LPD mixers, Komax mixer, Kenics and FixMix mixers.

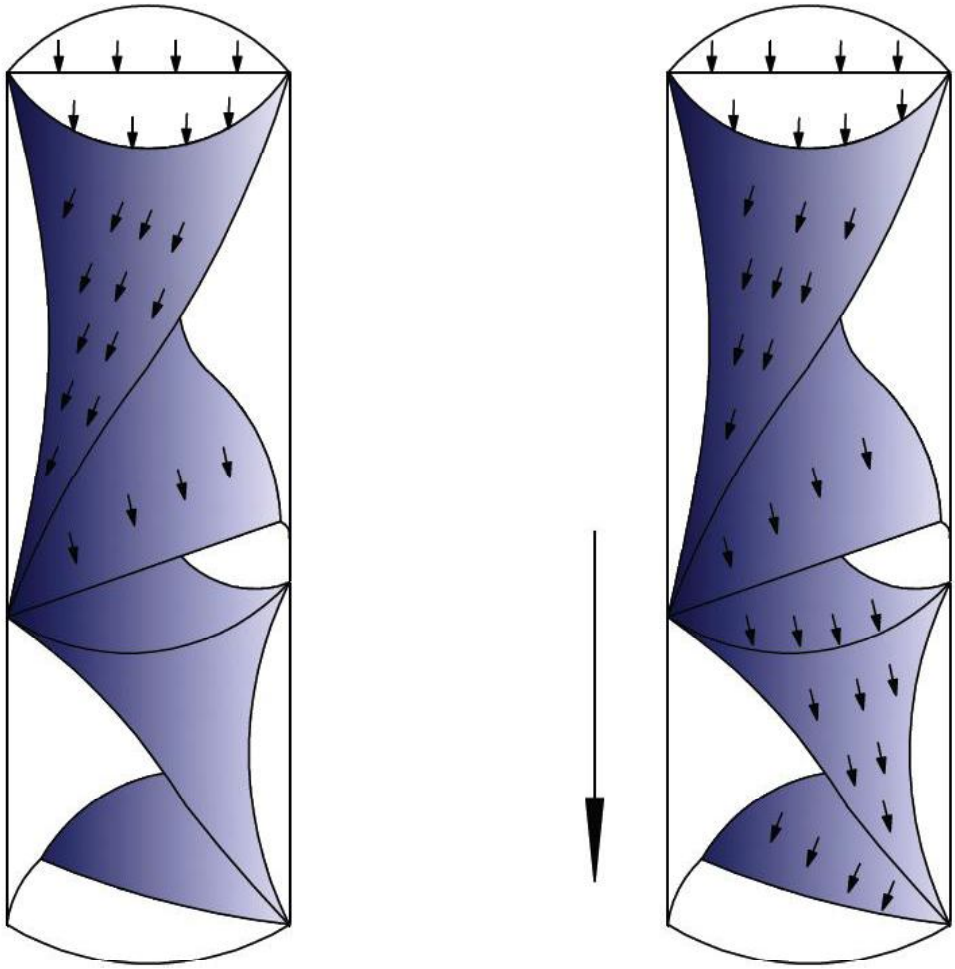

Figure 5.1 Flow of Fluid in the Tubular Reactor with Helical Element

The tubular reactor with helical element consists of a long cylindrical pipe containing a number of helical elements twisted by 180° alternately in left-hand and right-hand directions, perpendicular to flow direction. The adjacent elements are set by 90° in radial direction; therefore the outlet edge of a given element and the inlet edge of the next one are perpendicular to each other. The smooth helical surface directs the flow of material towards the pipe wall and back to the center, due to secondary vortices induced by the spiral-form twist of the flow channels. Additional velocity reversal and flow division results from shearing of the material along the tube cross-section between the adjacent elements as shown in the Figure 5.1. The systematic division of streams and their recombination in another way enhance the mixing effect proportionally to $2n$, where n is the number of the applied mixer elements. For fluids or in multiphase flows, a relatively narrow residence time is ensured, in addition to excellent radial mixing. Due to the smooth and mildly bending surfaces of the helices, the pressure drop along a Static mixer is very low, while it provides continuous and complete mixing and eliminates radial gradients in temperature, velocity and composition. For bulk solids, because of the non-uniform axial velocity profile, a certain degree of longitudinal mixing also takes place. Due to the smooth surfaces and relatively wide flow channels, the risk of plugging or blockage is very limited.

The individual elements are slanted relative to the tube axis and are tapered along their length. It results in several benefits like the slightly increasing gap between the mixer element and the tube wall eliminates the corners or contact points between them. Therefore, there are no dead zones, and deposition or blockage cannot occur. On the other hand, the cross-section

of the flow channels on the two sides of a mixer element changes continuously along its length: the cross-sectional area on one side expands while on the other side it contracts as shown in the figure 5.2. Due to the tangential flow at the wall and the pressure difference between the two sides, an intensive cross-flow takes place between the neighboring flow efficiency, lower pressure drop with suitable cross-sectional turbulence, and more uniform radial and tangential velocity fields. The higher velocity and the turbulence close to the tube wall results in higher heat transfer coefficients and a cleaner surface. In addition to this self-cleaning effect, the lack of corners makes the cleaning easier for difficult materials. This mixer provides higher mixing efficiency per unit mixer length and reduces the risk of blockage in bulk solids treatment.

5.2.1. RTD Models for Non-ideal Reactor (Static Mixer)

In the literature there exist many mathematical models for the hydrodynamics in static mixer whereby the model parameters are verified or obtained from residence time distribution data of the liquid phase in a static mixer reactor.

Since the residence time distribution does not provide a unique description of the flow patterns and mixing occurring within a reactor, an approach whereby models are used to determine mixing, i.e. macro and micro mixing (Robinson and Tester 1986), is essential. Difficulties do arise when flow models constructed as parameters are introduced into the model equations. If the model parameters do not have a specific meaning, i.e. physical meaning, the modeling becomes a step in curve fitting and the true meaning behind the flow model becomes lost. Following this, it can be stated

that different models will give different values for model parameters fitted to the same experimental data. For this reason it is important to consider what models will best represent experimental RTD data. It is at this point that certain guidelines are given when developing models for non-ideal reactors (Fogler 1999) viz.

- The model must be mathematically tractable, i.e. the equations used to describe a reactor should be solved without a great use of human or computer time.
- The model must realistically describe the characteristics of the non-ideal reactor, physically, mathematically and chemically.
- The model must not have more than two adjustable variables.

As mentioned above, the choice between models will basically depend on the objective of modeling, or on what type of criteria will be considered as a satisfactory answer to the problem. In this way, we will use the scalar difference equation viz. Ricker model as the fluid flow pattern is assumed to be a combination of parabolic path and exponential path.

5.3 RICKER MODEL

Accordingly by the above mechanism (shown in Figures 5.1 and 5.2), in tubular reactor with brazed helical mixing elements (Figure 4.1), the fluid flow pattern is assumed to be a combination of parabolic path $y_1(\theta) = \theta^2$ and exponential path $y_2(\theta) = e^{-\gamma\theta^2}$ (as shown in the Figure 5.2).

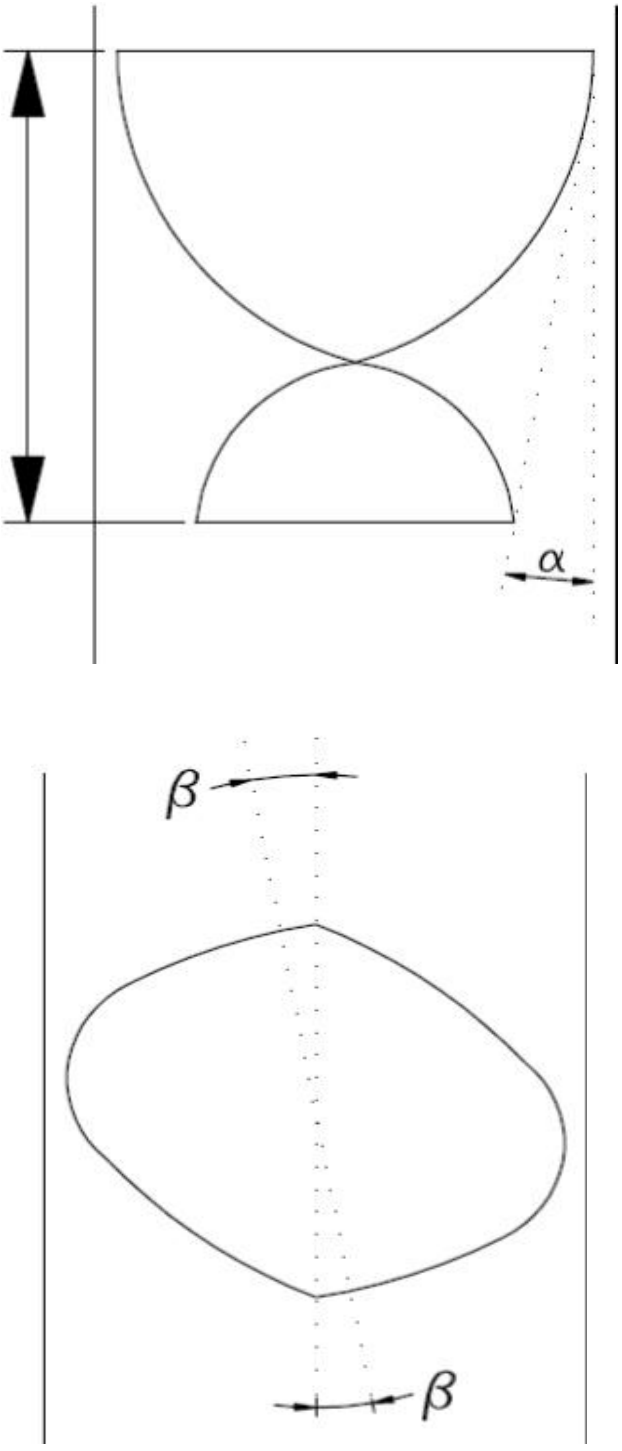

Figure 5.2 The Fluid Flow Pattern in the Tubular Reactor with Helical Element (Parabolic Path/Exponential Path)

Taking both the path into account, the exit age distribution in the tubular flow reactor is assumed to be of the form as stated in equation (5.1).

$$E(\theta) = \beta\left[\theta^2\right]\left[e^{-\gamma\theta^2}\right] \tag{5.1}$$

where β, $\gamma > 0$, are parameters of $E(\theta)$, θ is the residence time and $E(\theta)$ is the residence time distribution which is the form of Ricker equation.

The Ricker model has a long history in population ecology modelling and has been used as a discrete version of the well-known Verhulst logistic differential equation. Also, modifying the Ricker simulate the effects of immigration to, and emigration from, the population (Ruxton 1995). The Ricker equation expresses the one-step-ahead population size as a function of the current population size and includes a density-dependent effect.

The RTD was calculated numerically by this Ricker model. To check the reliability and the quality of the theoretically estimated RTD from the simulation by the application of the Ricker equation, we compare them with those obtained from observed data using statistical characteristics.

The mean of $E(\theta)$ is given by

$$\mu = \frac{\beta}{2\gamma^2} \tag{5.2}$$

Maximum value of $E(\theta)$ Vs θ is attained at $\theta = \sqrt{\frac{1}{\gamma}}$ and

the value of $E(\theta)$ at this point is $$E\left(\sqrt{\frac{1}{\gamma}}\right) = \frac{\beta}{\gamma e} \tag{5.3}$$

The variance of $E(\theta)$ Vs θ is $$\sigma^2 = \frac{\beta}{4\gamma^2}\left(\frac{3}{2\sqrt{\gamma}}\pi - \frac{\beta}{\gamma^2}\right) \tag{5.4}$$

The experimental Concentration Vs time data were used to obtain information about the mean fluid residence time, the variance of distributions, σ^2, and the RTD distribution functions at the reactor exit, inclusively in normalized form E(θ). From the experimental values of E(θ) Vs θ, the Maximum point, mean (μ) and variance (σ^2) of RTD are computed for different volumetric flow rate(40-120 l/hr). These values were utilised to determine the values of the parameters β and γ. The long-term behaviour of a RTD by equation (5.1) is dependent on volumetric flow rate. The values of β and γ in the Ricker equation with different volumetric flow rate for tubular reactor with brazed helical elements are shown in Table 5.1. Also the values of β and γ in the Ricker equation with different volumetric flow rate for tubular reactor without brazed helical elements are shown in Table 5.2. From Tables 5.1 and 5.2, the simulation of Ricker model can be carried out using the values of β and γ.

The β and γ values in the Ricker equation are determined by using the following three methods

Method I: By utilizing experimental maximum residence time and maximum residence time distribution and compare this with equation (5.3)

Method II: By utilizing experimental maximum residence time and variance of RTD and compare this with equation (5.4)

Method III: By utilizing experimental maximum residence time and mean RTD and compare this with equation (5.2)

Table 5.1 Simulation of β and γ Values in the Ricker Equation with various Volumetric Flow Rates - Turbulent Reactor with Brazed Helical element

S. No	Volumetric Flow Rate	Experimental Maximum point - (θ, E(θ))	Mean (μ)	Variance (σ^2)	γ value	β by method I	β by method II	β by method III
1.	40*l/hr*	0.578, 2.282	0.675653	0.054833	2.9933	18.5678	16.2345	17.9197
2.	60*l/hr*	0.5, 2.65	0.585346	0.056651	4	28.8138	9.6021	32
3.	80*l/hr*	0.6498, 2.598	0.760715	0.061906	2.3683	16.7252	6.396	11.2177
4.	100*l/hr*	0.778, 2.534	0.910933	0.088599	1.6521	11.3799	6.6162	5.4589
5.	120*l/hr*	0.745, 2.98	0.87204	0.081503	1.8017	14.5946	10.2637	6.4922

Table 5.2 Simulation of β and γ Values in the Ricker Equation with various Volumetric Flow Rates - Turbulent Reactor without Brazed Helical element

S. No	Volumetric Flow Rate	Experimental Maximum point - (θ, E(θ))	Mean (μ)	Variance (σ^2)	γ value	β by method I	β by method II	β by method III
1.	40*l/hr*	0.797, 1.695	0.96316	0.103814	1.5942	7.3453	32.7007	5.0829
2.	60*l/hr*	0.773, 1.77	0.820807	0.09135	1.6736	8.0523	8.1775	5.6019
3.	80*l/hr*	0.631, 1.872	0.72482	0.05718	2.5115	12.7801	13.8213	12.6153
4.	100*l/hr*	0.4526, 2.055	0.629851	0.030034	4.8817	27.2695	21.993075	47.66199
5.	120*l/hr*	0.925, 1.72	0.582956	0.025338	1.1687	5.4642	5.0542	2.7317

Tables 5.3 to 5.5 shows the determination of E(θ) for various values of experimental θs. It involves the solution of Ricker equation (5.1) for different volumetric flow rates (40-120 l/hr) by utilizing γ and β values obtained by Method I, Method II and Method III respectively.

Tables 5.6 to 5.8 gives the results for annulus without mixing elements.

Table 5.3 Simulated RTD Studies in Annulus with Mixing Elements - by Method I

E(θ) for various values of experimental θs(γ & β obtained by method I)										
Sl.No.	Volumetric flow rate = 40 l/hr		Volumetric flow rate = 60 l/hr		Volumetric flow rate = 80 l/hr		Volumetric flow rate = 100 l/hr		Volumetric flow rate = 120 l/hr	
	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)
1	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
2	0.385287	1.767474	0.5	2.650001	0.649789	2.598006	0.778481	2.534004	0.744526	2.97999
3	0.57793	2.282	1	0.527743	1.299578	0.517455	1.556962	0.502789	1.489051	0.595752
4	0.770574	1.86417	1.5	0.008001	1.949367	0.007846	2.335443	0.007576	2.233577	0.00909
5	0.963217	1.071791	2	$1.3e^{-05}$	2.599156	$1.27e^{-05}$	3.113924	$1.22e^{-05}$	2.978102	$1.49e^{-05}$
6	1.15586	0.454767	2.5	$2.5e^{-09}$	3.898734	$5.91e^{-14}$	3.892405	$2.32e^{-09}$	3.722628	$2.9e^{-09}$
7	1.541147	0.036044	3.5	$1.85e^{-19}$	4.548523	$1.82e^{-19}$	4.670886	$5.51e^{-14}$	4.467153	$7.08e^{-14}$
8	1.926434	0.001032	4.5	$3.87e^{-33}$	5.198312	$7.27e^{-26}$	5.449367	$1.67e^{-19}$		
9	2.119077	0.000121	5.5	$2.46e^{-50}$	5.848101	$3.81e^{-33}$				
10	2.311721	$1.12e^{-05}$	6.5	$4.89e^{-71}$						
11	2.504364	$8.18e^{-07}$								
12	2.697008	$4.73e^{-08}$								
13	2.889651	$2.17e^{-09}$								
14	3.274938	$2.27e^{-12}$								
15	3.660225	$9.54e^{-16}$								

Table 5.4 Simulated RTD Studies in Annulus with Mixing Elements - by Method II

E(θ) for various values of experimental θs(γ & β obtained by method II)										
Sl. No.	Volumetric flow rate = 40 l/hr		Volumetric flow rate = 60 l/hr		Volumetric flow rate = 80 l/hr		Volumetric flow rate = 100 l/hr		Volumetric flow rate = 120 l/hr	
	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)
1	0	0	0	0	0	0	0	0	0	0
2	0.385287	1.545366	0.5	0.883104	0.649789	0.993521	0.778481	1.473254	0.744526	2.095688
3	0.57793	1.995236	1	0.175869	1.299578	0.197883	1.556962	0.292318	1.489051	0.418964
4	0.770574	1.629912	1.5	0.002666	1.949367	0.003001	2.335443	0.004405	2.233577	0.006393
5	0.963217	0.937106	2	$4.32e^{-06}$	2.599156	$4.87e^{-06}$	3.113924	$7.08e^{-06}$	2.978102	$1.05e^{-05}$
6	1.15586	0.397619	2.5	$8.33e^{-10}$	3.898734	$2.26e^{-14}$	3.892405	$1.35e^{-09}$	3.722628	$2.04e^{-09}$
7	1.541147	0.031515	3.5	$6.17e^{-20}$	4.548523	$6.95e^{-20}$	4.670886	$3.2e^{-14}$	4.467153	$4.98e^{-14}$
8	1.926434	0.000903	4.5	$1.29e^{-33}$	5.198312	$2.78e^{-26}$	5.449367	$9.7e^{-20}$		
9	2.119077	0.000106	5.5	$8.19e^{-51}$	5.848101	$1.46e^{-33}$				
10	2.311721	$9.8e^{-06}$	6.5	$1.63e^{-71}$						
11	2.504364	$7.15e^{-07}$								
12	2.697008	$4.13e^{-08}$								
13	2.889651	$1.89e^{-09}$								
14	3.274938	$1.99e^{-12}$								
15	3.660225	$8.34e^{-16}$								

Table 5.5 Simulated RTD Studies in Annulus with Mixing Elements - by Method III

E(θ) for various values of experimental θs(γ & β obtained by method III)										
Sl. No.	Volumetric flow rate = 40 l/hr		Volumetric flow rate = 60 l/hr		Volumetric flow rate = 80 l/hr		Volumetric flow rate = 100 l/hr		Volumetric flow rate = 120 l/hr	
	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)
1	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
2	0.385287	1.705781	0.5	2.943036	0.649789	1.742499	0.778481	1.215553	0.744526	1.325606
3	0.57793	2.202348	1	0.5861	1.299578	0.34706	1.556962	0.241186	1.489051	0.265012
4	0.770574	1.799102	1.5	0.008886	1.949367	0.005263	2.335443	0.003634	2.233577	0.004044
5	0.963217	1.034381	2	$1.44e^{-05}$	2.599156	$8.53e^{-06}$	3.113924	$5.84e^{-06}$	2.978102	$6.61e^{-06}$
6	1.15586	0.438894	2.5	$2.78e^{-09}$	3.898734	$3.96e^{-14}$	3.892405	$1.11e^{-09}$	3.722628	$1.29e^{-09}$
7	1.541147	0.034786	3.5	$2.06e^{-19}$	4.548523	$1.22e^{-19}$	4.670886	$2.64e^{-14}$	4.467153	$3.15e^{-14}$
8	1.926434	0.000996	4.5	$4.3e^{-33}$	5.198312	$4.87e^{-26}$	5.449367	$8e^{-20}$		
9	2.119077	0.000117	5.5	$2.73e^{-50}$	5.848101	$2.56e^{-33}$				
10	2.311721	$1.08e^{-05}$	6.5	$5.44e^{-71}$						
11	2.504364	$7.9e^{-07}$								
12	2.697008	$4.56e^{-08}$								
13	2.889651	$2.09e^{-09}$								
14	3.274938	$2.19e^{-12}$								
15	3.660225	$9.21e^{-16}$								

Table 5.6 Simulated RTD Studies in Annulus without Mixing Elements - by Method I

E(θ) for various values of experimental θs(γ & β obtained by method I)										
Sl. No.	**Volumetric flow rate = 40 l/hr**		**Volumetric flow rate = 60 l/hr**		**Volumetric flow rate = 80 l/hr**		**Volumetric flow rate = 100 l/hr**		**Volumetric flow rate = 120 l/hr**	
	Residence time(θ)	**Residence time distribution E(θ)**	**Residence time(θ)**	**Residence time distribution E(θ)**	**Residence time(θ)**	**Residence time distribution E(θ)**	**Residence time(θ)**	**Residence time distribution E(θ)**	**Residence time(θ)**	**Residence time distribution E(θ)**
1	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
2	0.19797	0.27044	0.515284	1.370962	0.631206	1.872003	0.452586	2.054999	0.925234	1.720002
3	0.593909	1.476513	0.772926	1.770002	0.946809	1.205805	0.905172	0.409324	1.850467	0.342049
4	0.791878	1.69501	1.030568	1.44585	1.262411	0.372098	1.357759	0.006207	2.775701	0.005173
5	0.989848	1.509317	1.28821	0.831231	1.578014	0.061192	1.810345	$1.01e^{-05}$	4.626168	$1.6e^{-09}$
6	1.385787	0.660398	1.545852	0.35267	1.893617	0.005623	2.262931	$1.94e^{-09}$	6.476636	$1.17e^{-19}$
7	1.781726	0.147838	1.803493	0.113254	2.20922	0.000296	3.168103	$1.44e^{-19}$	8.327103	$2.42e^{-33}$
8	2.177665	0.018143	2.061135	0.027947	2.524823	$9.08e^{-06}$	4.073276	$3.02e^{-33}$	10.17757	$1.51e^{-50}$
9	2.573604	0.001263	2.576419	0.0008	3.156028	$1.74e^{-09}$	4.978448	$1.92e^{-50}$		
10	2.969543	$5.08e^{-05}$	3.091703	$8.68e^{-06}$	3.787234	$4.16e^{-14}$	5.883621	$3.83e^{-71}$		
11	3.365482	$1.2e^{-06}$	3.606987	$3.66e^{-08}$	4.41844	$1.27e^{-19}$				
12	3.761421	$1.66e^{-08}$	4.122271	$6.1e^{-11}$						
13			4.637555	$4.04e^{-14}$						

Table 5.7 Simulated RTD Studies in Annulus without Mixing Elements - by Method II

E(θ) for various values of experimental θs(γ & β obtained by method II)										
Sl.No.	**Volumetric flow rate = 40 l/hr**		**Volumetric flow rate = 60 l/hr**		**Volumetric flow rate = 80 l/hr**		**Volumetric flow rate = 100 l/hr**		**Volumetric flow rate = 120 l/hr**	
	Residence time(θ)	**Residence time distribution E(θ)**	**Residence time(θ)**	**Residence time distribution E(θ)**	**Residence time(θ)**	**Residence time distribution E(θ)**	**Residence time(θ)**	**Residence time distribution E(θ)**	**Residence time(θ)**	**Residence time distribution E(θ)**
1	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
2	0.19797	1.203965	0.515284	1.392279	0.631206	2.024516	0.452586	1.657373	0.925234	1.590944
3	0.593909	6.573238	0.772926	1.797523	0.946809	1.304042	0.905172	0.330123	1.850467	0.316383
4	0.791878	7.545959	1.030568	1.468331	1.262411	0.402413	1.357759	0.005006	2.775701	0.004785
5	0.989848	6.719281	1.28821	0.844155	1.578014	0.066178	1.810345	$8.12e^{-06}$	4.626168	$1.48e^{-09}$
6	1.385787	2.940003	1.545852	0.358154	1.893617	0.006081	2.262931	$1.57e^{-09}$	6.476636	$1.09e^{-19}$
7	1.781726	0.658156	1.803493	0.115015	2.20922	0.00032	3.168103	$1.16e^{-19}$	8.327103	$2.24e^{-33}$
8	2.177665	0.080769	2.061135	0.028381	2.524823	$9.82e^{-06}$	4.073276	$2.43e^{-33}$	10.17757	$1.39e^{-50}$
9	2.573604	0.005622	2.576419	0.000813	3.156028	$1.88e^{-09}$	4.978448	$1.55e^{-50}$		
10	2.969543	0.000226	3.091703	$8.82e^{-06}$	3.787234	$4.49e^{-14}$	5.883621	$3.09e^{-71}$		
11	3.365482	$5.33e^{-06}$	3.606987	$3.72e^{-08}$	4.41844	$1.37e^{-19}$				
12	3.761421	$7.41e^{-08}$	4.122271	$6.19e^{-11}$						
13			4.637555	$4.1e^{-14}$						

Table 5.8 Simulated RTD Studies in Annulus without Mixing Elements - by Method III

E(θ) for various values of experimental θs(γ & β obtained by method III)										
Sl.No.	Volumetric flow rate = 40 l/hr		Volumetric flow rate = 60 l/hr		Volumetric flow rate = 80 l/hr		Volumetric flow rate = 100 l/hr		Volumetric flow rate = 120 l/hr	
	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)	Residence time(θ)	Residence time distribution E(θ)
1	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
2	0.19797	0.187143	0.515284	0.953764	0.631206	1.847863	0.452586	2.054999	0.452586	3.591754
3	0.593909	1.021737	0.772926	1.231372	0.946809	1.190256	0.905172	0.409324	0.905172	0.715422
4	0.791878	1.172936	1.030568	1.005863	1.262411	0.3673	1.357759	0.006207	1.357759	0.010849
5	0.989848	1.044438	1.28821	0.578278	1.578014	0.060403	1.810345	$1.01e^{-05}$	1.810345	$1.76e^{-05}$
6	1.385787	0.456991	1.545852	0.245349	1.893617	0.005551	2.262931	$1.94e^{-09}$	2.262931	$3.39e^{-09}$
7	1.781726	0.102303	1.803493	0.07879	2.20922	0.000292	3.168103	$1.44e^{-19}$	3.168103	$2.52e^{-19}$
8	2.177665	0.012555	2.061135	0.019442	2.524823	$8.96e^{-06}$	4.073276	$3.02e^{-33}$	4.073276	$5.28e^{-33}$
9	2.573604	0.000874	2.576419	0.000557	3.156028	$1.72e^{-09}$	4.978448	$1.92e^{-50}$		
10	2.969543	$3.52e^{-05}$	3.091703	6.04e-06	3.787234	$4.1e^{-14}$	5.883621	$3.83e^{-71}$		
11	3.365482	$8.29e^{-07}$	3.606987	$2.55e^{-08}$	4.41844	$1.25e^{-19}$				
12	3.761421	$1.15e^{-08}$	4.122271	$4.24e^{-11}$						
13			4.637555	$2.81e^{-14}$						

5.4 CONCLUSION

The model formulated and developed in this chapter is based on fluid flow pattern in the tubular reactor with helical element and takes into account mass transfer resistances across static mixer. The model also presents residence time distribution for all the major reactions.

The Ricker model equations can be integrated to determine exit time distribution and to estimate kinetic parameters from static reactor experiments.