UNIVERSITI TEKNOLOGI PETRONAS

Mechanical Engineering Department

December 31

FYP Dissertation

2011

The report is a description of the topic of the final year project as well as the plan and the steps that have been taken in order to carry out the project named: "Study of Multi Staging Operation of a Swirling Fluidized Bed".

Study of Multi Staging Operation of Swirling Fluidized Bed

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CERTIFICATION OF APPROVAL

Study of Multi Staging Operation of Swirling Fluidized Bed

By

Mostafa Saleh Zakzouk

A project dissertation submitted to the

Mechanical Engineering Programme

Universiti Teknologi PETRONAS

In partial fulfillment of the requirement for the

BACHELOR OF ENGINEERING (Hons)

(MECHANICAL ENGINEERING)

Approved by,

____

(Prof. Dr. Vijay R Raghavan)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

December 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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Mostafa Saleh Zakzouk

ABSTRACT

The report is a description of the topic and the idea of the final year project as well as the plan and the steps that have been taken in order to carry out the project named: “Study of Multi Staging Operation of a Swirling Fluidized Bed”.

Detailed design of a multi stage swirling fluidized bed that can be used for laboratory experimental purposes in UTP was provided with all the components, assemblies and functions descriptions. The design was evaluated for its efficiency and ability to meet flow requirements.

Residence time distribution was investigated for several stages of swirling fluidized bed using a mathematical model that provides an $F(t)$ function that depends on the number of stages, system phase shift, coefficient of exponent and the average residence time.

The report contains a basic background about the swirling fluidized bed, the fluidization process, the definition of the main problem which centers on the residence time distribution for several stages of SFB, the objectives of the project, the methodology and the tasks to be taken in order to effectively achieve those objectives, a Gantt chart of the project life cycle as well as the results and the outcomes of the analysis.

ACKNOWLEDGEMENTS

In the opportunity of writing this report, I would like to express my gratitude to all those who have helped me successfully complete my final year project, starting and ending with my Lord, Allah, WHO has been guiding and supporting me throughout my entire life in general and during taking this project in specific.

Moreover, I would like to express my gratitude to my honorable supervisor Professor Dr. Vijay R. Raghavan who has been very supportive and encouraging. Without his wide knowledge and sincere support this project would have never come to success.

In the meantime, I would like to thank my family, which supported me during my study period in UTP and never burdened me with any loads although I've been far away from their side for more than five year. I would like also to thank my friends and colleagues in my university (UTP) specially my Egyptian country-mates who have been very supportive and encouraging.

Last but not least, gratitude is delivered to Universiti Teknologi PETRONAS for being a great host for my undergraduate studies in Mechanical engineering.

At the end, all praise and thankfulness should return to Allah, Lord of the worlds.

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ABBREVIATIONS AND NOMENCLATURE

SFB : Swirling Fluidized Bed

RTD : Residence Time Distribution

U_{mf} : Minimum Fluidization Velocity

CHAPTER 1: INTRODUCTION

1.1 Background of Study

The fluidization phenomenon is the process in which solid particles are converted into fluid-like form by the effect of suspension using an injected gas or liquid. This process of interaction between solid and fluid shows very interesting characteristics, the study of fluidization aims to utilize those characteristics into useful practical applications [1].

The fluidization process has various applications in many industrial fields and processes which require direct contact and interaction between solids and fluids (either liquids or gases). Fluidized beds are used for industrial purposes, such as chemical reactors, catalytic cracking for heavy oil products and others and heat or mass transfer process, fluidized bed combustion or interface modification, such as applying a coating onto solid items. Lately, swirling fluidized beds has been used in order to enhance the fluidization process [2].

There are several types of fluidized beds; the following are some of them:

1. Stationary or bubbling beds, in such type of beds the particles are kept relatively static while some other particles are entrained.
2. Circulating beds, in this type of beds the fluidization carries the particles in the bed because of the higher kinetic energy of the injected fluid. This results in a rougher surface of the bed so larger particles can be entrained from the bed than for stationary beds. Those particles can be separated from each other by a cyclone separator based on their size.
3. Vibratory Fluidized beds: This type of beds uses mechanical excitation to vibrate the bed and cause higher particles entrainment [3].

So how fluidized beds are created?! Fluidized beds are simply formed by placing a quantity of solid particles under designed conditions in order to force them to act like a fluid does. This can be achieved by injecting a fluid (usually gas) with a proper pressure, direction and flow rate through the particles. This forces the particles to have some properties of normal fluids; such as the ability to free-flow under gravity [4].

The basic mechanism of a fluidized bed can be described as the flow of the injected gas right through the solid particles via a distributor; as a result, the drag forces introduced by the injected gas balance the weight of the solid particles which experience a free flow regime as exhibited by fluids. There exist a large number of industrial applications that use the fluidization technique in their operations, for example: drying of crops, fuel combustion, gasification of solid fuels, heating of substances, oxidation reactions and catalytic cracking of heavy oil products and others [5].

Fluidization is usually used in processes where high levels of contact and interaction between gases and solids are required. Fluidization process has many advantages over other mixing processes as it promotes the following features [4]:

1. Very high extent of intermixing between particles.
2. Large surface area contact between solid particles and injected fluid.
3. High relative velocities between the fluid and the solid phase.
4. Numerous collisions between particles and bed walls.

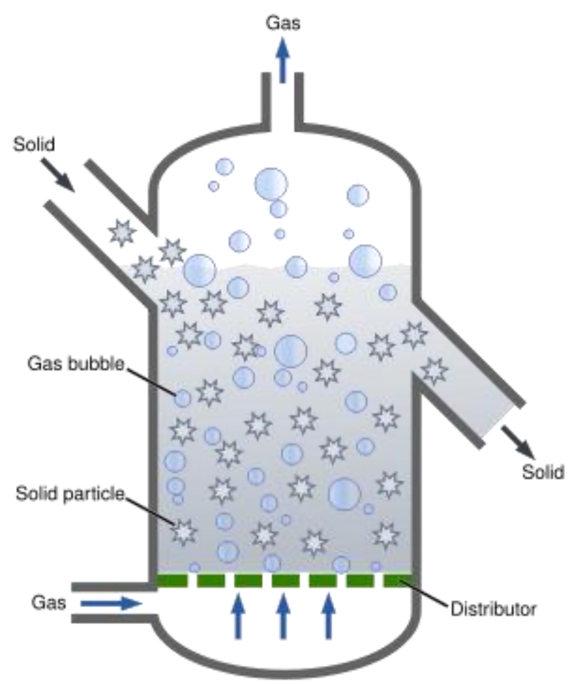

Figure : Fluidized Bed

1.2 Rationale

One may ask what is the purpose of multi-staging in Fluidized Beds; increasing the number of stages in a swirling fluidized bed introduces several advantages; First, the horizontal motion component of the injected gas can be maintained by adding more distributers, hence a better mixing between the gas and the particles can be achieved especially with greater bed height and bigger particle quantities. Second, a "plug flow" can be achieved at higher number of stages.

"Plug Flow" is that type of flow where all the particles enter and leave the system without back mixing. Hence, all the particles will have exactly the same residence time. In practical applications "plug flow" is highly favored because it allows all the particles in the system to react to the same exact desired extent so that no particles will be sub-normally or abnormally treated.

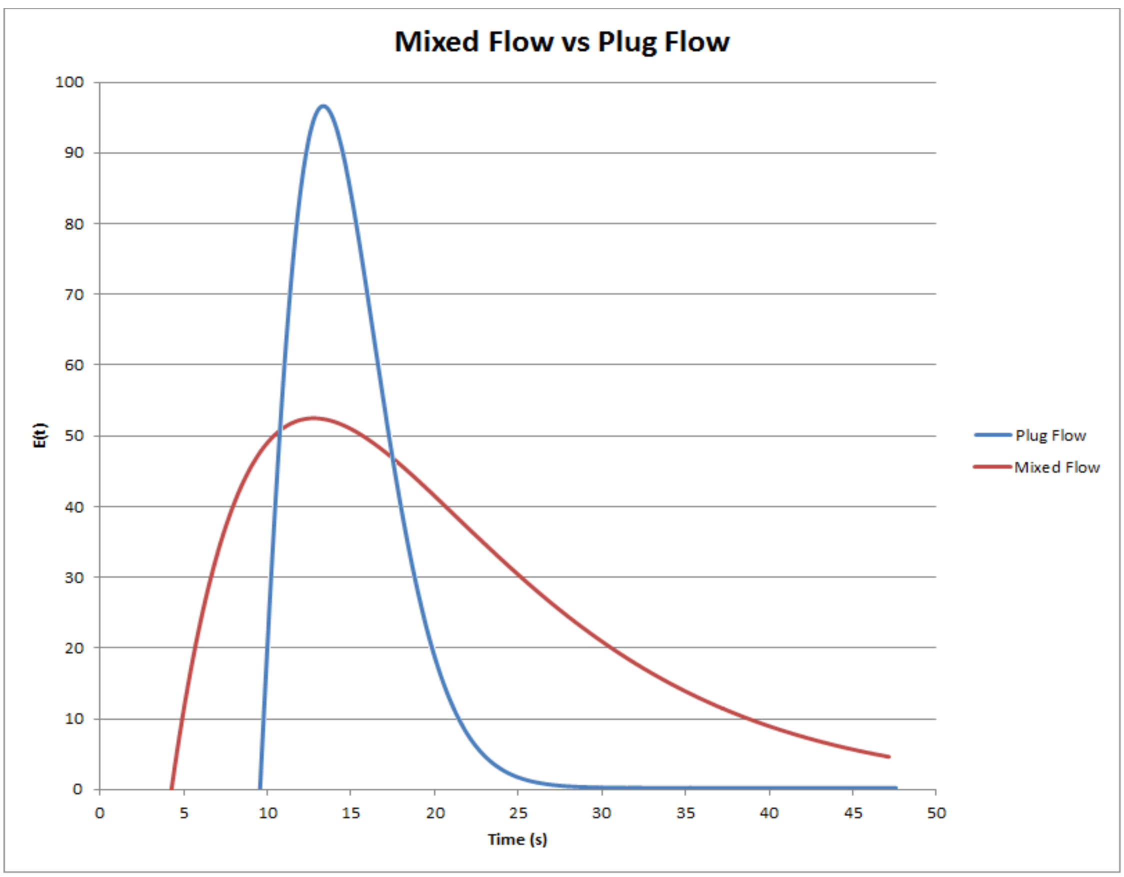

Figure : Mixed Flow vs Plug Flow

1.3 Problem Statement

- In normal single stage fluidized beds the stirring effect of the injected gas on the fluidized particles decreases as the vertical distance between the particles and the distributor increases.
- As a result, normal single stage fluidized beds can only be effective with shallow beds (low levels of bed height).
- Batch-wise operation of the system is time consuming and not cost effective, except for small operations.

1.4 Objectives

1. Design and fabrication of a multi-stage swirling fluidized bed for laboratory experimental use in UTP.
2. Determination of the factors that affect the residence time of the particles and verification whether it is invariant for different stages.
3. Analysis of the outcomes of the experiment and prediction the characteristics of similar devices.

1.5 Scope of Study

- The project is mainly about the design, fabrication and study of multi stage swirling fluidized bed. The design must fulfill all the flow requirements needed for SFB systems.
- The analysis is conducted in order to study the residence time distribution of the particles, how it changes when adding more stages to the SFB and how the desideratum of plug flow can be achieved.
- Residence time strongly affects the heat and mass transfer from the gas to particles. In case of combustion, drying, chemical reaction etc., residence time will affect the extent of burning, drying or reaction rates.

1.6 Multi-stage Swirling Fluidized Bed

- A multi Stage swirling fluidized bed is composed of consecutive columns of beds arranged vertically one after the other.
- The particles feed inlet is placed at the topmost stage and the discharge outlet is placed at the bottom-most stage.
- Particles are required to flow from top to bottom passing from each stage to the next one through a connecting gate (downcomer).
- The following sketch shows the main components of a multi stage SFB.

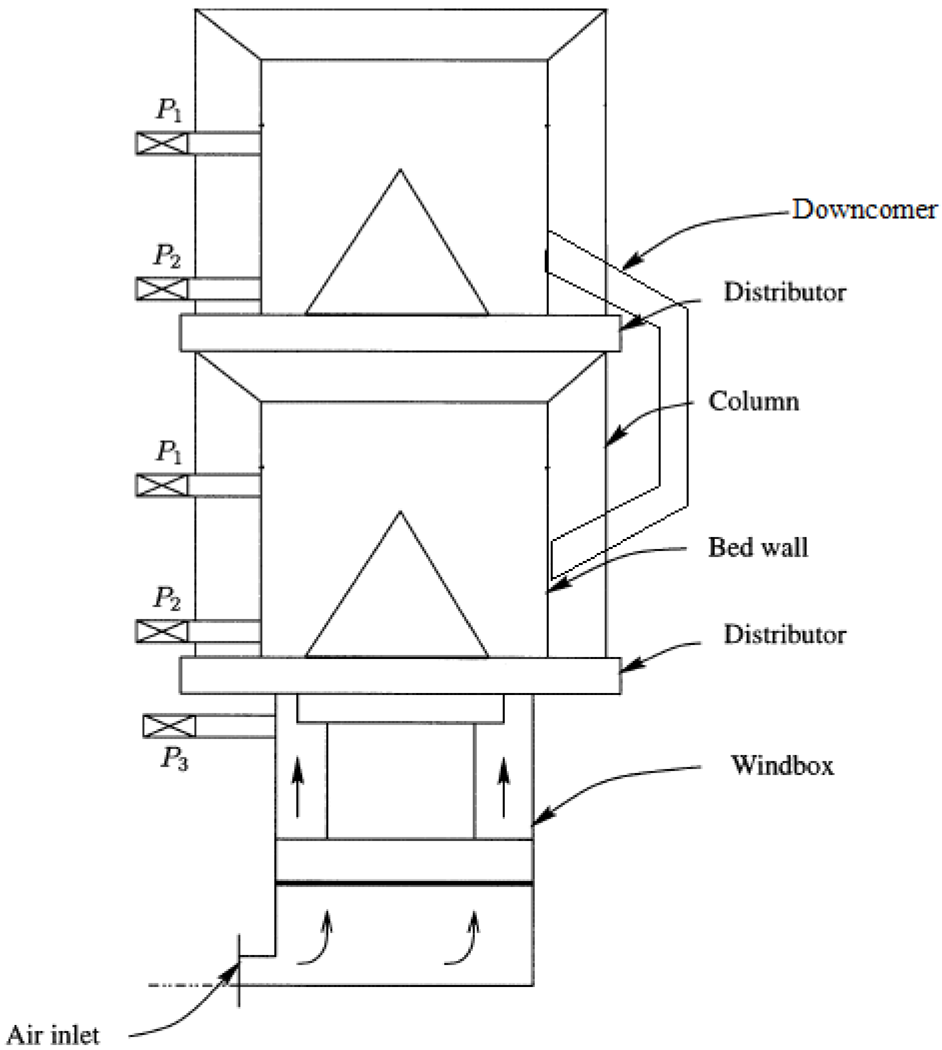

Figure : Multi Stage SFB

CHAPTER 2: LITERATURE REVIEW AND THEORY

2.1 Previous Research

Many research papers have been published in the field of fluidization processes and fluidized beds. Many of these papers were primarily concerned with the bed design, device fabrication and operation of the fluidized beds. In 1922 von Winkler made a design of a reactor that for the first time employed a coal gasification process. Additional practical applications of the fluidized beds included the catalytic cracking of heavy oil products coming from petroleum production in the 1940s. During that period, theoretical and experimental studies have been made to improve the design of the fluidized bed. In the 1960s VAW-Lippewerk in Lönen introduced the first industrialized fluidized bed for the burning of coal and then for the calcination of aluminum hydroxide [3].

Research papers in the past have been investigating with centrifugal fluidized beds, in which the weight of the particles is balanced by the lifting force of gas injected radially inward into the bed [5]. Devices using the swirling fluidized bed principle proved to be economically available and highly effective for some industrial processes like drying, granulation and exfoliation [6].

The swirling fluidized bed has showed higher efficiency than the other types of the fluidized beds such as circulating beds, where the kinetic movement of the particles is caused by the mechanical circulation of the bed itself powered by a mechanical gear system to create the movement. It has also showed higher efficiency over the vibratory fluidized bed where the motion of the fluidized particles is created by a complex mechanical vibration system [6].

In conventional fluidized bed reactors, sufficiently low gas velocities must be maintained in order to hold the particles in the bed for the required period of time to make sure the particles are completely treated and reacted. That’s why the swirling fluidized beds have higher efficiency as they improve the mass transfer form gas to particles as a result of the swirling motion [1].

The calculation and the precise analysis of residence time distribution (RTD) has turned out to be an essential tool in the study, analysis and design of continuous flow systems, for investigating the performance of a continuous fluidized bed and to get a deep understanding of the fluidization process. The concept of residence time concerns with the particles entrance, flow inside and leaving from the system. It's naturally expected that the fluidized particles will not have identical residence times inside the system [14].

Danckwerts was the first researcher to propose the idea of using the residence time distribution in the analysis of chemical reactors in an innovative paper by in 1953 in which he utilized the internal and external age distributions to describe the residence time distributions in a given system [14].

RTD can be calculated directly by a commonly used method of investigation, the tracers' response experiment, in which some tracers of distinct color are injected within the flow stream and then the residence time of the particles in this batch is measured at the outlet. There are several techniques for tracer injection that can be implemented such as pulse injection, step injection, periodic concentration fluctuation injection and random concentration change. The pulse and step injection techniques of tracers are easier to implement. Hence, they have been very widely and commonly applied in most of the studies and experiments [14].

As for pulse injection technique, the residence time distribution density function developed by Danckwerts represented by $E(t)dt$ is defined as the portion of the particles that spend a given period of time, $\boldsymbol{t}$ inside the fluidized bed.

$$\int_0^\infty E(t)dt = 1 \tag{1}$$

Another very useful function in the field of residence time distribution is F curve. The F curve is the integral of exit age distribution density function $E(t)$

$$F(t) = \int_0^t E(t)dt \tag{2}$$

2.2 Theory of Operation

When a bed filled with particles is exposed to a stream of injected fluid (gas or liquid), the particles are suspended by the effect of the balance between their weight and the drag force applied by the fluid on them which overcomes the gravitational force of the earth and the particles come to be freely hanging as known as fluidized “as shown in figure4” [7].

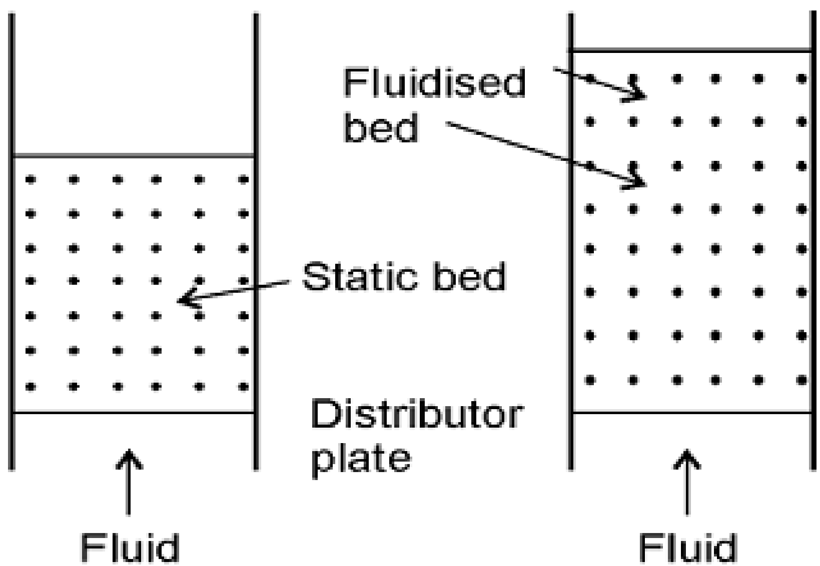

Figure : Fluidization process of packed particles

The injected gas enters the bed in an inclined direction via the distributor. Consequently the angular momentum of the gas is transferred to the particles, which causes the swirling effect. The collision among the particles and between the particles and the bed wall resists this swirling effect [2].

The distributor allows the gas jet to enter the bed at an angle θ as shown in figure 5 by the effect of the angled blades, Fluidization is caused by the vertical component of the jet while swirling is caused by its horizontal component. Acting together, they make a swirling fluidized bed [1].

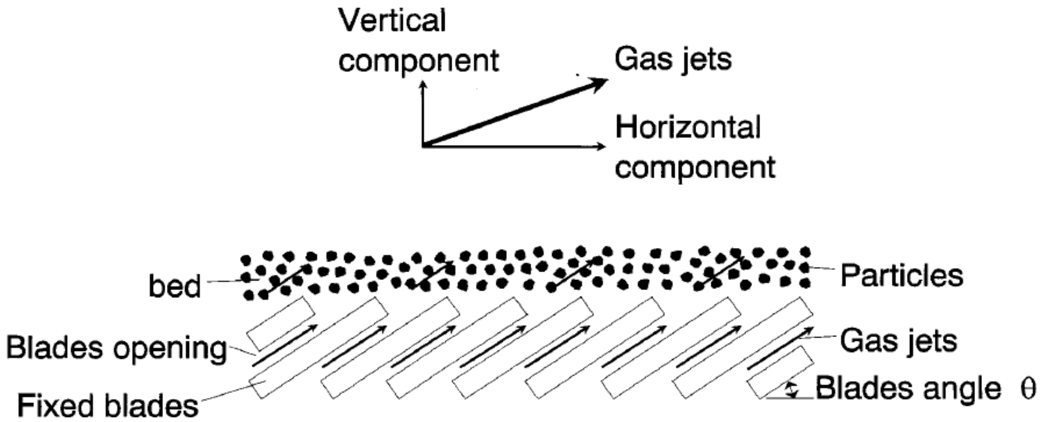

Figure : The path of the gas jets and its components

Minimum fluidization velocity (MFV) is the velocity at which the drag force offered by the gas jet is equal to the weight of the particles. So, for a system to exhibit a fluidization state, U_{mf} must be achieved or exceeded [7].

For shallow beds, the two components of velocity do not experience much reduction at distances away from the distributor. Hence, both the swirling and the fluidization effects are sufficiently maintained. While for deep beds, the horizontal component of velocity experiences a significant reduction due to the effect of momentum transfer from the gas jet to the swirling particles. As the height from the distributor increases, the decay in the swirling effect becomes more significant till it completely vanishes. Then the bed experiences two different regions, a region with swirling regime at the bottom of the bed and a region with fluidization regime at the top of the bed [8, 9].

2.3 Main Components of SFB

The most common swirling fluidized bed that exists nowadays consists mainly of a cylindrical bed attached to a distributor that directs the injected gas into the bed at the required angle, which causes the solid particles to swirl in the path designed for them.

The main components of the swirling fluidized bed are: Blower, Bed column, Distributor, Valve, Pipes, Flow meter and Pressure tappings. The following section is a brief description of the function of each of the components.

Blower

The source of the pressurized gas jet; it's powered by electrical source to provide the jet at the required specifications.

Bed column

The main component in the bed column is the hollow cylindrical body that acts as a container (wall) which encloses the particles during the process. It is mounted on the distributor. A metal cone is placed at the center of the base of the bed in order to avoid the creation of dead zone in the center of the bed [1] "figure 6".

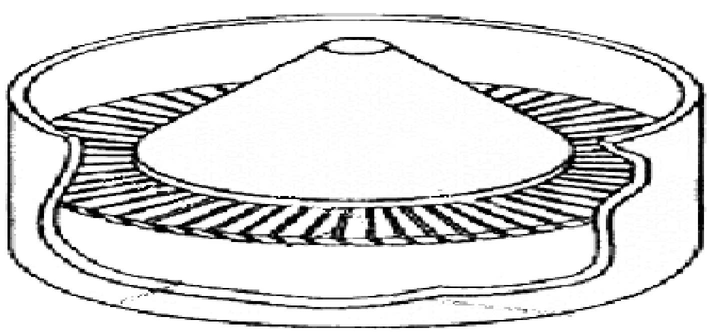

Figure : Bed column

Distributor

As it looks like in a normal fan, the distributor is made up of a number of blades but very near to each other; those blades are directed at an angle to the horizontal in order to provide the guiding inclined direction to the injected gas jet "as shown in figure7". [12].

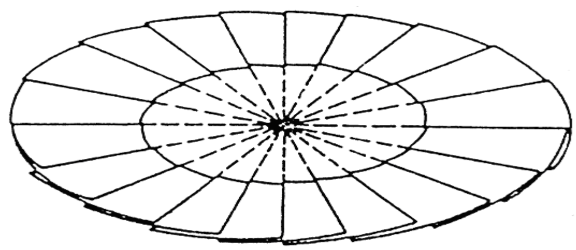

Figure : Distributor

Valve: Its main function is to adjust the flow rate of the injected gas jet.

Pipes: The medium for the path of the gas jet between the different device components.

Flow meter: It is used to measure the actual flow rate in the system by measuring the pressure drop across its two sides.

Pressure tappings: To measure the pressure in different parts and stages of the SFB.

Figure : Industrial SFB

CHAPTER 3: METHODOLOGY

3.1 Process Flow

The research process consists of five main elements starting with literature research followed by detailed design of the multi stage SFB. Then comes the fabrication of the device, analysis of the residence time distribution using a mathematical model and lastly the reporting. The process chart below shows the research stages in detail:

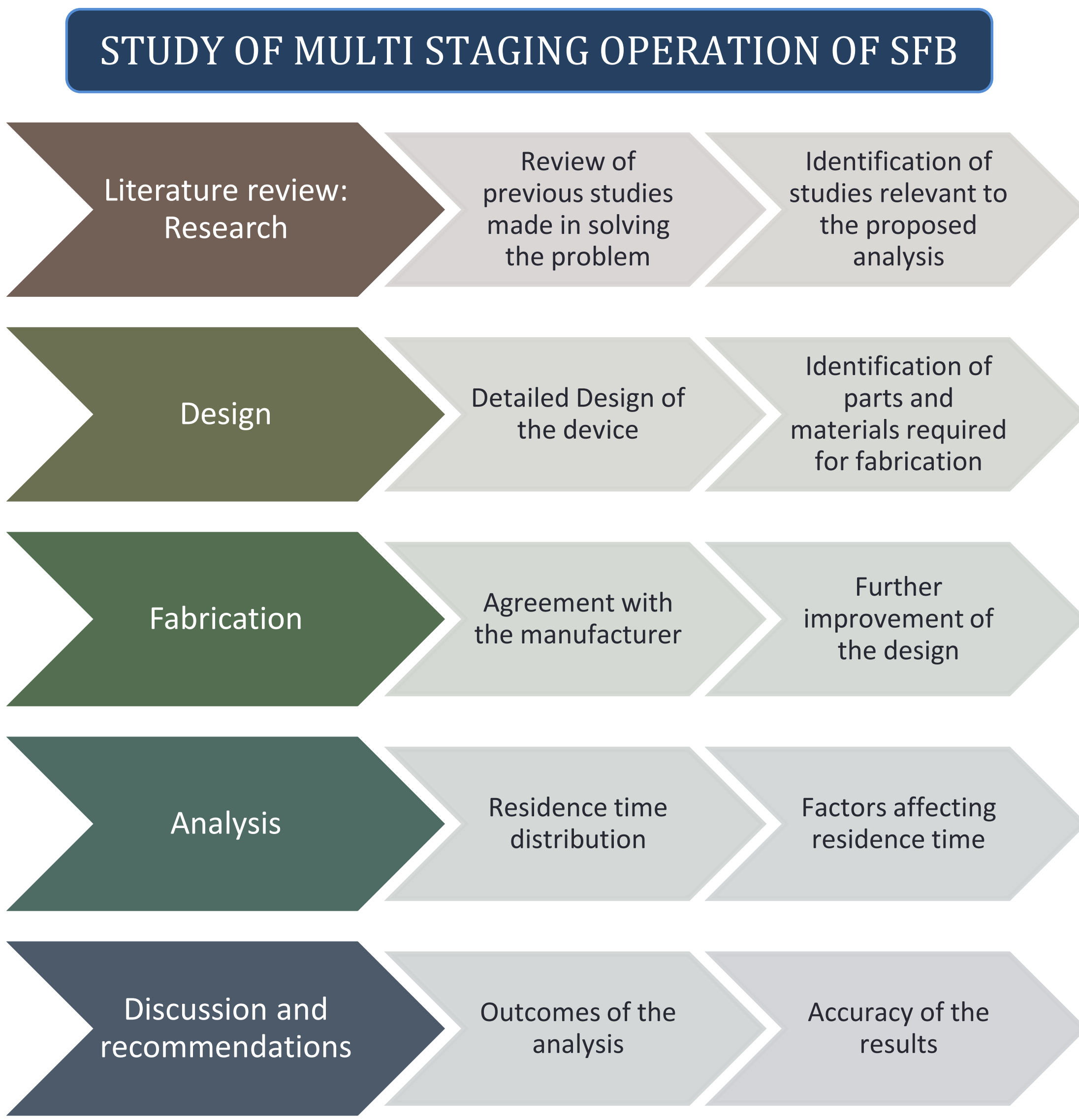

Figure : Methodology Process Chart

3.2 Software

- AutoCAD: The 2011 student version was used for technical design and detail drawing purposes.
- Microsoft Excel: The 2010 version was used for the calculation purposes.

3.3 Mathematical Model

A mathematical model equation for the single stage and the multistage residence time distribution functions was used for the analysis purpose. The formula was taken from a previous research paper [13].

3.4 Project Gantt chart

		FYP I							FYP II						
No.	Activities /Week	2	4	6	8	10	12	14	16	18	20	22	24	26	28
1	Topic Selection and Discussion														
2	Preliminary Research Work														
3	Design														
4	Fabrication														
5	Calculations														
6	Analysis														
7	Reporting														

Table : Project Gantt Chart

CHAPTER 4: RESULTS & DISCUSSION

4.1 Design

The designs and technical drawings of the Multi stage swirling fluidized bed have been successfully completed, starting with the conceptual design and taking into account some practical considerations the final design of the bed can be precisely explained in the following four drawings:

1. *<u>SFB Overview:</u>* It shows the main components of the multi stage SFB and their orientation with respect to each other:

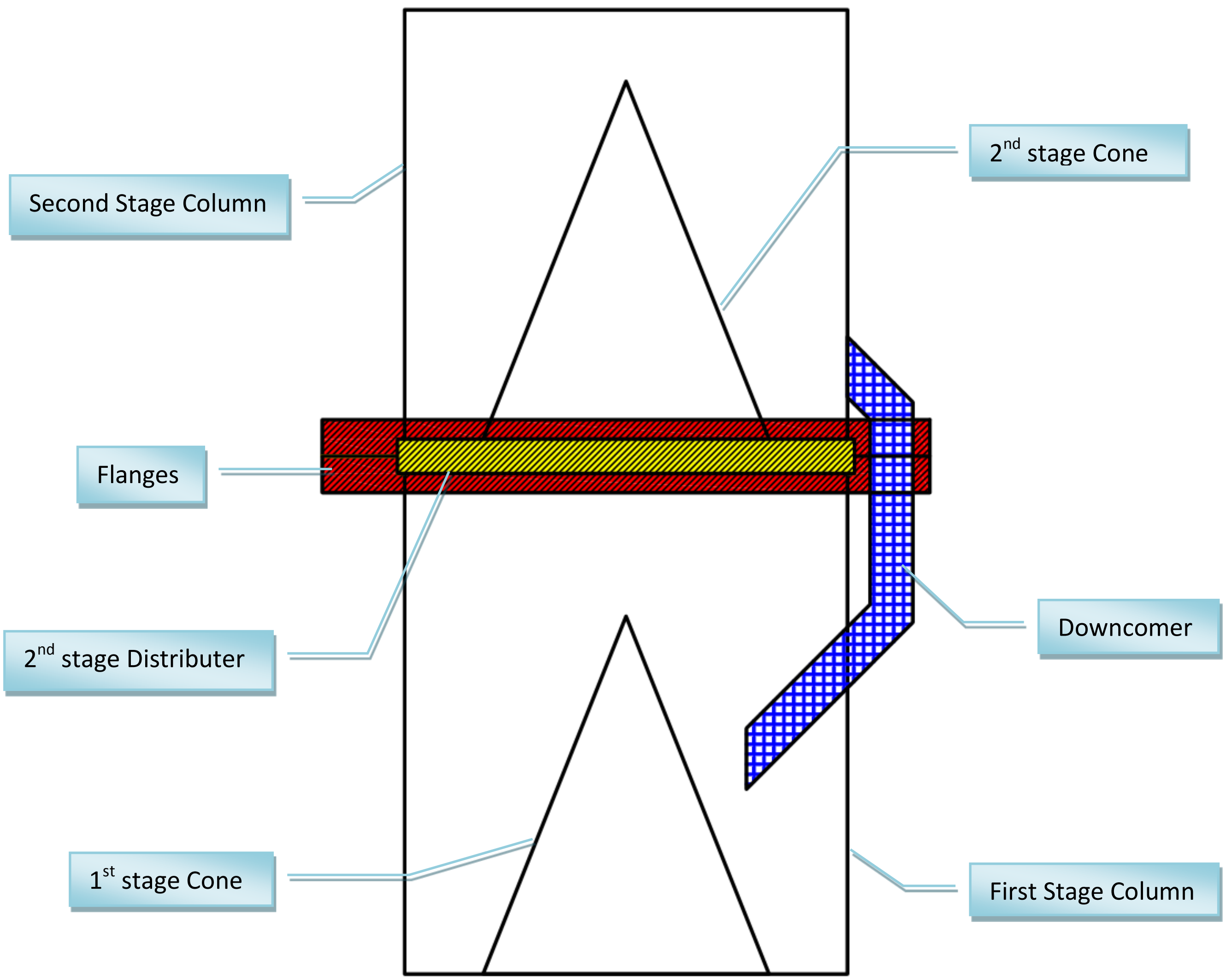

Figure : SFB Overview

2. *<u>SFB Detailed design:</u>* the drawing shows the detailed dimensions of the SFB main components in a 2-dimension field. (All dimensions are in millimeters)

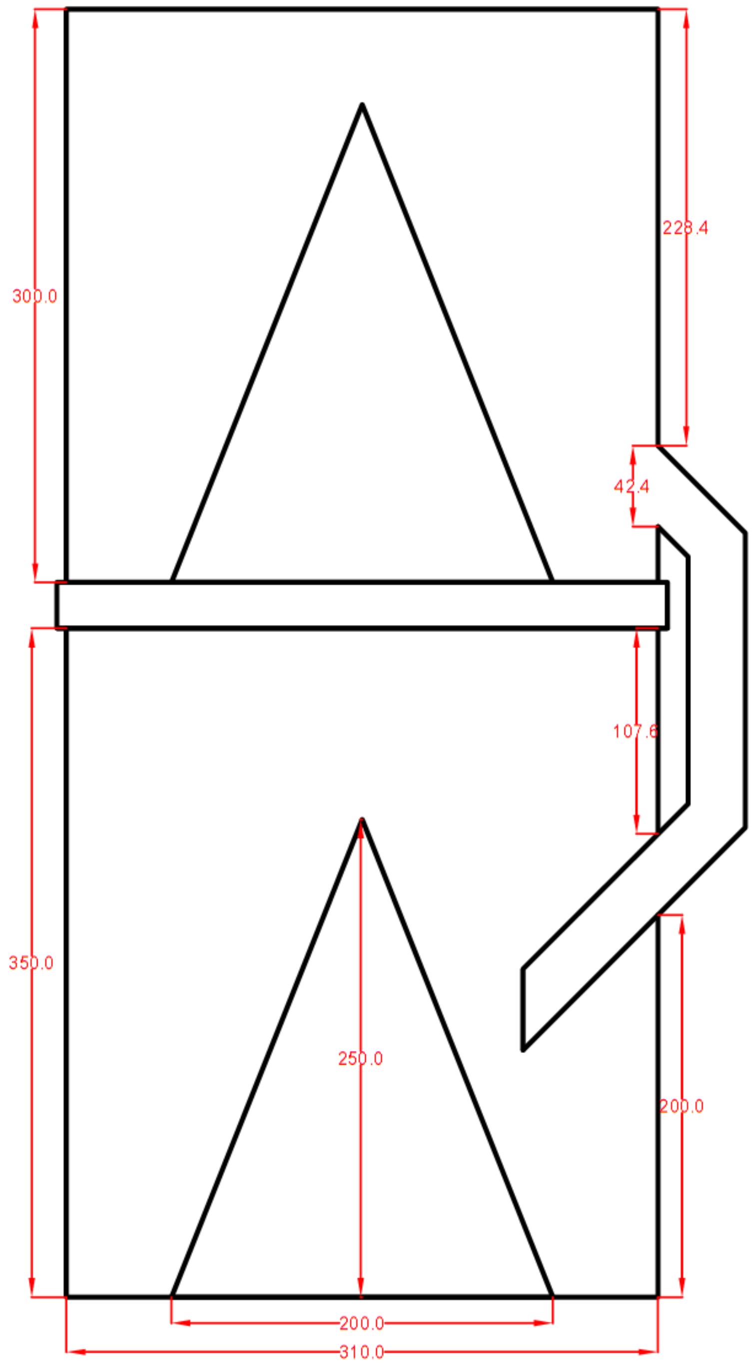

Figure : SFB Detailed Design

3. *<u>Downcomer Design:</u>* The drawing shows the detailed dimensions of the downcomer which will act as the connecting duct between the second stage and the first stage, An angle of 45 degrees has been chosen for the inclined path in order to ensure smooth and steady flow of the particles between the 2 stages: (All dimensions are in millimeters)

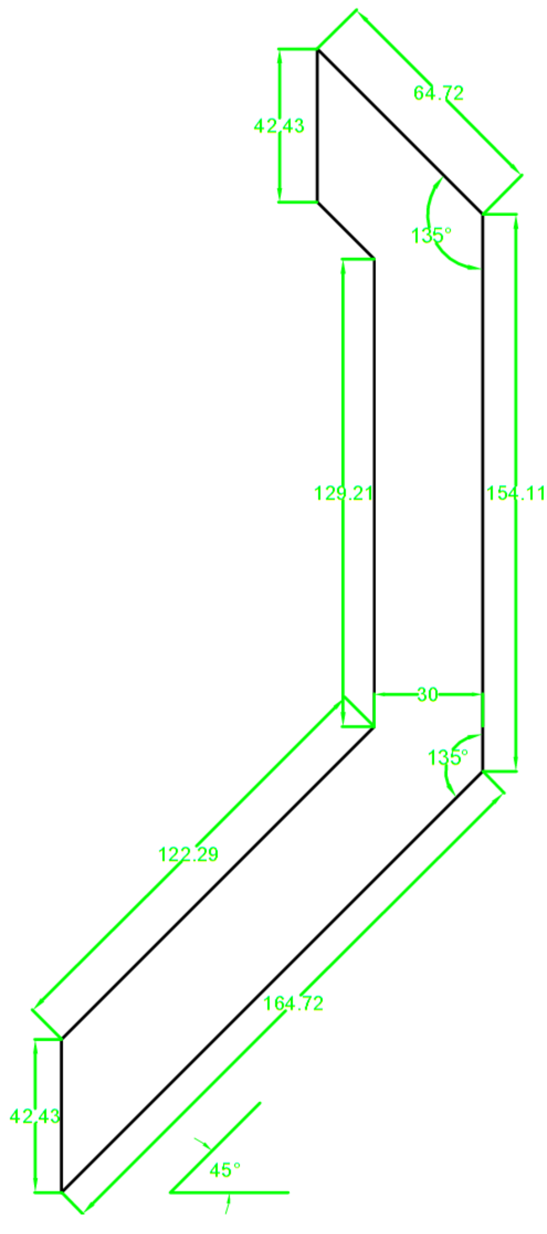

Figure : Downcomer Detailed Design

4. *Flange Design:* The 2 flanges act together to hold and support the distributer as well as to connect the bed columns of the 2 stages together and sealing them well to avoid any air leakages or unwanted flaws that may occur as a result of mounting and operating the second stage. For practical reasons, and in order to ensure smooth and steady flow of the particles from the second stage to the first stage of the bed, it was necessary to cut through the flanges in order for the downcomer to pass through them as shown in the drawing. (All dimensions are in millimeters)

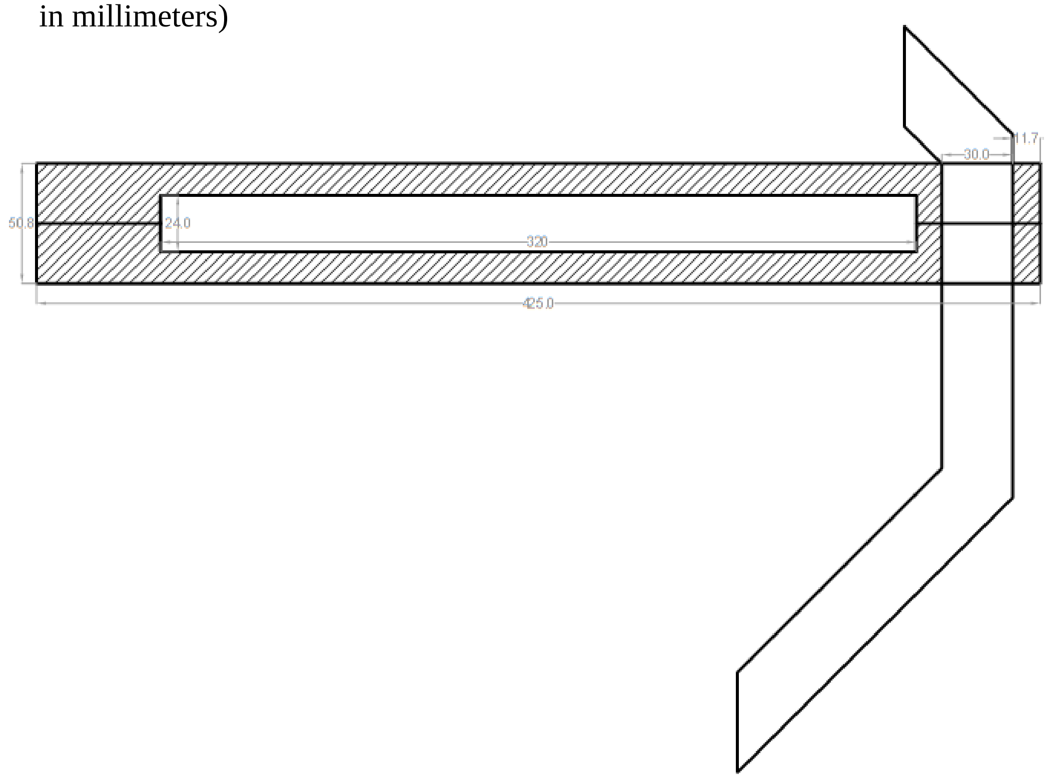

Figure : Flange Detailed Design

4.2 Fabrication

The fabrication process is complicated and the university facilities don't have enough tools to carry out such process that's why the detailed drawings were submitted to an external workshop for accurate fabrication. The device can be used for experimental purposes in UTP laboratory.

4.3 Mathematical Analysis

Single Stage Results

The purpose of this analysis was to investigate how the solids residence time distribution varies from single stage to multi-stage swirling fluidized beds as a function of solids and gas flow rate and of type of mixing.

For the single stage, the residence time distribution was calculated using an experiment where a pulse of tracer particles having distinct colour were injected within the flow of the normal particles, then the particles were collected at the outlet of the SFB every 1 second in separate tubes and the number of tracers coming out for each second was determined. The main purpose of this experiment was to determine the average residence time of particles as well as the extent of back mixing.

The results obtained from the single stage experiment were further used to analyse the system using the mathematical model provided by an earlier paper [13]. The research paper suggests that residence time data for real systems could be represented by:

$$F(t) = 1 - e^{-\eta\left(\frac{t-\varepsilon}{\theta}\right)} \qquad F(t) \geq 0 \tag{3}$$

where ***F(t)*** represents the portion of particles that spends a period of time t in the system, θ is the average residence time, and η and ε are measures of mixing efficiency and system phase shift respectively. [13]

The parameter η is a measure of the extent of the back mixing in the system, for the case of perfect mixing η is equal to one while for perfect plug flow η approaches infinity. The previous experiments [14] conducted on the single stage SFB showed a mean residence time $\theta = 17$ ***s.***

The values were inserted in the equation and the results for single stage were plotted as shown in figure (14) for ***F(t)*** and in figure (15) for ***E(t)***.

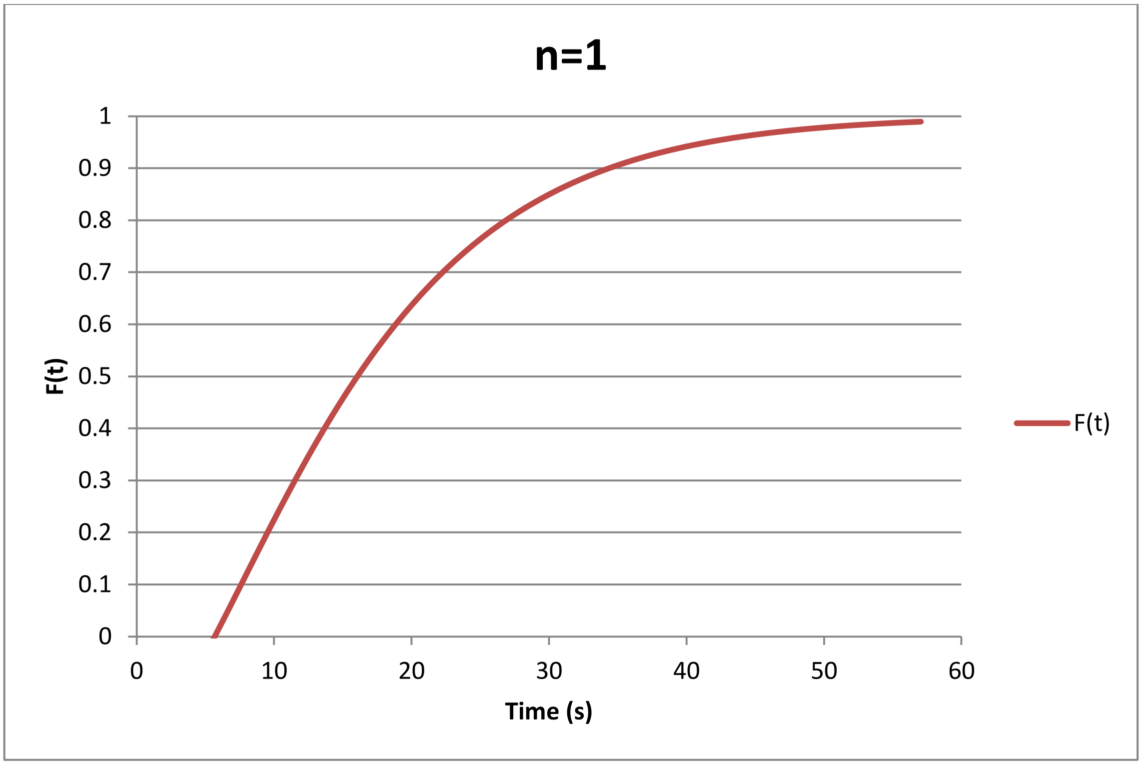

Figure : Single Stage RTD result - F(t)

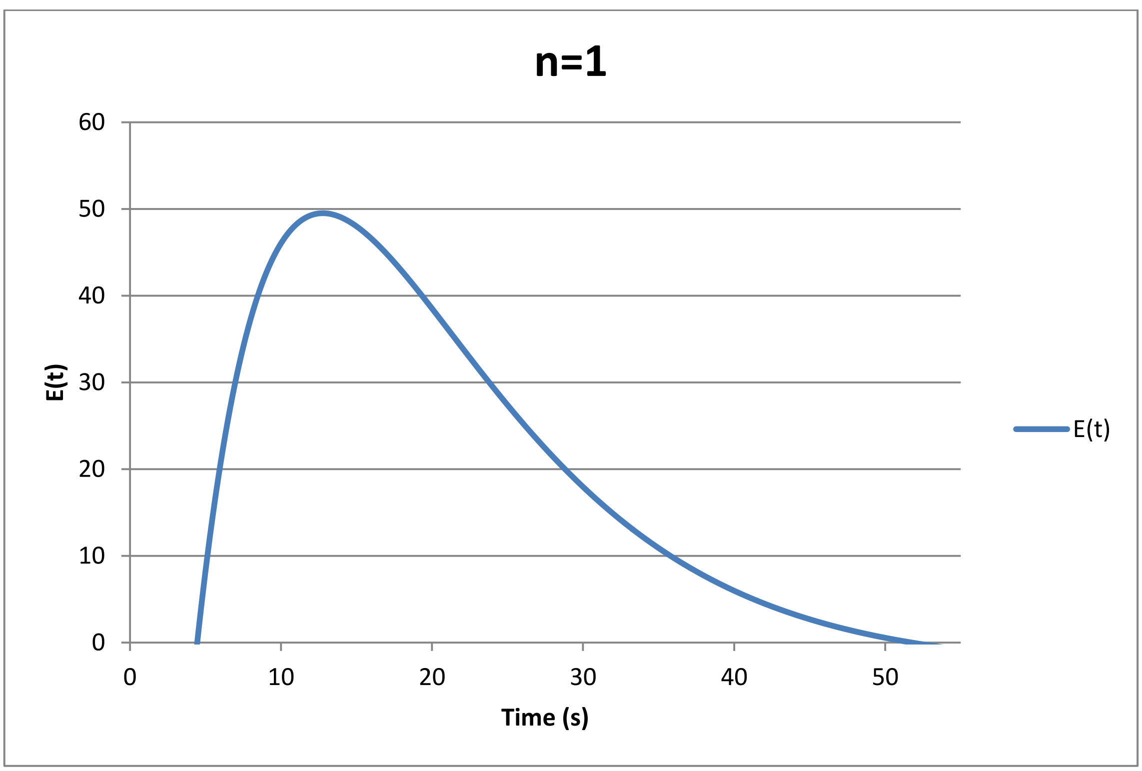

Figure : Single Stage RTD result - E(t)

Multistage results

The effect of multistage operation on the residence time distribution showed conformity with theoretical concepts. As the number of stages increases the residence time distribution approaches that of a perfect plug flow. For a multistage bed the equation is developed in the research paper [13] to be:

$$F(t) = 1 - \left\{1 + \eta\left(\frac{t - n\epsilon}{\theta}\right) + \dots + \frac{1}{(n-1)!}\left[\eta\left(\frac{t - n\epsilon}{\theta}\right)\right]^{n-1}\right\} \exp\left[-\eta\left(\frac{t - n\epsilon}{\theta}\right)\right] \qquad F(t) \geqslant 0 \tag{4}$$

where ***n*** is the number of stages in a multistage SFB and all the other parameters are the same as explained before in the single stage results section.

The values for ***θ, η*** and ***ε*** can be expected and obtained from the single stage results. The values were inserted in the equation and the results for ***n = 2, 3, 4 and 5*** were plotted in order to appreciate the effect of adding more stages to a SFB on the residence time distribution and the fluid flow properties.

The figures in the following section show the plotted results of F(t) and E(t) for each number of stages followed by a combined plot of the results of all the stages together.

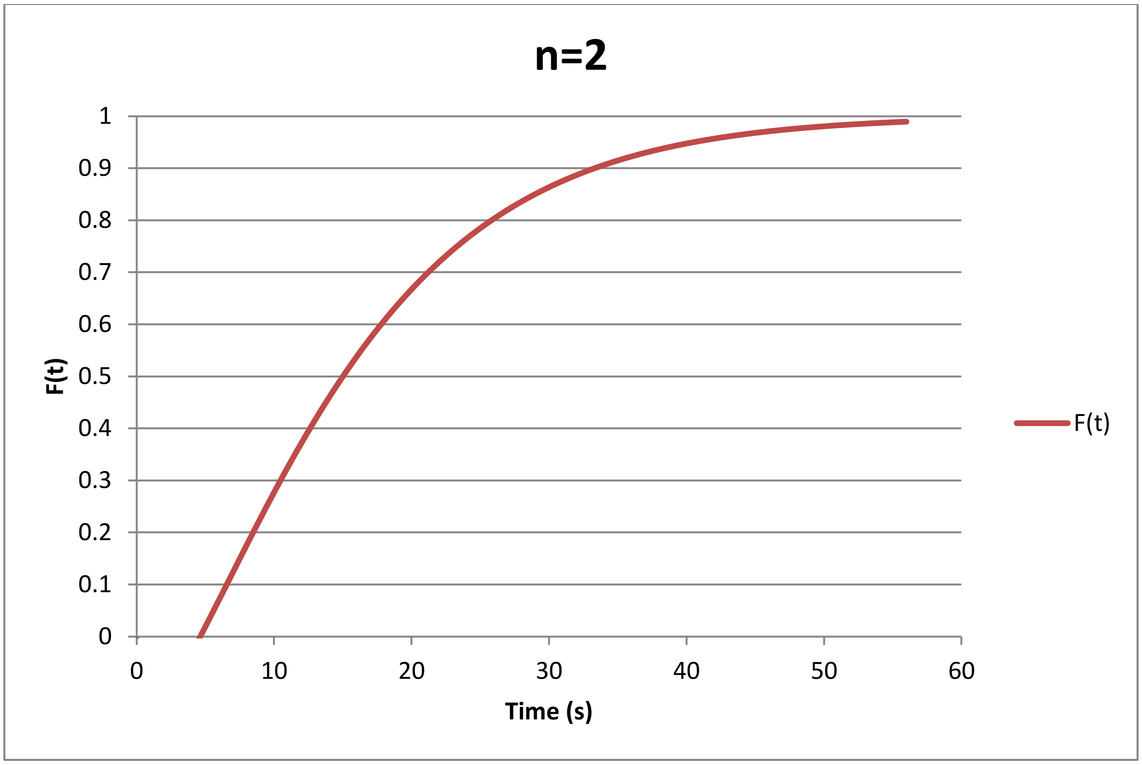

Figure : Two Stages RTD result - F(t)

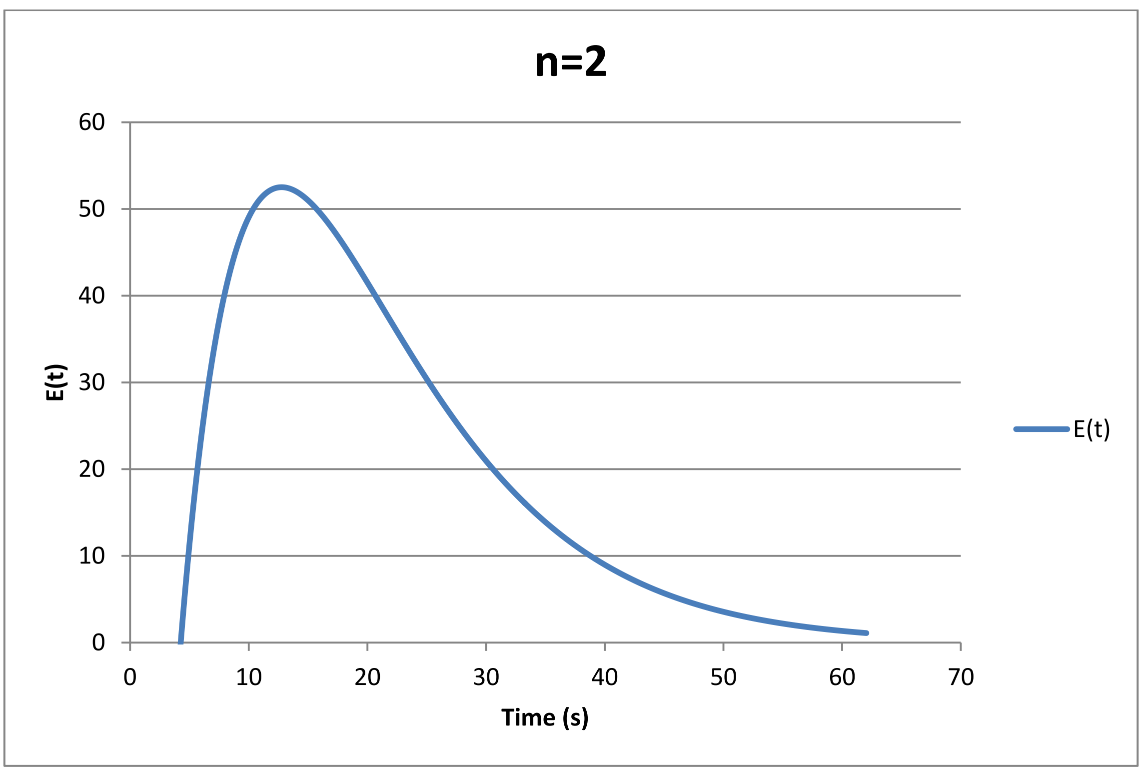

Figure : Two Stages RTD result - E(t)

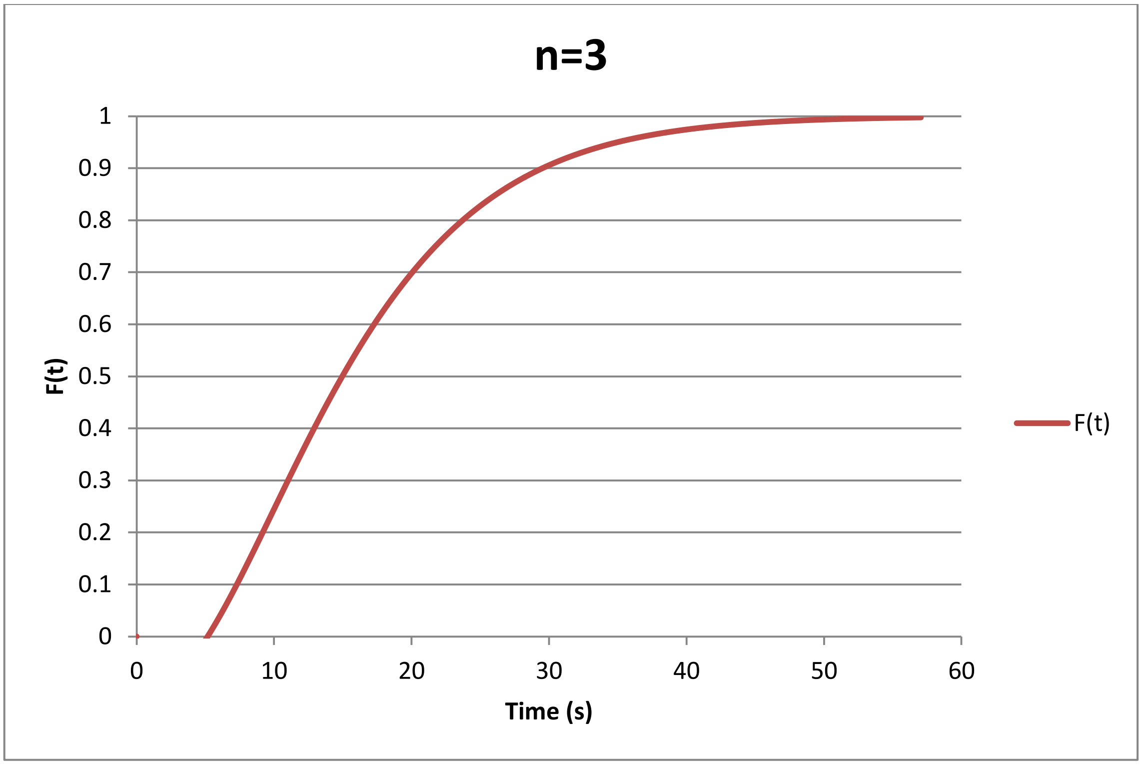

Figure : Three Stages RTD result - F(t)

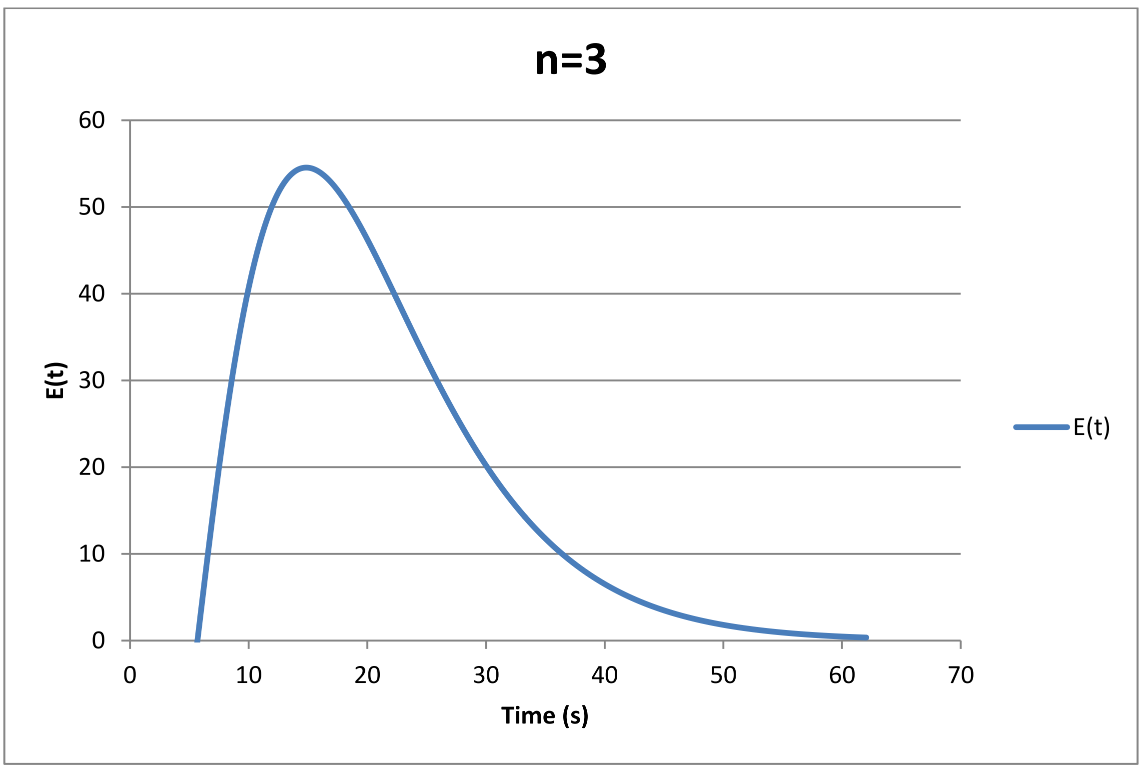

Figure : Three Stages RTD result - E(t)

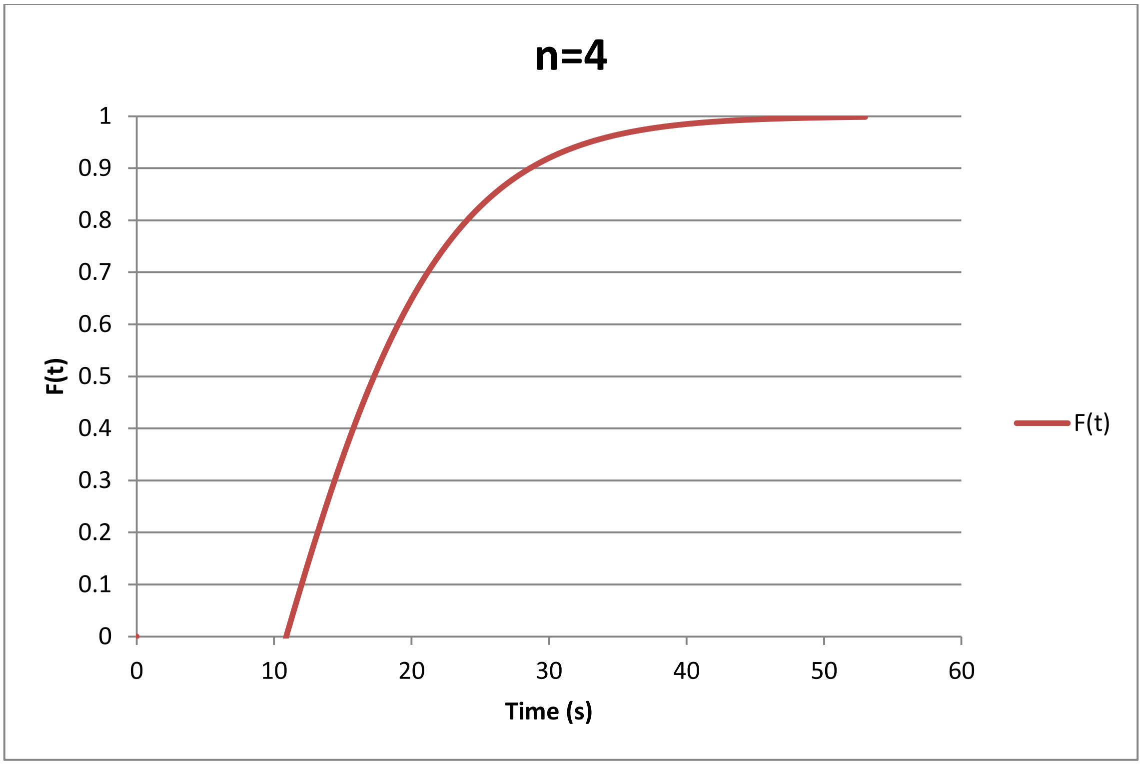

Figure : Four Stages RTD result - F(t)

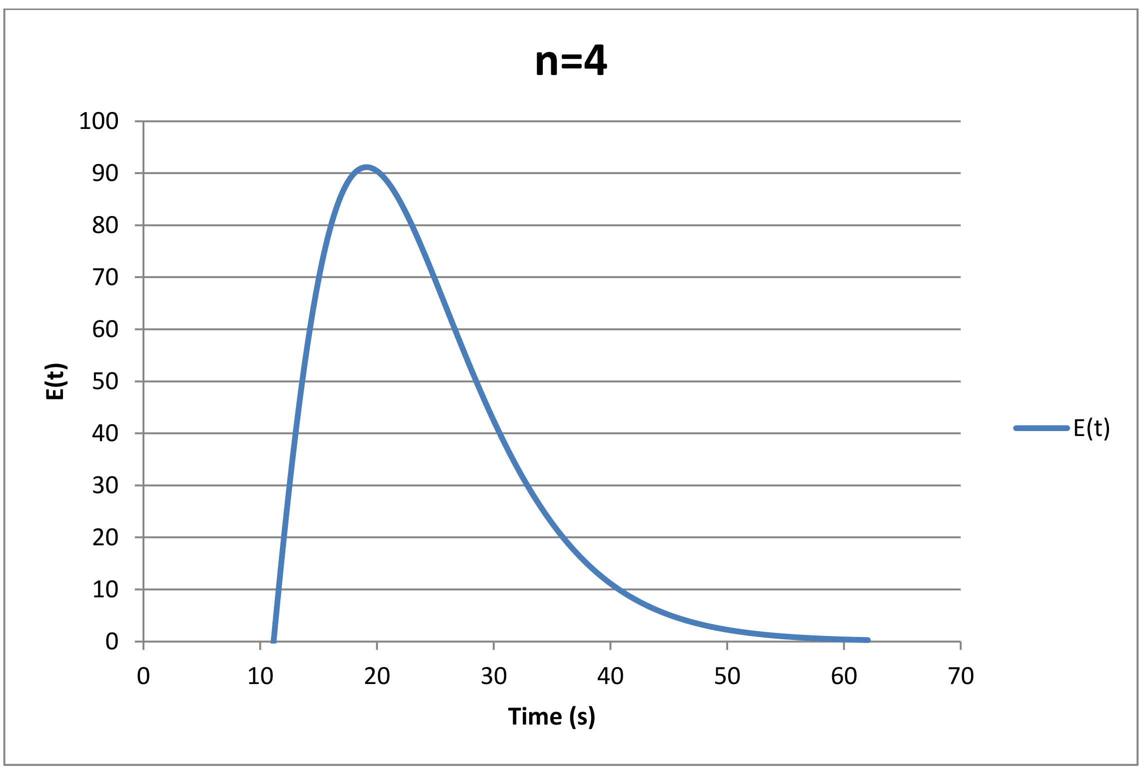

Figure : Four Stages RTD result - E(t)

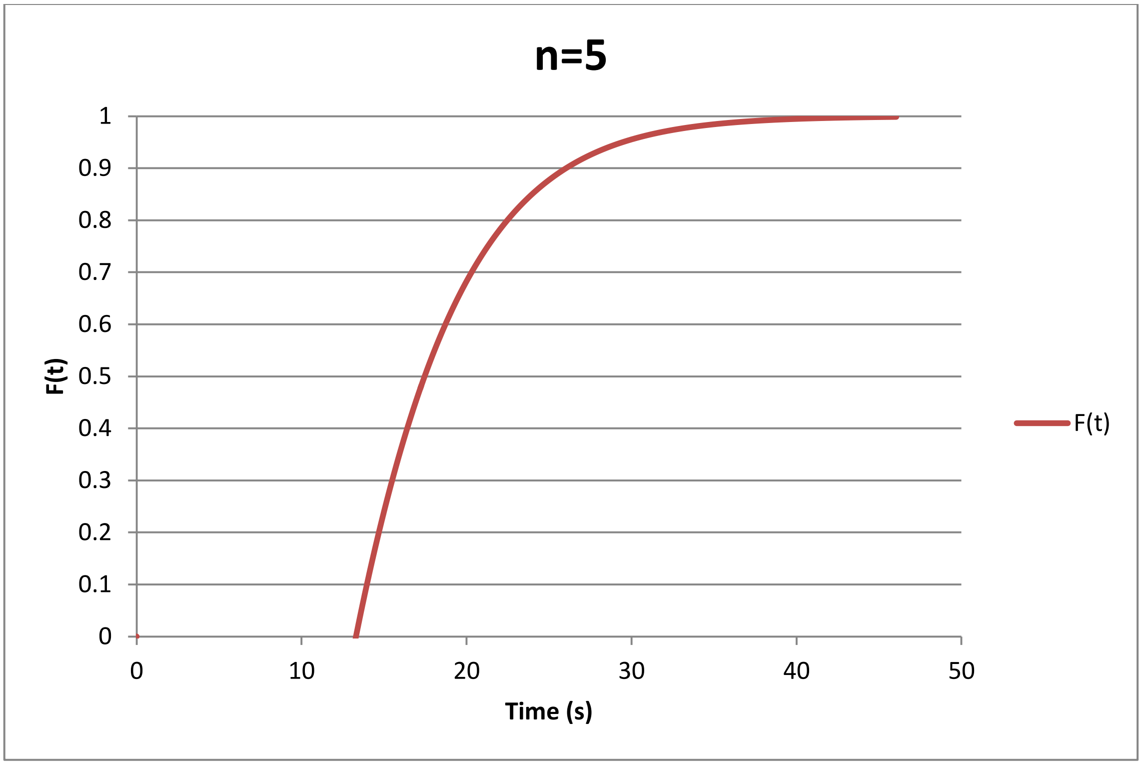

Figure : Five Stages RTD result - F(t)

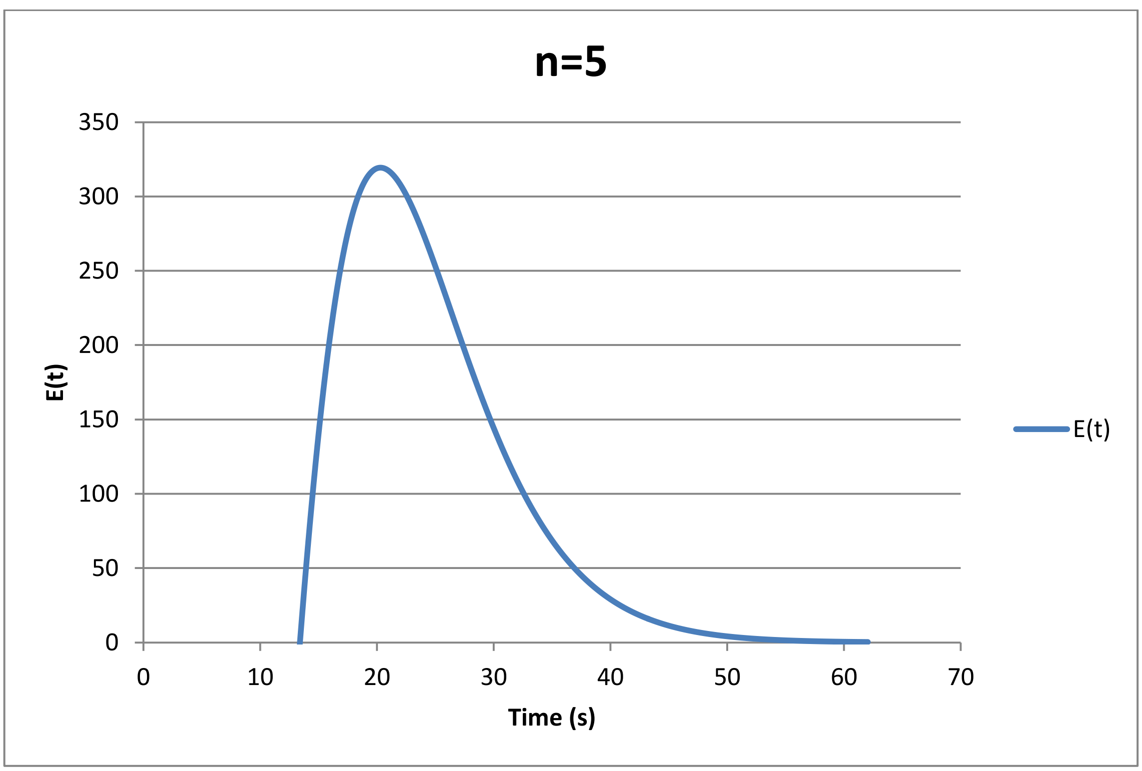

Figure : Five Stages RTD result - E(t)

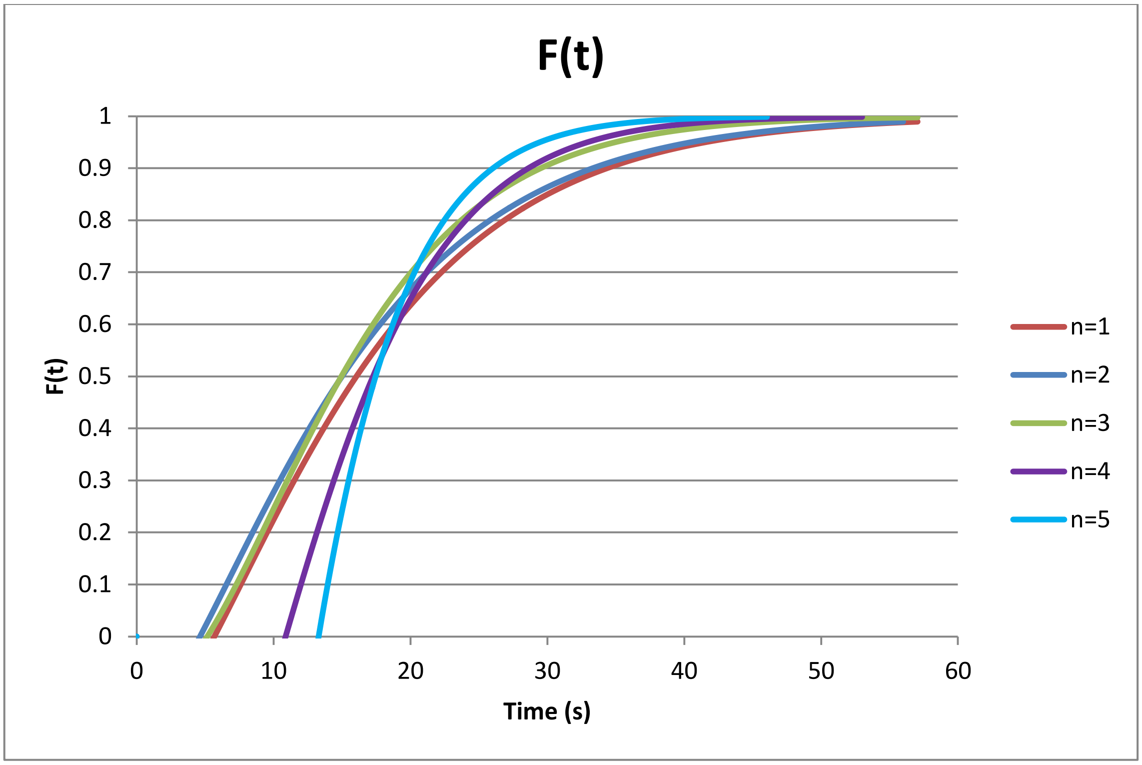

Figure : RTD results - F(t)

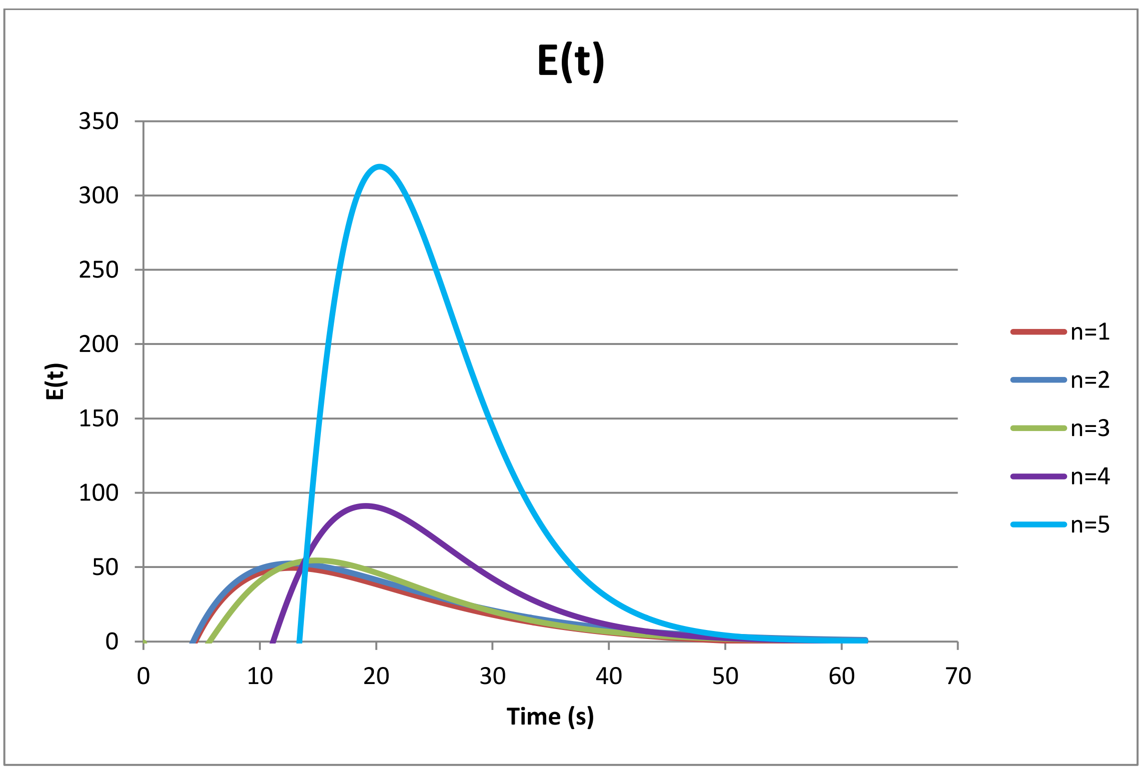

Figure : RTD results - E(t)

CHAPTER 5: CONCLUSIONS AND RECOMMENDATION

Multi stage swirling fluidized beds are considered a new field to be studied as there are no past researches on that topic. The characteristics of multi stage SFB are very interesting to be studied as they can have many industrial and research applications.

The project is mainly about the design, fabrication and study of a multi-stage swirling fluidized bed. The technical drawings and design were successfully done and sent to the workshop for fabrication. The new device shall help further laboratory experiments on multistage swirling fluidized beds.

The residence time distribution for the solids in a multistage fluidized bed can be presented by an F(t) function as defined in the equations. The two parameters n and ε vary with the several variables that can be expected from information about the physical behavior and the characteristics of the system.

It has been shown with the aid of the analysis results obtained from multistage operation that increasing the number of stages in a SFB has a positive effect on the residence time distribution of the particles as it drives the flow towards a perfect plug flow in which all the particles reside inside the system for the same time.

"Plug flow" is highly favored because it allows all the particles in the system to react to the same exact desired extent so that no particles will be sub-normally or abnormally treated.

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