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Modelling and Experimental Investigation of Paint Mixing Process Dynamics

Submitted by

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Abstract

In most paint mixing machines, users usually depend on visual observation of the paint mixture or they may specify a preset time for stirring chosen based on previous experience to ensure the homogeneity of the paint, but this period may be not sufficient to satisfy a perfect homogeneity of the paint mixture. So, such a practice may lead to inconsistency in paint quality. In this work, an automatic paint mixing machine that is equipped with a monitoring and control system has been designed and constructed. This machine aims to mix and analyze the desired paint color. Arduino Mega was used as micro-controller and a high-resolution camera was used for paint image capturing. A mixing algorithm for water-based paints was proposed. This algorithm guarantees a user to obtain a predefined paint color within a specific time. That means, the user determines the paint volume and color as inputs to the algorithm. Then, based on paints commercial database, the algorithm will specify the needed amount from the three basic colors (red, green and blue paints) to be mixed.

Experimental investigation of the effects of process parameters of the designed conventional mixing vessel has been implemented through measuring the time-varying color state of the paint mixture. The independent variables include the stirring speed, the tristimulus value of the desired paint color and the batch volume. The dependent variable is the color distance, which represents the range between the mixed and the unmixed paint color. The independent variables are manipulated separately, while reporting the values of the dependent variable with time. Three empirical models were proposed including the solution for first, second and complex second order differential equations. Then, the obtained color distance function was fitted to the empirical models in order to choose the best fit model, based on minimizing the objective function using least square method implemented as an algorithm in the Matlab framework.

The solution for complex second order differential equation provides the best fit for the observed dynamic curves. It is concluded that the speed of convergence to steady state increases with increasing stirring speed and decreasing batch volume. However, changing the tristimulus value of the desired paint color has no major effect of the speed of convergence to steady state, while it only changes the steady state distance of the desired paint color. Furthermore, the developed paint mixing machine can be used for experimental investigation of kinetic studies of various industrial and environmental reactive processes.

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Chapter 1

Introduction

1.1 Introduction

Paints science and technology has become a fascinating area of research for experts from different fields due to its unique ability to provide true engineering solutions for the control of corrosion and enhancement of aesthetics for protecting a wide variety of materials. While design and optimization of paint formulation with the right blend of ingredients are a critical elements in paint technology. The manufacturing of paint has not received adequate coverage since it apparently appears to be a simplistic process. But, in reality, the manufacturing process controls the science of dispersion which in turn governs the final film performance and optical attributes. The role of dispersion machineries, grinding media and processing steps cannot be undermined while formulating a right paint product. Any imbalance on this front will result in economic loss due to increase in cycle time and underutilization of the potential values of costly ingredients. In this respect, the manufacturing technology ensures true integration of coatings performance with organizational profitability [14].

Mixing is usually an important part of many industrial processes, such as blending of ingredients, reactants in chemical reactors, addition of energy to create or break molecular bonds [46]. Although mixing is widely used, a fundamental understanding is still somewhat limited. It is the oldest unit operation, improved in incremental stages by empiricism. However, increasing demands on close control of product quality and the trend towards intensive automation of the mixing process, have emphasized the need for obtaining quantitative and predictive design capabilities to optimize the design and performance of mixers. Some materials are rheologically complex and are typically difficult to mix uniformly [47].

Over the years the demand for high quality, greater efficiency and automated machines has increased in the industrial sector of different plants. With increasing labour and equipments costs as well as with the development of more severe, higher-capacity, higher-performance equipment and processes from 1940 to 1960, it became uneconomical and often impossible to run plants without automatic control devices. At this stage, feedback controllers were added to the plants with little real consideration of the dynamics of the process itself [31]. On the other hand, process control has become increasingly important in the process industries as a consequence of global competition, rapidly changing economic conditions, faster product developments, and more stringent environmental and safety regulations [56].

Computer vision is the science that develops the theoretical and algorithmic basis by which useful information about an object or scene can be automatically extracted and analysed from an observed image, image set or image sequence. Computer vision systems are being used increasingly in the industrial sectors for quality assurance purposes. Essentially, such systems replace human inspectors for the evaluation of a variety of quality attributes of raw and prepared products. Over the past few years, the explosive growth in both computer hardware and software has led to many significant advances in computer vision technology. Computer vision technology provides a high level of flexibility and repeatability at relatively low cost. It also permits fairly high plant throughput without compromising accuracy. Currently, computer vision systems are being developed as an integral part of products processing plants for on-line, real-time quality evaluation and quality control [21].

1.2 Industrial processing

Industrial process is the conversion of feed materials to products using chemical and physical operations. This definition applies to three types of common processes which are continuous, batch and semi-batch processes [56].

- In batch process, raw materials are fed into the process at the outset. The process then runs for some length of time, producing a product, but no product is removed, and no additional raw materials are input, while the process runs. At the end, the product is removed. The bottom line is that no mass enters or leaves while the process is running [56]. See Fig. 1.1. This type of process is used for small scale production, such as, bin blending, paints blending, and some reactors [56]. There are many advantages of the batch mixing process, they allow production of multiple different products in the same equipment, also, they are integrated enough such that they are preserved as they move from operation to operation. In addition, they are simple and very flexible as well as they are easier to clean and maintain sterile operation [63].

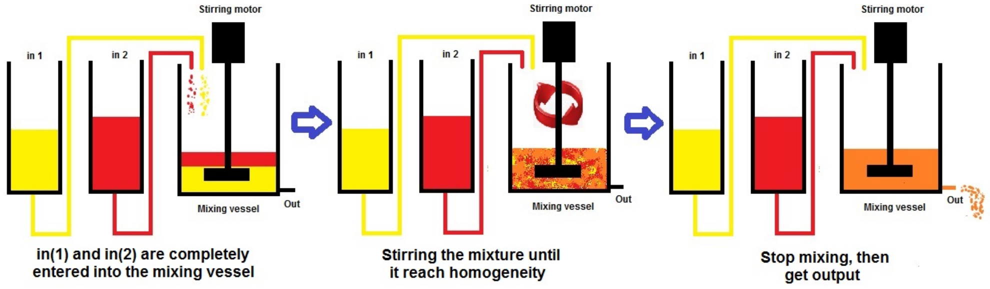


Figure 1.1: Batch mixing process.

- In continuous process, the input and the output flow continuously through the duration of the process. See Fig. 1.2. This type of process is used for large scale production, such as, petroleum refining, and much of food processing.

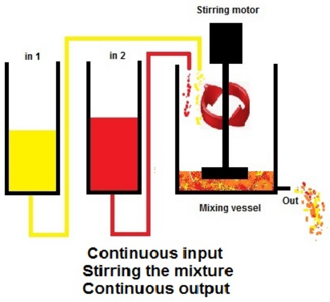


Figure 1.2: Continuous mixing process.

- In the semi-batch process, as shown in Fig.1.3 a part of the reactant can be fed or a part of product can be removed.

In the recent years the performance requirements for process plants become difficult to satisfy without control. Stronger competition, tougher environmental, safety regulation, and rapidly changing economic conditions have been key factors in tightening product quality specifications. A further complication is that modern plants have become more difficult to operate because

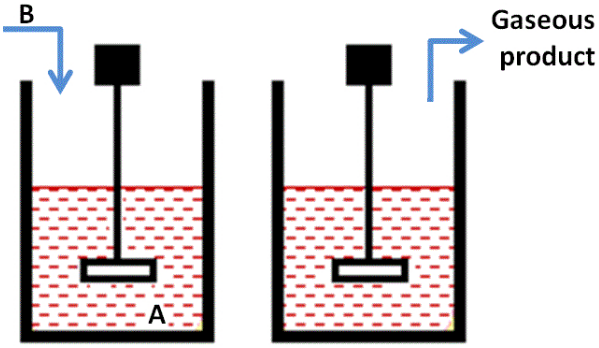


Figure 1.3: Semi-batch mixing process.

of the trend toward complex and highly integrated processes. For such plants, it is difficult to prevent disturbances by propagating from one unit to another interconnected units in the absence of control techniques [56].

1.3 Industrial and research need

Over the years, the demand for high quality, greater efficiency and automated machines have increased in the industrial sector of different plants. Many plants require continuous monitoring and inspection at frequent intervals. Process monitoring, is a tool that measures real-time process performance, permits proactive management of processes and enables their continuous improvement. So it is important to develop process monitoring in the industrial processes. This will allow processes to be planned, measured and continuously improved. In addition, process monitoring allows engineers to progress to higher levels of sophistication, and thus, produce better products and services, by assisting the active management of processes.

In many industrial processes, product purity has overriding importance. To avoid contamination between batches, the mixing vessel must be thoroughly cleaned after each usage. In this work, paint mixing has been done in a batch stirred tank, that means, no raw materials are input the mixing tank and no output is removed from it during mixing process. Each usage of the mixing vessel may aim to produce a new paint color, so if the mixing process has been done in a continuous stirred tank, the ability to clean the equipment becomes impossible after each cycle. Thus, this feature will increase the quality of the produced paint color.

Costs should be kept in perspective. Generally, paint mixing costs represent only a very small percentage of the total product manufacturing costs. Mixing becomes expensive only when production time is lost due to a failure to meet the product specification. Thus, to optimize the mixing process a high quality product must be produced in a minimum time.

1.4 Research problem

In the most paint mixing processes the stirrer motor must be programmed to begin mixing after the specified quantities of the raw paint colors are completely entered the mixing vessel. In many related researches, the paint mixing machine allows to specify a preset time for operating the stirrer motor, this period may be not sufficient to make the mixture that inside the mixing vessel homogeneous. Also, Some researches depend on the means of visual observation to ensure the homogeneity of the desired paint color. Furthermore, in some works, the time that is necessary to get a uniform mixture is neglected, so this does not grantee the homogeneity and the quality of paint color.

In addition, researchers do not depend on a specific technique or approach to analyse the desired paint color in the purpose of specifying the degree of homogeneity of it. Finally, the mathematical profile for the paint mixing process has not been developed theoretically (based on derivations) or empirically (based on experimental measurements).

1.5 Research relevance

Four key elements illustrate that this research problem is usually investigated in the fields of mechatronics, which are:

1. **Mechanical system**: In this system, designing and implementing the mechanical structure of the paint mixing process prototype are considered.

2. **Electrical system**: In this system, building-up and assembling the electrical and the electronics components and devices are considered.

3. **Information system**: In this system, developing the mathematical modelling of the mixing process and applying control algorithm are considered.

4. **Computer system**: This system is described by electronic hardware that are programmed by codes. The electronic hardware include micro-

controllers, while the soft codes can be programmed using high- or low-level programming language. Fig.1.4 shows the block diagram of the paint mixing process.

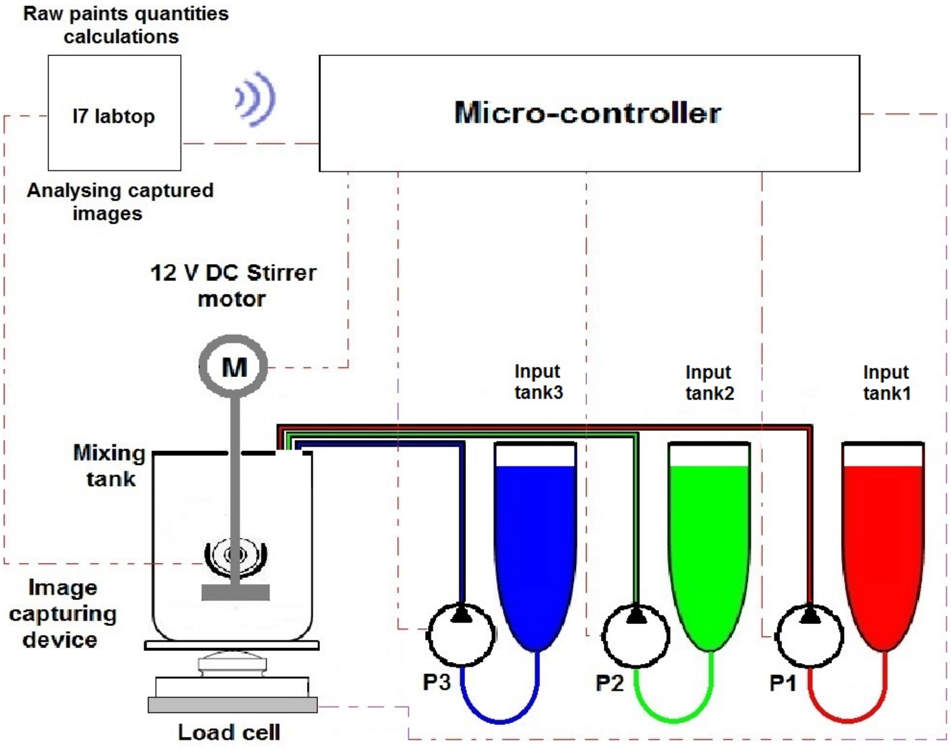


Figure 1.4: Block diagram of the paint mixing process.

In this work, a high-resolution camera is used in a paint mixing machine for paints analysing purpose. This technique is very important in paints manufacturing to increase the efficiency of getting the required and the desired paint color. In this case, the losses of raw materials will be reduced and the confidence of the customer in the quality of the paint will be increased.
This technique is not limited for mixing and making paints only, but, it is also very important for many engineering disciplines especially for chemical and process engineering. In other word, when the chemical engineers develop an experiment to make a reaction between two colored materials to produce a new material, it is possible to study the relation between the concentration of the output versus time, also, they be able to monitor the reaction and analyse it at each instant. Furthermore, they can evaluate the total time required for the reaction, thus, it is possible to compute the reaction speed.

Also, it is an essential technique for process engineering, especially in foods and drinks processing.

1.6 Thesis contribution

The contribution of this thesis can be summarized as follows:

- In a lab fashion. A fully automated paint mixing process has been implemented. A high-resolution camera was located outside the transparent mixing tank in the opposite of the dead zone region. This camera was employed to capture images for the paint color for analysis purposes. Thus, the mixture homogeneity state can be studied. In addition, by using this camera, it is possible to monitor the preparation of the desired paint during mixing process.
- The design of the paint mixing system is an essential issue especially the position of the inputs tanks with respect to the mixing vessel, so the three inputs tanks must be designed to be lower than the mixing tank level. In this case, the flow of the raw paints from the inputs tanks into the mixing tank is controlled by three pumps.
- A two-bladed paddle impeller was designed according to the geometric proportions for a standard agitation system. The allows mixing motor speed for the two-bladed paddle impeller from 20 rpm to 200 rpm. So it is possible to study the relationship between the stirring motor speed and the homogeneity time. A high mixing speed was avoided to obviate the diffusion that may occur in the mixing tank through the mixing process.
- The mathematical model of the paint mixing process has been developed empirically (based on experimental data), this model will describe the behaviour of the process.

1.7 Thesis outline

The thesis contents are organized in 6 chapters:
In Chapter 1, the general definition and the common types of the industrial processes are enlightened, also the need for control approaches to automate the industrial processes is illustrated. The research relevance in mechatronics engineering field, and the significant of this research in the scientific and industrial fields are also presented. In addition, the thesis contribution is

also illustrated in this chapter.

In Chapter 2, a background of paint manufacturing and color composition theory are illustrated. A general definition of industrial mixing process and its significant in industrial sector are also explained. Furthermore, the reasons for improving control techniques in industrial processes are mentioned. A review of paint mixing machine design is also presented. In addition, two sections are improved to review the modelling and the experimental studies of the mixing processes. Finally, a review of control techniques to automate the paint mixing system are presented.

Chapter 3 presents the paint mixing process description and design. The general description of the machine, as well as the detail of the process design are presented. In addition, the design of monitory, control of the system and the methods for manipulating process variables are described.

Chapter 4 explains the experimental approach that is used in the paint mixing process. The experiment conditions that must be created to get accurate measurements from the performed experiments are illustrated. Here, the method for analysing the experimental measurements is explained.

In Chapter 5, the empirical modelling approach is adopted to improve the mathematical model of the system based on the experiments measurements. Furthermore, some empirical functions are suggested to describe the mixing dynamics. Data regression (fitting) for these functions are done to chose one of the suggested empirical functions. Finally, a paint mixing algorithm is proposed to perform calculations.

The results and the discussion of the performed experiments are introduced in Chapter 6. The general behaviour of the paint mixing process is presented. A comparison between real process behaviour and the models is illustrated. The effect of stirring speed, targeted color, and batch volume are discussed.

Chapter 2

Background and literature review

2.1 Introduction

Blending is a common mixing operation in the chemical and process industries. The objective is to take two or more miscible fluids and blend them to a predetermined degree of homogeneity. Liquids are blended to provide a desired degree of uniformity in an acceptable mixing time. An efficient mixer design is important for good product quality at a high production rate. The critical issues that need to be addressed include number of liquids and their volumes, mixing tank configuration, batch mixing time or residence time distribution in a batch system, and physical properties.

Due to the variety of processing needs and process objectives. There are a number of ways to perform mixing in vessels; Mechanical agitation, gas sparing, and jets are often used. Mixing and contacting in agitated tanks can be accomplished in continuous, batch, or semi-batch mode. A good mixing result is important for minimizing investment and operating costs, providing high yields when mass transfer is limiting, and thus enhancing profitability. Batch mixing is mixing ingredients in any amount in individual batches in an individual mixer or a vessel. All ingredients are loaded into a mixer and agitated for a certain period until they are homogeneously distributed or mixed. The resulting mixture is then discharged out of the vessel. The critical parameters that influence the selection of such mixers is the mixing duration, the size and the geometry of the mixer, and the operating conditions [19]. Fluid mixing is carried out in mechanically stirred vessels for a variety of objectives, including for homogenizing single or multiple phases in terms of concentration of components, physical properties, and temperature.

The fundamental mechanism involves physical movement of materials between various parts of the entire mass using rotating impeller blades (mixing tool) [19].

In many scientific researches and works the paint mixing processes have been designed and implemented to achieve different goals. In some works, a fully automated paint mixing process has been implemented to reduce human workers, so that the errors generated from processing a complicated mathematical model will be reduced, due to reduce the participation of humans workers, thus, the efficiency of the paint mixing and the quality of the paints will be increased [8, 23, 51]. Furthermore, In the past, paint composition has been done manually where sometimes does not meet the required color, so some researchers suppose that the Paint composition is an important issue in the paint industry. for this reason, the automatic paint preparation techniques take place to solve the manual paint composition [39]. In addition, several control approaches can be applied to the paint mixing process. So the automatic paint mixing system has been performed to implement a professional control algorithm that aims to provide a simple technique for users to deal with the machine through working to produce a new desired paint color [55].

2.2 Background of paint manufacturing

The task of paint technology is to provide surface protection, decorative finishes and numerous special functions for commodities and merchandise by means of organic coatings. Many everyday products are only made usable and thus saleable because of their surface treatment. To achieve this, relevant coating formulations, their production plant, the coating material and suitable coating processes for the product must be available. However, the quality to be achieved by means of the coating process is not the only function of the coating material used. The object to be painted or coated itself with its specific material and design and an appropriate application process are further variables which play a significant role. In addressing the ongoing tasks of quality optimization and rationalization while minimizing the impacts for humans and the environment, it is vital that the dependencies mentioned above be not only recognized but also taken into account as the framework defining the conditions in which work is carried out from development to application [18].

paints manufacturing is one of the chemical and process industries. paints manufacturing requires a number of unit operation which are mixing, milling, and filtration[67, 27]. Mixing process is an essential operation in paint industry which usually depends on automatic control techniques. The main aim of this process is to move a heterogeneous paint solution into a homogeneous one using mixing technique [49, 56]. Some of paints factories still use old equipments and tools for paint colors mixing. These equipments and tools have many problems due to processing using complicated mathematical models [55]. In order to get a high quality and efficiency in paints production and preparation, the demands for automatic paint colors preparation techniques are increased.

Many researchers in some engineering disciplines interested in the development of the paint mixing machine, these developments have been done in different techniques to achieve several purposes. So as in [8, 23, 51], producing a wide range of new paint colors, the primary paint colors (red, yellow, and blue) can be mixed using a variety of different quantities of the paint in proportion to each other. in addition, mixing paints by using color mixing formulas ensure that specific paint color can be duplicated, which allows predictability in color mixing. Proportional color mixing can involve simple ratios, like using twice as much red as yellow, or complex formulas, such as mixing one part red, two parts blue, and three parts yellow. Each combination will produce a new and interesting result [8].

2.3 Color composition background

For the purpose of obtaining new paint color with paint mixing process, we have to tackle the coloring theory and its relation to the computer engineering. Several references discuss this issue in detail [10, 16, 17]. One of the very helpful tools in color vision theory is transforming the colors into numerical values, therefore one can easily deal with the type and transparency of the color. Three well known models are available in the literature to describe the color coding; either composting the color in red, green and blue (RGB) color space [39], physical model using Kubelka-Munk (KM) theory [66], or defining the any using red, yellow and blue (RYB) color space [8]. However, computer engineers normally employ the RGB color model in computer graphics which is defined by the three chromaticities of the red, green, and blue primaries [39, 41]. The RGB color model is an additive color model as shown in Fig. 2.1. Another color model is cyan, magenta, and yellow key model (CMYK) which is a well known color model for subtractive color composting used in printing [34, 41]. But both RGB and CMYK color models fail to reproduce paint like appearance such as yellow and blue makes green. Another RYB color model by Johannes Itten is widely used in art education [25]. In this work we use the RGB system, since one can convert a color system into another color system easily, as demonstrated elsewhere, e.g., to [25]. Fig. 2.1, shows how one can composite a new color using three color systems; RGB, RYB and CMYK, where Fig. 2.2, shows the RGB cube for the color spacing system.

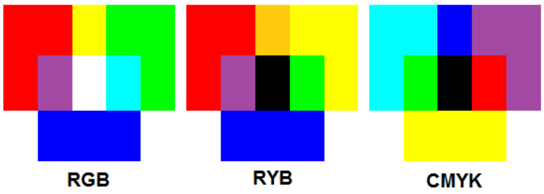


Figure 2.1: Color composition systems; RGB, RYB and CMYK.

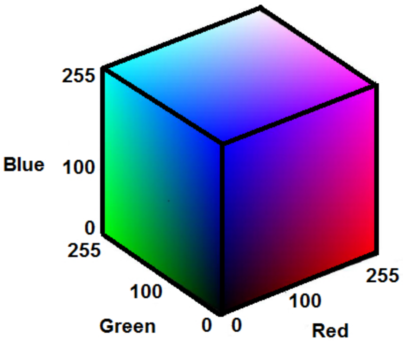


Figure 2.2: RGB cube for Color Spacing System

The RGB cube in Fig. 2.2 illustrates that the red, green and blue values can vary from 0 to 255. For example to composite the purple color one has to set the red, green and blue to 128, 0 and 128, respectively. These values are called red, green and blue tristimulus values. These values can be easily used with the following vector notation: $RGB_{purple} \in^3$, namely

$$RGB_{purple} = [R_{purple} \quad G_{purple} \quad B_{purple}]^T = [128 \quad 0 \quad 128]^T \tag{2.1}$$

Another method to represent the RGB coloring system is to use chromaticity space with relative tristimulus values. This is obtained by normalizing the tristimulus values as follows [11]:

$$r = \frac{R}{R+G+B}, \quad g = \frac{G}{R+G+B}, \quad b = \frac{B}{R+G+B}. \tag{2.2}$$

This results in chromaticity coordinates r, g and b that are invariant to overall brightness. By definition, $r+g+b=1$ so one coordinate is redundant

and typically only r and g are considered. Since the effect of intensity has been eliminated the 2-dimensional quantity $(r,\ g)$ represents color. Therefore the chromaticity vector for the purple is $rgb_{purple} = [0.5\ \ 0\ \ 0.5]^T$ or $rg_{purple} = [0.5\ \ 0]^T$.
When it is required to compose the purple color from red, green and blue colors, it is needed to calculate the desired ratios from these colors. Then they are mixed together very well until obtaining the purple. Before mixing the colors, they can be randomly over each other. For example, the green at the bottom, then comes the blue then comes the red, which has the chromaticity vector $rgb_{red} = [1\ \ 0\ \ 0]^T$. So that the distance between the red and purple d_{rp} using the color cube Fig. 2.3, but with relative tristimulus values, can be calculated by following equation:

$$d_{ij} = \sqrt{(r_i - r_j)^2 + (g_i - g_j)^2 + (b_i - b_j)^2} \tag{2.3}$$

where the indices i and j refer to the initial and final colors which are in the above example red and purple, respectively. Thus the distance d_{rp} will be about 0.707.

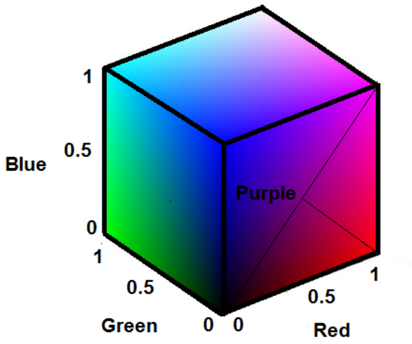


Figure 2.3: The distance between the red and purple on the rgb cube with relative tristimulus values.

To investigate this relation, a high resolution camera is located outside the transparent mixing tank to measure the tristimulus values of the surface color. Initially, the distance between the surface color and the color of the final mixed paint is 0.707 in our above example or, alternatively, the distance between the surface color of the unmixed paint and the color that is measured by the camera will be zero before starting to mix. Then this distance increases with mixing until the final mixed paint, with a steady state color will have the distance of 0.707. Furthermore, this distance represents the degree of homogeneity of the paint with respect to the steady state color and, thus, there is no need to continue mixing after this point.

2.4 Mixing process

Mixing operation is a type of industrial processes which is commonly used in many industries to ensure that the final product has certain specifications. As shown in Fig. 2.4, mixing process aims to mix the input streams to produce an outlet stream that has desired and homogeneous composition [56]. The final products from the plant must meet demanding quality specifications set by purchasers. The quality specifications may be expressed as the solution compositions, the required volume, the degree of homogeneity, or a combination of all three [33].

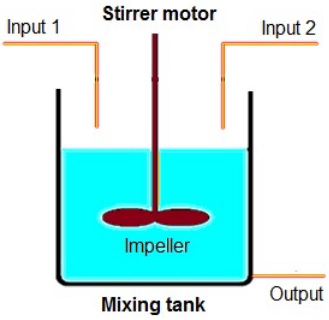


Figure 2.4: Mixing process diagram

Mixing process is done to reduce the inhomogeneity measure (index) in order to achieve the desired process result. The inhomogeneity can be one of concentration, phase, or temperature. Secondary effects, such as mass transfer, reaction, and product properties are also critical objectives [19]. Mixing operations are encountered widely throughout the productive industries in processes involving physical and chemical change. Although much of our knowledge on mixing has developed from the chemical industry, many other sectors carry out mixing operations on a large scale. Thus mixing is a central feature of many processes in, e.g, the food, pharmaceutical, paper, plastics, ceramics and paint industries [40]. Therefore, mixing process is an essential operation in paint industry. It aims to make a heterogeneous physical system homogeneous by using manipulating operations.

2.5 The design of paint mixing process

Mixing operation is ubiquitous and essential in many facets of the process industries, ranging from simple blending to complex chemical reactions for which the reaction yield and selectivity are highly dependent on the mixing

performance. So improper mixing can result in non-reproducible processing and lowered product quality [24]. It is important to design a mixing system that investigates high quality and efficiency while producing the desired products. So the design of the mixing vessel, impeller shape, and inputs tanks location must be considered.
A transparent flat-bottomed cylindrical tank was used as the mixing vessel. Various axial-flow and radial-flow impellers were utilized to agitate the solutions. To avoid creating a vortex, the tank was fitted with four equally spaced baffles. The tank was also fitted with inlet and outlet tubes. The mixing tank was equipped with a top entering impeller driven by a 2-HP motor, and the impeller speed was set to the desired speed in rpm. During the experiments, the fluid was pumped from the feed tank to the discharge tank through the mixing vessel [43, 52]. In section 3.3, the power that must be supplied to stirring motor in order to drive the impeller at the desired speed has been calculated.
A color mixing machine consist of four tanks for inputs; so three tanks for the primary color (RYB), and the forth input tank contains a cleaning material. With the help of mixing tank all colors that come from the process will be mixed with the required proportion. Stirrer motor that is coupled with the impeller was used for mixing the paint mixture inside the mixing vessel. As shown in Fig. 2.5, the stirrer motor is stationary at the side of the mixing tank horizontally [23].

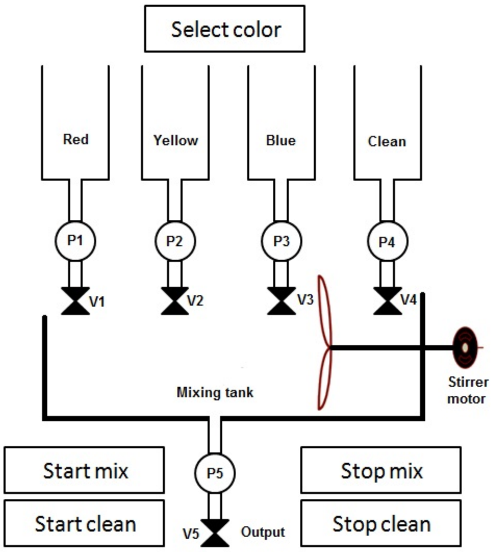


Figure 2.5: Side-entering mixer for cylindrical mixing vessel

Color mixing plant consists of a mixing tank in which colors are mixed from the two inputs tanks. The first input tank contains colored water, and the other tank contains clean water. The input flow to the mixing tank is controlled by two valves, which regulate the output flow from each input tank. After mixing process the resulting water has the desired coloration. As shown in Fig. 2.6, the stirrer motor is stationary at the bottom of the mixing tank [2, 5, 37, 55].

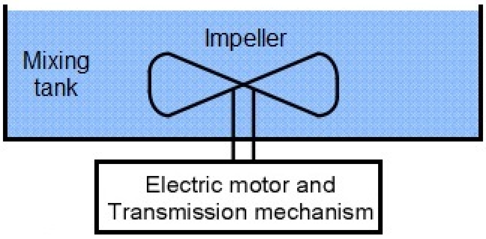


Figure 2.6: Bottom-entering mixer for cylindrical mixing tank

As in [39], the automatic paint mixing process consists of a mixing tank in which the paint colors are mixed. Also, it consist of five inputs tanks, three of them contain a tinctures for the primary color (RYB), and one of them contains the raw material (white paint), while the other contains a cleaning material. Furthermore, researcher used a DC motor in mixture stirring purpose. The author did not explain how to design the used impeller in this article. A color mixing machine consist of three tanks that contain the raw material. With the help of mixing tank all colors coming from the process will be mixed together using stir motor [8, 51].

In processing industries, many operations are dependent to a great extent on effective agitation and mixing of fluids. Generally, agitation refers to forcing a fluid by mechanical means to flow in a circulatory or other pattern inside a vessel. Mixing usually implies the taking of two or more separate phases, such as a fluid and a powdered solid, or two fluids, and causing them to be randomly distributed through one another. Generally, liquids are agitated in a cylindrical vessel which can be closed or open to the air. The height of liquid is approximately equal to the tank diameter. An impeller that is mounted on a shaft is driven by an electric motor [12]. For the impeller (mechanical agitator), several design can be chosen to prevent the materials from accumulating on the bottom of the mixing tank and to promote contact efficiency between the phases. Fig. 2.7 shows various types of paddle agitators which are often used at low speeds between 20 and 200 rpm.

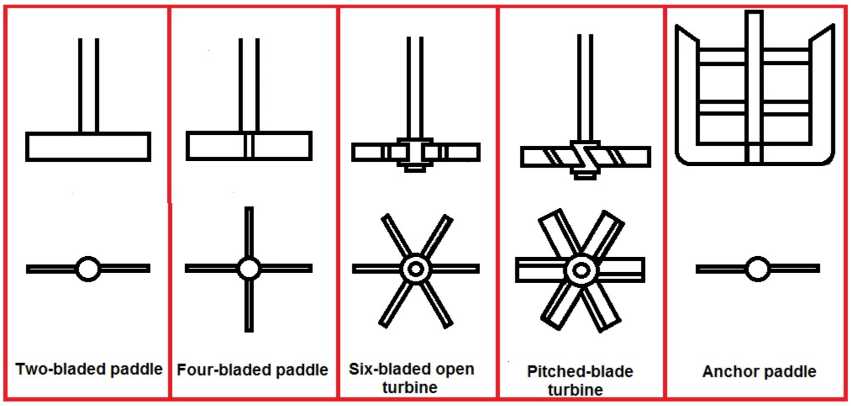


Figure 2.7: Various types of paddle agitators

The paint mixing machine generally consists of three auxiliaries (inputs) tanks that contain the raw paint colors, and the mixing tank in which the desired paint color to be mixed. The auxiliaries tanks can be designed to be higher than the mixing tank level as shown in Fig. 2.8. In this case, the quantities of the three basic paint colors contribute to get the desired paint color that can be controlled by adjusting the wait time for the DC valve for each input [8, 23, 39, 51, 55]. This technique can be applied at a same paint colors viscosity for all paints, that means at different viscosities, it is important to study the relationship between the paint quantity that must be added to the mixing tank and the waiting time for opening the valves, due to the inversely proportional between the viscosity and the speed of liquid flow.

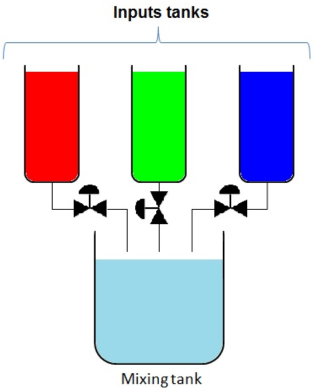


Figure 2.8: The position of the inputs tanks with respect to mixing tank

2.6 Review of modelling mixing processes

A mathematical model is a description of a system using mathematical concepts and language. The process of developing a mathematical model is termed as mathematical modelling. A model may help to explain a system and to study the effects of different components, and to make predictions about behaviour. Mathematical modelling is the method of translating the problems from real life systems into conformable and manageable mathematical expressions whose analytical consideration determines an insight and orientation for solving a problem and provides us with a technique for better development of the system. Using the high-level mathematical modelling methods is a powerful way of predicting and decision-making in financial markets [62].

The process model is a mathematical abstraction of a real process. In general, modelling involves a compromise between model accuracy and complexity, it also involves the cost and effort required to develop the model and verify it. [56].

Process models can be classified as follows [56]:

1. Theoretical models that are developed using the principles of chemistry, physics, and biology.
2. Empirical models that are obtained by fitting experimental measurements.
3. Semi-empirical models are a combination of the theoretical models and empirical models, i.e, the numerical values of one or more of the parameters in a theoretical model are calculated from experimental measurements.

The advantages of the theoretical models are:

1. They provide physical insight into process behaviour.
2. They are applicable over wide range of conditions.

However, the disadvantages of the theoretical models are:

1. They tend to be expensive and time-consuming to develop.
2. Theoretical models of complex process typically include some model parameters that are not readily available, such as reaction rate coefficients, physical properties, or heat transfer coefficient.

Although empirical models are easier to develop than theoretical models, they are typically do not extrapolate well, i.e, empirical models should be used with caution for operating conditions that were not included in the experimental measurements used to fit the model. The range of the measurements is typically quite small compared to the full range of process operating conditions.

Semi-empirical models have three inherent advantages:

1. They incorporate theoretical knowledge.
2. They can be extrapolated over a wide range of operating conditions than empirical models.
3. They require less development effort than theoretical models. Consequently, semi-empirical models are widely used in industry [56].

The theoretical model of mixing process in a continuous stirred tank reactor (CSTR) is usually based on conservation of mass law that is represented in Eq.(2.4) [56]. After simplifying the model, a set of ordinary differential equations (ODEs) will be resulted. These ODEs represent the dynamic model of the mixing process. In order to solve the ODEs system, the initial conditions are required, some of the dependent variables values at a certain instant of time will be known that depends on the experimental measurements [45, 64, 62].

$$\frac{d(V\rho)}{dt} = w_{in} - w_{out} \tag{2.4}$$

where, the left side of Eq.(2.4) represents the rate of accumulation of mass in the mixing tank, w_{in} is the rate of mass input and w_{out} is the rate of mass output. this law is not valid to use when the mixing process is done in a batch stirred tank, specially when there is no reaction between the inputs, because there is no accumulation in the mixing vessel like the continuous stirred tank.

2.7 Review of experimental studies of mixing processes

Experimental techniques for measuring mixing can be divided into two categories: those that are performed in a laboratory, and those measurements that are performed in actual process plant equipment. The instrumentation and techniques used in each type of measurement are often different, although they can be based on very similar principles. In the laboratory, experiments are most often carried out on a small scale using transparent vessels or pipework. It is straightforward to change the vessel and process configurations in the laboratory, making it possible to investigate a wide range of parameters relatively quickly and easily. The instrumentation that is used will require careful setup and expert operation, but with such treatment will yield precise and accurate data [44].

Process plant measurements are constrained by the nature of the process plant being used. The vessels are usually much larger than those found in a mixing laboratory, access to the vessels is often difficult, and visual observations of the mixing process are usually very difficult. Making alterations to the plant is costly and time-consuming, particularly as a frequent requirement is that production must not be interfered with. In most cases, the actual process fluids must be used, which may be difficult or dangerous to handle. The instrumentation used must be extremely robust and must be able to tolerate possible mishandling under the plant conditions. Measurements may have to be made at elevated temperatures or pressures, further increasing the cost and difficulty. The penalty for this robustness is usually a greatly reduced accuracy of the measurement [44].

Experimental research is a study that strictly adheres to a scientific research design. It includes assumptions, variables that can be manipulated by the researcher, and variables that can be measured, calculated and compared. In Experimental research, researcher collects data that will either support or reject the assumptions. Experimental research seeks to determine a relationship between two variables, the dependent variable and the independent variable. After completing an experimental research study, Based on the variables that have been studied, the assumptions are either accepted or rejected [22].

So in this section it is important to review some related research in the experimental study that applied to the mixing process, such, An experimental study of mixing characteristics by means of steady and unsteady pumping in two mixing vessels each of them has a certain volume was studied. These experiments aim to reduce the mixing time factor which permits the evaluation of the mixing time. The efficiency of different configurations of pumping are then compared through a degree of transient inhomogeneity and required power [57]. Dynamic experiments were made using the frequency-modulated random binary input of a brine solution to determine the magnitude of non ideal flow parameters [53].

Also, several dynamic tests were carried out by injecting a saline solution into the fresh feed stream before it was pumped into the mixing vessel using a metering pump. The injection of the solution was controlled by a computer-controlled on-off solenoid valve. The conductivity values of the input and output streams were measured as functions of time using flow through conductivity sensors, and these values were recorded using a data acquisition system controlled by LabVIEW software to estimate dynamic model parameters [43]. Furthermore, Fluid flow and mixing process in a bottom stirring electrical arc furnace (EAF) with the single-plug and multi-plug are experimentally and numerically studied [30]. Also, Two experimental methods are presented that were used to describe the mixing performance of five mixers differing in mixing principle and internal geometry [42].

2.8 Review of control approaches

Process control of these plants has also become important in the process industries since consequences of rapidly changes in economic conditions and fast product development are highly demanding. Process control is also critical in the development of more flexible and complex processes [49, 56]. Therefore the advancement in electronic and digital control theory will be very useful for these kinds of processes. Examples for these controller are programmable logic controller (PLC) and supervisory control and data acquisition (SCADA) [23, 51]. Also arduino micro-controller can be used for the internal storage of instruction as well as implementing control functions such as logic, sequencing, timing, counting and arithmetic to control through digital, analog input or output modules of various types of these types of plants [8]. Another example of an automatic paint mixing control, also used for demonstration, is a laboratory virtual instrument engineering workbench (LabVIEW) [39]. In addition, investigating the kinetics of batch reactors and dynamic behaviour of unsteady continuous stirred reaction demands an easy and simple monitoring system for experimental studies [3, 26].

Monitoring is an essential tool in process control. A Light-induced fluorescence (LIF) was evaluated as a process analytical technology to monitor blend homogeneity. In addition, it is used to determine a blend steady-state, acceptable mixing time interval, and mixing end point [28]. Also, A soft independent modelling of class analogy (SIMCA) model was developed to determine the homogeneity of the blends in-line and real-time using raman spectroscopy in combination with a fiber optical immersion probe [15]. Furthermore, Near-infra-red (NIR) spectroscopy was employed as a process analytical technique in three steps of tabletting process: to monitor the blend homogeneity, evaluate the content uniformity of tablets and determine the tablets coating thickness. A diode-array spectrometer that is mounted on a lab blender was used to monitor blend uniformity using a calibration-free model with drug concentration [36].

2.9 Review of process kinetics

Kinetic studies are receiving much importance in the recent years since they provide us the most powerful method of investigating the detailed mixing mechanisms. For synthetic purpose, knowledge of mixing mechanism will often allow the mixing condition to be selected for maximum product yields [7, 6].

The process kinetics study is an important approach specially in experimental researches, for example, An experimental approach for obtaining kinetic models and parameter values of the models is important because the results can depend on the experimental procedure which is employed. So four theories exemplified the approaches of using kinetic data from batch systems to predict the performances of continuous systems [9]. In addition, Batch experiments were carried out for the sorption of methylene blue onto rice husk particles. The sorption was analysed using pseudo-first-order and pseudo-second-order kinetic models and the sorption kinetics was found to follow a pseudo-second-order kinetic model [65].

2.10 Identified knowledge gab for research

In most scientific researches, the kinetics behaviour for several industrial processes have been studied to provide a detailed knowledge about the process mechanism and the suitable conditions for it. The kinetics study for the paint mixing process has not been introduced and illustrated in scientific researches. So a paint mixing lab-made equipment has been implemented. A kinetics study has been done by performing set of experiments in order to ensure the relation between the dependent and independent variables at the same mixing and environmental conditions. Furthermore, these experimental data leads to develop the mathematical model of the paint mixing process.

In many works, researchers have studied the homogeneity of the final material during mixing process based on several techniques and approaches. But, Specifying the degree of homogeneity for the paint mixture in a paint mixing process, and determining the time required for mixing to get homogeneity based on a hight resolution microscopic camera have not been studied.

Chapter 3

Paint mixing equipment

3.1 Paint mixing machine description

The paint mixing process in this work is done using a transparent mixing tank. Three supplying tanks are used. These tanks contain red, green, and blue paints as raw materials. The flow of the raw paints from the inputs tanks into the mixing tank is controlled by three pumps. A DC motor that is connected with a two bladed paddle impeller is used as a mixing device. In addition, a load cell is used to measure the masses of the paints that are pumped into the mixing tank. Furthermore, a high-resolution camera is located outside the transparent mixing tank to capture a set of images for the desired paint color during the mixing process for color analysing purposes. Fig. 3.1 shows schematic paint mixing process set-up, where Fig. 3.2 shows the lab-made equipment for paint mixing.

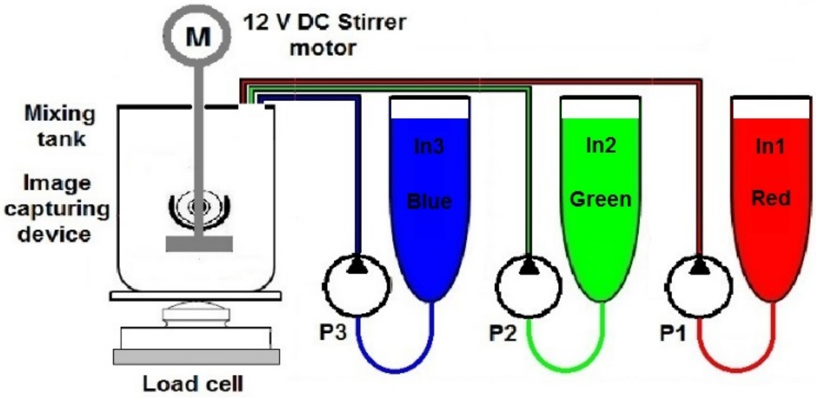


Figure 3.1: Paints mixing equipment set-up

Figure 3.2: Paint mixing lab-made equipment

3.2 Process design

In this work, a mixing algorithm for paint preparation process is presented. This algorithm enables the user to obtain a predefined paint color (desired color). It allows also to specify the wanted paint color and volume or mass. Then, based on the paints commercial database, the algorithm will specify the suitable amounts from red, green and blue paints that must be fed into the mixing tank, then, the stirring motor which is connected directly to a two bladed paddle impeller begins mixing the pumped paint colors ratios. At the same instant a microscopic camera starts capturing images for the paint mixture that inside the mixing tank. When the desired paint color is homogeneous, stirrer motor stops mixing and the camera stops capturing images. Finally, user can get the product from the mixing vessel.

3.2.1 Pump selection

As mentioned in section 3.1, the paint mixing system has three pumps that control the flow of the raw paint colors from the inputs tanks into the mixing tank. There are many specifications of the paint mixing machine that are necessary to determine the suitable pump, which is required to transfer the liquid from the input tank into the mixing vessel. Fig. 3.3 shows some details that is required to compute the energy added to the fluid by the pump.

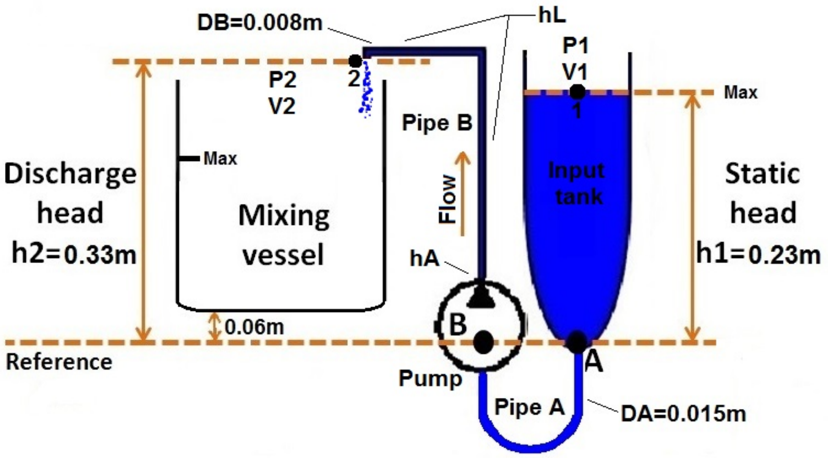


Figure 3.3: Detailed dimensions to compute the energy added and lost from the fluid.

A pump is a common mechanical device that adds energy to the fluid, while the pipe causes energy to be lost from the fluid as it flows through them. Also, even as the fluid flows through straight length of pipe, energy is lost and that causes the fluid pressure to decrease. So Bernoulli's equation is not adequate to analyse such systems. These restrictions can be overcome by making a few addition to Bernoulli's equation to produce an expanded form, it well be called the general energy equation that represents in Eq. (3.1) [54].

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + h_1 + h_A - h_L = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + h_2 \tag{3.1}$$

The energy losses and additions in a system will be accounted in terms of energy unit weight of fluid flowing in the system. This is known as ”head”. The symbol ”h” will be used for energy losses and additions. So h_A represents the energy added to the fluid with a mechanical device such as pump, and h_L represents the energy losses from the system due to friction in pipes. The magnitude of energy losses produced by fluid friction in pipes is directly proportional to the velocity head of the fluid. This can be expressed mathematically by Darcy's equation that shown in Eq. (3.2).

The behaviour of a fluid, particularly with regard to energy losses, is quite dependent on whether the flow is laminar or turbulent. For this reason the type of flow can be predicted without actually observing it. Indeed, direct observation is impossible for fluid in opaque pipes. It can be shown experimentally and verified analytically that the character of flow in around pipe depends on four variables: fluid density, fluid viscosity, pipe diameter, and average velocity of flow. Reynolds was the first to demonstrate that laminar or turbulent flow can be predicted of the magnitude of a dimensionless number, Eq. (3.4) shows the basic definition of the Reynolds number [38].

$$h_L = f \frac{L}{D} \frac{v^2}{2g} \tag{3.2}$$

$$f = \frac{64}{N_R} \tag{3.3}$$

$$N_R = \frac{vD\rho}{\mu} \tag{3.4}$$

where, h_L is the energy loss due to friction (N.m/N, m), L is the length of flow stream (m), D represents the pipe diameter (m), v is the average velocity of flow (m/s), f represents the friction factor (dimensionless), g is the acceleration of gravity (9.807 m/s^2), N$_R$ is the Reynolds number, ρ represents the fluid density (1180 kg/m^3)and μ is the fluid viscosity (0.914 pa.s). In order to calculate the energy added to the fluid by the pump, it is important to solve for h_A, so Eq. (3.5) indicates that the total head on the pump, h_A is the measure of all of the tasks the pump is required to do in a system. It must increase the pressure from that at point 1 at the inlet to the pump to the pressure at point 2. It must raise the fluid by the amount of elevation difference between points 1 and 2. It must supply the energy to increase the velocity of the fluid from that in the large pipe at the pump inlet (suction pipe) [38].

$$h_A = \frac{P_2 - P_1}{\gamma} + (h_2 - h_1) + \frac{v_2^2 - v_1^2}{2g} + h_L \tag{3.5}$$

Now, as shown in Fig. 3.3, there are two point of interest, point 1 is at the top of the input paint surface, and point 2 is at the discharge stage. Therefore, P_1 is the pressure at the surface of the input paint that exposed to atmosphere pressure, and P_2 is the pressure at the point of the discharge stage that also exposed to atmosphere pressure. The paint flows at a volumetric flow rate of $Q = 8.48 * 10^{-6} m^3/s$ through a pipe system. The pipe that at the inlet of the pump has a diameter of $D_A = 0.015m$, while the pipe that is at the pump outlet has a diameter of $D_B = 8 * 10^{-3} m$. So the cross section areas (A_A and A_B) of these pipes can be calculated. Thus, it is possible to compute the average velocities at point 1 and 2 (v_1 and v_2) as follow:

$$v_1 = \frac{Q}{A_A} = Q * \frac{D_A^2}{2} * \pi = 0.0479 m/s.$$
$$v_2 = \frac{Q}{A_B} = Q * \frac{D_B^2}{2} * \pi = 0.169 m/s.$$

As the paint flows from a pipe at a very low velocity, the flow appears to be smooth and steady. The stream has a fairly uniform diameter and there is a little or no evidence of mixing of various parts of the stream. This is called laminar flow. Based on Eq. (3.4), The Reynolds number of the fluid flow in pipe A and pipe B can be calculated as follows:

$$N_{RA} = \frac{0.0479 * 0.015 * 1180}{0.914} = 0.9276.$$
$$N_{RB} = \frac{0.169 * 8 * 10^{-3} * 1180}{0.914} = 1.745.$$

it is noticed that the flow has a very small Reynolds number, that is due to a low velocities and small pipes diameter. Therefore, the friction factor depends on the Reynolds number, it can be calculated based on Eq. (3.3) as follows:

$$f_A = \frac{64}{0.9276} = 68.9.$$
$$f_B = \frac{64}{1.745} = 36.67.$$

After that, based on Eq. (3.2), it is possible to compute the energy losses by the fluid friction in the pipe system as follows:

$$h_{LA} = 68.9(\tfrac{0.335}{0.015})(\tfrac{0.0479^2}{2*9.807}) = 0.18m.$$

$$h_{LB} = 36.67(\tfrac{0.33}{8*10^{-3}})(\tfrac{0.169^2}{2*9.807}) = 2.2m.$$

$$h_L = h_{LA} + h_{LB} = 2.38m.$$

Finally, based on Eq. (3.5), it is possible to compute the total energy added to the fluid by pump. It is equal $h_A = 2.48m$. So, in this work, a pumps with head = 2.8 m and volumetric flow rate = 300 L/H were chosen.

3.2.2 Power used in agitated vessel

In the most applications, when precise speed control is needed, the DC motor is preferable because its speed could easy be varied by changing the input voltage, whereas, varying the speed of AC motor requires varying the frequency which is more difficult. Also DC motor has more advantages over the AC motor which are [29]:

- DC motors is easier and cheaper to control of speed than AC motor.
- It can be started and stopped quickly.
- It has higher starting torque.
- DC motors do not have harmonic effect.

In the design of an agitated vessel, an important factor is the power required to drive the impeller to rotate at the desired speeds. Since the power required for a given system cannot be predicted theoretically, empirical correlations have been developed to predict the power required. The presence or absence of turbulence can be correlated with the impeller Reynolds number [12].

$$N_R = \frac{D_a^2 N \rho}{\mu} \tag{3.6}$$

where D_a is the impeller diameter in m, N is rotational speed in rev/s, ρ is fluid density in kg/m^3, and μ is viscosity in $pa.s$. The flow is laminar in the tank for $N_R < 10$, turbulent for $N_R > 10^4$, and for a range between 10 and 10^4, the flow is transitional, being turbulent at the impeller and laminar in remote parts of the vessel [12].

A lab-made paint mixing equipment is equipped with a two-bladed paddle impeller with a diameter of $D_a = 50.5mm$. The mixing tank is a cylindrical vessel with an inside diameter of $D_t = 101mm$, filled to a height of $H = 101mm$. Normally, the impeller is rotated at different speeds. So based on Eq. (3.6), the Reynolds number can be computed. Then, the power number N_P can be specified at a certain Reynolds number N_R.

$$N_P = \frac{P}{\rho N^3 D_a^5} \tag{3.7}$$

Table 3.1, shows the computed Reynolds number at each desired speed based on Eq. (3.6). When two-bladed paddle impeller was used and no baffles in the mixing vessel, the power number (N_P) can be specified based on the Reynolds number. The power required is related to fluid density ρ, fluid viscosity μ, rotational speed N, and impeller diameter D_a. So based on

Eq. (3.7), it is possible to compute the required power that must be supplied to the DC motor to run the impeller at the desired speeds.

Table 3.1: Power that must supply to stirring motor at each desired speed

$N(RPM)$	$N(rev/s)$	N_R	N_P	$P(watt)$	$V(volt)$
200	10/3	10.97	550	7.9	3.8
160	8/3	8.78	865	6.4	3.07
120	2	6.58	1540	4.8	2.3
80	4/3	4.39	3475	3.2	1.54

3.2.3 Impeller design

In the chemical and other processing industries, many operation are dependent to a great extent on effective agitation and mixing of fluids. Generally, agitation refers to forcing a fluid by mechanical means to flow in a circulatory or other pattern inside a vessel. liquids are agitated in a cylindrical vessel which can be closed or opened to air. An impeller mounted on a shaft is driven by electric motor [12].

The two-bladed and four-bladed flat paddles are the most common used agitators in mixing processes. The total length of the paddle impeller is usually 60% to 80% of the mixing tank diameter and the width of the blade $\frac{1}{10}$ to $\frac{1}{6}$ of its length. In the paint mixing machine the two-bladed flat paddles is used as agitator tool, it can be designed according to the geometric proportions for a "standard" agitation system that shown in Fig. 3.4 [12].

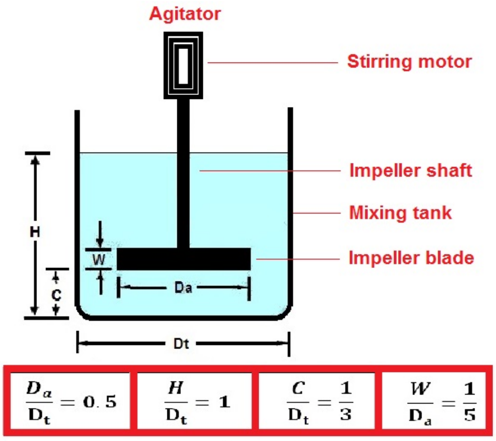


Figure 3.4: geometric proportions for a 'standard' agitation system

The mixing tank is a cylindrical vessel, the diameter of the mixing tank is $D_t = 101mm$, the maximum height of the liquid inside the mixing tank is $H = 101mm$.

Thus, $(\frac{H}{D_t}) = 1$.

The volume of the mixing tank V_t can be computed as follows:

$V_t = (\frac{D_t}{2})^2 \pi H$.

$V_t = 809mL$.

Now, it is important to calculate the distance between the bottom of the two-bladed paddle impeller and the bottom of the mixing tank (C).

$(\frac{C}{D_t}) = (\frac{1}{3})$.

$C = (\frac{D_t}{3}) = (\frac{101}{3}) = 33.7mm$.

Also, the length of the two-bladed paddle impeller (D_a) can be computed as follows:

$(\frac{D_a}{D_t}) = 0.5$.

$D_a = 50.5mm$.

The width of the two-bladed paddle impeller can be calculated as follows:

$(\frac{W}{D_a}) = (\frac{1}{5})$.

$W = 10.1mm$.

These dimensions of the impeller blade and the mixing tank must be taken into consideration through the design of the paint mixing machine.

3.2.4 Mechanical design for impeller shaft

Most mechanical loads come from an interaction between the mixer and the fluid. Obviously, a force is necessary to rotate the impeller. That force is represented by a torque load transmitted by the shaft from the drive to the impeller. Besides the fluid forces that resist the rotating impeller, moving fluid creates random hydraulic forces that act perpendicularly to the shaft. These forces create a bending moment on the shaft. A typical cantilevered shaft, which is supported only by the mixer drive, can experience significant bending loads. So, selection of shaft diameter requires consideration of both the torque and bending loads. Torque is easily calculated from the basic relationship of power divided by speed [44]:

$$T = \frac{P}{2\pi\ N} \tag{3.8}$$

where, T is the motor torque in $N.m$, P is the applied power in *watt*, and N is the rotational speed in rev/s. So from the applied power and mixer speed the torque can be calculated based on Eq. (3.8), which is equal to 0.3819 $N.m$.
An expression for the bending load on a mixer shaft with a single impeller represents in Eq. (3.9) [44]:

$$M = 19000\ \frac{P\ L\ fH}{N\ D_a} \tag{3.9}$$

$$N.m = 0.112985\ lb.in. \tag{3.10}$$

where M is the bending moment in ($lb.in$), L is the "shaft length to support" in (*inch*) which is equal to (0.165 m = 6.4961 in), fH is the hydraulic load (fH = 2.5 for liquid), and Da is the impeller diameter in (*inch*) which is equal (0.0505 m = 1.9882 in). The "shaft length to support" may exceed the shaft length inside the tank because the nearest support bearing may be in the drive or seal above the tank mounting or flange. Based on Eq. (3.10), it is possible to convert the moment unit from ($lb.in$) to ($N.m$). So based on Eq. (3.9), the bending moment is equal to (8.32161 $lb.in$ = 0.9401 $N.m$).
The torque and bending moment have been calculated, So based on Eq. (3.11), it is possible to compute the shear stress of the impeller shaft.

$$\sigma_s = \frac{16\ \sqrt{T^2 + M^2}}{\pi\ d^3} \tag{3.11}$$

where, σ_s is shear stress in *psi*, d is the impeller shaft diameter in (*inch*) which is equal to (0.314961 $in = 8*10^{-3}\ m$). The shear stress for the shaft is equal to (1464.05 psi = 10.09 Mpa), while the typical allowable shear stress for carbon and stainless steels is (6000 psi = 41.369 Mpa). This stress level takes into account the effects of fluctuating mixing forces that could result in a fatigue failure.
Then, based on Eq. (3.12), it is possible to compute the tensile stress of the

impeller shaft.

$$\sigma_t = \frac{16\ (M + \sqrt{T^2 + M^2})}{\pi\ d^3} \tag{3.12}$$

where, σ_t is tensile stress in psi. The tensile stress for the shaft is equal to ($2820.513\ psi = 19.4468\ Mpa$), the allowable tensile stress level for steels is ($10,000\ psi = 68.9476\ Mpa$). Higher-than-allowable stress levels may lead to a fatigue failure of the mixer shaft.

A solid stainless steel shaft in a paint mixing machine transmits power $6.4\ W$, and the motor torque is $0.3819\ N.m$. It is possible to determine the smallest safe diameter of the shaft. The maximum shear stress for stainless steel does not exceed $\tau_{max} = 41.3686\ MPa$ and it is assumed that the angle of twist Θ is limited to 3° in the shaft length of $L = 0.165\ m$. It is important to know that the shear modulus for stainless steel is equal to $G = 77.2\ GPa$.

To satisfy the strength condition, it is important to apply the torsion formula that is represented in Eq. (3.13):

$$\tau_{max} = \frac{T\ r}{J} = \frac{16\ T}{\pi\ d^3} \tag{3.13}$$

Which yields that the shaft diameter $d = 3.609\ mm$. Then, apply the torque-twist relationship that is represented in Eq. (3.14), to determine the diameter necessary to satisfy the requirement of rigidity. Knowing that Θ in radians:

$$\Theta = \frac{T\ L}{G\ J} = \frac{32\ T\ L}{G\ \pi\ d^4} \tag{3.14}$$

Which yields that the shaft diameter $d = 3.55\ mm$. Therefore, to satisfy both strength and rigidity requirements, it is important to choose the larger diameter that equal to $d = 3.609\ mm$. In this study a shaft with diameter $d = 8\ mm$ was chosen.

3.3 Design of monitoring and control

In industrial plants, large number of process variables must be maintained within specified limits in order to operate the plant properly. Excursions of key variables beyond these limits can have significant consequences for plant safety, the environment, product quality and plant profitability.

3.3.1 Monitoring design

Process monitoring plays a key role in ensuring that the plant performance satisfies the operating conditions. The general objectives of process monitoring are [56]:

1. Monitoring routine, this means that process variables need to be within specified limits.

2. Detection and diagnosis, this means that the abnormal process operation and the root case are detected and diagnosed.

3. Monitoring preventive, this means that the abnormal situations is early enough detected so that corrective action can be taken.

Abnormal operation in the paint mixing machine can occur for a variety of reasons, including equipment problems (plugging the inlet or the outlet of the pumps), instrumentation malfunctions (burn out the pumps, inaccurate mass sensor), and unusual disturbances (slowly pumping the raw material due to high viscosity). Severe abnormal situations can force the plant to shut-down.

The monitoring system have been built-up to determine whether the process and instrumentation are working properly. So based on Matlab GUI the monitoring system has been designed, Fig. 3.5 shows the GUI control panel. The right side of the GUI control panel has been designed to monitor the performance of the paint color preparation during experiments. It also help the user to shut down the process in abnormal conditions. Furthermore, in this monitoring technique, user be able to detect the the inaccurate measurements and take decisions.

Density(g/ml^3) 1 1 1

Initial values 0 0 0

Figure 3.5: GUI control panel

In this work, when the raw paints are fed into the mixing vessel, stirrer motor runs and starts mixing with specific speed. It is assumed that the beginning of mixing operation is at time (t=0 sec). At that time the camera starts to capture images of the mixture each 16 ms. Matlab codes are intended to analyse the paint mixture and to monitor the preparation of the desired paint as follows:

- User can press on 'start preview' push button to monitor the paint mixture during mixing process.
- A Matlab code is intended to observe and display the tristimulus values (RGB) of the paint mixture image each 16 ms.
- Then, these values are converted to normalized tristimulus values (rgb), and display it on GUI control panel.
- Based on eq. 2.3, Matlab be able to compute the distance (d) of the desired paint color and shows it in a specific label in GUI control panel. The distance (d) is used to specify the degree of homogeneity of the desired paint mixture.
- When the paint is completely homogeneous, the stirrer motor stop mixing, and the camera stop capturing images.
- It is possible to plot the time-varying tristimulus values curve of the mixture. In addition, the time-varying distance curve.
- User can display the distance-time curve at any time by pressing on 'plot distance' push button, that's to ensure the performance of the experiment, also, It is possible to estimate the remaining time to reach a state of complete homogeneity.

In order to get a real-time and stable system, the frequency of the processor must be greater than the frequency of the system. The minimum time required to get a homogeneous mixture is at a maximum allowable speed (200 RPM) which is equal to 21.04 s (will be illustrated in results chapter), so the frequency of the system is equal to 0.04753 Hz, but, the time required to capture an image is 16 ms, that means, the frequency of the processor is 62.5 Hz. Thus, the frequency of the processor is so larger than the frequency of the system, therefore, the system is real-time and stable. T=16 ms is enough for Matlab to capture and process the image in order to determine the tristimulus value of the desired color mixture, that's due to deal with one sample only instead of analysing the overall image.

3.3.2 Control design

Pump flow control

A pump is generally used to raise the pressure of the fluid. The pump imparting energy to the fluid by means of a centrifugal force developed by the rotation of an impeller that has several blades or vanes. The speed of the

impeller can be varied by controlling the speed of the pump motor. Also, it is important to know that the speed of the impeller is directly proportional to the volumetric flow of the pump [29].
In this paint mixing machine, pumps with volumetric flow rate 300 L/H and head of 2.8 m were used, so three pumps were used to control the flow of the raw paint colors from the inputs tanks into the mixing tank with the help of PID controller that has been tuned manually to get minimum error between the desired values and the actual values of the color masses. A load cell that is located under the mixing tank was used to measure the mass of the pumped-paint color. Fig. 3.6 shows the block diagram of the pump-motor flow control.

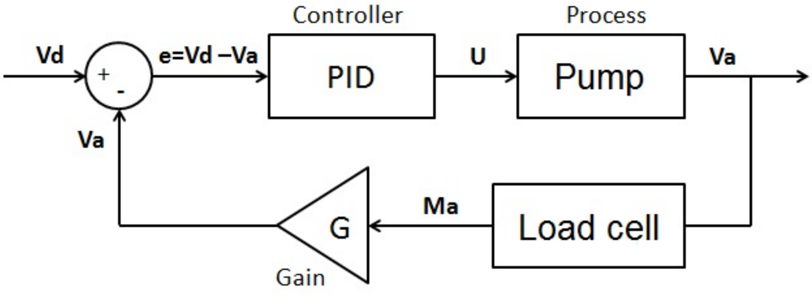


Figure 3.6: Block diagram of the pump flow control

when the desired raw paint volumes (Vd) are specified depends on paint database, each of the three pumps starts to feed the computed raw paint volumes (Va) into the mixing tank. A load cell is used to measure the mass for each of the fed raw paints (Ma), after that, these mass values are converted into volume values through gain G which represents ($1/paint\ density$). Based on the computed error between the desired and the actual paint volumes, the PID controller be able to generate a suitable voltage signal (U) to ensure that the desired paint volumes are close as possible to the actual fed paint volumes.
If it is assumed that $120g$ of red, $80g$ of green, and $160g$ of blue are required to produce a $305mL$ of RGB_x color, these values called the desired masses values that must be pumped into the mixing vessel to be mixed. The micro-controller gives instruction to the red color pump in order to enter a $120g$ of red into the mixing tank, a load cell was located under the mixing vessel in order to give feedback (actual pumped color mass) to the micro-controller to ensure that the actual red mass value is equal to the desired red mass value. Then, when the red color is completely entered the mixing tank, the micro-

controller directly gives instruction to the green color pump to enter a $80g$ of green into the mixing tank without delay time between them, the pump continuously works until the total mass reach $200g$ $(120g + 80g)$. After that, the blue color pump starts, it continuously works until the total mass reach to $360g$ $(120g + 80g + 160g)$, see Fig. 3.7. Sometimes may the total mass of the three colors reaches $362g$, the difference between the actual values and the desired values does not exceed $2g$, this difference has no effect on the desired color accuracy.

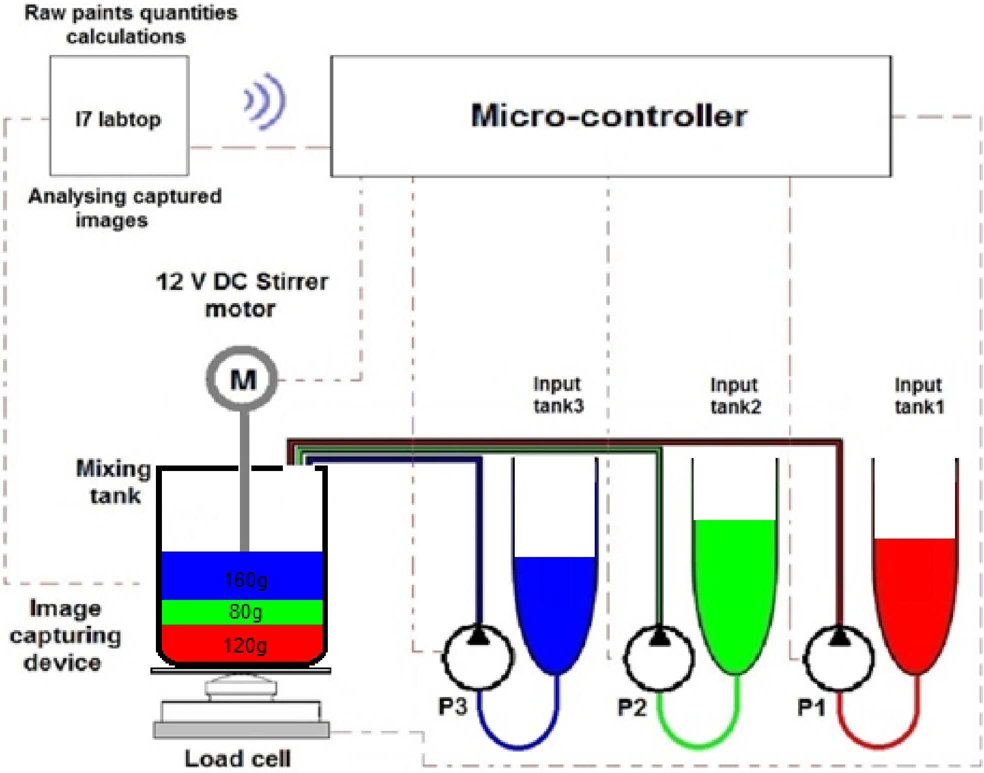


Figure 3.7: controlling the paint quantity

Stirrer-motor speed control

Stirrer motor speed control is an important requirement in this work to study the effects of stirrer speed (rpm) on mixing time (sec). Two points are essential to investigate the speed control:

1. Pulse width modulation (PWM): is a technique which allows us to adjust the average value of the voltage that goes to the electronic device

by turning on and off the power at a fast rate. The average voltage depends on the duty cycle, or the amount of time the signal is on versus the amount of time the signal is off in a single period of time.

2. The L298N: is a dual H-Bridge motor driver which allows speed control of a DC motor. This module can drive DC motors that have voltages between 5 and 35 V, with a peak current up to 2A.

Then, by using arduino we can control the speed of the motor by controlling the PWM output. As shown in Fig. 3.8, we controlled the speed of the DC motor to run at a different speeds (200 RPM, 160 RPM, 120 RPM, and 80 RPM).

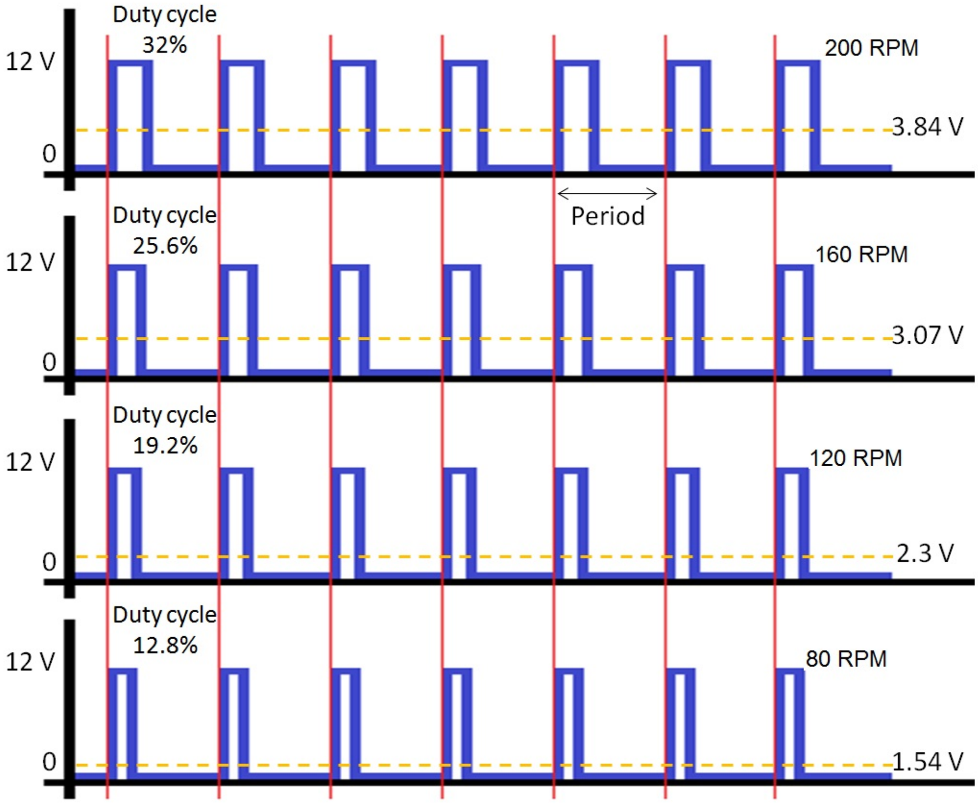


Figure 3.8: stirring motor speed control based on PWM

Also, to ensure that the motor runs at the desired speeds, a closed loop speed control for the dc motor has been done. Fig. 3.9 shows the used block diagram of the dc motor speed control.

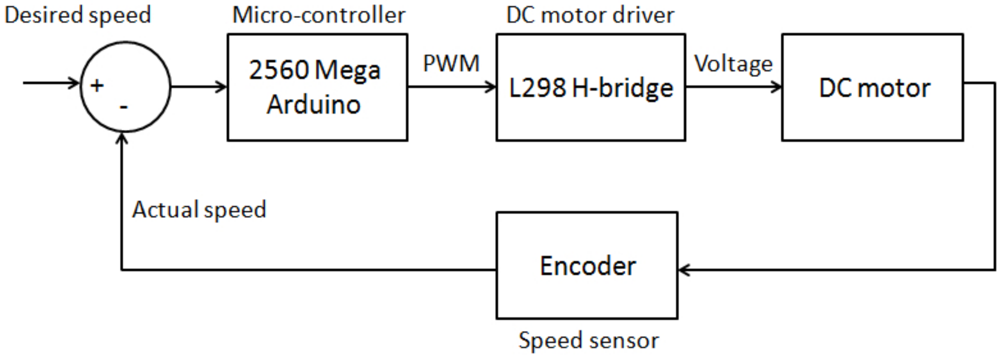


Figure 3.9: The block diagram of the dc motor speed control

3.4 Process variables manipulating

Experiment is a controlled procedure that is carefully designed to test assumptions about the effect of one or more independent variables on an outcome measure. So experiments provide insight into cause-and-effect by demonstrating what outcome occurs when a particular factor is manipulated. We will run sets of experiments to verify that results are repeatable. In other words, it important to verify that we obtain essentially the same results every time you repeat the experiment with the same value for the independent variables.

It is known that any physical or chemical quantity which is usually measured and controlled in the operation of industrial plant is called a variable. During experiments, two types of variables must be considered which are the independent and the dependent variables. So the independent variables are an effect which potentially influences the outcome of an experiment, which the researcher specifically manipulates to test a predefined assumptions. The independent variables in the paint mixing experimental procedures are the stirrer motor speed in (rpm), the tristimulus value of the desired paint color (RGB_x), and batch volume in (ml). while the dependent variables are the parameters that the researcher focuses his observations on to see how they respond to the change made to the independent variable. The dependent variables in the paint mixing experimental procedures are the mixing time (homogeneity time) in (sec) and the main variable that specifies the degree of homogeneity which is the paint color distance (d).

During the performance of experiments in order to study the relation between these variables and homogeneity time, it is assumed that mixing time is the time required for the mixture to reach homogeneity. At the beginning

of mixing process, the dependent variable (color distance) has a transient response, it will take some time to reach its steady state value and also it is likely to overshoot the steady state value before it finally settles down to the steady state value. Therefore, it is assumed that the homogeneity of the mixture occur at settling time.
In the paint mixing experimental procedures there are three independent variables. If we changed more than one variable at a same time in the same experiment, it would be hard to figure out which of the independent variables cause the change in the experimental results. So to study the effect of the independent variables on the dependent variables, we based on the separation of variable method, this method allows us to change one of the independent variables at a same experiment and other variables remain constant, this method enables us to find out the effects of changing this variable on the dependent variables.

In this work, we assume the following:

- Increasing stirrer motor speed will reduce the time required to reach homogeneity state and vice versa.
- Increasing batch volume will increase the time required to reach homogeneity state and vice versa.
- Changing the tristimulus value of the paint color will change the color distance.
- changing stirring speed and the batch volume do not affect on the color distance.

Chapter 4

Experimental approach

4.1 Materials

SIPES SI-TONE paints have been adopted for mixing in all the performed experiments. This paint is a water-base paint; formulated, thinned and cleaned up with water, in addition, its density is equal to $1.18 g/mm^3$ [59]. Three coloured paints have been used as a basic paint colors which are red, green, and blue.

Figure 4.1: SIPES SI-TONE paint

The production of oil-based paint is more expensive than water-based paint. In water-based paint, water can be used as a cleaning material to clean up the mixing vessel after each usage, while oil-based paint is more difficult to remove the remaining paint from the mixing tank boundaries, it requires a special material for cleaning up the mixing vessel.

The mixing algorithm that has been applied in the paint mixing machine is valid to prepare oil-based paint, but, analysing the paint mixture based on Matlab with the help of a camera is impossible when this type of paint is used. At the beginning of the mixing process, the paint mixture is stuck on the boundaries of the transparent cylindrical mixing vessel, that means, what happens inside the mixing tank does not appear on its transparent boundaries, thus, it is impossible to analyse the paint mixture when the oil-based paint is used.

4.2 Equipments

The proposed work is implemented and tested using a lab-made equipment. In this lab-made equipment the following was used:

- The materials of construction of the mixing tank must be compatible with the fluids that are to be mixed. For most mixing experiments the ability to see clearly what is happening inside the mixing tank is extremely useful [44]. So a transparent cylindrical vessel was used as mixing tank with mixing size about 809 ml, it was used for ease cleaning purpose after each paint mixing process, also the tank remains shiny and its color does not change with time. This feature guarantee high-accuracy results through capturing images for the paint mixture using the camera. Fig. 4.2 shows the dimension of the used mixing tank.

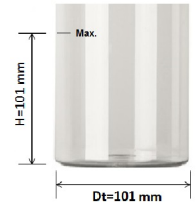


Figure 4.2: The transparent mixing tank

- Three transparent tanks for raw paint colors (red, green, and blue paint) were used. These tanks are a plastic-made, the lower part of them seems to be conically in order to smoothly flow of the raw paint. The capacity of each tank is approximately 1120 ml. Fig. 4.3 shows the shape and the dimension of the inputs tanks.

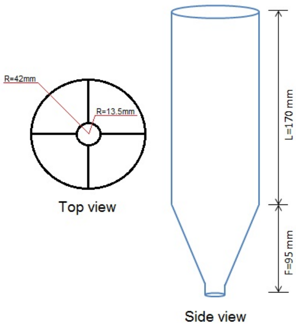


Figure 4.3: The top and the side view of the inputs tanks

- Pump is a mechanical device that use to transfer the liquid from one point to another by adding kinetic energy to the liquid. In this lab-made equipment, three pumps with volumetric flow rate ($Q = 300L/H$) and head ($h = 2.8m$) were used, these pumps have been employed to transfer the raw paint colors from the inputs tanks into the mixing tank. Fig. 4.4 shows the used pumps that have 15 mm inlet diameter and 8 mm outlet diameter.

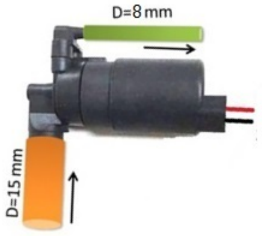


Figure 4.4: pump with volumetric flow rate ($Q = 300L/H$) and head ($h = 2.8m$)

- A two-bladed paddle impeller which is driven by DC motor was used in the purpose of mixture stirring. In section 3.4, the power that must be supplied to motor in order to get the desired speed has been computed, that means, a 12 V DC motor with maxinum speed ($N = 625RPM$) can satisfy the required speed. As shown in Fig. 4.5 the impeller is connected with stirring motor by the means of rigid coupler.

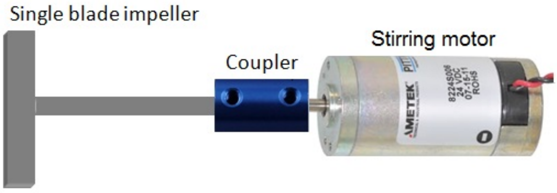


Figure 4.5: Two-bladed paddle impeller connected to 12V DC motor

- A high-resolution camera was used for capturing images for the paint color mixture that inside the stirred tank, namely, 12 Mega-pixel microscope camera. The position of the camera with respect to transparent mixing tank always be constant during capturing images to ensure the accuracy of the mixture analysis. The camera is located in the opposite of dead zone region of the mixing vessel as shown in Fig. 4.6.

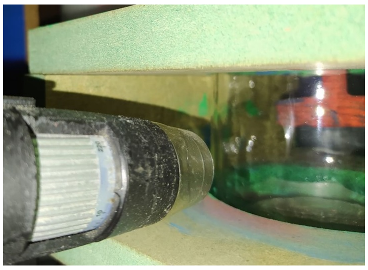


Figure 4.6: The position of the camera with respect to transparent mixing tank

- An arduino Mega was used as controller for the paint mixing machine. An I7 laptop machine was used for algorithm implementation and data regression (fitting). As shown in Fig.4.7 the laptop machine is interfaced with 2560 mega arduino through HC05 bluetooth module.

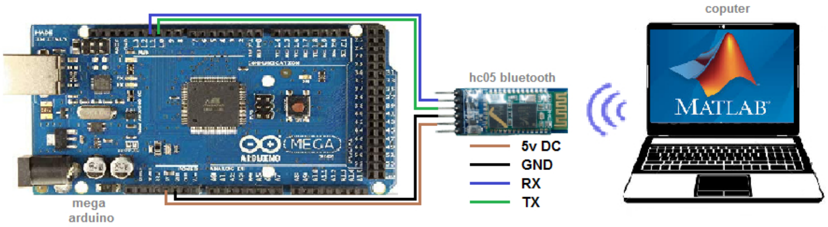


Figure 4.7: Interfacing the laptop machine with arduino mega

- Also a load cell with a desired control loop beyond the mixing tank attributes was used. The load cell is connected with HX711 amplifier module. This amplifier is a small breakout board for the HX711 IC that allows easily read load cells to measure weight. By connecting the amplifier to micro-controller, it is possible to read the changes in the resistance of the load cell and with some calibration it becomes capable to get very accurate mass measurements. The HX711 uses two wires interface (clock and data) for communication as shown in Fig. 4.8.

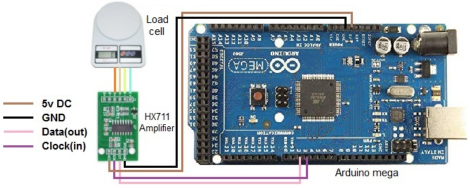


Figure 4.8: Load cell with HX711 load cell amplifier

Fig. 4.9 shows the electrical circuit board of the paint mixing machine.

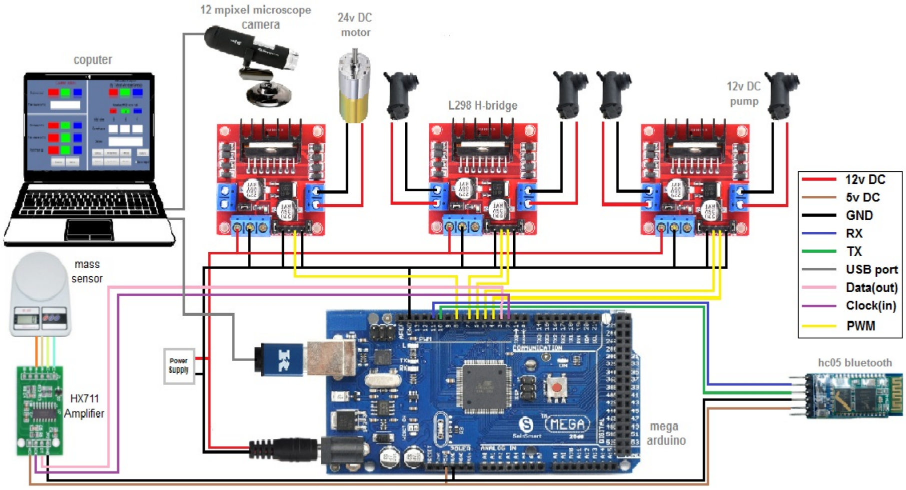


Figure 4.9: Electrical circuit board of the paint mixing machine

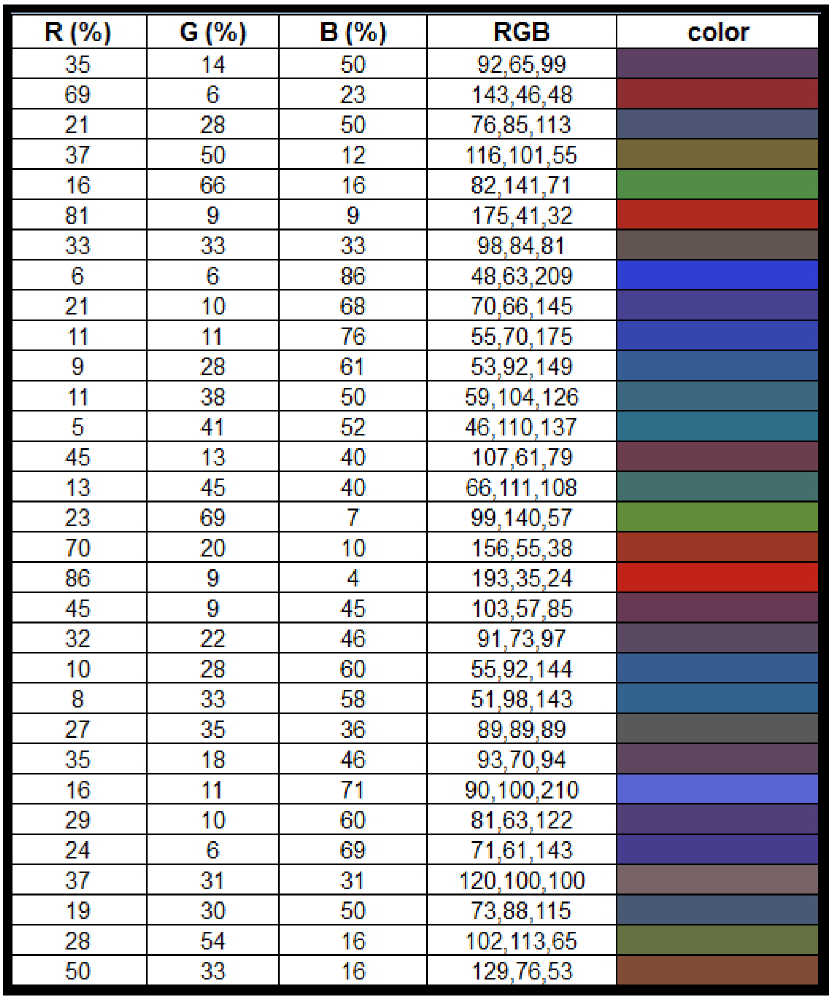
4.3 Experiment conditions

It is known that the experimental data leads to derive the paint mixing process model, so to ensure the accuracy of the experimental data through paint mixing, all experiments must be performed at the same conditions. Thus, the working conditions are as follows:

- The same camera was used in all the performed experiments. Also, the location of the camera must be constant.
- The mixing motor speed depends on impeller shape, a two bladed paddle impeller was used, so the mixing motor speed allows in this case from 20 RPM to 200 RPM.
- All experiments have been performed at the same luminous intensity, therefore, the tristimulus value (RGB) has the same accuracy through capturing images for the desired paint color.
- At a same temperature, the viscosity of the raw paint colors remain constant. So all experiments have been performed at the same room temperature.

4.4 Experiment procedures and data analysis

In this section, a detailed steps for producing a new desired paint color have been introduced. The *RGB* color model is an additive color model in which red, green, and blue are added together in various ways to reproduce a broad array of colors. In *RGB*, colors are represented by their red, green and blue values, grouped together in a three dimensional vector.
The distance formula (d) in Eq. (2.3) assists to analyse the paint in the purpose of paint homogeneity test. The distance represents the range between the current normalized value (r_j, g_j, b_j) (the rgb value of the mixture each 16 ms) and the initial normalized value (r_i, g_i, b_i) (the rgb value of the mixture at time t=0 sec).



R (%)	G (%)	B (%)	RGB	color
35	14	50	92,65,99	🟪
69	6	23	143,46,48	🟥
21	28	50	76,85,113	🟦
37	50	12	116,101,55	🟫
16	66	16	82,141,71	🟩
81	9	9	175,41,32	🟥
33	33	33	98,84,81	🟫
6	6	86	48,63,209	🟦
21	10	68	70,66,145	🟦
11	11	76	55,70,175	🟦
9	28	61	53,92,149	🟦
11	38	50	59,104,126	🟦
5	41	52	46,110,137	🟦
45	13	40	107,61,79	🟪
13	45	40	66,111,108	🟩
23	69	7	99,140,57	🟩
70	20	10	156,55,38	🟥
86	9	4	193,35,24	🟥
45	9	45	103,57,85	🟪
32	22	46	91,73,97	🟪
10	28	60	55,92,144	🟦
8	33	58	51,98,143	🟦
27	35	36	89,89,89	⬛
35	18	46	93,70,94	🟪
16	11	71	90,100,210	🟦
29	10	60	81,63,122	🟪
24	6	69	71,61,143	🟪
37	31	31	120,100,100	🟫
19	30	50	73,88,115	🟦
28	54	16	102,113,65	🟩
50	33	16	129,76,53	🟫

Figure 4.10: Paint commercial database .

1. First, the user can select the tristimulus value of the desired paint color (RGB), and the required quantity of that paint color in (mL). So if a 500 ml of $(71, 61, 143)$ color wish produce.

2. Each of the three basic colors contribute with a specific ratio to produce a new desired paint color, these ratios can be specified based on the paint comertial database that shown in Fig. 4.10.

3. Based on the paint manufacturing data, the density of the paint must be taken into consideration, In order to accurately convert between the volumes and masses of the basic colors that contribute to produce a new paint color. The densities for the three paint colors are equal ρ_R $= \rho_G = \rho_B = 1.18$ g/ml.

4. After that, the suitable volumes and the masses that must be mixed together to produce the predefined color can be computed. Thus, the required raw paint colors volumes and masses to produce 500ml $(71, 61, 143)$ color will be as follows:

   - $Red\ color\ volume\ (V_r) = 24\%\ *\ 500mL = 120\ mL$
   - $Green\ color\ volume\ (V_g) = 6\%\ *\ 500ml = 30\ mL$
   - $Blue\ color\ volume\ (V_b) = 69\%\ *\ 500ml = 345\ mL$
   - $Red\ color\ mass\ (m_r) = 120\ mL\ *\ 1.18 = 141.6g$
   - $Green\ color\ mass\ (m_g) = 30\ mL\ *\ 1.18 = 35.4g$
   - $Blue\ color\ mass\ (m_b) = 345\ mL\ *\ 1.18 = 407.1g$

   .

5. Then, the computed raw paint colors masses have to be pumped into the mixing tank using three pumps.

6. When the raw materials are completely entered the mixing vessel, the mixing motor runs and starts mixing with specific speed. It is assumed that the beginning of mixing operation occurs at time (t=0 sec).

7. At that time the camera starts to capture images of the mixture each 16 ms.

8. A Matlab code is intended to read the tristimulus value (RGB) of the paint mixture images that have been captured by camera.

9. Then, these values are converted to normalized tristimulus values (rgb).

10. Using the normalised values, Matlab code be able to compute the distance (d) using Eq. (2.3). Therefore, the distance is used to specify the degree of homogeneity of the desired paint mixture.
11. User can monitor the paint mixture during mixing process. When the paint is completely homogeneous, stirrer motor stop mixing, and the camera stop capturing images.
12. Then, Matlab can plot the the time-varying tristimulus values of the mixture as well as the time-varying distance.
13. All images of the paint mixture that captured by the camera can be saved in a specific folder.

Finally, the accuracy of the produced color is an important issue. So if it assumed that (RGB_y) is the tristimulus value of the output color, and (RGB_x) is the tristimulus value of the desired color, then, based on Eq. (4.1), the error between the output color and the desired color can be computed, which is equal to the norm for the difference of these two vectors.

$$||RGB_y - RGB_x||\ \% = (\sqrt{(R_y - R_x)^2 + (G_y - G_x)^2 + (B_y - B_x)^2})\% \quad (4.1)$$

where,

$RGB_y = [R_y\ G_y\ B_y]$

$RGB_x = [R_x\ G_x\ B_x]$

One of the performed experiment was designed to produce [71 61 143], the output color has tristimulus value of [70 62 143], so the error is equal to 2.2361%. Thus the accuracy of this paint color is equal to 97.764%

Chapter 5

Modelling approach and paint mixing algorithm

5.1 Empirical modelling approach

The dynamic behaviour of the mixing processes can be obtained through a plot of dimensionless time -varying distance function (d) from the first instant of mixing. Our next goal is to find the relation of changing the distance with respect to time. This relation clearly represents the model of mixing. The dynamic behaviour of the mixing process can be modelled mathematically (e.g., diffusion and flow fluxes) or empirically based on 'reasonable' exponential models that describe the process of mixing.
Empirical models in industrial process engineering employs experimental measurements to gain insight into the development of the process. The empirical modelling approach has been adopted to develop the model of the paint mixing process. This is due to the relative simplicity of this method as well as its ability to both integrate into a system model and provide insight into the inner workings of the process. The accuracy of the models was then determined through comparisons with experimental measurements [13, 32, 58].

5.2 Empirical functions

Curve fitting is used to specify a model that provides the best fit to observed data that has been determined based on experiments. So before assuming the empirical formula that can be well suited to the paint mixing, it is important to note that, not all the distance observations by the camera will satisfy the following inequality:

$$0 \leq d(t) \leq d_{ss} \tag{5.1}$$

where d_{ss} is the final distance between the surface color before mixing and the steady state surface color. This is because that the camera can observe other transient colors with tristimulus values that gives $d > d_{ss}$. Therefore the formula of transient response must involve the initial distance, which must be zero, final distance which must be d_{ss}, overshoot which will be greater than or equal to d_{ss} and some oscillations until reaching the final steady state distance d_{ss}. Based on this physical understanding of the process Eq. (5.2) can satisfy Constraint (5.1) and, at the same times, describes the distance as a time-varying function:

$$d(t) = d_{ss} + e^{-A_1 t} \left(A_2 \cos(A_4 t) + A_3 \sin(A_4 t) \right), \tag{5.2}$$

where A_1 represents the speed of convergence to reach the final desired paint color (i.e. equivalent to some kind of rate coefficient of the process), A_2 and A_3 represent the overshoots with respect to cosine and sine terms, respectively, and A_4 is called the damping speed. Eq. (5.2) is a solution of a second order differential equation. Eq. (5.2) can be simplified by assuming the oscillation happens only with cosine term and shifted with a certain angle θ, namely:

$$d(t) = d_{ss} + A_5 e^{-A_6 t} \cos\left(A_7 t + \theta \right), \tag{5.3}$$

here the overshoot is only represented by A_5, where A_6 represents the speed of convergence to reach the final desired paint color and A_7 is the damping speed . On the other hand, if there is no oscillations, (i.e., when all the observed distances are below the distance of the mixed paint which satisfy Inequality (5.1)) then Eq. (5.3) can be rewritten as follows:

$$d(t) = d_{ss} + A_8 e^{-A_9 t}, \tag{5.4}$$

where A_8 and A_9 represent the overshoot; which is a kind of distance initial rate, and the speed of convergence to reach the final desired paint color, respectively. Eq. (5.4) is a simple first order model that is used typically in modelling kinetic chemical processes. In the next section, the method of data fitting for Eqs. (5.2) -(5.4) and the observed data from the camera will be illustrated.

5.3 Experimental data regression

Now, the question whether the observed readings that come from the camera can fit one of the Eqs. (5.2) - (5.4) well. This can be answered through the most powerful tool of non-linear least square method [20]. In the non-linear least square method, a non-linear programming problem using the observed data from the camera and one of the time-varying functions in Eqs. (5.2) - (5.4) has been formulated. To summarize this procedure, it is assumed that the observed distance vector from the camera D, namely:

$$D = [d_0 \;\; d_1 \;\; \dots \;\; d_n]^T \tag{5.5}$$

Where d_k is the distance at kth sampling, $k = 0, 1, \dots, n$. Now to use the non-linear least square method to fit the distance vector D (cf. Eq. (5.5)) to the time-varying function, e.g., Eq. (5.2), a non-linear programming (NLP) problem will be formulated as follows. Find the parameters: d_{ss}, A_1, A_2, A_3 and A_4 that describe the empirical function $d(t)$, cf. Function (5.2) and minimize the objective function:

$$L = \sum_{k=0}^{n} (d(t_k) - d_k)^2 \tag{5.6}$$

Here the difference $(t_{k+1} - t_k = \Delta t)$ is the sampling time of the camera. This objective function can be also used for empirical Functions (5.3) and (5.4), by finding the optimal describing parameters therein. The above NLP problem can be solved easily using NLP solver. The well-known fitting Matlab subroutine `lsqcurvefit` was used [48] to solve this NLP problem.

5.4 Paint mixing algorithm

A mixing algorithm with the help of SIPES SI-TONE paint commercial database is demonstrated here. The desired color and its quantity must be selected by the user, then, The ratio for each basic color that contributes to get the desired color can be specified from the SIPES SI-TONE database as in Eq. (5.7).

$$V_h = input(Paint\ commertial\ database) \tag{5.7}$$

So based on Eq. (5.8), the volume for each basic paint color can be computed [1]

$$V_h = Paint\ color\ ratio * V_T \tag{5.8}$$

---

[1] In this work, we use $V_{h=X_h\ V_T}$ for simplicity.

where, V_h is the volume for color h. V_T represents the total volume of the paint mixture. Then, for simplicity, three paint colors with similar viscosity and density were used as basic colors. So based on Eq. (5.9), the mass for each basic color can be computed.

$$m_h = \rho_h V_h \tag{5.9}$$

where, the mass of the paint color m_h, index h refer to the basic colors which are red, green or blue and ρ_h is the paint density which is equal to 1.18 g/mL. The algorithm that shown in Fig. 5.1 was used to implement and observe the data measurements for the paint mixing process. The following steps represent the pseudo code for the paint mixing process:
Inputs: The total required paint volume, the required color, i.e., the tristimulus values R, G and B, homogeneity tolerance `tol`.
Outputs: The volumes of red, green and blue paints, the required mixed paints, the parameters d_{ss}, A_i, $i = 1, \dots 9$, θ (cf. Eqs. (5.2)-(5.4)), mixing time that guarantees a color homogeneity that is with certain accepted tolerance `tol`.

- **Step 0**: Initialize: The input paint colors $rgb_r = [1\ 0\ 0]^T$, $rgb_g[0\ 1\ 0]^T$, $rgb_b = [0\ 0\ 1]^T$.
- **Step 1**: Compute the relative tristimulus values of the desired paint color; $rgb_h = [r_h\ g_h\ b_h]^T$ using Eq. (2.2).
- **Step 2**: Compute volume of the input paints using Eq. (5.8).
- **Step 3**: Pump the computed volumes in Step 2 into the mixing tank, simultaneously.
- **Step 5**: Set the counter $k = 0$. Initialize the distance $d_k = 0$. Observe the tristimulus values of the surface color, i.e.$rgb_0 = [r_0\ g_0\ b_0]^T$, using the top camera. Start mixing.
- **Step 6**: Set $k = k+1$. Observe the tristimulus values $rgb_k = [r_k\ g_k\ b_k]^T$ of the surface color. Compute the distance between rgb_0 and rgb_k, i.e. $d_k = rgb_k - rgb_0$ using Eq. (2.3). Set $d_k = [d_{k-1}\ \ d_k]$
- **Step 7**: If $|rgb_h - rgb_k| >$ `tol`; go to Step 6. Else, stop mixing.
- **Step 8**: Use the subroutine lsqcurvefit to fit the vector d_k with Functions (5.2), (5.3) or (5.4).
- **Step 9**: **Out**: Mixing time= $k\Delta t$, the parameters d_{ss}, A_i, $i = 1, \dots 9$, θ. Exit.

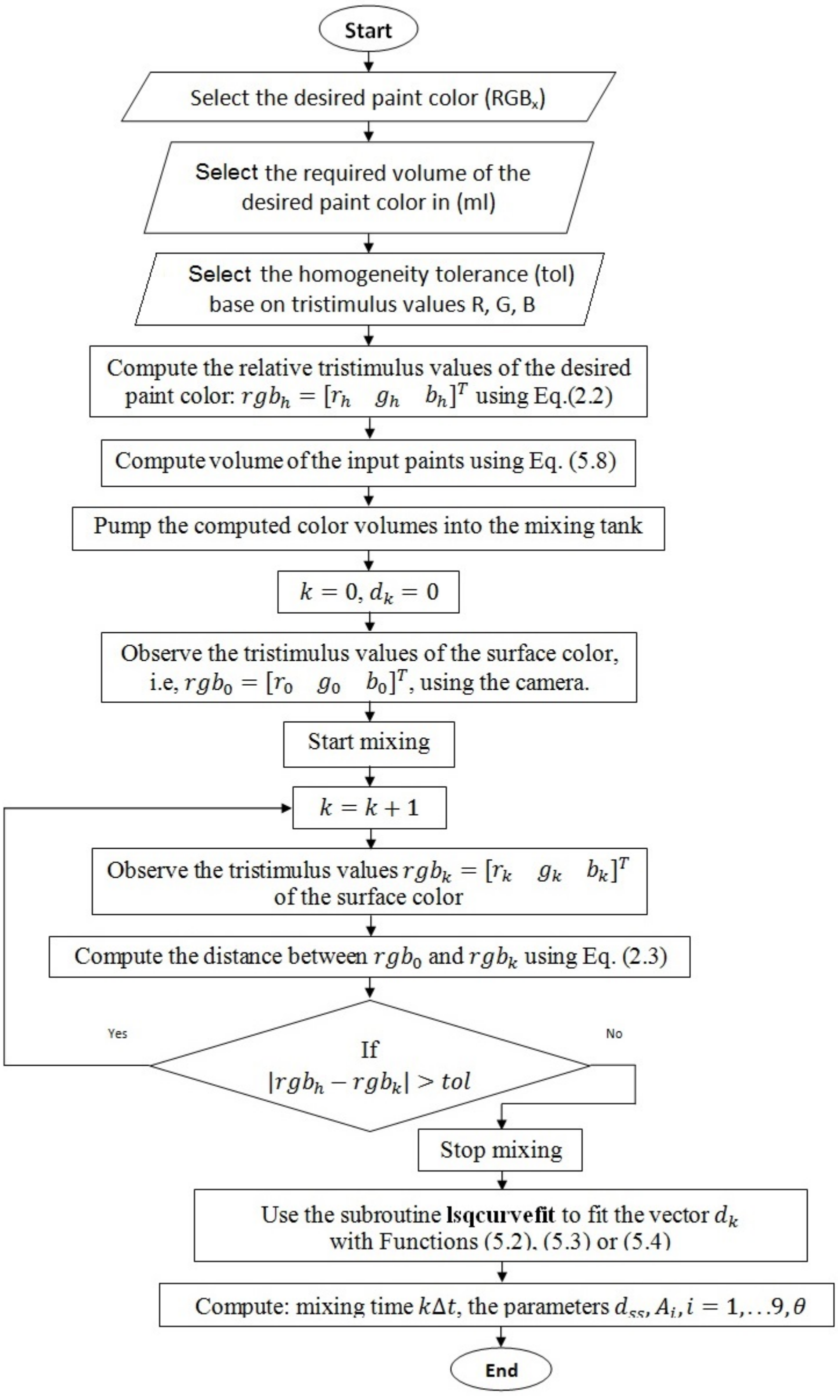


Figure 5.1: Paint mixing algorithm

Chapter 6

Results and discussion

6.1 General process behaviour

In this section, the general behaviour of the paint mixing process will be introduced. Fig. 6.1 shows the time-varying distance function ($d(t)$) for one of the performed experiment based on the lab-made equipment.

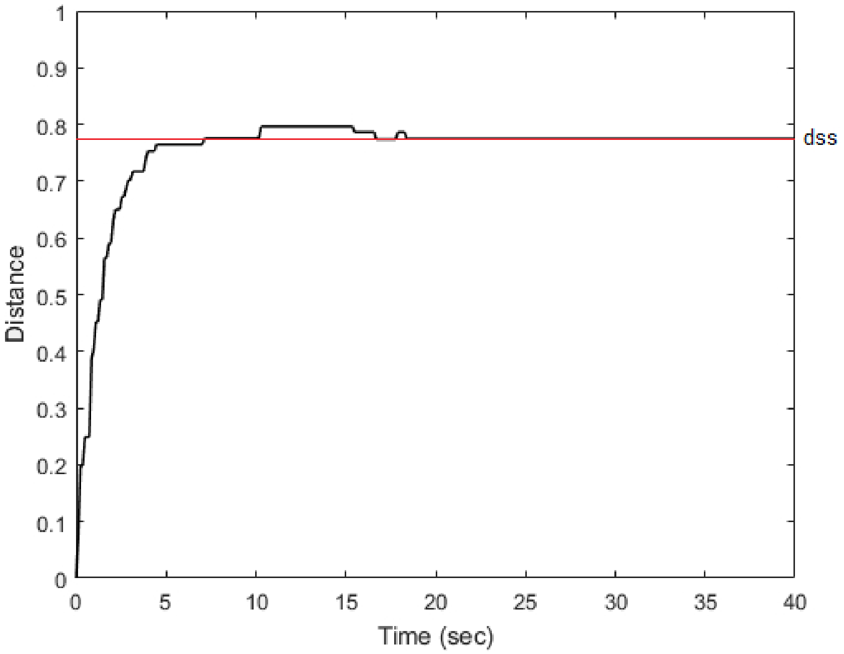


Figure 6.1: General paint mixing process behaviour

- At time zero, all the raw paint color ratios that contribute to produce the desired paint color are pumped into the mixing tank, the stirrer motor begins mixing, and the camera stars capturing images for the mixture each 16 ms.
- In transient region the paint mixture is converted from inhomogeneity toward the homogeneity state. The speed of convergence of the steady state depends on the stirrer motor speed (will be illustrated in Section 6.3), batch volume (will be illustrated in Section 6.5). The viscosity of the raw paint colors is constant, therefore, the paint viscosity did not effect on the speed of convergence to steady state.
- Before the paint mixture is completely homogeneous ($d_k < d_{ss}$), an overshoot may be occurred, This is because that the camera can observe other transient colors with tristimulus values that gives $d > d_{ss}$.
- Finally, during time the distance between the mixed and the unmixed paint color will reach to saturation region, that mean, the distance of the paint color reach to the steady state value, thus, the homogeneity of the desired paint color is investigated.

In general, there are some variables effect on the paint mixing, specially on the mixture homogeneity time. The effects caused by the different variables on the paint mixing process will be explained in sections (6.3, 6.4, and 6.5).

6.2 Comparison real process behaviour with models

Several experiments have been done to test our proposal. Each experiment aims to produce a 300 mL of a new desired paint. The first set of experiments is intended to produce x_1 color with tristimulus vector $RGB_{x_1} = [180 \;\; 210 \;\; 100]^T$, at maximum mixing motor speed of 200 RPM. This experiment has been repeated four times, to ensure the validity of paint mixing algorithm that shown in Fig. 5.1, and to chose the proper fitting function. Fig. 6.2 shows the time-varying distance for these experiments. Here it is seen that the measured distance as function with the time (black) where the fitting curves cf. Eqs. (5.2), (5.3) and (5.4) are in blue, green and red, respectively.

In each experiment the desired paint color reaches homogeneity almost at a same instant. Also the distances are equal at a same tristimulus value (R, G, and B) which means the distance depends only on tristimulus value for

the predefined color. The mixing motor speed is constant (200 RPM), so the speed of convergence to the steady state is almost constant.
From Table 6.1, it is noticed that the best fit empirical function in this case is the Function (5.2), since it has the minimum objective function less than others.

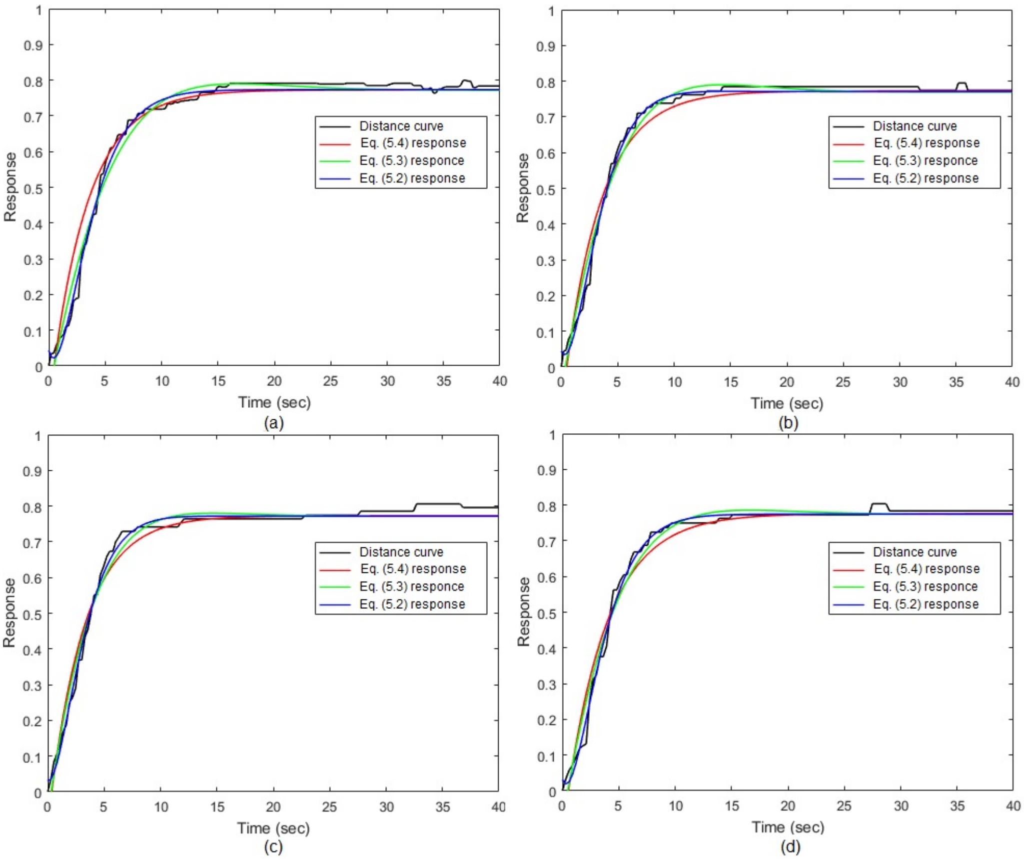


Figure 6.2: The result of producing the color with the $RGB_{x_1} = [180 \quad 210 \quad 100]^T$ (repeated four times: a, b, c and d). Black: measured distance curve. Blue, green and red curves: response with fitting Functions (5.2)-(5.4), respectively.

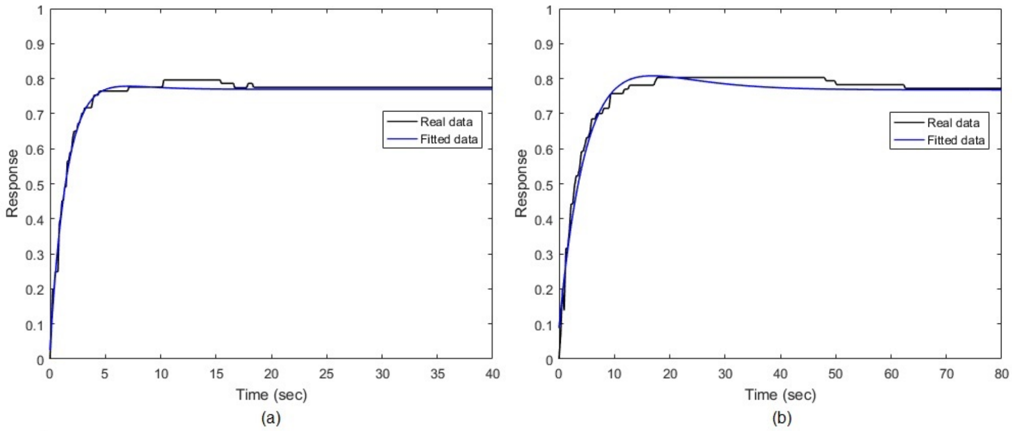
6.3 Effect of stirrer speed

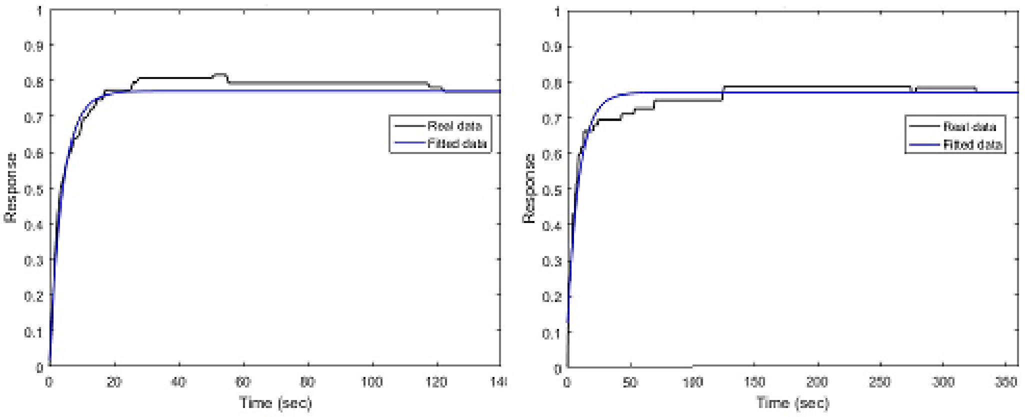
The second set of experiments has been performed to investigate the effect of the mixing speed to the distance response 'homogeneity response'. In this set, it is intended to produce x_1 color, i.e., with tristimulus vector

Table 6.1: Comparison between the responses of mixing paints with $RGB_{x_1} = [180 \quad 210 \quad 100]^T$

Exp. No.	**Empirical fun.**	**Obj. value (L) cf. Eq.** (5.6)
1	Eq. (5.4)	0.1731
	Eq. (5.3)	0.1257
	Eq. (5.2)	0.0741
2	Eq. (5.4)	0.1731
	Eq. (5.3)	0.0904
	Eq. (5.2)	0.0462
3	Eq. (5.4)	0.1619
	Eq. (5.3)	0.1361
	Eq. (5.2)	0.1007
4	Eq. (5.4)	0.2069
	Eq. (5.3)	0.1697
	Eq. (5.2)	0.1205

$RGB_{x_1} = [180 \quad 210 \quad 100]^T$ but, with different mixing speeds, namely, 200, 160, 120 and 80 rpm. Fig. 6.3 shows the time-varying distance response according the measured distance (black) and empirical Function (5.2) with the previous speeds, respectively. Here, it is seen that a slower mixing speed results more delay to reach the homogeneous paint. Obviously, increasing the mixing speed increases the rate of mass transfer between regions of various color. Thus, this decreases the time required to reach color homogeneity.





(c)

(d)

Figure 6.3: The result of producing the color with the $RGB_{x_1} = [180 \quad 210 \quad 100]^T$ (repeated four times: a, b, c and d). Black: measured distance curve. Blue curves: response with fitting Function(5.2).

Based on table 6.2, the relation between mixing speed (rpm) and homogeneity time (sec) has been drawn as shown in Fig.6.4. The relationship between these two variables was fitted to the second order polynomial function as in Eq. (6.1). So it is possible to estimate the required mixing time at any desired mixing speed.

$$y = -0.0023x^2 - 1.3253x + 225.57 \tag{6.1}$$

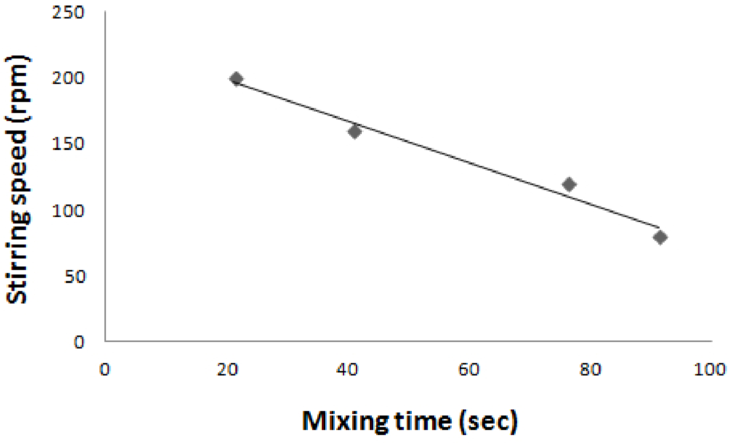
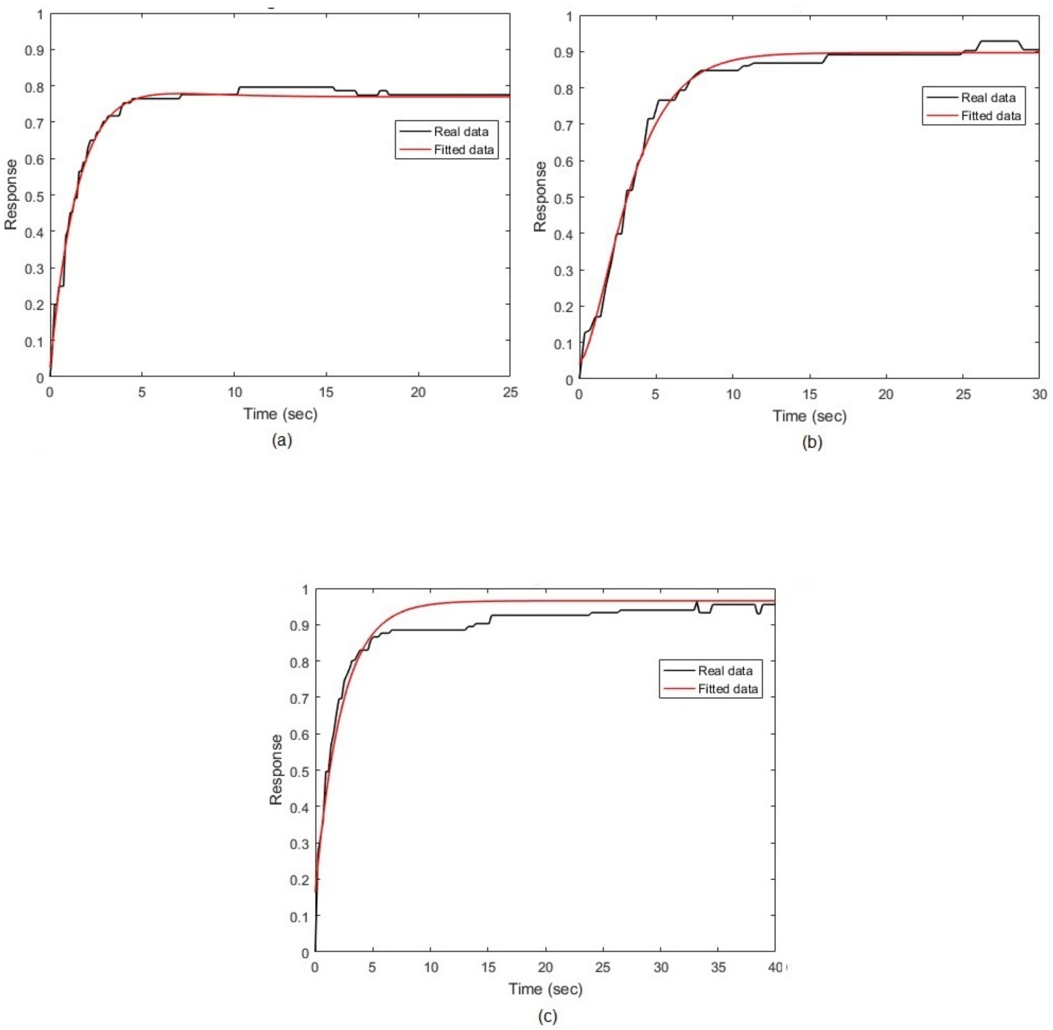


Figure 6.4: Relation between stirring speed and homogeneity time

6.4 Effect of targeted color

The third set of experiments was done to compare the mixing responses for producing different colors with the same mixing speed. Fig. 6.5 shows the responses of mixing to produce three colors with tristimulus vectors $RGB_{x_1} = [180 \;\; 210 \;\; 100]^T$, $RGB_{x_2} = [90 \;\; 100 \;\; 215]^T$ and $RGB_{x_3} = [120 \;\; 100 \;\; 100]^T$, respectively.



(a)

(b)

(c)

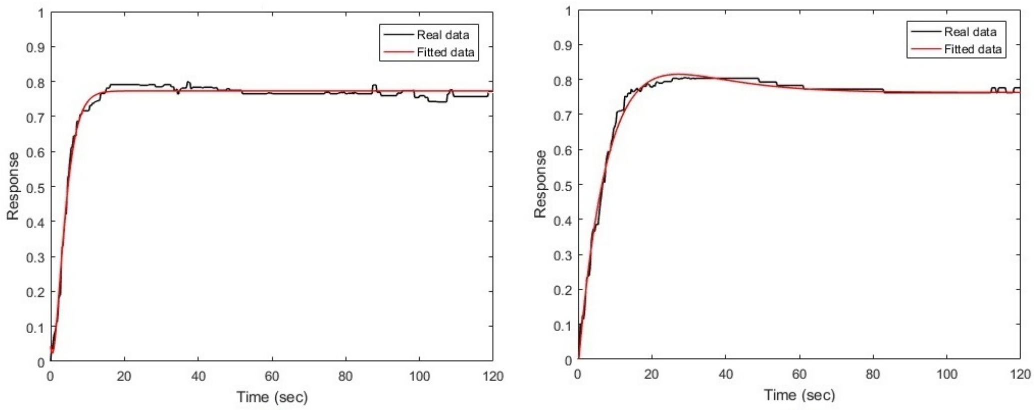
Figure 6.5: The result of producing the colors with the $RGB_{x_1} = [180 \;\; 210 \;\; 100]^T$, $RGB_{x_2} = [90 \;\; 100 \;\; 215]^T$ and $RGB_{x_3} = [120 \;\; 100 \;\; 100]^T$ in a, b and c, respectively, with mixing speed $200 rpm$. Black: measured distance curve. Red: response with fitting Function (5.2)

6.5 Effect of batch volume

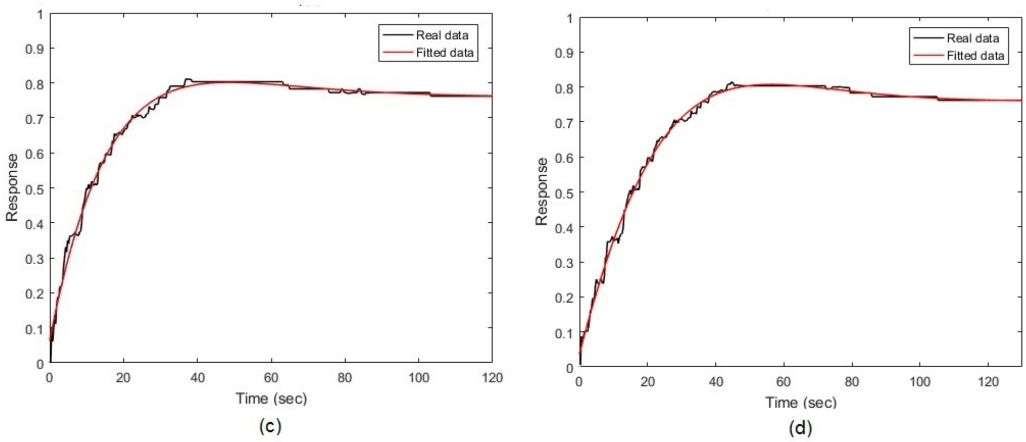
The fourth set of experiments was performed to investigate the effect of the total volume of the desired paint color to the homogeneity response. This set is intended to produce x_1 color, i.e., with tristimulus vector $RGB_{x_1} = [180 \;\; 210 \;\; 100]^T$ with the same stirring speed (200 rpm), but, with different batch volume, namely, 300, 400, 500 and 600 ml.

Fig. 6.6 shows the time-varying distance response according the measured distance (black) and empirical Function (5.2) with the previous volumes, respectively. Here, it can be seen that a large batch volume results more delay to reach the homogeneous paint. Obviously, reducing the volume will decrease the time required to reach color homogeneity.

Table 6.2 shows the parameters of experiments Sets 1, 2, 3 and 4. As shown in Section 5.2. In these experiments, we are interested in the steady state distance with speed of convergence to reach the homogeneous paint as well as the overshoot terms which are represented through the parameters d_{ss}, A_1, A_2 and A_3. Here, it can be seen that the mixing motor speed can affect the speed of convergence to the steady homogeneous paint color, but, however, when different paints are intended to produce different colors, as in experiments Set 3, minor effect on the speed of the convergence can be noticed. The reason of this can be attributed to the distance between the surface color and the desired color is not a physical distance, but it is a distance due to tristimulus vector in chromaticity space.



(a) (b)



(c)

(d)

Figure 6.6: The result of producing the color with the $RGB_{x_1} = [180 \;\; 210 \;\; 100]^T$ with constant stirring speed ($200 rpm$). (repeated four times: a: 300 ml, b: 400 ml , c: 500 ml and d: 600 ml). Black: measured distance curve. Red curves: response with fitting Function(5.2).

Based on table 6.2, the relation between batch volume (ml) and homogeneity time (sec) has been drawn as shown in Fig.6.7. The relationship between these two variables was fitted to the second order polynomial function as in Eq. (6.2). So it is possible to estimate the required mixing time for specific volume of the desired paint.

$$y = 0.0106x^2 + 0.9894x + 274.04 \tag{6.2}$$

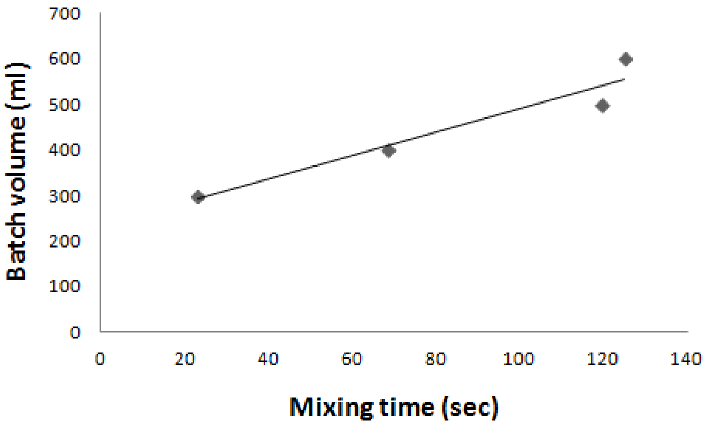


Figure 6.7: Relation between batch volume and homogeneity time

Table 6.2: Parameters of empirical Function for the experiments Sets 1-3

Figure	**Exp. No.**	**Mixing time(sec)**	**Distance**	d_{ss}	A_1	A_2	A_3
6.2a	1	21.56	0.7737	0.7732	0.502	-0.73	-4.7458
6.2b	2	23.19	0.7737	0.7709	0.491	-0.7265	-2.0178
6.2c	3	22.53	0.7737	0.7716	0.516	-0.7411	1.9839
6.2d	4	21.15	0.7737	0.7745	0.502	-0.7427	-3.4092
6.3a	1	21.17	0.7737	0.7696	0.498	-0.7437	2.9998
6.3b	2	40.82	0.7737	0.768	0.1455	-0.6797	7.7353
6.3c	3	76.29	0.7737	0.7709	0.244	-0.7516	0.3581
6.3d	4	91.42	0.7737	0.7701	0.106	-0.6446	-0.3525
6.5a	1	21.17	0.7737	0.7696	0.499	-0.7437	2.9998
6.5b	2	22.04	0.8931	0.8946	0.538	-0.855	-5.9717
6.5c	3	21.04	0.9746	0.9654	0.434	-0.8004	0.1999
6.6a	1	23.11	0.7737	0.773	0.1119	-0.7299	-4.0514
6.6b	2	68.46	0.7619	0.7682	0.0048	-0.7857	10.2752
6.6c	3	119.62	0.7619	0.7605	0.0226	-0.6967	0.8706
6.6d	4	124.9	0.7619	0.7619	0.0358	-0.7252	0.1934

Chapter 7

Conclusion and recommendation

In this work, a paint mixing machine was designed and implemented. A lab-made equipment was built using four tanks with the desired pumps, pipes, micro-controller and high resolution camera. One of the tanks was used for paint mixing using two bladed paddle impeller that is coupled with a speed controlled DC motor. A paint mixing algorithm for water paints with the help of paint commercial database was presented. It was presented using pseudo code. Then, the paint mixing machine will use this algorithm to compute the required raw paints to get the wanted paint color and then mix them for an enough period to produce a fully homogeneous paint color.

After paint mixing, one of the suggested empirical functions can be successfully used to describe the color homogeneity response that is occurred during the mixing process. To do this step, the non-linear programming problem that described by the non-linear least square problem has been solved, which is formulated using the empirical function and observed measurement from the camera.

Three sets of experiments were done using this lab-made paint mixing equipments to show the different responses of the paint mixing as well as the effectiveness proposed algorithm. The first set was applied to chose the best fit empirical function among three suggested functions. The second set was done to show the effect of the mixing speed on the paint homogeneity. While the third set was done to show the mixing behaviours when different colors were produced. This algorithm was applied using RGB chromaticity space, but, it can be applied for other chromaticity space like RYB and CMYK.

This approach for investigating the dynamics of color mixing process can be generalized for investigating the kinetic of various physiochemical processes in liquid phases. Such an investigation is the subject of our future work.

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