PROPOSED AUTOMATION OF TEA WITHERING PROCESS USING FUZZY LOGIC CONTROLLER

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by

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DECLARATION

The work submitted in this dissertation is the result of my own investigation, except where otherwise stated.

It has not already been accepted for any degree, and is also not being concurrently submitted for any other degree.

J.M.I Jayasundara

Date

endorse the declaration by the candidate.

Dr. Lanka Udawatta

UOM Verified Signature

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ABSTRACT

Tea processing is one of the major energy intensive food processing industries in Sri Lanka and the process "withering", which is the first stage of the complete process, accounts for about half of the total electrical energy consumption in the tea industry. This process consumes electrical energy mainly to run the withering fans. The traditional methods of controlling withering process have proven to be very inefficient in energy point of view.

This study proposes a fuzzy logic based withering control methodology which will optimize the electrical energy consumption of the process while maintaining the quality of the processed tea.

Present process analysis was done with field experimental data and the performance of the proposed system was evaluated on Matlab® platform.

This proposed control structure can be implemented, modified and field tuned for optimization depending on the practical installation characteristics and expected to save a considerable amount of electrical energy in tea processing industry.

To my wife Thilini

ACKNOWLEDGEMENT

I would like to express thanks to my supervisors Dr. Lanka Udawatta and Mr. K.Raveendran for their continuing guidance, encouragement, and support throughout the course of my study.
My sincere thanks go to the officers at Tea Research institute of Sri Lanka, Thalawakelle, Faculty of Engineering, University of Moratuwa, for helping in various ways to clarify the things related to my work in time with excellent cooperation and guidance. Also I must thank the management and staff of Rotax Limited, for support and encouragement extended to me in making this study a success.

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Chapter One

Introduction

1.1 Background

Tea is nearly 5,000 years old and was discovered, as legend has it, in 2737 B.C. by a Chinese emperor when some tea leaves accidentally blew into a pot of boiling water. In the 1600s, tea became popular throughout Europe and the American colonies. Now, tea is consumed as a beverage throughout the world and grown widely in countries of Asia, Africa and the Near East. Earliest mention of tea is from China in 350 B.C. It found its way to Europe in 1559, to England in 1615, and to Indonesia in 1684. Commercial cultivation began in India in 1823 and in 1867 in Sri Lanka. [6]

Tea industry plays a vital role in the economy of Sri Lanka. It is the major plantation crop in the country and Sri Lanka has the dignity of being the world third largest tea producer. Based on the 2003 data from World Bank, tea export is around 13% of the total export (663billion/5,133billion) of the country. According to annual report-2005 of Central Bank of Sri Lanka, annual production of made tea is nearly 317 thousand metric tones and 97% (309 thousand metric tones) of this production is exported. [8]

Tea plantation was first introduced in mid 19^{th} century, during the British colonial era and since then tea industry faces ups and downs, being the major commercial crop in the country. Geographical conditions of the country, especially of the hill country is well suited for tea plantation and this factor causes largely for this industry to be flourished.

Electrical energy is a critical element in tea industry, because many machines which are used for tea processing are operated by electrical power. During the time when tea was first introduced to Sri Lanka, there was not a minute crisis of energy. In some cases, up-country factory owners generated their own power from micro hydro resources available at their plantations. However the condition is different now. Electricity price has been increased rapidly during the past decade, making it comparatively higher than the electricity prices of neighbouring countries as well as other tea export countries. Due to this reason unit cost of made tea has increased tremendously during the last few years.

High prices due to the high production cost of made tea ultimately impedes its competitiveness in the world market, even in spite of the quality and undeniable flavour of Sri Lankan Tea. Therefore it is distinct that, to reduce the production cost of made tea, reducing the operational cost or energy cost is a must. Yet most of the machines used in tea factories are those used during colonial times and the concern for energy efficiency of these machines is very little. Lot of uneducated and inexperienced employees are engaged in tea sector. Further, most of the employees of tea factories are non-technical people and energy conservation practices are very rarely being applied. Tendency of the factory owners to use better and energy efficient systems seems to be poor and the efforts put so far to change this situation have not achieved the expected results.

Tea production associates with a number of machinery which are operated by electrical energy. Hence energy cost is a crucial factor in the production cost of made tea. Therefore unit cost of made tea can be brought down by reducing the specific energy (energy required to produce 1 kg of made tea) consumption of the production. For it to be achieved energy conservation and efficient methods and practices should be exercised at plant level. In-house expertise knowledge and capacity is a vital factor for achieving this. But many small and medium scale tea industries do not have facilities to undertake tests like testing the quality of tea, estimation of moisture, measuring process parameters like air flow rate, pressure, etc. Therefore it has become difficult to know and assess their current level of performance. Lack of dedicated technical resource persons to look in to technical improvements, lack of capacity to access latest technological information are also barriers encountered in improving energy efficiency and tea quality by the tea industry in Sri Lanka.

Withering process consumes electrical energy to run the blower fans. Withering accounts for about 50% of the total electricity consumption in tea processing. [1] Withering is achieved by placing tea leaves on the troughs and air being blown by an axial flow fan.

To assist in having a control over the process a combination of hot and ambient air is used. It has been found that around 50% of the withering is achieved during the first 4-6 hours of the process and for the rest it takes around 6-10 hours. During the initial phase of the withering process, moisture on the surface of the leaf gets evaporated and from there onwards moisture from the interior of the leaf is propagated to the surface through diffusion process. The moisture removal becomes slower when the diffusion process takes place from the interior of the tea leaves. [1]

Industry has always required tools for increasing production rate and/or product quality while keeping the costs as low as possible. Doubtless, one of these tools is automatic process control. In the early days, engineers essentially used their knowledge of the process and their understanding of the underlying physics to design controllers, such as PID controllers. Analysis methods were combined with an empirical approach of the problem to design controllers with an acceptable level of performance. During the last decades, with the increasing competition on the markets, more powerful control techniques have been developed and used in various industrial sectors in order to increase their productivity [23].

Tea withering process is very difficult process to model and involves multiple variables. Also it is a non linear process and involves high level of operator expertise. In this type of situations fuzzy logic base controlled systems have proved to be the more appropriate approach for achieving process automation objectives.

There are five types of systems where fuzziness is necessary or beneficial:

- Complex systems those are difficult or impossible to model
- Systems controlled by human experts
- Systems with complex and continuous inputs and outputs
- Systems that use human observation as inputs or as the basis for rules
- Systems those are naturally vague

Fuzzy logic controller system has several advantages over conventional control methodologies:

- Fewer values, rules, and decisions are required
- More observed variables can be evaluated
- Linguistic, not numerical, variables are used, making it similar to the way humans think
- It relates output to input, without having to understand all the variables, permitting the design of a system that may be more accurate and stable than one with a conventional control system
- Simplicity allows the solution of previously unsolved problems

- Rapid prototyping is possible because a system designer doesn't have to know everything about the system before starting work
- They're cheaper to make than conventional systems because they're easier to design
- They have increased robustness
- They simplify knowledge acquisition and representation
- A few rules encompass great complexity

Also there are few drawbacks of fuzzy systems when compared with conventional systems:

- It's hard to develop a model from a fuzzy system
- Though they're easier to design and faster to prototype than conventional control systems, fuzzy systems require more simulation and fine tuning before they're operational [14].

1.2 Motivation

While the research institutions dedicated to the tea industry have the best knowledge on the tea process and the related quality and energy issues, they lack the knowledge in new technologies and research capacities especially in electrical and automation related areas. Lack of unified effort between these two fields has severely affected the utilization of new concepts and technologies for the improvement of the tea industry in Sri Lanka. This study is a result of an effort to utilize advancements in the field of electrical engineering for the advancement of the tea processing industry.

1.3 Objective

The objective of this study is to develop a withering control methodology which will optimize the electrical energy consumption of the process while maintaining the quality of the processed tea. Also it is a main objective to make the system flexible in terms of control algorithm considering the non linear behaviour of the process and the need for using the developed concept and the system as a structural basis for further research and experiments.

Chapter Two

Tea Processing

Sri Lankan tea industry is around 150 years old and a main source of foreign exchange of the island. The tea manufacturing process consists of five main stages,

1. Withering
2. Rolling
3. Fermentation
4. Drying
5. Grading & Packaging

2.1 Withering

Withering is principally a drying process to remove the surface moisture and partially the internal moisture of the freshly harvested green leaves. In addition, withering is done to get the correct physical condition, which will allow the leaves to be rolled without breaking. Also, the withering promotes dissipation of heat generated during continuous respiration (chemical changes). There are two major types of withering, open or natural withering and artificial or trough withering. In the open method, withering is controlled by the thickness of spread, and the length of time of the withering phase.

Trough withering is a widely used withering process. Usually, the green leaves from the tea estates are brought to the factory in the afternoons and are spread thinly on banks of troughs (tats). The troughs are made of metal wire meshes with wooden support on which tea leaves are spread and the air is blown from the bottom so that the air passes through the green leaves. The air is supplied either directly from an air heater or the exhaust from the dryer, which is usually located at ground level whereas troughs are located in an upper floor. Withering is done at 20–30°C depending on the climatic conditions. For best withering, a wet and dry bulb temperature difference of 4°C is maintained. During withering, the moisture content of the green leaves is reduced up to 55% for Orthodox tea production. Depending on the weather and the condition of the leaf, withering takes about 12-18 hours. [6]

In withering, more air is blown at the initial stage and on an average the air flow rate is about 15,000-20,000 cubic feet per minute (CFM) depending on the size of the trough. After four to five hours, the flow rate can be reduced to two-thirds of its initial value. To reduce the air flow rate, throttle valves are provided at the fan inlets. Once proper withering is achieved, the air flow is continued to prevent the spoiling of withered leaves. Withering troughs are generally installed in the first floor of the factory. Green leaf is spread over a wire mesh which is fitted on plenum chamber. The trough should be fitted with a suitable fan to deliver the required quantity of air as per the size of the trough. To achieve proper withering the fan has to deliver around 15-20 CFM air for every one square foot of trough area. For artificial withering hot air from the drier room is mixed with outside air and used. Fans are arranged in such a way that they can draw hot air from the drier and cool air from the atmosphere.

The current of air performs a twofold function: Conveying heat to the leaf as well as carrying of water vapour through a bed of green leaves to achieve physical withering. Whenever the hygrometric difference is below 3° C, hot air is mixed in suitable proportion or heat energy is supplied to increase the hygrometric difference with a corresponding rise in the dry bulb temperature of air. But the dry bulb temperature of air after mixing should not exceed a maximum limit beyond which the quality of the withered leaf is not acceptable. At present, almost all the Sri Lankan tea factories practice trough withering. The dimensions of trough in most of the factories vary considerably. The width of the standard (conventional) trough is 6' and its length varies between 60' and 120'. [1]

2.2 Rolling

The chemical compounds of the tea leaves are released to initiate oxidation in the fermentation process. Rolling twists the leaf, and at the same time, breaks the leaf structure (cells) to release the juices (catechins and enzymes) for oxidation.[6] A compressed drum/roller twists the withered leaves on a continuous circular motion. A rolling machine size varies from 150–325 kg of leaf per hour. The roller has minimum cutting action and more compressed rolling action. The compression of the roller depends on the type of withering. Low pressure rollers are suitable for under-withered leaves and high pressure rollers for over-withered leaves. Normally, light rolling at the initial stage and heavier rolling at the later stage of the rolling operation are done. The duration of rolling varies from 15 to 45 minutes.

2.3 Fermentation

The rolling process is followed by fermentation, which is a biochemical oxidation process where tea flavours are produced. The fermentation is an important process in black tea production. Oxidation takes place in a room where high humidity air at a temperature of 23-29°C is maintained. The fermentation process does not require any energy unless humidifiers are used.

2.4 Drying

The fermented tea particles are dried or fired to arrest the fermentation and also to reduce the moisture to about 3%. Clean and odourless hot air is passed through the fermented tea particles in dryers. The temperature of the hot air varies between 90–160°C depending on the type of dryer. Drying or firing is a thermal energy intensive operation that also consumes electrical energy to drive blowers and dryers.

2.5 Grading and Packaging

Dried tea consists of particles of different sizes, stalks, fibres, leaf portions, etc. The dried tea is sorted into different grades by passing it over mechanically oscillated sieves for grading. In grading, tea particles are sifted into different sizes then classified according to appearance and type. The colour separator recently being used in the grading process could remove stalk particles by tracing the colour electronically. After grading, tea is packed in airtight containers in order to prevent absorption of moisture. Packaging could be either in tea chests (wood based) or tea bags, etc. packaging as per requirement.

Chapter Three

Fuzzy Controllers

A fuzzy control system is a control system based on fuzzy logic - a mathematical system that analyzes analog input values in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical or digital logic, which operates on discrete values of either 0 and 1 (true and false). Fuzzy logic has the advantage that the solution to the problem can be cast in terms that human operators can understand, so that their experience can be used in the design of the controller. This makes it easier to mechanize tasks that are already successfully performed by humans.

3.1 Fuzzy Logic History and Applications

Fuzzy logic was first proposed by Lotfi A. Zadeh of the University of California at Berkeley in a 1965 paper. [12] He elaborated on his ideas in a 1973 paper that introduced the concept of "linguistic variables", which in this article equates to a variable defined as a fuzzy set. Other research followed, with the first industrial application, a cement kiln built in Denmark, coming on line in 1975.

3.2 Fuzzy Logic In Industrial Automation

Fuzzy logic has proven well its broad potential in industrial automation applications. In this application area, engineers primarily rely on proven concepts. For discrete event control, they mostly use ladder logic, a programming language resembling electrical wiring schemes and running on programmable logic controllers (PLC). For continuous control PID type controllers are mostly employed.

While PID type controllers do work fine when the process under control is in a stable condition, they do not cope well in other cases [10]:

The presence of strong disturbances (non-linearity)
Time-varying parameters of the process (non-linearity)
Presence of dead times

The reason for this is that a PID controller assumes the process to behave in a strictly linear fashion. While this simplification can be made in a stable condition, strong disturbances can push the process operation point far away from the set operating point. Here, the linear assumption usually does not work any more. The same happens if a process changes its parameters over time. In these cases, the extension or replacement of PID controllers with fuzzy controllers has been shown to be more feasible.

3.3 Multivariable Control

The real potential of fuzzy logic in industrial automation lies in the straightforward way fuzzy logic renders possible the design of multi-variable controllers. In many applications, keeping a single process variable constant can be done well using a PID controller. However, set values for all these individual control loops are often still set manually by operators. The operators analyze the process condition, and tune the set values of the PID controllers to optimize the operation. This is called "supervisory control" and mostly involves multiple variables.

PID controllers can only cope with one variable. This usually results in several independently operating control loops. These loops are not able to "talk to each other". In cases where it is desirable or necessary to exploit interdependencies of physical variables, one is forced to set up a complete mathematical model of the process and to derive differential equations from it that are necessary for the implementation of a solution. This is not practical in many situations. The general observation in industry is that single process variables are controlled by simple control models such as PID, while supervisory control is done by human operators. Fuzzy logic provides an efficient solution to the problem. Fuzzy logic enables design supervisory multi-variable controllers from operator experience and experimental results rather than from mathematical models.

3.4 Structure of a Fuzzy Controller

With fuzzy logic, practical experience which can be described verbally is implemented qualitatively or quantitatively, in the form of IF-THEN assignments (fuzzy logic rules). The block diagram of a fuzzy logic system is shown below. Several input variables are linked with an output variable. In the context of fuzzy logic, we often speak of linguistic input and output variables. This is because when fuzzy logic rules are stated, the input and output variables are added verbally

When the structure of a complete fuzzy controller is considered, there are specific components characteristic of a fuzzy controller that supports the design procedure. The following is a block diagram representation of these components.

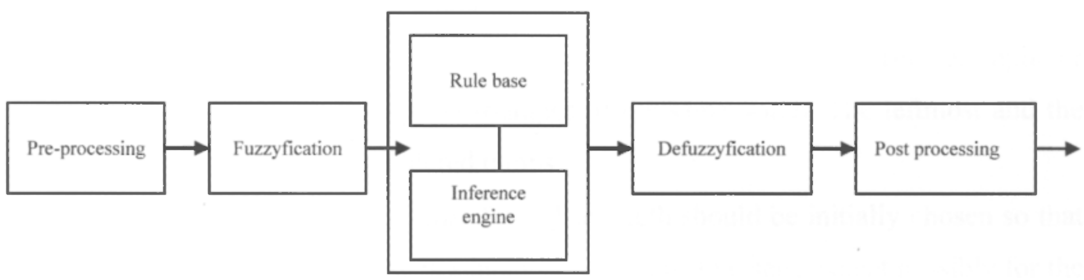

Figure 3.2: Standard Fuzzy Logic Controller.

3.4.1 Pre-processing

The inputs from process sensors/transducers have to be first fed to a pre-processor which will do the necessary filtering to remove noise, scaling of the inputs, etc.

3.4.2 Fuzzyfication

The first block inside the controller is Fuzzyfication and it converts the input data to degree of membership by interacting with the membership functions. The Fuzzyfication block therefore matches the input data with the conditions of the rules to determine how well the condition of each rule matches the particular input at that instance.

Membership functions:

In designing a fuzzy controller, building the membership functions is a first most task to be accomplished. There are two specific questions to consider,

1. How to determine the shape of the membership functions?
2. How many membership functions are necessary and sufficient?

According to fuzzy set theory, the choice of shape and width is subjective, but some rules of thumb apply. [12]

- The membership functions should be sufficiently wide to allow for noise in the measurements.
- A certain amount of overlap is desirable; otherwise the controller may run in to poorly defined states, where it does not return a well defined output.

The following is a recommended practice to start with a design [12].

- *Start with triangular sets.* All membership functions for a particular input or output should be symmetrical triangles of the same width. The leftmost and the rightmost should be shouldered ramps.
- *The overlap should be at least 50%.* The width should be initially chosen so that each value of the universe is a member of at least two sets, except possibly for the elements at the two extreme ends. If on the other hand there is a gap between two sets no rules will fire for values in the gap.

3.4.3 Rule Base

The rules may use several variables both in the condition and the conclusion of the rules. The controllers therefore can be applied for multi input multi output (MIMO) and single input single output (SISO) situations.

Rule formats: A linguistic controller contains the rules in an "IF-THEN" format but they can be presented in different formats.

3.4.4 Inference Engine

In the fuzzy inference engine, fuzzy logic principles are used to combine the fuzzy "IF-THEN" rules in the fuzzy rule base into a mapping from a fuzzy set in the input universe to a fuzzy set in the output universe. There are two ways to infer with a set of rules: composition based inference and individual-rule based inference,

Composition Based inference:

In composition based inference, all rules in the fuzzy rule base are combined into a single fuzzy relation, which is then viewed as a single fuzzy "IF-THEN" rule.

Individual-Rule Based inference:

In individual-rule based inference, each rule in the fuzzy rule base determines an output fuzzy set and the output of the whole fuzzy inference engine is the combination of the individual fuzzy sets. The combination can be taken either by union or by intersection.

3.4.5 Defuzzification

The resulting fuzzy set must be converted to a number that can be sent to the process as a control signal. This operation is called Defuzzification. There are several defuzzification methods.

3.4.6 Post processing

In case the output is defined on a standard universe, this must be scaled to engineering units. The post processing block often contains an output gain that can be tuned.

Chapter Four

Statement of the Problem

4.1 Preliminaries

In the present practice, withering process is controlled manually by experienced operators using mostly rules of thumb deciding factors which they have developed through several years of experience. As a result the energy consumption of the process is not optimized and also the quality of withering is not uniform. The withering process is a highly nonlinear process involving multiple variables and difficult to model mathematically.

The present practice of manual feeling of the flow of air through the withering bed is very much dependent on the operator's skills and direct instrumentation and automation of the process is also not possible due to the very low air velocity present at the withering bed. Therefore an alternate way of achieving a more consistent control is required.

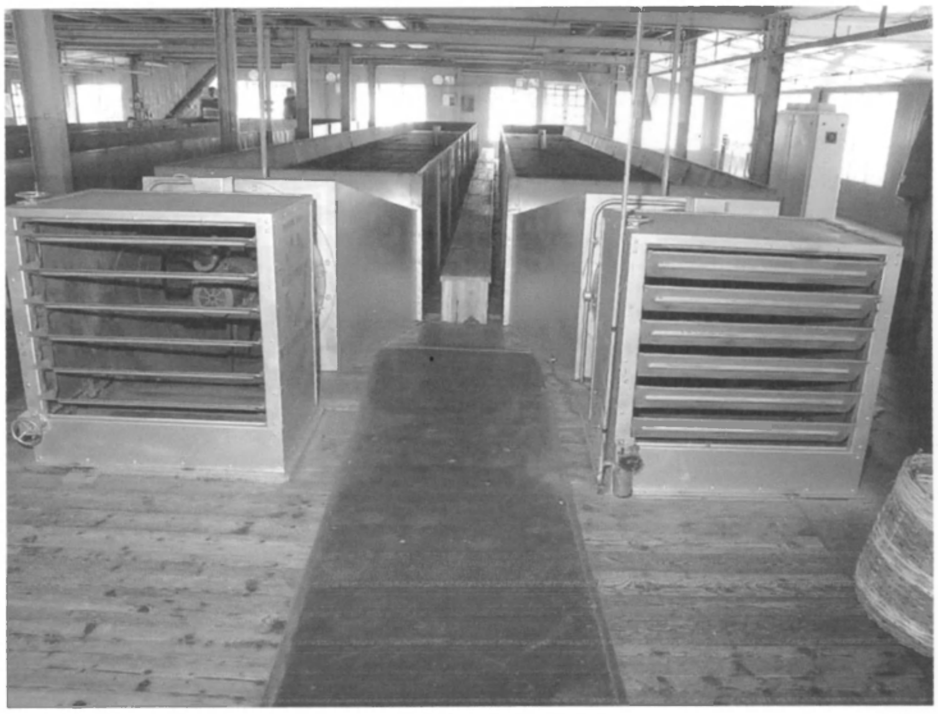

Figure 4.1: A Photograph of the Withering Trough Arrangement.

4.2 Behaviour of Process Parameters

Withering process has four process inputs of interest,

1. Air Flow:

   The air flow rate through the withering bed is a critical factor that determines the rate of withering. The rate of removal of moisture from the tea leaves varies on the level of moisture content in the leaves. In the initial stage of the process the leaves contains a high level of surface moisture and during that period, the rate of removal of moisture has a strong relationship with the air flow rate. The internal moisture is hard to remove and the rate of removal is low compared to the initial stage. So maintaining the same air flow rate is not necessary.

   The air velocity out of the bed through the tea leaves is difficult to measure as it is in the range of 0-0.5 m/s and needs averaging through a large area to get an accurate measurement. To overcome this problem air velocity is measured at the input to the chamber and air velocity at the exit through tea leaves is calculated using the input output areas.

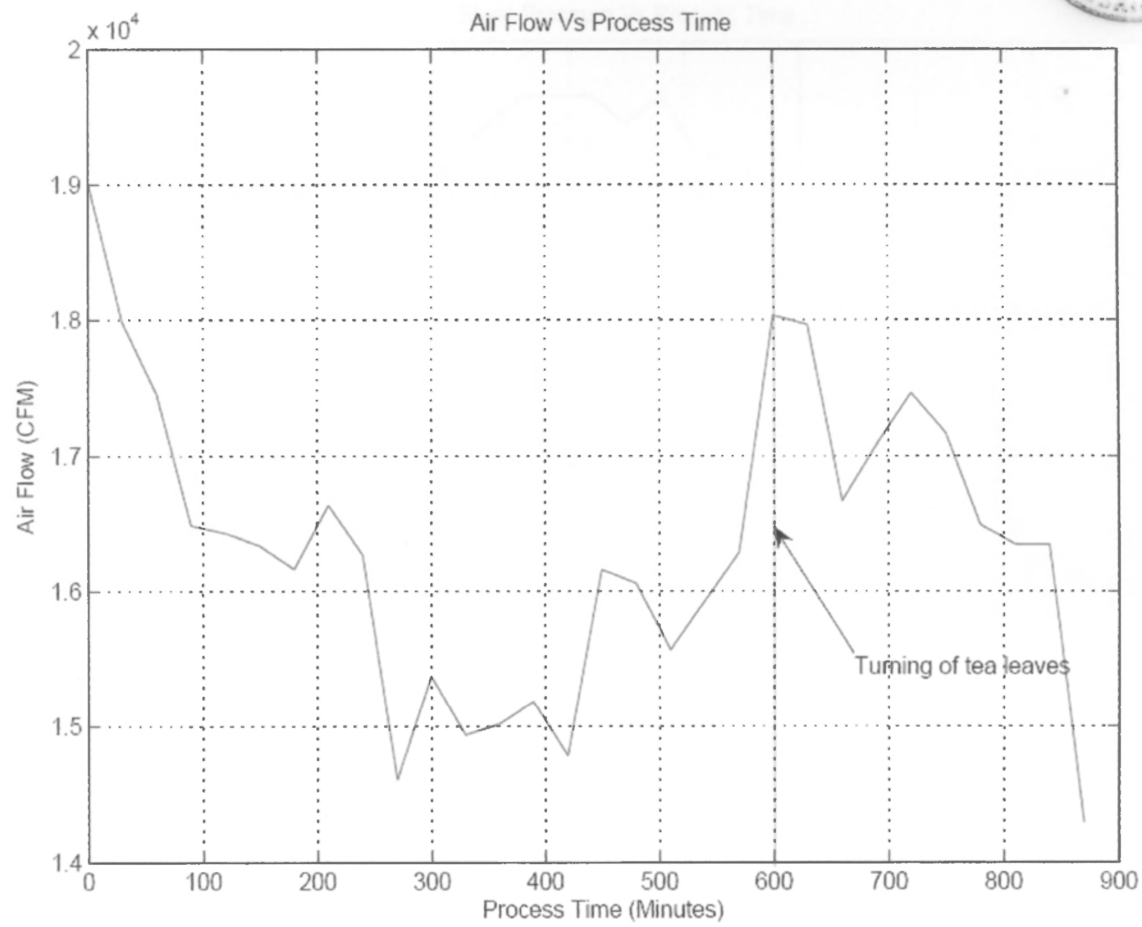

Figure 4.2: Variation of Air Flow with Process Time.

2. Chamber Pressure:

   As the tea leaves get withered it increases the resistance to flow of air through the withering bed. This in turn increases the withering chamber pressure. As the pressure builds up, the air flow rate drops at the same fan speed and the operation point of the withering fan gets shifted away from the most efficient point of operation on its performance curve.

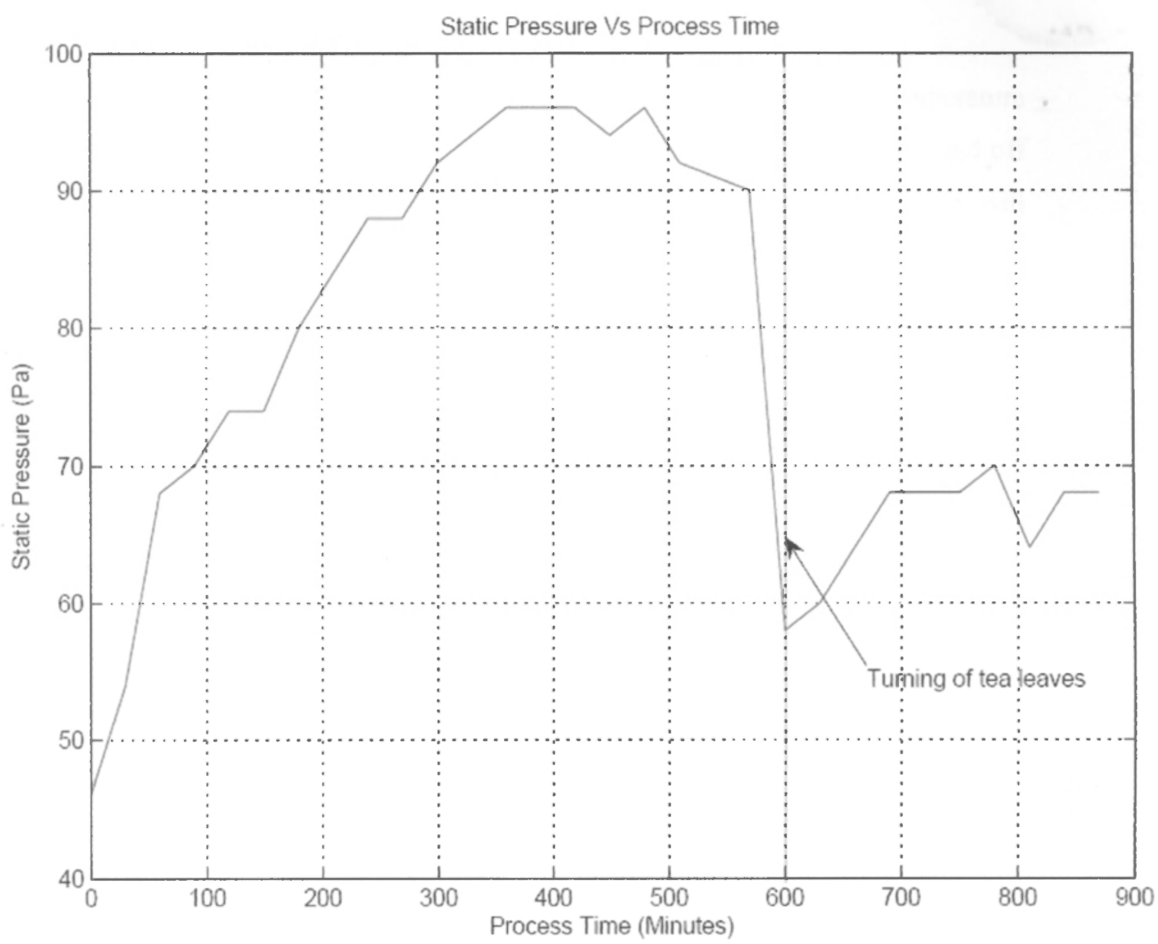

Figure 4.3: Variation of Chamber Pressure with Process Time.

3. Relative Humidity:

   The relative humidity level of the withering air flow is another factor that determines the rate of withering and maintaining a low relative humidity level can compensate for reduced air flow rate.

4. Process Air Temperature:

   Since the process air humidity is reduced by means of heating, the air temperature goes high and cannot be avoided. Temperature rises for shot durations on and off will not affect the quality of the tea badly but continuous over temperature will damage the tea leaves and results in poor quality processed tea.

Chapter Five

Proposed Solution

A fuzzy logic based approach is proposed for automated control of the process considering,

- Highly non linear nature of the process,
- Involvement of multiple variables,
- Necessity to base the control on operator past experience,
- Necessity for easy reconfiguration on field experiments for different climate conditions and physical trough characteristics depending on the factory location.

5.1 Methods and Techniques

An averaging flow grid is proposed for obtaining the air flow rate input to the control system. The air flow grid consists of two tubes mounted diagonally across the trough and the tubes are drilled with a series of equally spaced holes. The holes in one tube face directly upstream and sense total pressure, while the pair of tubes on the second tube faces forward in an inclined angle so that it senses static pressure. The total and static pressure are averaged along the length of each tube and provide pressure signals out the trough. The pressure differentials across these connectors can be fed to a pressure transmitter with square rooting function which can give a 4-20mA electrical signal which is the input signal for the control system.

$$M = \frac{\Delta P}{PV} \tag{5.1}$$

Where,

M = Flow grid magnification factor,

ΔP = Flow grid differential pressure (Pa)

PV = Chamber mean velocity pressure (Pa)

The velocity relationship is

$$V = \sqrt{\frac{2}{\rho} \times PV} \tag{5.2}$$

V = Mean air velocity (m/s)

ρ = Density of air (kg/m^3)

Therefore the basic formula for the flow grid is

$$V = \sqrt{\frac{2}{\rho} \times \frac{\Delta P}{M}} \tag{5.3}$$

And allowing for changes in air density,

$$V = \sqrt{\frac{2}{\rho_0} \times \frac{\Delta P}{M} \times CF} \tag{5.4}$$

Where,

ρ_0 = Standard density of air 1.2 kg/m^3

$$CF = \frac{\rho_0}{\rho} = \frac{101350}{B} \times \frac{T}{293} \times \frac{101350}{101350 + P_s} \tag{5.5}$$

B = Barometric pressure (Pa)

T = absolute air stream temperature degrees K

P_s = Chamber static pressure (Pa)

To obtain the volume flow rate,

$$Q = A \times V \tag{5.6}$$

$$Q = A \times \sqrt{\frac{2}{\rho_0} \times \frac{\Delta P}{M} \times CF} \tag{5.7}$$

Where,

Q =Volume flow rate

For Fuzzyfication of the input Air Flow, five membership functions are defined. The input universe is 0 to 30,000 cfm. The width of each membership function is selected to be around 10,000 cfm. The leftmost and rightmost membership functions are shouldered ramps and the three in the centre are symmetrical triangles of the same width. Overlap is selected to be around 50%.

MF NAME	NoFlow	LowFlow	StandardFlow	HighFlow	FullFlow
BASE x (10^3)	0-10	5-15	10-20	15-25	20-30
SHAPE	Trapezoidal	Triangular	Triangular	Triangular	Trapezoidal
POINTS	0,0,5,10	5,10,15	10,15,20	15,20,25	20,25,30,30

Table 5.1: Fuzzyfication of Input Air Flow

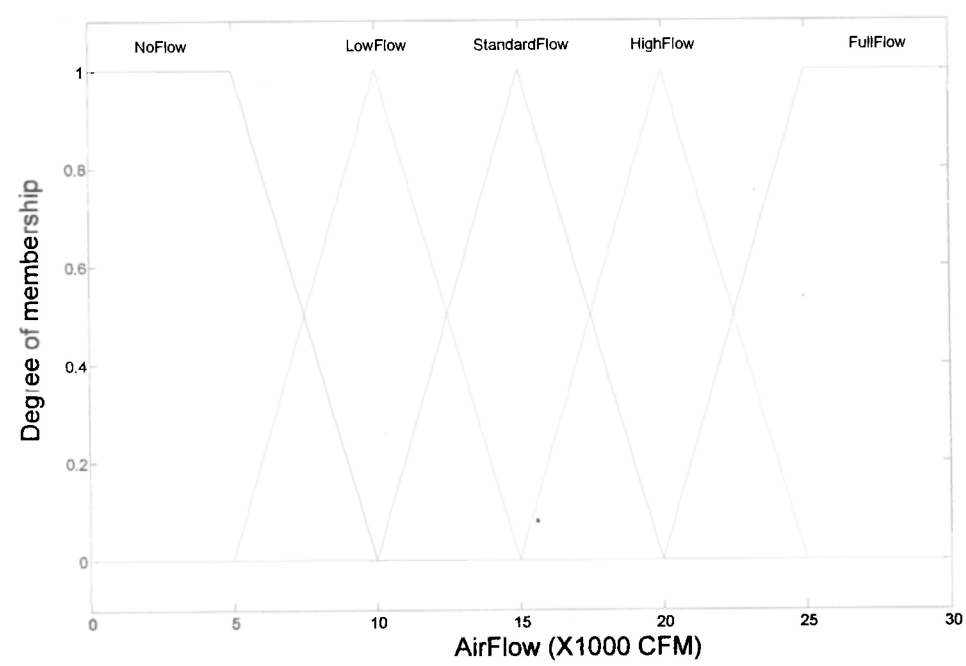

Figure 5.1: Fuzzyfication of Input Air Flow

For Fuzzyfication of the input Chamber pressure, four membership functions are defined. The input universe is 0 to 100 Pa. The width of each membership function is selected to be around 25 Pa. The leftmost and rightmost membership functions are shouldered ramps and the three in the centre are symmetrical triangles of the same width with an overlap of around 50%.

MF NAME	VLowPressure	LowPressure	MediumPressure	HighPressure
BASE	0-40	20-60	40-80	60-100
SHAPE	Trapezoidal	Triangular	Triangular	Trapezoidal
POINTS	0,0,20,40	20,40,60	40,60,80	60,80,100,100

Table 5.2: Fuzzyfication of Input Chamber Pressure

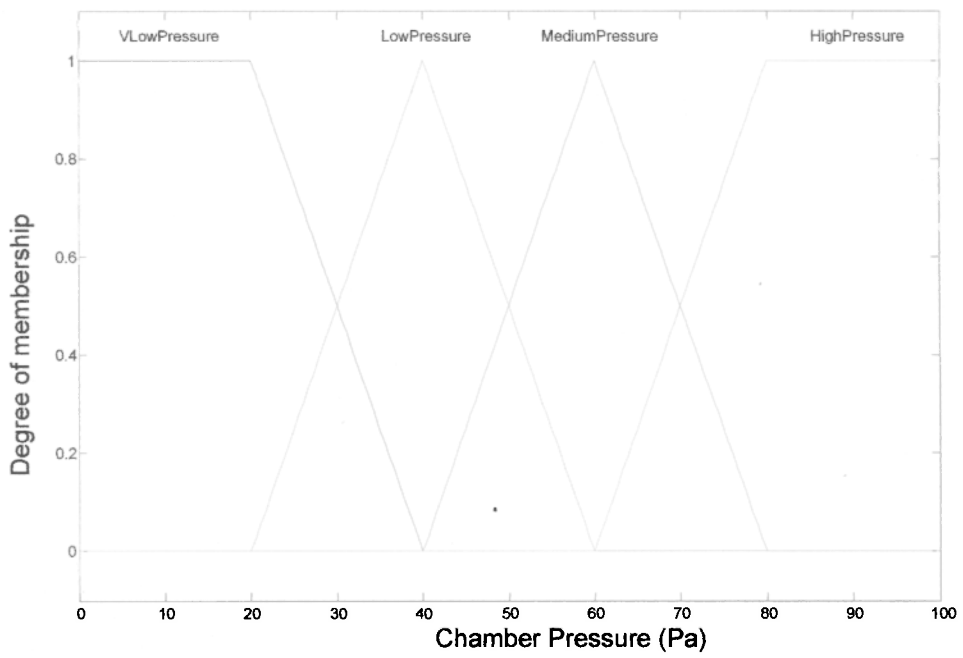

Figure 5.2: Fuzzyfication of Input Chamber Pressure

For Fuzzyfication of the input Relative Humidity, four membership functions are defined. The input universe is 0 to 100 %.The width of each membership function is selected to be around 40%. The leftmost and rightmost membership functions are shouldered ramps and the three in the centre are symmetrical triangles of the same width with an overlap of around 50%.

MF NAME	Dry	MediumRH	HighRH	Humid
BASE	0-40	20-60	40-80	60-100
SHAPE	Trapezoidal	Triangular	Triangular	Trapezoidal
POINTS	0,0,20,40	20,40,60	40,60,80	60,80,100,100

Table 5.3: Fuzzyfication of Input Relative Humidity

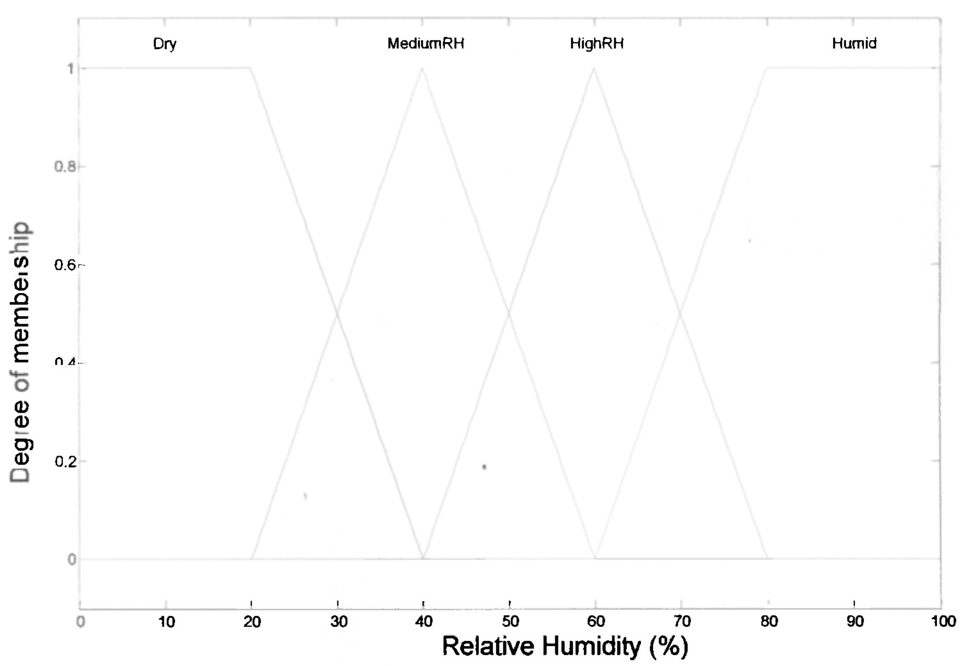

Figure 5.3: Fuzzyfication of Input Relative Humidity

For Fuzzyfication of the input Chamber Temperature, four membership functions are defined. The input universe is 0 to 50 C. The width of each membership function is selected to be around 20 C. The leftmost and rightmost membership functions are shouldered ramps and the three in the centre are symmetrical triangles of the same width with an overlap of around 50%.

MF NAME	VLowTemp	LowTemp	MediumTemp	HighTemp
BASE	0-20	10-30	20-40	30-50
SHAPE	Trapezoidal	Triangular	Triangular	Trapezoidal
POINTS	0,0,10,20	10,20,30	20,30,40	30,40,50,50

Table 5.4: Fuzzyfication of Input Chamber Temperature

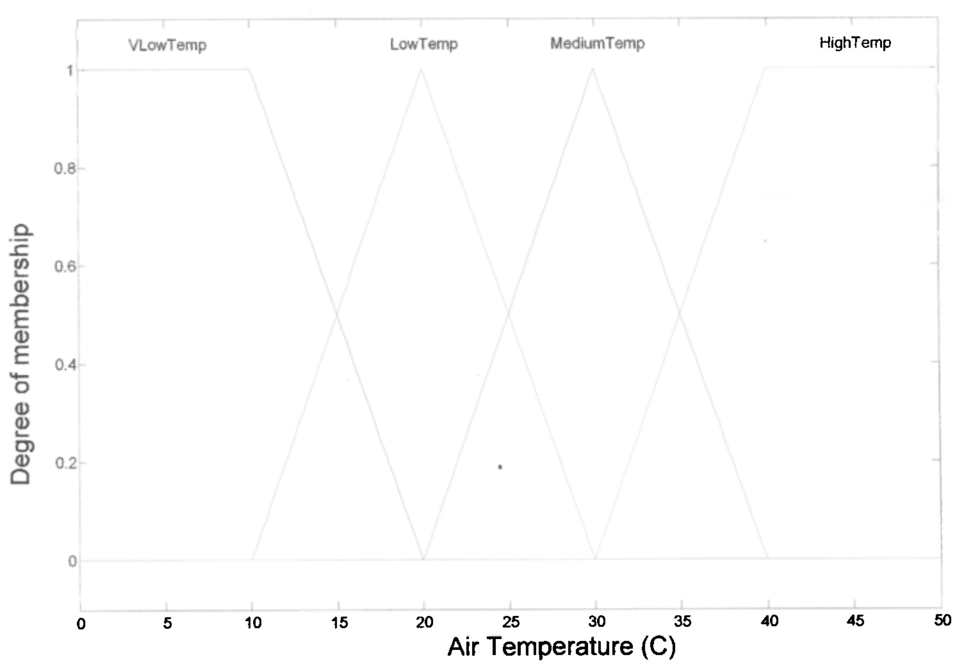

Figure 5.4: Fuzzyfication of Input Chamber Temperature

The blower fan is controlled by a variable speed drive and the fan speed is directly proportional to the operated frequency.

$$fanspeed(rpm) = \frac{120 \times frequency(Hz)}{no.of.motor.poles}$$

For Fuzzyfication of the input/output fan speed, six membership functions are defined as it is the most important controlled variable in terms of energy saving. The input universe is 0 to 50Hz. The width of leftmost membership function is selected to be around 10Hz while all other membership functions are of the width of 20Hz. All membership functions are symmetrical triangles with an overlap of around 50%.

MF NAME	Stop	VSlow	Slow	Fast	VFast	FullSpeed
BASE	0-10	0-20	10-30	20-40	30-50	40-60
SHAPE	Triangular	Triangular	Triangular	Triangular	Triangular	Triangular
POINTS	0,0,10	0,10,20	10,20,30	20,30,40	30,40,50	40,50,50

Table 5.5: Fuzzyfication of Output Motor Frequency

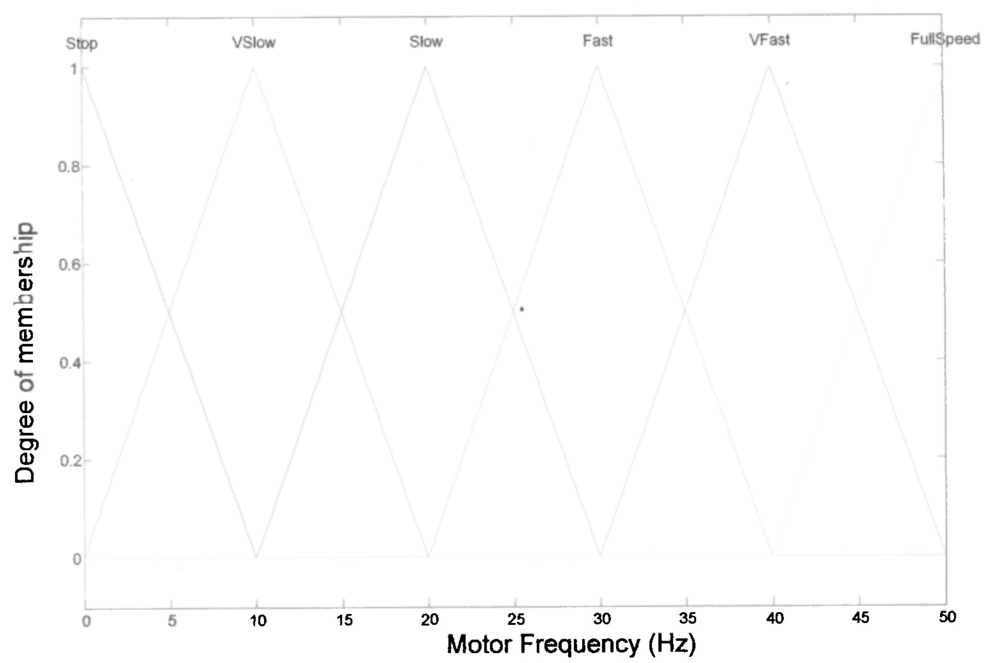

Figure 5.5: Fuzzyfication of Output Motor Frequency

The mixing of hot air with ambient air is done to achieve low relative humidity levels in the process air input. The degree of mixing is controlled by controlling the damper angle.

For Fuzzyfication of the input hot air damper angle, five membership functions are defined. The input universe is 0 to 90 degrees. The width of each membership function is selected to be around 30 degrees. The leftmost and rightmost membership functions are shouldered ramps and the three in the centre are symmetrical triangles of the same width with an overlap of around 50%.

MF NAME	Close	LittleOpen	HalfOpen	Open	FullOpen
BASE	0-30	15-45	30-60	45-75	60-90
SHAPE	Trapezoidal	Triangular	Triangular	Triangular	Trapezoidal
POINTS	0,0,15,30	15,30,45	30,45,60	45,60,75	60,75,90,90

Table 5.6: Fuzzyfication of Output Damper Angle

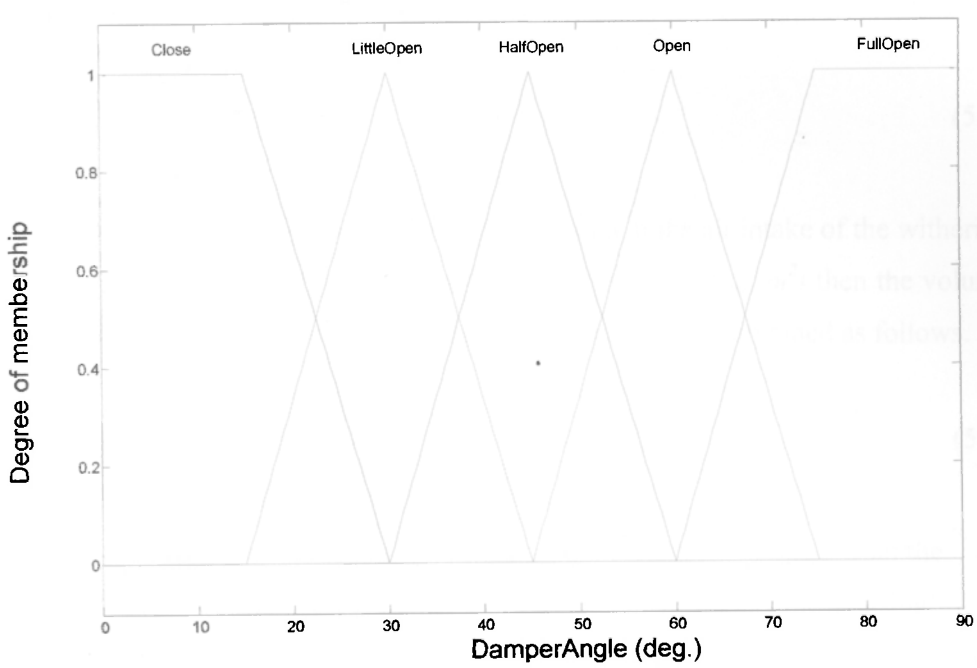

Figure 5.6: Fuzzyfication of Output Damper Angle

5.2 Development of the Control Algorithm

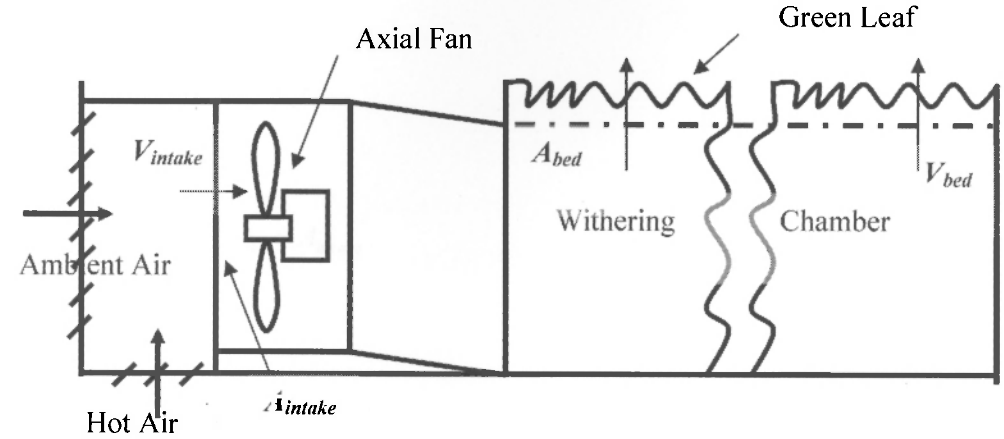

Figure 5.7: Layout of the Withering Trough

If the air velocity at the exit of the withering trough is V_{bed} (m/s), and the air exit area of the trough is A_{bed} (m^2) then the volume flow rate through the withering bed Q_{bed} (m^3/min) can be obtained as follows.

$$Q_{bed} = V_{bed} A_{bed} \tag{5.8}$$

In the same way if the air velocity at the measuring point at the air intake of the withering trough is V_{intake} (m/s), and the air intake area of the trough is A_{intake} (m^2) then the volume flow rate through at the intake of the bed is Q_{intake} (m^3/min) cab be obtained as follows.

$$Q_{intake} = V_{intake} A_{intake} \tag{5.9}$$

Instead of measuring the air velocity directly we can derive the air velocity from the differential pressure reading obtained at the point of measurement as follows using equation 5.2.

$$V_{intake} = \sqrt{\frac{2}{\rho} \times PV_{intake}} \tag{5.10}$$

$$V_{bed} = \sqrt{\frac{2}{\rho} \times PV_{bed}} \qquad (5.11)$$

$$Q_{\text{int}ake} = V_{\text{int}ake} A_{\text{int}ake} \qquad (5.12)$$

$$Q_{\text{int}ake} = \sqrt{\frac{2}{\rho} \times PV_{\text{int}ake}} \times A_{\text{int}ake} \qquad (5.13)$$

$$Q_{bed} = V_{bed} A_{bed} \qquad (5.14)$$

$$Q_{bed} = \sqrt{\frac{2}{\rho} \times PV_{bed}} \times A_{bed} \qquad (5.15)$$

$$Q_{\text{int}ake} = Q_{bed} \qquad (5.16)$$

Considering experimental trough dimensions and equal pressure at two measuring points.

$A_{intake}=0.85m^2$

$A_{bed}=27m^2$

$$V_{\text{int}ake} \times A_{\text{int}ake} = V_{bed} \times A_{bed} \qquad (5.17)$$

For an air intake velocity of 5.0 m/s, the air velocity through the tea leaves is 0.15m/s. As the air velocities of this range cannot be measured accurately in the process environment, air velocity at the intake can be measured and output air velocity can be calculated for processing.

Degree of withering:

Percent wither (P_w), which can represent the degree of withering, may be expressed as,

$$P_W = \left(\frac{F_M}{I_M}\right) \times 100, \qquad (5.18)$$

Where I_m is initial mass of leaf, kg; F_m is final mass of leaf, kg.

If M_L is moisture loss, in percent (wet basis) of tea leaf during withering then,

$$M_L = \frac{(I_M - F_M)}{I_M} \times 100 \qquad (5.19)$$

Or $M_L = 100 - P_W$ (5.20)

Thus, percent moisture loss (physical withering) is inversely related to the magnitude of percent wither; the exact relation being the value of percent moisture loss is complement of percent wither, and vice versa.

5.3 The fuzzy inference system

Following is the summary of details of the fuzzy inference system.

Name = FWC

Type = mamdani

Number of Inputs = 6

Input Labels =

AirFlow
Pressure
RHumidity
Temperature
MFrequency
DamperAngle

Number of Outputs = 2

Output Labels =

MFrequency
DamperAngle

Number of Rules = 45

And Method = min

Or Method = max

Imp Method = min

Agg Method = max

Defuzzyfication Method = centroid

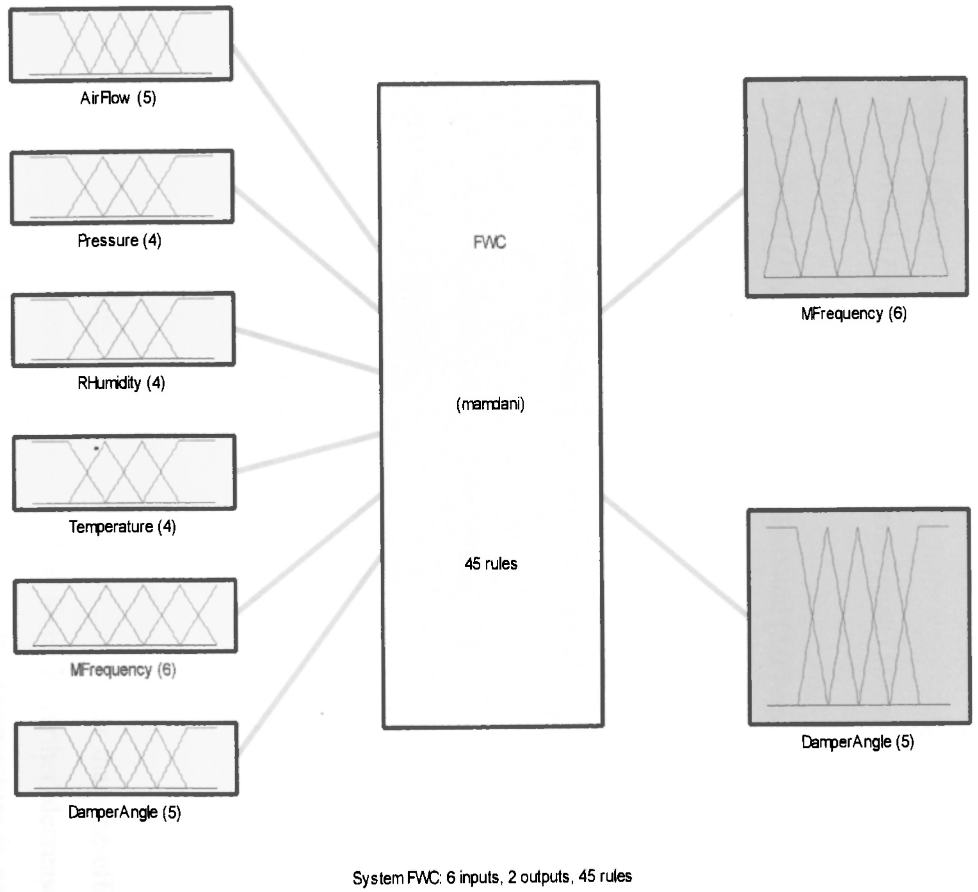

Figure 5.8: The Fuzzy Withering Control System

5.4 Rule base

At the start of the process there is no flow and pressure build-up is minimal. It is necessary to build-up the flow and pressure gradually preventing the tea leaves thrown up, out of the bed or creating blow holes.

IF (*AirFlow* is *NoFlow*) and (*Pressure* is *VLowPressure*) and (*MFrequency* is *Stop*) **THEN** (*MFrequency* is *VSlow*)
IF (*AirFlow* is *LowFlow*) and (*Pressure* is *VLowPressure*) and (*MFrequency* is *VSlow*) **THEN** (*MFrequency* is *Slow*)
IF (*AirFlow* is *LowFlow*) and (*Pressure* is *LowPressure*) and (*MFrequency* is *VSlow*) **THEN** (*MFrequency* is *Slow*)

If the required flow level is achieved with maintaining the correct chamber pressure level then the process can be continued in the same range of fan speed.

IF (*AirFlow* is *StandardFlow*) and (*Pressure* is *LowPressure*) and (*MFrequency* is *VSlow*) **THEN** (*MFrequency* is *VSlow*)
IF (*AirFlow* is *StandardFlow*) and (*Pressure* is *LowPressure*) and (*MFrequency* is *Slow*) **THEN** (*MFrequency* is *Slow*)
IF (*AirFlow* is *StandardFlow*) and (*Pressure* is *MediumPressure*) and (*MFrequency* is *Slow*) **THEN** (*MFrequency* is *Slow*)

If the air flow rate is at correct range, but chamber pressure is higher than the efficient range, then the fan speed is reduced and air humidity level is further decreased to compensate for the deduced air flow provided that the chamber temperature is not too high. Also low flow rates at higher pressures also imply inefficient operation and reduced fan speed with improved relative humidity levels will save energy.

IF (*AirFlow* is *StandardFlow*) and (*Pressure* is *MediumPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *Fast*) and (*DamperAngle* is not *FullOpen*) **THEN** (*MFrequency* is *Slow*) (*DamperAngle* is *FullOpen*)

IF (*AirFlow* is *StandardFlow*) and (*Pressure* is *HighPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *FullSpeed*) and (*DamperAngle* is *LittleOpen*) **THEN** (*MFrequency* is *VFast*) (*DamperAngle* is *HalfOpen*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *HighPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *FullSpeed*) and (*DamperAngle* is *LittleOpen*) **THEN** (*MFrequency* is *VFast*) (*DamperAngle* is *HalfOpen*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *HighPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *VFast*) and (*DamperAngle* is *LittleOpen*) **THEN** (*MFrequency* is *Fast*) (*DamperAngle* is *HalfOpen*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *HighPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *Fast*) and (*DamperAngle* is *LittleOpen*) **THEN** (*MFrequency* is *Slow*) (*DamperAngle* is *HalfOpen*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *HighPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *FullSpeed*) and (*DamperAngle* is *HalfOpen*) **THEN** (*MFrequency* is *VFast*) (*DamperAngle* is *Open*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *HighPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *FullSpeed*) and (*DamperAngle* is *Open*) **THEN** (*MFrequency* is *VFast*) (*DamperAngle* is *FullOpen*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *HighPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *VFast*) and (*DamperAngle* is *HalfOpen*) **THEN** (*MFrequency* is *Fast*) (*DamperAngle* is *Open*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *HighPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *VFast*) and (*DamperAngle* iş *Open*) **THEN** (*MFrequency* is *Fast*) (*DamperAngle* is *FullOpen*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *HighPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *Fast*) and (*DamperAngle* is *HalfOpen*) **THEN** (*MFrequency* is *Slow*) (*DamperAngle* is *Open*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *HighPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *Fast*) and (*DamperAngle* is *Open*) **THEN** (*MFrequency* is *Slow*) (*DamperAngle* is *FullOpen*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *MediumPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *FullSpeed*) and (*DamperAngle* is *LittleOpen*) **THEN** (*MFrequency* is *VFast*) (*DamperAngle* is *HalfOpen*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *MediumPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *FullSpeed*) and (*DamperAngle* is *HalfOpen*) **THEN** (*MFrequency* is *VFast*) (*DamperAngle* is *Open*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *MediumPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *FullSpeed*) and (*DamperAngle* is *Open*) **THEN** (*MFrequency* is *VFast*) (*DamperAngle* is *FullOpen*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *MediumPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *VFast*) and (*DamperAngle* is *LittleOpen*) **THEN** (*MFrequency* is *Fast*) (*DamperAngle* is *HalfOpen*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *MediumPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *VFast*) and (*DamperAngle* is *HalfOpen*) **THEN** (*MFrequency* is *Fast*) (*DamperAngle* is *Open*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *MediumPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *VFast*) and (*DamperAngle* is *Open*) **THEN** (*MFrequency* is *Fast*) (*DamperAngle* is *FullOpen*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *MediumPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *Fast*) and (*DamperAngle* is *LittleOpen*) **THEN** (*MFrequency* is *Slow*) (*DamperAngle* is *HalfOpen*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *MediumPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *Fast*) and (*DamperAngle* is *HalfOpen*) **THEN** (*MFrequency* is *Slow*) (*DamperAngle* is *Open*)

IF (*AirFlow* is *LowFlow*) and (*Pressure* is *MediumPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *Fast*) and (*DamperAngle* is *Open*) **THEN** (*MFrequency* is *Slow*) (*DamperAngle* is *FullOpen*)

IF (*AirFlow* is *StandardFlow*) and (*Pressure* is *HighPressure*) and (*Temperature* is *LowTemp*) and (*MFrequency* is *Fast*) and (*DamperAngle* is not *FullOpen*) **THEN** (*MFrequency* is *Slow*) (*DamperAngle* is *FullOpen*)
IF (*AirFlow* is *LowFlow*) and (*Pressure* is *HighPressure*) and (*MFrequency* is *FullSpeed*) **THEN** (*MFrequency* is *VFast*)

It is required to avoid very low chamber temperatures

IF (*Temperature* is *VLowTemp*) and (*DamperAngle* is not *FullOpen*) **THEN** (*DamperAngle* is *FullOpen*)

Air flow rates higher than the moisture removal capacity of leaves is a waste of energy and should be avoided.

IF (*AirFlow* is *FullFlow*) and (*MFrequency* is *FullSpeed*) **THEN** (*MFrequency* is *Slow*)
IF (*AirFlow* is *FullFlow*) and (*MFrequency* is *VFast*) **THEN** (*MFrequency* is *Slow*)
IF (AirFlow is *FullFlow*) and (*MFrequency* is *Fast*) **THEN** (*MFrequency* is *VSlow*)
IF (*AirFlow* is *FullFlow*) and (*MFrequency* is *Slow*) **THEN** (*MFrequency* is *VSlow*)
IF (*AirFlow* is *HighFlow*) and (*MFrequency* is *FullSpeed*) **THEN** (*MFrequency* is *Slow*)
IF (*AirFlow* is *HighFlow*) and (*MFrequency* is *VFast*) **THEN** (*MFrequency* is *Slow*)
IF (*AirFlow* is *HighFlow*) and (*MFrequency* is *Fast*) **THEN** (*MFrequency* is *VSlow*)
IF (*AirFlow* is *HighFlow*) and (*MFrequency* is *Slow*) **THEN** (*MFrequency* is *VSlow*)

The relative humidity of the process air has to be maintained at minimum level provided that the air temperature limit is not exceeded.

IF (*RHumidity* is *Humid*) and (*Temperature* is not *HighTemp*) and (*DamperAngle* is not *FullOpen*) **THEN** (*DamperAngle* is *FullOpen*)
IF (*RHumidity* is *HighRH*) and (*Temperature* is not *HighTemp*) and (*DamperAngle* is not *FullOpen*) **THEN** (*DamperAngle* is *FullOpen*)

Maintaining the air temperature close to lower levels improves the quality of processed tea.

IF (*Temperature* is *HighTemp*) **THEN** (*DamperAngle* is *Close*)

IF (*Pressure* is not *HighPressure*) and (*Temperature* is *MediumTemp*) and (*DamperAngle* is *FullOpen*) **THEN** (*DamperAngle* is *Open*)

IF (*Pressure* is not *HighPressure*) and (*Temperature* is *MediumTemp*) and (*DamperAngle* is *Open*) **THEN** (*DamperAngle* is *HalfOpen*)

IF (*Pressure* is not *HighPressure*) and (*Temperature* is *MediumTemp*) and (*DamperAngle* is *HalfOpen*) **THEN** (*DamperAngle* is *LittleOpen*)

IF (*Pressure* is not *HighPressure*) and (*Temperature* is *MediumTemp*) and (*DamperAngle* is *LittleOpen*) **THEN** (*DamperAngle* is *Close*)

Chapter Six

Results and Analysis

6.1 Evaluation of the Proposed Control Strategy

The fuzzy inference system developed on Matlab® was evaluated with sample process input readings using "evalfis" function of the fuzzy logic tool box. The motor frequency was kept constant throughout the process while the damper angle is varied to control relative humidity and air temperature. The fuzzy controller output along with the process data is shown in figure 6.1 while the complete test data set is given in table 6.1.

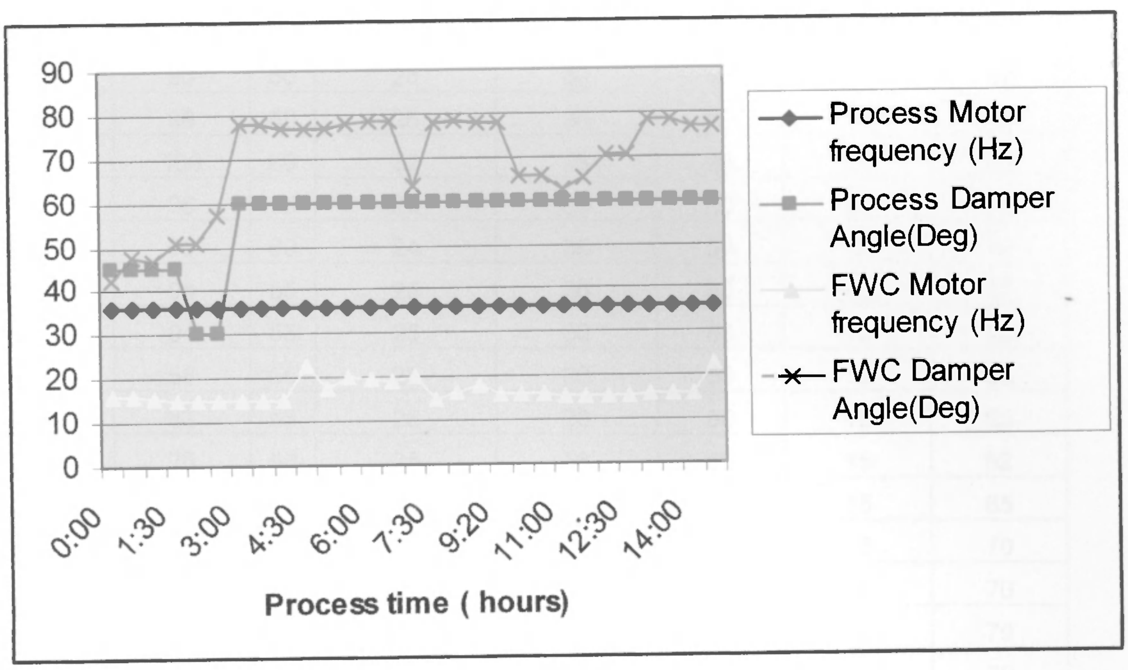

Figure 6.1: Comparison of Normal Process and Fuzzy Withering Controller Outputs

Inputs						Outputs	
Air Flow (10^3CFM)	Pressure (Pa)	RH (%)	Temperature (C^0)	Motor frequency (Hz)	Damper Angle (Deg)	Motor frequency (Hz)	Damper Angle (Deg)
19.026	54	50	35	36	45	16	43
17.986	60	50	32	36	45	16	48
17.456	62	55	34	36	45	15	46
16.485	80	60	34	36	45	15	51
16.429	80	60	34	36	30	15	51
16.336	84	60	33	36	30	15	57
16.163	88	65	30	36	60	15	78
16.635	90	65	30	36	60	15	78
16.269	88	70	30	36	60	15	77
14.606	88	70	28	36	60	23	77
15.373	92	70	28	36	60	17	77
14.937	94	65	30	36	60	20	78
15.021	96	60	28	36	60	20	79
15.186	96	60	26	36	60	19	79
14.785	100	60	32	36	60	20	63
16.16	96	55	28	36	60	15	78
16.06	96	60	24	36	60	17	79
15.567	94	55	25	36	60	18	78
16.287	94	55	25	36	60	16	78
18.035	58	55	25	36	60	16	65
17.969	62	55	25	36	60	16	65
16.667	70	50	25	36	60	15	62
17.082	74	50	24	36	60	15	65
17.465	74	60	25	36	60	15	70
17.167	74	60	25	36	60	15	70
16.491	70	60	20	36	60	16	79
16.347	72	60	20	36	60	16	79
16.345	74	70	20	36	60	16	77
14.287	70	70	20	36	60	23	77

Table 6.1: Matlab Fuzzy Inference Evaluation Results

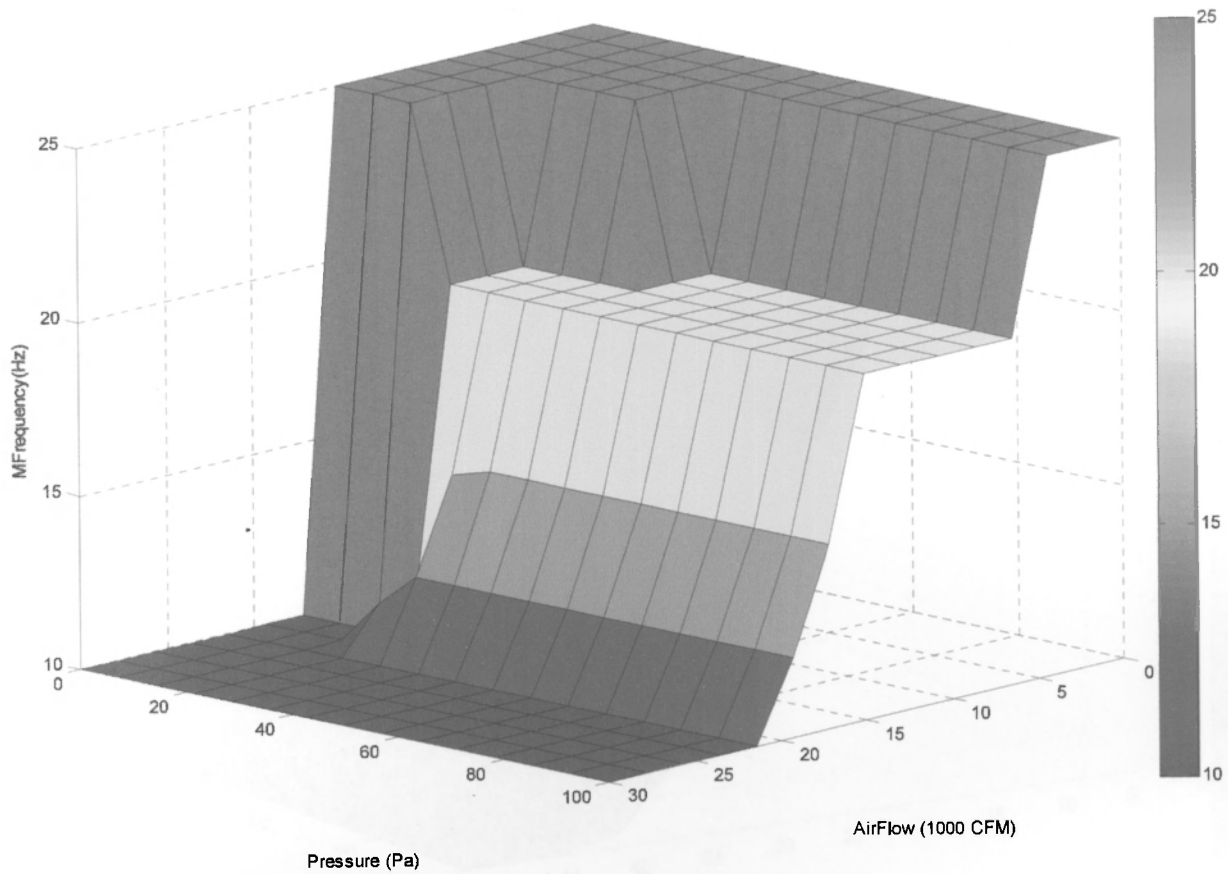

Figure 6.2: Graphical View of Motor Frequency Pattern with Relation to Chamber Pressure and Air Flow Readings.

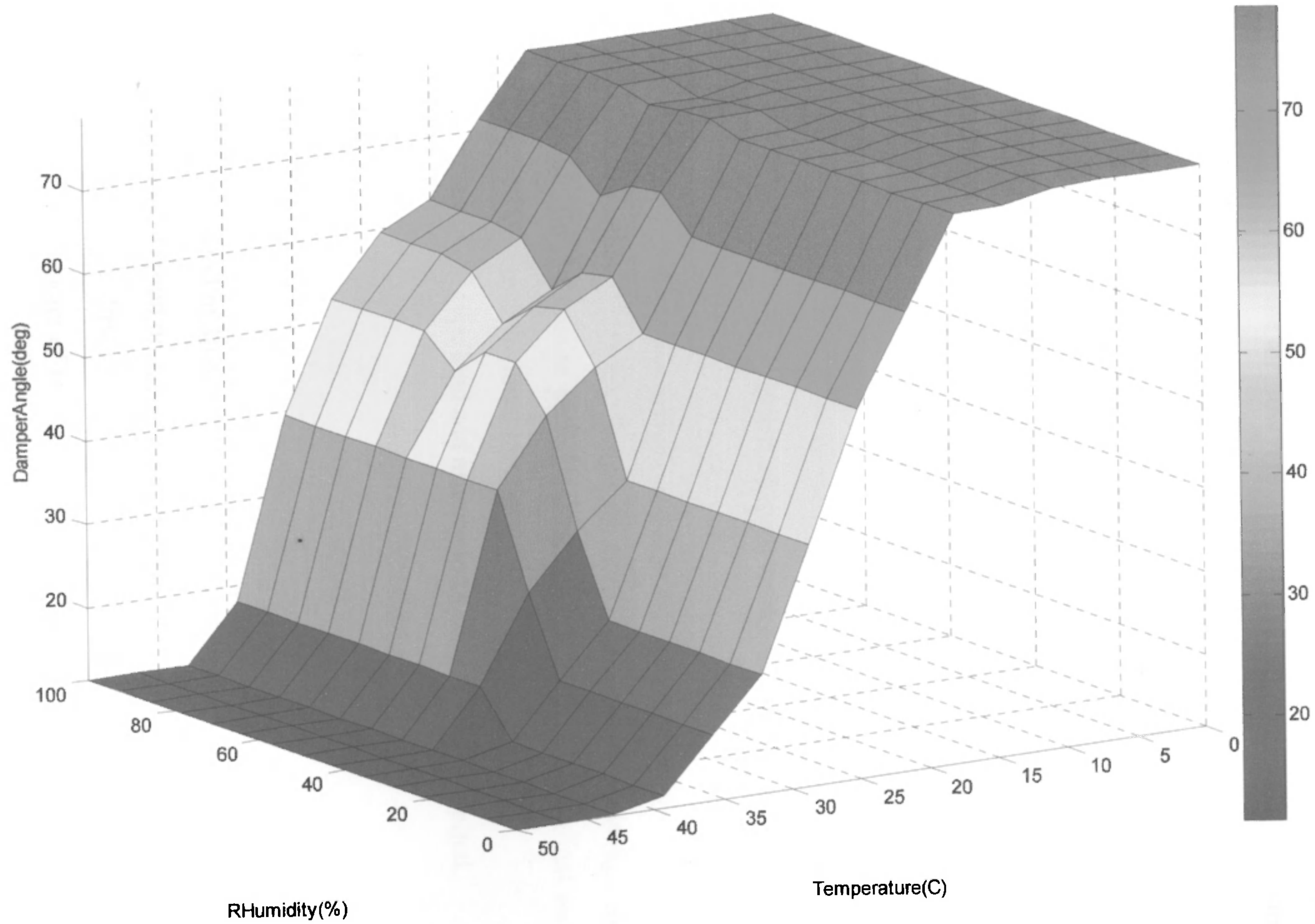

Figure 6.3: Graphical View of Damper Angle Variation Pattern With Relation to Humidity and Chamber Pressure Readings

Figure 6.2 shows the motor frequency pattern with respect to chamber pressure and air flow rate. At low chamber pressure levels motor frequency is increased at a faster rate to maintain the required air flow rate. But if the chamber pressure is high, motor frequency is increased at a slower rate. If the air flow rate is at a satisfactory level but the chamber pressure is high, motor frequency can be reduced to reduce the chamber pressure.

Figure 6.3 shows the damper angle pattern with relation to relative humidity and chamber pressure. At very high temperatures the dampers are closed completely to protect the quality of the tea leaves and at very low temperatures the dampers are opened completely to accelerate the withering process. Damper angle is increased if the relative humidity level is high and closed as the relative humidity level drops down to acceptable levels.

6.2 Energy Saving Approximations

The fan motor power consumption pattern of the present system is shown in Figure A.1 and it is almost constant despite the process changes as the motor frequency is fixed at 36Hz.

Table 6.1 shows the proposed control system output motor frequency at 30 minute data intervals. If we assume that the motor frequency can be taken as the average motor frequency through out the 30 minute period we can approximate the electrical energy savings of the proposed system as bellow.

The motor load is a centrifugal type load and affinity lows can be readily applied.

$$\frac{P_{proposed}}{P_{present}} = \left(\frac{f_{proposed}}{f_{present}}\right)^3 \quad (6.1)$$

Therefore for each time period of 30 minutes we can estimate the power consumption of the proposed system as a fraction of the present system.

For example if we consider the first time slot, the motor frequency is taken as the average of the starting and end frequencies of the respective time period.

i.e. $f_{present} = \frac{36+36}{2} = 36Hz$ (6.2)

$$f_{proposed} = \frac{16+16}{2} = 16Hz \quad (6.3)$$

Applying 6.2 and 6.3 to 6.1,

$$\frac{P_{proposed}}{P_{present}} = \left(\frac{16}{36}\right)^3 = 0.0878 \quad (6.4)$$

If the power measurement is also averaged using the starting and end readings of the respective time period from Table A.4,

$$P_{present} = \frac{1480+1948}{2} = 1714W \quad (6.5)$$

Substituting in 6.4,

$$P_{proposed} = 0.0878 \times 1714 = 150.49W \quad (6.6)$$

∴ The energy consumption for the time period,

$$E_1 = 150.49 \times 0.5 = 75.25Wh \quad (6.7)$$

Same calculation can be extended to the other sets of readings of Table 6.1 and the results are summarised in Table 6.2 below.

Time Period	Present Motor frequency (Hz)	Present Energy Consumption (Wh)	Proposed Motor frequency (Hz)	Proposed System Energy Consumption (Wh)
1	36	857.00	16	75.24
2	36	976.50	15.5	77.94
3	36	994.75	15	71.96
4	36	1005.75	15	72.75
5	36	1005.00	15	72.70
6	36	1012.50	15	73.24
7	36	1014.75	15	73.40
8	36	1012.00	15	73.21
9	36	1008.25	19	148.23
10	36	1008.00	20	172.84
11	36	1012.50	18.5	137.41
12	36	1015.25	20	174.08
13	36	1019.75	19.5	162.07
14	36	1021.75	19.5	162.38
15	36	1021.50	17.5	117.34
16	36	1023.00	16	89.81
17	36	1019.25	17.5	117.08
18	36	1017.25	17	107.12
19	36	999.00	16	87.70
20	36	989.50	16	86.87
21	36	996.50	15.5	79.54
22	36	990.25	15	71.63
23	36	992.25	15	71.78
24	36	996.75	15	72.10
25	36	996.25	15.5	79.52
26	36	999.75	16	87.77
27	36	997.75	16	87.59
28	36	995.00	19.5	158.13

Table 6.2: Electrical Energy Consumption of the Present and Proposed systems

∴ By adding the 28 30 minute time periods,

Total electrical energy consumed by the present system = 28.00 kWh

Total electrical energy consumed by the proposed system = 2.86 kWh

When converted to a percentage,

$$\frac{2.86}{28.00} \times 100 = 10.21\%$$

This calculation is based on the system output simulated with a sample set of practical data set and the output was determined considering the present system parameters at a given point of time in the process. The effect of the proposed system parameter settings on the next set of settings is not considered.

The electrical energy consumption of the system will be reduced considerably by the proposed system and the corresponding increment of thermal energy required for the operation of the dryers will be increased due to the fact of reduced humidity levels of the process air and since most of the factories are using firewood which is freely available in the areas, the cost of producing low humidity process air will be less than the savings obtainable through electrical energy savings.

Chapter Seven

Application of the Proposed Method

7.1 Implementation

The set values for the fan speed and damper angle are determined by the fuzzy logic system while the variables are maintained constant by means of individual PID controllers as shown bellow.

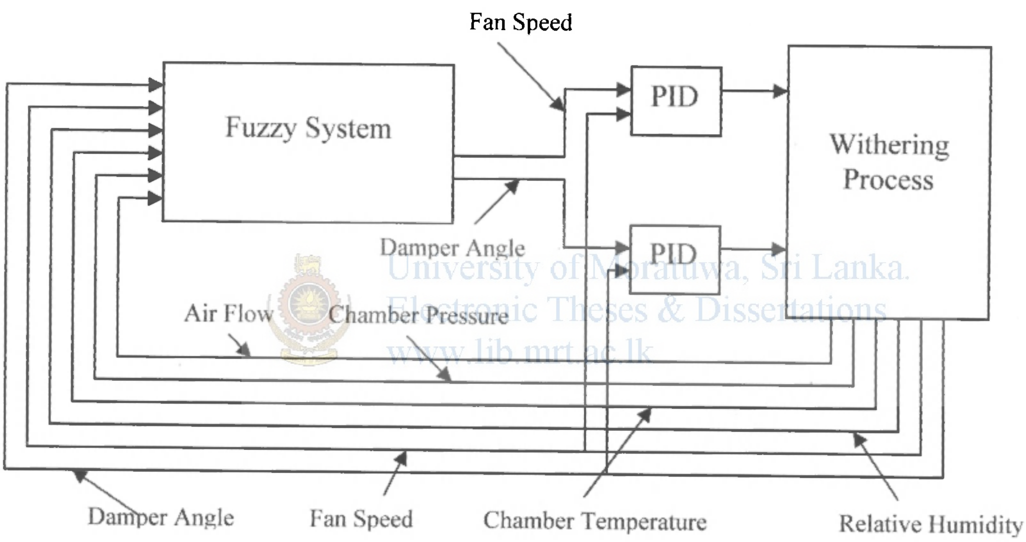

Figure 7.1: Structure of the Proposed Control System

A typical tea factory has more than five withering troughs close to one another and in such situations a central control system to control all the troughs with a single large fuzzy system can be considered. It will run individual control algorithms for each individual trough and the number of inputs and outputs will be multiplied by the number of troughs to be controlled.

7.2 Configuring Fine Tuning and Commissioning

The rules are based on the operator experience and very much dependant on the respective trough characteristics as well as other factors such as the source of air heating, climate conditions, etc. The system has to be thoroughly experimented and fine tuned to suite each trough and should be retuned from time to time after commissioning.

7.3 Practical Issues

There are some practical issues that needed to be considered in practical implementation of the system. Mainly effect of dust on flow sensors, effect of varying loading conditions, harmonics generated by the variable speed drives and there effect on the control system, are few of them.

Chapter Eight

Conclusions

8.1 Conclusions, Remarks and Discussion

The use of fuzzy logic in withering control needs much practical experimentation with the basic structure in place, so that the membership functions and the rule base can be modified based on trial and error so that maximum energy efficiency and quality of the processed tea is ensured. This study provides the basis for such industrial experiments.

This study shows that a considerable amount of energy is wasted in conventional tea withering process by the way of excessive air flow rates and also due to inefficient operation of the fan motor. The proposed fuzzy logic based system provides solutions for both these issues.

The experimental and simulation results shows that with proper utilization of low humid air by controlling the damper angle, withering fan motor speed can be reduced without affecting the rate of withering. Also this study shows that chamber pressure build-up can be used as an indicator for inefficient operation of the withering fan and energy wastage due to this inefficient operation of the withering fan can be reduced by means of improved relative humidity levels of the process air for compensation of a motor speed reduction.

The nature of the process does not require high accurate control and also does not require very fast reaction to system changes. The proposed fuzzy logic based control system well suites these process characteristics and can effectively integrate the operator experience to an automated withering control system for more consistent energy efficient and quality process.

8.2 Considerations for Future Research

In a broader perspective for future advancements in the tea processing industry, the withering process should be looked at as a hole and new conceptualisation is required to overcome the inherent draw backs of the present system that was developed hundreds of years ago to suit the environmental, commercial and technical resources available at that period of time.

For example, the present open withering system releases the used air which is very high in moisture content, to the process environment and it poses two problems.

The fans sucks in this high moisture content air through the ambient air stream and mixes with dry air out from the dryer room and blows through the withering bed. The resulted air is high in moisture content and as a result withering becomes slow and energy inefficient.

The high moisture content air out from one trough can deposit on already withered tea leaf on adjacent troughs as the withering troughs are located close by and also the withering times are also staggered among the individual troughs to facilitate distributed plucking and collection times.

To solve these issues, a mechanism which can guide the used air out of the process environment has to be developed.

Another concern related to the ambient air stream is that during different weather conditions and climates the humidity level of the ambient air stream can be very high and therefore improvisation of some method to source the ambient air stream through a processing chamber where you can reduce the .humidity level to a certain extent by the way of utilisation of the refrigeration cycle or any other method, it will improve the process.

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Appendix

Time	Anemometer reading(ft/m)									Manometer Reading	
										P_1	
	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_T	V_S
12:30	2241	2107	1909	1977	2048	1891	2326	2345	2246	0.27	0.23
13:00	2113	1941	1819	1933	2005	1842	2124	2205	2064	0.30	0.27
13:30	1970	1872	1870	1845	1900	1706	2122	2171	2058	0.31	0.34
14:00	1591	1842	1734	1627	1808	1799	1998	2017	2124	0.40	0.35
14:30	1816	1748	1705	1639	1815	1787	1926	2014	2034	0.40	0.37
15:00	1708	1674	1837	1712	1770	1681	1894	2107	2008	0.42	0.37
15:30	1750	1851	1770	1543	1776	1621	1928	1987	1991	0.44	0.40
16:00	1823	1830	1799	1795	1732	1728	1932	2001	2051	0.45	0.42
16:30	1881	1854	1822	1639	1685	1695	1810	2019	1918	0.44	0.44
17:00	1491	1343	1529	1595	1587	1602	1678	1944	1886	0.44	0.44
17:30	1822	1642	1637	1638	1664	1586	1679	1902	1854	0.46	0.46
18:00	1772	1283	1795	1460	1559	1589	1792	1878	1859	0.47	0.47
18:30	1644	1624	1606	1700	1655	1420	1666	1880	1876	0.48	0.48
19:00	1721	1576	1579	1651	1671	1518	1813	1870	1838	0.48	0.48
19:30	1633	1344	1587	1469	1695	1748	1613	1913	1832	0.50	0.48
20:00	1738	1791	1662	1684	1772	1686	1950	1989	1942	0.48	0.47
20:30	1817	1803	1786	1587	1647	1717	1834	1961	1962	0.48	0.48
21:00	1742	1584	1798	1755	1583	1757	1657	1877	1866	0.47	0.46
22:00	1864	1811	1729	1688	1665	1742	1830	1952	2060	0.47	0.45
22:30	2070	1707	2157	1869	1995	1835	2042	2196	2224	0.29	0.29
23:00	1968	1809	2019	1849	1850	1957	2068	2211	2298	0.31	0.30
23:30	1705	1620	1760	1750	1795	1911	2034	2142	2006	0.35	0.32
0:00	1943	1817	1945	1721	1839	1838	1925	2061	2050	0.37	0.34
0:30	1837	2001	1913	1796	1783	1864	2008	2144	2177	0.37	0.34
1:00	2029	1983	2020	1499	1779	1733	1923	2160	2098	0.37	0.34
1:30	1717	1529	1823	1911	1755	1805	1888	2126	1992	0.35	0.35
2:00	1901	1818	1745	1722	1713	1774	1711	2059	1959	0.36	0.32
2:30	1885	1630	1890	1628	1745	1708	1956	2042	1916	0.37	0.34
3:00	1571	1416	1624	1446	1517	1609	1592	1811	1749	0.35	0.34

Table A.1: Field Experiment Data

Calculation of withering bed air velocity from field data

$$V_{intake} = \frac{V1+V2+V3+V4+V5+V6+V7+V8+V9}{9}\left(\frac{ft}{\min}\right)$$

$$Q_{intake} = V_{intake} \times A_{intake}$$

Q_{intake}=

$$V_{intake} \times \frac{38}{12} \times \frac{34}{12}\left(\frac{ft^3}{\min}\right) = V_{intake} \times \frac{38}{12} \times \frac{34}{12} \times \frac{25.4 \times 25.4 \times 25.4}{1000 \times 1000 \times 1000} \times 60\left(\frac{m^3}{s}\right)$$

$$V_{bed} = \frac{Q_{bed}}{A_{bed}}$$

But $Q_{intake} = Q_{bed}$ *(at same pressure)*

$$\therefore V_{bed} = \frac{Q_{intake}}{A_{bed}} = \frac{Q_{intake}}{33.4}\left(\frac{m}{s}\right)$$

Process time (minutes)	Q_{intake} (CFM)
0	19026
30	17986
60	17456
90	16485
120	16429
150	16336
180	16163
210	16635
240	16269
270	14606
300	15373
330	14937
360	15021
390	15186
420	14785
450	16160
480	16060
510	15567
570	16287
600	18035
630	17969
660	16667
690	17082
720	17465
750	17167
780	16491
810	16347
840	16345
870	14287

Table A.2: Air velocity through Withering Bed.

Process time (minutes)	Q_{intake} (CFM)
0	19026
30	17986
60	17456
90	16485
120	16429
150	16336
180	16163
210	16635
240	16269
270	14606
300	15373
330	14937
360	15021
390	15186
420	14785
450	16160
480	16060
510	15567
570	16287
600	18035
630	17969
660	16667
690	17082
720	17465
750	17167
780	16491
810	16347
840	16345
870	14287

Table A.2: Air velocity through Withering Bed.

Chamber pressure calculations from field data

Chamber pressure = meter reading × meter constant (0.2kPa)

Process Time (Minutes)	Total Pressure (Pa)	StaticPressure (Pa)
0	54	46
30	60	54
60	62	68
90	80	70
120	80	74
150	84	74
180	88	80
210	90	84
240	88	88
270	88	88
300	92	92
330	94	94
360	96	96
390	96	96
420	100	96
450	96	94
480	96	96
510	94	92
570	94	90
600	58	58
630	62	60
660	70	64
690	74	68
720	74	68
750	74	68
780	70	70
810	72	64
840	74	68
870	70	68

Table A3: Withering Chamber Pressure Variation during the Process

Motor power consumption variation during the process

Process Time (Minutes)	Motor Power (W)
0	1480
30	1948
60	1958
90	2021
120	2002
150	2018
180	2032
210	2027
240	2021
270	2012
300	2020
330	2030
360	2031
390	2048
420	2039
450	2047
480	2045
510	2032
570	2037
600	1959
630	1999
660	1987
690	1974
720	1995
750	1992
780	1993
810	2006
840	1985
870	1995

Table A.4: Motor Power Consumption with Time (At Constant Frequency of 36Hz)

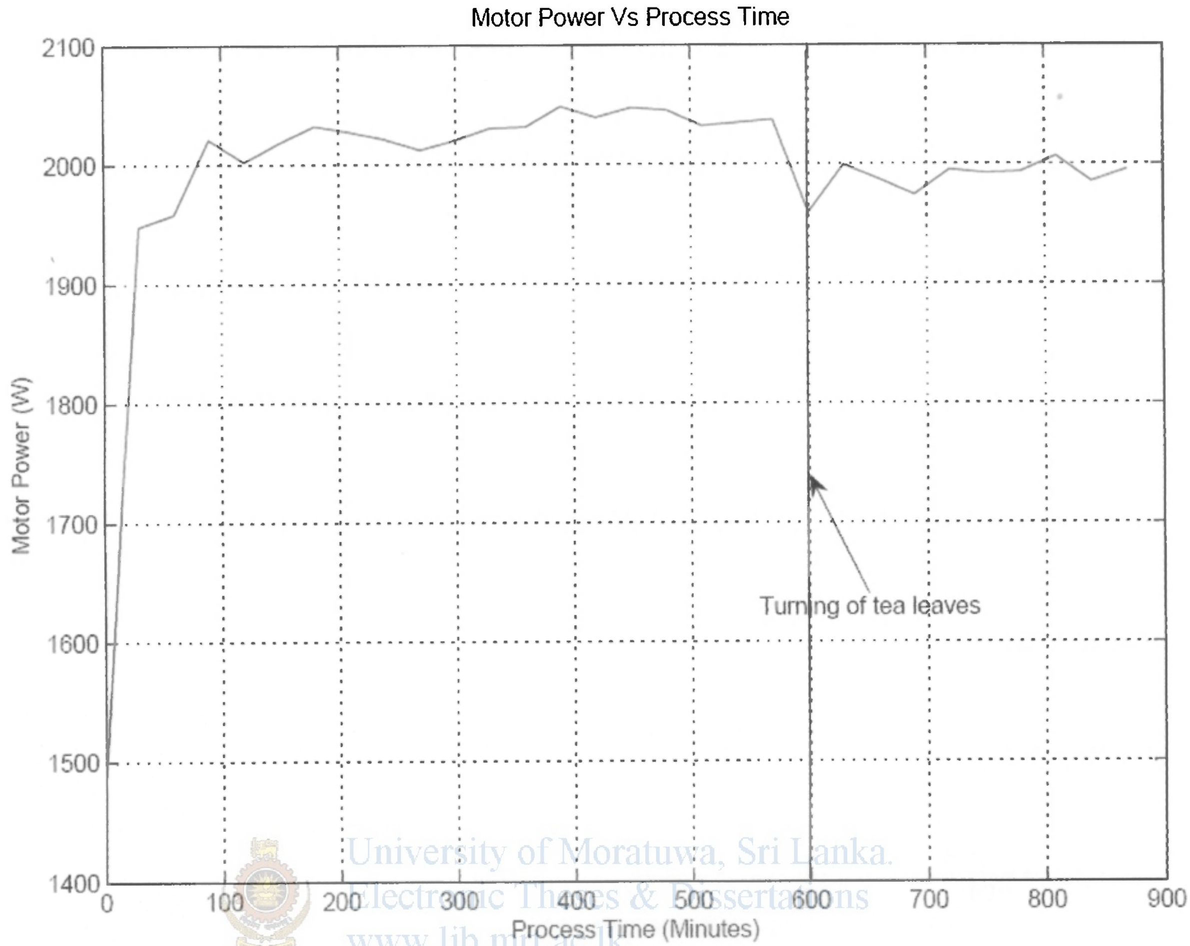

Figure A.1: Motor Power Consumption with Time (At Constant Frequency of 36Hz)

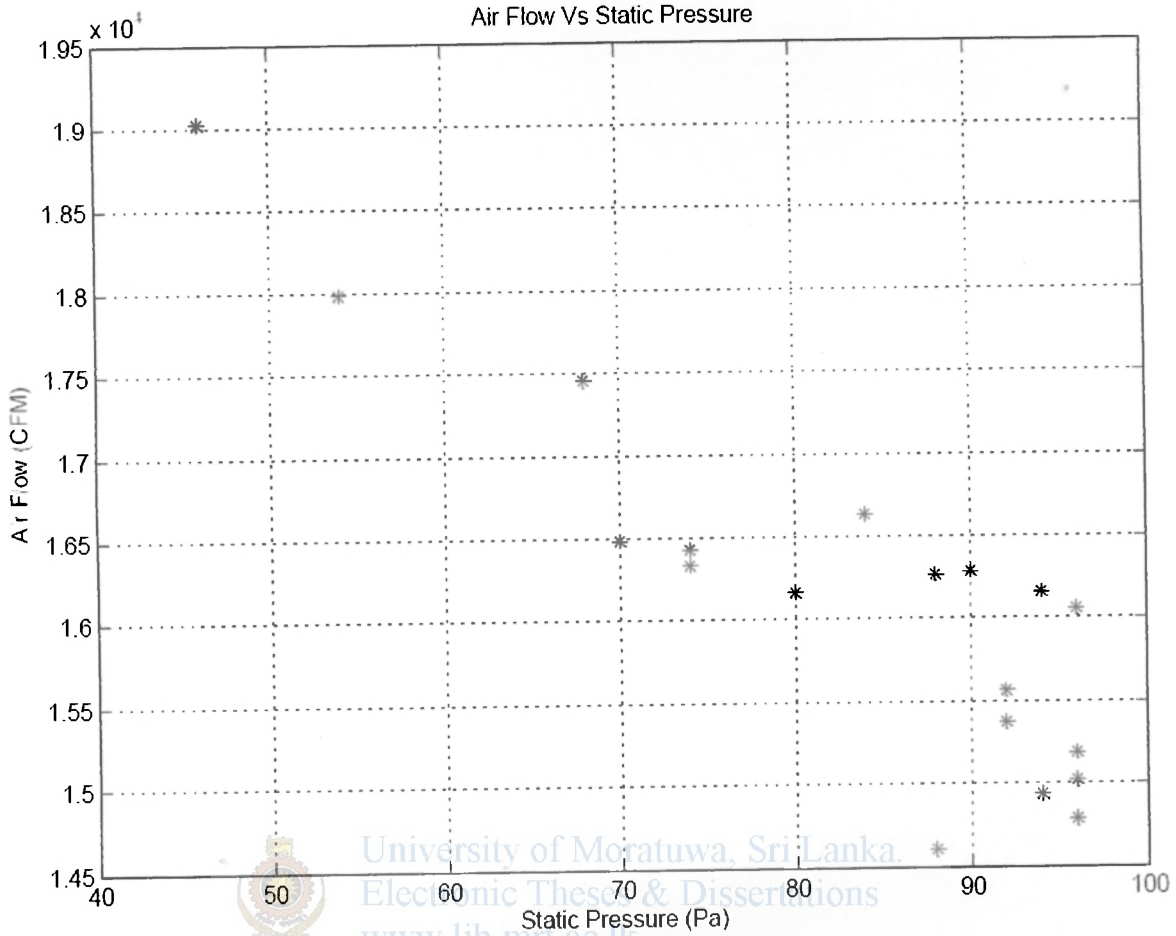

Figure A.2: Air Flow Vs Chamber Pressure