THE IMPORTANCE OF FLUIDIZATION PARAMETERS FOR THE PRODUCTION OF QUALITY BLACK TEA AT HIGHER EFFICIENCIES

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Declaration

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Dedication

I would like to recollect the love and earnest encouragement from my wife without whose loving care and inspiration it would not have been possible for me to come up this far in life.

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Abstract

Orthodox broken type teas, currently producing in tea factories in Sri Lanka, have on average smaller size particles than that of tea produced a decade ago. However most of the tea factories still use the conventional fluid bed dryers and hence they are experiencing difficulties in achieving fluidization with required co-existence of continuous phase and bubble phase. In the present study, fluidization behavior of Orthodox broken type tea was examined in a pilot-scale fluid bed dryer. Six different bedplate configurations were evaluated against the conventional bedplate having perforations of 36 mm × 0.5 mm with 3.4 % opening area. The bedplate of 36 mm × 0.6 mm with 5 % opening area gave the best performance. A stable fluidized tea-bed with co-existence of continuous phase and bubble phase was achieved without stagnation and entrainment at higher loadings of 44.5 – 50.5 kg/m^2 than the conventional loading of 38.5 kg/m^2. Further, the fluctuations were found to be minimized for a wide range of fluidizing velocities of 1.3 - 1.9 m/s.

A new mathematical model was developed to predict the minimum fluidization velocity by correlating dimensionless Archimedes number, Reynolds number and moisture ratio. The variations in particle size and particle density due to shrinkage during the drying process were incorporated in the new model. The predicted fluidization velocity was found to be in good agreement with the experimental data and the difference was below 10 % for majority of the cases. An empirical model relating the dimensionless moisture ratio to an easily measurable parameter, tea-bed temperature, was also proposed and validated.

Drying characteristics of Orthodox broken type tea and the quality variations with the fluidization parameters were also examined using a laboratory-scale fluid bed dryer. Page model was found to give better predictions than the other thin-layer drying models. Free moisture was found to be present above moisture contents of 60 % (w/w, dry basis) and the effective diffusivity was found to be 2.52 x 10^{-11} m^2/s. During the final stage of drying, effective diffusivity was found to vary between 2.660 x 10^{-11} m^2/s and 2.782 x 10^{-11} m^2/s. Quality variations were examined by the method of chemical analysis and organoleptic analysis. The results indicated that better quality tea could be achieved with higher loadings than conventional loading of 38.5 kg/m^2 and lower hot air temperatures than the conventional temperature of 124 °C. However, the drying time was found to increase by 22-33 % for higher loadings and by 12 – 77 % for lower hot air temperatures.

Keywords: Orthodox broken type tea, minimum fluidization velocity, shrinkage, moisture ratio, thin-layer drying model

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
BOPF	Broken Orange Pekoe Fannings
BP	Bedplate
BR	Brightness
CBSL	Central Bank of Sri Lanka
CTC	Crush Tear Curl
ECM	Environmentally Controlled manufacture
FBD	Fluid Bed Dryer
PID	Proportional–Integral–Derivative
PWM	Pulse-Width Modulation
RH	Relative Humidity
RMSE	Root Mean Square Error
TC	Total Colour
TF	Theaflavin
TR	Thearubigin
VSD	Variable Speed Drive

LIST OF NOMENCLATURE

Symbols	**Description**
Ar	Archimedes Number
d_i	mean diameter of the size interval of sieves (µm)
d_p	mean particle size (µm)
g	gravitational acceleration constant (m/s^2)
$ERe_{mf}(\%)$	Percentage absolute error for Reynolds number at minimum fluidization
Re_{mf}	Reynolds number at minimum fluidization
$Re_{mf}(calc)$	Calculated value of Reynolds number at minimum fluidization
$Re_{mf}(exp)$	Experimental value for Reynolds number at minimum fluidization
u_{mf}	minimum fluidization velocity (cm/s)
W	average moisture content in percentage (w/w, dry basis)
W_e	equilibrium moisture content in percentage (w/w, dry basis)
W_i	initial moisture content in percentage (w/w, dry basis)
X_i	weight fraction in the size interval of sieves
ρ_g	density of fluidizing air (kg/m^3)
ρ_p	Particle density of dhool (kg/m^3)
μ	dynamic viscosity of fluidizing air (kg/m/s)
ϕ	dimensionless moisture content
t	drying time
M	Average moisture content
M_o	initial moisture content
M_e	equilibrium moisture content
A_o, k_o, A_1, k_1, n	empirical coefficients
χ^2	Chi-square
D_{eff}	Effective diffusivity
T	Tea-bed temperature
ΔP	Total differential pressure

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1. INTRODUCTION

1.1 Background

Tea, produced and consumed, in the world is mainly in two categories, black tea and green tea. It is produced in more than 35 countries and the total tea production reached 6 billion kilograms in 2013 (Tea market Update, 2013). The quantity of tea produced in Sri Lanka during the year 2013 was 340 million kilograms which is about 5.6 % of the world total tea production. Being the third largest tea exporter in the world, Sri Lanka exported 94 % of the production during 2013 with total earnings of U$ 1,540 Million.

Sri Lanka is famous for producing special type of black tea called Orthodox tea in about 586 tea factories. Orthodox black tea is again classified into two categories, Orthodox leafy type tea and Orthodox broken type tea. Orthodox broken type tea with distinct characteristics is the preferred option for consumption in western countries and Japan. Moreover, it is popularly and widely used in the production of value added tea such as tea bags and scented tea. It is about 20 % of the total tea production and is produced in 180 tea factories in Sri Lanka.

The manufacturing processes involved in the production of Orthodox tea include withering, rolling & roll breaking, fermentation, drying, grading and packing. Green leaf shoots with 2 leaves and a bud are plucked from the plants in the field and are brought to tea factories. The initial moisture content in the shoots is about 400 % (w/w, dry basis). The moisture content is reduced down to 130 % during withering process to make them into a rubbery stage so that chemical constituents in tea are not lost during breaking it in rollers. The withered leaves are broken down to smaller particles in rollers during rolling process. The small particles are separated from the bulk using roll breakers and spread on tables at a thickness of 5 – 7.5 cm to facilitate enzymatic chemical reactions which result in products that contribute to required tea character. The chemical reactions are allowed to take place in tea for 2 to 3 hours in order to obtain the required optimum level of quality products. This stage is judged by colour change in tea from green to coppery colour. Once the fermentation is judged optimum, it is immediately dried in tea dryers and the moisture content is reduced to 2.5 –3.0 % (w/w, dry basis). The dried-tea is then separated into tea grades according to their particle sizes suitable to the market. The different types of tea grades are then packed separately in suitable packaging.

1.2 Justification of the project

Main grades of Orthodox broken type tea produced in tea factories according to their particle sizes are Pekoe (1400 – 2000 µm), BOP (850 – 1400 µm), BOPF (500 – 850µm) and Dust No.1 (355 – 500 µm). In the recent past, notable changes had been taken place in the tea manufacturing and more percentage of BOPF and Dust No.1 grades are produced at present to cater the demand. The moisture content achieved in leaf after withering process is little higher than that was maintained in the past (130 % against 122 %, w/w, dry basis). This is to match with the rolling process during which leaf undergo severe maceration in rollers in the present day manufacturing. Further, small size mesh (No.8) is used in Roll breakers to separate broken tea from the bulk of macerated leaf. The over-size tea collected from the Roll breakers is processed again and again for three to four times to produce tea with sizes suitable for the different tea grades as required for the market.

Table 1.1 shows the results of particle size analysis conducted on tea produced at present and earlier. The tea produced at present have more amount of smaller size particles compared to tea that was produced in 1990. More than 95 % of tea is less than 1 mm in size whereas it was only about 44 % earlier. The fluidizing behaviour of the tea with more amounts of small size particles is much different to that of large particles and the effectiveness of already available conventional Fluid Bed Dryers (FBDs) became questionable. At present, many factories are experiencing difficulties in obtaining fluidization of tea with required co-existence of continuous phase and bubble phase in the dryer. As a result, discharging time from the dryer is affected and tea often get under-fired or over-fired and fine tea particles are carried over by the fluid stream leading to increased blowout. Orthodox broken type tea with consistent moisture content could be achieved and loss of tea in exiting air stream could be avoided through improved drying process. Detail study on fluidizing behavior, drying characteristics and fluidized bed drying parameters of tea is required in this regard. Fine tuning the important parameters with possible automation can improve the drying process. A suitable fluidized bed drying model is required for effective automation. Hence, it may be necessary to have modifications to fluid bed tea dryers in order to improve the drying process.

Table 1.1: Results of sieve analysis on tea produced during 1990 and 2012

Aperture size (μm)	**% of tea retained**		**Tea grade**
	Tea produced during 1990	**Tea produced during 2012**	
2000	0.99	0.06	Pekoe & BOP
1400	28.51	0.25	
1000	26.12	2.90	
710	11.30	17.90	BOPF & Dust No.1
355	22.80	62.50	
250	6.96	13.78	Other grades
150	3.09	2.58	
125	0.22	0.06	
Bottom	0.03	0.00	

1.3 Objectives of the project

Primary objective

The primary objective is to study the effect of fluidized bed parameters on the quality of Orthodox broken type black tea. The specific objectives can be identified as

1. Identify the suitable configuration in bedplate and the range of fluidizing velocities to have coexistence of continuous phase and bubble phase in fluid bed drying of Orthodox broken type tea.
2. Study the drying characteristics of Orthodox broken type tea and evaluate the applicability of existing thin layer drying models for Orthodox broken type tea.
3. Develop new mathematical models for describing the fluidized bed drying of Orthodox broken type tea
4. Examine the effect of loading and the hot air temperature on the quality of dried-tea.

1.4 Outline of the thesis

Chapter 1: A brief introduction of the tea industry is given. Manufacturing process and the particle size of Orthodox broken type tea, produced earlier and at present, are described. The need of a detailed study with the objective of overcoming the problems encountered presently in drying of Orthodox broken type tea in fluid bed tea dryers is discussed.

Chapter 2: An overview of tea industry and market potential of Orthodox broken type tea is described. Manufacturing processes are elaborated giving special attention to obtaining required tea character. Principle of fluidization is briefly described and fluidization characteristics related to particle size is discussed. Fluid bed drying and development of fluid bed tea dryer are described. Mathematical models for drying food products are described and the work done in the past is given. Finally, the methods for analyzing the quality parameters in tea are described.

Chapter 3: Methods used in analyzing the moisture content and quality parameters in tea samples are described. Method of analyzing the data for adequacy of fit of different drying models and estimating empirical constant are given.

Chapter 4: Materials and equipment used and methods adopted in pilot-scale study on fluidizing and drying behavior of Orthodox broken type tea are given. Methods of obtaining differential static pressure across fluidized tea-bed, particle size analysis for tea and density of tea are also described. Further, materials and equipment used and methods adopted in laboratory-scale study on drying characteristics, effect of loading and effect of hot air temperature on quality of tea are given.

Chapter 5: Results on drying characteristics of Orthodox broken type tea is presented. Drying curve for the tea was obtained at different hot air temperatures. Variation of tea-bed temperature with time is presented. Method to identify suitable semi-theoretical thin-layer drying model for describing drying characteristics of tea and effective diffusivity of water are described and the results are presented.

Chapter 6: Results of pilot-scale study on fluidizing and drying behavior of Orthodox broken type tea is presented. Differential static pressure variation and fluidizing velocity variation, studied at different loadings using dried tea and dhool are presented separately to show the performance of bedplates having different configurations.

Chapter 7: A new mathematical model was developed to analyze the fluidizing behavior of dhool during drying. The effect of shrinkage and the variations in particle density were included in the model. This model predicts the minimum fluidizing velocity with the reduction of moisture which is common observed in industrial type continuous fluid bed dryers. Since the measurement of tea-bed temperature is easier in practice than the measurement of moisture content, another correlation was proposed and verified. It simply relates the moisture ratio and the tea-bed temperature.

Chapter 8: The effects of loading and effect of hot air temperature on the quality of tea are described. The results of chemical analysis and organoleptic analysis are presented and discussed.

Chapter 9: The conclusions of the experimental studies are summarized. Recommendations are given for further research and developments of fluidized bed drying of tea.

2. LITERATURE REVIEW

2.1 Tea Industry in Sri Lanka

First commercial planting of tea was tried out by James Tailor, a Scottish planter in 1860s in the Kandy district of Sri Lanka. The first commercially viable tea was manufactured by him in 1867 (Wimaladharma, 2003). Tea export started with 23 lbs of tea sent to London in 1873. At present, the tea industry is expanded with cultivation in 203,000 Ha in 14 tea growing districts (Statistical information on plantation crops, 2013) and production of more than 300 million kg of final made tea in 652 tea factories. The major export destinations are Russia, Iran, Turkey, Iraq, Syria, UAE, Kuwait, Azerbaijan, Japan and Ukraine. The raw material, green leaf is produced in estates owned by Plantation Companies, state owned estates, private estates and lands of tea smallholders. About 70 % of the total made tea production comes from green leaf supplied by Tea Smallholders. Estimated number of smallholders in the country is about 400,000. Black tea and green tea are the two main types of made tea produced in Sri Lanka. Black tea which is 99 % of the total tea production is divided into two types as Orthodox and “Crush Tear & Curl” (CTC) which accounts 92 % and 7 % respectively. Orthodox tea has wide range of tea grades separated according to particle sizes during the grading process. The particle size of tea varies as “long wiry (and leafy) type” and “broken type” depending on the manufacturing processes followed by individual tea factories. CTC tea has only few tea grades with broken type tea particles. Sri Lanka is the major Orthodox tea producer in the world. Most of the other tea producing countries manufacture and export CTC tea as the main tea product. Orthodox tea grades (that consists both long wiry and broken type particles) produced in Sri Lanka fetch very high price for its unique quality and special tea character in the world market compared to CTC tea grades produced and exported mostly by other tea growing countries. Bulk Tea which is different grades of tea, and packed in paper sacks at the factory location is sold to Tea Buyers by tea broking firms in 8 major auction centers; Kolkata (India), Cochin (India), Chittagong (Bangladesh), Mombasa (Kenya), Jakarta (Indonesia), Colombo (Sri Lanka), Guwahati (India), and Malawi. Tea Buyers in Sri Lanka either bulk the tea and repack with value addition or export it as it is, to other countries. The total earnings from export of tea in 2013 was US$ 1,542 Million (CBSL Annual Report for the year 2013, 2014). The tea industry contributes approximately two percent of the country's Gross Domestic Production (GDP).

The tea industry is looked after by three major organizations, Tea Board, Tea Small Holdings Development Authority (TSHDA) and Tea Research Institute (TRI). The Tea Board is acting as the control body while TSHDA is acting as service provider to the tea smallholders. TRI was established in 1925 and is involving in research, advisory and extension on various aspects in tea cultivation and manufacture. A “tea cess” is raised on all tea that is exported to provide funding for research, market development and various promotional activities. There are about 1.4 million people directly or indirectly employed in the tea industry that contributes to the economy of the country in addition to the export earnings and enhancement to livelihood of 12.5 % of the country’s population.

2.2 Tea manufacturing Process

Processing steps involve in tea manufacture are withering, rolling & roll-breaking, fermentation, drying and grading (Figure 2.1).

2.2.1 Withering

Green tea leaves contain 233.3 – 488.2 % moisture (w/w, dry basis) and other important chemical constituents, which contribute to the final quality of made tea. The objective of withering is to prepare the leaves for rolling (the next operation) by making the leaf tissues flaccid and permeable to the chemical constituents so that it will come out of the leaves and spread evenly upon the surface while rolling. To achieve this, withering process is carried out using troughs and its moisture content is reduced by sending air with a relative humidity of about 70 % through the leaves. In Orthodox type manufacture, the required moisture content in withered leaf is 122.2 – 138.1 % (w/w, dry basis). In the manufacturing of CTC tea, severity of rolling the leaf is very high. Therefore, in order to avoid temperature build up and damage to chemical constituents, moisture content in leaf is reduced only up to 212.5 – 233.3 % (w/w, dry basis).

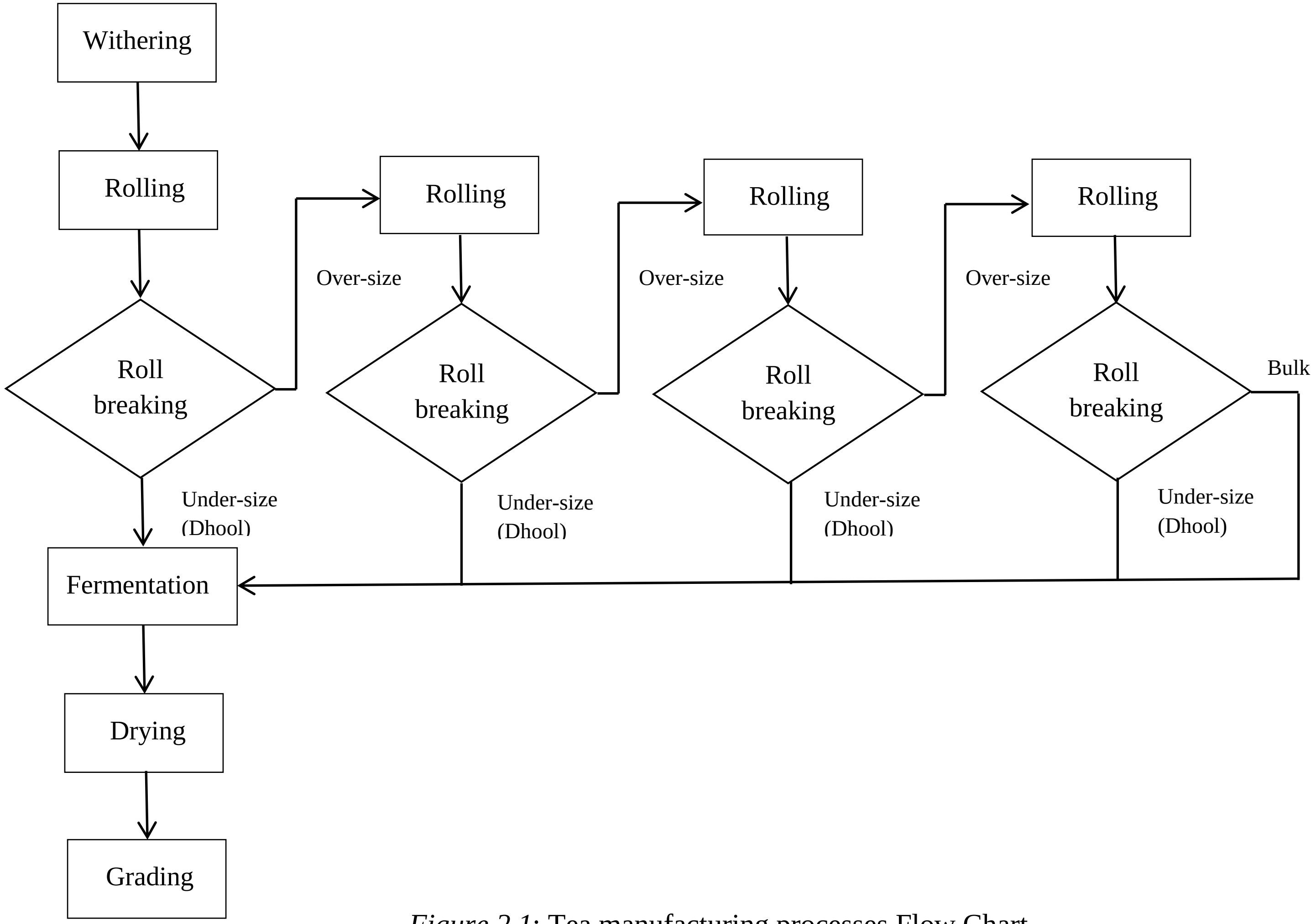


Figure 2.1: Tea manufacturing processes Flow Chart

2.2.2 Rolling & Roll-breaking

The withered leaves are subjected to maceration in rollers to break them into desired sizes suitable for different tea grades. In manufacturing of Orthodox tea, Orthodox rollers are popularly used for producing leafy type tea. In 1958, McTear of the Tocklai Experimental Station in India developed a machine called rotorvane (Kirtisinghe, 1967) to produce Orthodox broken type tea. Crushing, tearing and curling machine known as CTC roller which was invented by William Mckercher in 1932 (Kirtisinghe, 1967) is used to produce CTC tea. Reduction of particle size of tea is achieved at this stage. Further reduction of particle is avoided after drying as it may alter the liquoring characteristics of the tea (Abdul Gaffar and Thevathasan, 1981). The roller pressure is adjusted to control the severity of the maceration of leaves to obtain required size of tea particles. After discharging from the rollers, the leaf mass is sifted to extract tea particles using the machinery called Roll-Breakers. The over-size leaves which are remained after extraction from this unit are rolled and extracted again for three or four times in order to obtain desired size of tea particles.

2.2.3 Fermentation

Fermentation reactions start when the leaves are macerated in rollers and continue throughout the entire rolling operation. A maximum period of about 200 minutes is needed for the reactions to complete. Therefore, the extracted tea from the roll breakers is bulked and then spread on the floor or on tables to a thickness of 5 - 7.5 cm to facilitate the fermentation reactions. The most important compounds in tea leaf that contribute to the quality and character in made tea is called polyphenols (Samaraweera and Mohamed, 2008). These compounds undergo a series of changes during the manufacturing process of black tea. The tea leaf contains a group of proteins called enzymes. The important enzyme that involve in the oxidation of polyphenols to oxidized polyphenols is called polyphenol oxidase. The oxidized polyphenols are unstable and joins with one or more other polyphenolic units. This results in production of two types of compounds namely, Theaflavins (TF) and Thearubigins (TR). The TFs are exclusively dimeric compounds and orange red in colour and the TRs are made up predominantly of polymeric compounds and are dark brown. These two compounds give the character to the tea. During fermentation process, Theflavin and Thearubigin are formed to the required level for the taste, colour and strength of the tea liquor (Liyanage et al., 1997). The unoxidized polyphenols are sharply bitter and a pleasant taste is developed with the formation of the theaflavins and the thearubigins. This taste is felt mostly in the rear end of the tongue.

2.2.4 Drying

Prolonged fermentation reactions reduce the TF content and increase the proportion of TR in made tea. Excessive amounts of TRs could be harmful to the quality of tea (Liyanage et al., 1997). Therefore, when the fermentation reactions are optimum it is immediately dried so that the fermentation reactions are arrested when the tea is exposed to high temperature. Tea is dried with hot air to achieve final moisture content of 2.5 – 3.0 % (w/w, dry basis).

Endless Chain Pressure (ECP) dryers were popularly used in the past to dry tea. The ECP dryers were first introduced in 1907. In the ECP dryers, hot air temperature is maintained at 88-91 °C and drying is carried out on perforated trays arranged one on top of another and fitted on two or three endless bands. The Tea Research Institute of Sri Lanka (TRI) in collaboration with Colombo Commercial Company (Engineers) Limited (CCC) conducted research on fluidized bed drying of tea and developed Fluid bed tea dryer in early 1970s. At present this dryer is widely used in almost all the factories that are producing Orthodox broken type tea. Hot air temperature is maintained at 124 - 127 °C in fluidized bed dryers (Samaraweera, 1986). After drying, the dried tea is cooled immediately to avoid burned tea character.

During drying process, post fermentation reactions take place for first few minutes. Fermentation reactions are accelerated as the temperature of the tea is raised and the level of oxidized products are changed slightly (Samaraweera and Mohamed, 2008). When the tea temperature goes above 50 °C, fermentation reactions are arrested and the level of TF and TR and the ratio of TR:TF at this stage are then retained in tea. Generally accepted level of TF and the ratio of TR:TF in quality tea produced in the past were 0.75 % (Roberts and Smith, 1963) and 10:1 respectively (Roberts, 1986). However, no studies were conducted to find the level of these parameters in tea produced at present.

2.2.5 Grading

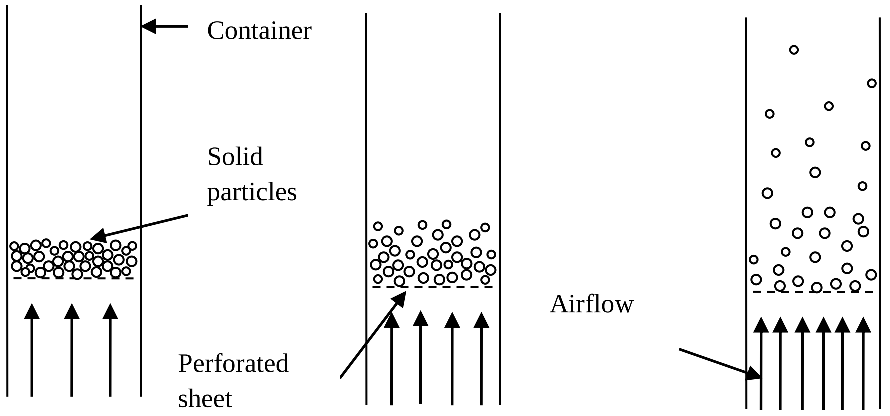
The quality of dried tea varies according to their sizes as the chemical composition and the amount of oxidized product vary with the size of tea. The dried tea from the dryer contains stalks and fibres, which are not desired for the tea character and are removed using fibre extractors. The cleaned tea is sifted in sifters to different size tea. The over-size tea is crushed to small particles and sifted. Where more breakdown of tea is needed, tea cutters are used for that purpose. Finally the sifted tea is cleaned in units called winnowers to remove dust, grits and any other foreign particles. The uniformity in sizes of tea particles is maintained as far as possible for every grade. The main Orthodox broken type tea grades produced in Sri Lanka are Pekoe, Broken Orange Pekoe (BOP), Broken Orange Pekoe Fannings (BOPF) and Dust No.1.

Generally tea is brewed in hot water and consumed by the people in the world. To ease the preparation for brewing and disposal of spent tea after brewing, people prefer to use tea bag though it is little expensive. In order to reduce the cost of tea bag and to increase its consumption, low cost CTC tea grades from other countries are selected for packing in the tea bags. However, to improve the mouth feel of tea brews from the tea bags, certain percentages of the tea grade called Broken Orange Pekoe Fannings (BOPF) produced in Sri Lanka is mixed with the CTC tea grades. The BOPF tea grade has broken type tea particles similar in size to that corresponding to a particular CTC grade called Pekoe Fannings (PF1). Since 1981 the tea factories which were engaged in manufacturing Orthodox broken type tea have been compelled to manufacture this particular tea grade (BOPF) to meet the increasing demand (Abdul Gaffar and Thevathasan, 1981).

Green tea is not popularly produced in Sri Lanka as Orthodox black tea grades have a huge variety of characters and flavours and the country has built up a reputation for black tea grades over many years. The expansion in green tea is further affected with the finding that black tea is equal in health benefits to green tea (Modder and Amarakoon, 2002).

2.3 Fluidization

Fluidization is a phenomenon created by a fluid (liquid or gas) on a solid so that the solid behaves like a fluid. Schematic explanation of fluidization in a gas-solids system is given in Figure 2.2.



Lower fluid velocity,
Particles stationary

Sufficient fluid velocity,
Particles fluidize

Excess fluid velocity,
Particles entrain

Figure 2.2: Schematic explanation of fluidization

When a fluid is passed upwards through a bed of solids, no relative movement between the particles takes place at lower fluid velocities. However, when the fluid velocity is gradually increased, the frictional drag on the particles becomes equal to their apparent weight that is the actual weight less the buoyancy force. Then the particles become rearranged thus offering less resistance to flow of fluid and the bed starts to expand with a corresponding increase in voidage. This process continues with increase in velocity, with the total frictional force remaining equal to the weight of the particles, until the bed has assumed its loosest stable form of packing. If the velocity is then increased further, the individual particles separate from one another and become freely supported in the fluid. At this stage, the bed is described as fluidized. Further increase in the velocity causes the particles to separate still further from one another. At higher velocities two separate phases may form: a continuous phase often referred to as the dense phase, and a discontinuous phase known as lean or bubble phase. The fluidization is then said to be aggregative. Gas bubbles pass through a high-density fluidized bed with the result that the system closely resembles a boiling liquid, with the lean phase corresponding to the vapour and dense phase to the liquid. The bed is then referred to as a boiling bed. At higher airflow, drag force exerted by the gas on particles is so high that particles get entrained.

Categorization of powders in relation to fluidization characteristics is given in Table 2.1 (Richardson et al., 2002). Depending on the particle size distribution, fluidization behavior varies. Dry tea falls into Group B as size of about 78 % of the particles is less than 710 µm (Table 1.1). Therefore, boiling bed is achievable for tea. Further, as most of the bubbles in fluidized bed of Group B particles have velocities greater than interstitial gas velocity, some amount of air by-pass without being interacted with the fluidized bed.

Table 2.1: Categorization of powders in relation to fluidization characteristics

Group	**Typical particle size (µm)**	**Fluidization/Powder Characteristics**
A	30–100	Particulate expansion of bed will take place over significant velocity range.
B	100–800	Bubbling occurs at velocity $>U_{mf}^{*}$. Most bubbles have velocities greater than interstitial gas velocity.
C	20	Fine cohesive powders, difficult to fluidise and readily form channels.
D	1000	All but largest bubbles rise at velocities less than interstitial gas velocity.

$^{*}U_{mf}$ – minimum fluidizing velocity

2.4 Fluid bed drying of tea

The first application of fluidized bed principle in the industry was the adoption of fluidized catalysts by the petroleum industry for the cracking of heavy hydrocarbons and for the synthesis of fuels from natural gas or from carbon monoxide and hydrogen (Richardson et al., 2002). Now, fluid bed dryers are widely used for drying of pharmaceuticals, tea, etc., where hot air is used to fluidize wet materials and their moisture content is reduced to required level for packing and storage. Also, literature is available on fluid bed drying of products other than food products such as lignite (Diamond et al., 1990). The process is highly advantageous due to its high thermal efficiency, ease of operation, low construction cost and large capacity (Brenner et al., 1991).

Industrial fluid bed dryers are the most popular family of dryers used for drying Orthodox broken type as well as CTC type tea (Akhtaruzzaman et al., 2013, Temple and van Boxtel, 2000 and Lang'at et al., 2016). When a fluid, in this case hot air, is passed upwards through a perforated support into and through a bed of tea of particulate solid nature, the bed is expanded and the tea particles are suspended. The term “fluidization” is used to describe this state. In the beginning of fluidization, not all particles are fluidized because of the adhesive forces in the bed. Further increase in the fluid velocity increases the drag force exerted on the particle, which can then break apart more contact points between particles, thus bringing them to the fluidized state. The hot airflow rate is adjusted in this manner to change the degree of fluidization to achieve moisture removal to the acceptable level of 2.5 – 3.0 % (w/w, dry basis) from initial moisture content of 106 – 178 % (w/w, dry basis) depending on the type of tea and the moisture loss during rolling process. Intimate mixing occurs, and because of the high degree of turbulence, temperatures are quickly attained throughout the system. During this process simultaneous heat and mass transfer occurs (Syahrul et al, 2002). Heat, necessary for evaporation, is supplied to the tea particles and moisture is removed from it into the drying medium. Heat is transported by convection from the surroundings to the particle surface and from there, by conduction, further into the particle. Moisture is transported in the opposite direction as a liquid or vapour; on the surface it evaporates and passes on by convection to the surroundings (Syahrul et al, 2003). Free moisture from the particles evaporates quickly due to high heat and mass transfer coefficients in fluid bed systems.

Few studies have been reported on the minimum fluidization velocity of tea. Temple and Boxtel studied the fluidization of dried CTC (Crush-Tear-Curl) type tea having 71 % moisture content on wet basis and a mean diameter of 0.84 mm which is somewhat similar to orthodox broken type tea. They measured the minimum fluidization velocities of tea on four different types of bedplates ranging from bed loadings 6 kg/m^2 to 42 kg/m^2. Full fluidization was obtained up to 18 kg/m^2 and the minimum fluidization velocity was found to be between 0.9 and 1.2 m/s. For the bed loadings above 18 kg/m^2, it was difficult to obtain full fluidization due to channeling (Temple and Van Boxtel, 1999). In another study on black tea samples with the average geometric mean diameter of 0.84 mm and moisture content of 8 to 10 % on wet basis using a vibro-fluidized bed dryer with four types of bedplates, the minimum fluidization velocity was found to be between 0.35 and 1.2 m/s (Sadeghi and Khoshtaghaza, 2012). But a correlation to predict the minimum fluidization velocities was not developed on either of the aforementioned studies.

Research was started in 1967 on using fluid bed technology for drying the tea and satisfactory fluidization of CTC tea was achieved (Joseph and Kandappah, 1969). Fluid bed technology was successfully applied to drying of tea and a dryer was constructed in 1973 (Samaraweera and de Silva, 1974). The first industrial and continuous type fluid bed tea dryer called “TRI-CCC FBD” was introduced to tea factories in early seventies (Kirtisinghe, 1974) and now it is used in almost all the factories producing Orthodox broken type tea. Schematic diagram of a TRI-CCC FBD is given in Appendix A. Samaraweera (1986) made an attempt to modify fluid bed tea dryer into three segment chamber in order to adjust weir plate thickness in individual drying sections. In 1992, preliminary investigations were carried out to compare the efficiency of fluid bed tea dryer having 3 drying sections arranged stepwise. It was designed and used at St.Coombs Estate at Talawakelle and examined against the standard fluid bed tea dryer with 4 drying sections. Drying curve was obtained and compared. The results showed that the drying curves for the 2 methods were similar (Mohamed and Weerawardene, 1993). Experiments were conducted by varying the weir plate thickness in the 3 drying sections in 1993 by Koneswaramoorthy et al (1994) and the results did not show any significant difference in made tea output or the moisture evaporated from each chamber. Samaraweera (1985) identified the potential for improvement of heat and mass transfer efficiency by recirculation of exhaust air from the end section of the dryer. The industrial fluid bed dryers are operated with hot air in the temperature of 124 – 127 °C. In many gas-solid fluidized beds, bubbling occurs at flow rates only slightly in excess of that corresponding to the minimum fluidizing velocity, and continuous phase and bubble phase co-exist (Richardson Backhurst & Harker, 1998). Same condition is maintained throughout the drying process of tea in FBDs for two reasons. The hot air temperature which is maintained in the dryer is high (124 to 127 °C) and any stagnation could lead to over-heating of tea and result in burned tea character. Second reason is the difficulty in maintaining fluidized tea-bed without entrainment at higher fluidizing velocity as the tea contains small particles with a wide range of sizes. This situation becomes worse when the tea loses its weight with time as the moisture is removed during drying.

In FBDs, bedplate configuration and fluidizing velocity are the limiting factors for fluidization of particles. Bedplates of the TRI-CCC FBD that has been in operation for more than two decades in the tea factory belonging to Tea Research Institute of Sri Lanka was found to have slot type perforations of size 36 mm long and 0.5 mm wide. Percentage of opening area of the perforations to the total area is about 3.4. However, the bedplates used in the industrial FBDs are found to have perforations of varying sizes; length varied between 33 and 44 mm and width varied between 0.5 and 0.9 mm. This variation is mainly attributed to the manufacturing faults done by the suppliers of bedplates. Further, the perforations tend to be enlarged as these are cleaned carelessly to remove blocking particles such as grit (mainly) and tea. As a result, percentage of opening area of bedplates in the TRI-CCC FBD may vary with the usage. When the perforation size varies the opening area also varies and that lead to change the amount of air entering through the perforation. As a result, fluidizing velocity that is required for lifting the particles is affected. Tea has particles with wide size variation and if the fluidizing velocity is not maintained at optimum, obtaining the fluidized tea-bed without any stagnation area or entrainment is difficult.

Shah and Goyel (1980) studied the basic parameters affecting the drying of tea in vibrating fluidized bed dryer, a newer version of the FBD which was introduced mainly to dry a different type of tea called “CTC teas” that are heavier than Orthodox broken type tea. Temple and Boxtel (1999) studied the fluidizing behaviour of tea using Lawrie Tea Processor, a machine used to process soft-wither tea. The tea tested in that study had particles with a mean diameter of 0.84 mm and was heavier due to the presence of higher moisture content (about 178 %, w/w, dry basis) as compared to Orthodox broken type tea (moisture content of 106 %, w/w, dry basis). Temple et al. (2001) studied the effect of drying on the quality of same type of tea using a batch type FBD and found that tea could be effectively dried without a risk of damage to particles by starting the drying process with an inlet air temperature of 140 °C which was gradually reduced to 95-100 °C at the end. Some work was also reported on the study of fluidization stability for grains with large size particles such as millet, paddy and barley (Khoshtaghaza and Chayjan, 2007).

The orthodox broken type tea has wide particle size distribution and sphericity. They are subject to a substantial change in size during the drying in a continuous type fluid bed dryer. Consequently, the prediction of the fluidization parameters of tea is crucial for the optimal design and operation of fluid bed dryers. The minimum fluidization velocity is one of the critical parameters required in this scenario. It is the minimum superficial velocity of the fluid where the pressure drop across the bed is equal to the weight of the bed per unit area. It sets a lower limit on the flow rate needed for fluidization and is necessary when modeling the fluidization process (Hilal et al., 2001).

2.5 Mathematical models for fluidization

The Ergun equation (Ergun, 1952) given in Eq.2.1 is the widely accepted model to predict the minimum fluidization velocity which denotes a correlation between the two dimensionless numbers, Reynolds number at minimum fluidization and Archimedes number (Brenner et al., 1991).

$$\frac{1.75}{\varepsilon_{mf}^3 \emptyset_s} Re_{mf}^2 + \frac{150(1-\varepsilon_{mf})}{\varepsilon_{mf}^3 \emptyset_s^2} Re_{mf} = Ar \qquad (2.1)$$

Where Re_{mf} is the Reynolds number at minimum fluidization (Eq.2.2); Ar is the Archimedes number (Eq.2.3); ε_{mf} is the voidage at minimum fluidization and $\emptyset_s$ is the sphericity.

$$Re_{mf} = \frac{\rho_g u_{mf} d_p}{\mu} \qquad (2.2)$$

$$Ar = \frac{\rho_g d_p^3(\rho_p - \rho_g)g}{\mu^2} \tag{2.3}$$

Where, ρ_g is the fluid density, U_{mf} is the minimum fluidization velocity, d_p is the mean particle size, μ is the dynamic fluid viscosity and ρ_p is the particle density.

The values predicted by the Ergun equation are mostly reliable for relatively small particles with narrow size distribution and uniform sphericity, such as peas, diced potato and potato strips (Vazquez and Calvelo, 1980 & 1983). An equation (2.4) similar to Ergun is valid for peas (De Michelis and Calvelo, 1994).

$$\frac{\Delta P}{(1-\varepsilon)H} = K_1 \frac{\mu(1-\varepsilon)}{D_p^2\varepsilon^3} V_o + \frac{K_2}{D_p^2\varepsilon^3} V_o^2 \tag{2.4}$$

Where, ΔP is the bed pressure drop, ε is the bed voidage, H is the bed height, μ is the air viscosity, D_p is the effective diameter, V_o is the air superficial velocity and K_1 & K_2 are coefficients.

Based on the Ergun equation Wen and Yu (1966) developed a correlation (Eq.2.5) independent of sphericity and bed porosity at minimum fluidization which is widely used and accepted to predict the minimum fluidization velocity (Dhodapakar, 2012).

$$Re_{mf} = \left(33.7^2 + 0.0408\,Ar\right)^{\frac{1}{2}} - 33.7 \tag{2.5}$$

However, the Wen and Yu’s correlation still remains controversial because of the standard deviation of 34 % of the data set used in the approach (Dhodapakar, 2012). Some have attempted to modify the Wen and Yu’s correlation for three range of sphericities; $0.8 \leq \emptyset_s \leq 1$ (Eq.2.6), $0.5 \leq \emptyset_s < 0.8$ (Eq.2.7) and $0.1 < \emptyset_s < 0.5$ (Eq.2.8) to minimize the error (Lucas et al., 1986).

$$Re_{mf} = (29.5^2 + 0.0357\,Ar)^{1/2} - 29.5 \tag{2.6}$$

$$Re_{mf} = (32.1^2 + 0.0571\,Ar))^{1/2} - 32.1 \tag{2.7}$$

$$Re_{mf} = (25.2^2 + 0.0672\,Ar))^{1/2} - 25.2 \tag{2.8}$$

But, when the particles are relatively large or have a wide range of size distribution or sphericity the minimum fluidization values predicted from Ergun equation do not conform to the experimental values (Mclain and Mckay, 1981 & Mckay and Murphy, 1987). Hence, vast number of correlations has been developed between Reynolds number at minimum fluidization and Archimedes number which are limited to a range of Reynolds numbers, particle sizes, sphericity and the type of solid particle to be fluidized (Pata and Hartman, 1978 & Lippens and Mulder, 1993).

Though many correlations are proposed for the modeling of shrinkage during drying (Katekawa and Silva, 2006 & Mayor and Sereno, 2004), the effect of shrinkage on the minimum fluidization velocity has been little investigated. Instead correlations have been developed for the effect of moisture content. Senadheera (2009) developed a correlation for minimum fluidization velocity with the variation of moisture content (dry basis) of beans (cylindrical particulates) and green peas (spherical particulates). Irigoyen and Giner (2011) did the same for precooked whole soybeans. But in either of those correlations, Reynolds number at minimum fluidization and Archimedes number were not considered. Moreover, the shrinkage is modeled for monodisperse systems of relatively large particles such as pieces of apple, soybean, apricot, potato etc. which were easily regarded as a standard geometry; sphere, cylinder, cube and slab (Katekawa and Silva, 2006 & Mayor and Sereno, 2004).

General correlations for predicting the minimum fluidization velocity, where air was used as the fluid and the particles were considered to have constant physical properties with time, were proposed; equation 2.9 for coal, char and ballotini that are coarse particles (Chitester and Kornosky, 1984), equation 2.10 for binary solid mixtures (Thonglimp et al., 1984), equation 2.11 for $0.78 < Re_{mf} < 78$, $1800 < Ar < 500000$, $d_p < 1500\,\mu m$ and wide size distribution of d_p (Gauthier et al.,

1999) and equation 2.12 for a polydisperse system with $90 < d_p < 1500\,\mu m$, $76 < Ar < 1010000$ (Doichev and Akhmakov, 1979).

$$Re_{mf} = \left(28.7^2 + 0.0494\,Ar\right)^{\frac{1}{2}} - 28.7 \qquad (2.9)$$

$$Re_{mf} = 0.0279Ar^{0.63} \qquad (2.10)$$

$$Re_{mf} = 0.0022Ar^{0.818} \qquad (2.11)$$

$$Re_{mf} = 0.00108Ar^{0.94} \qquad (2.12)$$

Considering the wide particle size distribution, nonuniform shape of tea and the significance of the change in size (shrinkage) during drying, none of the available correlations cannot be used with reasonable accuracy for predicting the minimum fluidization velocity. Consequently, it is recommended that the minimum fluidization velocity for such particles be experimentally measured whenever feasible (Dhodapakar et al., 2012).

2.6 Mathematical models for the drying of food products

In the past many theoretical, semi-theoretical and empirical models were developed for thin-layer drying of various foods and agro-based products. Theoretical models based on Fick’s second law (Eq. 2.13) consider only the internal resistance to moisture transfer. Therefore, this model is only useful in predicting the drying behaviour of regularly shaped food products such as hazelnuts (Demirtas et al., 1998) and rapeseed (Crisp and Woods, 1994).

$$\frac{\partial M}{\partial t} = D\nabla^2 M. \qquad (2.13)$$

Semi-theoretical models are generally derived by simplifying general series solutions of Fick’s second law or modification of simplified models. Lewis model (Eq. 2.14), Henderson and Pabis model (Eq. 2.15), Logarithmic model (Eq. 2.16), Page model (Eq. 2.17), modified Page model (Eq. 2.18) and Two-term exponential model (Eq.

2.19) are the widely used semi-theoretical thin-layer drying models (Botheju et al., 2011, Panchariya et al., 2002).

$$MR = \frac{M - M_e}{M_o - M_e} = \exp(-k_o t) \tag{2.14}$$

$$MR = \frac{M - M_e}{M_o - M_e} = A_o \exp(-k_o t) \tag{2.15}$$

$$MR = \frac{M - M_e}{M_o - M_e} = A_o \exp(-k_o t) + C \tag{2.16}$$

$$MR = \frac{M - M_e}{M_o - M_e} = \exp(-k_o t^n) \tag{2.17}$$

$$MR = \frac{M - M_e}{M_o - M_e} = \exp(-k_o t)^n \tag{2.18}$$

$$MR = \frac{M - M_e}{M_o - M_e} = A_o \exp(-k_o t) + A_1 \exp(-k_1 t) \tag{2.19}$$

Where *MR* is the moisture ratio; *M* is the average moisture content in percentage (w/w, dry basis) at drying time *t*; M_o is the initial moisture content in percentage (w/w, dry basis); M_e is the equilibrium moisture content in percentage (w/w, dry basis); A_o, k_o, A_1, k_1 and *n* are the empirical coefficients.

Botheju et al. (2011) performed a regression analysis for various semi-theoretical models on their single layer drying data and suggested the Two-term model (Eq. 2.19) as the most appropriate for drying fresh tea leaves. In several other studies the semi-theoretical thin-layer drying models were successfully used to describe the drying phenomenon of many products such as apple pomace (Zhengfu Wang et al, 2007), rough rice with high moisture content (Chiachung Chen & Po-Ching Wu., 2001), pistachio nuts (Kashaninejad et al., 2007), chicory root slices (Lee et al., 2004), garlic slices (Madamba et al., 1996), pre-dried young coconut (Madamba, 2003) and quercus (Tahmasebi et al., 2011). In tea manufacturing, due to severe maceration on leaf, a large number of cells are ruptured, cell sap has been mixed and there is a good accessibility for gas exchange within the particles of leaf (Temple and Van Boxtel, 1999). Therefore, evaporation of water enhances due to increased surface area resulting in reducing the role of diffusion within the particle relative to the surface and air boundary layer resistance. Temple and Van Boxtel (1999) studied drying rate kinetics of CTC tea considering Lewis model with an assumption that the resistance for water vapour transport is all over the surface of the particle. They varied the drying temperature between 50 and 150 °C. Panchariya et al. (2002) studied thin-layer drying characteristics of CTC tea produced in India at drying air temperatures in the range of 80 – 120 °C. They found that drying is dominated in the falling rate period and Lewis model gave better predictions for CTC tea compared to other widely used semi-theoretical thin-layer drying models.

2.7 Quality analysis of tea

The content of theaflavins and thearubigins in dried tea are analyzed chemically following Roberts and Smith method (Liyanage et al, 2003). However, scientists greatly depended on oganoletptic analysis (Ramaswamy, 1963, De Silva and Sanderson, 1964, Kirtisinghe, 1969, Abdul Gaffar et al., 1980) for the made tea as the professional tea tasters ultimately value it based on this analysis. The major parameters that are considered for the analysis are infused leaf appearance, liquor colour, liquor strength and liquor quality. Infused leaf is what is left after brewing the tea. If the colour is greenish, fermentation reactions are not enough to get the colour changed to coppery colour during fermentation. This tea lacks required colour and strength with lesser amount of theaflavins and thearubigins which are formed during fermentation process. If the colour is dark (or dull) brown, over-fermentation must have taken place resulting in increased liquor colour and reduced liquor quality. The infused leaf colour indirectly indicates the level of fermented products in tea. Similarly liquor colour also indirectly indicates the level of fermented products in tea. Dark liquor colour indicates over fermentation and poor liquor quality with reduced amount of theaflavins and increased amount of thearubigins. Professional tea tasters evaluate the teas by visual observation of brew and infused leaf and by tasting a spoonful of liquor.

3. DATA ANALYSIS

3.1 Determination of moisture content

Moisture content in tea samples is analyzed using standard oven method. Weight of tea samples is measured using an Electronic balance (Denver Instrument, S203) with an accuracy of ± 0.001 g. The tea samples are kept in a standard oven (Venticell 222, Germany) at 103 ± 2 °C for 6 hours (ISO 1573-1980 (E)). Samples are removed from the oven after drying and its final weight is measured using the analytical balance. The moisture content in tea samples on dry basis (w/w) is determined by obtaining the difference in weight as a percentage of its initial dry weight.

$$MC = (m_0 - m_1) \times \frac{100}{m_1} \tag{3.1}$$

Where,

MC – Moisture content on dry basis (w/w)

m_0 – initial mass, in grams of the test portion

m_1 – mass, in grams of the dried test portion

Initial mass of the sample was selected as given in Table 3.1.

Table 3.1: Initial mass of tea samples for moisture determination

Tea sample	Initial weight (g)
Raw tea (MC is 106 %)	25
Partially dried tea (MC is 6 – 106 %)	25
Dried tea (MC is 3 %)	10

3.2 Statistical analysis of experimental data

Non-linear regression analysis was conducted with experimental data to find constants in mathematical models. “LABFit” software was used to conduct the analysis. The coefficient of determination (R^2), root mean square error (RMSE) and reduced chi-square (χ^2) which are defined by the equations 3.2, 3.3 and 3.4

respectively were used to find the best fit. The model with least root mean square error and reduced chi-square and the highest coefficient of correlation was selected as the best fit (Tahmasebiet al., 2011).

$$R^2 = 1 - \frac{\Sigma_{i=1}^{N}(MR_{\exp,i} - MR_{\mathrm{Pre},i})^2}{\Sigma_{i=1}^{N}(MR_{\exp,i} - MR_{Mean,i})^2} \tag{3.2}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{\mathrm{Pr}e,i}\right)^2\right]^{\frac{1}{2}} \tag{3.3}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{\exp,i} - MR_{pre,i})^2}{N-m} \tag{3.4}$$

3.3 Chemical analysis for quality parameters in tea

The dried tea samples were used for chemical analysis. Roberts and Smith method was followed to determine quality parameters such as Theflavin (TF), Thearubigin (TR), Total Colour (TC) and Brightness (BR) (Roberts and Smith, 1963).

Standard liquor for the analysis was prepared by brewing 9 g of tea sample with 375 ml hot distilled water in a vacuum flask. The flask was shaken for 10 minutes in a mechanical shaker. The brew was filtered, cooled and mixed with isobutyl methyl ketone (IBMK). The method followed to prepare solutions A, B, C & D for spectrophotometric measurements is described in Figure 3.1.

Theaflavin (TF) %, Thearubigin (TR) %, Total colour (TC) and Brightness (TB) % were calculated using equations 3.5, 3.6, 3.7 & 3.8 respectively.

TF % = (2.25) (E_C) (3.5)

TR % = (1.77 E_D + E_A - E_C) (7.06) (3.6)

TC = (6.25) (E_A' + 2E_B') (3.7)

TB % = (E_C') (100)/ (E_A' + 2 E_B') (3.8)

Where E_A, E_C and E_D are absorbance values at 380 nm wave length and E_A', E_B' and E_C' are absorbance values for 460 nm wave length.

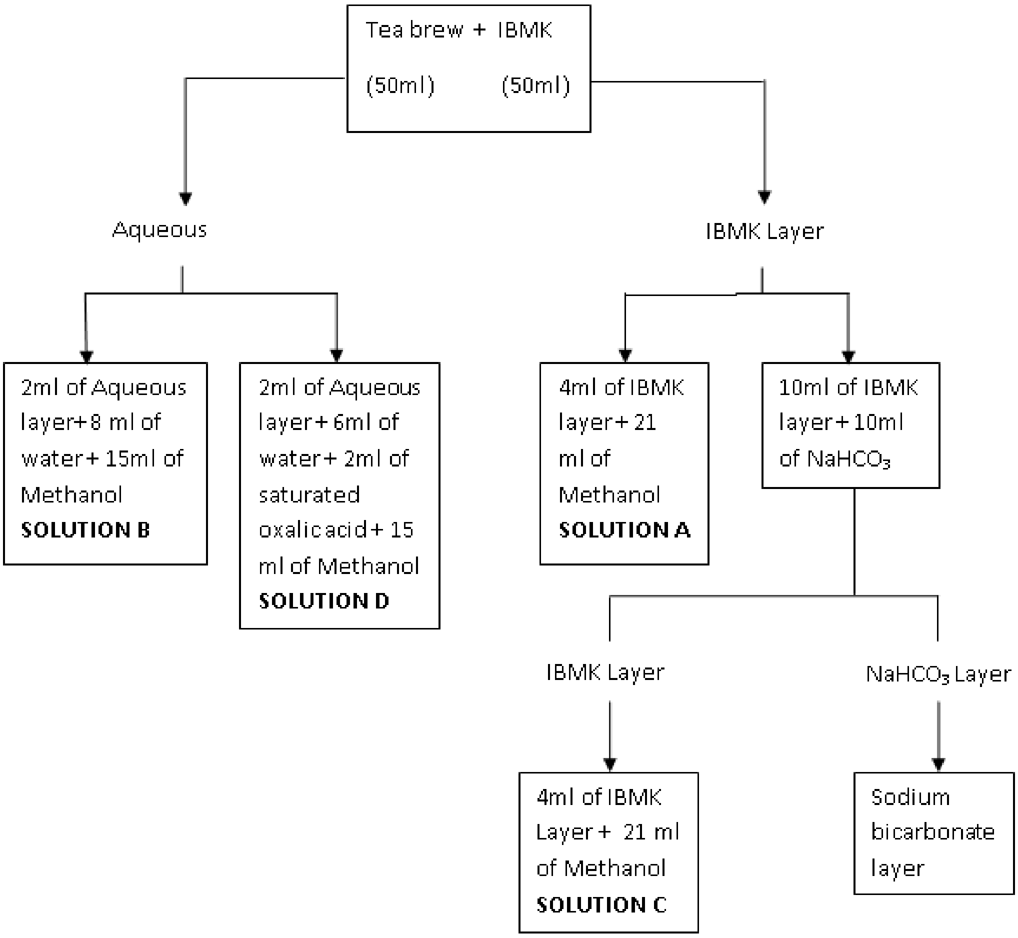


Figure 3.1: Method for preparing solutions for spectrophotometric measurements

3.4 Organoleptic analysis for quality parameters in tea

The dried and cleaned tea samples from at least six trials were sent to three professional tea tasters of different leading Tea Broking organizations for organoleptic analysis. Comments on infused leaf appearance, liquor quality, liquor colour and liquor strength were obtained for the tea samples. The comments were ranked as given in the Table 3.2. The mean and the standard deviation of ranking given by different tea tasters for each quality parameter were calculated and rank for overall quality parameter was computed as the sum of mean values of all the quality parameters. The tea samples with higher ranking for different quality parameters and for the overall quality parameter are considered to be good quality tea and they fetch higher prices.

Table 3.2: Ranking for tea taster’s comments

Parameters	**Comments**	**Ranking**
Infused leaf appearance	Very Dull	1
	Dull	2
	Fair colour	3
	Fair bright	4
	Quite bright	5
	Bright	6
	Very bright	7
Quality	Plain	1
	Rather plain	2
	Very little quality	3
	A little quality	4
	Some quality	5
	Fair quality	6
	Quite fair quality	7
	Very fair quality	8
	Quite nice quality	9
	Nice quality	10
Colour	Very light	1
	Rather light	2
	Light	3
	Fair colour	4
	Quite fair colour	5
	Coloury	6
	Very coloury	7
Strength	Very light	1
	Rather thin	2
	Thin	3
	Fair strength	4
	Useful strength	5
	Strong	6
	Very strong	7

4. MATERIAL & METHODS

4.1 Materials

Green leaves with bud, first leaf and second leaf that are tender and contain more amounts of polyphenols are preferred for manufacturing tea with required tea character. However, third leaves that may be coarse leaves are also harvested with the tender ones and brought to the factories for processing. Further, the leaves when not handled carefully during harvesting, collecting and transporting to tea factories get damaged leading to production of tea with reduced tea character. Therefore, undamaged tender leaves are considered as good leaves for manufacturing. In this study, green leaves of *Camellia sinensis* with 60 % – 65 % good leaves (weight basis) harvested from St. Coombs Estate (6°56'13.56" N 80°39'29.16" E) were selected for processing in the Estate tea factory at Talawakelle, Sri Lanka. The leaves were processed at different stages during manufacturing as described below.

The moisture content was reduced to about 108 % (w/w, dry basis) during withering process. Withered leaves were rolled to produce the dhool. Dhool is the tea with broken particles obtained during rolling process and the size distribution of these broken particles is controlled as far as possible by adjusting required level of maceration in rollers and visual observation. Dhool was spread on tables at 6.4 cm thickness to allow the fermentation reactions to take place and the fermenting environment was maintained with required relative humidity above 90 % by operating the humidifiers to avoid moisture losses in tea. Fermentation was allowed for about 2 hours and 40 minutes. The fermented dhool was having slightly lower moisture content (106 %, w/w, dry basis) than withered leaf due to losses during manufacturing. It was dried to about 3 % moisture (w/w, dry basis) in a conventional fluid bed dryer (TRI-CCC FBD, Appendix A) using hot air maintained at around 124 °C. Leaves were processed batch wise at regular intervals in tea manufacturing. Dry tea and fresh dhool samples were collected directly from the factory for the current study.

4.1.1 Materials for pilot-scale study

Fluidizing behavior of dry tea was first studied to identify the bedplate with suitable configuration, among the bedplates with slot type perforations of different sizes and different opening area percentages. Dry tea was fluidized using the ambient air at 25 °C in order to maintain similar conditions for all the bedplates used in the study. Dried tea samples were collected directly from the fluid bed tea dryer at the factory and it was exposed to ambient air at about 25 °C to achieve an equilibrium moisture content of 7.5 ± 0.5 % (w/w, dry basis) in order to avoid moisture absorption while studying the fluidizing behavior.

In tea factories, dhool with moisture content about 106 % (w/w, dry basis) is dried in the conventional fluidized bed dryers. The airflow for fluidizing the tea is adjusted along the dryer as the moisture is lost from tea. Therefore, minimum fluidizing behavior of partially dried dhool with different moisture contents were also examined using the bedplate which was selected in the dry tea analysis. The pilot-scale dryer which is described in section 4.2.1, was used to partially dry the dhool using hot air at 124 °C to obtain the dhool samples with different moisture levels. The moisture contents of the fresh dhool sample, 3 partially dried dhool samples and dried tea sample were determined (Section 3.1) and were found to be 106.0 %, 74.0 %, 56.1 %, 35.0 % and 3.0 % (w/w, dry basis) respectively. The samples of fresh and partially dried dhool were kept in the environmentally controlled manufacture unit (ECM Unit, Figure 4.1).

Figure 4.1: ECM unit

The ECM Unit (model TMC 185/CRP-15, Teacraft, UK) consists of an environmentally controlled chamber with temperature and humidity controlling facility with an accuracy of ± 0.1 °C and ± 0.1 % respectively. Moisture loss from the dhool samples can be prevented by keeping the samples under controlled condition (temperature of 20 °C and RH of about 98 %). The chamber incorporates a sealed refrigeration unit, modulated electric heating and a water vaporizing system coupled with a programmable control unit that can maintain required set conditions of 15 °C – 25 °C and up to 98 % RH.

The particle size distributions of dhool samples with different moisture contents were determined by the sieve analysis and the mean diameter was calculated by equation 4.1 (Paudel & Zhi-Gang Feng, 2013).

$$d_p = \frac{1}{\sum_{i=1}^{n}\left(\frac{x_i}{d_i}\right)} \tag{4.1}$$

Specific gravity of the dhool particles were measured using oil with known density to minimize the error due to change in moisture content during measurements.

4.1.2 Materials for laboratory-scale study

Drying characteristics of tea was studied by drying the fresh dhool in a laboratory-scale fluid bed tea dryer. The effect of the operating parameters namely, loading and hot air temperature, on the final quality of tea was also studied using the laboratory-scale fluid bed tea dryer. Therefore, fresh samples of dhool were obtained from the factory and they were kept in the ECM unit (Figure 4.1) under controlled conditions.

4.2 Equipment

Dhool is dried on bedplates with slot type perforations and limited opening area percentages in industrial and conventional type fluid bed dryers. Therefore, the fluidizing behavior of dry tea and the drying behavior of dhool were studied using a pilot-scale fluid bed dryer which was designed to simulate industrial fluid bed dryers. For studying the drying characteristic of dhool, several number of dhool samples from a particular lot needed to be dried under controlled hot air temperatures and fluidizing velocity. Therefore, a laboratory-scale small capacity fluid bed tea dryer was also used in this study.

In the study of examining the factors (specifically the loading and the hot air temperature) affecting the quality of final made tea, dhool samples from the same bulk needed to be dried simultaneously in two identical type fluid bed tea dryers. Therefore, two numbers of the laboratory-scale fluid bed tea dryers were used in this study.

4.2.1 Equipment for pilot-scale study

The schematic diagram of the pilot-scale fluid bed dryer unit is given in Figure 4.2.

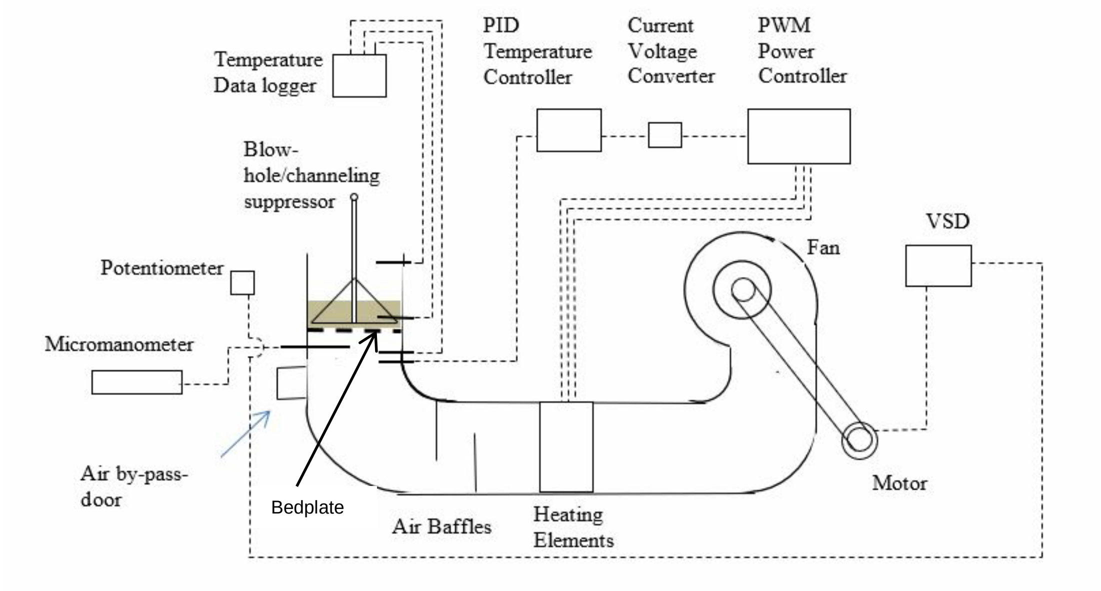


Figure 4.2: Schematic diagram of pilot-scale fluid bed tea drying unit

A turbo-centrifugal type fan was used to deliver air in a rectangular duct arrangement. Airflow requirement changes with the reduction of moisture in dhool and hence a variable speed drive (VSD) was used to control the air flow. The fluidizing section had the facility to change the bedplates. Effective area of the bedplate for fluidizing the tea was 345 mm x 351 mm. A blow-hole/channeling suppressor at 60 oscillations per minute was also placed above the bedplate as in the case of industrial fluid bed tea dryer. The blow-hole/channeling suppressor gently pushed the tea forward and backward at a height of 16 mm above the bedplate to avoid channeling and by-pass of air. A micromanometer was used to measure the total differential static pressure across the bedplate and tea-bed and also across the bedplate alone.

An electrical air heater of 12 kW was inserted into the air duct for generating hot air. A k-type thermocouple with an accuracy of ± 0.1 °C was fixed in the hot air duct, just under the bedplate and was connected to the Proportional–Integral–Derivative (PID) temperature controller. A power controller (rating 27 kW, 3 phase) was also connected to the PID temperature controller in order to maintain steady inlet hot air temperature. The air inlet area of the fan was coupled to a cylindrical duct of 1.9 m long and 0.25 m diameter and an anemometer was fixed inside the duct to measure the air velocity with an accuracy of ± 0.25 m/s.

Tea was fluidized to have continuous phase and bubble phase as required. Tea-bed temperature was measured at a height of 7 cm from the bedplate as fluctuations were found to be low at this height. The exhaust air temperature was measured at a height of 30 cm from the bedplate.

Fluidizing and drying behavior of the tea was examined using bedplates with six different configurations and also the bedplate of conventional type fluid bed dryer. All the bed plates were fabricated using aluminium sheet of 0.85 mm thickness. Configuration of the perforations on the bedplates is given in Figure 4.3 and the details of the configuration for each bedplate is given in Table 4.1.

The loading was defined as the weight of dhool (moisture content of about 106 %, w/w, dry basis) on a bedplate per unit cross sectional area (kg/m^2). Since the moisture is lost during drying, the initial weight of the sample on the bedplate was used for calculating the loading. In addition to that for the experiments using partially dried dhool and dry tea, the equivalent weight of dhool (moisture content of 106 %, w/w, dry basis) was calculated first and then it was used to calculate the loading.

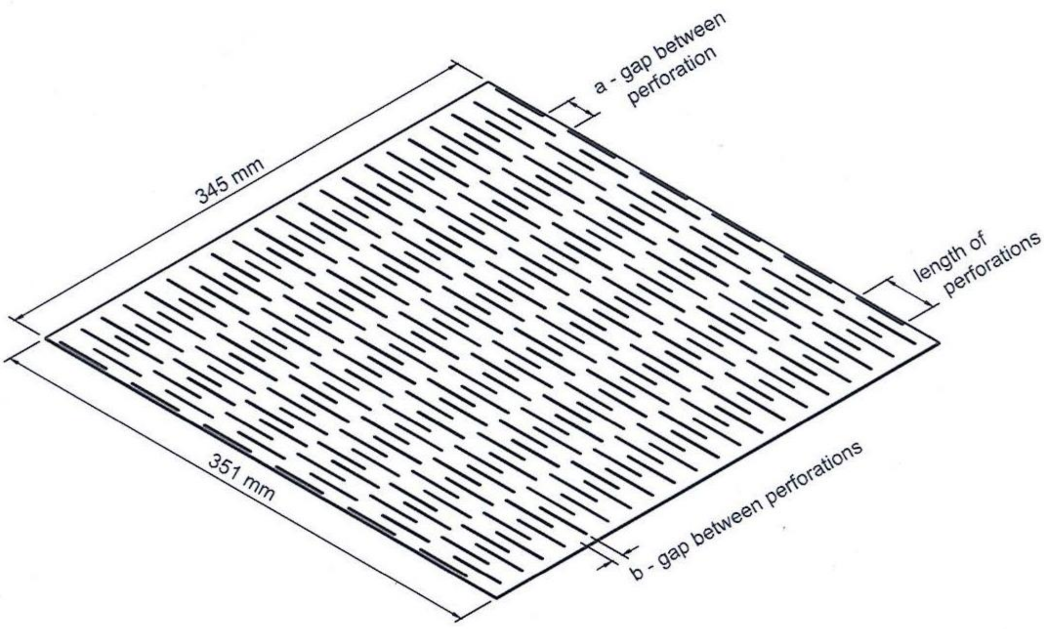


Figure 4.3: Perforation pattern of bedplate

Table 4.1: Details of the configuration of bedplates

Bedplate Number	Opening area (%)	Perforation			Gap between perforations	
		Length (mm)	Width (mm)	Numbers (/m^2)	"a" (mm)	"b" (mm)
1	3	36	0.5	1,624	20	11
2	4	36	0.5	2,177	20	8.2
3	5	36	0.5	2,748	20	6.5
4	3	36	0.6	1,356	20	13.3
5	4	36	0.6	1,820	20	9.9
6	5	36	0.6	2,266	20	7.9
7*	3.4	36	0.5	1,785	20	10

* bedplate of conventional type fluid bed tea dryer, TRI-CCC FBD

4.2.2 Equipment for Laboratory-scale study

Dhool samples were dried using a laboratory-scale fluid bed tea dryer unit (Teacraft, UK). The unit was fixed with a cylindrical loading vessel (diameter 10 cm and height 48 cm) which was fabricated with transparent material (Figure 4.4). The loading vessel was covered using a lid fitted with nylon net to avoid entrainment of tea particles. Temperature was controlled by a PID controller with an accuracy of ±1 °C. Inlet hot air temperature could be set between 100 and 150 °C. Fluidization of tea with co-existence of continuous phase and bubble phase was obtained in the unit by adjusting the air flow rate. A k-type thermocouple probe was placed in the loading vessel at a height of 7 cm to measure tea-bed temperature. The moisture content in tea was found to reach the final level of 2.5 % – 3.0 % (w/w, dry basis) when the tea-bed has reached a temperature in the range of 102 °C - 104 °C.

Figure 4.4: Laboratory-scale fluid bed tea dryer

4.3 Methodology

Four main types of experiments were carried out in this study.

1. Study on the drying characteristics of dhool
2. Study on the bedplate configuration
3. Study on the mathematical modeling of the fluidization of dhool
4. Study on the factors affecting the quality of orthodox broken type tea

Experiments on the “bedplate configuration” and “mathematical modeling of the fluidization of dhool” were carried out using the pilot-scale fluid bed dryer while the experiments on the “drying characteristics of dhool” and “factors affecting the quality of orthodox broken type tea” were carried out using the laboratory-scale fluid bed dryers.

4.3.1. Experimental methods for studying the drying characteristics of dhool

Eight kilograms of fresh dhool was collected and packed in eight separate polythene bags to contain 1 kg each. The polythene bags were then placed in ECM unit (Figure 4.1) under controlled conditions. Initial moisture content was determined by oven drying of 25 g sample (Section 3.1).

Industrial fluid bed dryers for producing the orthodox broken type tea are generally operated at an average temperature of 124 ± 1 °C. The use of hot air temperatures as high as 125 °C affects the TF content of tea (Agarwal, 1989). On the other hand, controlling the drying rate becomes difficult when tea is dried above 127 °C and also tea tends to get high fired. Considering these facts, four different hot air temperatures (116 °C, 121 °C, 124 °C and 127 °C) were selected for studying the drying characteristics of orthodox broken type tea.

A loading of 32 kg/m^2 was recorded when the loading vessel of the laboratory-scale fluid bed dryer was loaded with 250 g of tea sample. The dryer unit was set to deliver hot air at 127 °C. The moisture content was measured at intervals of 1 minute. Drying was continued until the acceptable moisture content of 2.5 % – 3.0 % (w/w, dry basis) was achieved in the tea. Moisture content in dried tea was determined by oven drying of 25 g sample (Section 3.1). Thereafter the experiment was repeated for the other three different hot air temperatures.

4.3.2. Experimental methods for studying the bedplate configuration

4.3.2.1 Estimation of fluidization velocity

A measured quantity of tea was uniformly fed into the pilot-scale fluid bed dryer while operating the blow-hole/channeling suppressor. Airflow was kept low at the beginning and then gradually increased while feeding. Once the tea was completely fed, airflow was adjusted to have the tea-bed with co-existence of continuous phase and bubble phase without stagnation and entrainment. Fluidization of tea with co-existence of continuous phase and bubble phase without stagnation and entrainment was considered as the *required fluidization* for tea which was confirmed through visual observation.

Air velocity in the inlet duct to the fan was measured and airflow rate was calculated. The fluidizing velocity was obtained by dividing the total airflow rate by the effective area of the bedplate. Negligible amount of tea and fiber particles were blown out during the feeding of tea and also while adjusting airflow to achieve the fluidization. The blowout was collected and the weight was measured.

Loading was changed within the range of 29.5 kg/m^2 to 47.5 kg/m^2 in the steps of 3 kg/m^2 and the fluidization velocity was recorded.

4.3.2.2 Estimation of bed pressure drop under different loading conditions

The second type of experiments was performed to examine the relationship between the differential static pressure across tea-bed and the loading for orthodox broken type tea. The differential static pressure across tea-bed is an important parameter for analyzing the fluidizing and drying behavior of tea in fluid bed dryers. Equation (4.2) was used to find the differential static pressure across tea-bed.

$$\Delta P_{tea-bed} = \Delta P_{total} - \Delta P_{bedplate} \qquad (4.2)$$

Where,

ΔP_{total} - total differential static pressure across bedplate and tea-bed
$\Delta P_{tea-bed}$ - differential static pressure across tea-bed
$\Delta P_{bedplate}$ - differential static pressure across bedplate

ΔP_{total} was measured using micromanometer. Temple and Van Boxtel (1999) suggested the relationship between $\Delta P_{\mathrm{bedplate}}$ and the air velocity in the form of Equation (4.3).

$$\Delta P_{bedplate} = kU^2 \tag{4.3}$$

where,

U - air velocity and
k - empirical constant

The $\Delta P_{bedplate}$ corresponding to air velocities in the range of 1.0 m/s – 2.1 m/s were measured. The air temperature was maintained at 25 °C which is the average temperature of air used in dry tea analysis. The empirical constant, k, for each bedplate was then calculated. In the analysis of dhool, hot air at 124 °C was used to examine the fluid bed drying behavior of tea for the bedplates No.2, 3, 5 and 6. Therefore, hot air at 124 °C was used to find the k value for each bedplate. The correlation coefficient (R^2) for actual and predicted values of $\Delta P_{bedplate}$ for each bedplate was found to be 0.98 or above. Since correlation coefficient was close to 1, equation (4.3) was assumed to be correct and it was used to calculate $\Delta P_{bedplate}$ for a given air velocity. Hence $\Delta P_{tea-bed}$ could be computed using equation (4.2).

4.3.2.3 Study of bed pressure drop at different air velocities

In the third type of experiments, the fluctuation of $\Delta P_{tea-bed}$ was analyzed by varying the air velocity for a given loading. Six different loadings 32.5, 35.5, 38.5, 41.5, 44.5 and 47.5 kg/m^2 were used in this analysis. Initially the *required fluidization* was achieved for a given loading. That is the condition of achieving the tea-bed with co-existence of continuous phase and bubble phase. Once the required fluidization was achieved further increase in air velocity was not possible due to entrainment and blowout of tea particles. Therefore, airflow was gradually reduced and at each stage airflow and total differential static pressure were measured. The fluidizing velocity was calculated at each airflow rate and the corresponding differential static pressure across tea-bed was also calculated.

4.3.2.4 Study of drying behavior

The analysis of bedplate configuration was further extended to examine the fluidizing and drying behavior of dhool for the loadings in the range of 38.5 kg/m^2 to 50.5 kg/m^2. A hot air temperature of 124 °C was used with an accuracy of ± 0.5 °C. Data logger was set to measure and record the hot air temperature, tea-bed temperature and exhaust air temperature at intervals of five seconds. Airflow was adjusted to achieve the *required fluidization* during feeding and also during drying to minimize entrainment and blowout. Total differential static pressure and airflow rate were recorded in every 15 seconds. Drying was continued until the acceptable moisture content of 2.5 % – 3.0 % (w/w, dry basis) was achieved in the tea. Initial and final moisture contents were determined (Section 3.1).

4.3.3. Experimental methods to verify the proposed mathematical models

4.3.3.1 Experiments to verify the new mathematical model for predicting the minimum fluidization velocity

Experiments were conducted in the pilot-scale fluid bed dryer using the bedplate No.6. Fresh dhool samples were collected from the factory, bulked and kept in the ECM Unit (Figure 4.1) under controlled conditions. Partially dried dhool samples were prepared by drying in the pilot-scale fluid bed dryer using hot air at 124 °C. Fresh dhool (moisture content of 106 %, w/w, dry basis), partially dried dhool of 3 different moisture contents (74.0 %, 56.1 % and 35.0 %, w/w, dry basis) and dried dhool (moisture content of 3 %, w/w, dry basis) were used in developing and verifying the mathematical models.

The moisture contents of the bulk samples were determined (Section 3.1) and their particle size distributions were determined using sieve shaker (Podmores, Model No.9785).

4.3.3.1.1 Determination of Particle size distribution

Particle size distribution of the fresh, partially dried and dried dhool samples were studied using a Sieve Shaker (Podmores, Model No.9785). Sieves with aperture sizes of 250, 355, 500, 710, 1,000, 1,400, 2,000 and 2,000 μm were selected for the analysis. 100 g samples were measured and loaded into the sieve shaker. The sieve shaker was operated for 10 minutes and the weights of tea retained in each sieve were measured and recorded. The mean diameter of each particle range was calculated using equation (4.1) (Paudel & Zhi-Gang Feng, 2013).

$$d_p = \frac{1}{\sum_{i=1}^{n}\left(\frac{x_i}{d_i}\right)} \qquad (4.1)$$

4.3.3.1.2 Determination of Particle density

The particle density of the dhool was determined by using the density bottle with 50 ml capacity. Coconut oil was selected for the study instead of water to minimize the error due to change in moisture content during measurements. Weight of the empty bottle and bottle with oil was measured and the density of coconut oil was determined using Eq.4.3. The bottle was partially filled with tea and its weight was determined. The bottle with the tea is filled with oil and its final weight was determined. The density of the tea was determined using Eq.4.4.

$$\rho_{oil} = \frac{(w_1 - w_0)}{V} \qquad (4.3)$$

$$\rho_{tea} = \frac{(w_2 - w_0)}{\left[V - \frac{(w_3 - w_2)}{(w_1 - w_0)} \times V\right]} \qquad (4.4)$$

Where, w_0 is the weight of bottle, w_1 is the weight of bottle filled with oil, w_2 is the weight of bottle with tea, w_3 is the weight of bottle with tea & oil and V is the volume of bottle.

4.3.3.1.3 Determination of minimum fluidization velocity

Experiments for finding the minimum fluidization velocity were carried out in the pilot-scale fluid bed dryer using ambient air at 25 °C. The minimum fluidization velocity was obtained for the dhool having five different moisture contents and for three different loadings of 44.5, 47.5 and 50.5 kg/m^2.

Initially the fluidizing section was loaded with dhool and the ambient air at a temperature of 25 °C was passed through the bed gradually. Pressure drop across the bed was measured while increasing the air velocity for each run. Airflow to the fluidizing section was measured. The superficial air velocity for fluidization was obtained by dividing the total airflow with the effective area of the bedplate. The blowhole/channeling suppressor was started, immediately after the sudden bed expansion, which can be regarded as the point of minimum fluidization. The mechanical action after minimum fluidization is required since dhool having appreciably non-isometric shape will never fluidize readily in a gas (Richardsonet al., 2002).

Minimum fluidization was calculated as the point of intersection of the fixed bed pressure drop versus air velocity trend line and the loading line as given by Kunii and Levenspiel (1991). Since the mechanical action of blowhole/channeling suppressor was started only after achieving the minimum fluidization condition, its effect on fluidization could be neglected.

4.3.3.2 Experiments to verify the new mathematical model for predicting the Dimensionless moisture content

Fresh dhool was collected and packed in three separate polythene bags to contain 1 kg each. The polythene bags were then placed in ECM unit (Figure 4.1) under controlled conditions. Initial moisture content was determined by oven drying of 25 g sample (Section 3.1).

The laboratory-scale fluid bed dryer unit was set to deliver hot air at 124 ± 1 °C. The loading vessel of the dryer was loaded with tea sample at 44.5 kg/m^2. Both the tea-bed temperature and the moisture contents were measured at different time intervals to study moisture variation with tea-bed temperature. Drying was continued until the acceptable moisture content of 2.5 % – 3.0 % (w/w, dry basis) was achieved in the tea. Moisture content in dried tea was determined by oven drying of 25 g sample (Section 3.1). Thereafter the experiment was repeated for the loadings of 47.5 kg/m^2 and 50.5 kg/m^2.

4.3.4. Experimental methods for analyzing the quality of orthodox broken type tea

Effect of the drying parameters on the quality of orthodox broken type tea was studied. The fresh dhool samples were collected from the factory and kept in the environmentally controlled manufacture unit (Figure 4.1). Experiments were performed simultaneously in two separate laboratory-scale fluid bed tea dryers; one for the control sample (control) and the other one for the sample under testing for load variation (treatment). The recommended hot air temperature for the conventional fluid bed dryer (124 °C) was selected with an accuracy of ± 0.5 °C. Both samples were fed into the loading vessels of the dryers at the same time and the drying was carried out simultaneously to avoid quality variations due to parameters other than loading density. The conventional loading in TRI-CCC FBD of 38.5 kg/m^2 was selected as the control and the loadings of 41.5, 44.5, 47.5 and 50.5 kg/m^2 were tested. Loadings lower than 38.5 kg/m^2 were not possible to test due to the observation of channeling and entrainment. Drying was continued until the acceptable moisture content of 2.5 % – 3.0 % (w/w, dry basis) was achieved in the tea.

Six replicates were conducted for each loading. Quality parameters of the final product could vary due to inconsistent standard of the raw green leaf and uncontrollable processing parameters such as temperature of the leaf that undergo severe maceration in rollers. Therefore, in each replicate the loading under investigation was compared with a control sample which was dried with the conventional loading of 38.5 kg/m^2.

Orthodox broken type tea has wide range of particles from 250 – 1000 µm (Table 1.1) and hence it was very difficult to achieve co-existence of continuous phase and bubble phase. At the same time tea particles began to rise with the reduction of moisture resulting in entrainment. As a result of this, fluidized tea-bed gets disturbed. Therefore, fluidization of tea was monitored throughout the drying process and airflow was gradually and carefully reduced to achieve tea-bed with co-existence of continuous phase and bubble phase. Further, the use of nylon lid prevented entrainment of very fine tea particles.

Effect of hot air temperature on quality of final made tea was tested in a similar way. The dhool samples were dried at 38.5 kg/m^2 in the fluid bed dryers. The conventional hot air temperature of 124 °C was selected with an accuracy of ±0.5 °C as the control and hot air temperatures of 127, 121, 118 and 115 °C were tested. Six replicates were conducted for each hot air temperature and also for the control. Drying was continued until the acceptable moisture content of 2.5 % – 3.0 % (w/w, dry basis) was achieved in the tea.

The dried tea samples obtained in both types of experiments (48 samples from each experiment) were allowed to cool down to around 30 °C. They were cleaned by removing fibres using a laboratory-scale fibre extractor (Teacraft, UK). The dried and cleaned tea samples were used for the chemical analysis and the organoleptic analysis. Roberts and Smith method was used to determine the quality parameters such as Theflavin (TF), Thearubigin (TR), Total Colour (TC) and Brightness (BR). The dried tea samples were also sent to professional tea tasters of three different leading Tea Broking organizations for organoleptic analysis.

5.0 STUDY OF DRYING CHARACTERISTICS OF ORTHODOX BROKEN TYPE TEA

5.1 Background

Tea is macerated in tea rollers to produce the broken type tea particles. Due to severe maceration a large number of cells are ruptured, cell sap has been mixed and there is a good accessibility for gas exchange within the particles of leaf. Therefore, evaporation of water enhances due to increased surface area resulting in reducing the role of diffusion within the particle relative to the surface and air boundary layer resistance (Temple and Van Boxtel, 1999). Therefore, drying characteristics of tea produced at present is expected to change due to the presence of high amount of small particles. Detail study on drying characteristic of tea will help to identify a suitable model for drying of Orthodox broken type tea and to find the effective diffusivity of water, diffusivity constant and activation energy. Further, extending the study to different hot air temperatures will help to understand the effect of hot air temperature on the drying behavior of tea. An experiment was conducted as described in 4.3.1 and the results are presented and discussed in the following sections.

5.2 Results and Discussion

Variation of moisture content with drying time and the drying rate versus drying time for fermented dhool dried at 124 °C are shown in Figures 5.1 and 5.2 respectively. Drying rate was calculated as the amount of moisture evaporated per kg of dry tea within a unit time of 1 minute. Even though four different hot air temperatures were selected for the study, the results of only one hot air temperature is shown in the Figures for clarity.

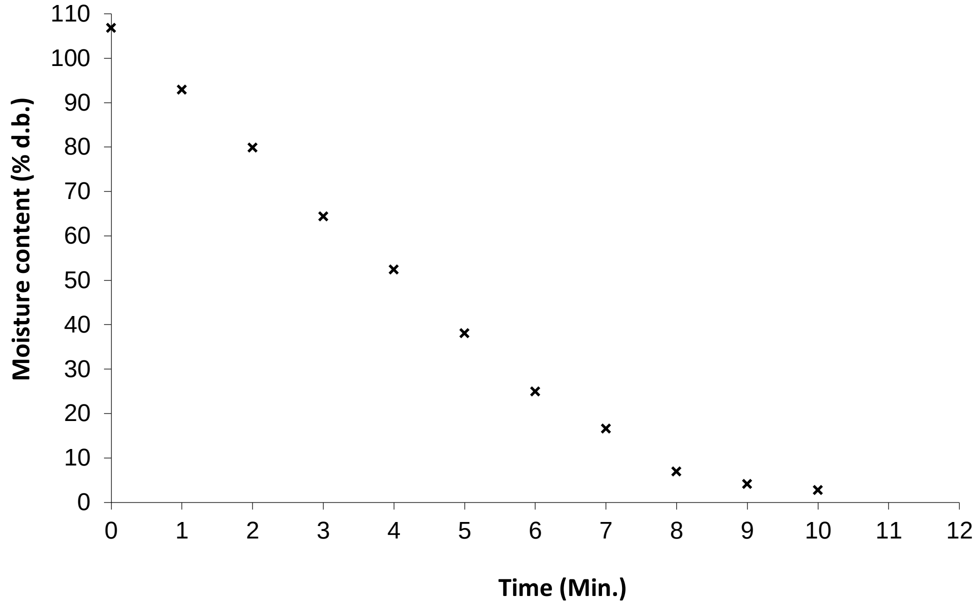


Figure 5.1: Variation of moisture content of tea with time for drying at 124 °C

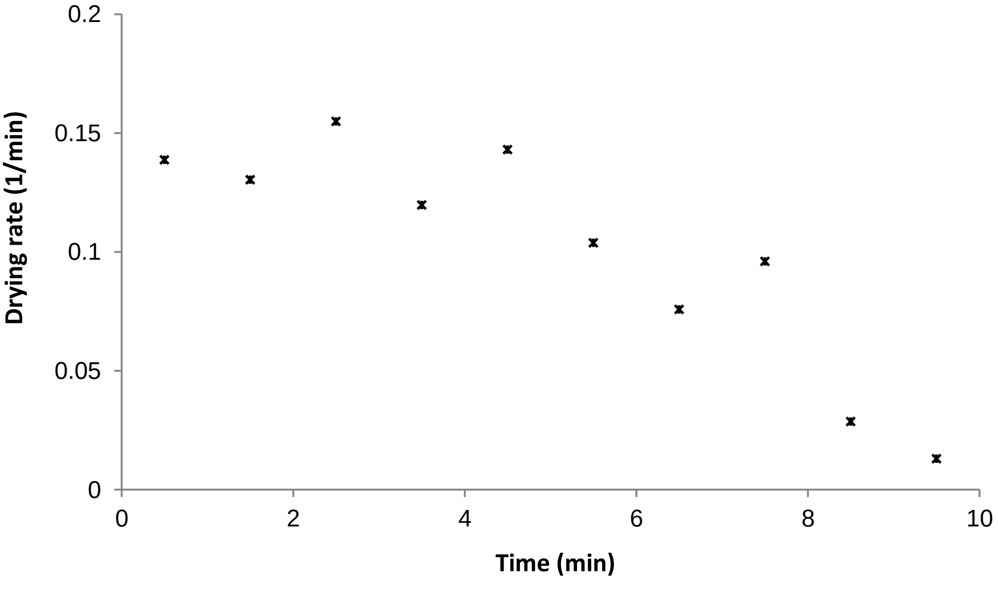


Figure 5.2: Drying rate versus time duration for the tea dried at 124 °C

Variation of drying rate with time was very similar for all the different hot air temperatures examined in this study. The initial drying rate was low for a very short period (less than 01 minute) due to the presence of sticky tea particles with high moisture content that prevented intensive mixing with hot air. Drying was almost started with a constant rate and it was remained up to about 4 minutes (as depicted in Figure 5.2). This may be attributed to the removal of free moisture. The presence of free moisture is also confirmed by the observation of marginal increase in tea-bed temperature (as shown in Figure 5.3) during first 4 minutes of drying. The constant rate period was followed by the falling rate period as depicted in Figure 5.4. Figure 5.4 shows that free moisture was available in tea when the moisture content was above 60 % (w/w, dry basis). A final moisture level in tea of 2.5 to 3.0 % (w/w, dry basis) was achieved within a short period of 10 to 11 minutes from 108 % (w/w, dry basis).

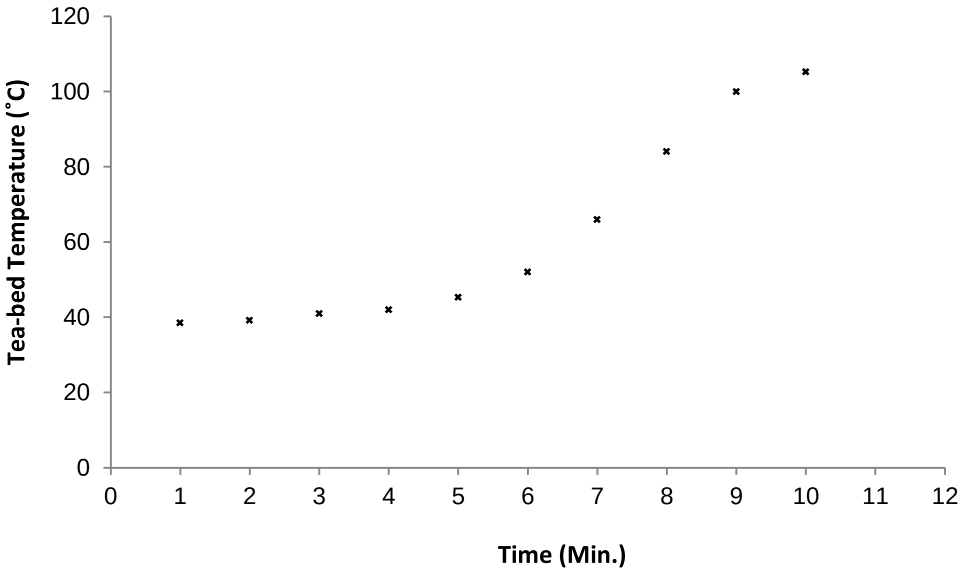


Figure 5.3: Tea-bed temperature versus drying time for drying at 124 °C

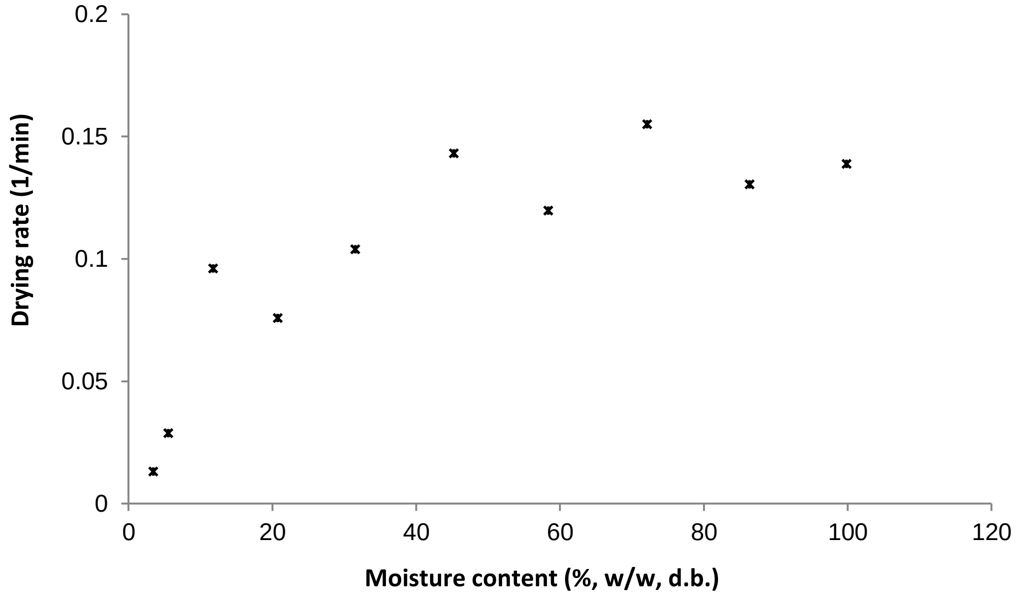


Figure 5.4: Drying rate versus moisture content of tea for drying at 124 °C

A difference of about 1.8 °C was observed between tea-bed temperature and exhaust air temperature measured at a height difference of 22 cm during drying of tea at the hot air temperature of 124 ± 0.5 °C (Figure 5.5). The Figure 5.5 was obtained by drying separate dhool samples with an initial moisture content of 122 % (w/w, Dry Basis) to examine the drying behavior. This result indicates intensive mixing of tea with hot air, very low fluctuations in fluidizing velocity and efficient drying of tea. Similar observations were made for the other three hot air temperatures also. Therefore, semi-theoretical thin layer drying models were selected and tested in this study.

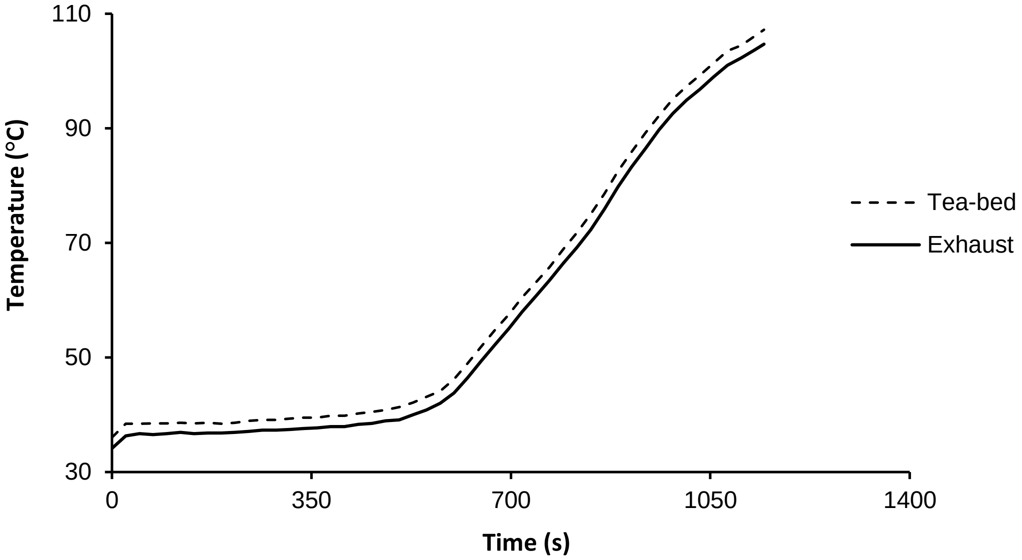


Figure 5.5: Variation of tea-bed and exhaust temperatures for drying at 124 °C

A typical characteristic drying curve (moisture ratio vs. time) for orthodox broken type tea is shown in Figure 5.6. Equilibrium moisture content was taken as zero in the calculation of moisture ratios (Temple &Van Boxtel, 1999). Drying data were fitted to six different semi-theoretical thin-layer drying models (Eq. 2.14 to 2.19). The results of the analysis in evaluating the models based on correlation coefficient (R^2), root mean square error (RMSE) and reduced chi-square (χ^2) are presented in Table 5.1. Results indicate that semi-theoretical thin-layer drying models under investigation were in good correlation with the experimental data and Page model gave the best fit with a correlation coefficient above 0.9945 for all the hot air temperatures. The RMSE and χ^2 values were less than 0.0254 and 0.0051 respectively. Since the semi-theoretical thin-layer models under investigation were derived using Fick's Law as the basis, internal resistance to moisture transfer was considered to be dominant.

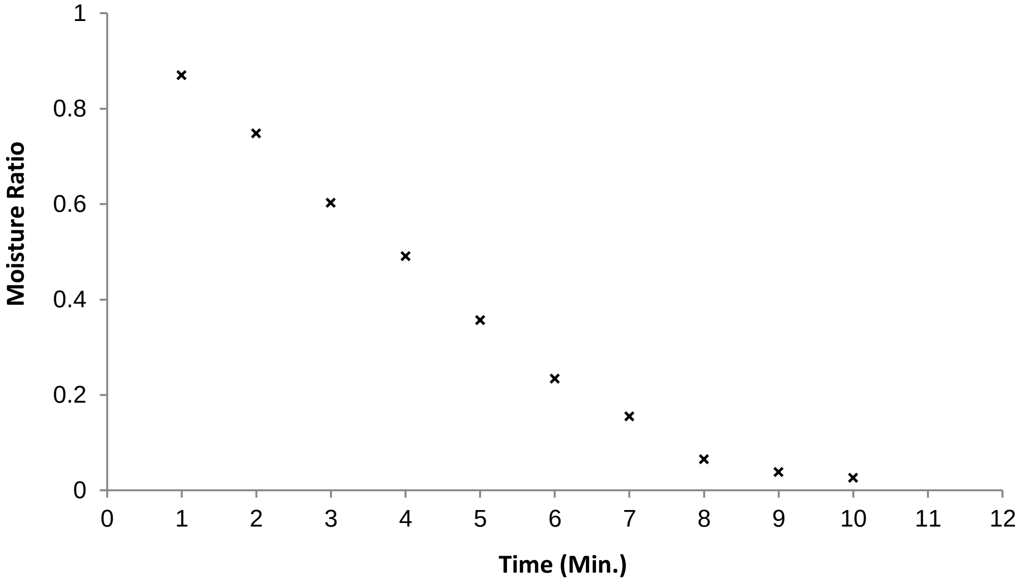


Figure 5.6: Variation of moisture ratio of tea with time for drying at 124 °C

Table 5.1: Results of the statistical analysis obtained from different drying models

Model	T (°C)	Constants				R^2	RMSE	χ^2
Lewis	127	$k_o = 0.23292$				0.9883	0.0798	0.0510
	124	$k_o = 0.22344$				0.9836	0.0830	0.0620
	121	$k_o = 0.22396$				0.9889	0.0790	0.0624
	116	$k_o = 0.23009$				0.9906	0.0765	0.0586
Henderson and Pabis	127	$k_o = 0.28840$	$A_o = 1.2403$			0.9751	0.0542	0.0205
	124	$k_o = 0.27425$	$A_o = 1.2359$			0.9695	0.0605	0.0293
	121	$k_o = 0.27750$	$A_o = 1.2552$			0.9780	0.0515	0.0238
	116	$k_o = 0.28694$	$A_o = 1.2648$			0.9820	0.0461	0.0191
Logarithmic	127	$k_o = 0.15122$	$A_o = 1.4665$	$C = -0.3700$		0.9961	0.0216	0.0028
	124	$k_o = 0.14796$	$A_o = 1.4369$	$C = -0.3406$		0.9920	0.0309	0.0067
	121	$k_o = 0.18648$	$A_o = 1.3288$	$C = -0.1841$		0.9913	0.0321	0.0082
	116	$k_o = 0.20933$	$A_o = 1.3059$	$C = -0.1369$		0.9913	0.0319	0.0081
Page	127	$k_o = 0.10381$	$n = 1.5290$			0.9958	0.0217	0.0033
	124	$k_o = 0.09128$	$n = 1.5606$			0.9945	0.0254	0.0051
	121	$k_o = 0.09294$	$n = 1.5440$			0.9966	0.0194	0.0033
	116	$k_o = 0.09931$	$n = 1.5288$			0.9972	0.0172	0.0026
Modified Page	127	$k_o = 0.50358$	$n = 0.4624$			0.9883	0.0853	0.0510
	124	$k_o = 0.44580$	$n = 0.5011$			0.9836	0.0880	0.0620
	121	$k_o = 0.50488$	$n = 0.4435$			0.9889	0.0832	0.0624
	116	$k_o = 0.46624$	$n = 0.4934$			0.9906	0.0807	0.0586
Two-term exponential	127	$k_o = 0.28833$	$k_1 = 0.28845$	$A_o = 0.67530$	$A_1 = 0.56505$	0.9751	0.0641	0.0205
	124	$k_o = 0.27019$	$k_1 = 0.27019$	$A_o = 0.61505$	$A_1 = 0.61505$	0.9681	0.0714	0.0306
	121	$k_o = 0.27750$	$k_1 = 0.27750$	$A_o = 0.62762$	$A_1 = 0.62762$	0.9780	0.0584	0.0238
	116	$k_o = 0.28636$	$k_1 = 0.28753$	$A_o = 0.63243$	$A_1 = 0.63243$	0.9820	0.0523	0.0191

Panchariya et al. (2002) used general series solution of Fick’s second law in spherical coordinates as given in Eq. 5.1 to describe the drying of CTC black tea (average diameter of 500 μm). He made the assumptions of constant diffusivity and spherical tea particles in the equation where D_{eff} is the effective diffusivity (m^2/s) and R is the radius of the tea particles (m). Orthodox broken type tea produced at present has particles in the range of 355 to 710 μm. Therefore, Eq. 5.1 was used to examine the drying behaviour of Orthodox broken type tea in this study.

$$MR = \frac{M - M_e}{M_o - M_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{n^2 D_{eff} \pi^2}{R^2} t \right) \qquad (5.1)$$

The first term of Eq. 5.1 is known as the Henderson and Pabis model (Eq.2.15). The slope, coefficient *k*, of this model is related to the effective diffusivity as given in Eq. 5.2.

$$k = \frac{D_{eff} \pi^2}{R^2} \qquad (5.2)$$

The effective diffusivity of water was calculated using the slope of Eq. (5.1) and deduced from the linear regression of ln(MR) versus time (Figure 5.7). Variation of effective diffusivity with temperature is presented in Table 5.2. Free moisture is expected to be present in tea during first 4 minutes. Therefore, effective diffusivity was also calculated with the data obtained after 4 minutes and is included in the Table 5.2. It shows that the overall effective diffusivity assumed almost a constant value of 2.52×10^{-11} m^2/s. However, for the final stage of drying (after 4 minutes) a slight increase in diffusivity was obtained with the increase in hot air temperature, from 2.660×10^{-11} m^2/s at 116 °C to 2.782×10^{-11} m^2/s at 127 °C. This confirms that internal mass transfer resistance had fully controlled the drying behaviour during the final stages of drying. Comparatively, the effective diffusivity values obtained by Panchariya et al. (2002) for CTC black tea, 1.141×10^{-11} to 2.985×10^{-11} (m^2/s) in the temperature range from 80 °C to 120 °C is very close to that obtained for Orthodox broken type tea in this study.

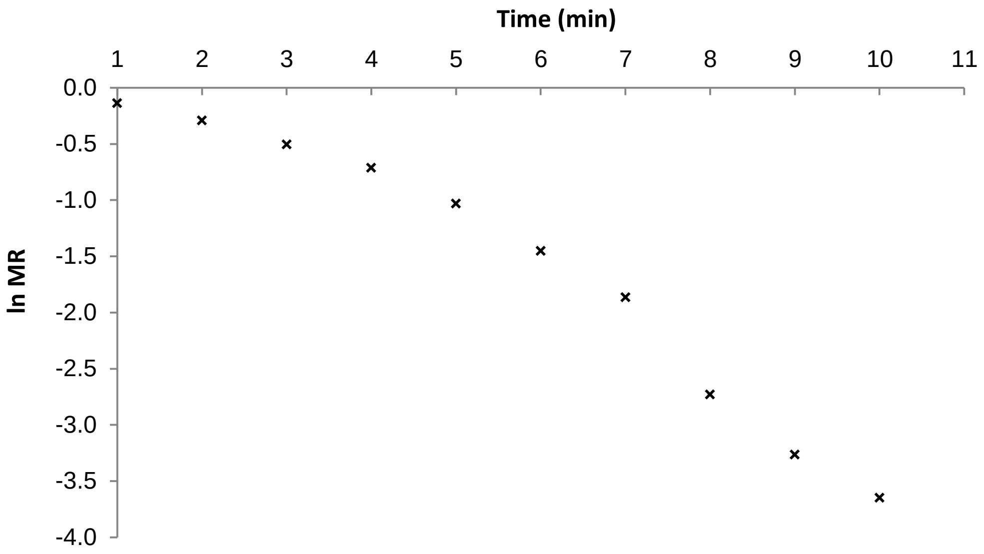


Figure 5.7: Experimental logarithmic moisture ratio

Table 5.2 Effective diffusivity of water for tea

Drying temperature (°C)	Total Drying time (min)	Effective diffusivity (m^2/s)	
		Overall	After 4 minutes of drying
116	11	2.51×10^{-11}	2.660×10^{-11}
121	11	2.52×10^{-11}	2.687×10^{-11}
124	10	2.52×10^{-11}	2.740×10^{-11}
127	9	2.53×10^{-11}	2.782×10^{-11}

In previous studies, Arrhenius-type relationship (Eq.5.3) was used to describe the effect of temperature on effective diffusivity for agricultural products (Aregbesola et al., 2015; Amiri Chayjan et al., 2012; Sridhar and Madhu, 2015; & Radhika et al., 2011).

$$D_{eff} = D_o \exp\left[\frac{-E_a}{RT_a}\right] \tag{5.3}$$

where, D_o is a diffusivity constant equivalent to the diffusivity at infinitely high temperature and E_a is the activation energy (kJ/mol).

A linear relationship is obtained when the logarithm of D_{eff} as a function of the reciprocal of absolute temperature (T_a) is plotted (Figure. 5.8). The diffusivity constant (D_o) and activation energy (E_a) were calculated using the linear regression and the values are 1.3838 x 10^{-10} and 53.4 kJ/mol respectively.

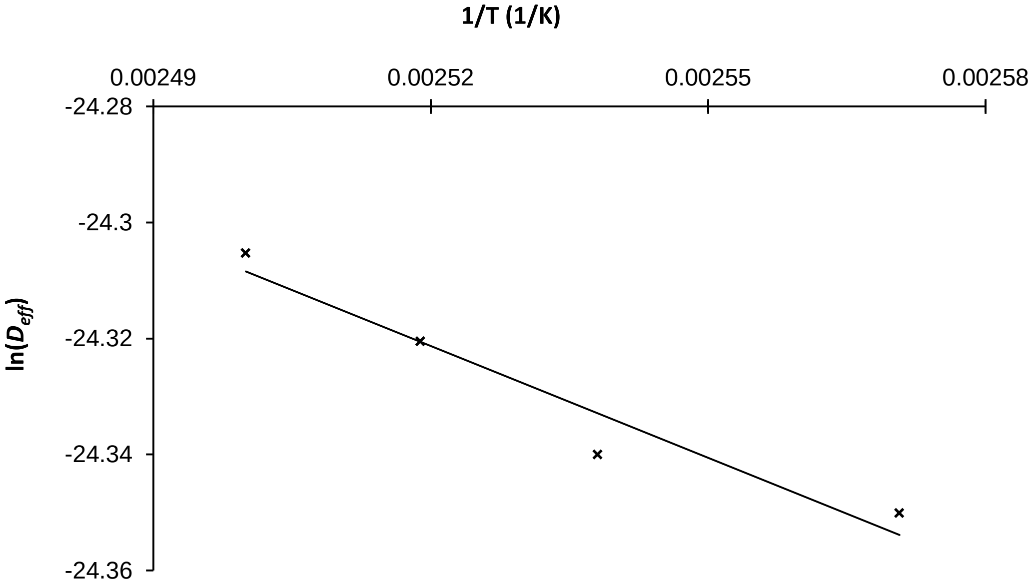


Figure 5.8: Effect of temperature on moisture diffusivity in tea

5.3 Conclusions

Free moisture was expected to be present in tea with moisture contents above 60 % (w/w, dry basis). Drying characteristics of orthodox broken type tea was best described by Page thin-layer drying model. The overall effective diffusivity of water was found to be a constant around 2.52 x 10^{-11} m^2/s. However for the final stage of drying, the effective diffusivity varied between 2.660 x 10^{-11} and 2.782 x 10^{-11} m^2/s for the hot air temperatures in the range of 116 °C to 127 °C. The diffusivity constant and the activation energy for the diffusion of water in the orthodox broken type tea were found to be 1.3838 x 10^{-10} and 53.4 kJ/mol respectively.

6.0. STUDY ON BEDPLATE CONFIGURATION

6.1 Background

In industrial fluid bed tea dryers, tea with a moisture content of about 106 % (w/w, dry basis) is dried to a moisture content of 2.5 % – 3.0 % (w/w, dry basis). Tea is fluidized using hot air (124 °C – 127 °C) in a nearly 5 m long drying section. A weir plate is fixed at the discharge-end to maintain the fluidized tea-bed with a uniform thickness in the drying section. The required moisture content of 2.5 % – 3.0 % could be achieved when the tea-bed temperature is maintained around 95 °C at the discharge end. Feeding rate of tea is adjusted manually during the operation to avoid fluctuation in the tea-bed temperature.

Fluidized tea-bed with co-existence of continuous phase and bubble phase gives good stability without stagnation and entrainment during drying. The effect of bedplate configuration on the fluidized-bed drying behaviour of tea was studied using bedplates having different configurations. Both dry tea and dhool were used in this analysis. Parameters studied were loading rate, fluidizing velocity, tea-bed temperature and differential static pressure across the fluidized tea-bed. Experiments were conducted as described in section 4.3.2 and the results are presented and discussed in the following sections.

6.2 Results and Discussion

6.2.1 Study on fluidizing behavior using “dry tea”

6.2.1.1 Analysis on bedplate configuration

Results of the dry tea analysis are summarized in Table 6.1. Based on the opening area percentage, bedplates could be categorized into 3 types; low area %, moderate area % and high area %. When the opening area percentage is low (less than 4 %), number of perforations per square meter is low and hence the airflow distribution is poor. As a result, achieving the fluidization with co-existence of continuous phase and bubble phase became difficult. Airflow was increased to avoid stagnation areas but it caused channeling, entrainment and blowout. For all the experiments blowout was found to be less than 0.15 % of the corresponding load.

Table 6.1: Fluidizing velocities for different loadings of tea with different bedplates

Bedplate	TRI-CCC FBD	No.1	No.2	No.3	No.4	No.5	No.6
Perforation size (mm x mm)	36 x 0.5	36 x 0.5	36 x 0.5	36 x 0.5	36 x 0.6	36 x 0.6	36 x 0.6
Number of perforations/ m^2	1,785	1,624	2,177	2,748	1,356	1,820	2,266
Opening area (%)	3.4	3	4	5	3	4	5
Loading (kg/m^2)	Fluidizing velocity (m/s)						
29.5	-	1.39	-	-	1.41	-	-
32.5	1.46	1.3	1.27	1.43	-	1.43	1.31
35.5	1.56	-	1.26	1.51	-	1.42	1.4
38.5	-	-	1.24	1.52	-	1.41	1.41
41.5	-	-	1.28	1.48	-	1.41	1.42
44.5	-	-	1.3	1.46	-	1.42	1.45
47.5	-	-	1.29	1.36	-	-	1.39

When the opening area percentage was moderate (4 %), distribution of air over the bed was improved and tea with wide range of loading (32.5 – 47.5 kg/m^2) could be successfully fluidized. The fluctuation of fluidizing velocity for a step change in loading was found to reduce with the increase of perforation size (from “36 mm x 0.5 mm” to “36 mm x 0.6 mm”) for a given area percentage. A similar observation was recorded with the increase of opening area percentage for a given perforation size.

This result suggests that air entering through a wider cross section with moderate and high opening area percentage (equal to or above 4 %) had reduced the effect of channeling and by-passing. The lower limit was found to be the bedplate having moderate area percentage of 4 % and narrow cross section of 36 mm × 0.5 mm. On the other hand, increasing the area percentage is restricted with the maximum number of perforations that can be practically accommodated in the plate area and the maximum width of perforations to avoid tea particles being fall through. Therefore, the upper limit was found to be the opening area percentage of 5 % and cross sectional area of 36 mm x 0.6 mm. The findings of this study clearly indicate that the bedplate configuration (opening area percentage of 3.4 % and cross sectional area of 36 mm × 0.5 mm) of the fluid bed dryers, currently operating in almost all the tea factories in Sri Lanka, can be modified accordingly to have better performances.

6.2.1.2 Variation of differential static pressure with loading

Temple and Van Boxtel (1999) suggested a simple model relating the differential static pressure across the tea-bed ($\Delta P_{tea-bed}$) for the fluidization of dried CTC tea as given in Equation (6.1).

$$\Delta P_{tea-bed} = k_1 M \tag{6.1}$$

Where,	$\Delta P_{tea-bed}$	- differential static pressure across tea-bed (kN/m^2)
	k_1	- constant
	M	- loading (kg/m^2)

In the present study, validity of this model for dried orthodox broken type tea was examined using regression analysis. Bedplates with moderate and high opening area percentages were used and the actual and predicted data were compared (Table 6.2).

Table 6.2 Results of statistical Analysis obtained for different bedplates

Bedplate No.	**Constant**	**R^2**	**RMSE**	**χ^2**
2	0.0075	0.97	0.0059	0.35 x 10^{-4}
3	0.0071	0.98	0.0041	0.17 x 10^{-4}
5	0.0076	0.95	0.0061	0.37 x 10^{-4}
6	0.0071	0.99	0.0016	0.03 x 10^{-4}

Bedplates having high opening area percentage (more than 4 %) performed better with $R^2 \geq 0.98$, RMSE < 0.0041 and $\chi^2 < 0.17 \times 10^{-4}$ compared to bedplates having moderate opening area percentage of 4 % with $R^2 \leq 0.97$, RMSE > 0.0059 and $\chi^2 \geq 0.35 \times 10^{-4}$. This result indicates that the model which is applicable for the fluidization of CTC tea is also applicable for orthodox broken type tea. However the bedplates must be having high area percentages of greater than 4 % for better performance.

6.2.1.3 Variation of differential static pressure with fluidizing velocity

As explained in section 6.2.1.1, the required fluidization could be achieved only for a very narrow range of velocities in bedplate No.1 and bedplate No.4 due to severe fluctuations. Figures 6.1, 6.2, 6.3 and 6.4 show the variation of differential static pressure across tea-bed with the fluidizing velocity for bedplates No.2, 3, 5 and 6 respectively. Differential static pressure across tea-bed did not vary considerably with fluidizing velocity in bedplates having higher opening area percentage (>4 %) compared to that in bedplates having moderate area percentage (4 %).The least fluctuations were observed with bedplate No.6 having the highest area percentage and also with wider cross section of perforations (36 mm × 6 mm). This result suggests that for a given loading, the fluctuation of $\Delta P_{\text{tea-bed}}$ can be minimized with high opening area percentage (> 4 %) and wider cross section of perforations.

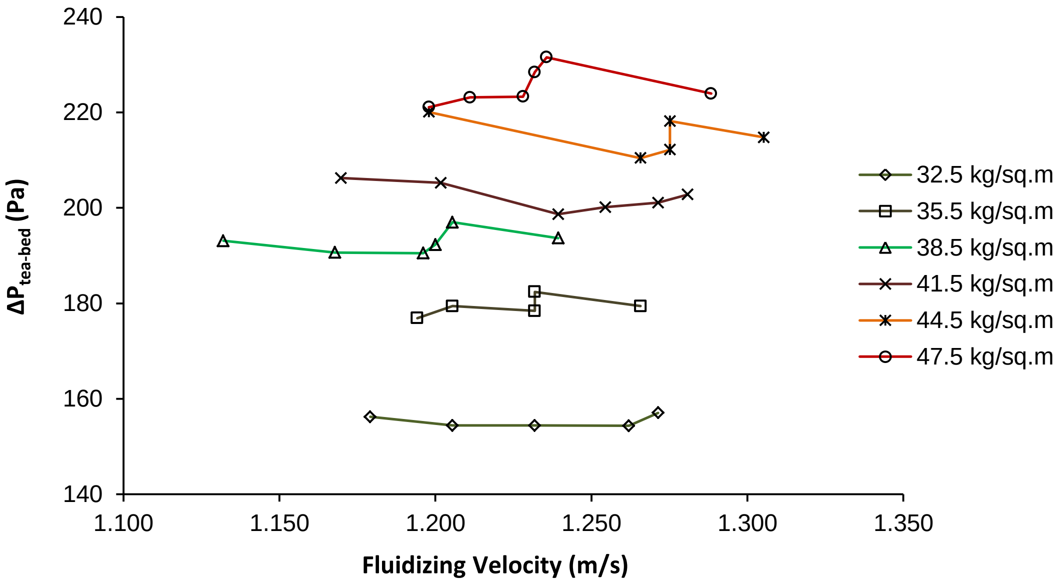


Figure 6.1: Variation of $\Delta P_{\text{tea-bed}}$ with the fluidizing velocity in Bedplate No.2

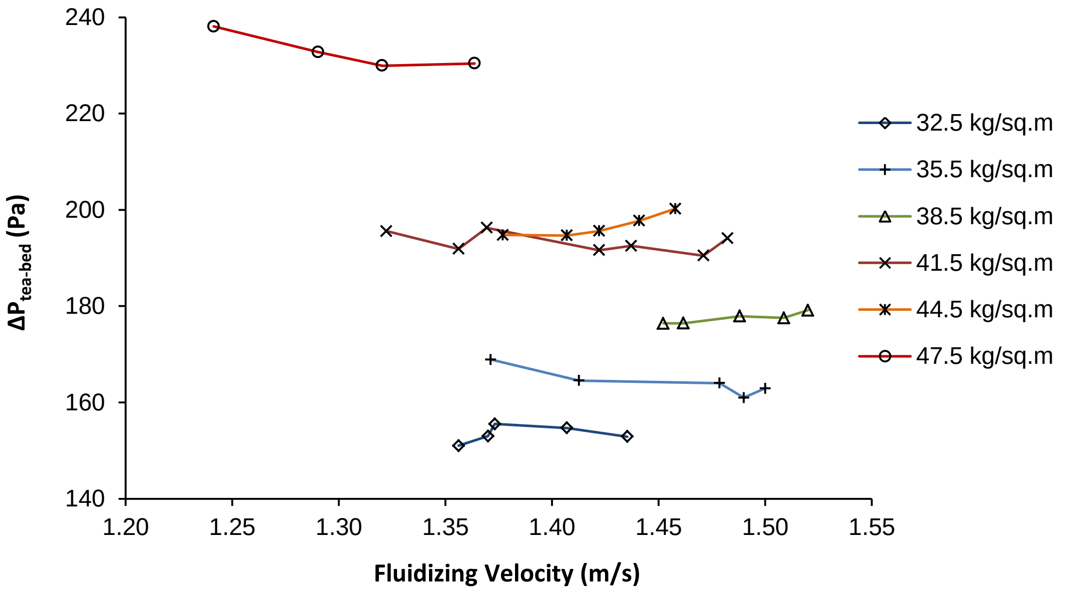


Figure 6.2: Variation of $\Delta P_{\text{tea-bed}}$ with the fluidizing velocity in Bedplate No.3

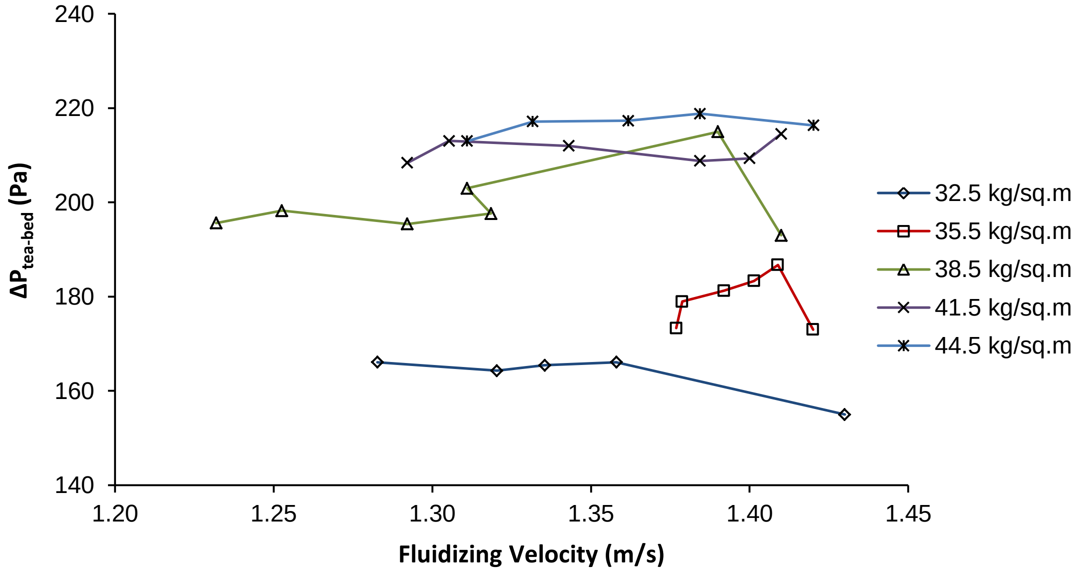


Figure 6.3: Variation of $\Delta P_{\text{tea-bed}}$ with the fluidizing velocity in Bedplate No.5

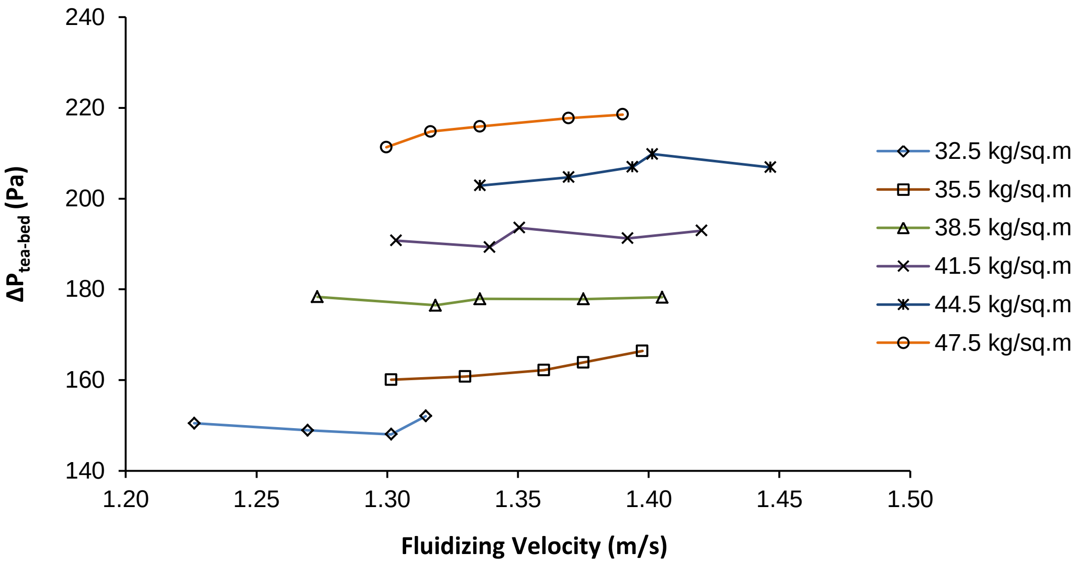
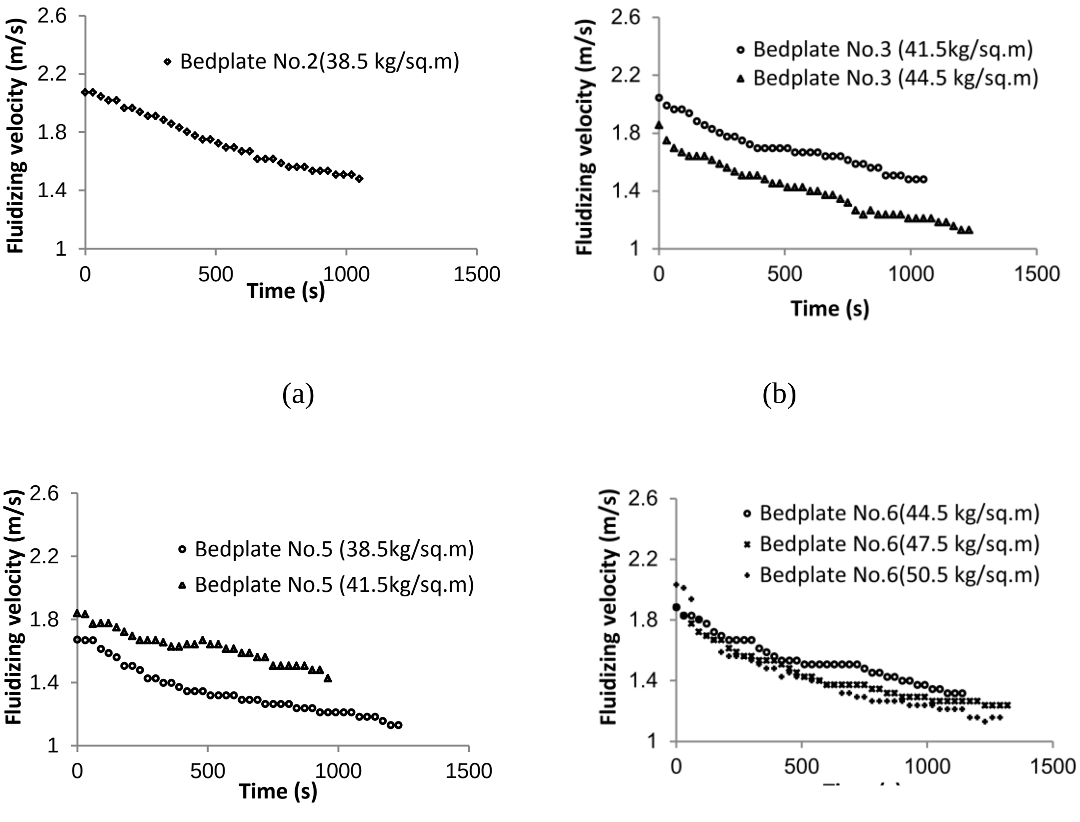


Figure 6.4: Variation of $\Delta P_{tea-bed}$ with the fluidizing velocity in Bedplate No.6

6.2.2 Study on fluidizing and drying behavior of "dhool"

Dry tea analysis revealed that bedplates having low area % (< 4%) gave poor performance and hence only the bedplates having moderate area % (No.2 and No.5) and bedplates having high area % (No.3 and No.6) were used in the analysis on dhool. The initial moisture content of dhool was 106 ± 1.8 % and drying was continued until a final moisture content of 2.5 - 3.0 % is achieved. Particle weight was reduced but the bulk density of the tea-bed was found to increase slightly during drying. Consequently, the fluidizing velocity was manually adjusted to achieve the required fluidization (i.e. coexistence of continuous phase and bubble phase while minimizing the entrainment, channeling and blowout). The variations of fluidizing velocity with the drying time for different bedplates are given in Figure 6.5. The complete range of loading (29.5 - 47.5 kg/m^2) could not be used in the raw tea analysis for all the bedplates due to difficulty in achieving required fluidization. Results indicate that the required fluidization could be achieved for bedplates having high area % (> 4 %) only with higher loadings (≥ 41.5 kg/m^2) while for the bedplates having moderate area % the required fluidization could be achieved with moderate loadings in the range of 38.5 to 41.5 kg/m^2. For a given area percentage, the fluidizing velocity was found to be lower for bedplates with larger perforation sizes.

Further, when the perforation size was large, the required fluidization could be achieved for a wider range of loadings. Bedplate No.6 with higher opening area percentage and larger perforation size gave the best performance; lower fluidizing velocities, wider range of loadings and most importantly lesser fluctuations for a given step change in the loading. Therefore bedplate No.6 has the most benefits if use in industrial type fluid bed dryers. The fluctuations of fluidizing velocity in industrial fluid bed dryers are unavoidable during the drying, but it can be minimized with bedplate No.6. Further bedplate No.6 is having the lower jet velocities which are direct function of fluidizing velocity, cross sectional area of perforations and the area percentage (see Appendix E). Consequently, the loss of black tea particles due to entrainment and blowout can also be minimized with the bedplate No.6.



(a) (b)

(c) (d)

Figure 6.5: Variation of fluidizing velocity with time (a) Bedplate No.2 (b) Bedplate No.3 (c) Bedplate No.5 (d) Bedplate No.6

6.3 Conclusion

Results of dry tea analysis suggested that bedplates having opening area less than 4 % are not suitable for fluidizing the orthodox broken type tea. Majority of the tea factories in Sri Lanka still use conventional FBDs having opening area percentages of around 3.4 %. Therefore, it can be recommended to modify them in order to improve the fluidization to achieve fluidized tea-bed with coexistence of continuous phase and bubble phase and to minimize the entrainment and blowout. This could be achieved by increasing the opening area and the perforation size within the practical limitations. The lower limit and the upper limit to have the required fluidization was found to be the opening area of 4 % and perforation size of 36 mm × 0.5 mm and the opening area of 5 % and perforation size of 36 mm × 0.6 mm respectively. The analysis of dhool has confirmed the improvement in fluidization with high opening area and high perforation size by giving fewer fluctuations for step changes in loading and also by having a wider range of loading with the required fluidization. Due to lower jet velocities, entrainment and blowout can be minimized.

7.0 MODELING THE FLUID BED DRYING OF ORTHODOX BROKEN TYPE TEA

7.1 Background

Dhool is an intermediate product in the manufacturing process of orthodox broken type tea. It is the macerated and fermented tea before drying. Dhool has polydisperse small size particles having a wide range of sphericity. They are subject to a substantial shrinkage during the drying and hence the drying becomes progressively difficult along the continuous type fluid bed dryer. Further, the smaller tea particles are easily lifted during fluidization and carried away by the hot air stream leading to entrainment and blowout. At least the minimum fluidization velocity has to be maintained to have good interaction between the hot air and the tea particles for efficient drying. Consequently, the prevention of entrainment and blowout losses are restricted by the requirement of minimum fluidization velocity. Therefore, the minimum fluidization velocity can be identified as a critical parameter in the optimal design and operation of fluidized bed dryers and it is necessary for the modeling of the fluidization process (Hilal et al., 2001).

New mathematical models were developed in this study for predicting the minimum fluidization velocity in terms of moisture content and tea-bed temperature. Since the particle size of dhool is reduced considerably due to shrinkage during the drying process, shrinkage was considered as a parameter when developing these models. The other important parameters required for the model development are particle density and the properties of the hot air stream. Experiments were conducted as described in section 4.3.3 and the results are presented and discussed in the following sections.

7.2 Results and Discussion

7.2.1 New mathematical model to predict the minimum fluidization velocity of dhool during the drying

7.2.1.1 Particle properties of dhool during drying

The particle size distributions of dhool at 5 different moisture contents are shown in Figure 7.1.

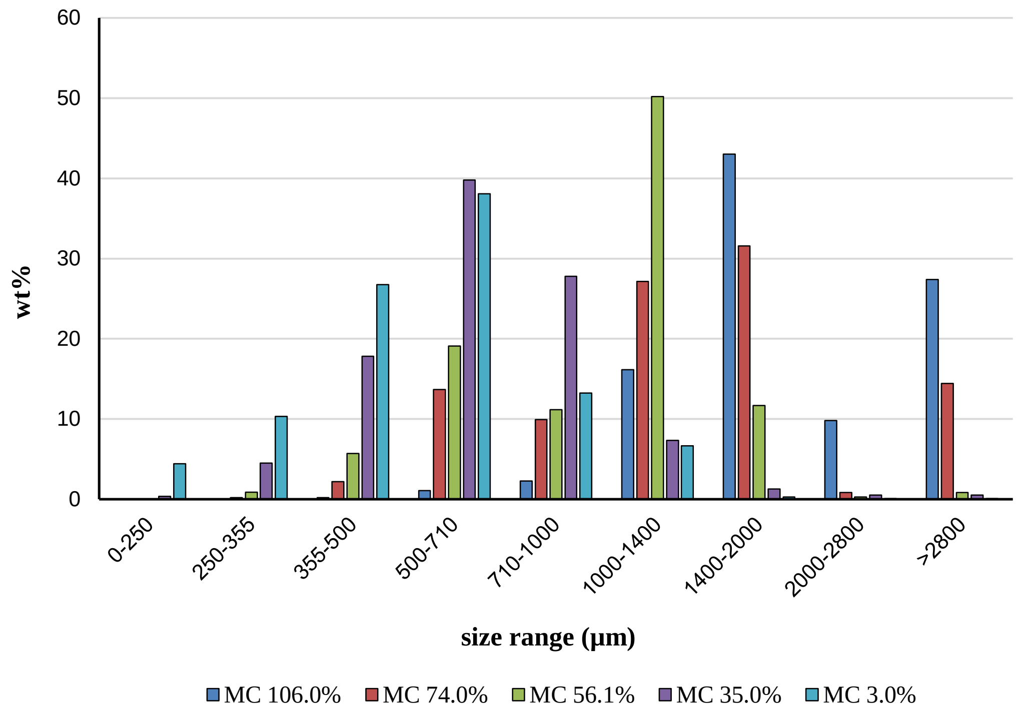


Figure 7.1: The particle size distributions of dhool at different moisture contents

At high moisture contents the particle size distribution is skewed to the right and at low moisture contents the particle size distribution is skewed more to the left. This significant variation of particle size distribution during the drying process of dhool indicates that the shrinkage during drying is significant and cannot be ignored in modeling the fluidization behavior of dhool.

Figure 7.2 shows the variation of the particle density of dhool relative to the hot air density at 124 °C $(\rho_p - \rho_f)$ with respect to the reduction of particle size during drying. Table 7.1 summarizes the variation of the physical properties of dhool due to shrinkage during drying with hot air at 124 °C. According to the Geldart classification (Richardson et al., 2002) particle seems to change from group D which is spoutable (at 106 % moisture) to group B (at 3 % moisture) which is sand-like. This is shown in the Figure D1 (see Appendix D). This significant change in particle characteristics adds complexity to the prediction of the minimum fluidization velocity of the dhool during drying.

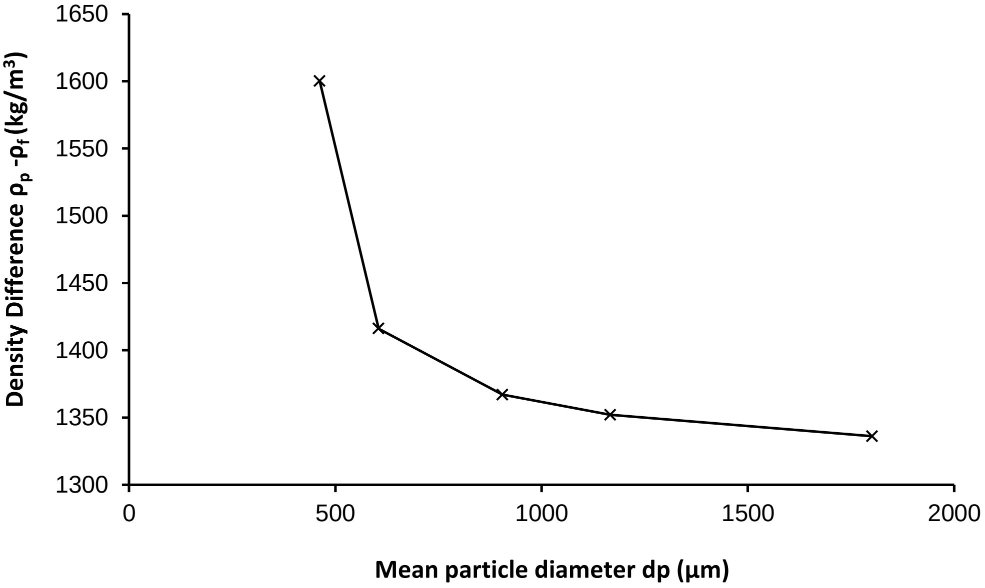


Figure 7.2: Effect of shrinkage on the physical properties of dhool during drying

Table 7.1: The physical properties of dhool during drying

Moisture Content (%, dry basis)	Mean particle Size (µm)	Particle density (kg/m^3)
106.0	1801	1336
74.0	1166	1352
56.1	905	1367
35.0	605	1416
3.0	462	1600

7.2.1.2 Modeling the effect of shrinkage of dhool

The dimensionless Archimedes number (*Ar*) has been widely used in predicting the minimum fluidization of particles. It is defined as (Eq.2.3 in Section 2.5),

$$Ar = \frac{\rho_g d_p^3(\rho_p - \rho_g)g}{\mu^2} \qquad (2.3)$$

where, ρ_g is the fluid density, d_p is the mean particle size, μ is the dynamic fluid viscosity and ρ_p is the particle density.

The Archimedes number is a function of the physical properties of the fluidizing material and changes with size and density of the particles. For the dhool, *Ar* changes drastically with the moisture ratio due to the shrinkage of particles as presented in Figure 7.3. Here the moisture ratio is the dimensionless form of moisture content which has been used to generalize the data. The moisture ratio (ϕ) is defined as

$$\phi = \frac{W - W_e}{W_i - W_e} \qquad (7.1)$$

where, W is the moisture content at any given time, W_e is the equilibrium moisture content and W_i is the initial moisture content.

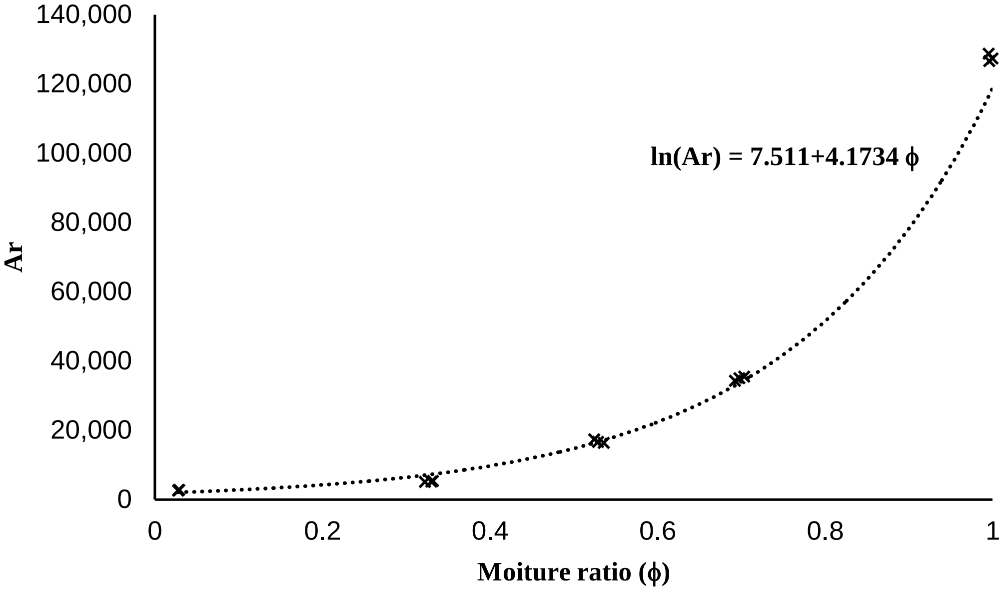


Figure 7.3: Relation between Archimedes number (*Ar*) and dimensionless moisture ratio (ϕ)

Since the dhool is dried at 124 °C, equilibrium moisture content is assigned the value zero (Temple & Van Boxtel, 1999). The results suggest that the moisture content can be identified as the critical parameter in determining the size and the density of dhool, which ultimately affects the minimum fluidization velocity.

During the drying of dhool, the value of ϕ decreases from 1 to near zero and Ar decreases exponentially. Hence, the relationship between Ar and ϕ can be modeled by a logarithmic function with the model constants given in equation (7.2).

$$\ln(Ar) = 7.5110 + 4.1734\phi \quad (7.2)$$

7.2.1.3 Prediction of minimum fluidization

Experiments for finding the minimum fluidization velocity were carried out in the pilot-scale fluid bed dryer using ambient air at 25 °C to minimize the error due to slight moisture loss during the experiment. The results are presented in Table 7.2.

Table 7.2: Velocity of air at minimum fluidization

Loading (kg/ sq.m)	Particle moisture content (%, w/w, dry basis)	Velocity of air at minimum fluidization (m/s)
41.5	106	0.82
44.5		0.88
47.5		0.98
50.5		1
41.5	74	0.77
44.5		0.92
47.5		0.88
50.5		1
41.5	56.1	0.77
44.5		0.78
47.5		0.91
50.5		0.92
41.5	35	0.77
44.5		0.84
47.5		0.88
50.5		0.87
41.5	3	0.72
44.5		0.8
47.5		0.74
50.5		0.84

The minimum fluidization velocity was found to be varying only marginally in the loading of 44.5, 47.5 and 50.5 kg/m^2.

The general relationship given by equation $Re_{mf} = aAr^b$ (where, Re_{mf} is the Reynolds number at minimum fluidization) was found to be applicable for variety of the materials (Gupta et al., 2009 & Lippens and Mulder, 1993) and the model constants were altered based on fluidizing conditions and the particle characteristics. Therefore, the applicability of this equation for the dhool was also examined and the model parameters a and b were found by the method of curve fitting (Eq.7.3). The difference in minimum fluidizing velocities for using the ambient air at 25 °C and the hot air at 124 °C was found to be negligible. This is in agreement with the previously reported work on similar studies (Knowlton, 1998, Subramani et al., 2007 & Nakamura et al., 1985). Since the industrial dryers are operated with hot air at 124 ± 1 °C, the model was developed for the properties of air corresponding to 124 °C.

$$Re_{mf} = 0.6792Ar^{0.3909} \qquad (7.3)$$

The proposed model given in equations 7.2 and 7.3 were validated using orthodox broken type tea produced from *Camellia sinensis* grown in Up-country in Sri Lanka with the change in mean particle size with moisture as presented in Table 7.1. Drying was carried out in a fluid bed dryer having bedplate with opening area of 5 % and perforation size of 36 mm × 0.6 mm and the drying air temperature was 124 °C.

Among the vast number of general correlations between Reynolds number at minimum fluidization (Re_{mf}) and Archimedes number (Ar) to predict the minimum fluidization velocity, several correlations were selected for this study (Table 7.3). These are general correlations for fluidization using air for the particles having constant moisture contents and constant particle diameter.

The experimental results for the dhool were compared against the selected correlations by defining a comparison criterion (ERe_{mf}) according to equation (7.4) (Gauthier et al., 1999).

$$ERe_{mf}(\%) = 100 * \left|\frac{Re_{mf}(calc) - Re_{mf}(exp)}{Re_{mf}(exp)}\right| \tag{7.4}$$

where, ERe_{mf} is the relative difference on the Reynolds number at minimum fluidization, $Re_{mf}(calc)$ and $Re_{mf}(exp)$ are the predicted and experimental values of the dimensionless Reynolds number at minimum fluidization which is defined by equation 2.2 (given in Section 2.5).

$$Re_{mf} = \frac{\rho_g u_{mf} d_p}{\mu} \tag{2.2}$$

where, ρ_g and μ are the density and viscosity of air at 1 atm and 124 °C, respectively u_{mf} is the velocity of air at minimum fluidization and d_p is the mean particle size.

Using the correlations between Re_{mf} and Ar one can predict the $Re_{mf}(calc)$ for a given air velocity at minimum fluidization. The comparison of the error associated with the selected models is given in Table 7.3 which indicates that the error values are considerably high.

The selected models are general equations for given fluidization conditions and particle characteristics. Consequently, their applicability is limited for predicting the fluidization of dhool during drying where shrinkage is significant and the particle characteristics vary accordingly.

Comparatively, the proposed model predicts the fluidization of dhool much better than the existing models as indicated by the low error values as given in Table 7.3.

Table 7.3: Comparison of existing correlations and proposed correlation for predicting the minimum fluidization of Orthodox broken type tea

Authors	**Correlation**	**Mean particle size (μm)**				
		1801	**1166**	**905**	**605**	**462**
		$\boldsymbol{ERe_{mf}}(\%) = \boldsymbol{f(d_p(\mu m))}$				
Wen and Yu (1966)	$Re_{mf} = (33.7^2 + 0.0408\, Ar)^{\frac{1}{2}} - 33.7$	30.2	59.4	70.6	85.2	89.1
Chitester et al (1984)	$Re_{mf} = (28.7^2 + 0.0494\, Ar)^{\frac{1}{2}} - 28.7$	15.3	47.6	60.8	79.5	84.8
Thonglimp et al (1984)	$Re_{mf} = 0.0279Ar^{0.63}$	30.1	51.2	57.9	69.7	72.0
Gauthier et al (1999)	$Re_{mf} = 0.0022Ar^{0.818}$	49.8	72.5	79.4	88.1	90.3
Doichev and Akhmakov (1979)	$Re_{mf} = 0.00108Ar^{0.94}$	0.8	53.2	68.2	84.2	88.3
This Study	$Re_{mf} = 0.6792Ar^{0.3909}$	2.3	2.6	0.5	4.3	4.3

In continuous fluid bed dryers, the dhool particles have to be maintained in a fluidized state along the bed from the inlet to the outlet. Since there is substantial particle shrinkage of dhool during fluidized bed drying, the superficial velocity of hot air has to be changed along the bed from the inlet to the outlet. Hence the development of a correlation between the minimum fluidization velocity and the moisture content is highly advantageous in optimizing the design and operation of continuous fluid bed dryers for the drying of dhool.

Using equations 7.1, 7.2, 7.3 and 2.2, u_{mf} can be predicted for known moisture contents in dhool. Figure 7.4 shows the predicted and experimental values of u_{mf} for the fluidization of dhool at 1 atm, 124 °C and loading in the range of 44.5 – 50.5 kg/m^2.

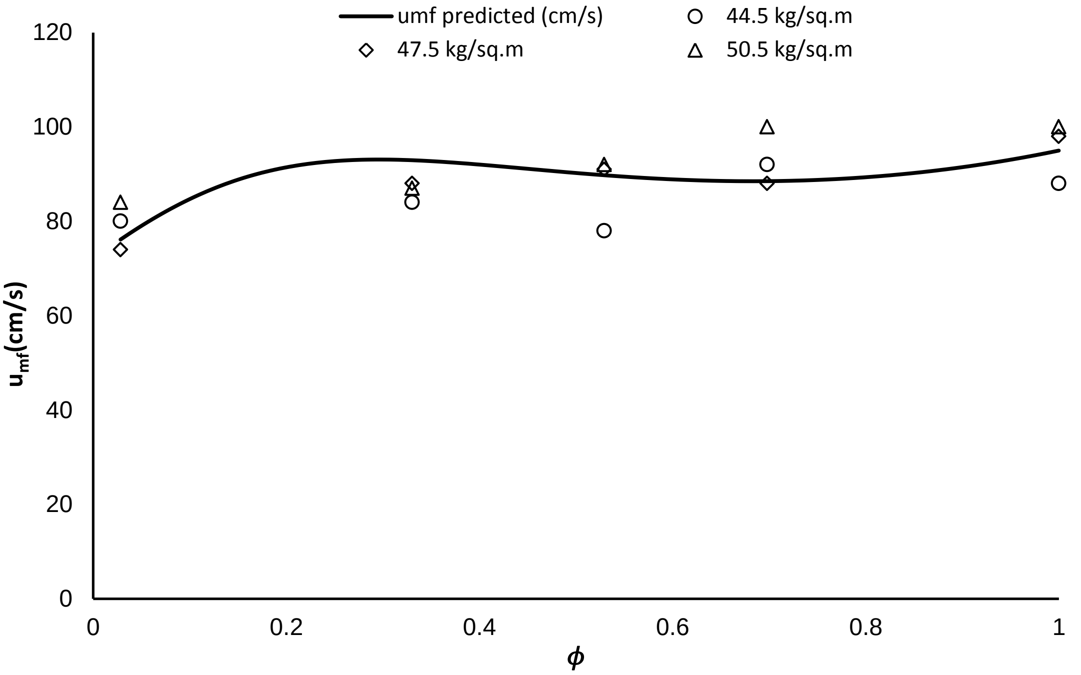


Figure 7.4: Predicted and experimental u_{mf} against the moisture ratio for dhool

It can be seen that the predicted u_{mf} values are consistently in good agreement with the experimental values and the difference is below 10 % for majority of the cases.

7.2.2 New empirical correlations for controlling the continuous fluid bed dryers

In industrial type fluid bed tea dryers, online monitoring of tea-bed temperature is more convenient than the online monitoring of moisture content of dhool. Therefore, an empirical model was proposed and validated with the experimental data for hot air temperature of 124 ± 1 °C and the loading in the range of 44.5 kg/m^2 – 50.5 kg/m^2. Experimental results suggested that the variation of moisture content of dhool follows a relationship with tea-bed temperature as given by equation (7.5).

$$\phi = 0.00684 e^{186.7/T} \tag{7.5}$$

where, ϕ is the moisture ratio of tea and T is the tea-bed temperature.

Non-linear regression analysis was conducted to find the values of the constants with reduced Chi.Sq of 1.0, RMSE of 0.053 and correlation coefficient of 0.9739. Figure 7.5 indicates that the variation of predicted moisture ratio with the tea-bed temperature is in good agreement with the experimental data.

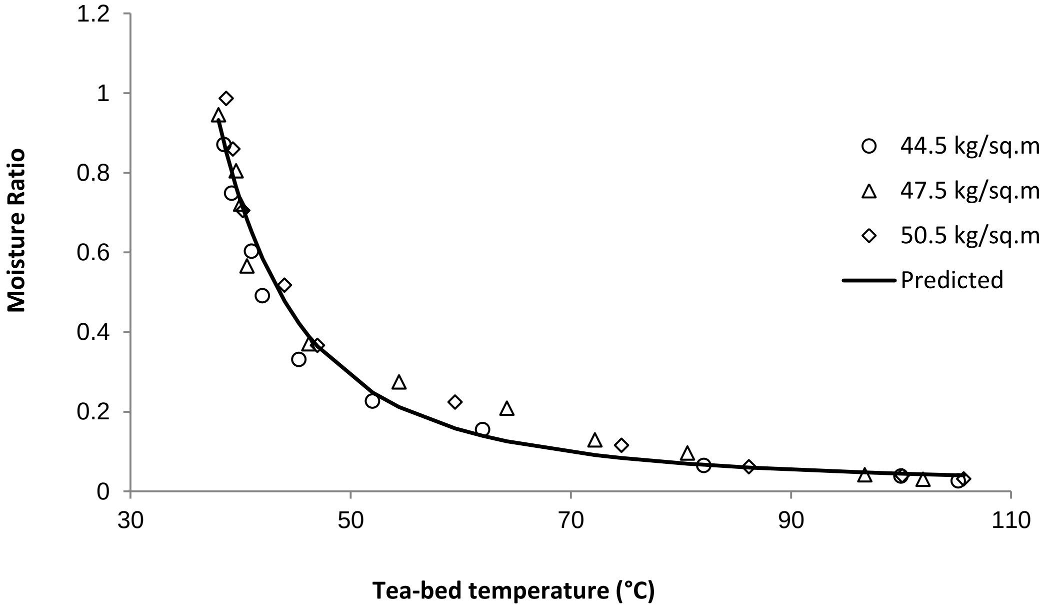


Figure 7.5: Variation of moisture ratio with the tea-bed temperature for the hot air temperature of 124 °C

7.3 Conclusion

A new model was proposed to predict the variation of minimum fluidization velocity of dhool with the reduction of moisture content during drying. The effect of shrinkage on the physical properties of dhool was analyzed by developing a correlation between the Archimedes number and the dimensionless moisture ratio in the form $\ln(Ar) = 7.5110 + 4.1734\phi$. Another correlation was developed between the Reynolds number at minimum fluidization and the Archimedes number in the form $Re_{mf} = 0.6972Ar^{0.3909}$. These two correlations could be used to predict the minimum fluidization velocity for given moisture content of dhool. The results were validated for orthodox broken type tea, drying at 124 °C, in a fluid bed dryer having bedplate with opening area of 5 % and perforation size of 36 mm × 0.6 mm and with loading in the range of 44.5 kg/m^2 to 50.5 kg/m^2. The predicted fluidization velocity was found to be in good agreement with the experimental data and the difference was below 10 % for majority of the cases.

In practice the measurement of tea-bed temperature is easier than measuring the moisture content. Therefore, an empirical model relating the moisture ratio to the tea-bed temperature in the form $\emptyset = 0.00684e^{186.7/T}$ was proposed and validated with the experimental data for the fluidized bed drying of dhool at 124 ± 1 °C and the loading in the range of 44.5 kg/m^2 to 50.5 kg/m^2.

8. STUDY ON QUALITY OF ORTHODOX BROKEN TYPE TEA

8.1 Background

During fermentation process in tea manufacture, enzymic oxidation reactions are mainly taking place in tea and the polyphenols in tea are converted mainly into Theaflavin (TF) and Therubigin (TR) which give the tea character. During the drying process, post fermentation reactions are taken place for first few minutes and these reactions are accelerated with the increase of temperature. Therefore, the level of oxidized products and specially the TR:TF ratio may also change. However, the chemical reactions are arrested at temperatures above a critical temperature of 54 °C (Agarwal, 1989). Consequently, the fermentation process is affected by the change of hot air temperature and loading in the dryer. Lower hot air temperatures and higher loadings than conventional may delay arresting the fermentation reactions and vice versa. In this study, fluidizing behaviour of tea was examined at higher loadings than the conventional loading.

The effect of loadings on quality of the final product was studied with a view to identify the suitable range of loadings for drying of tea in the industrial dryer. Loadings were increased in steps of 3 kg/m^2 (41.5, 44.5, 47.5 & 50.5 kg/m^2) starting from the conventional loading of 38.5 kg/m^2. Drying tea at loadings below the conventional loading led to channeling and entrainment affecting the fluidization and therefore not considered here. In the meantime, fluidizing the tea at higher loadings than 50.5 kg/m^2 was found to be practically difficult to achieve.

The drying of tea at lower hot air temperatures is possible with the production of small tea particles in present day manufacture and hence the effect of hot air temperature on the final quality of tea was also studied to identify the suitable range of hot air temperatures. A detailed study on the variation in quality parameters in tea, dried at temperatures decreasing in step of 3 °C (121, 118 and 115 °C) against conventional hot air temperature of 124 °C, was done. The study was extended to one step higher temperature (127 °C) as well. In industrial fluid bed dryers, use of lower hot air temperatures found to affect the blackness of tea which is not desirable.

On the other hand, controlling the drying rate become difficult when tea is dried above 127 °C and tea tends to get high-fired.

Chemical analysis was conducted following Roberts and Smith method (Liyanage et al, 2003) to determine the quality parameters. Further, the quality parameters were also evaluated by the method of organoleptic analysis, using the ranking given by the professional tea tasters. Experiments were conducted as described in section 4.3.4 and the results are presented and discussed in following sections.

8.2 Results and discussion

8.2.1 The effect of loading on the quality of made tea

The results of moisture content, chemical analysis and organoleptic analysis are presented in Table 8.1. Initial moisture content in tea samples that were collected from the factory was almost the same and the final moisture content of dried tea samples were within acceptable limit of 2.5 – 3.0 % (w/w, dry basis). Results of chemical and organoleptic analysis are presented with mean ± standard deviation. TF % for control samples was found to be above 0.86 % which is more than the acceptable value of 0.75 % and is preferred by Tea Tasters as reported by Roberts and Smith (1963). TR:TF ratio for the control sample was found to be above 11.48:1 and within the range of 10:1 to 15:1 for giving better liquor, brightness and strength as reported by Roberts (1986). Nowadays, tea manufacturing aims at producing higher percentage of smaller size particles. Therefore, leaf is subject to severe maceration in rollers and the number of passes through rollers has been increased. Due to the severe maceration, a large number of cells are ruptured, cell sap is mixed and there is a good accessibility for gas exchange within the particles of leaf (Temple et al., 2001). This may enhance the chemical reactions and may result in more oxidized products in tea. Further, due to severe maceration in the rollers, temperature of the tea may rise as high as 30 °C to 43 °C. This leads to accelerate the fermentation reactions, resulting in increased and inconsistent percentage of TF and TR and also the ratio of TR:TF as indicated by high standard deviation values.

Table 8.1: Results of chemical analysis and organoleptic analysis for tea samples dried at different loadings.

Parameters	Experiment 1		Experiment 2		Experiment 3		Experiment 4	
	38.5 kg/sq.m	**41.5 kg/sq.m**	**38.5 kg/sq.m**	**44.5 kg/sq.m**	**38.5 kg/sq.m**	**47.5 kg/sq.m**	**38.5 kg/sq.m**	**50.5 kg/sq.m**
Drying time (sec)	472.5 ± 8.2	577.5 ± 8.2	467.5 ± 6.1	610.0 ± 7.7	465.0 ± 9.5	622.5 ± 8.2	470.0 ± 7.7	627.5 ±11.3
Moisture content								
Initial (%, w/w, dry basis)	107.3 ± 0.4	107.3 ± 0.4	106.0 ± 0.9	106.0 ± 0.9	106.1 ± 0.7	106.1 ± 0.7	106.6 ± 0.7	106.6 ± 0.7
Final (%, w/w, dry basis)	3.0 ± 0.3	2.9 ± 0.2	3.2 ± 0.3	3.0 ± 0.4	2.9 ± 0.3	2.9 ± 0.4	3.0 ± 0.2	3.0 ± 0.2
Chemical Analysis								
TF (%)	0.88 ± 0.05	0.91 ±0.04	0.87 ± 0.04	0.96 ± 0.08	0.88 ± 0.04	0.99 ± 0.05	0.86 ± 0.03	0.95 ± 0.04
TR (%)	10.60 ±0.76	11.43 ±0.76	10.21 ±1.15	11.61±0.96	10.12 ±0.66	11.96±0.62	9.92 ± 0.45	12.42±0.40
Total Colour	2.66 ± 0.32	2.86 ± 0.24	2.70 ± 0.30	2.96 ± 0.09	2.66 ± 0.21	3.08 ± 0.06	2.53 ± 0.19	3.13 ± 0.08
Brightness	28.94 ±3.28	27.13 ±3.39	28.98 ±3.40	26.29±3.07	29.69 ±2.50	26.58±1.97	29.32 ±0.77	25.73±1.5
TR:TF	12.08 ±0.24	12.56 ±0.67	11.73 ±0.77	12.18±1.36	11.55 ±0.62	12.14±2.40	11.48 ±0.55	13.10±0.45
Organoleptic Analysis								
Infused leaf appearance	4.22 ± 0.27	3.95 ± 0.33	4.22 ± 0.17	3.89 ± 0.34	4.78 ± 0.46	4.44 ± 0.40	4.83 ± 0.41	4.39 ± 0.44
Liquor colour	4.61 ± 0.39	4.78 ± 0.40	4.78 ± 0.50	5.17 ± 0.59	4.17 ± 0.28	4.39 ± 0.25	4.11 ± 0.27	4.45 ± 0.27
Liquor strength	4.50 ± 0.28	4.61 ± 0.39	4.39 ± 0.33	4.72 ± 0.25	3.83 ± 0.28	4.17 ± 0.35	3.89 ± 0.27	4.22 ± 0.34
Liquor quality	4.22 ± 0.27	4.28 ± 0.33	4.28 ± 0.25	4.72 ± 0.25	4.39 ± 0.34	4.39 ± 0.65	4.22 ± 0.34	4.22 ± 0.54
Overall quality	17.56 ±0.78	17.61 ±0.80	17.66 ±0.42	18.50±0.66	17.00 ±0.73	17.39±0.71	17.06 ±0.53	17.28±0.65

The change in TF %, TR %, TR:TF ratio and overall quality for given loading as a percentage of the corresponding values of the conventional loading (38.5 kg/m^2) is given in Figure 8.1. An increasing trend can be observed in both TF % and TR % with loadings. However, the trend was seen only up to 47.5 kg/m^2 in the case of TF which results in very high percentage change of TR:TF ratio for the loading of 50.5 kg/m^2. This may be due to the conversion of part of TF into TR due to longer drying time for the loading of 50.5 kg/m^2. Figure 8.1 also shows the overall ranking of the organoleptic analysis. It indicates that the loading of 44.5 kg/m^2 gave the best results for the overall quality with higher percentage change.

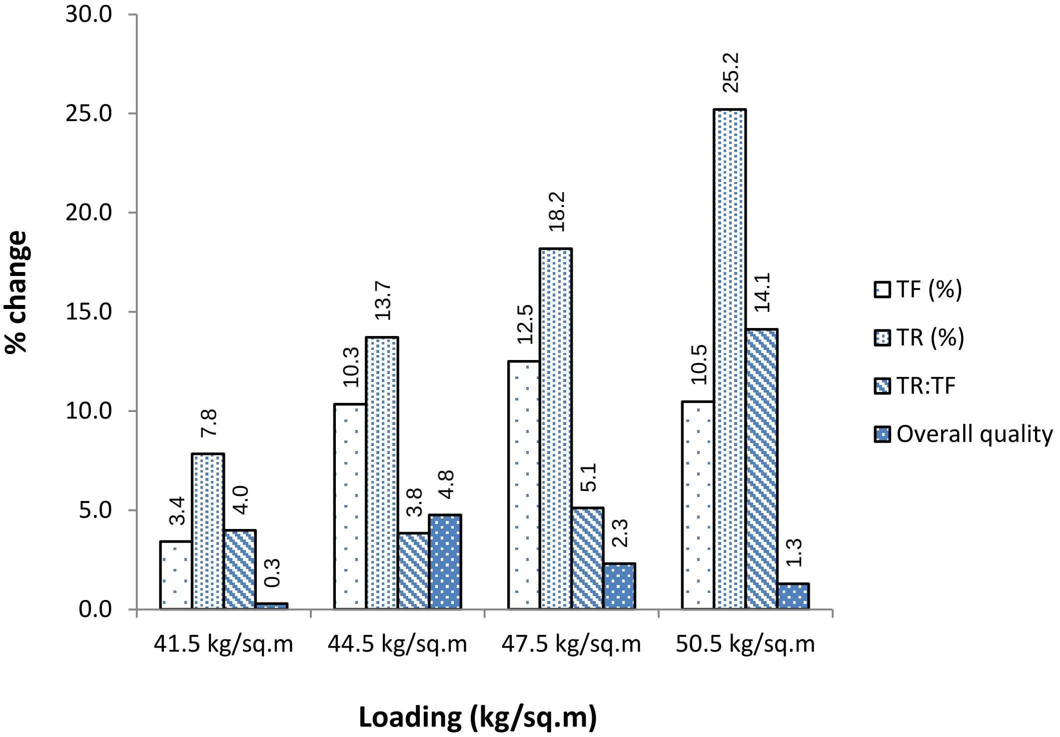


Figure 8.1: Variation of quality and sensory parameters with loadings

Figure 8.2 shows the variation of tea-bed temperature with time duration for drying at five different loadings. Tea attained the critical temperature of 54 °C (Agarwal, 1989) about 60 seconds later for the loadings of 41.5 and 44.5 kg/m^2 and about 80 seconds later for the loading of 47.5 & 50.5 kg/m^2, relative to control loading of 38.5 kg/m^2. The delay would have resulted in extended post fermentation reactions in tea. The extended post fermentation reactions generally lead to a reduction in TF % as some amount of TF is transformed into TR (Agarwal, 1989). The increase in both TF % and TR % shows that un-oxidized polyphenols were available in tea and were oxidized during the extended post fermentation resulting in further production of TF and TR.

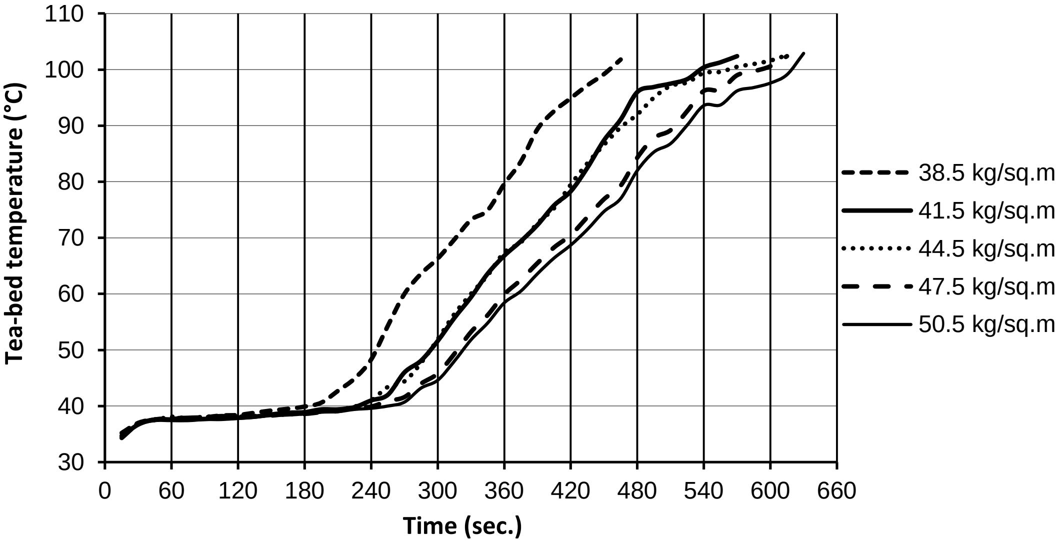


Figure 8.2: Variation of tea-bed temperature with time during drying at different loadings of tea

Colour and brightness of tea is related to TF % and TR % (Samaraweera and Mohamed, 2008). The increase in TF % and TR % at higher loadings might have increased the liquor colour at the expense of brightness (Table 8.1).

The individual tea samples have their own tea character with a combination effect of TF and TR percentages along with many other constituents such as un-oxidized polyphenols, caffeine, etc. This combination effect influences the preference of professional Tea Tasters and the tea samples get ranks depending on the combination effect. The results of the ranking given by Tea Tasters suggest that the infused leaf appearance suffered at higher loadings, while liquor colour and strength increased in general. Changes in the liquor quality of tea were marginal due to the combination effect of various constituents in tea. The professional Tea Tasters of the leading tea broking firms preferred the tea dried at loadings higher than the conventional loading. It is reflected by the higher values for overall quality. However, higher loading needed longer drying times to achieve the final moisture content as compared to that for the industrial norm of 38.5 kg/m^2. Table 8.1 indicates that increase in loading resulted in 22 % - 33 % increase in drying time. Therefore, the increase in loading must be in compromise with drying time and quality of tea.

Higher loadings caused the variation of both chemical and organoleptic properties as compared to the control samples. But, statistical analysis revealed that the variations are not significant at $p = 0.05$. This is mainly due to high standard deviation values observed in these experiments. However, it is interesting to note that even small variation in Tea Tasters' evaluations (as indicated by higher scores for organoleptic analysis) lead to significant variations in the prices.

8.2.2 Results of study on effect of hot air temperature on quality of made tea

The results of quality variations due to hot air temperature are given in Table 8.2. Initial moisture content in tea samples collected from the factory was almost the same and the final moisture content of dried tea samples were within the acceptable limit of 2.5 % – 3.0 % (w/w, dry basis). Results of chemical and organoleptic analysis are presented with mean ± standard deviation. TF % for control samples was found to be above 0.85 % which is more than the acceptable value of 0.75 % and is preferred by Tea Tasters as reported by Roberts and Smith (1963). TR:TF ratio for the control sample was found to be above 10.69:1 and is within the range of 10:1 to 15:1 for giving better liquor colour, brightness and strength as reported by Roberts (1986). Percentage change in TF %, TR %, TR:TF ratio and overall quality with the hot air temperature is given in Figure 8.3. An increasing trend is observed in both TF % and TR % with the reduction in hot air temperature. However, ranking given for the overall quality in organoleptic analysis does not follow the same trend. This confirms that the overall quality of tea is influenced by a combination effect of TF % and TR:TF ratio.

Table 8.2: Results of chemical analysis and organoleptic analysis for tea samples dried at different hot air temperatures

Parameters	Experiment 1		Experiment 2		Experiment 3		Experiment 4	
	124 °C	**127 °C**	**124 °C**	**121 °C**	**124 °C**	**118 °C**	**124 °C**	**115 °C**
Drying time (sec)	592.0±10.9	424.0 ±8.9	592.0±10.9	664.0±16.7	593.3±10.3	883.3±15.05	606.6±10.3	1075.0±10.48
Moisture content								
Initial (%, dry basis)	107.2±0.7	107.2±0.7	107.2±0.2	107.2±0.2	107.1±0.5	107.1±0.5	107.0±0.6	107.0±0.6
Final (%, dry basis)	2.8±0.2	2.9±0.2	2.9±0.2	2.8±0.2	2.8±0.2	3.0±0.1	2.9±0.1	2.8±0.2
Chemical Analysis								
TF (%)	0.90±0.05	0.89±0.06	0.89±0.05	0.92±0.03	0.87±0.04	0.96±0.08	0.85±0.02	0.97±0.06
TR (%)	9.61±0.34	9.49±0.18	9.64±0.32	10.02±0.11	9.86±0.27	12.16±0.52	9.61±0.42	12.98±0.68
Total Colour	2.69±0.24	2.61±0.15	2.53±0.08	2.54±0.04	2.61±0.26	2.99±0.12	2.49±0.16	2.98±0.11
Brightness	27.63±1.66	28.34±1.72	28.05±1.04	27.98±1.21	27.87±0.87	23.95±1.03	28.88±0.84	25.95±1.29
TR:TF	10.69±0.33	10.71±0.53	10.84±0.65	10.92±0.46	11.39±0.62	12.72±0.82	11.35±0.34	13.44±0.32
Organoleptic Analysis								
Infused leaf appearance	3.67±0.52	4.17±0.55	3.84±0.46	3.50±0.41	3.44±0.58	3.06±0.49	4.33±0.52	3.56±0.62
Liquor colour	4.00±0.30	3.94±0.33	3.89±0.27	4.50±0.55	3.56±0.66	3.78±0.69	3.89±0.40	4.09±0.44
Liquor strength	4.28±0.39	4.06±0.33	4.00±0.21	4.28±0.25	3.94±0.25	4.22±0.54	3.67±0.30	4.57±0.28
Liquor quality	5.33±0.56	5.22±0.34	5.17±0.28	5.06±0.39	5.50±0.51	5.44±0.34	5.17±0.62	5.06±0.80
Overall quality	17.28±0.65	17.39±0.83	16.94±0.95	17.33±0.67	16.44±1.42	16.49±1.37	17.06±0.04	17.5±0.75

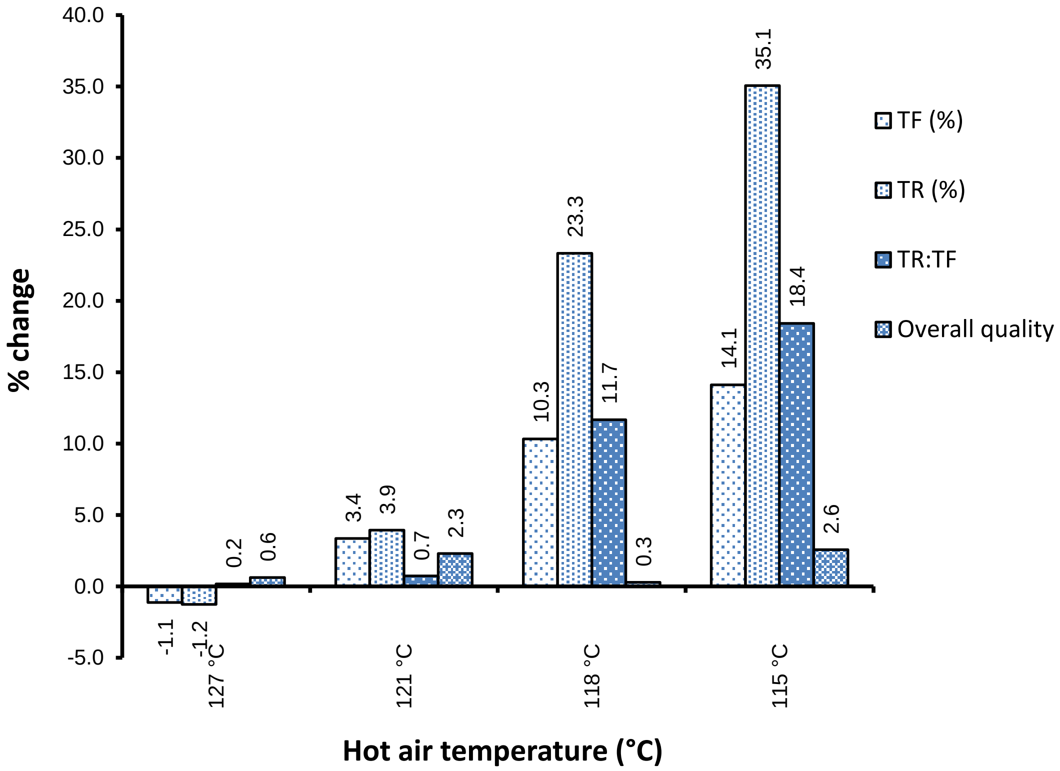


Figure 8.3: Variation of quality and sensory parameters with hot air temperatures

Figure 8.4 shows the variation of tea-bed temperature with time during drying at five different hot air temperatures. Tea attained the critical temperature of 54 °C (Agarwal, 1989) at which fermentation reactions are arrested about 48, 102 and 108 seconds later for hot air temperatures of 121 °C, 118 °C and 115 °C, respectively as compared to control sample dried at 124 °C. For the hot air temperature of 127 °C, the drying time was advanced by 90 seconds. The delay at lower temperatures would have resulted in extended post fermentation reactions leading to higher percentages of the TF and TR in tea as explained under 8.2.1. As expected, the increased percentages of TF and TR increased the liquor colour at the expense of brightness.

The results of Tea Tasters' evaluation suggest that the infused leaf appearance has decreased at lower hot air temperatures than the conventional of 124 °C. Both liquor colour and strength have increased but the liquor quality has suffered marginally. However, the overall quality which is a summation of the ranking given to all these parameters has increased.

Table 8.2 indicates that reduction in hot air temperature (121 °C, 118 °C and 115 °C) resulted in 12 % to 77 % increase in drying time. Hence drying at lower hot air temperatures than 124 °C must be in compromise with drying time and quality of tea. Further studies on energy savings with lower hot air temperatures needs to be done in the conventional continuous type fluid bed tea dryers in tea factories as a separate study. Another important parameter, blackness in tea must also be ensured when tea is dried at lower hot air temperatures in the industrial fluid bed dryers.

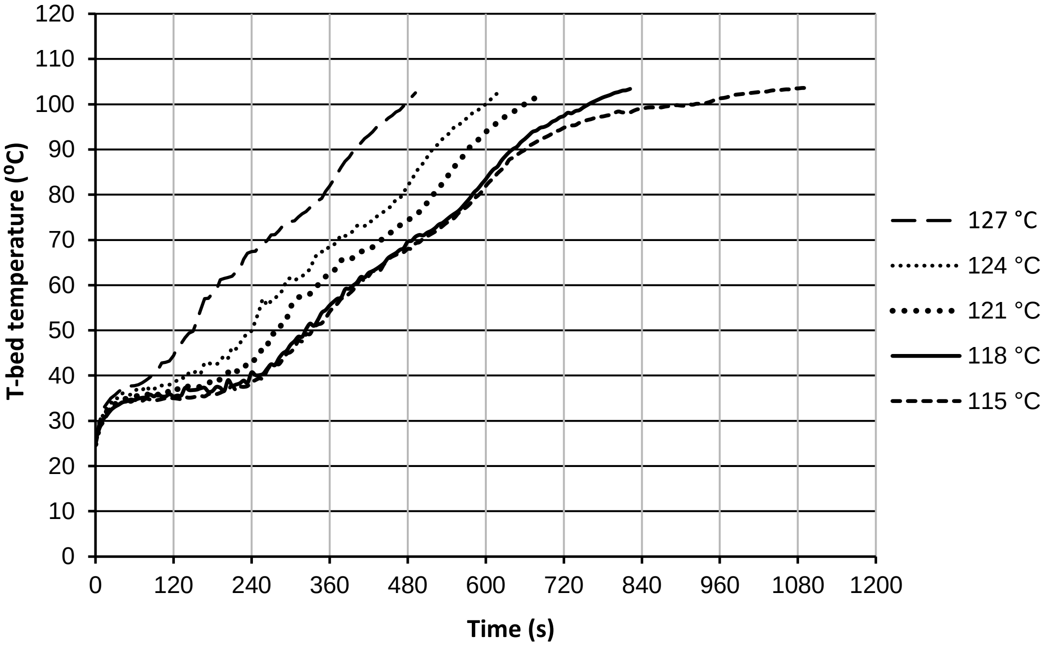


Figure 8.4: Variation of tea-bed temperature with time during drying tea at different hot air temperatures

It is interesting to note that one step higher hot air temperature of 127 °C than the conventional hot air temperature of 124 °C lead to marginal change in the overall quality. The drying time was reduced by about 28 %. However, drying at higher temperatures in industrial dryers may lead to over-drying of smaller tea particles due to difficulties in controlling the drying parameters such as tea-bed temperature at the discharge end. Therefore, further study is recommended to verify the benefits of using hot air temperature of 127 °C in industrial type fluid bed dryers.

Higher and lower hot air temperatures lead to vary both chemical and organoleptic properties as compared to the control samples. But, statistical analysis revealed that the variations are not significant at $p = 0.05$. This is mainly due to high standard deviation values observed in these experiments.

8.3 Conclusions

Percentage of TF and the ratio of TR:TF of orthodox broken type tea were found to be in the range of 0.85 - 0.90 % and 10.69 – 12.04 respectively under conventional loading of 38.5 kg/m^2 and temperature of 124 °C. Both TF % and TR % were found to increase considerably in the tea dried at higher loadings and with lower hot air temperatures than conventional. The TR:TF ratio was also increased at higher loadings as well as at lower hot air temperatures. The variations in chemical properties lead to different ranking in organoleptic analysis given by the professional Tea Tasters. Even though the variations were not significant (at $p = 0.05$) against control samples, Tea Tasters preferred the tea dried at higher loadings and lower hot air temperatures.

Increase in loading has resulted in the increase in drying time by 22 % - 33 % to achieve the final moisture content. The drying time was increased by 12 % - 77 % when the tea was dried at lower hot air temperatures of 121 °C, 118 °C and 115 °C. These results suggest that both of the factors, increasing the loading and decreasing the hot air temperature must be in compromise with the drying time and the quality of the tea. Drying with higher hot air temperature of 127 °C than the conventional hot air temperature of 124 °C, has reduced the drying time by 28 % but the increase in TF %, TR:TF ratio and overall quality was found to be only marginal.

9.0 CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

Main grades of Orthodox broken type tea produced in tea factories according to their particle sizes are Pekoe (1400 – 2000 µm), BOP (850 – 1400 µm), BOPF (500 – 850 µm) and Dust No.1 (355 – 500 µm). In the recent past, notable changes had been taken place in the tea manufacturing and more percentage of BOPF and Dust No.1 grades are produced at present to cater the demand. Conventional fluidized bed dryers fitted with bedplates having area percentage of 3.4 % are initially designed to dry teas with relatively large particle sizes. Therefore, the conventional fluid bed dryers were found to be ineffective in drying the present-day teas. Results of the present study on dry tea analysis suggested that bedplates having opening area less than 4 % are not suitable for fluidizing the orthodox broken type tea. Increase of area percentage gave better fluidization characteristics with coexistence of continuous phase and bubble phase and minimizing the entrainment and blowout. However, this could be done within practical limitations of opening area of 5 % and perforation size of 36 mm × 0.6 mm as upper limits.

A new correlation between Reynolds number at minimum fluidization (Re_{mf}) and Archimedes number (Ar), $Re_{mf} = 0.6972Ar^{0.3909}$ was proposed for drying orthodox broken type tea in a fluid bed dryer. The effect of shrinkage on the minimum fluidization velocity was accounted by proposing another new correlation, $ln(Ar) = 7.5110 + 4.1734\phi$ which describes the variation of Archimedes number (Ar) with the change in dimensionless moisture content (ϕ). These two correlations could be used to predict the minimum fluidization velocity for given moisture content of dhool. The results were validated for orthodox broken type tea, drying at 124 °C, in a fluid bed dryer having bedplate with opening area of 5 % and perforation size of 36 mm × 0.6 mm and with loading in the range of 44.5 kg/m^2 to 50.5 kg/m^2. The predicted fluidization velocity was found to be in good agreement with the experimental data and the difference was below 10 % for majority of the cases.

In industrial point of view, measurement of tea-bed temperature is practically easier than the measurement of moisture content at a given time. Hence, an empirical model, $\phi = 0.00684e^{186.7/T}$ relating the dimensionless moisture content (ϕ) to tea-bed temperature (T) was proposed to obtain the moisture ratio at different tea-bed temperature during drying at the hot air temperature of 124 ± 1 °C and in the loading range of 44.5 - 50.5 kg/m^2.

Drying characteristics of orthodox broken type tea produced at present is best described by Page thin-layer drying model, $MR = \exp(-k_o t^n)$. Effective diffusivity of water was found to be about 2.52 x 10^{-11} m^2/s at hot air temperatures within the range of 116– 127 °C. During the final stage of drying, it was found to vary between 2.660 x 10^{-11} and 2.782 x 10^{-11} m^2/s. The diffusivity constant and the activation energy for the diffusion of water in the orthodox broken type tea were found to be 1.3838 x 10^{-10} and 53.4 kJ/mol respectively.

Theaflavin % and the Thearubegin:Theaflavin ratio in orthodox broken type tea produced at present were found to be in the range of 0.85 - 0.90 % and 10.69 – 12.04 respectively. Theaflavin %, Thearubegin %, Therubegin:Theaflavin ratio and the overall liquor quality were found to increase in the tea dried at higher loadings as well as at lower hot air temperatures. Professional Tea Tasters preferred the tea dried at higher loadings as well as the tea dried at lower hot air temperatures. Increase in loading has resulted in increasing the drying time by 22 % - 33 %. Drying at lower hot air temperatures of 121 °C, 118 °C and 115 °C resulted in increasing the drying time by 12 % - 77 %. Increasing the loading and decreasing the hot air temperature must be in compromise with the drying time and the quality of the tea. Drying tea at higher hot air temperature of 127 °C reduced the drying time by 28 % but only with a marginal changes in Theaflavin %, Thearubegin %, Therubegin:Theaflavin ratio and the overall quality.

9.2 Recommendations

The conventional fluid bed tea dryer, TRI-CCC FBD could be incorporated with identified bedplate having opening area of 5 % and perforation size of 36 mm × 0.6 mm for drying Orthodox broken type tea produced at present. With the improvement of fluidization, dryer operating parameters such as hot air temperature, loading of dhool, weir plate height and tea-bed temperature at the discharge end could be studied and revised.

A data acquisition and control system could be developed and incorporated into the dryer to regulate the dryer operating parameters. The models developed in this study could be incorporated into the control system for further improvement of drying tea as detailed below.

1. Tea-bed temperature (T) could be monitored at regular distance in the drying section and using the empirical model, $\phi = 0.00684e^{186.7/T}$, the dimensionless moisture content (ϕ) could be predicted at different drying stages along the dryer.
2. Using the empirical model, $\phi = 0.00684e^{186.7/T}$, the correlation, $ln(Ar) = 7.5110 + 4.1734\phi$, $Re_{mf} = 0.6972Ar^{0.3909}$ and the equation, $Re_{mf} = \frac{\rho_g u_{mf} d_p}{\mu}$, minimum fluidization velocity could be predicted at different drying stages along the dryer. The most commonly used fluid bed dryer has four drying sections. The drying sections could be further divided and fluidizing velocity could be adjusted in each section more effectively.
3. The identified thin layer drying model ("Page"), $MR = \exp(-k_o t^n)$ could be used to study the drying of tea in the continuous fluid bed dryer.

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Appendix A – Schematic diagram of TRI-CCC FBD

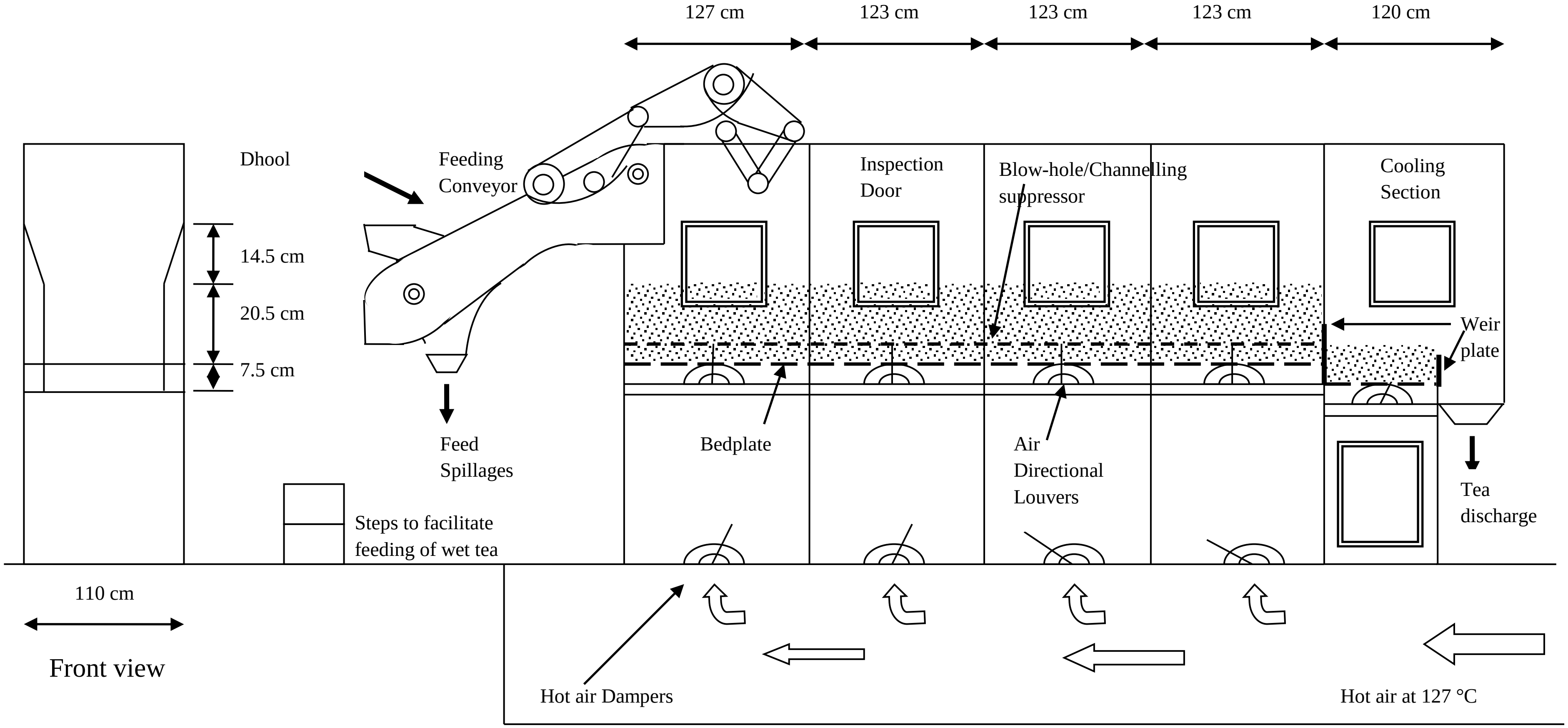

Figure A1: Schematic Diagram of TRI-CCC FBD

Appendix B

Specifications of Power Controller

Power/(current ratings): 27kW (38A) @ a typical supply of 415V RMS

Input voltage: 400V RMS +/- 10%

Frequency: 50/60Hz

Control input options: Signal: (using SW4**):** 0 to 10V dc (set as standard) / 0 to 5V OR **Manual:** using 5K Potentiometer

Alarms relay circuit rating: 2A @ 125V ac Max.

Fan 'switch-on' Temp.: Typically 55 ºC

Status indicator: (Tracking control signal) LED indicator changes intensity

Over temperature: Trip in temperature @ 90 ºC, +/- 1 ºC (LED indicator 'flashes' continuous fast pulsing), Trip out temperature @ 85 ºC, +/- 1 ºC

SW1 = OFF - Relay is continuously energized (normally closed); trips in fault condition.

SW1 = ON - Relay is de-energized (normally open); closes in fault condition.

Phase loss detection: LED indicator 'flashes' continuous slow pulsing.

Sensor loss detection: LED indicator 'flashes' on/off fast pulsing.

Cable terminations: Phase power - 10mm² rising clamp terminal block

Earth - 10mm² rising clamp terminal block

Remote supply Auxiliary alarm (relay) 2.5mm² rising clamp terminal block

Control signal - 2.5 mm² rising clamp terminal block

Terminal torque settings: 1.2 Nm (10 mm²) Power terminals only.

Fusing: 40A High-Speed Semiconductor type, ferrule fuse (14 mm ø x 51 mm long)

Working temperature: 65 °C (maximum operational)

Dimensions: 150 mm (D) x 240 mm (W) x 100 mm (H)

Fixing centres: 4 x 5.5 mm ø holes on centres 220 mm (W) x 130 mm (D)

Weight: 2.6 kg

Appendix C

Table C1: Specifications of PID Temperature controller

Type	Temperature PID
Digits	4
Allowable Voltage Range	90 ~ 110% of power supply
Power Consumption	5 VA
Display Method	7 Segment LED Display [Process value (PV) : Red, Setting value (SV) : Green]
Character Size	PV: W7.8 x H11 mm
	SV: W5.8 x H8 mm
Thermocouple Input	E (CR)
	J (IC)
	K (CA)
	N (NN)
	R (PR)
	S (PR)
	T (CC)
	W (TT)
RTD Input	Pt 100Ω
	JIS Pt 100Ω
Analog Input	0 - 10 VDC
	1 - 5 VDC
	4-20 mADC
Output	12 VDC ±3 V 30 mA Max. SSR
	250 VAC 3 A 1c Relay
	4 - 20 mA DC Load 600Ω Max. Current
Control Type	ON/OFF, P, PI, PD, PIDF, PIDS control
Display Accuracy	3 °C (Higher one)
	F•S ±0.3%
Sampling Time	0.5 sec
LBA Setting Time	1 ~ 999 sec
RAMP Setting Time	Ramp Down at 1 ~ 99 min.
	Ramp UP
PID Controller	Nema 4 Digital
Voltage	100-240 VAC
Dimensions	DIN W48 x H48mm (Terminal Type)
Power Supply	100 - 240 VAC
Control Output	Relay
Sub Output	Event 1

Appendix D

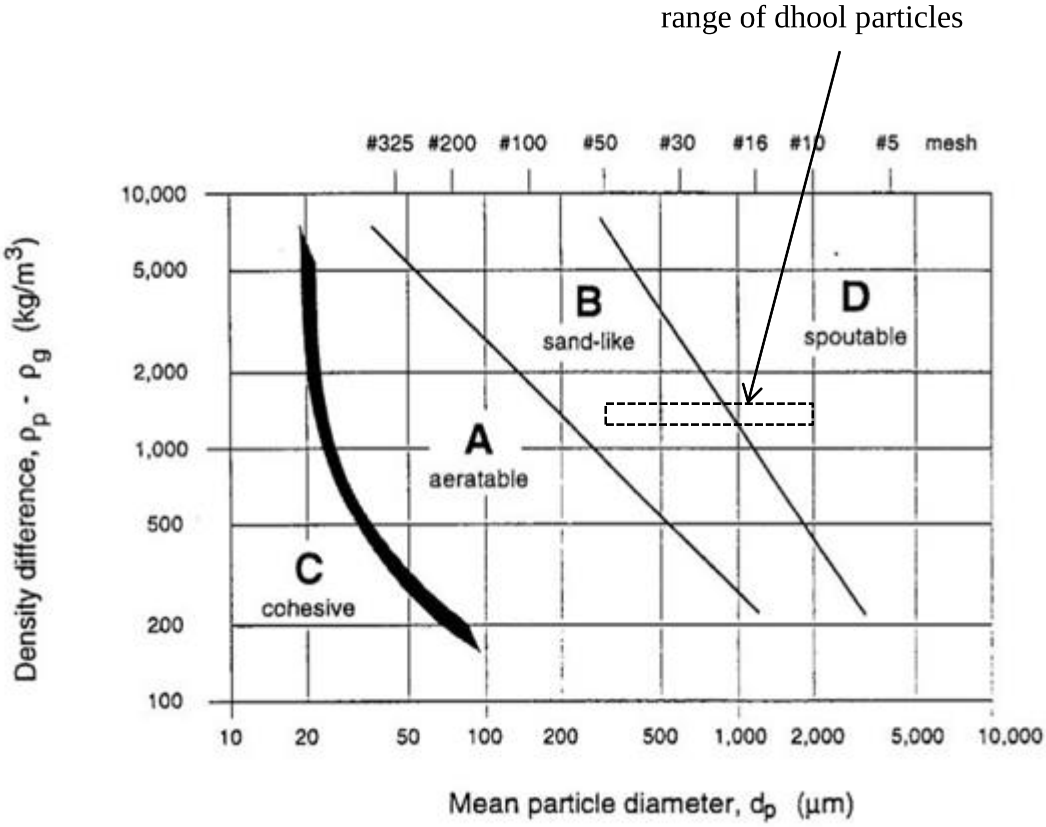

Figure D1: Mean particle sizes in Geldart groups (Richardson et al., 2002)

Appendix E

Table E1: Variation of jet velocity with time for drying dhool on bedplates at different loadings.

Bedplate	**No.2**	**No.3**	**No.3**	**No.5**	**No.5**	**No.6**	**No.6**	**No.6**
Perforation size (mm x mm)	36 x 0.5	36 x 0.5	36 x 0.5	36 x 0.6	36 x 0.6	36 x 0.6	36 x 0.6	36 x 0.6
Number of perforations/ m^2	2,177	2,748	2,748	1,820	1,820	2,266	2,266	2,266
Opening area (%)	4	5	5	4	4	5	5	5
Loading (kgm^{-2})	38.5	41.5	44.5	38.5	41.5	44.5	47.5	50.5
Time	**Jet velocity (ms^{-1})**							
0	33.8	26.5	24.1	38.5	42.4	29.6	29.6	32.8
30	33.8	25.8	22.7	38.4	42.2	28.8	28.8	32.6
60	33.3	25.5	22.0	38.4	40.8	28.8	27.9	30.4
90	32.9	25.5	21.6	37.2	40.9	28.3	27.1	28.3
120	32.9	25.1	21.3	36.6	40.9	27.9	26.6	26.6
150	32.0	24.4	21.3	36.0	40.3	27.1	26.2	26.2
180	32.0	24.1	21.3	34.7	39.7	26.6	26.2	24.9
210	31.6	23.7	20.9	34.7	39.1	26.2	25.4	24.5
240	31.1	23.4	20.6	34.1	38.4	26.2	24.9	24.5
270	31.1	23.0	20.2	32.9	38.4	26.2	24.5	24.5
300	30.7	23.0	19.9	32.9	38.4	26.2	24.5	24.1
330	30.2	22.7	19.5	32.2	38.1	25.4	24.1	23.7
360	29.8	22.3	19.5	32.2	37.5	24.9	24.1	23.3
390	29.4	22.0	19.5	31.6	37.5	24.5	24.1	23.3
420	28.9	22.0	19.2	31.0	37.8	24.1	23.7	22.4
450	28.5	22.0	18.8	31.0	37.8	24.1	23.3	22.8
480	28.5	22.0	18.8	31.0	38.4	24.1	22.8	22.4
510	28.1	22.0	18.5	30.4	37.8	23.7	22.4	22.4
540	27.6	21.6	18.5	30.4	37.8	23.7	22.4	22.0
570	27.6	21.6	18.5	30.4	37.2	23.7	22.0	22.0
600	27.2	21.6	18.1	30.4	37.2	23.7	21.6	21.6
630	27.2	21.6	18.1	29.8	36.6	23.7	21.6	21.6
660	26.3	21.3	17.8	29.8	36.6	23.7	21.6	20.7
690	26.3	21.3	17.8	29.8	36.0	23.7	21.6	20.7
720	26.3	21.3	17.4	29.1	36.0	23.7	21.6	20.3

750	25.9	20.9	17.1	29.1	34.7	23.3	21.6	20.3
780	25.4	20.6	16.4	29.1	34.7	22.8	21.1	19.9
810	25.4	20.6	16.0	29.1	34.7	22.8	21.1	19.9
840	25.4	20.2	16.4	28.5	34.7	22.4	20.7	19.9
870	25.0	20.2	16.0	28.5	34.7	22.4	20.7	19.9
900	25.0	19.5	16.0	28.5	34.1	22.0	20.3	19.9
930	25.0	19.5	16.0	27.9	34.1	22.0	20.3	19.5
960	24.5	19.5	16.0	27.9	32.9	21.6	20.3	19.5
990	24.5	19.2	15.7	27.9		21.6	20.3	19.5
1020	24.5	19.2	15.7	27.9		21.1	19.9	19.5
1050	24.1	19.2	15.7	27.9		21.1	19.9	19.0
1080			15.7	27.3		20.7	19.9	19.0
1110			15.4	27.3		20.7	19.9	19.0
1140			15.4	27.3		20.7	19.9	19.0
1170			15.0	26.7			19.9	18.2
1200			14.7	26.0			19.9	18.2
1230			14.7	26.0			19.5	17.8
1260							19.5	18.2
1290							19.5	18.2
1320							19.5	