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Performance of an Improved Fluidized System for Processing Green Tea

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Abstract**—**Green tea is made from the top two leaves and buds of a shrub, *Camellia sinensis*, of the family Theaceae and the order Theales. The green tea leaves are picked and immediately sent to be dried or steamed to prevent fermentation. Fluid bed drying technique is a common drying method used in drying green tea because of its ease in design and construction and fluidization of fine tea particles. Major problems in this method are significant loss of chemical content of the leaf and green appearance of tea, retention of high moisture content in the leaves and bed channeling and defluidization. The energy associated with the drying technology has been shown to be a vital factor in determining the quality of green tea. As part of the implementation, prototype dryer was built that facilitated sequence of operations involving steaming, cooling, pre-drying and final drying. The major findings of the project were in terms of quality characteristics of tea leaves and energy consumption during processing. The optimal design achieved a moisture content of 4.2 ± 0.84%. With the optimum drying temperature of 100 ºC, the specific energy consumption was 1697.8 $kj.Kg^{-1}$ and evaporation rate of 4.272×10^{-4} $Kg.m^{-2}.s^{-1}$. The energy consumption in a fluidized system can be further reduced by focusing on energy saving designs.

Keywords**—**Evaporation rate, fluid bed dryer, maceration, specific energy consumption.

I. INTRODUCTION

TEA as a beverage is of great importance to humans. Tea consumption has a long history of over 2,000 years. Originated in China, drinking tea as a habit of daily life has spread all over the world. Currently, tea is one of the most popular beverages globally. Green tea as opposed to other types such as black tea has unique medicinal characteristics making it popular in the recent times. In China and Japan, medicinal value of green tea outweighs other uses [1]. According to [1], health benefits of green tea have been known for many years, with recent research findings showing that it can prevent cancer, reduce the growth of tumor and inhibit nitrosomine formation. Green tea catechin has been established to limit excessive rise in blood cholesterol and prevent high blood pressure. Also, laboratory tests have verified that catechin can inhibit the activity of the AIDS virus [2]. According to the report of [3], more evidences of the potential health benefits of the green tea have boosted outputs among the three major green tea producers: China, Japan and India. In 2013 total tea production rose significantly by 6% to 5.07 million tones. Black tea and green tea output increased by 5.4% and 5.1% respectively because of steady prices in the market. The report [3] further indicated that India was responsible for 29.0 percent of world tea output in 2012, followed by China with 27.5 percent. Most Japanese green tea was consumed locally with only 5% exported.

Processing of green tea involves four steps: Steaming, shaping, drying and post-processing. Drying is an important sub-process as it reduces the bulk moisture content of steamed tea to an acceptable level for storage. Fluid bed drying is most commonly used for drying CTC tea because its gentleness and uniformity. The method is capable of drying materials to low moisture content with a high degree of efficiency. This process is characterized by high moisture and heat transfer rates and excellent thermal control capacity compared to other drying process [4]. It is also a very convenient method for drying heat sensitive food materials as it prevents them from overheating due to mixing [5]. Despite its popularity, bed channeling and defluidization have been some of the major setback to its performance especially for high moisture content product like steamed green tea. Bed channeling and defluidization leads to uneven drying, stewing and prolonged resident time. A study was carried out by [6] on vibration effect on particle bed aerodynamic behavior in black tea and recommended the use of vibration system to increase fluidization and reduce channeling characteristics. Vibratory system could be in form of reciprocator, oscillatory or rotary. The advantage of the latter is the additional centrifugal forces with reduced minimum fluidization [7]. The main objective of this study was to develop an improved fluidized dryer based on the recommendations by [6] and analyzed its performance based on the energy consumption.

II. METHODOLOGY

A. Improved Prototype Dyer

According to [8], the prototype dryer consisted of a shaft which connected a meshed cylindrical agitator barrel to driving motor. The stainless steel barrel with 1 mm mesh openings measured as 300 mm and 500 mm in diameter and length respectively. The barrel which acted as a drying chamber was mounted horizontally on vertical metal frames and could rotate around its axis of symmetry inside an enclosed plenum chamber. The cylindrical metal pipe shaft which rotated the barrel measured 40 mm and l500 mm in

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diameter and length. Pressure and temperature taps were mounted on the hot air inlet and exit and also in the inner part of the barrel so as to measure the temperature and pressure across the barrel bed. The dryer configuration arrangement appeared as in Fig. 2.

B. Pre-Drying Processes

Before drying, steaming was carried out under optimum conditions of temperature 100 ˚C, pressure 0.5 bar and barrel rotation 31.40 rad/s as recommended by [9]. Cooling was the next step. It was done to room temperature of 21 ˚C through an average duration of 300 seconds according to [10]. The cooling was meant to stabilize the leaf temperature and chemical compounds in the leaves and stop losses of fresh aroma and color. A short period physical withering then followed. [11] Recommended 15 minutes physical withering at a temperature of at least 60 °C in order to achieve appropriate moisture content of tea leaf to be macerated. According to [12], maceration machines operate most effectively within a narrow green-leaf moisture range of 68 to 72% wet basis. It is thought that excessive moisture in the green leaf will clog both the rotorvane and CTC rollers [13]. The orthodox method utilizes leaves at 60 to 66% [12]. The physical goal of predrying is to reduce the moisture content in the leaf, making the leaf flaccid and pliable, which prepares the leaf for shaping and rolling. It also helps to reduce the possibility of clumping, reduce the time period of drying and reduce energy consumption. This process enhanced moisture removal of macerated leaves in the subsequent drying stage. The maceration process was performed using a pair of CTC rollers. The slow and high speed rollers meshed through helical grooves where reduced leaves pass through.

C. Drying Process

1. Variation of Airflow, Agitation Rate and Temperature with Moisture Content

Three experiments were conducted to investigate the impact of air flow, leaf agitation and temperature on the moisture content. Moisture content measurements of the samples were taken with a Mettler-Toledo-HR83 device with a resolution of 0.01%. Samples of macerated predried green tea samples were introduced into the rotary drying chamber through the barrel opening and the closing flap was closed tightly. A suitable rotating speed of the barrel was preselected in the inverters. The initial moisture content for the three tests was obtained from the predried products at 69.78% wet basis. In the first test, the samples were dried at varying air flow between 0.041 to 0.167 m^3/s through increments of 0.014 m^3/s with a temperature of 80 ºC under a static barrel. In the second test, drying was done for 1200 seconds in equal intervals of 300s with a temperature of 80 ºC under barrel rotation between 6.28 and 31.4 rads/s and air flow of 0.167 m^3/s. While in the third test, temperature was varied between 20 to 100ºC against moisture content with an air flow of 0.167 m^3/s and agitation rate of 12.56 rad/s. The flow of air into the drying chamber assumed the configuration, presented in Fig. 2.

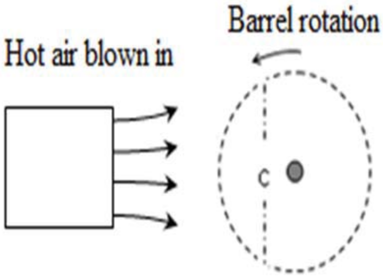

Fig. 1 Flow of air into the drying chamber [8]

2. Variation of Airflow with Pressure Drop

The pressure measurements were taken with a digital hot-wire anemometer. Pressure taps were mounted on the inlet and exhaust air ducts and inside the barrel, so that the manometers (1) and (2) measured the pressure drop across the green tea dhool bed and barrel, while manometer (3) measured pressure drop across the barrel during idling without samples or at the air exit (Fig. 2). The change in pressure at different points in the dryer system was monitored for air velocities that ranged between 0.05 and 0.4m/s at intervals of 0.05m/s. For verification, change in pressure was also monitored for different agitation rates of drying chamber: 2, 2.5 and 3 Hz.

The pressure drop across the green tea dhool bed, ΔP, was determined as the difference between the two pressures P_1 and P_3 in Fig. 2.

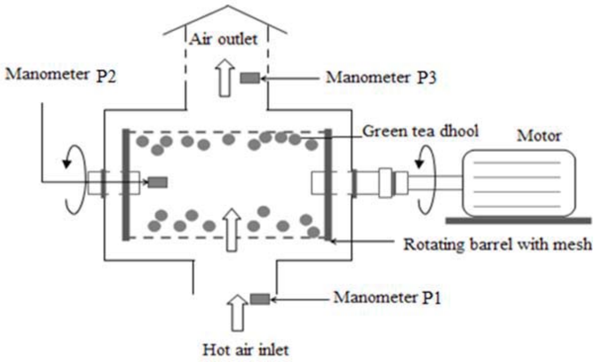

Fig. 2 Airflow direction and pressure tap

3. Variation of fluidization velocity with agitation rate

An experimental study was carried out to establish the relationship between barrel rotation and fluidization during drying. The drying temperature was fixed at 80 ºC. The frequency of barrel rotation was preset at a range of between 0 to 3.4 Hz with intervals of 0.4 Hz. For every frequency, airflow was varied between 0.0m/s and 0.45 m/s with an interval of 0.05 m/s and pressure drop readings were recorded. The air velocity corresponding to the maximum pressure drop was identified to be minimum fluidization velocity as revealed by [7]. The correlation of barrel rotation and minimum fluidization was then established.

4. Specific Energy Consumption and Evaporation Rate

The evaporation rate and the specific energy consumption were calculated to evaluate the thermal performance of drying operation according to [6]. The green tea samples were prepared as indicated in the sample preparation stage. The first step was to perform steaming as recommended by [9]. Predrying and/or drying process was done for a predetermined period as previously established. During the drying process, the inlet temperature of the dryer set to values of 80, 100, and 150 ^{o}C as the exit temperature and drying time were monitored. Applying (1) and (2), the SEC and ER for the dryer were determined. This analysis was used to determine the drying capacity of the dryer.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Results for Variation of Airflow, Agitation Rate and Temperature with Moisture Content

A tabulated summary of the results corresponds to an agitation rate of 6.28 rad/sec. The tabulation, shown in Table I, reveals expected behavior of lower moisture content with longer drying times and higher air flowrates.

TABLE I
MOISTURE CONTENT IN A BARREL AGITATED AT 6.28 RAD/SEC

Air flow (m^3/s)	Drying time *(seconds)*/Moisture content *(%)*			
	600	*1200*	*1800*	*2400*
0.041	69.78±1.08	60.34±0.67	52.9±0.45	40.73±0.50
0.055	68.79±1.18	58.01±0.27	50.63±0.47	38.52±1.14
0.069	67.91±0.45	53.96±0.15	48.79±0.77	36.21±0.58
0.083	66.47±0.83	52.25±0.58	46.24±0.87	33.71±1.12
0.097	65.13±1.56	49.85±0.24	37.06±0.25	24.45±0.29
0.111	63.75±1.49	48.38±0.27	32.21±0.67	20.86±0.60
0.125	60.09±1.72	42.12±0.43	23.35±0.48	15.44±0.68
0.139	58.29±0.42	41.03±0.24	20.49±0.47	11.68±0.50
0.153	56.78±0.95	38.24±0.55	18.65±2.11	5.02±1.41
0.167	53.05±0.84	35.98±0.75	13.92±0.64	3.77±0.39

In the first test, the impact of airflow on the moisture content of green tea was monitored under an agitation rate of 12.56 rad/s and a temperature of 80 ˚C. The results showed that at low air speed much of the heat was concentrated on the heating source and little was conveyed to the drying chamber, hence the rate of drying was low. However, when the speed of air was increased there was a lot of turbulence which led to instability in the dryer bed and insufficient drying. But because of high intensity of air, the remaining samples dried at a faster rate. Also noted was that high air flow rates (0.167 m^3/s) led to cooling effect which lowered that rate of drying. The desired drying temperature was fixed at 80 °C using control switches while the average exhaust temperate was 45 ˚C. In Table I, it was observed that the resident time of drying was inversely proportional to the rate of drying. The lowest and highest rates of drying were observed at 600 and 2400 seconds respectively. From these results the drying duration of 2400 seconds was observed to yield the lowest moisture content of 3.77±0.39% which falls within the accepted range of 3-5%.

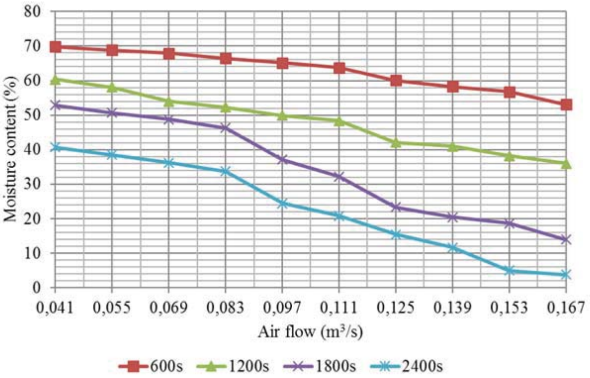

Fig. 3 Variation of airflow and moisture content during drying

A second test was meant to establish the correlation between speed of the barrel (agitation rate) and moisture content. The drying conditions corresponded to a constant air flow of 0.167 m^3/s and an air temperature of 80 ˚C. The results of the test showed that lower speed of the barrel enhanced the drying rate of green tea samples. However, it was established that the bottom layer dried faster than the top layer as the former received the hottest incoming air. High rotation rates prohibited enough drying air to go through the mesh and slowed down the drying rate. In Table II, although the accepted range (2-5%) of moisture content was achieved after 1200 seconds, the optimum taken was 2.56±0.45 and 3.77±0.11% with equivalent agitation rate of 12.56 and 18.84 rads/s respectively.

TABLE II
VARIATION OF BARREL ROTATION AND MOISTURE CONTENT UNDER 0.167M^3/S AIR FLOW

Agitation (rads/s)	Drying time *(seconds)*/Moisture content *(%)*			
	300	*600*	*900*	*1200*
6.28	51.00±3.38	32.13±1.86	10.07±0.18	2.05±0.05
12.56	51.38±0.36	34.42±0.76	11.36±0.56	2.56±0.45
18.84	53.05±0.56	35.98±0.99	13.92±1.04	3.77±0.11
25.12	54.45±0.55	37.40±0.86	16.17±1.03	4.19±0.38
31.4	56.78±0.41	38.24±1.87	18.65±0.14	5.02±0.25

The third test was carried out to study variation of temperature with moisture content under barrel agitation rate of 12.56 rad/s and airflow of 0.167 m^3/s. The results obtained within the preset period of 1200 seconds were displayed in Table III and Fig. 4. It was observed that the rate of moisture loss during drying was higher in the prototype dryer compared to the conventional FBD. The highest rate of evaporation occurred between the temperatures of 40 ºC and 80 °C. The reason attributed to this was that the initial moisture content of green tea dhool was at a process condition where moisture was loosely attached on the material surface due to the first sub-process of predrying. This enhanced transfer of sensible heat to the product which enabled the subsequent drying stages to take place faster. The temperature which gave the accepted moisture content of 2-5% was between 80 °C and 100 ºC.

TABLE III
VARIATION OF TEMPERATURE AND MOISTURE CONTENT IN THE PROTOTYPE DRYER

Temperature, °C	Moisture content, (wb) *(%)*
20	69.81±0.13
30	67.64±1.46
40	60.20±1.05
50	45.69±1.83
60	26.51±0.64
70	12.03±0.68
80	5.78±1.21
90	3.42±0.31
100	2.11±0.20

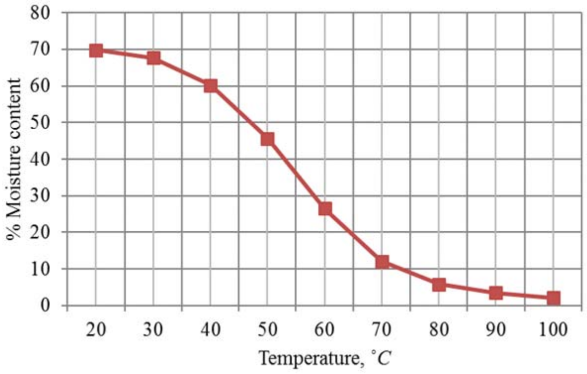

Fig. 4 Variation of temperature and moisture content with 12.56rads/s agitation

B. Results for Airflow versus Pressure Drop

Table IV and Fig. 5 show the pressure drop plotted against airflow velocity under different rotating conditions. The pressure drop increased with increasing air velocity. Increasing the air velocity further increased the drag force exerted on the tea particles, which could break the adhesive forces between the particles, hence bringing them to the fluidized state. The pressure drop increased to a peak at minimum fluidization velocity and then showed a constant pressure drop regardless of a further increase in air velocity. At all rotational speeds, the pressure drop did not show a linear increase before reaching the minimum fluidization velocity. This was attributed to compression due to the high centrifugal force and formation green tea dhool into clustered balls. Thus, a higher-pressure drop through the dhool bed was recorded until all the tea particles uniformly fluidized at the minimum fluidization velocity.

C. Results for Fluidization Velocity versus Barrel Rotation

Fig. 6 shows the relationship between the minimum fluidization velocity and the rotational speed. The minimum fluidization velocity increased approximately linearly with rotational speed as provided by [7]. It was observed that particles contacting the cylinder wall experienced a direct centrifugal force, whereas other particles away from the wall also transmitted the centrifugal force due to particle collisions and slip. The results in Table V and Fig. 6 showed the behavior of cohesive fine dhool in the rotating fluidized bed suggested that the adhesion force between fine tea particles was negligible under a high centrifugal force.

TABLE IV
AVERAGE PRESSURE DROP AGAINST AIR FLOW VELOCITY IN THE DUCT

Air flow velocity (m/s)	Rotational speed (Hz) and Pressure drop (N/m^2)		
	3hz	2.5hz	2.0hz
0.05	1150.04±35.04	806.86±07.45	599.77±05.30
0.1	1499.83±50.98	900.28±05.11	749.97±69.78
0.15	1599.95±19.44	1025.22±27.89	800.05±09.91
0.2	1799.98±70.32	1300.28±09.21	949.97±70.29
0.25	2350.05±100.15	1401.67±40.72	946.74±75.53
0.3	2500.18±35.42	1499.93±13.07	1029.98±58.23
0.35	2499.66±26.06	1500.26±13.98	999.95±30.35
0.4	2501.89±24.39	1499.85±95.14	998.89±73.89

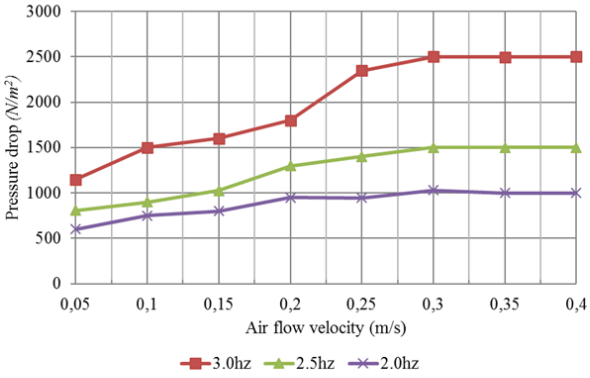

Fig. 5 Pressure drop against airflow velocity (N/m^2)

TABLE V
SAMPLED DATA FOR MINIMUM FLUIDIZATION AGAINST ROTATIONAL SPEED

Frequency, f *(hz)*	Angular velocity, ω *(rads/s)*	Minimum fluidization velocity *(m/s)*
0.0	0.0	0±0.00
1.4	8.8	0.07±0.07
1.8	11.6	0.13±0.13
2.2	14.1	0.23±0.23
2.6	16.3	0.28±0.28
3.0	18.8	0.34±0.34
3.4	21.3	0.43±0.44

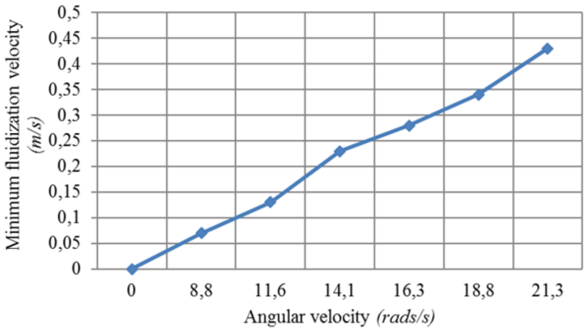

Fig. 6 Minimum fluidization and angular velocity

D. Results for Specific Energy Consumption and Evaporation Rate

The evaporation rate and the specific energy consumption were calculated to evaluate the thermal performance of drying operation according to [6].

The energy consumption of each dryer was determined using (1) and (2)

$$\mathrm{SEC} = \frac{\dot{\mathrm{V}}\cdot\rho\cdot(\mathrm{C_a}+\mathrm{C_v h_a})(\mathrm{T_{inlet}}-\mathrm{T_{exit}})\mathrm{t}}{\mathrm{V_h}\times\mathrm{M_v}} \quad (1)$$

ER was done to establish evaporating capacity of the conventional fluid bed dryer and the prototype dryer. The calculation was done according to [6].

$$\text{Evaporation Rate, ER} = \frac{\text{Evaporated moisture mass (Kg)}}{\text{Drying chamber area}(\mathrm{m}^2)\times\text{drying time(s)}} \quad (2)$$

A summary showing variation of temperature with Specific Energy Consumption and Evaporation Rate has been done in Table VI.

TABLE VI
TEMPERATURE VERSUS SPECIFIC ENERGY CONSUMPTION AND EVAPORATION RATE

Dryer type	Initial Temperature, ºC	Final temperature, ºC	Drying time (s)	*ER* 10^{-4}(kgm^{-2}s^{-1})	*SEC* (kJ kg^{-1})
Conventional FBD	80	58	2280	4.105	2,755.5
	100	70	1800	5.200	2,966.5
	120	95	1200	7.800	1,648.0
Prototype Dryer	80	60	900	7.578	1,441.7
	100	78	720	9.472	1,268.7
	120	90	480	14.208	1,153.3

The results obtained in the experiment and calculations showed that drying at 120 ºC using the prototype presented lower specific energy of 1,153.3 kJkg^{-1}compared to conventional FBD with 1,648.0 kJkg^{-1}. In addition, the prototype presented the highest drying capacity through Evaporating Rate of $14.208 \times 10^{-4}\mathrm{kgm^{-2}s^{-1}}$ against $7.800 \times 10^{-4}\mathrm{kgm^{-2}s^{-1}}$ for FBD. These revealed the importance drying green tea in a rotating chamber. In rotating chamber green tea particles received mechanical agitation which helped in enhancing the rate of drying through breaking of adhesive forces between the particles. Also the rotary motion in the prototype introduced centrifugal forces helped in fast attainment of minimum fluidization. In addition, the vibration effect carried out by [6] on particle bed aerodynamic behavior showed that the highest evaporation rate and the lowest specific energy consumption were $10.031 \times 10^{-3}\mathrm{kgm^{-2}s^{-1}}$ and $4953.79\mathrm{kJ\,kg^{-1}}$ respectively. These results showed that the prototype was more improved in terms of energy consumption. The energy consumptions translated to $1203.1\mathrm{kJ/Kg_{made\ tea}}$ and drying cost Ksh44.01 per hour for FBD and $823.03\mathrm{kJ/Kg_{made\ tea}}$ and drying cost Ksh44.88 per hour for prototype dryer.

IV. CONCLUSION AND RECOMMENDATION

The use of prototype dryer led to improved removal rate of moisture content because of predrying process and rotary mode agitation. In addition, it was economical to dry green tea using the prototype dryer as evident in the reduced energy consumption. The prototype's Specific Energy Consumption was lower than for conventional fluid bed dryer in all the drying temperatures tested. For the temperatures of 80°C, 100 °C and 120 °C the SEC in kJ kg^{-1} were 1441.7, 1268.7 and 1,153.3 against 2755.5, 2966.5, 1648.0 respectively. The reduced energy consumption was also evident in prototype because the rotating fluidized bed operated near the minimum fluidization velocity (less than 3 times the minimum fluidization velocity), whereas a conventional fluidized bed operated at a velocity more than 5-10 times the minimum fluidization velocity, especially in wet drying of tea, to avoid blocking. Basing on Evaporation Rate obtained from three drying temperatures, the drying capacity for the prototype was higher than for conventional Fluid bed dryer. This was attributed to improved contact efficiency between the particles and drying air which led to enhanced moisture evaporating rate and reduced drying time.

The prototype dryer uniformly and efficiently fluidized green tea particles than conventional fluidized beds. Unlike conventional fluidized beds, the prototype dryer imparted high centrifugal forces which enabled fine particles of tea to behave like dusty powder and hence fluidized. Micro-granulation featured in the green tea drying. Micro-granulation occurred when fine green tea dhool formed into round shaped granules with improved chemical and physical quality. This feature was achieved through balanced forces on the tea samples due to airflow (drag force and buoyancy) and the centrifugal forces.

ACRONYMS AND ABBREVIATIONS

C_{pa}	Specific heat capacity of dry air*(kJ/kgºC)*
C_{pv}	Specific heat capacity of vapor (*kJ/kgºC)*
H_a	Absolute humidity *(kg$_{vapor}$/kg$_{dry\ air}$)*
T_d	Dry bulb (*ºC)*
T_w	Wet bulb (*ºC)*
ω	Relative Humidity *(%)*
V_h	Specific volume of the air *(m^{3}kg$_{dry\ air}^{-1}$)*
ρ_a	Density of air *(kg/m^3)*
M_v	Evaporated moisture mass *(kg)*
CTC	Cutting Tearing & Curling
ER	Evaporation Rate
FBD	Fluid Bed Dryer
SEC	Specific energy consumption

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