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Development of a Mathematically Controlled System for Electrical Energy Saving in Trough Withering of Tea

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ABSTRACT

A control system was developed for optimizing the electrical energy consumption in tea withering. The electrical energy saving was achieved by controlling the speed of the fan through variable speed drive coupled with fan motor and controlling hot and ambient air delivering into the trough. The fan speed was determined based on theoretical mass flow rate requirement of air, calculated by the mathematical model developed for simulating the withering process, while calculating the thermodynamic properties of withering air and the moisture content of tea leaves in real time. A single board computer, Raspberry Pi 3 model B was used to run the mathematical model and the software programme to actuate the VSD for controlling the mass flow rate of air delivered by withering fan as well as to control the withering air temperature. The experiments were conducted and electrical energy consumption of the fan and the quality parameters of the manufactured tea were measured and compared in the withering process with and without the control system. The results showed that the energy consumption was in the range of 36 to 39 kWh with the control system while it was in the range of 55 to 67 kWh in without control system. The specific electricity consumption was 0.17 to 0.18 kWh.kg-1 of made tea with control system and it was 0.27 to 0.35 kWh.kg-1 of made tea in without control system. Therefore, 39% of electrical energy can be saved by introducing the control system compared to the withering process without control system.

Keywords: Control system, mathematical model, Raspberry Pi 3 model B, tea withering

INTRODUCTION

Black tea production process involves five major unit operations such as withering, rolling and roll breaking, fermentation, drying, grading and packing. Withering is the first and the most important unit operation in black tea manufacture. The main purpose of the withering is to reduce moisture content in tea leaves to render its physical condition suitable for the subsequent rolling stage (Millin, 1987). The moisture content of the green leaves varies from 70-83% wet basis (w.b.) depending on the climatic condition, type of tea cultivar and weather pattern (Samaraweera, 1986). The large amount of moisture is removed (withered up to 55% w.b.) from green tea leaves during withering. The ambient conditions such as temperature and humidity have a greater influence on the removal of moisture from leaves other than climatic condition (Daranagama *et al.*, 2002).

Withering consumes highest amount of electrical energy and considerable amount of thermal energy (Haskoning, 1989). It consumes about 49% of total electrical energy in the Up-country tea factories and about 61% of total electrical energy in the Low-country tea factories. Thermal energy consumption in withering is about 9.0 MJ to produce 1 kg of made tea (De Silva, 1994). The thermal and electrical energy consumption in tea withering can be minimized by adoption of more efficient process control systems.

Withering process parameters such as relative humidity, air flow rate and temperature are needed to control carefully in order to achieve desired and even wither in tea leaves and thereby better final quality of made tea (Gupta *et al.*, 2012). The airflow rate of withering is regulated by ensuring adequate air movement through withering leaves and avoiding blowholes and throwing of leaves at the latter part of withering. Further, temperature of the withering air is needed to control below 32 ºC (90 ºF) to avoid discoloration of withered leaves. Therefore, the withering air temperature and the rate of air flow are regulated by adjusting hot and ambient air dampers manually in the mixing chamber during the withering process.

Variable speed drives (VSD) were introduced to the tea industry during 2002 with a view to reduce the electrical energy consumption in tea withering (Daranagama *et. al.*, 2002). The study revealed that 40% of electrical energy could be saved by proper control of mass flow rate of air by adjusting speed of the trough fan using VSD that is coupled to the fan motor without affecting quality of withered leaves (Daranagama *et. al.*, 2002). During this period, different types of VSD systems were installed to troughs in tea factories with manual or programmable fan speed adjustment facility. However, most of the tea factories could not achieve the real benefits of VSD systems as conventional practices of adjusting air control dampers was continued without paying attention on use of VSD. Therefore, new installation of VSDs was not carried out in tea factories and as a result VSDs were slowly removed away from tea withering.

Therefore, in this study, an attempt was made to develop a mathematically controlled process to automate the trough withering process of tea to achieve electrical energy saving while maintaining the quality of tea.

MATERIALS AND METHODS

A control system was developed for the existing tea withering trough for optimizing the electrical energy consumption while assuring the required quality of withered tea leaves. The electrical energy saving was achieved by controlling the speed of the fan of the withering trough through a variable speed drive (VSD). The fan speed was determined based on the theoretical mass flow rate of withering air. In this study, the temperature (T1, T2) and the relative humidity (RH1, RH2) obtained from the sensors were fed as input data to the mathematical model to calculate thermodynamic properties of withering air and the moisture content of tea leaves in real time for determining the mass flow requirement of air. A mathematical model developed (Botheju *et al.*, 2010) was used for calculating mass flow rate of air during withering. A single board computer, Raspberry Pi 3 model B is used to run the mathematical model and the software programme to actuate the VSD and the heat source which provides the hot air for withering. Experiments were conducted in assessing the electrical energy saving and the quality attributes of withered tea leaves. The flow chart of the operational procedure of the control system is shown in Figure 1.

The experiment was carried at St. Coombs Estate Tea Factory, belongs to the Tea Research Institute, Talawakelle. Green leaves plucked from St. Coombs estate were used in these withering experiments. The experimental withering trough selected in this study has a length of 18.29 m and a width of 1.83 m and coupled with a withering fan having 1.22 m diameter with a capacity of 5.5 kW motor.

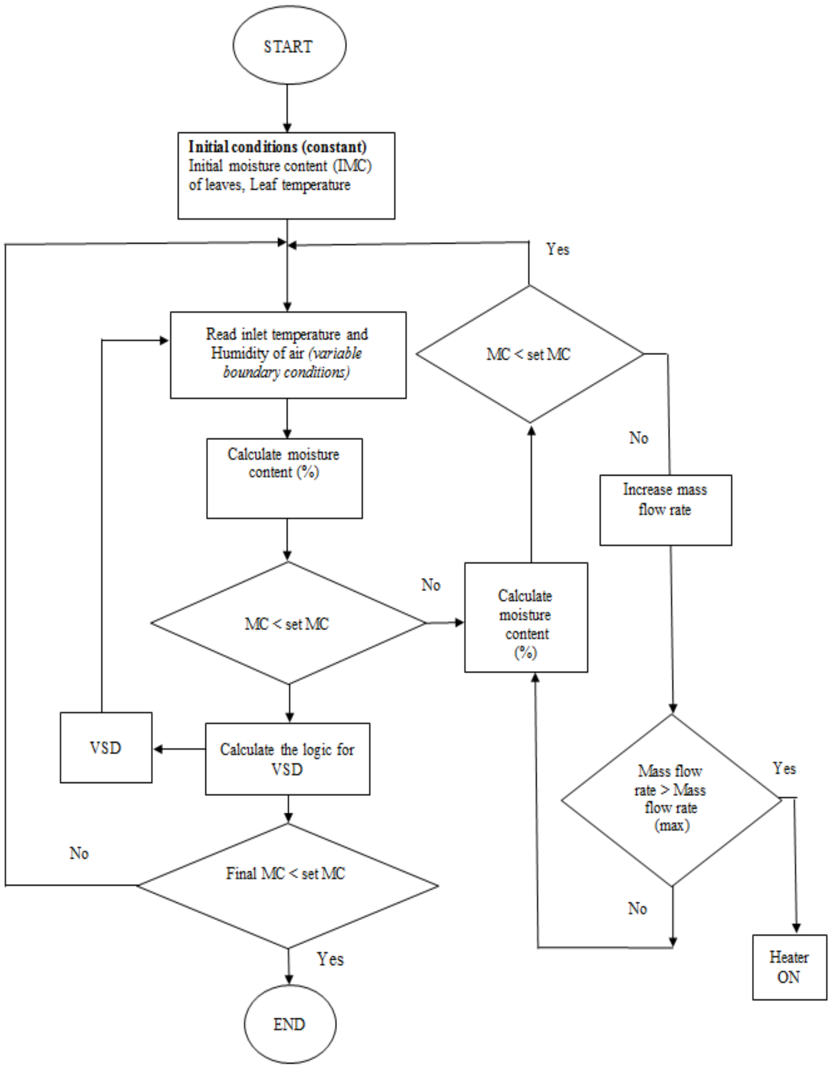

Figure 1. Flow diagram of the developed control system for trough withering

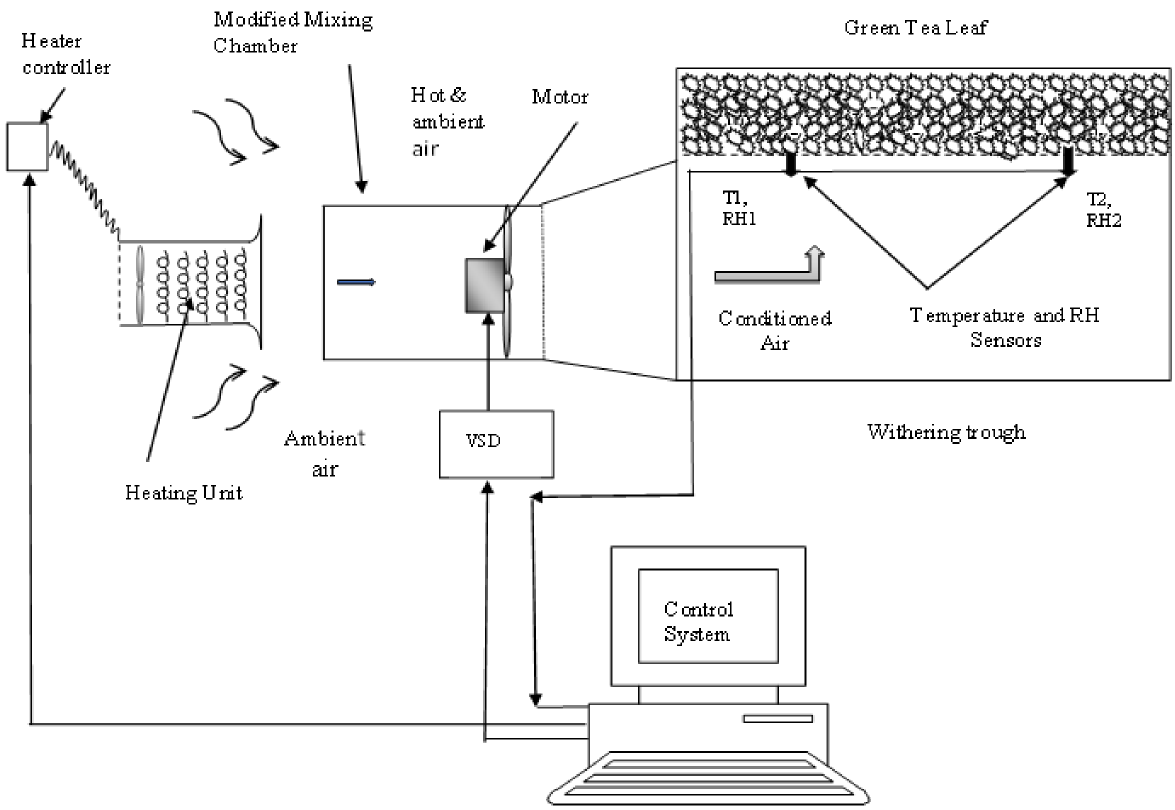

Figure 2. Experimental set up for the control system

The Figure 2 shows the experimental set up of the control system, developed for optimizing the electrical energy consumption in tea withering. In this system VSD was used to regulate the mass flow rate of air through the fan motor. Hot air ducting arrangement consisted of heating elements with a capacity of 27 kW to generate and supply of hot air for withering. The temperature and the RH sensors were placed close to the front and the rear ends in the withering trough chamber to measure temperature and relative humidity. The measured temperature and RH data were used to calculate the real time moisture content and psychometric properties of air by the mathematical model. The model calculated real time moisture contents were taken as the controller output while predicting the moisture content in the next ten minutes of withering, assuming the air conditions are not varying. In this study, standard withering curve of moisture content versus time was taken as the set points of control system. The linear standard curve was obtained by setting initial moisture content at time zero and final required moisture content at the desired set time (12 hours). In achieving this, the controller continuously calculates the difference between a desired set point (required moisture) and the predicted moisture content within the ten minutes interval. When the difference between set and predicted moisture content of leaves was high, software programme identifies required mass flowrate of air. Error for different mass flowrates was tested iteratively until minimum error was achieved. The program then provides necessary output signals for operating the VSD and heating device in order to adjust the mass flow rate delivered by withering fan as well as the temperature of air. This process was repeated in a loop in real time for the entire period of withering for achieving the electrical energy saving in trough withering.

Validation of the control system for energy saving and quality of tea withering

The tea leaves plucked from St. Coombs Estate (900 kg) was loaded on the experimental withering trough with the recommended loading rate of 3.75 kg·m^{-2}. The trough fan was switched on and the leaves were loosened properly. The initial moisture content of fresh leaves was determined by randomly drawing leaf samples from withering trough by microwave oven method (Mohamed *et al*., 2003). The initial moisture content and the leaf temperature were measured and given as the initial condition to the mathematical model. The withering process was carried out with the microprocessor-based control system. The inlet air temperature, relative humidity, real time moisture content and the frequency of the VSD were recorded by the control system during the withering period.

Three withering experiments were conducted without control system with leaves loaded at the same loading rate. Speed of the trough fan motor was varied manually. Frequency of VSD was kept at 50 Hz until turning of leaf and reduced to 45 Hz after turning of leaf. After four hours of turning the leaves, frequency was reduced up to 40 Hz towards the end of withering process.

A power analyzer (Fluke, model 434 series ii) was used to measure electrical power and energy consumption by the fan motor in all the experiments.

Tea samples were prepared by manufacturing withered leaves at the St. Coombs tea factory. The quality parameters of the tea samples, such as Thearubigins, Theaflavin, total color and the brightness were analyzed by Robert and Smith method (1963) in all the experiments.

RESULTS AND DISCUSSION

Three withering trials with the control system were carried out under this study. The initial moisture content of the green leaves of the first trial was 78%. At the beginning of the trial, the fan speed was maintained at 44 Hz frequency and then it was reduced automatically to 39 Hz frequency with increase of temperature of the inlet air to the withering trough. However, after few minutes the frequency of the fan was increased again, according to the next set point of the linear standard withering curve. Following the control algorithm (Fig. 1) the control system automatically changed the frequency of VSD as and when necessary throughout the withering period.

The measured power consumption, frequency, real time temperature and the relative humidity of inlet air and the real time moisture content with time, during the withering period with the control system in first trial are presented in Figure 3 and Figure 4.

The power consumption varied between 2500 W to 3500 W depending on the withering condition in the first trial. The total electrical energy consumption was recorded as 36.25 kWh.

Figure 4 shows that the temperature and the relative humidity of the inlet withering air were maintained between 20 and 32 °C and between 50 and 90% during the first trial.

The initial leaf moisture content of the second trial and the third trial were 76.2% w.b. and 75.2% w.b., respectively.

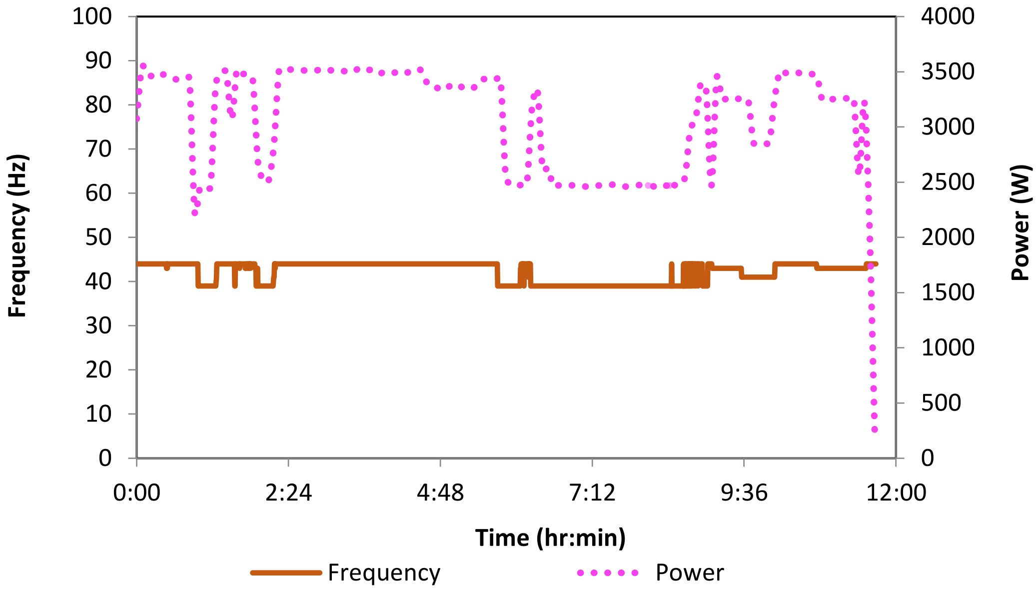

Figure 3. The variation of frequency and the power consumption with time (Trial I)

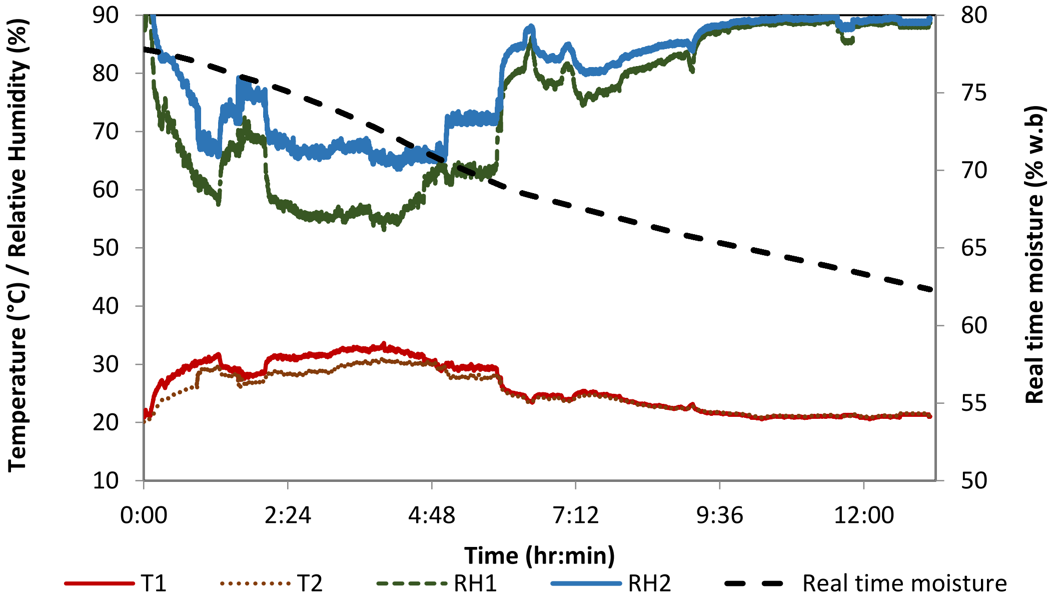

Figure 4. The variation of temperature, relative humidity of inlet air and the real time moisture content with time (Trial I)

The power consumption, frequency, temperature and relative humidity of the inlet air and the real time moisture contents of withered leaves with time during the withering period, with the control system of the second trial are presented in Figure 5 and Figure 6, respectively.

The power consumption varied between 3000 W to 3500 W depending on the withering condition in the second trial. The total electrical energy consumption was recorded as 38.76 kWh and the frequency of the VSD was varied in the range of 39 to 44 Hz.

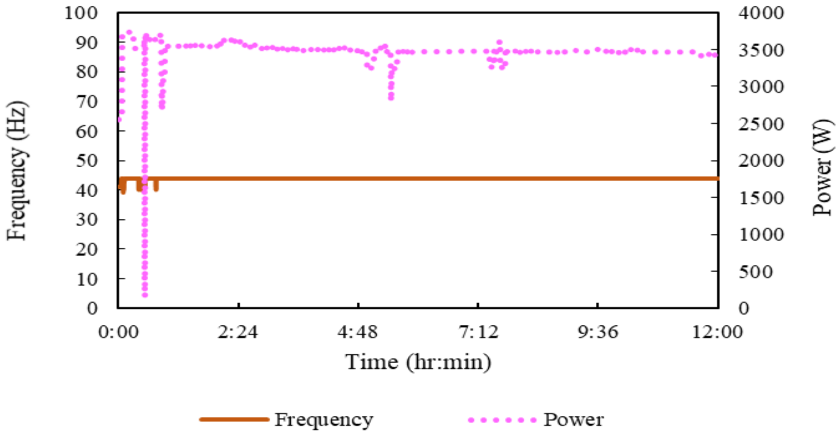

Figure 5. The variation of frequency and the power consumption with time (Trial II)

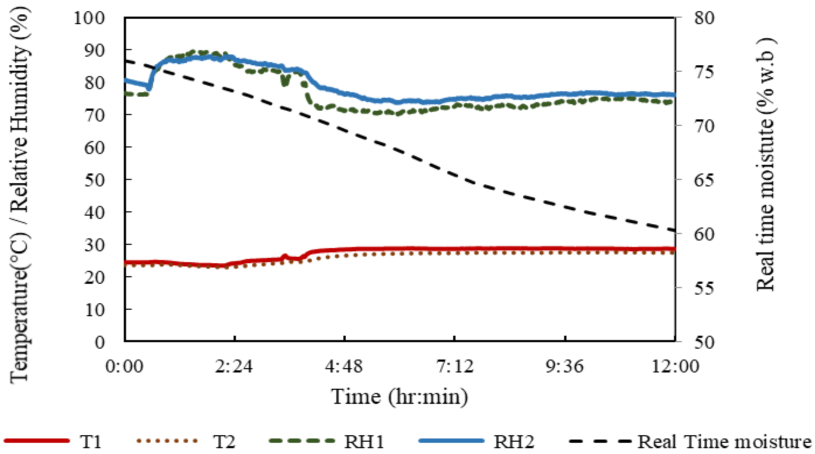

Figure 6. The variation of temperature, relative humidity of inlet air and the real time moisture content with time (Trial II)

The temperature of the inlet air does not exceed 30 °C and it was maintained between 24 to 30 °C in the second trial. The corresponding relative humidity values were varied between 70 to 90%. The power consumption, frequency, temperature and relative humidity of inlet air and the real time moisture contents of wither leaves with time during the withering period of the third trial are presented in Figure 7 and Figure 8, respectively.

The power consumption varied between 2500 W to 3000 W except in few conditions, depending on the withering condition. The total electrical energy consumption was recorded as 38.57 kWh and the frequency of the VSD was varied in the range of 39 to 44 Hz during the third trial.

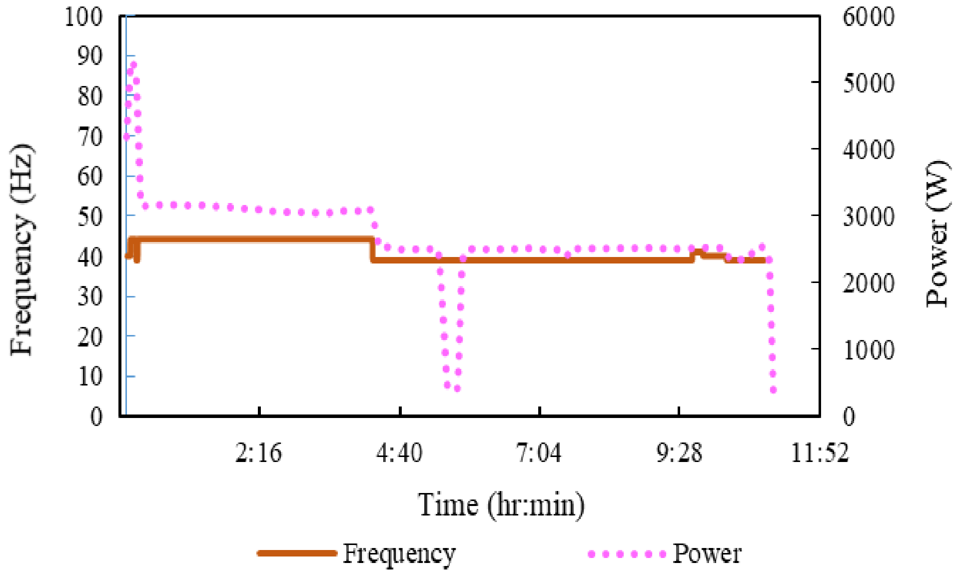

Figure 7. The variation of frequency and the power consumption with time (Trial III)

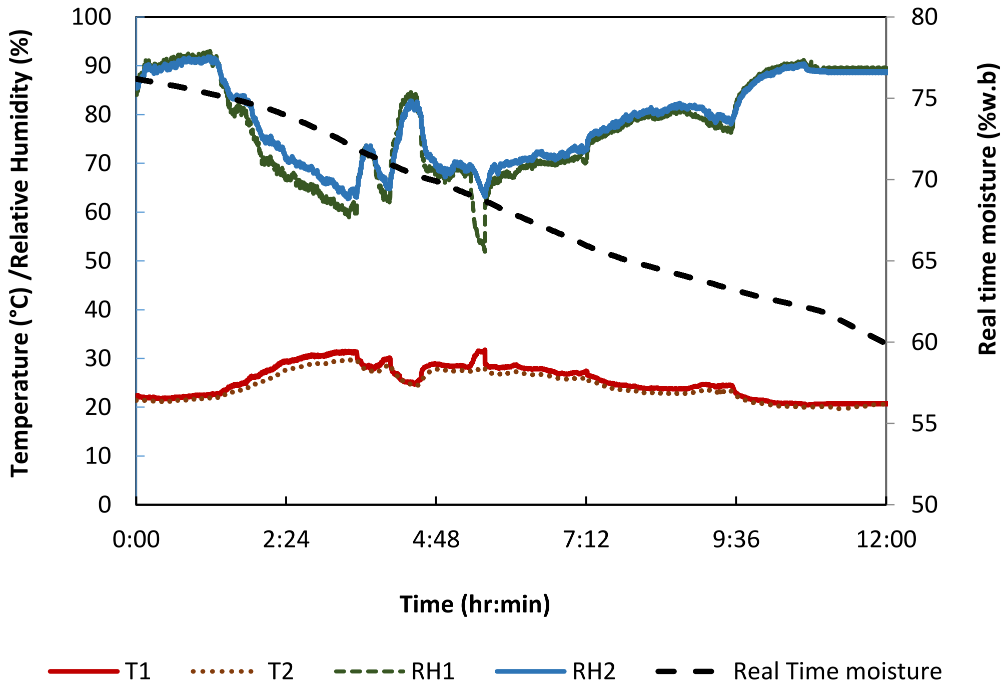

Figure 8. The variation of temperature, relative humidity of inlet air and the real time moisture content with time (Trial III)

Figure 8 shows that the temperature of the inlet air does not exceed 30 °C and it was maintained between 21 to 30 °C and relative humidity varied between 60 and 90% during the trial.

The total electrical energy consumption, specific electricity consumption, initial and final moisture contents and the rate of removal of moisture with and without control system for three different trials are presented in Table 1.

Table 1 depicts that the electrical energy consumption was in the range of 36 kWh to 39 kWh with the control system while it was in the range of 55 kWh to 67 kWh without control system. The specific electricity consumption was 0.17 to 0.18 kWh.kg^{-1} of made tea with control system and it was 0.27 to 0.35 kWh.kg^{-1} of made tea in withering process without control system.

De Silva (1994) stated that the theoretical specific electrical consumption is about 0.16 kWh·kg^{-1} of made tea while the actual consumption is about 0.46 kWh·kg^{-1} of made tea. Therefore, the results show that the controlling of withering parameters leads to have better electrical energy savings. The rate of moisture removal was 9.9 to 11.97 kg moisture for one unit of energy (kWh) with control system and it was 6.82 to 8.48 kg moisture for one unit of energy (kWh) without control system with the standard deviation of 0.7562 and 0.461 respectively.

The quality parameters (Percentages of Thearubigins, Theaflavins, brightness, ratio of Thearubigins to Theaflavin and total color) of the made tea samples produced with control system and without control withering system were presented in Table 2.

Table 1. Energy consumption, initial and final moisture content, rate of removal of moisture and the specific electricity consumption with and without control system

Experiments		Initial MC (% w.b)	Final MC (% w.b.)	Energy (kWh)	Removal of moisture (kg. kW^{-1}h^{-1})	Specific electricity consumption (kWh.kg^{-1}) made tea
With control system	Trial I	78.0	57.5	36.25	11.97	0.18
	Trial II	76.2	57.6	38.76	10.18	0.18
	Trial III	75.2	56.6	38.57	9.90	0.17
Without control system	Trial I	77.2	57.1	55.92	7.55	0.27
	Trial II	79.3	56.3	64.34	8.48	0.35
	Trial III	78.6	57.0	66.24	6.82	0.34

Table 2. Quality parameters of the made tea, produced with control system and without control withering system

Quality parameters	TF (%)	TR (%)	Total color	Br (%)	TR/TF
With control withering system	0.952	14.8	4.98	17.82	15.5
	0.936	13.7	3.84	23.29	14.7
Without control withering system	0.839	13.7	3.9	21.2	16.3
	0.857	13.6	3.9	19.8	15.8

The ratio of Thearubigins (TR) to Theaflavin (TF) was very much closer in withering process with and without control system. It was reported that TF to TR ratio of 1:10 gives an idealized liquor color and brightness (Robert and Smith, 1963). The significant difference was not observed in the quality parameters such as percentage Thearubigins, Theaflavin, brightness, and total color, in withering process with and without control system.

The results showed that the electrical energy consumption was considerably low with the control system while preserving the quality of black tea. Withering is the first and most important process of tea processing and also contributes considerably to the cost of production of black tea. At present, tea withering process is based on human skills and experiences and leads to several problems including high cost and the issues with quality. Therefore, the developed tea withering control system would be a better solution in achieving the quality of tea at lower cost of production.

CONCLUSIONS

The results indicated that the developed control system for trough withering process conserves electrical energy during the withering process while maintaining the quality of tea. The energy consumption with the control system was in the range of 36 to 38 kWh whilst it was in the range of 55 to 67 kWh without control system. The specific electrical consumption varied 0.17 to 0.19 kWh per kg of made tea and it was reduced by about 39% as against the withering process without control system.

Further, the rate of removal of moisture during the withering period with control system was about 10.9 kg moisture per one electrical energy unit wherevers, without control system it was in the range of 6.82 to 8.48 kg moisture per one electrical energy unit.

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