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Retrofit Mango Chip Drying Plant for High Productivity

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Abstract – *Dryer is an equipment widely used to remove the moisture from products/materials. This study is focused on an industrial cabinet/tray type dryer which used to dry mango chips. The dryer is designed to operate by steam or electricity and due to the prevailing capabilities and limitations of the factory the electricity has been used to run the dryer. This research is focused on reducing the drying time of the dried chip production process. The reduction of the drying time will reduce the cost and increase the productivity. Initially the total production process was evaluated, and the drying stage parameters were identified. Then a comprehensive literature survey was conducted to theoretically recognize the parameters related to drying, and to identify the possible modifications which can be introduced to minimize the drying time. It was identified that the controlling the level of relative humidity would appropriately affect the drying time. The existing drying plant was retrofitted to reduce the relative humidity of air to optimize the dying time and it was carefully conducted in cost-effective manner. A designed and developed unit mainly consists with heat exchangers were introduced to the existing dryer. The two most important process parameters, moisture content and the water-activity, were continuously monitored and kept within the limits. After the introduction of the unit, the total process was reassessed. A 3.26% reduction of the drying time with an energy saving of 12.65% was recorded. Hence the productivity of the plant is improved. Even considering the reduction in energy consumption, the capital cost can be recovered within less than 2 ½ month which is further shortened if taken the productivity improvement into account. The findings of this research could be applied to similar cabinet/tray type dryers to optimize the drying process thereby to shorten the drying time to enhance the productivity.*

Keywords: *Cabinet Dryer, Energy Saving, Productivity, Relative Humidity, Tray Dryer*

Nomenclature

Kcv - Drying rate for constant rate period ($kgm^{-2}s^{-1}$)
Td - Dry bulb temperature of air (˚C)
Tw - Wet bulb temperature of air (˚C)
h - Convective heat transfer coefficient ($Wm^{-2}K^{-1}$)
b - 14.31 (Constant for SI unit)
G - Air flow rate (kgs^{-1})
W - Initial moisture content in dry basis
Wc - Critical moisture content
Wi - Final moisture content in dry basis
t - Theoretical drying time ($sm^{-2}kg^{-1}$)
T - Total drying time (min)
X - Relative humidity x 100
A - Constant for drying process

Greek Letters

λ - Latent heat of vaporization at temperature *Tw* ($kJkg^{-1}$)

Subscripts

c - critical
i - final
d - dry bulb
w - wet bulb

1 INTRODUCTION

One of the leading industries in Sri Lanka which produces food-based items for both local and international markets, has recently started a new venture which is to produce dry-mango-chips. These chips which consume as a snack, are totally exported to Europe and Middle East. The mango chip processing method and the recipe is not yet exposed by other producers. The venture had to conduct a fair bit of R&D to finalize a process which could adapt to reform the wet mango chips to dry chips while maintaining the anticipated quality standards.

Productivity is a key factor, and any productivity improvement not only benefits the employers but also to the employees in different ways, such as salary increments, bonus, health insurance, annual get-togethers, etc. Hence this study is focused on productivity improvement of the mango chip drying plant by refining the drying process. Optimization of the energy usage is also another aspect that the study was focused on.

The production process (Earle, 2004) of dry mango chips is consists with different stages (Fig.1). Starting from washing, the total process takes about 52 *hours* per cycle. Approximately 800 *kg* of wet mango chips are processed in one cycle.

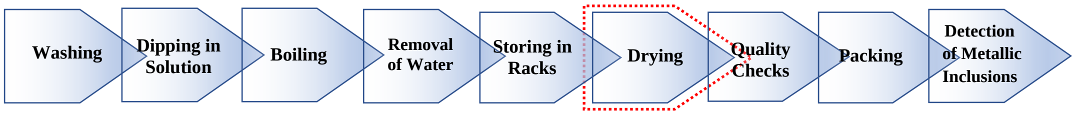


Fig. 1. Production process of dried mango chips

The time study confirmed that the drying stage is the highest time-consuming stage of the entire production process which takes about 24 hours. That is about 46% of the total time per cycle (Fig.2). Stages such as 'dipping in the solution' and 'boiling' must be performed for the specific time (pre-determined according to the quality requirement of final product) which cannot be modified. 'Washing', 'storing on racks', 'quality checking' and 'packing' are manual processes and if required, the time could be reduced by assigning more labor force which is a trade-off where more wages must be paid. But it is obvious that the reduction of time other than 'drying' stage will not significantly improve the productivity of the entire process. So, a reduction in time-consumption for drying would affect the productivity of the entire process.

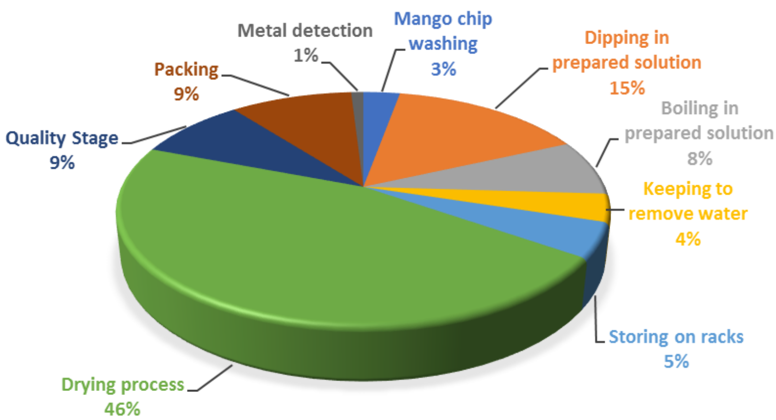


Fig. 2. Time consumption percentage of each production stage

The top management of the industry is also interested in analyzing the possibilities of improving the drying process and given their blessings to incorporate modifications to reduce the drying time. The wet mango chips at 'water removing stage' and 'stored in racks for drying' are shown in Fig.3 *a* and *b* respectively.

a. Chips at water removing stage **b. Wet chips on racks before send to dryer**

Fig. 3. Wet mango chips used for ongoing production process

Changes to any stage of the process must be done without affecting the quality standards of the end-product. The main aim is to propose suitable modification to reduce the drying time of mango chip production process. The total process needed to be studied and must identify the parameters related to ongoing drying process. After the proposed modification is implemented, the improvements are assessed and justified.

2 METHODOLOGY

A time study was carried out (average value of randomly selected five production cycles over a time span of two weeks were considered) and identified that the most effective way to increase the productivity is by reducing drying time. Hence drying stage was further studied. Specifications, controlled parameters, working ranges of the existing dryer were identified. Dryers, working principles of dryers, controllable factors, and efficiency of drying etc., were studied under literature review.

Two modifications were proposed, and experiments were conducted to select the effectiveness of each. A mathematical model was developed and the variation of the theoretical drying time with the relative humidity was studied. Results of these analysis were used to propose feasible and cost-effective method which could reduce the drying time and thereby to improve the productivity. Finally, the proposed modification was implemented and evaluated.

2.1. Drying Process, Parameters and Quality Requirements

The existing dryer (length-3.5 *m*, width-2 *m*, height-2.4 *m*) manufactured in India, is shown in Fig.4. It can operate by steam or electricity. To obtain the dried chips in acceptable standards, the parameters such as drying temperature, duration, set after conducting extensive R&D work. Any parametric changes should be done after careful investigation. Initially, the drying temperature is set at 70˚C for 2 *hours* and thereafter, it is set to 60˚C until the drying completes. This drying plant is electrically operated to accommodate easy change in temperature. If steam is used, the heated air temperature cannot be varied.

Quality inspections are conducted within the drying stage and after the drying stage. Within the drying stage the moisture value of the product is measured several times to verify the product's moisture content, which is the most critical quality parameter.

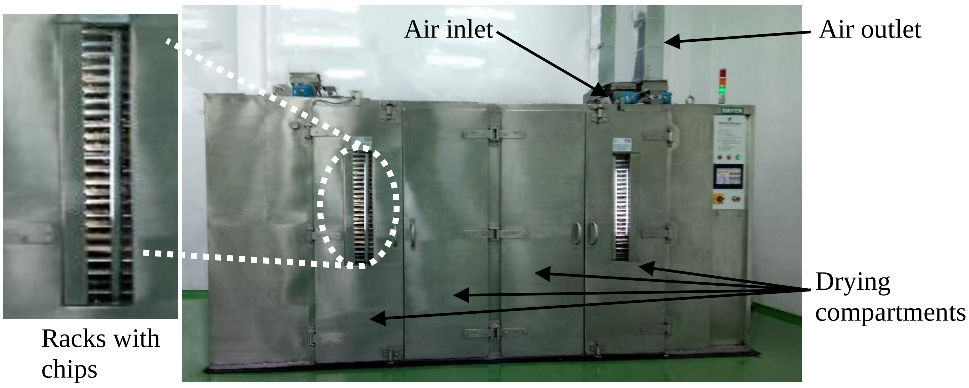


Fig. 4. Dryer used for the production process of dried mango chips

Moisture content was initially measured after 2 *hours* and then once in every 4 *hours* until the value comes down to 20%. Once the moisture content becomes below 20%, hourly measurements were taken to verify the specific dryness of the chips. The moisture content should be less than 14% to minimize the activeness of microorganisms (Parikh, 2014). At the end of drying water-activity was also checked. The water activity must be maintained below 0.7 to prevent the growth of microorganisms (FDA, 2014). The limiting values and measurement intervals are indicated in Table 1. After meeting the required levels of moisture content and water-activity, the drying stage completes. The dried mango chips will be sorted out by color and the size before packaging.

Table 1 Summery of controlled parameters and their ranges

Set temperature	*Duration*	*Moisture Checking Interval*
70 ˚*C*	Initial 2 *hours*	After 2 *hours*
60 ˚*C*	2hrs - Until drying complete	Every 4 hours; till moisture reading gets down to 20%
		Every hour when moisture reaches below 20%
Limiting values of Moisture and Water Activity		
Parameter		*Limit*
Moisture		Below 14%
Water activity		Below 0.7

2.2. Existing Air Path of Dryer

The current configuration of the dryer is shown in Fig.5. The ambient air is directly fed into the dryer and the humid air release to the atmosphere from the exhaust.

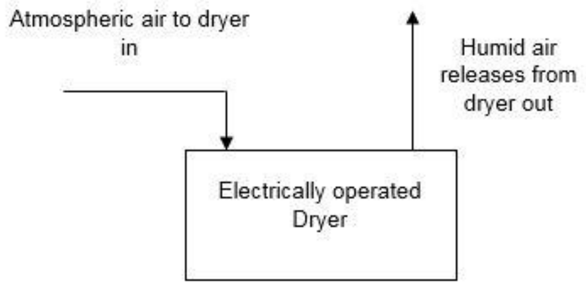


Fig. 5. Schematic diagram of existing configuration of the air path of dryer

2.3. Experiments

The concept behind the ‘condensing dehumidifiers’ (Jessica Lamond, 2011) was used to develop the experimental model. Two locally made finned heat exchanges with appropriate dimensions (14” x 18”) were used to cool the air-in. Since the dryer has its own heating elements it could be used to perform the role of the condenser of the dehumidifier. Chilled water was used as the cooling media. Considering the following two scenarios, experiments were conducted to evaluate the performance.

1. Effect on the drying time by reducing the humidity of ambient air which directs to the dryer.
2. Effect on the drying time by recycling the outlet air back into the dryer after reducing its humidity.

The appropriately equipped experimental model (dehumidification unit) in Fig.6, is made of stainless steel well-sealed housing enabling following assumptions to be made; the heat loss to the surrounding is negligible, kinetic and potential energy changes of the air flow is negligible, pressure drop through the heat exchanger is negligible, air flow is equally distributed over the heat exchanger, heat exchanger tube surface area is negligible, parameters such as air properties, initial product moisture, unit inlet air temperature, cooling water inlet temperature, air flow rate and cooling water flow rate remain constant throughout the experiment and a complete heat transfer occurs through the process.

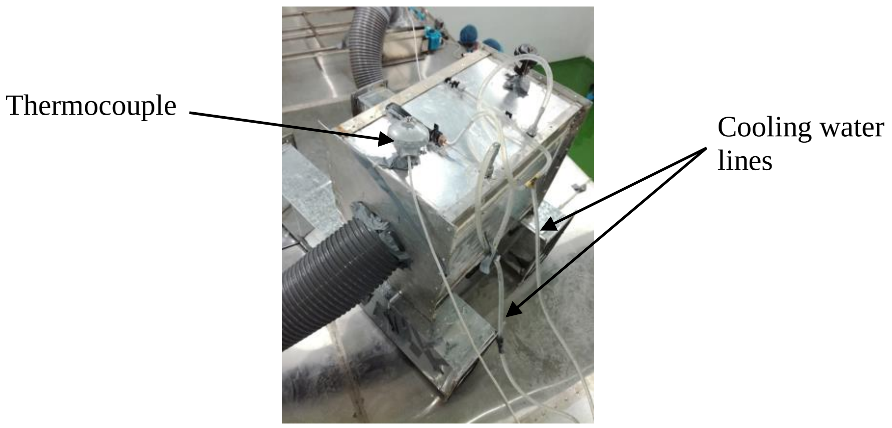


Fig. 6. Model unit used for experiments

Experiment 1

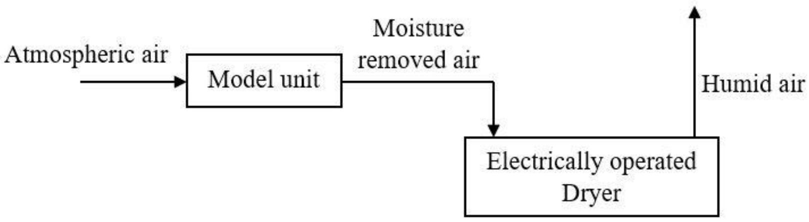


Fig. 7. Setup of Experiment 01

The relative humidity of the ambient air was reduced by the unit (Fig.7) and it was maintained until the experimental cycle is finished. The total drying time and outlet temperatures was measured. The dryer energy consumption was also noted with the product qualities. The measured parameters are;

Calculated dew point - 25.17 ˚C
Avg. unit out air Temp. - 25.67 ˚C
The drying time - 23 hrs 46 min
Product moisture - 13%
Water activity - 0.65
Power Consumption - 1028.6 kWh

Experiment 2

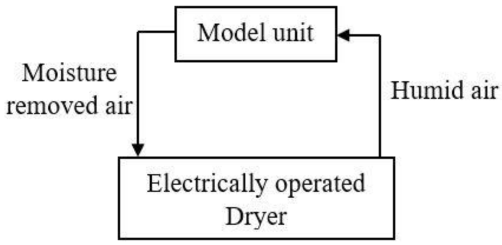


Fig. 8. Setup of Experiment 02

This was done by connecting the dryer exhaust into the inlet of the unit (Fig.8) and procedure and observations were similar to the Experiment 01. The measured parameters are;

Calculated dew point - 55.6 ˚C
Avg. unit out air Temp. - 46.0 ˚C
Total drying time - 20 hrs 13 min
Product moisture - 11.78%
Water activity - 0.6
Power Consumption - 815.4 kWh

Results of experiments

In experiment 1 it was difficult to achieve model unit outlet air temperature below to the dew point temperature. There was no considerable variation of the drying times, and it increases the energy consumption of the dryer. In experiment 2, model unit air temperature goes below to the dew point temperature and drying time was considerably reduced. The power consumption was also reduced.

2.4. Mathematical Model

Water can only evaporate from an object if the air around it can absorb more water (Ahrens, 2006). This could be measured by the relative humidity. A mathematical model was developed to verify the effect of the relative humidity to the drying process. Fig.9 illustrate the overview of the mathematical model.

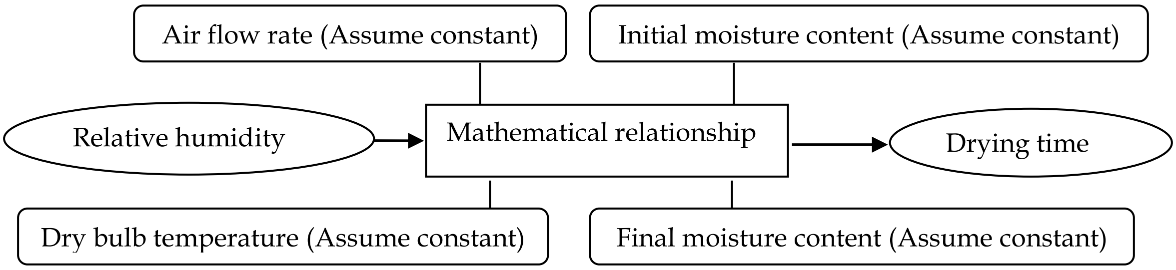


Fig. 9. Overview of the mathematical model

The relationship of drying rate at constant rate period (Perry, 1997) is given by equation (1).

$$Kcv = \frac{bG^{0.8}(Td - Tw)}{\lambda} \quad (1)$$

The total drying time of a material is a combination of constant rate drying and the falling rate drying (IASRI, 2012). The relationship of total drying time is given in equation (2).

$$t = \frac{(W - Wc)}{Kcv} + \frac{Wc}{Kcv \times \ln\frac{Wc}{Wi}} \quad (2)$$

At a certain moisture level of a material, it tends to fall the drying rate. This moisture level is called as the critical moisture level. This is occurred due to the limited moisture content of the material. Critical moisture content for a material needs to find through lengthy experiments. Hence assumed that the total drying time occurs at constant drying region. An equation for the theoretical drying time (t) derived using equations (1) & (2),

$$t = \frac{\lambda K}{bG^{0.8}(Td - Tw)} \quad (3)$$

Considering the constant parameters of the process, assigning a constant factor 'K',

$$t = \frac{\lambda K}{(Td - Tw)} \quad (4)$$

According to equation (4), the total drying time is depending on the dry bulb temperature of the air (T_d), wet bulb temperature of the air (T_w) and latent heat of vaporization (λ) at temperature T_w. The dry bulb and wet bulb temperatures depends on relative humidity. Latent heat of vaporization is depending on the temperature.

Based on the second scenario of the experiments, consider the dry bulb temperature as 60˚C for calculations for several relative humidity values. Wet bulb temperature for the relative humidity is taken from an online calculator (Knight, 2006). The latent heat of vaporization (λ) is taken from an online calculator (EngineeringToolBox, 2010). The constant factor (K) assumed as '1' for the calculation and plotted a scatterplot to identify the theoretical drying time variation with relative humidity (Fig.10) for 60˚C dry bulb temperature. In the practical case, the 'K' having a value specified to the production process.

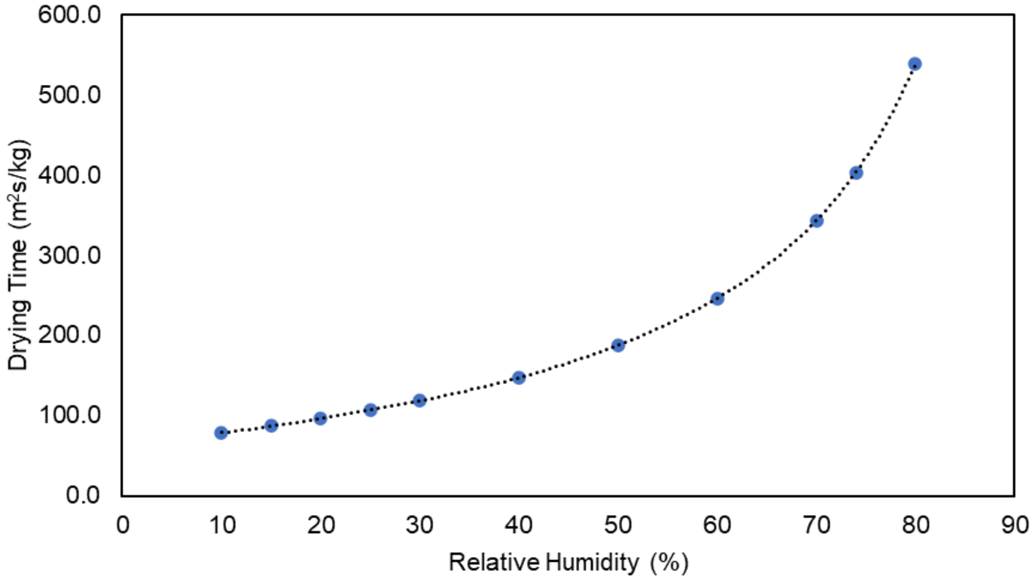


Fig. 10. Theoretical drying time variation with dryer inlet air relative humidity for 60˚C dry bulb temperature

Fig.10 confirmed that the reduction of relative humidity direct to reduce the drying time.

Equation (4) does not include the relative humidity directly. Hence, a higher polynomial equation is generated from Microsoft excel based on the curve of Fig.10 as the modified mathematical model. Equation for the total drying time (T) against relative humidity for 60 ˚C,

$$T = (2\times10^{-8} X^6) - (4.35\times10^{-6} X^5) + (3.8516\times10^{-4} X^4) - (168.1113\times10^{-4} X^3) + (3975.9582\times10^{-4} X^2) - (2.90311755X) + 81.2726042 \quad (5)$$

This equation gives the total drying time in square meter seconds per kilogram (m^2s/kg). Hence another constant 'A' assigned to the equation to get drying time in seconds related to current drying process. This constant aligns the equation with the mango chip drying process. The unit of the constant is kilograms per square meters (kg/m^2).

$$T = A\{(2\times10^{-8} X^6) - (4.35\times10^{-6} X^5) + (3.8516\times10^{-4} X^4) - (168.1113\times10^{-4} X^3) + (3975.9582\times10^{-4} X^2) - (2.90311755X) + 81.2726042\} \quad (6)$$

Drying Time and Constant 'A'

The constant 'A' is estimated by observing the drying time for several relative humidity levels. Experiment 2 was done again to observe the drying time and the relative humidity. This was done by throttling the chilled water flow of the experimental unit to change the heat transfer. Due to the practical limitations, only 3 trials were done (Table 2).

Table 2 Theoretical and experimental drying times of mango chips

Relative humidity (%)	Theoretical drying time from mathematical model (m^2s/kg)	Experimental drying time (min)	Constant 'A' (kg/m^2)
65	291.5	1396	287
63	273.0	1322	291
57	228.0	1213	319

Comparing observed drying time with mathematically observed time, the constant 'A' for 3 cases found as 287, 291 and 319. Therefore, as fair value the average of above 3 is taken as the constant for the equation to set up the equation for the current process.

$$\text{Constant 'A'} = \frac{(287+291+319)}{3} = \underline{\underline{299\ kg/m^2}}$$

2.5. Comparison of the Results from Experiments and Mathematical Model

The experimental drying time is much higher than the theoretical drying time obtained through the mathematical model. The mathematical model was formed using few constants and assumptions. But in the practical scenario it is difficult to control all these parameters constantly without minor changes. The experimental value is higher than to the theoretical value. A multiplication constant 'A' to the mathematical model was considered to minimize the effect of such assumptions. By the experimental data the constant 'A' was calculated. Practically it is not possible to operate every cycle with similar/constant parameters (e.g., Initial moisture content of the mango chips, slice thickness, constant surface area etc.). Hence it changes the 'A' value from one cycle to another. Due to the practical limitations, the constant 'A' was defined considering only three cases. It can be further correct by increasing the number of trials.

3 PROPOSED DESIGN

Since the critical temperature limits are known, Logarithmic Mean Temperature Difference (LMTD) method is used to design the heat exchangers (Ezgi, 2016), The proposed modification is to install an external unit to the dryer inlet air path to reduce the relative humidity of the of the air which sends into the dryer (Fig.11). Prior tests were carried out to check and optimize the operational parameters.

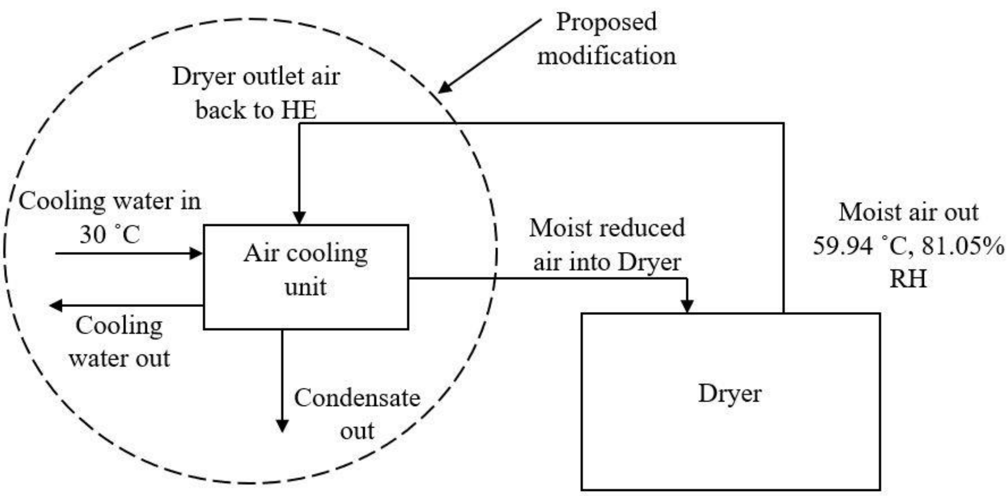
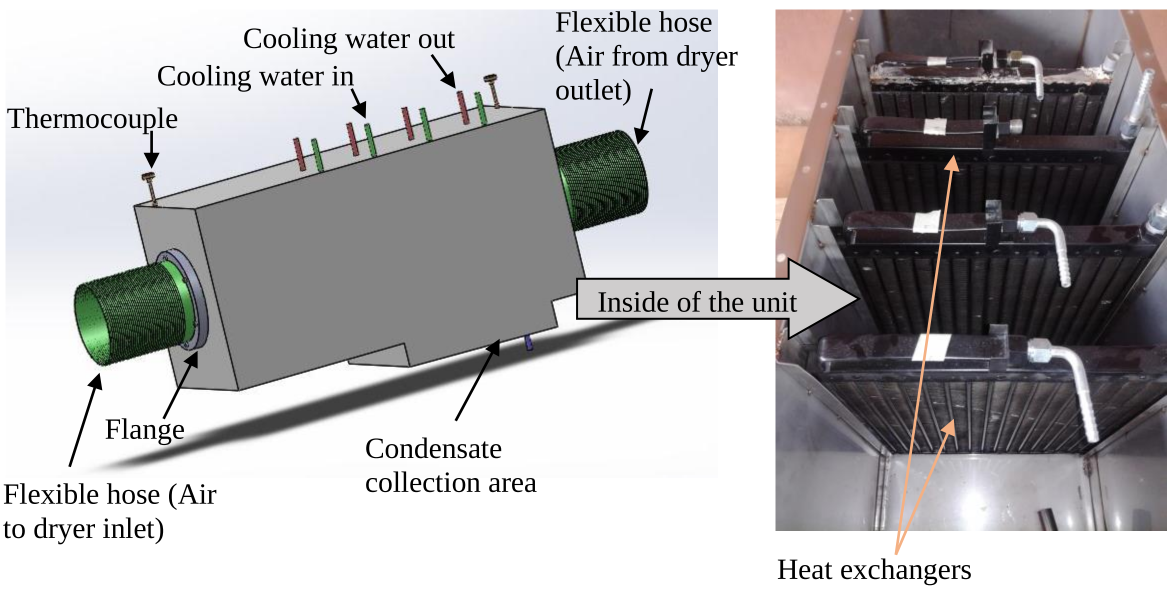


Fig. 11. Schematic diagram of the proposed arrangement

Considering the cost factor and feasibility, raw water (30˚C) is proposed to use as cooling media since the expected temperature difference can be achived. Along with the humidity reduction, the energy can also be saved due to the re-circulation of the air.

4 RESULTS AND DISCUSSION

The outer 3D view and the internal arrangement of the unit is illusrated in Fig.12 (a) and (b). A picture of the total drying unit with the intruduction of the new unit is shown in the Fig.13.



a. Details of the unit **b. Inside of the unit**

Fig. 12. Designed unit

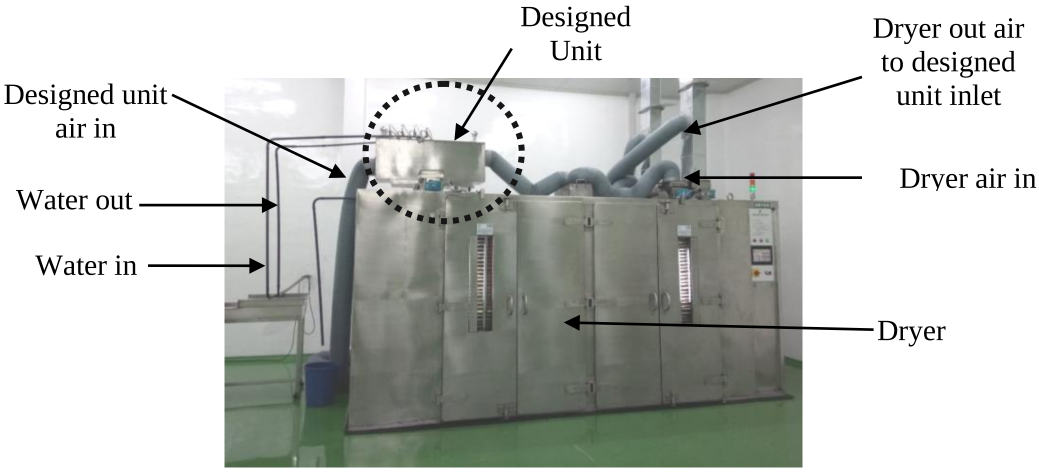


Fig. 13. Introduction of the new unit to the dryer for testing

The retrofitted dryer was tested for 3 production cycles and results were observed (Table 3). From the observed data, the average temperature at unit outlet and the average relative humidity at dryer inlet were calculated.

Table 3 Comparison of test results before and after the modification

Observation	Total Drying Time (min)	Product Moisture (%)	Water Activity	Avg. Temperature at Unit Outlet (˚C)	Avg. Relative Humidity Dryer inlet (%)	Power Consumption (kWh)
1	1383	11.69	0.62	53.5	65	834.3
2	1404	11.58	0.64	55.08	67.25	839.1
3	1392	11.36	0.61	53	64.1	836.6
Before modification	1440.7	11.21	0.61	-	86.4	957.93

Samples were taken from the batches prior and after the modification. The taste is the key factor of the final product as this is a snack. Considering the taste of the chips, no one who involved in taste testing trials (20 people were used) were able to distinguish a taste different in any sample.

The capital cost for the proposed modification is evaluated as around Rs. 109,000.00. Considering only the 'energy saving' aspect this capital cost could be recovered withing 2 ½ months. If the 'increment of profit' due to upsurge of the productivity, the payback period will be reduced further.

5 CONCLUSION

After implementing the proposed modification, the drying time was reduced, and the productivity of the total mango chip manufacturing process was increased by a considerable margin. A significant reduction of power consumption has also been achieved. A saving of 3.26% drying time per one batch was observed. Since the production process runs continuously, this reduction saves a time for nearly extra one batch for a month, i.e., it allowed to process additional one batch (800 kg) of wet mango chips per month with current facilities. Taking it to consideration a 3.26% increment of the productivity could be achieved. Also, a considerable reduction of 12.65% energy usage per batch is obtained. The capital cost for the proposed modification is Rs. 109000.00. Considering the savings only due to reduction in energy consumption, this capital cost can be recovered within less than 2 ½ month and this payback period could be further reduced by accounting productivity improvement.

Based on the outcome of the project, the humidity reduction of the dryer exhaust air and recirculating the air back to the dryer have improved the productivity of the plant. This improvement can be further enhanced by reducing the relative humidity of the air (proves by the mathematical model). This is be achieved by reducing the temperature (or by using chilled water) of the cooling media. But it needs a continuous supply of chilled water which incur an additional cost and needed to be done in a controlled manner, otherwise the power consumption of the dryer will be increased. This modification can be adapted to any organization who used cabinet dryer/tray dryer for food drying purpose to improve the productivity while reducing the energy consumption.

6 ACKNOWLEDGEMENTS

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