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Drying Performances and Economic Investigations of Forced Convectional Re-circulating Paddy Dryer

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***Abstract*— The main objective of this study is to investigate forced convectional re-circulating paddy dryer with three main aspects such as technical operation, drying performances, and economic analysis. To cover the primary aim of research, various initial moisture contents 30%, 25%, 20% and 16% wet basis of paddy are dried until final or safe moisture content of 14% wet basis. Technical operations including drying temperature requirement, water removal rate, mass flow rate of drying air, electrical and thermal energy consumptions are evaluated. Drying temperature of paddy dryer is assumed according to ambient temperature and its range varies within 60-44℃. In electrical energy consumption, both main mechanical drying machines, and supporting machines such as conveyors and elevators are considered. Maximum and minimum electrical energy consumptions are 578.36 kWh and 101.78 kWh for 30% and 16% initial moisture content paddy drying respectively. Since holding capacity of paddy dryer is 30 tonnes in average, specific thermal energy consumption differs within 19.209 kWh/tonne and 3.393 kWh/tonne. In terms of thermal energy, paddy dryer works with rice husk heating system. Thus, husk consumption is estimated to require 163.878 kg/hour for maximum drying time, and 136.565 kg/hour for minimum drying. Drying performance results indicate that average drying time required is about 7 hours with consideration of tempering while average drying capacity is about 4.813 tonne dry paddy/hour. Maximum drying rate of paddy dryer is 0.027 kg water/hour and 0.007 kg water/hour is for minimum rate. The resultant drying efficiency is 62.874% in average that represents further evidence of good paddy drying performance. Economic analysis is studied with milling quality achievement, operation cost, and profit for one-kilogram rice. Exceptional amount of rice that is about 95.75% is recovered after milling, and so this provides leading to extensive profit achievement by using forced convectional re-circulating paddy dryer.**

***Index Terms*— Forced convectional paddy dryer, drying performance, drying efficiency, milling quality**

I. INTRODUCTION

Cereal grains are edible seeds that can provide food energy to all people worldwide. Among other cereal crops, paddy is life for more than three billions of people around the world, which is about 50% of the world's population according to IRRI (International Rice Research Institute). Almost every country has rice in their diet and many agricultural areas in Southeast Asian countries produce rice. The agricultural sector is a common denominator for all most of the ASEAN Member States reported by ASEAN Farmers' Organizations Support Programme (AFOSP).

Nearly 40% of cereal crops losses occur at post-harvest and processing levels in developing countries (FAO, 2018). Among post-harvest operations, drying and storage are key processes to improve yield in rice production. Thus, the importance of moisture content reduction of cereal crops, which is known as drying, is a decrease in water activity to secure levels consequently preventing microbiological growth.

In Myanmar, about 50 million farmers involve in rice processing stages while there are approximately 50,000 technical experts only. Because of lack of knowledge and tradition, most of the farmers from developing countries are still using natural sun drying method to dry agricultural products. Therefore, these few amounts of technical experts, now, have to take responsibility in Myanmar Agriculture sharing knowledge, convincing and guiding technical methods on both pre-harvest and post-harvest operations.

It is reported that there will be 12-14% decline in rice production of most of Southeast ASEAN countries including Myanmar due to soil salinity, water scarcity, and environmental issues in 2050 by IFPRI (International Food Policy Research Institute). On the other hand, there will be upward trend in rice consumption and on the other hand, post-harvest losses and environmental challenges can slow down rice production as well. Hence, the study on how to increase rice production without any losses in post-harvest operation will make impact to the future of agricultural aspects. Therefore, paddy-drying technology, one of the most important management practices, will now play vital role for Myanmar Agriculture.

II. MATERIALS AND METHODS

A. Forced Convectional Re-circulating Paddy Dryer

Figs 1 and 2 show the photographs of industrial paddy drying plant, and accessories required for paddy drying system.

Fig. 1 Industrial drying plant (Good Brothers, Ltd)

(a) (b)

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(c) (d)

Fig. 2 Accessories for grain drying system
(a) Pre-cleaner, (b) Three dryers, (c) Husk tank and furnace (right to left) (d) Storing silo

Plant observation and specifications of forced convectional paddy dryer are shown in Table 1 and 2. Simple diagram of forced convectional paddy dryer is given in Fig 3.

Table 1: Plant observation and data collection

Items	Conditions
Location	Sar Ma Lauk, Nyaung Tone
Brand	Suncue husk furnace dryers
Sponsored company	Good Brothers.,Ltd
Crop	Paddy (Sin Thu Kha)
No. of dryer	3
No. of floor in one dryer	12
Total weight of paddy in one dryer (12 floors)	30,000 kg (30ton)
Weight of paddy per floor	2500 kg (2.5 ton)
Final moisture content for storage (% wet basis)	14%
Ambient air temperature (°C)	25-35°C
Ambient relative humidity	15-40%
Maximum allowable hot air temperature (°C) of dryer	60°C
Minimum allowable hot air temperature (°C) of dryer	45°C
Drying time (hours)	4-10 hours

Table 2: Specifications of forced convection paddy dryer

Dryer model	PHS – 320B
Capacity (kg paddy/hour)	7,800 – 32,000
Dimension (m) (L × W × H)	6.671 × 4.871 × 13.410
Net weight (tonne)	6.115
Function (Loading)	55 min approximate
Function (Unloading)	50 min approximate

According to industrial drying layout, wet harvested paddies from markets are firstly stored in dumping chute. Then, they are moved into pre-cleaner by the support of elevators and conveyors. Pre-cleaners remove dust, and stones, leave fertilizing seeds, and clean foreign crops by passing paddies through scalper and big to small size screens. After cleaning process, paddy-drying operation is started in dryer. There are totally three dryers in industry each having capacity of 30 tonnes paddy. Drying operation is initiated after drying temperature of hot air released from husk furnace is set. Hot air ducts carry drying air, and mechanical air blowers are used for forced convectional drying of paddy. To enhance greater milling recovery, drying, cooling, and tempering operations are intermittently operated in the dryer. Finally, dry paddies are placed in storing silo, and further milling processes are done to remove husks and brans of paddy grain.

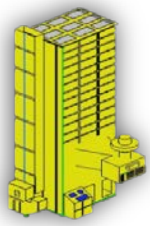

Fig 3. Forced convectional paddy dryer

Initial moisture contents of paddy used in this study are 30, 25, 20, 16% MC (wb), and the remaining or safe moisture content after paddy drying is 14% (wb). Paddy samples are cooled with forced air after heating or tempering. Tempering can increase moisture equalization between paddies and improve the milling quality of rice. Alternate heating and tempering completely kill the insects. Dryer can completely protect paddies from insect, animals, and rain. Not only it can dry very large amount of products but also it can accelerate drying time for drying of products. A specification of rice husk furnace is shown in Table 3.

Table 3: Specifications of rice husk furnace

Rice husk furnace	SB - 80
Maximum thermal energy (MJ/tonne)	731.988
Husk consumption (kg/hour) under maximum combustion	163.878
Exhaust ash release (kg/hour) under maximum combustion	21.8449
Dimension, m (L × W × H)	6.766 × 3.30 × 8.57
Net weight (tonne)	17.4
Attached dryer	PHS – 320B × 3

B. Technical Operations

Drying temperature is assumed according to ambient air temperature and the maximum temperature needed for good quality drying without developing the stress within the paddy kernel as given in Fig 4. Drying temperature should be selected by comprising between energy consumption and maximum head rice yield.

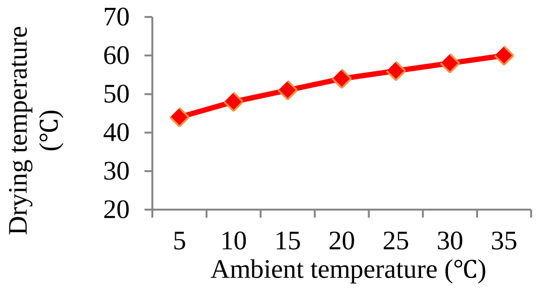

Fig.4 Relationship of drying temperature and ambient temperature

Before paddy filling into dryer, paddy should be pre-cleaned to remove chaffs, weeds, etc. to prevent uneven drying. If drying temperature is set higher than normal because of high humidity in rainy days or different grain conditions, there is a condition of grain cracking. In case of relative humidity under 65% or over maturity and hulled rice, 4-5°C that is lower than reference temperature should be set. (Source-Suncue Dryer PHS 320 B, Taiwan Product)

Drying temperature can significantly influence on head rice yield and specific energy consumption. Furthermore, the relative humidity of air inside the dryer is always less than that of ambient air since temperature inside the dryer is more than that of surrounding.

Drying process fundamentally takes place by heat and mass transfer. This convectional circulating dryer is able to reduce the dryness of the paddy samples up to 14% from over 30% moisture content.

To determine water removal rate for both minimum and maximum paddy entering rate, the calculation of mass balances for dry matter, water, and dry air are required. First, the amount of dry matter (solids) and water entering and leaving within paddies is calculated with the equations shown below.

$$\text{Initial MC of paddy (decimal)}, m_1 = \frac{\dot{m}_{w1}}{\dot{m}_{t1}} \quad (1)$$

$\dot{m}_{w1}$= water entering rate within paddy before drying kg /hour H_2O

$\dot{m}_{t1}$ = paddy entering rate before drying kg/hour

Amount of dry paddy before drying kg/hour dry paddy is

$$\dot{m}_{d1} = \dot{m}_{t1} - \dot{m}_{w1} \quad (2)$$

Since only water is removed, the dry matter in the dry product is the same as that entering in un-dried paddies.

$$\text{Final MC of paddy (decimal)}, m_2 = \frac{\dot{m}_{w2}}{\dot{m}_{w2} + \dot{m}_{d2}} \quad (3)$$

$\dot{m}_{w2}$ =water exiting rate within paddy after drying kg/hour H_2O

$\dot{m}_{t2}$ = paddy exiting rate after drying kg/hour

$\dot{m}_{d2}$ = amount of dry paddy after drying kg/hour dry paddy

Water removal rate of paddy by using forced convectional dryer is determined as follows.

$$\text{Water removal rate}, \dot{m}_w = \dot{m}_{w1} - \dot{m}_{w2} \quad (4)$$

Then, moisture collected by unit air mass after passing through wet paddies is calculated to determine mass flow rate of drying air.

Moisture gained by unit air mass = $W_{outlet} - W_{inlet}$

$$\dot{m}_a = \frac{\dot{m}_w}{W_{outlet} - W_{inlet}} \quad (5)$$

where $\dot{m}_a$ = mass flow rate of drying air (kg dry air/min)

W_{inlet}, W_{outlet} =Humidity ratio of inlet and outlet drying air (kg moisture/kg dry air) obtained from psychometric chart

Electrical energy consumption must be calculated so that running cost of paddy dryer can be estimated. To compute electrical energy consumption of dryer, both rotating mechanical parts and other supporting parts are considered. Electrical energy used by rotating mechanical parts of a dryer is calculated as follows.

$$E_{mech} = P_{mech} \times t \quad (6)$$

where E_{mech} is electrical energy for mechanical parts (kWh), P_{mech} is power consumed by mechanical parts (kW), and t is drying operation time (hour).

Electrical energy used by supporting mechanical parts of a dryer is computed as follows.

$$E_{support} = P_{support} \times t \quad (7)$$

where $E_{support}$ is electrical energy for supporting parts (kWh), $P_{support}$ is the power consumed by supporting parts (kW), and t is drying operation time (hour).

Total electrical energy consumption is the sum of electrical energy for both mechanical parts and supporting parts of a drying system.

$$E_{total} = E_{mech} + E_{support} \quad (8)$$

where E_{total} is total electrical energy (kWh), E_{mech} is electrical energy for mechanical parts (kWh), and $E_{support}$ is electrical energy for supporting parts (kWh).

Specific electrical energy consumption can be computed as follows.

$$SPEEC = \frac{E_{total}}{W_p} \quad (9)$$

where SPEEC represents specific electrical energy consumption (kWh/tonne), and W_P is amount of moist paddy to be dried (tonne).

Thermal energy released from burning of rice husks can be found by following equation.

$$E_{th} = H_w \times C_h \times t \quad (10)$$

where E_{th} is thermal energy (MJ), H_w is rice husk consumption rate of dryer (kg/hour), C_h is heat value of rice husk which is 13.4 MJ/kg, and t is for drying time (hour).

After calculating thermal energy from rice husks, specific thermal energy consumption is determined as follows.

$$SPTEC = \frac{E_{th}}{W_P} \quad (11)$$

where SPTEC represents specific thermal energy consumption (MJ/tonne), and W_P is amount of moist paddy to be dried (in tonne).

C. Drying Performances

In considering drying characteristics, drying capacity, drying rate and drying efficiency are mentioned. Drying capacity is the amount of dried paddy that can be dried with particular drying time and is given by:

$$C_d = \frac{W_d}{t} \quad (12)$$

where C_d is drying capacity of dryer (tonne dry paddy/hour), W_d is weight of dried paddy (tonne), and t = drying time (hour).

Drying rate is proportional to mass of water exists in one kilogram of dry matter before and after drying. Drying rate considers mass of water, not weight of dried product like drying capacity.

$$R = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (13)$$

where $M_{t+\Delta t}$ is mass of water/kg dry matter at time t+Δt, M_t is mass of water/kg dry matter at time t, Δt is time difference required for complete drying (hour), and R represents drying rate (kg/hour).

Energy efficiency of drying process by using mechanical dryer can be calculated by the following equation.

$$\eta = \frac{E_{theo}}{E_{thermal}} \times 100\% \quad (14)$$

where E_{theo} is theoretical energy requirement (J/kg), $E_{thermal}$ is thermal energy supplied to the dryer (J/kg), and η represents drying efficiency (%). To predict E_{theo} requirement, equation developed by Billiris et al. (2011) for medium-grain is used.

$$E_{theo} = (3{,}150{,}878 - 2377T)(MC_i - MC_f) + \left[e^{-23.2MC_i} - e^{-23.2MC_f}\right]\left(\frac{12{,}725{,}771 - 9601T}{-23.2}\right) \quad (15)$$

where MC_i is initial moisture content (dry basis) (decimal), MC_f is final moisture content (dry basis) (decimal), and T is grain temperature (10~60°C). To determine drying efficiency of paddy dryer, grain temperature T is assumed to be around 30°C (303 K) in average.

D. Economic Analysis

Economic analysis using forced convectional paddy drying deals with two sections: estimation of electricity cost for operation and profit calculation.

Electricity cost must include when total cost of paddy is considered. Profit obtained by selling rice can be determined as follows.

Profit = Total income – Total Cost (16)
= Milled rice×Rice selling price –
(Paddy Cost +Electricity Cost)

III. RESULTS AND DISCUSSIONS

A. Technical Operations

Maximum and minimum water removal rates of mechanical paddy dryer are determined in accordance with drying of 30% (wet basis) initial moisture content paddy to 14% (wet basis) final moisture content. Drying air-entering temperature of paddy dryer is operated with 60°C while drying air exit temperature is assumed to be 30°C and its relative humidity is 50% as well. Water removal rates for both minimum and maximum paddy entering rate are calculated and the results are shown in Table 4 below.

Table 4: Results of water removal rates

Calculations	Water removal rate (kg H_2O/hour)
Minimum paddy entering rate (7,800 kg/hour)	1421.861
Maximum paddy entering rate (32,000 kg/hour)	5953.488

The drying air follows a constant wet bulb process as it collects water from the moist paddy. Using temperature and humidity of the exiting air, its wet bulb temperature can be found on psychometric chart. Following this constant wet bulb temperature of 26.3°C to the inlet drying air, properties of drying air are then observed from psychometric chart. Humidity ratios of inlet drying air is 8 g moisture/ kg dry air and that of outlet drying air is 18 g moisture/kg dry air.

Hence, mass flow rates of air are 2.369 tonne dry air/min and 9.922 tonne dry air/min for minimum and maximum paddy entering rates respectively representing that the performance of paddy dryer is quite satisfactory.

Power requirement of paddy dryer has considered for both main rotating and other supporting mechanical parts. Contributions of power consumption with drying machines are shown in Fig 5 and 6.

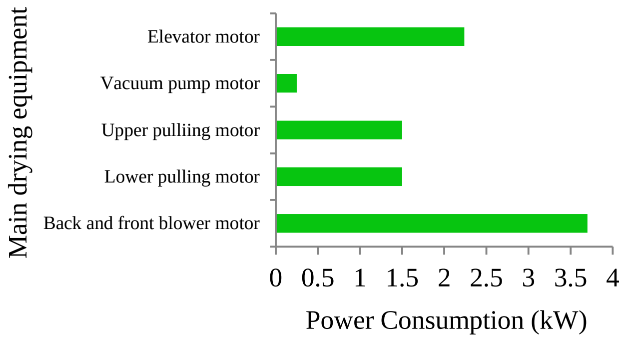

Fig.5 Power consumption of main drying equipments

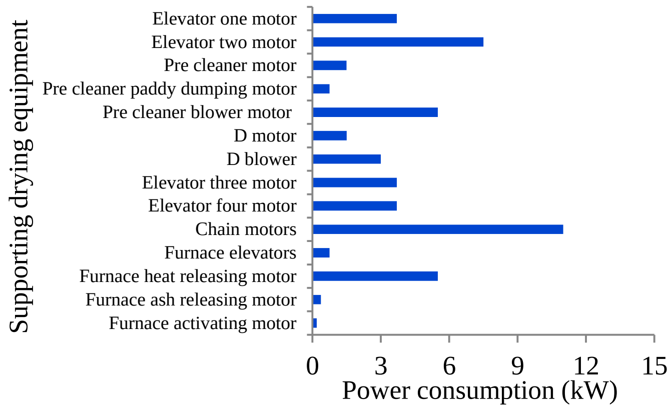

Fig.6 Power consumption of supporting equipments

When initial moisture contents of paddy to be dried is greater, drying time also takes longer. Electrical energy consumption varies with machine running time of 10, 8, 6, 4 hours for 30%, 25%, 20%, 16% initial moisture contents paddy respectively.

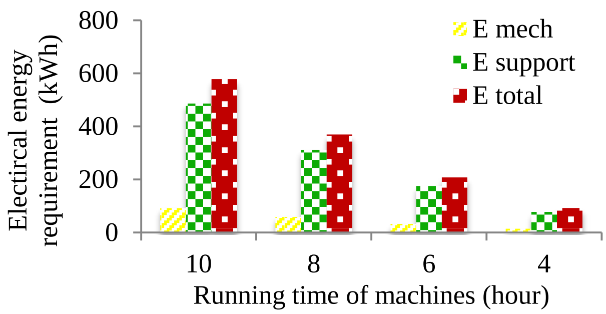

Fig.7 Electrical energy consumption with drying time

As seen from Fig 7, electrical energy consumption for mechanical drying parts, supporting drying parts, and total electrical requirement of 30 tonnes paddy versus drying time are shown. It is found that total electrical energy varies within the range of 578.36 kWh and 101.78 kWh.

Fig 8 shown below represents the variations of specific electrical energy consumption of one dryer according to drying time. Maximum and minimum SPEEC values are 19.279 kWh/tonne and 3.392 kWh/tonne respectively.

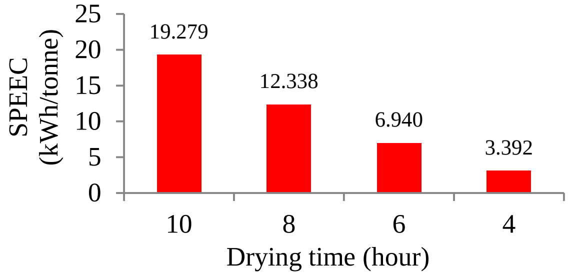

Fig. 8 SPEEC with drying time

In comparison to natural sun drying, rice husk furnace generates higher temperature, lower RH, lower product moisture, and even reduce spoilage. Thus, it is essential to determine requirement of rice husks for heating air. Thermal energy from rice husk with respect to drying time is shown in Fig 9.

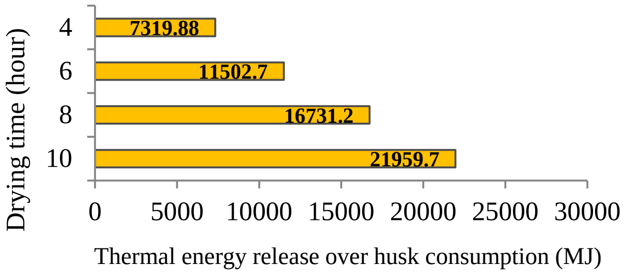

Fig. 9 Thermal energy from rice husk with respect to drying time

The above results indicate that when drying time takes longer, consumption of rice husks will be greater as expected.

B. Drying Performances

It is found out that one circulation paddy dryer can dry about 30 tonnes of paddy in one drying pass. There are totally three dryers operating in drying plant. According to the initial moisture content of paddy, drying time may vary. Moisture losses of paddy with drying time are given in Fig 10.

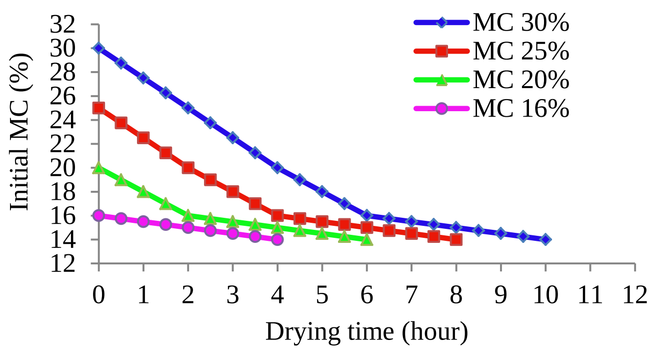

Fig.10 Moisture losses of paddy with drying time

As shown in Fig 10, it can be seen drying curve starts with constant drying period, and after that, falling rate period occurs. This is because dryer only delivers heating air when it reaches its maximum setting temperature. Drying with mechanical dryer involves tempering process that is to stop drying operation for a specific time. In order to reduce moisture content from 30 %, 25 %, 20 %, and 16 % wet basis to 14% wet basis, drying time takes approximately 10, 8, 6 and 4 hours including tempering operation respectively.

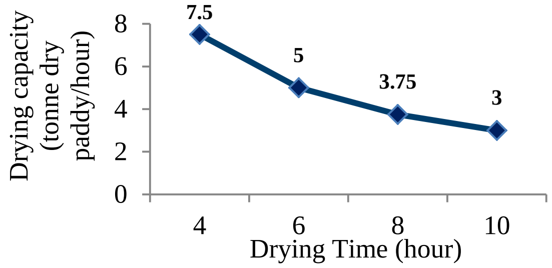

Fig.11 Drying capacity with drying time

According to Fig 11, the results indicate that when drying time increases, drying capacity decreases. Therefore, drying capacity is inversely proportional to drying time.

As can be deduced from Fig 12, drying rate decreases with decrease in initial moisture content of paddy. The results appear to confirm that drying rate is directly proportional to initial moisture content of product to be dried.

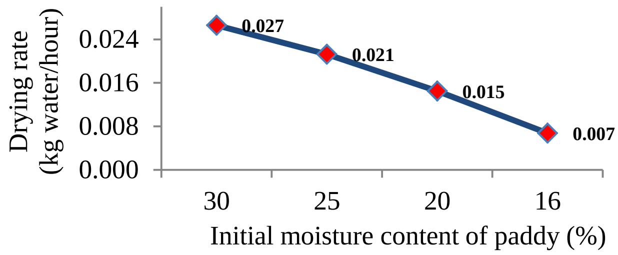

Fig.12 Drying rate with initial MC of paddy

Fig 13 shown below confirms that drying efficiency increases with increase in initial moisture content of paddy. Thermal energy supplied to dryer is greater than theoretical energy requirement, and the average drying efficiency of mechanical dryer is approximately 62.8%.

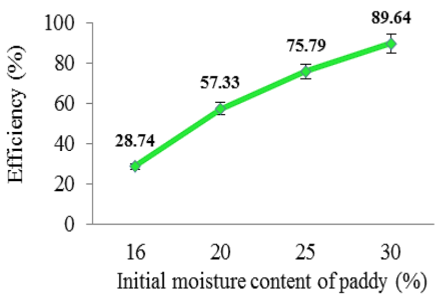

Fig. 13 Drying efficiency with Initial MC of Paddy

C. Milling Quality and Economic Analysis

Moisture content for milling process is recommended within the range of 10 – 14% wet basis because thermal and moisture content gradients while drying can produce stress within paddy kernels. This stress more than allowable limit causes some cracks in kernels and can reduce head rice recovery. Milled rice recovery result by using one paddy dryer is given in Fig 14.

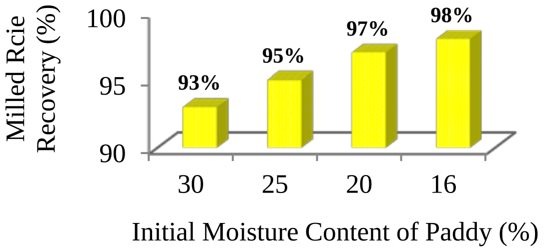

Fig. 14 Milled rice recovery (%)

From the milling results, industrial paddy dryer can produce almost 95.75% milled rice recovery in average, and this result provides clear evidence of paddy dryer's performance.

Electricity costs recommended by Myanmar Electric Line Distribution are 35 Kyats/unit for the first 100 units, 40 Kyats/unit for the next 100 units, and 50 Kyats/unit for all electric units in excess of 200 units.

Table 5: Estimated Cost for Running of One Dryer and Other Related Supporting Machines

IMC (%) (wb)	Unit (kWh)	Cost (Kyats)
30	579	26,450Ks (0.882 Ks/kg)
25	371	16,050Ks (0.535 Ks/kg)
20	209	7,950Ks (0.265 Ks/kg)
16	102	3,580 Ks (0.119 Ks/kg)

As shown in Table 5, electricity units for drying 30%, 25%, 20%, 16% initial moisture content paddy are 579 units, 371 units, 209 units, and 102 units respectively. According to electricity units, electricity cost will vary.

This economic analysis is done upon actual demand of paddy and rice (Sin Thu Kha) evaluated from rice market.

Cost of a sack of paddy (108lb = 49.091kg) (1kg =2.2lb)	=17,500Ks
Cost of 1kg of paddy	= 356.481Ks
Selling price of a sack of rice	= 23,700Ks
Selling price of 1 kg of rice	=482.778 Ks

After electricity cost and paddy cost are determined, profits gained by selling one-kilogram rice are 91.621, 101.623, 111.549, and 116.522 Kyats for 30, 25, 20, 16% initial moisture content as given. As positive impacts, higher head rice yield and larger profit will provide a feasible of the use of paddy dryer.

IV. CONCLUSION

The results of this study might have supplemental impact on Agricultural sectors of Myanmar representing consistency of current research with earlier findings such as:

- Providing practical significant technical operations, drying performance, milling results, and economic potential, and so forth
- Understanding theory behind fundamentals of drying such as moisture loss, drying rate, drying capacity, drying efficiency, and so on with clearer outcomes

Research activities presented here are limited to drying of paddy as described earlier, and from this study, it can extend an idea on further drying of other agricultural cereal crops such as wheat, corn, maize, etc. This study may shed light upon further possible contribution to research community of engineering fields of mechanical drying and agricultural roles.

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