Chapter 7

A SEQUENTIAL NUMERICAL TECHNIQUE FOR EFFICIENT UTILIZATION AND QUALITY IMPROVEMENT OF ROUGH RICE USING MULTISTAGE DEEP BED DRYING WITH TEMPERING.

7.1. Introduction

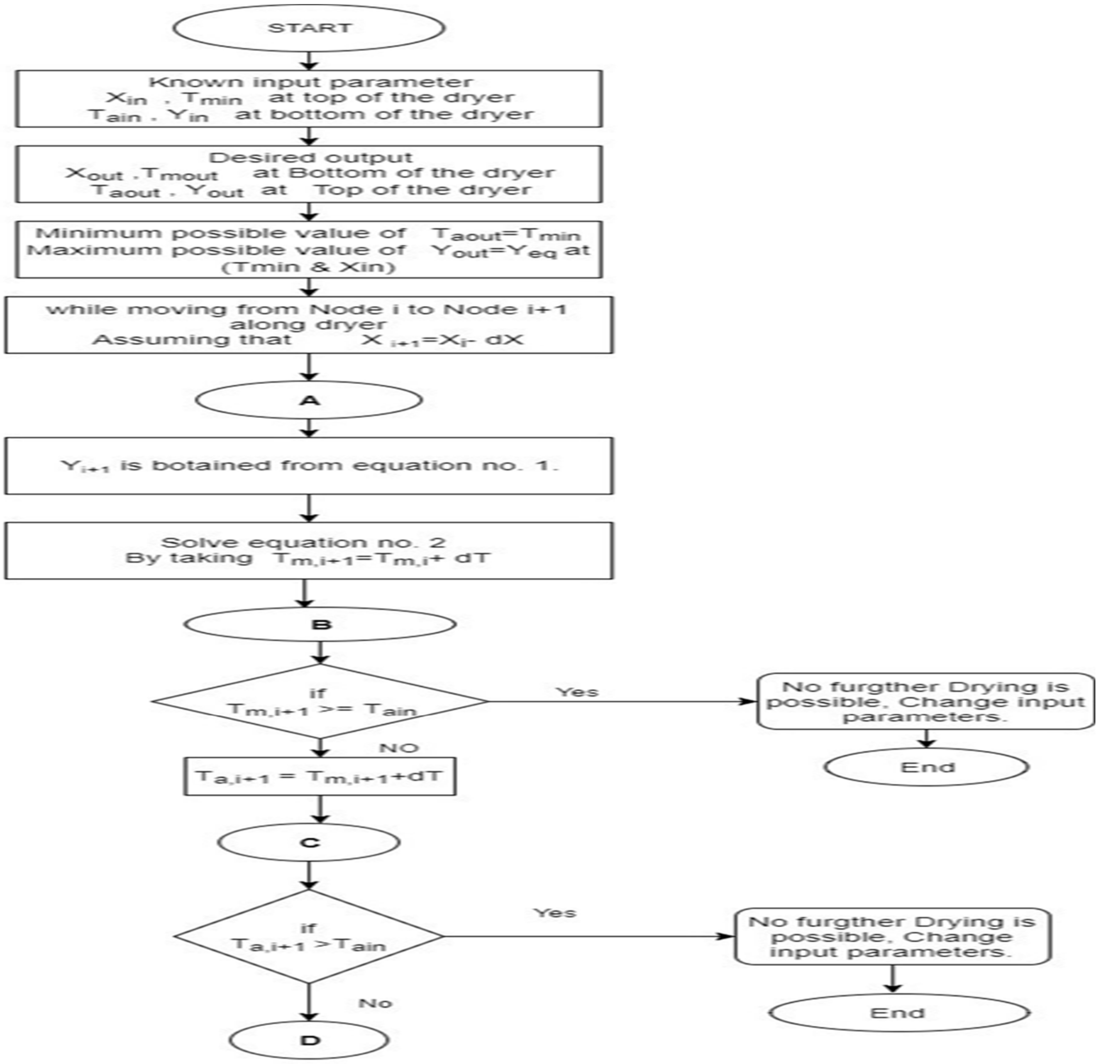
Rough rice, commonly known as paddy, is one of the staple foods for human beings and is hygroscopic in nature. When the water vapour pressure outside the kernel is greater or lesser than the pressure inside the kernel, it acquires or loses moisture. Harvesting rough rice at 20-22 percent moisture content usually leads to higher yields, less breakage, and fewer field losses due to falling and shattering, but such high moisture restricts the safe storage of these grains for long durations.. Therefore, it must be dried to approximately 13 to 15 % moisture content (w.b.) for storage over a year [Wongwises & Thongprasert, 2000]. Since the physical structure and appearance of the dried product are essential considerations, the drying temperature and the rate of heat and mass transfer play an essential role in determining the quality of grain. The drying rate and efficiency of the dryer depending on the temperature and humidity of the drying air. We can get an increased material flow rate at high temperatures, although this is frequently accompanied by a decrease in the grain's germination ability. It is thus necessary to understand the kernel temperature and moisture content during the drying process in order to establish acceptable operating temperatures for a specific dryer.

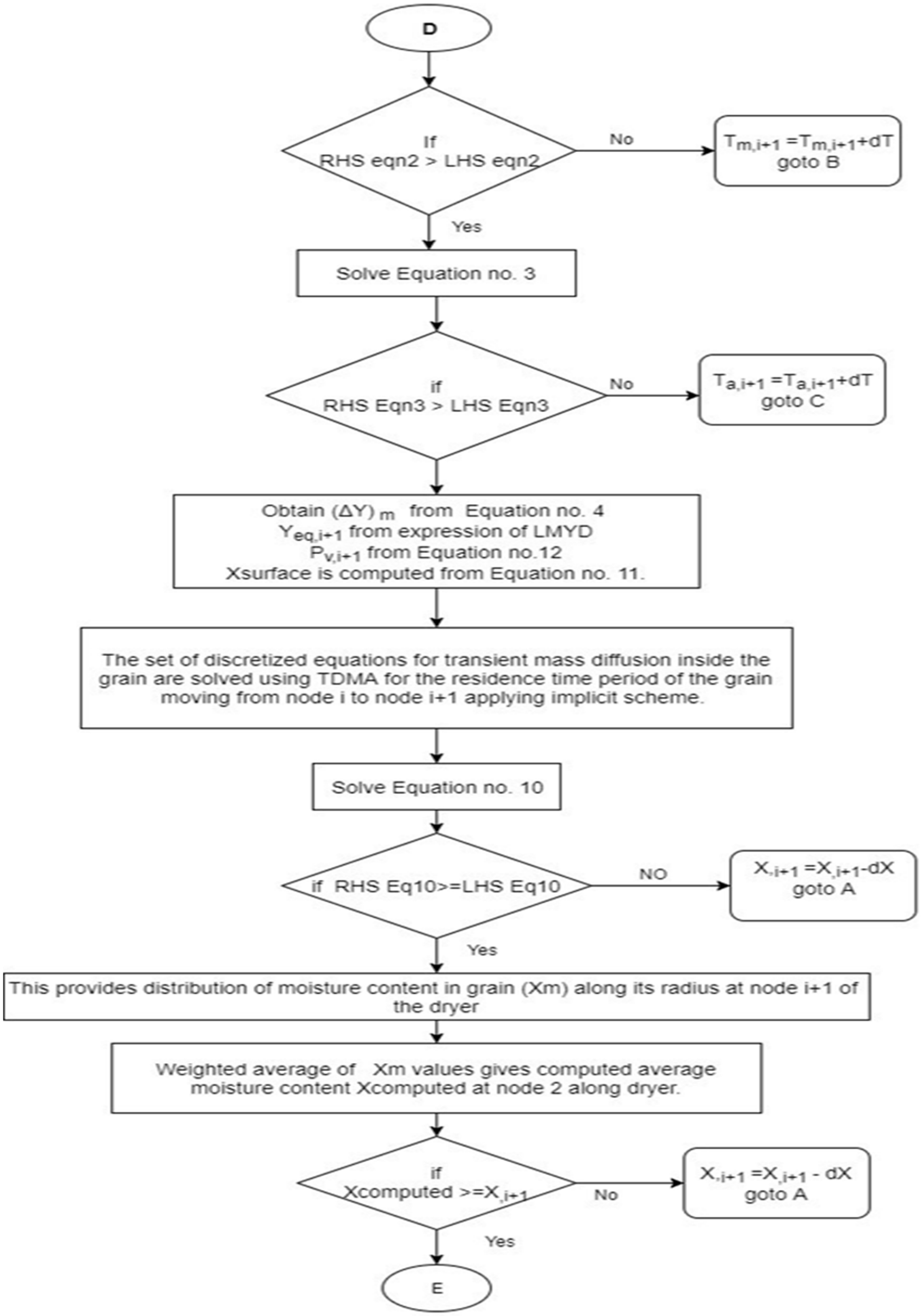
Here Two different cases of rough rice utility, one for commercial usage and the other for germination, are taken for study. It is found that in the first case, the moisture content drops from 25% d.b. to 14.8% d.b. in a single pass. To achieve this moisture content, the air supplied was

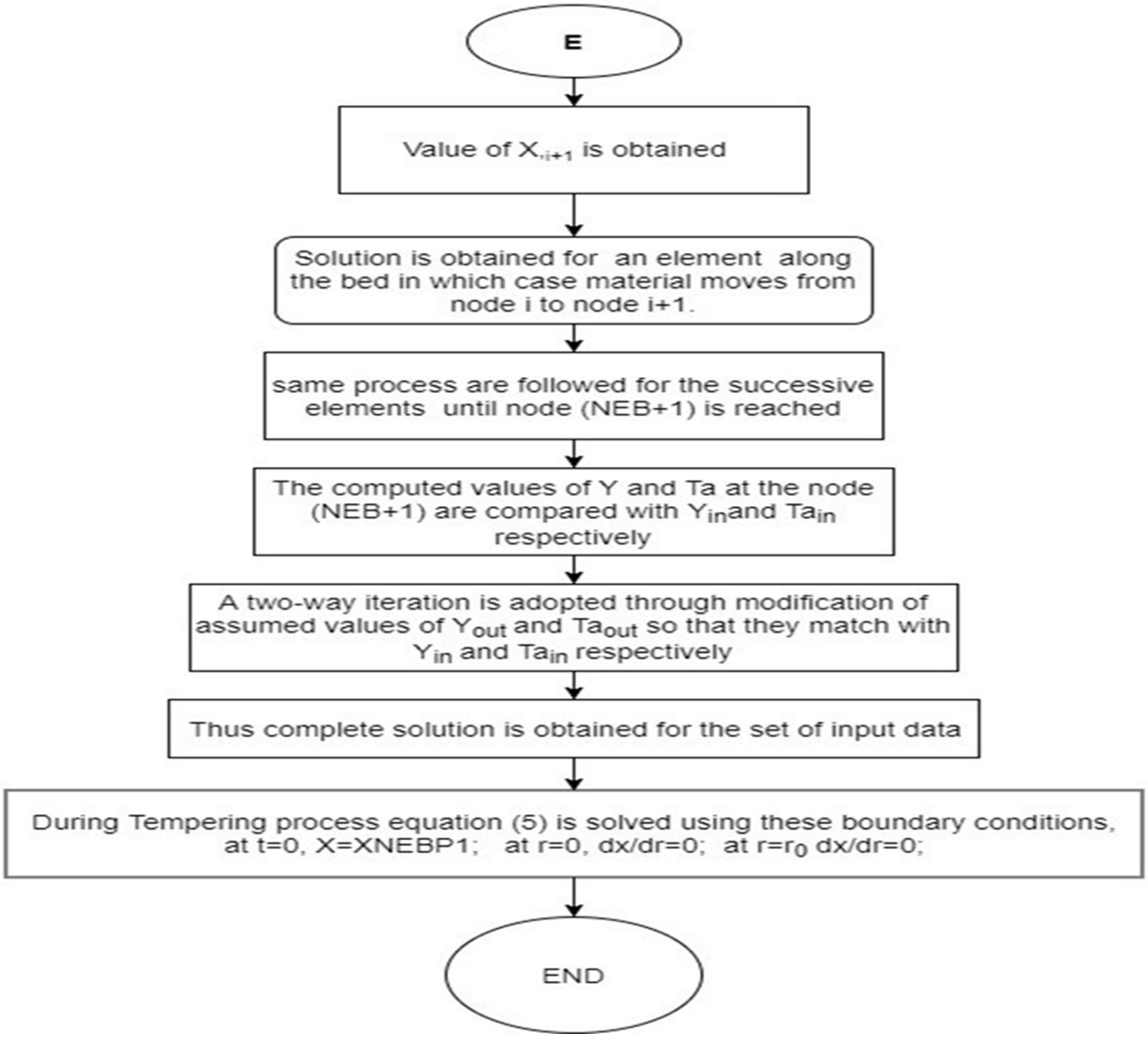
55℃, which is not viable to achieve the desired conditions both for germination as well as commercial utility. Hence two-stage drying is used with tempering where the air inlet temperature is limited to 43℃. The results obtained are in an acceptable range and can be used for commercial usage and germination purposes

7.2. The detailed algorithm for computing the mathematical model from node 1 to node 2 is shown below.

Any change lower than dX (for moisture content) and dT (for temperature) has no practical consequence. After NEB =15 and NEP=10, no change in grain's moisture content appears, and hence these values are taken for further analysis.




D
If
RHS eqn2 > LHS eqn2
No
$T_{m,i+1} = T_{m,i+1} + dT$
goto B
Yes
Solve Equation no. 3
if
RHS Eqn3 > LHS Eqn3
No
$T_{a,i+1} = T_{a,i+1} + dT$
goto C
Obtain $(\Delta Y)_m$ from Equation no. 4
$Y_{eq,i+1}$ from expression of LMYD
$P_{v,i+1}$ from Equation no.12
Xsurface is computed from Equation no. 11.
The set of discretized equations for transient mass diffusion inside the grain are solved using TDMA for the residence time period of the grain moving from node i to node i+1 applying implicit scheme.
Solve Equation no. 10
if RHS Eq10>=LHS Eq10
NO
$X_{,i+1} = X_{,i+1} - dX$
goto A
Yes
This provides distribution of moisture content in grain (Xm) along its radius at node i+1 of the dryer
Weighted average of Xm values gives computed average moisture content Xcomputed at node 2 along dryer.
if
Xcomputed >=$X_{,i+1}$
No
$X_{,i+1} = X_{,i+1} - dX$
goto A
Yes
E



The developed program has been simulated using two different cases, A and B.

Case A- High temperature with single-stage drying: Air at 55^0C is used to heat the grains. At this temperature, the grain can be dried in a single pass from 25% to 14.8% (d.b). There is no need of tempering, but there is a possibility of a loss of germination of paddy. This is because germination percentage is a function of air temperature, and germination percentage decreases with the increase in drying air temperature exponentially [Bala, 2016]. In this case, the quality of grains obtained can be used for human consumption and other purposes such as cattle feed. But there is a need for another design that could preserve the germination viability of paddy and can be safely dried to desired moisture content at the same time.

Table 7.0.1 Constant values for Rough Rice:

Parameter	Case A	Case B
Dryer Geometry		
Shape	Vertical cylinder, H = 0.50 m	Vertical cylinder, H = 0.20 m
Area of circular cross section of the dryer	= 0.36 m^2	0.36 m^2
Recommended maximum values of temperature and outlet moisture content of rice for safe storage over a year.[Wongwises , 2000,Bala, 2016] X_{out} 14-15 %, d.b., T_{mout} 43^{o}C for germination purpose. T_{mout} 55^{o}C for commercial purpose.		
simulation Parameters		
Tain	55^{o}C	43 ^{o}C
(RH)	30% - 80%,	30% - 80%
Wm	80-130 kg/hr	80-130 kg/hr
Usup	0.7 – 1.3 m/sec	0.8 – 1.4 m/sec
X_{in}	18-30 %	18-30 %
Standard input data for result interpretation		
T_{amb}	30^{0}C	30^{0}C
T_{ain}	55^{0}C	43^{0}C
T_{min}	30^{0}C	30^{0}C
Y_{ain}	0.0133 kg/kg, d.b.	0.0133 kg/kg, d.b.
T_{min}	30^{0}C	30^{0}C
X_{in}	0.25 kg/kg, d.b.	0.25 kg/kg, d.b.
W_m	100 kg/hr	100 kg/hr
Usup	0.8 m/sec	1.2 m/sec
D_p	4.4 mm	
h	116 W/m^2 ^{0}C	148.5 W/m^2 ^{0}C
h_m	0.1357 kg/m^2	0.1828 kg/m^2
dX	0.0005 (kg/kg; d.b.)	0.0005 (kg/kg; d.b.)
dT	0.1^{0}C	0.1^{0}C

ρ_p = 981 kg/m^3 bone dry, Dp = 0.0044m [ASME Feb, 1999],

$D_{wg} = 6.72 \times 10^{-6} \exp(-31500/RT)$ [Thakur & Gupta, 2006]

Case B- Moderate Temperature with two-stage drying: uses an air temperature of 43^0C with two stages of drying. This is the safe temperature limit for paddy for germination as well as commercial use [Bala, 2016]. The final moisture content obtained in this case after the first stage drying was 18.6% (d.b.). Further drying was not possible since the temperature potential was exhausted. This concluded the need for tempering. After allowing the grain to temper for a sufficient period of time, the grains are resent for second-stage drying. The final moisture content obtained was 15% d.b.

Equilibrium moisture content for rough rice

Studies have reported that long with the modified Henderson equation, the empirical Chung-Pfost equation is frequently employed to predict the moisture content values of grains.[G. O. Ondier et al.,2010.] Estimated that Chung-Pfost equation gives the most satisfactory result for drying characteristic of rough rice.

The Chung-Pfost equation has the form,

$$\mathbf{X_{eq} = E - F \times \ln\left(-(T + C) \times \ln\left(\frac{P_v}{P_{vs}}\right)\right)} \tag{4.51}$$

Here Xeq is the equilibrium moisture content (decimal d.b) and T is the temperature °C;

Where, E=0.29394, F=0.046015 and C=35.703

7.3. Results and Discussions

Using (Table7.1) A numerical study of the developed program for optimum use of the dryer's provided geometry for both cases (CASE-A & CASE-B) has been performed.

7.3.1. CASE-A

The average moisture content of the material decreases along with the bed height. It is clearly seen that the moisture content reduces along the travel length. This drop-in moisture content is high in the initial stage which is due to the high potential for mass transfer owing to the high moisture content. Along with the bed height, as the moisture content decreases, this potential drops significantly, and hence the moisture removal rate decreases. This removal of moisture can also be predicted with an increase in material temperature shown in Fig. 7.1.

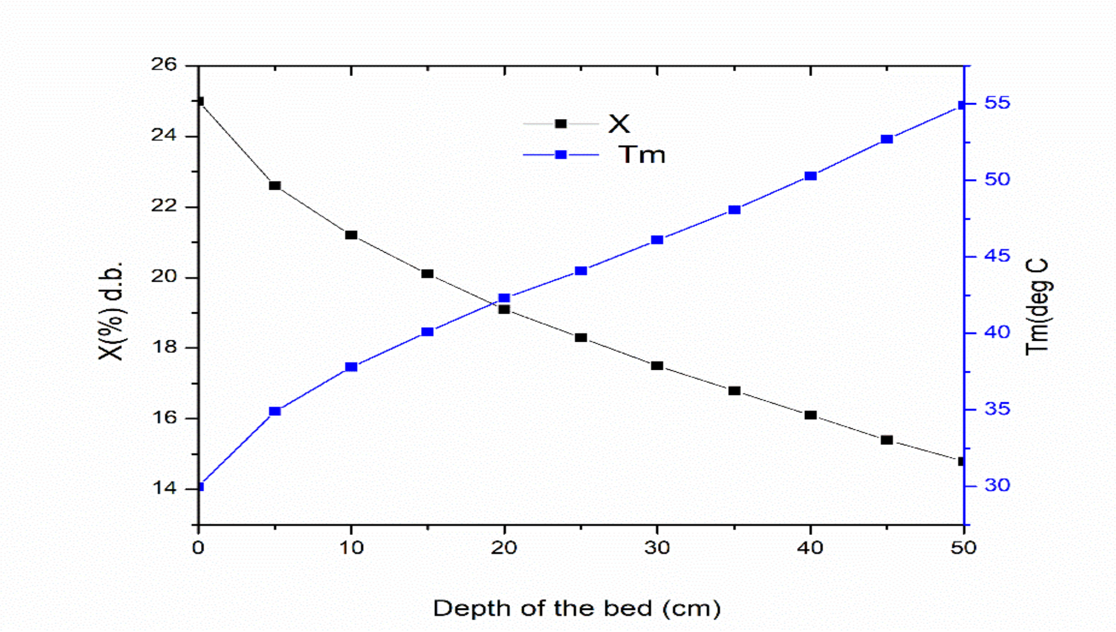


Figure 7.1. Average moisture content and temperature of grain vs. Depth of bed.

The counter flow behavior is reflected in the moisture content of the grain and the drying air. We can see that the temperature of the air at the inlet of the drying chamber is high. The temperature of the drying air continues to drop as it absorbs the moisture from the grains. Maximum drying is seen to occur in the upper zone of the dryer due to the higher availability of moisture content. Hence the temperature drop of the drying air is accelerated in the upper zone. Fig. 7.2 characterizes the behaviour of the drying air where the moisture is seen to increase along with the bed height, and the temperature is seen to decrease along with the bed height.

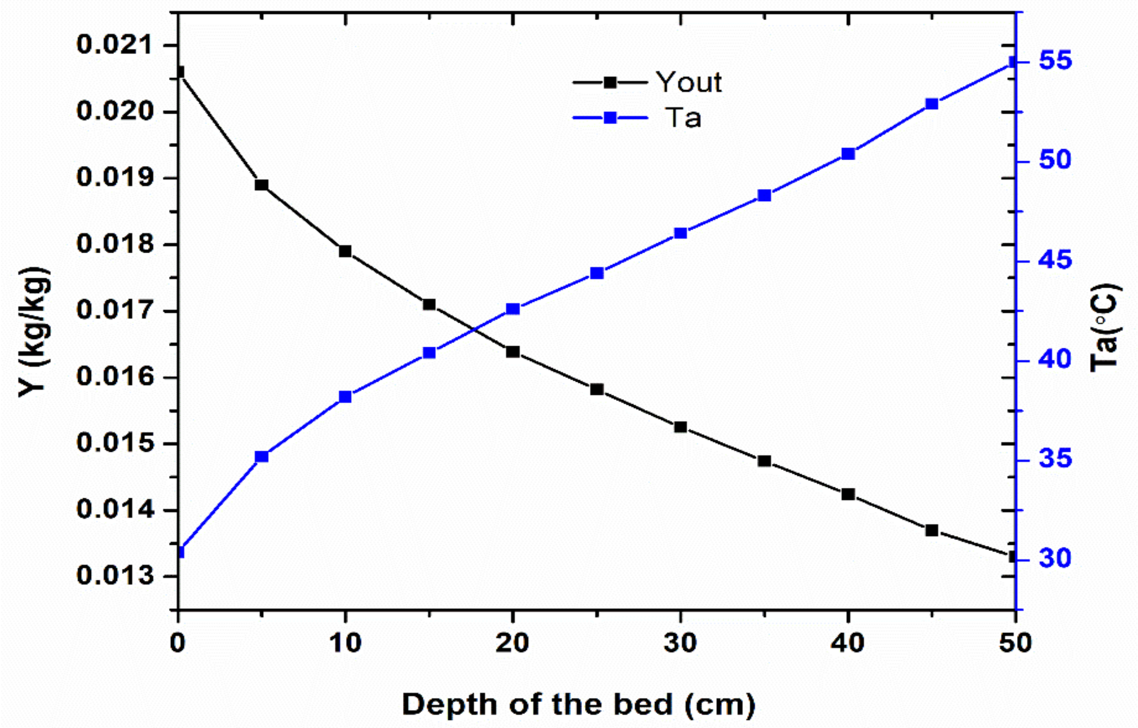


Figure 7.2. Specific humidity and temperature of air vs. Depth of bed.

The behaviour of the moisture removal process from the inner kernel to the outer surface of the grain is complex. This can be comprehended by discretizing the grain into a number of nodes. It is seen that with the initial moisture content of 25% d.b, the outer surface approached equilibrium moisture content of 5.42% d.b, and the inner core has 24.4% moisture content. This was achieved by maintaining a residence time of 66 minutes. Fig 7.3 shows that the moisture content drops steeply at the outer nodes due to convective heat transfer at the outermost surface. Whereas the inner kernels undergo conductive heat transfer and therefore the temperature drop is relatively slow and hence the moisture content is high. At node 17, this transition effect between convective heat transfer at the outer surface and conductive heat transfer at inner kernels is seen in fig. 7.3.

This moisture gradient created inside the rice kernel during drying causes thermal stresses inside the kernel, leading to fissuring.

$$\text{Moisture Gradient (\% d.b/ mm)} = \frac{\text{Moisture content at the centre} - \text{Moisture content at surface}}{\text{Radius of the kernel}}$$ In this case Moisture gradient= 8.58 % d.b. / mm

Thus, the process of tempering is essential in paddy drying.

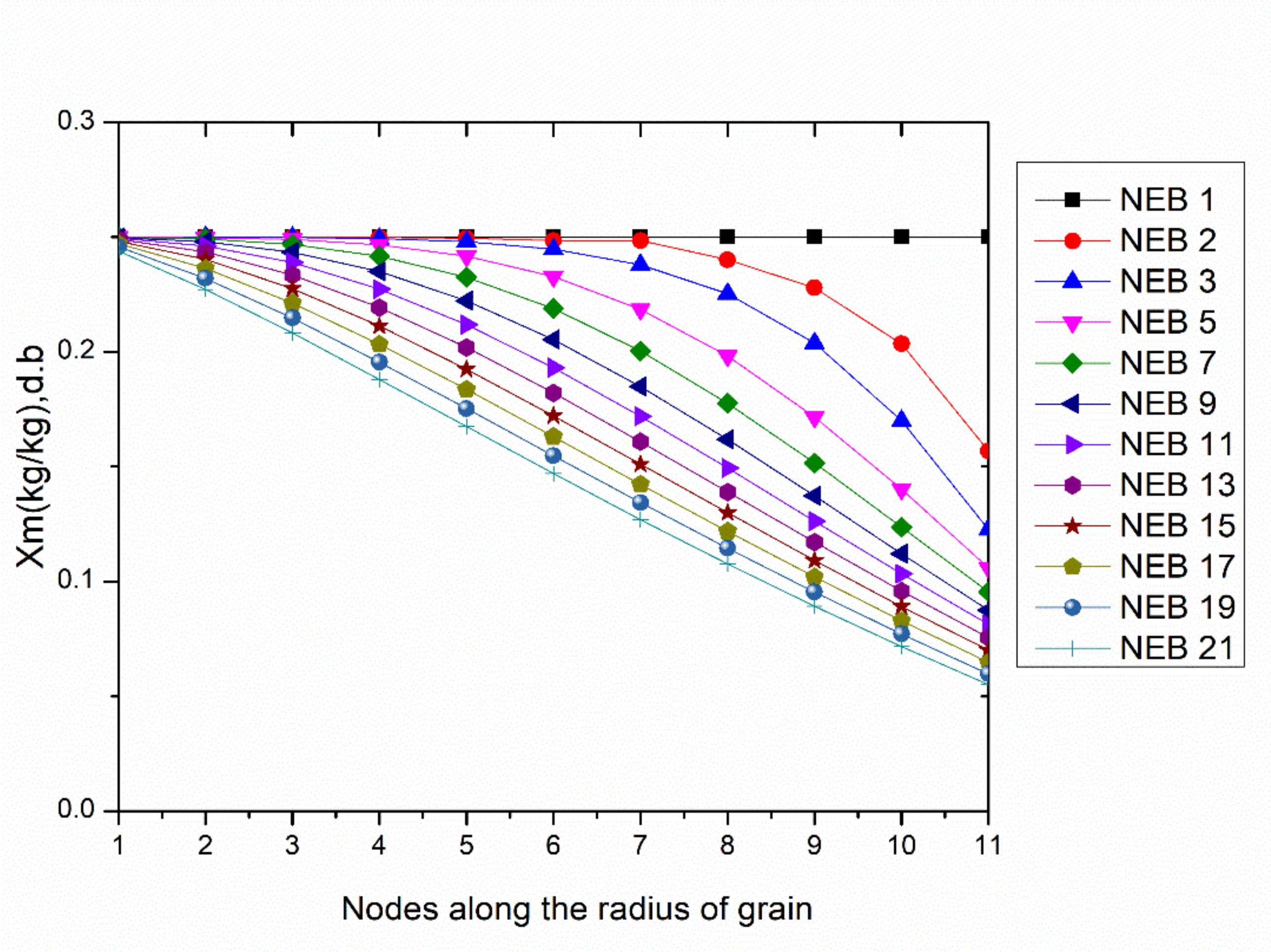


Figure 7.3. Intra-kernel moisture distributions.

This moisture content in the grain is also dependent upon the mass flow rate. If the mass flow rate increases, the residence time reduces, and the moisture content increases at the outlet (Table.2).

Although, heat utilization increases with increased mass input, and hence the efficiency of the dryer increases. Since our desired range for rice grain storage is between 14 to 15 % (d.b.), we can analyze that the optimum mass flow rate of material is between 80 to 100 kg/hr. A flow rate of 100 kg/hr gives the best efficiency of the dryer (66.4%) within the desired moisture content.

On the other hand, if the drying air temperature at the inlet is increased, then under the influence of higher driving potential for mass transfer, the average content of the outlet moisture is seen to decrease relatively. Also, from Table.2, we deduce that for a particular inlet air temperature, if the mass flow rate is increased, then the moisture content of the grain at outlet is proportionately high. Therefore, we conclude that the desired quality of air is obtained with a mass flow rate between 80-100 kg/hr with an inlet air temperature of 55^0C, where the efficiency is nearly 66.4% (Table7.2). Among different factors responsible for efficient drying of the grains, the superficial velocity is one factor that largely affects the pressure drop and power consumption and, therefore, the dryer's efficiency. Pressure drop is directly proportional to the square of superficial velocity, whereas power consumed is proportional to the cube of velocity. Thus high velocity is a limiting factor in deep bed dryers due to high energy consumption. Fig.7.4 shows the relationship between powers consumed and pressure drop. The effect of superficial velocity on the efficiency reveals that with the increase in velocity, the rate of heat utilization is reduced and thus efficiency of the dryer drops.

From Table7. 2 and Table 7.3 following inferences are drawn:

(i) Cold Climate (T_{amb}=25 °C and RH=50%)

Inlet air at this condition carries less heat, and hence the heat supplied is less, resulting in an efficiency drop to around 55%. Paddy in such conditions can be dried to 14.4%. In this safe moisture limit range, the mass flow rate can be increased to approximately 115kg/hr. However, the mass flow rate must be reduced to 75 kg/hr for paddy with higher moisture content around 30% d.b.

(ii) Hot Climate (T_{amb}=35 °C and RH=50%)

Under such conditions, the mass flow rate is reduced by 20% to keep the final moisture content within the acceptable limit. Whereas for material with a higher moisture content of 30 % d.b. mass flow rate is limited to 45 kg/hr.

(iii) Humid Environment (T_{amb}=30 °C and RH=80%)

Poor performance is recorded for such conditions where the efficiency is limited to 38%. Under such humid conditions, the mass flow rate is limited to 60 kg/hr to keep the moisture content within acceptable limits. For materials with a moisture content of 30% d.b., the mass flow rate is limited to 30kg/hr.

Table 7.0.2 Performance comparison for a given Y_{in}

Y_{in} (kg/kg)	X_{in} (%) (d.b)	Ta_{in} (^{0}C)	Wm (kg/hr)	Material outlet Condition		Air Outlet Condition		Flow Ratio	RT (min)	Eff. (%)
				Xout (kg/kg)	Tmout (^{0}C)	Taout (^{0}C)	Yout (kg/kg)			
0.0133 Tamb=30 C RH 50%	25	55	80	14.5	54.8	31.2	0.01936	17.45	82.7	55.1
	25	55	100	14.8	54.9	30.4	0.02062	13.95	66.2	66.4
	25	55	120	15.7^*	54.8	30.2	0.02135	11.63	55.2	73.3
	18	55	100	12.0	54.9	33.1	0.0179	13.18	62.5	41.6
	20	55	100	12.7	54.9	31.0	0.0188	13.40	63.5	49.8
	30	55	100	18.4^*	54.8	31.9	0.0214	14.50	68.8	73.1
	25	43	100	18.7^*	42.7	30.8	0.0207	14.40	66.2	76.6
	25	50	100	16.7^*	49.8	31.4	0.0.195	14.17	66.2	67.0
	25	60	100	14.3	59.2	32.5	0.01978	13.75	66.2	59.3

Table 7.0.3 Performance comparison for varying Y_{in}

Y_{in} (kg/kg)	X_{in}(%) (d.b)	Ta_{in} (^{0}C)	Wm (kg/ hr)	Material outlet Condition		Flow Ratio	RT min	Eff. (%)
				Xout (kg/kg)	Tmout (^{0}C)			
0.0098 [Tamb=25 C RH 50%] Cold Climate	25	55	100	14.4	54.7	13.96	66.2	55.8
	25	55	115	15.0	54.6	12.14	57.5	63.9
	30	55	75	14.9	54.7	19.35	91.8	60.2
0.0177 [Tamb=35 C RH 50%] Hot Climate	25	55	100	16.4*	54.8	14.50	66.2	65.4
	25	55	80	14.9	54.6	18.14	86.1	61.8
	30	55	45	15.0	54.8	32.26	153.0	51.6
0.01877 [Tamb=30 C RH 80%] Rainy Climate	25	55	100	19.5*	54.7	13.96	66.2	34.,62
	25	55	60	15.0	54.8	23.26	110.3	38.03
	30	55	30	14.9	54.8	48.39	229.5	27.49

* Moisture content beyond acceptable limit for longer storage

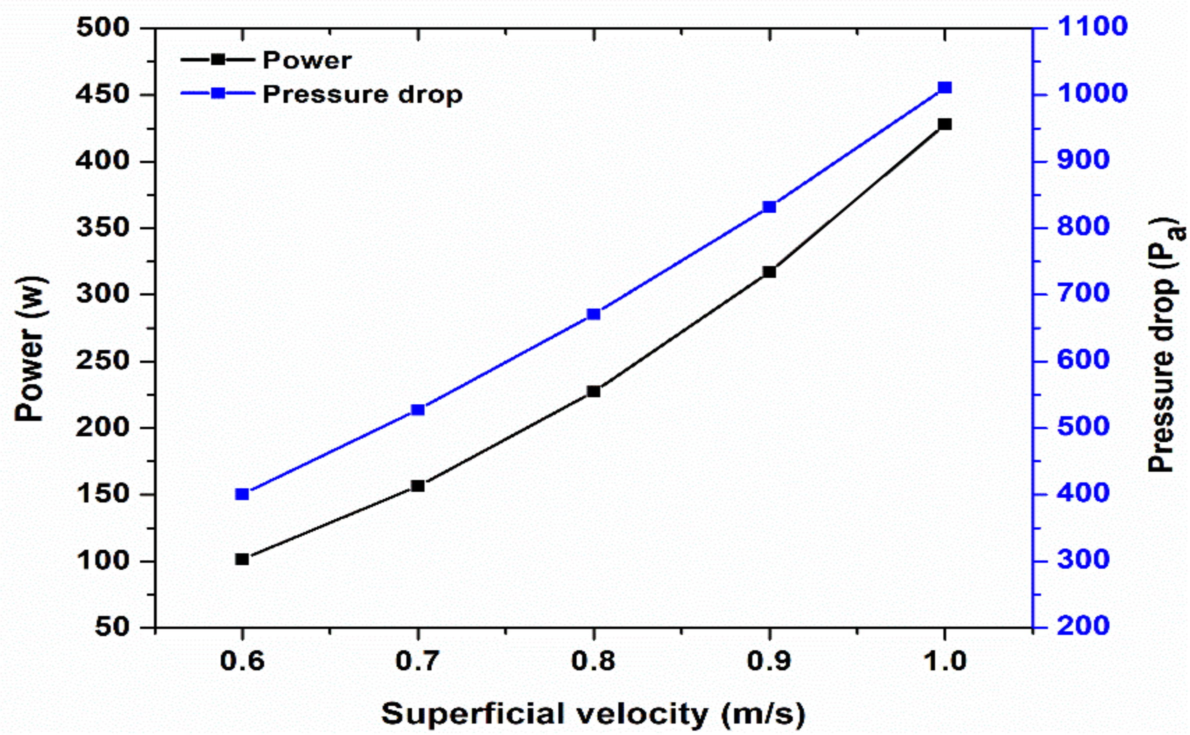


Figure 7.4. Power and Pressure in the dryer at different velocities

7.3.2. CASE-B

Despite variation in several parameters like mass flow rate of material, superficial velocity of air, and air temperature (Fig. 7.5, Fig. 7.6, Fig. 7.10), the desired moisture content for paddy was not achieved. Hence, there is a need for a second stage of drying where the grain is exposed to tempering. Tempering will allow the moisture at the center of the grain to travel to the surface of the grain, thus allowing more drying. There will be a considerable drop in moisture content at the center as the water will travel to the surface by mass diffusion. Rough rice with 25% moisture was subjected to drying for 26 minutes, the moisture content at the surface decreased rapidly to 7.88% from the existing 25%, but the inner kernel remained almost unchanged (Fig.7.7). This demands tempering in the drying of the rough rice. Fig.7.8 shows the moisture content inside the kernel of the rough rice that has been left for tempering for 240 minutes.

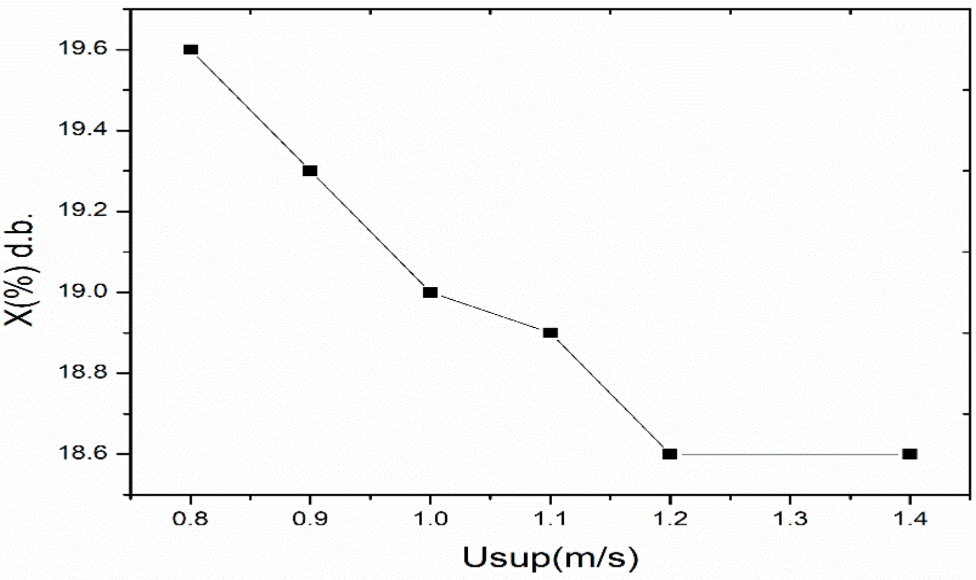


Figure 7.5. Average moisture content vs Superficial Velocity of air.

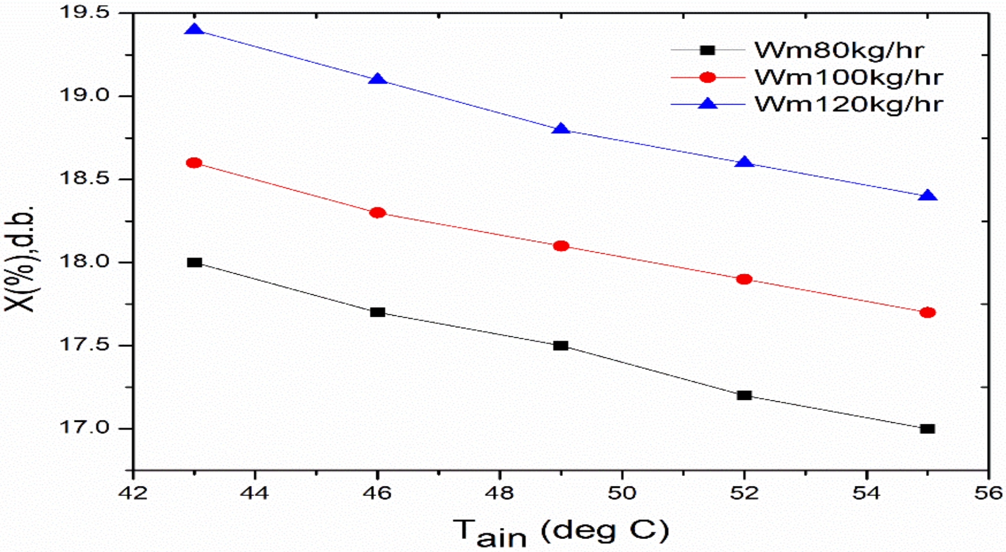


Figure 7.6. Average moisture content vs Temperature of air at different material flow rate.

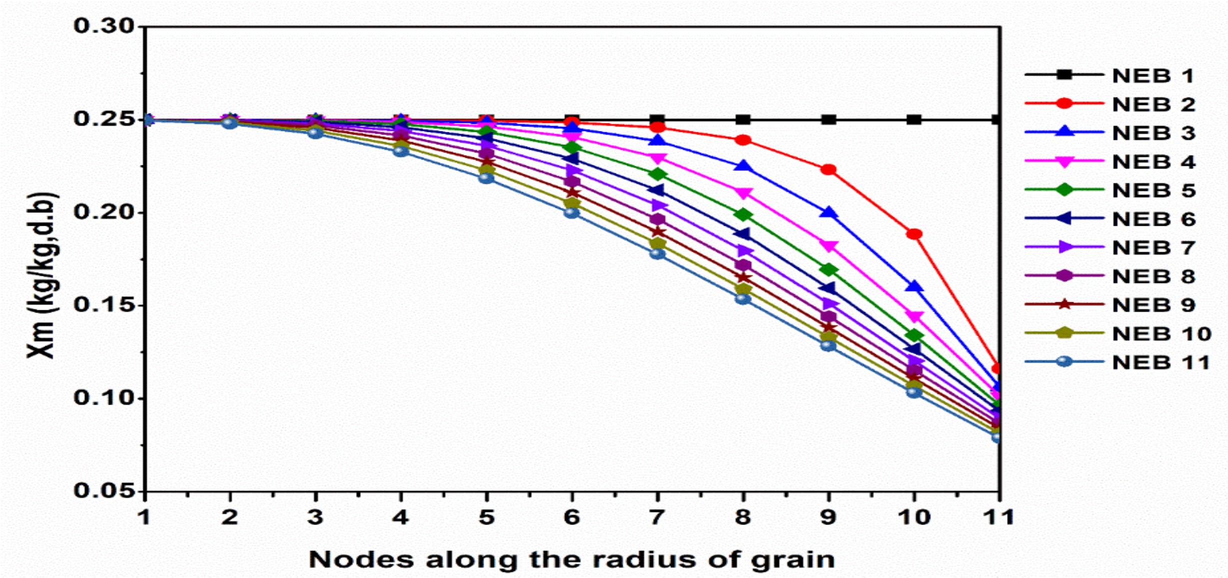


Figure 7.7. Intra-kernel moisture distributions.

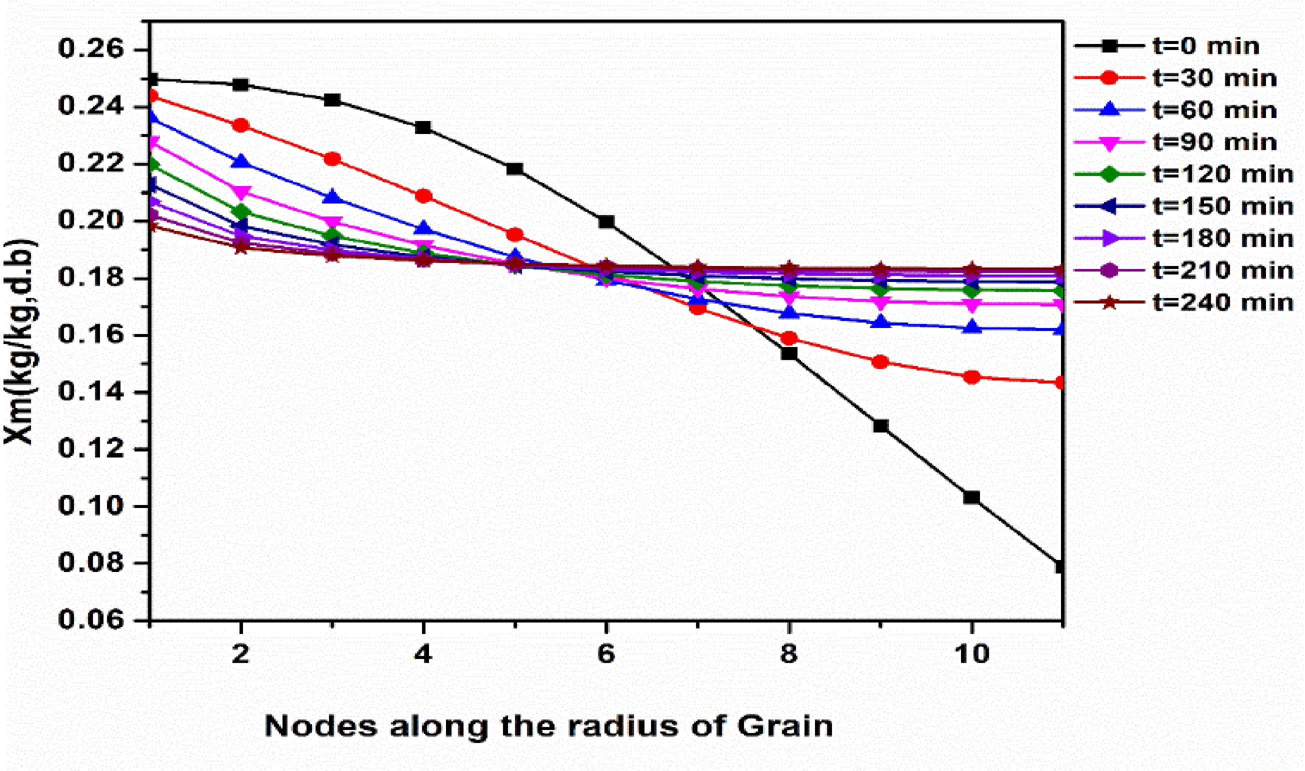


Figure 7.8. Intra-kernel moisture for different tempering duration

The tempering curve at t=0 min represents the moisture content inside a kernel just after the first drying stage for 26 minutes duration. The central node (NEG=1) has a moisture content of 24.9% d.b., while the surface node (NEG=11) has a moisture content of 7.88 %d.b. Thus a significant gradient in moisture content is developed between the center and the surface of the kernel. The moisture content gradient obtained in this drying curve is 7.78 % d.b. /mm. After t=30 min, there was a considerable amount of drop in the moisture gradient. The moisture content at the surface was recorded as 14.3%d.b. The moisture content at the center of the grain showed no convincing drop and recorded 24.3%d.b. When exposed to a period of 240 minutes of tempering, the center of the kernel reported a compelling drop in the moisture content to 19.8%d.b. The surface value was 18.3%d.b. Thus moisture content gradient was dropped to 0.68%d.b./mm from existing 7.78%d.b./mm.

$$\text{Moisture Gradient (\%d.b./mm)} = \frac{\text{Moisture content at the centre} - \text{Moisture content at surface}}{\text{Radius of the kernel}}$$

The estimated moisture content gradients within a rice kernel during drying at 43°C and 50% RH for 26 min and then tempering for different durations is shown in Fig 7.9. A high rise in moisture content gradient is seen, which is diminished when tempered. With 60 min temper, the moisture gradient dropped about 45%. Further tempering for 120 min removed about 76% of moisture content gradients. And almost all moisture content gradients were eliminated after about 360 minutes of tempering. The curve shows a steep drop in the early temper while the slope reduces throughout tempering and tends towards a zero gradient. Table 7.4 shows the relation of moisture gradient (% d.b./mm) and fissured kernel (%)

Table 7.0.4 Relation of moisture gradient (% d.b./mm) and fissured kernel (%)[Dong et al., 2009]

Moisture Gradient (% d.b./mm)	Fissured Kernel (%)
17	60
13	40
10	35
7.5	30
5	20
3	8

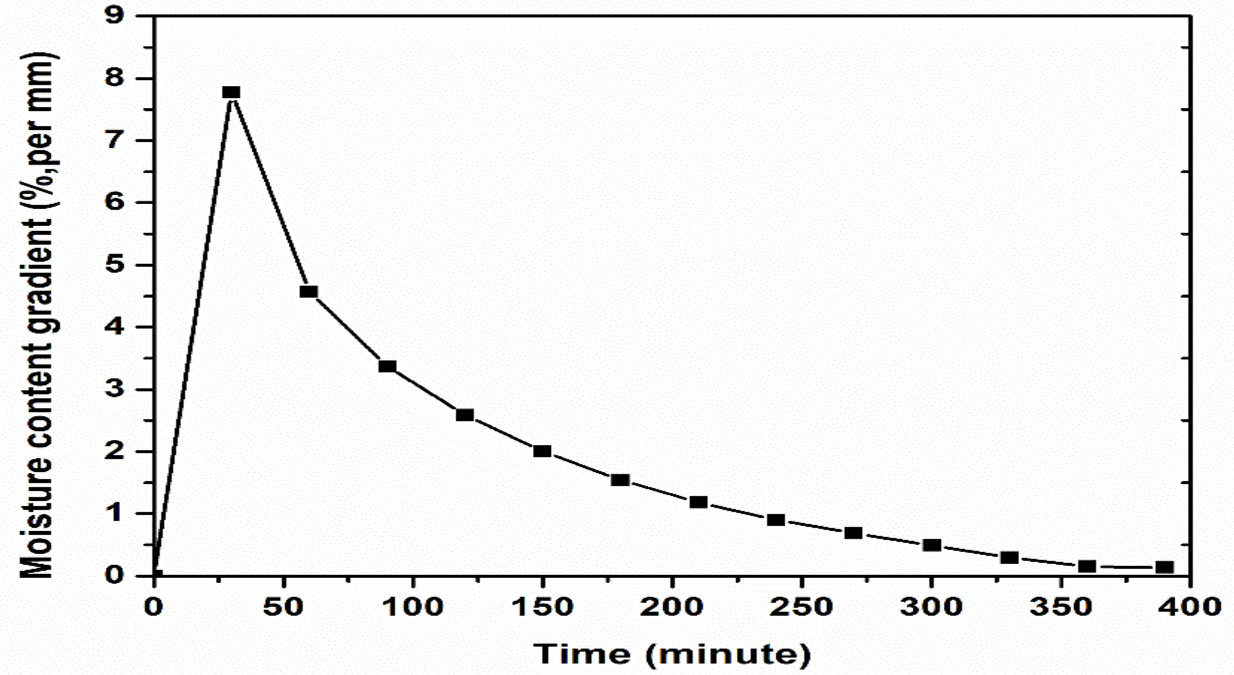


Figure 7.9. Moisture content gradient vs tempering time (minutes).

The two-stage drying of rough ice is illustrated in Fig.7.10. The first stage of drying limited the moisture content to 18.6%, with no further reduction possible. Further reduction was accomplished using the tempering process. The final quality of rough rice after 120 minutes of tempering brought the moisture content into safe limits of 14-15% d.b., maintaining the dryer efficiency of 30.68%. The efficiency of the dryer slightly increases to 32.4% with the moisture content of 14.8% d.b. when tempered for 240 minutes. Therefore, we conclude that 120 minutes of tempering with nearly 15% moisture content is the optimum time for the safe storage condition of rough rice in the two-stage drying process. Table 7.5 shows the final quality of rice obtained in Stage II drying after allowing the grain to temper for the specified amount of time

Table 7.0.5 Quality of paddy at different tempering period.

Time for tempering (min)	Final moisture content (X_{out}) of Rice, % d.b.	Outlet Air Temperature (°C)
30	15.6	34.5
45	15.4	33.8
60	15.3	33.4
90	15.1	33.3
120	15.0	33.3
180	14.9	33.2
240	14.8	33.0

As per Table 7.6. We can conclude that,

- If paddy with 25% d.b. moisture is tempered for 30 minutes, the throughput observed is 77kg/h for safe drying, where the moisture content gradient is reduced by 44%. Increasing the temper duration for 60 minutes increases our throughput limit to 92 kg/h with a 58% reduction in moisture content gradient. Further tempering of 120 minutes gives a throughput of 100 kg/h with a 77% reduction in moisture content gradient, thus providing rice of high head yield and less fissured and stress-prone kernels. Therefore tempering of 120 minutes is ideal for two-stage drying of rough rice in this case.

- If the initial moisture content of the grain is high (say 30 % d.b.) and tempered for 120 minutes, the maximum throughput we can obtain is 65 kg/hr with 75% reduction in moisture content. Mass flow rate can be boosted by increasing the material flow rate by increasing the tempering duration.
- If the initial moisture content of grain is low (say 20 % d.b.), tempering of 30 minutes is sufficient in order to get a throughput as high as 220 kg/hr with 60% reduction in moisture content gradient.

Table 7.0.6 Performance comparison in two stage of drying.

Yin (Kg/kg)	Xin (%d.b)	Wm (kg/hr)	Tain (^{0}C)	Xout (%d.b.)	dX/dr (%d.b./ mm)	Fissured Kernel(II) (%)	Eff. (%)	RT (min)	Temp. time (min)
0.0133 (Tamb =30 C, RH=50 %)	25 (I) 18.0(II)	77 77	43 43	**18.0*** 14.9	7.74 4.38 (44%)**	20	45.3 21.2	33.1 33.1	30
	25 (I) 18.2(II)	92 92	43 43	**18.2*** 14.8	7.75 3.26 (58%)**	17	46.7 24.7	31.2 31.2	60
	25 (I) 18.6(II)	100 100	43 43	**18.6*** 15.0	7.78 1.76 (77%)**	5	51.8 30.6	26.5 26.5	120
	30 (I) 19.5(II)	65 65	43 43	**19.5*** 13.6	9.92 2.53 (75%)**	10	48.6 24.4	45.9 45.9	120
	20(I) 17.1(II)	220 220	43 43	**17.1*** 14.9	5.50 2.27 (60%)**	10	48.6 40.6	11.3 11.3	30

*Moisture content beyond acceptable limit for longer storage

** % reduction in moisture content gradient

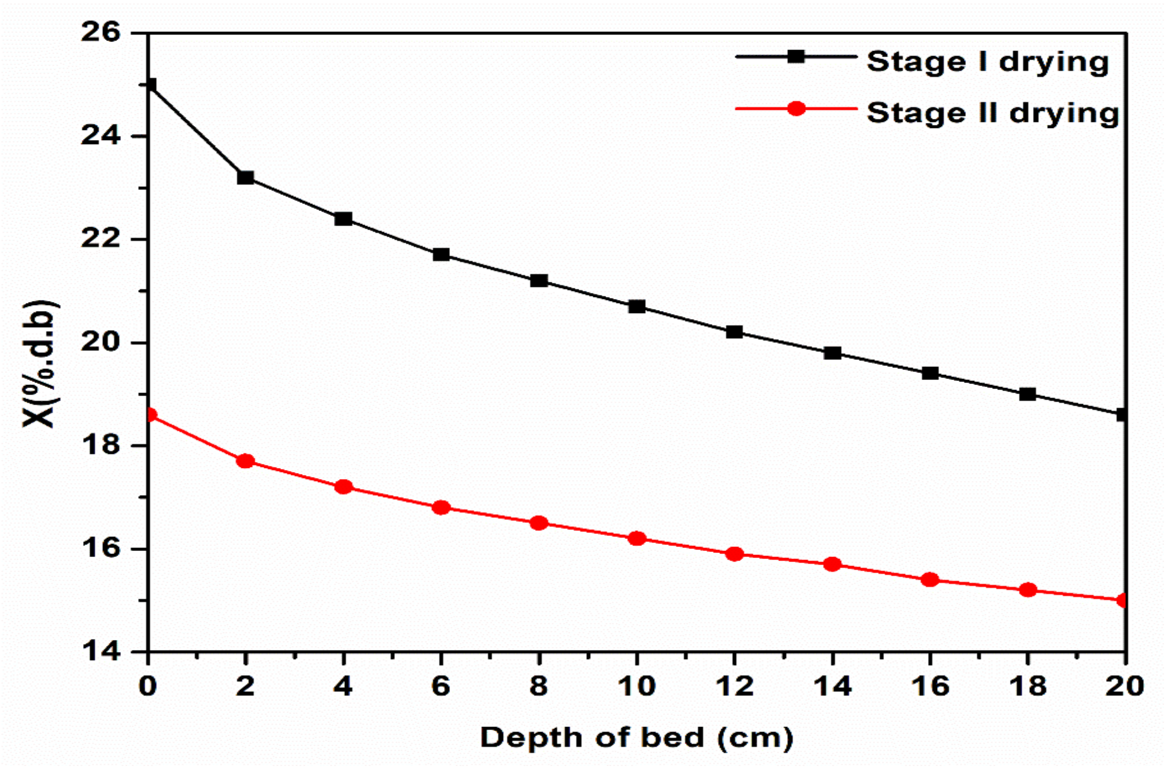


Figure 7.10. Variation of moisture content of paddy in two-stage drying

7.4. Validation of Results

The accuracy of the computed results from the present computer program for the same set of input operating variables in terms of inlet air temperature, inlet moisture content of the grain, and residence time in the current wok is verified through the experiment. The comparison is reported in Fig.7.11. The two results match a close approximation that justifies the validity of the computations based on the current computer program.

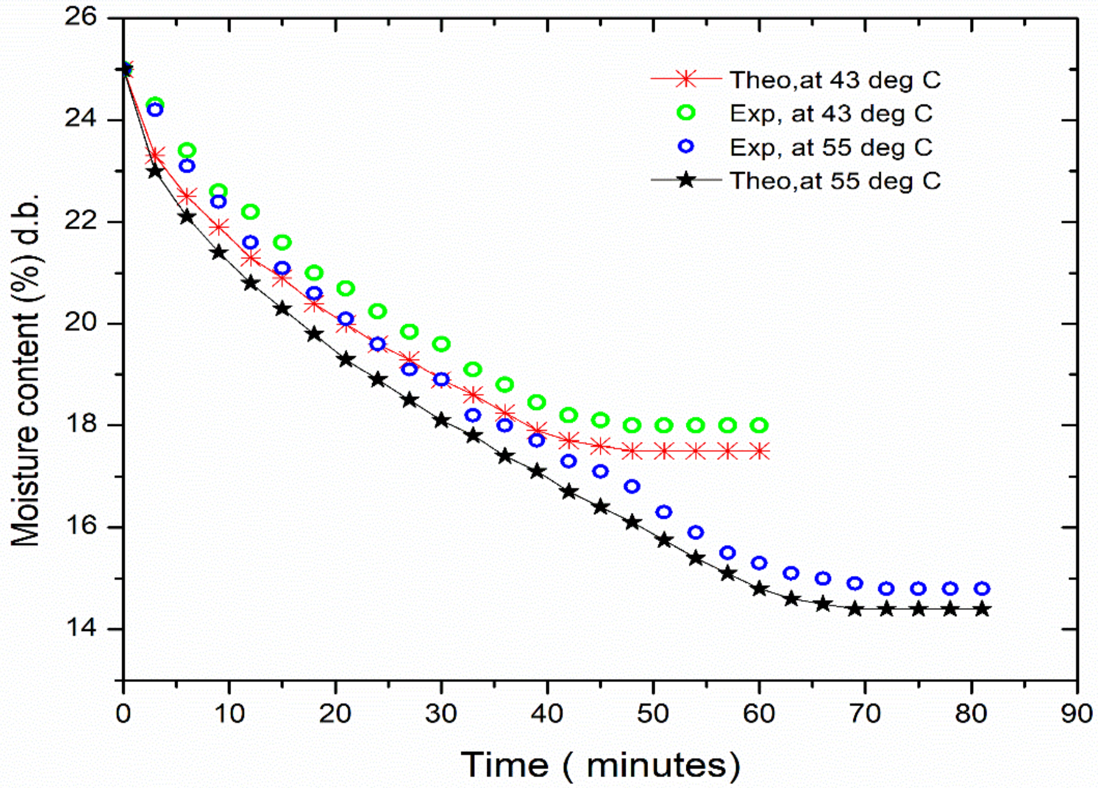


Figure 7.11. Avg. Moisture content of the grain vs. Time at 55℃, RH 50%. And 43℃, RH 50%. At air velocity 1 m/sec.

7.5. CONCLUSION

Based on a developed computer program (based on a mathematical model) and experimental investigations, the performance of a counter flow continuous deep bed dryer was investigated in detail. The effect of tempering and drying treatments on the fissuring of rough rice was also investigated, integrating the intra-kernel moisture distribution. The following outcomes were drawn from the present study:

- The developed mathematical model and computer program for counter flow deep bed drying with tempering is well suited to analyze the drying phenomena of rough rice. It can be easily extended for the analysis of other materials.
- Optimum design conditions and performance parameters can be approached with the help of the Intra-kernel moisture distribution model proposed in this study.
- Tempering is found to be a very effective tool for preserving higher quality in terms of keeping the maximum value of moisture gradient inside the rice kernel coming out from the dryer to an acceptable limit. This reduces the chances of fissuring from 20 % to 5% by proper drying, leading to increased head rice yield during milling. And temper time for safe drying is found to be 120 min for 25% d.b moisture content. The throughput can be increased with an increase in temper duration.
- The detailed rating analysis results provide insight for efficient utilization of a given dryer geometry during varying climates over the year. Such developments for varying operating parameters can be utilized for designing an optimum geometry for a specific purpose.