Chapter 6

PERFORMANCE ANALYSIS OF DEEP BED DRYING OF CANOLA SEEDS USING NUMERICAL TECHNIQUE.

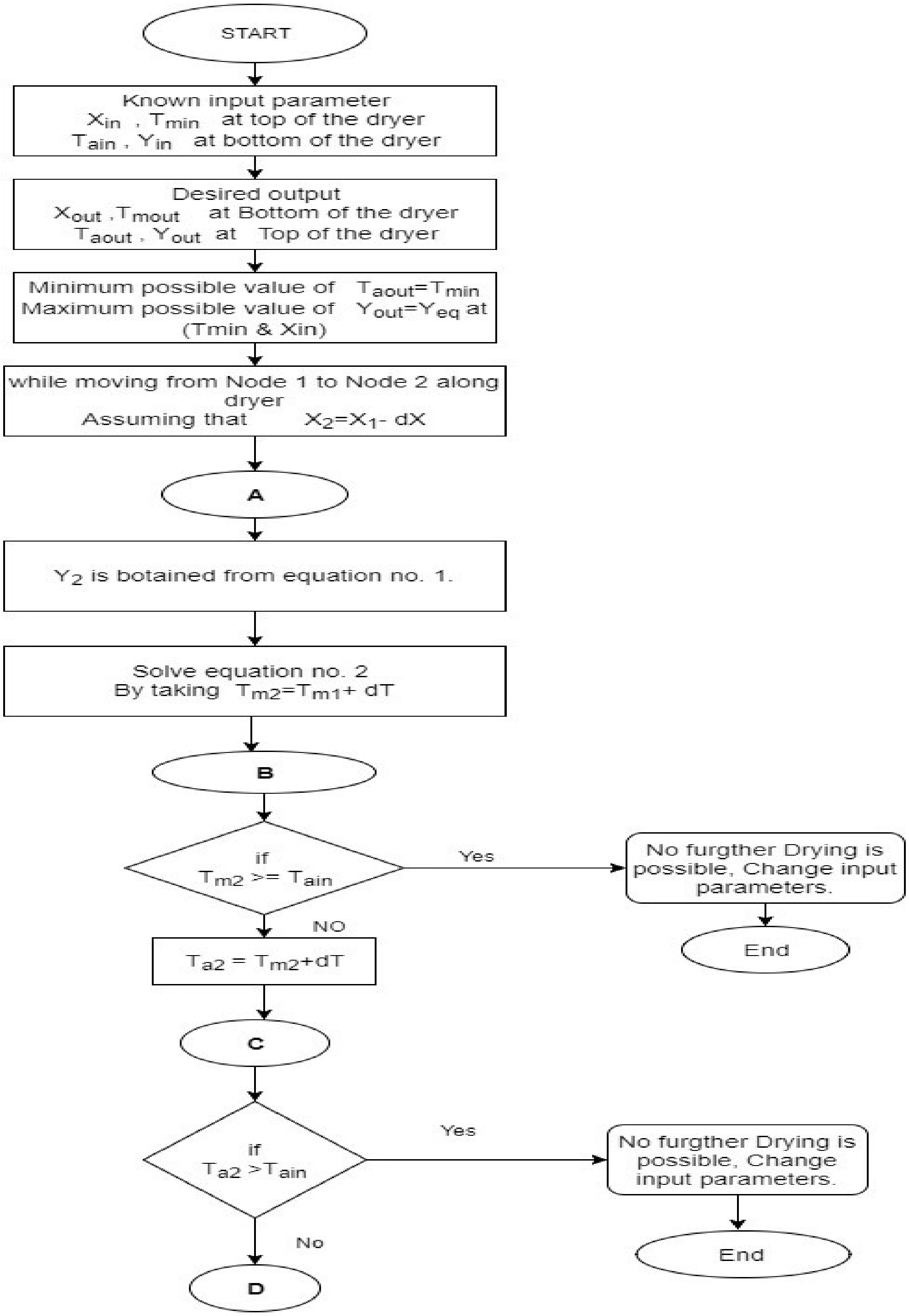
6.1. Introduction

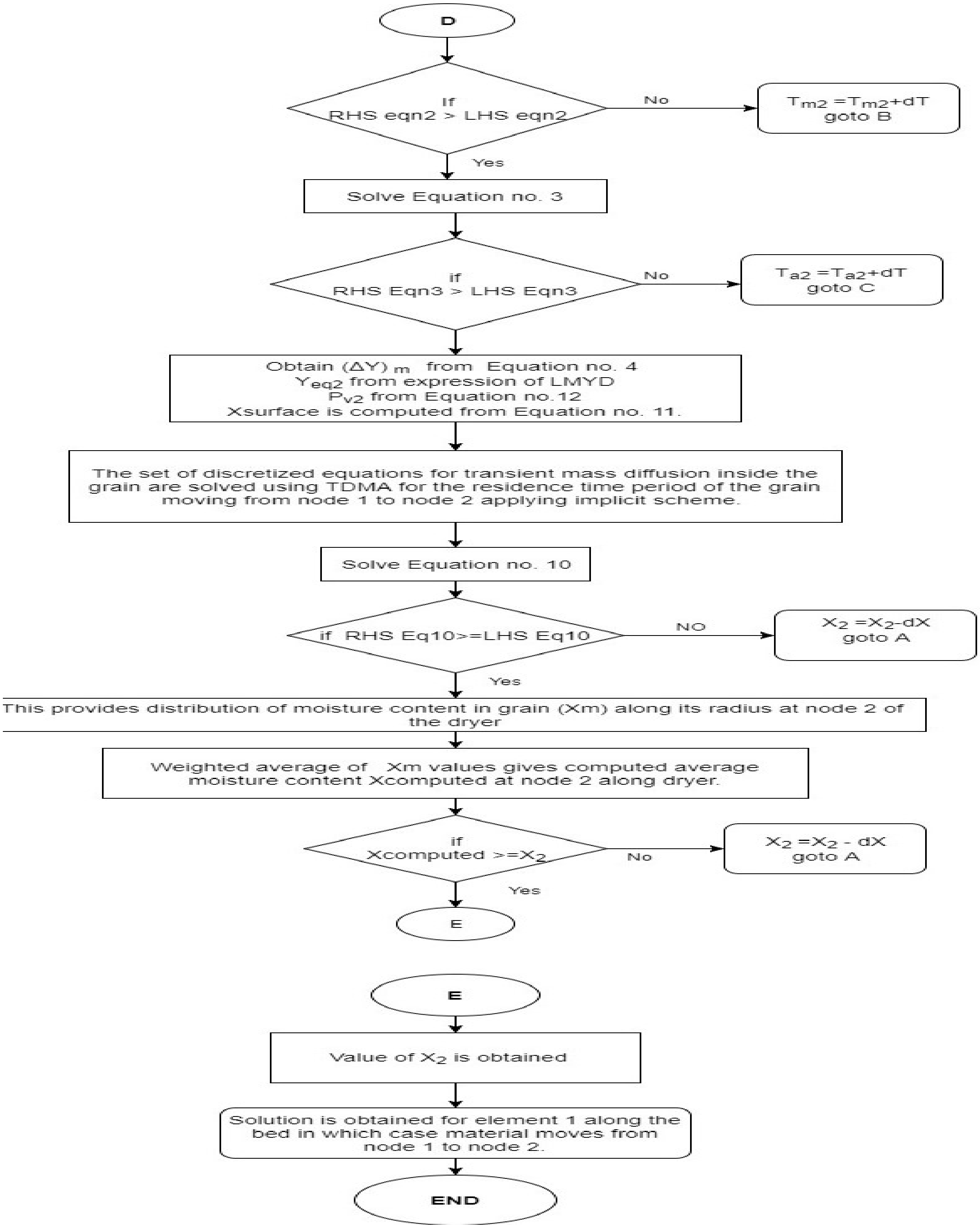
Globally produced canola is one of the major cash crop with nearly 75.4 million tons produced in the year 2017-18 [FAO, 2021]. Canola grain containing 18-20% moisture during harvesting is not suitable for safe storage. Canola generally contains moisture in the range of 18-20 wt.% (wet basis) and is thus unsafe to store for longer period. To increase the storage longevity of the grains, they must be dried to approximately 8-9% which renders it possible to store for over a year [Talbot, 2003;Hellevang, 2011.]. The storage conditions for these grains need to be optimized through drying technique to prevent both fungal attack and suppression in germination. Hence, the present investigation has been carried out to analyse coupled heat and mass transfer phenomena during steady state counter flow deep bed drying.

6.2. Numerical Solution Technique

Minimum step sizes, dX for X and Xm, and dT for T_a and T_m, are selected such that any change smaller than them is of no practical consequence. Beginning from the node 1 in the dryer, an iterative scheme is adopted for the computation of the unknown parameters at the next node vertically. The scheme is reported below considering inlet and exit of material and air for a general element. Beyond NEB = 20 and NEG =15 there is no change in Xout, hence, these values are taken for the proposed analysis

6.3. Algorithm for solving the governing equation from node1 to node 2.





- The same process is applied for moving to next node in the dryer till the end node (NEB+1) is reached.

- The computed values of Y and Ta at the node (NEB+1) are compared with Y_{in} and Ta_{in} respectively.

- A two-way iteration is adopted through modification of assumed values of Y_{out} and Ta_{out} so that they match with Y_{in} and Ta_{in} respectively.
- Thus complete solution is obtained for the set of input data.

Table 6.0.1 Input parameters used for computation

Dryer geometry	
Cross section area	0.2 m^2
Height	0.25m
Properties of canola	
D_m	0.002m
D_{wg}	$\mathbf{9.598 \times 10^{-7} exp} \left(-\frac{\mathbf{3423.8}}{\boldsymbol{T}\mathbf{+273.2}}\right)$ m^2/s [Duc et al., 2011]
ρ_m	1075kg/m^3 [ASAE, Feb, 1999]
Recommended maximum values for safe storage over one year for commercial use of canola are [Schoenau et al., 1995]	
X_{out}	8–9 % (kg/kg;d.b.)
T_{Mout}	49^0C
Water diffusivity into air [Duc et al., 2011]	
D_{wa}	31*$10^{-6}m^2/s$

Table 6.0.2 Range of operating variables used for rating analysis.

T_{amb}	20 – 40^0C
RH of ambient air	50 –70%,
T_{Ain}	$\mathbf{45 - 49}^0$C
X_{in}	16–20 % (kg/kg; d.b.),
For above combination, resulting moisture content range of ambient air becomes	
Y_{amb}	0.0133 – $\mathbf{0.0235}$ kg/kg
W_m	50 –80kg/hr

Table 6.0.3 Design set of operating data:

Bed height	0.25 m
X_{in}	18%(kg/kg;d.b),
T_{Min}	30^0C
T_{Ain}	49^0C (T_{Ain} is kept at 49^0C to make sure that T_{Mout} does not exceed the recommended limit of 49^0C)
W_m	50kg/hr
T_{amb}	30^0C
RH of ambient air	50%
Y_{amb}	0.0133 kg/m^2
ΔX	0.0005 (kg/kg; d.b.)
ΔT	0.1^0C
U_{sup}	1.m/s
RT	46 min
h	261 W/m^{20}C
h_m	0.2846 kg/m^2
With the above set of input data, the value of X_{out} comes out to be 8.15 %.	

Equilibrium moisture content for canola seed.

A study by[Duc et al., 2011] indicates the most appropriate equation for canola., The Halsey equation is most suitable for predict the Equilibrium moisture content values of rape seed (canola). The Halsey equation has the form

$$Xeq = \exp\,[C1 + C2T - C3\left(-\ln\left(\frac{Pv}{Pvs}\right)\right)]$$

Where c_1, c_2, c_3 are constants and their values for rape seeds are.[D. W. Sun & Byrne, 1998]

C1=2.8989, C2=-0.014596, C3=1.5454,

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

6.4. Results and Discussions

It is considered that the inlet conditions of the air used for drying exhibits falling rate drying. This behaviour is reflected in figure 3 where two different modes of moisture removal is seen. For the nodes away from the centre the drying rate is rapid and therefore the curve follows a steep slope, On the other hand the modes close to the centre, initially shows steadiness followed by drop in the moisture. This phenomenon can be explained on the basis of diffusion rate of water vapour. Each grain at internal node1 has moisture content around 18%, and by the time these grain reaches the exit point of the dryer the grains significantly loses its moisture content to nearly 2.9%. Thus a point of inflection is observed at node 7, in moisture content versus radius plot.

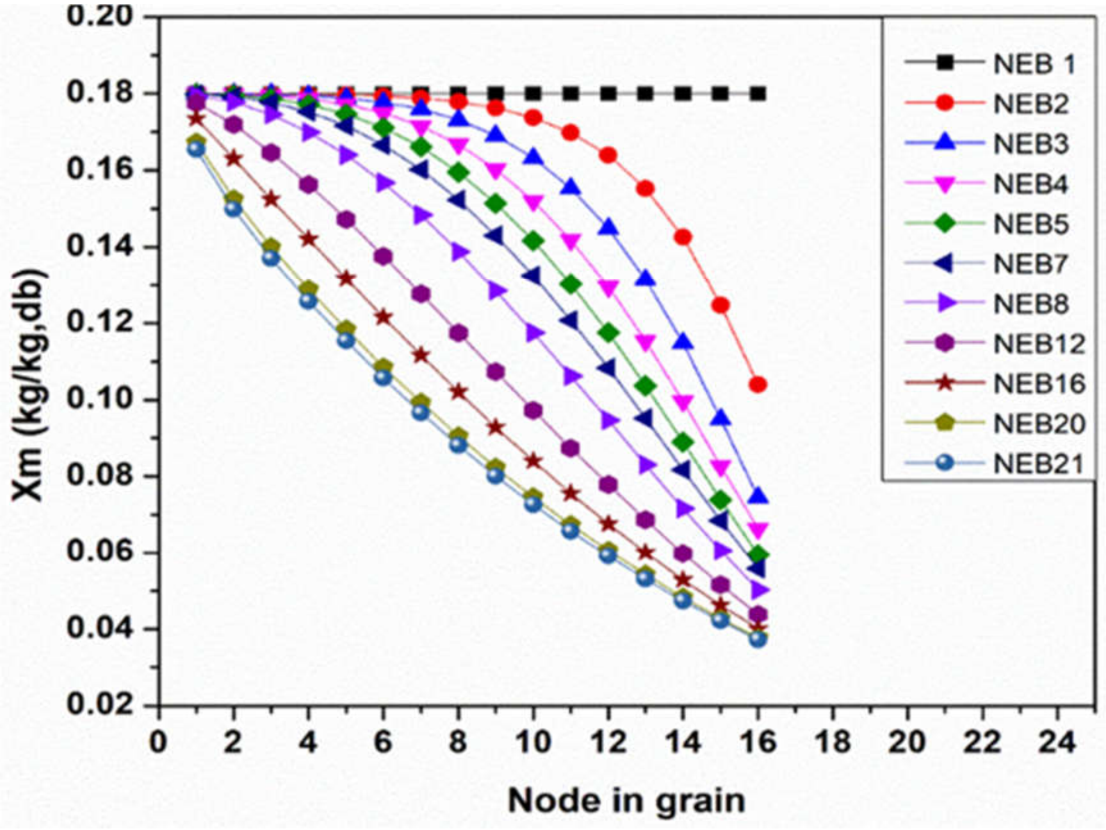


Figure 6.1. Variation of moisture content with radius inside the grain at different locations in the bed

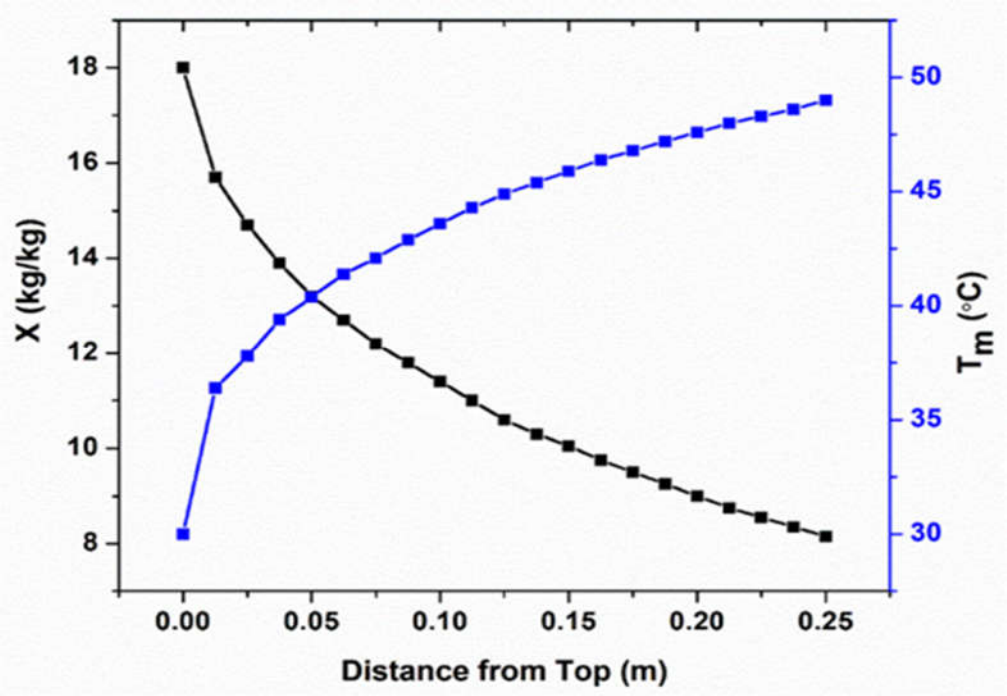


Figure 6.2. Average moisture content of grain and Material temperature Vs. length of the dryer

The mass transfer potential is high at the top of the drier and therefore the moisture content drops steeply in top region, as shown in Fig 6.2. Along the depth of the drier, the mass transfer potential drops, and hence the average moisture content decreases relatively at slower rate. Change in material temperature along dryer height is plotted along Y-axis in Fig 6.2. The change in the material temperature shows the inverse behaviour to that of moisture content. It is seen, the material temperature increases rapidly initially when most of drying takes place, and then it increases with a decreasing rate. Figure 6.3 shows variation of air outlet humidity along the height of the dryer. The moisture content in the air is low at the bottom end of the drier whereas it is significantly higher at the top end, as expected. Y-axis in Figure 6.3 shows air temperature as a function of distance from dryer top. Since, a very small difference in temperatures of air and material is able to supply the required rate of heat, the air temperature remains slightly higher than that of material throughout the dryer practically, except at the top. The difference in the two temperatures goes on decreasing towards the bottom of the dryer where it becomes the minimum. This behavior at the dryer bottom does not get altered, even when grain mass flow rate is varied as depicted in Figure 6.4 and represents the unique feature of countercurrent drying phenomena**.**

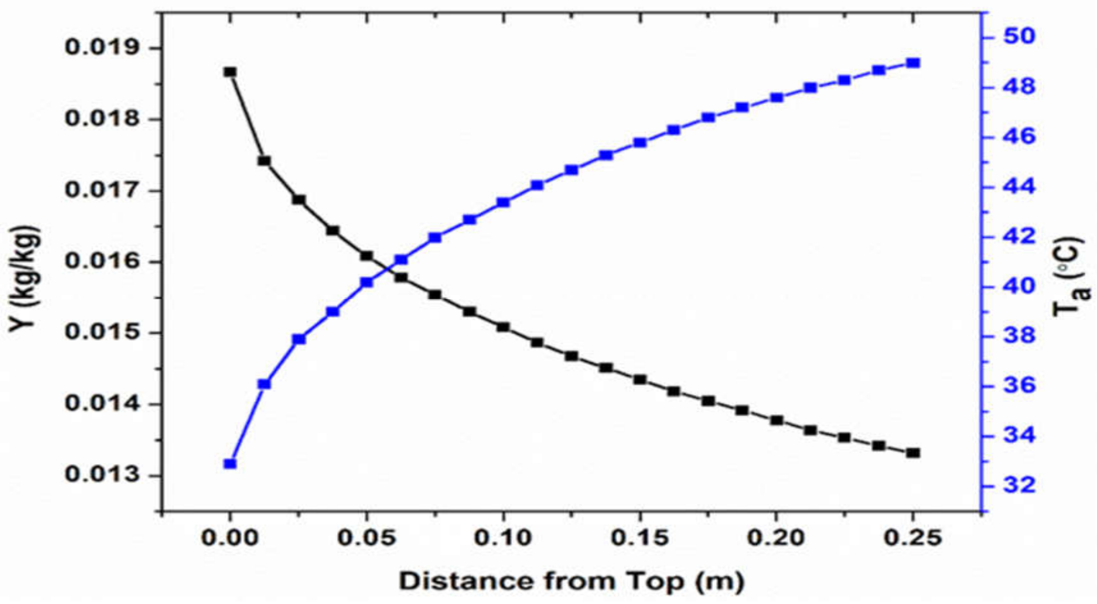


Figure 6.3. Air temperature and Air outlet moisture vs. height of the dryer

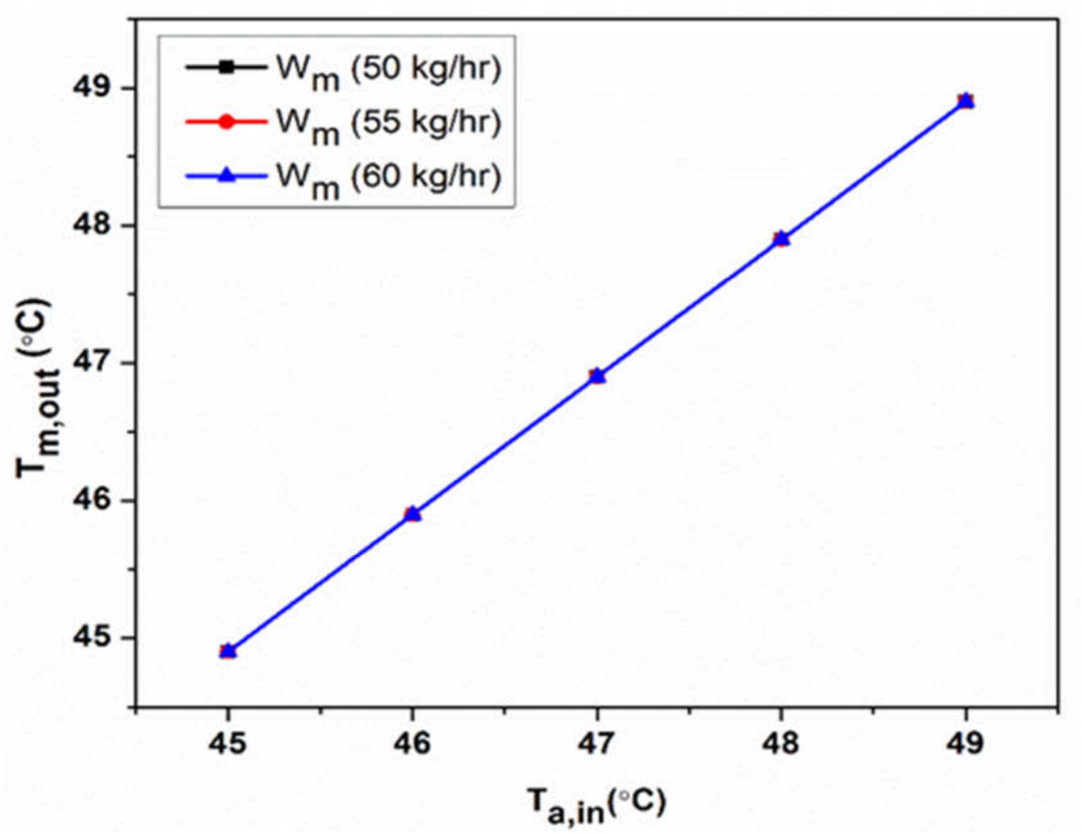


Figure 6.4. Material outlet temperature vs. inlet air temperature

Figure 6.5. Depicts variation in average moisture content of the grain on exit from the dryer. It is seen that with increase in the mass flow rate the moisture content of the canola at the outlet also increases. This is because with increase in mass flow rate the interaction time between drying air and inlet grain is less and hence the moisture drop is less. Therefore, we conclude that the material flow rate has significant impact on final moisture content. Along the mass flow rate line it is seen that with increase in the inlet air temperature the moisture content decreases. This is attributed to the high thermal gradient associated with the inlet air.

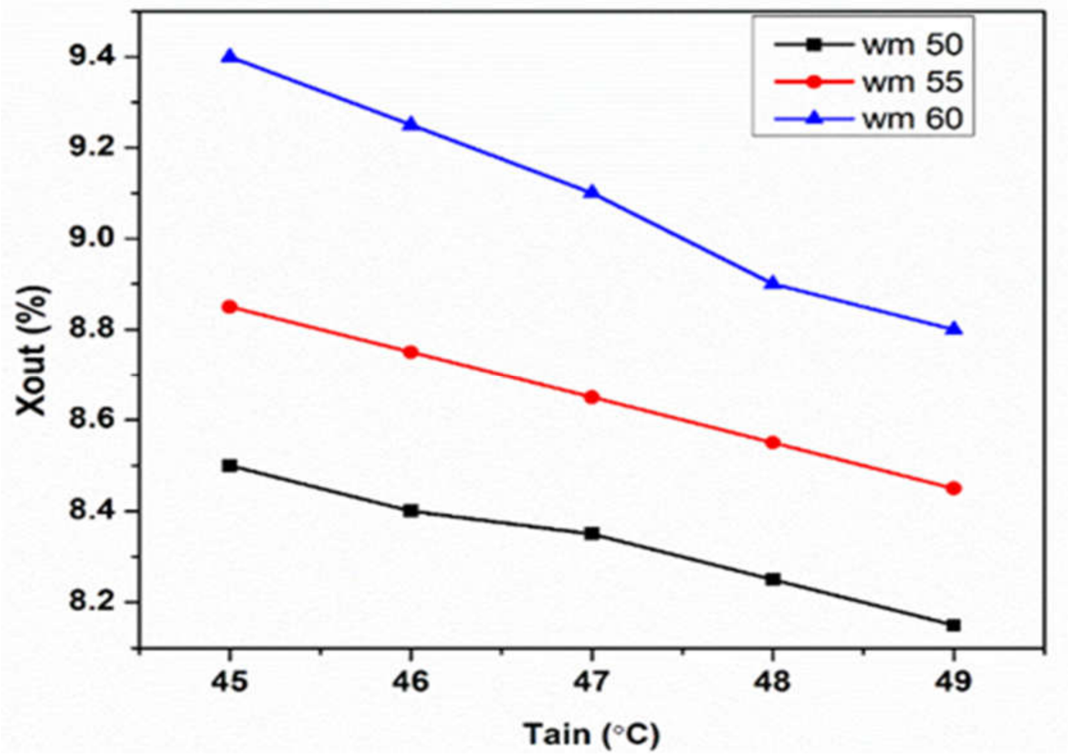


Figure 6.5. Material outlet moisture content vs. inlet air temperature at different mass flow rate**.**

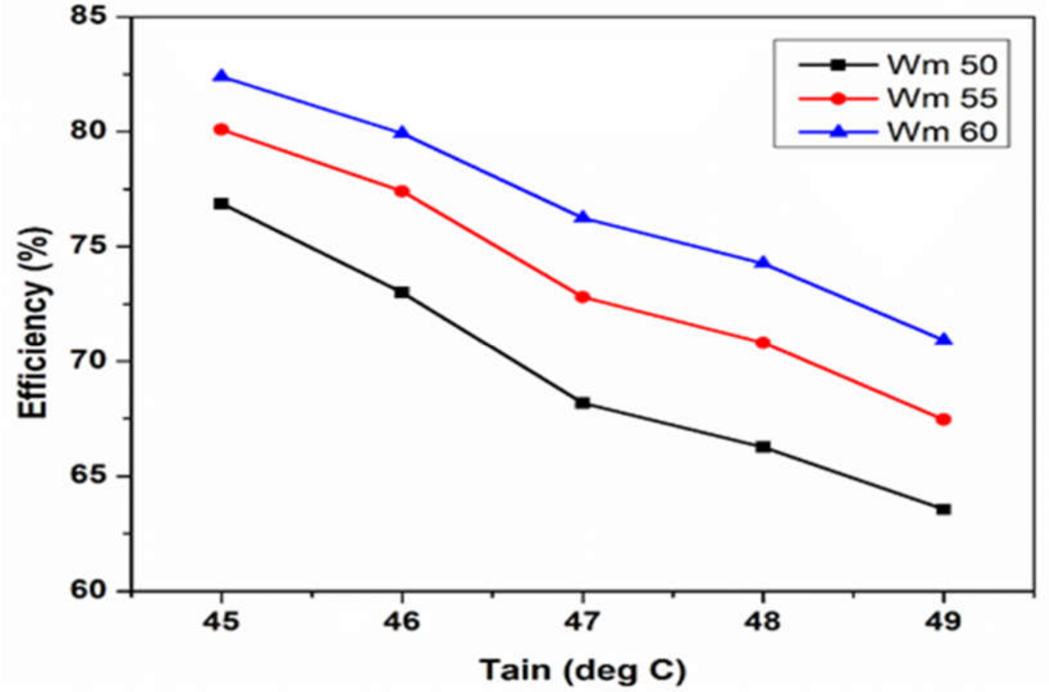


Figure 6.6. Efficiency vs. inlet air temperature at different mass flow rate

Drying efficiency which is the most promising variable has been critically analysed under all parameters. Efficiency vs T_{ain} graph (Fig. 6.6) Shows that with increase in the inlet temperature there is drop in efficiency. This is because the heat supplied by the inlet air is more and therefore a major part of the heat is underutilized. Higher mass flow rate is more prone to lose the moisture content and hence the heat supplied is better utilized and thus the efficiency of the dryer increases (Fig.6.7). Efficiency of the dryer is seen to reflect linear increase with increase in the moisture content of the grain. This is surely due to the high potential gradient between the inlet air and grains. On analysing the variation of efficiency with superficial velocity (Fig.6.8), decrement in efficiency is seen. This is because with increase in superficial velocity the available heat for drying is more. However, the heat utilization remains constant under constant mass flow rate which result in decreasing the efficiency of the dryer. On the contrary, if the inlet air has lesser moisture content, then the heat supplied is reduced and hence the drying capacity is reduced. This results in drop in efficiency of the dryer (Fig. 6.9).

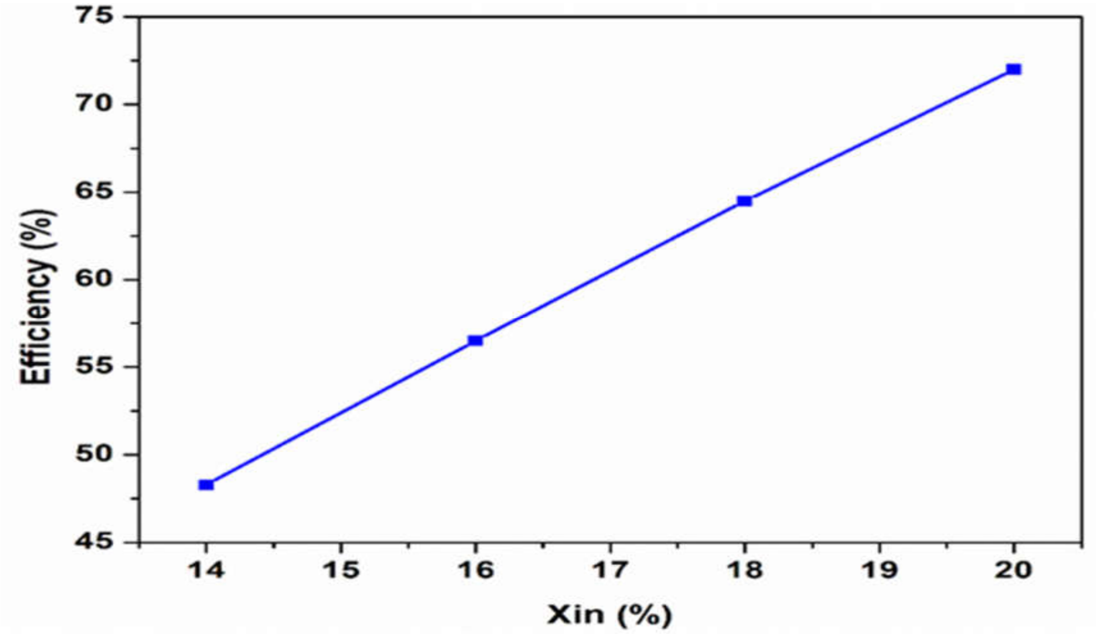


Figure 6.7. Efficiency of dryer vs. Inlet moisture content of the grain

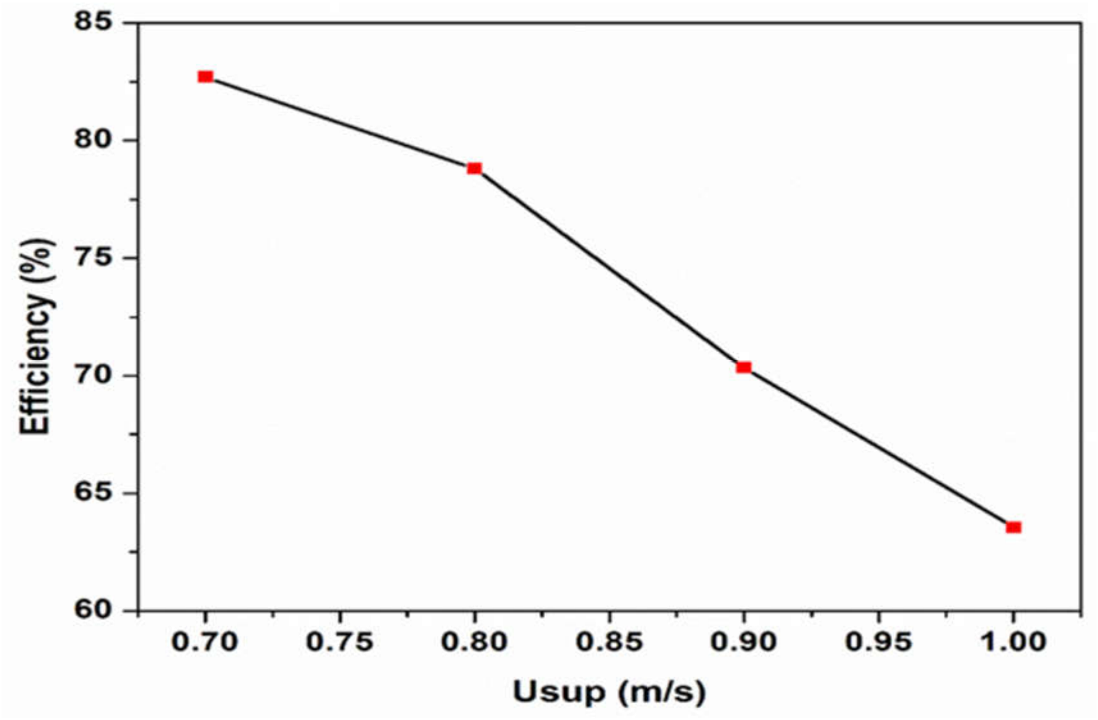


Figure 6.8. Efficiency of dryer vs. Superficial Velocity

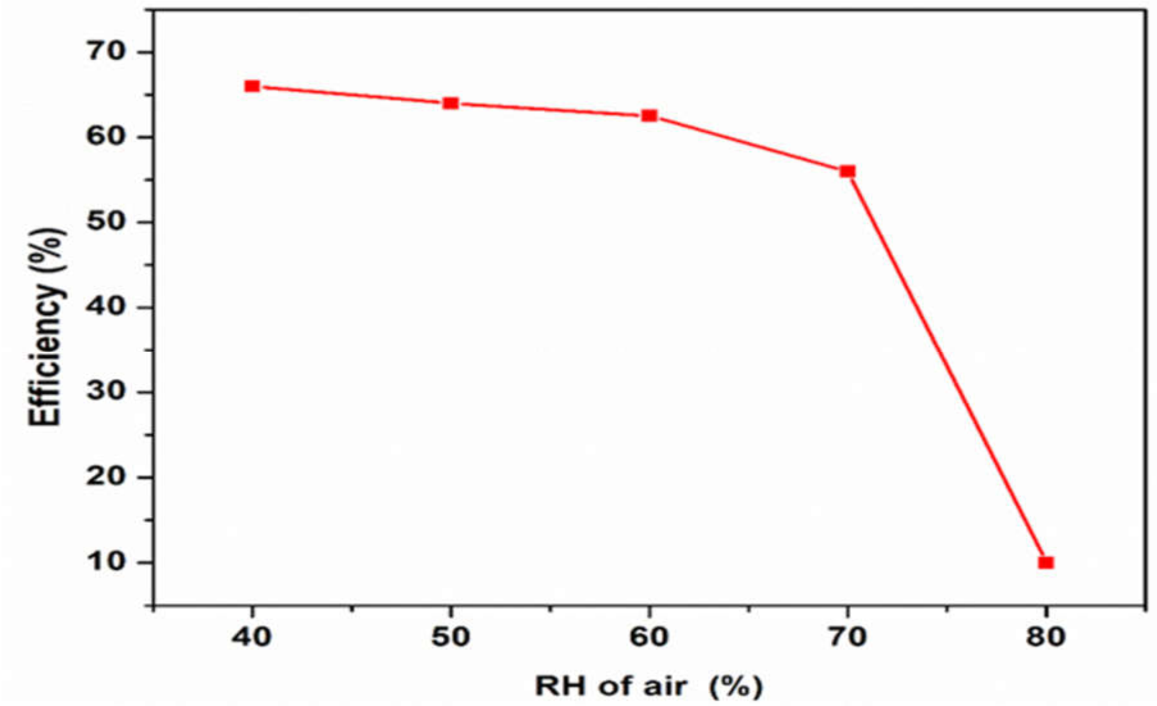


Figure 6.9. Efficiency of dryer vs. Relative humidity of air

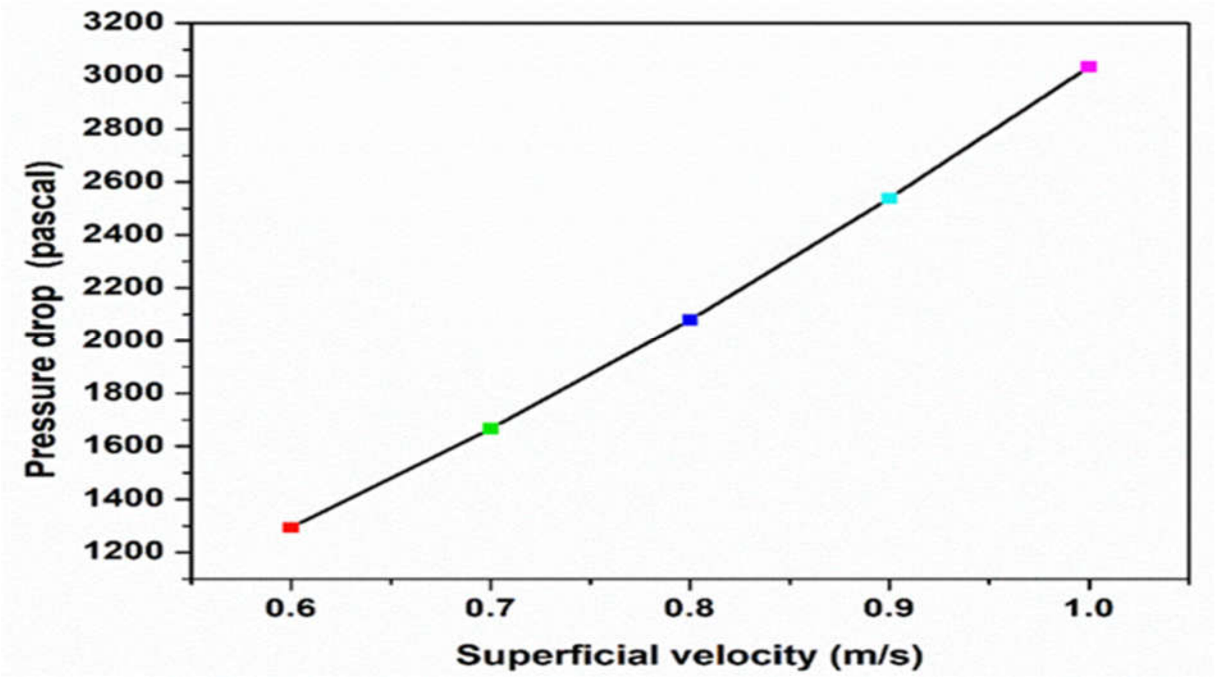


Figure 6.10. Pressure drop in dryer vs. Superficial Velocity

6.5. Pressure drop in bed

The Ergun equation is used to calculate the pressure drop in the drier chamber. The geometric dimension of the grain is assumed to be spherical. It is found that with increase in the superficial velocity the pressure drop increases (Fig.6.10). This is due to reduced pressure in bottom section of the chamber which is outcome of increased velocity of the inlet air. This evidently leads to reduction in efficiency of the dryer.

6.6. Rating Analysis of the Drier

Numerical analysis of the developed program for maximum utilization of the given geometry of the dryer has been carried out, and the following inferences are drawn:

I. Design Ambient Condition

The design conditions are X_{in}= 18%, T_{ain} = 49ºC and W_m = 50 kg/hr with 100% of drier useful length without reaching limiting values of X_{out}.

Rating analysis of selected geometry is reported for its optimum use at design ambient condition in terms of maximum values for drying efficiency and throughput rate. Possibility of attaining minimum possible moisture in the output material, without tempering, is investigated with initial material moisture content values lower and higher than the design value.

(a) Increase in throughput rate

At design values of X_{in} and T_{ain}, the throughput rate (W_m) can be raised up to 61 kg/hr with Eff = 70.5%. Beyond this limit the throuput cannot be increases as it will demand for increase in the temperature of inlet air. And if the temperature of inlet air is increased beyond 49°C then it will suppress the possibility of grain germination.

(b) Minimum moisture content in the exit material.

With the objective of reaching moisture content below the designed value (8.15%), in order to store for a period greater than one year, the mass flow (W_m) rate has to be reduced. This will certainly drop the efficiency of the drier because any increase in T_{ain} is likely to cause T_{mout} to cross its limiting value of 49ºC.

(c) Performance of the dryer when the initial moisture content of the inlet material is varied

(i) During drying of material with lower initial moisture content (X_{in}=16%), material flow rate of 80 kg/h can be used with air inlet temperature of 49ºC with efficiency around 73.7%.

(ii) Maintaining the same efficiency, if material with higher inlet moisture content of 20% is to be dried then mass flow rate of 53kg/h must be used.

II. Off-design Ambient Conditions

In order to evaluate the performance of the selected dryer geometry at varied locations and during different seasons over a year, three sets of ambient conditions, other than the design condition, are considered, as reported below.

A. Colder Ambient (T_{amb}=20°C, RH=50%, Y_{in}= 0.00725)

In a colder climate, as considered here, two opposing features affecting the dryer performance come into picture simultaneously. The lower value of Y_{in} is favorable to mass transfer and therefore drying. Nevertheless, lower value of T_{amb} demands more heat input and therefore reduced drying efficiency.

(a) Design set of X_{in}, T_{ain} and W_m (X_{in}= 18%, T_{ain} = 49°C and W_m = 50 kg/hr)

X_{out} goes slightly high to 8.35% in comparison to its design value of 8.15%; whereas, the drying efficiency drops down to 41.83% from its design value of 63.56%.

(b) Maximum throughput rate

Keeping X_{in}= 18%, T_{ain} = 49°C, canola can be dried at flow rate of 54 kg /hr with X_{out}=9% and Efficiency = 41.9%. The resulting T_{mout} is 48.8°C.

(c) Attaining lowest level of acceptable exit material moisture content

It is possible to reach lower limiting value of X_{out} (=8%) without any need of tempering at a reduced flow rate 48kg/hr. In this case, only 90% of dryer length is utilized and drying efficiency drops down to 41.6%.

B. Humid Ambient (T_{amb}=30^{o}C, RH=70%, Y_{in}= 0.01877)

In a humid climate, Y_{in}(=0.01877) is much higher than its design value (=0.01329), thus mass transfer rate gets reduced.

(a) Design set of X_{in}, T_{Ain} and W_m (X_{in}= 18%, T_{ain} = 49°C and W_m = 50 kg/hr)

Material moisture content at exit from drier, X_{out} (=9.95%), becomes higher than its limiting value of 9% which is not acceptable. However, If material flow rate is reduced to 48 kg/hr, the results become acceptable. The resulting drying efficiency is 54.8%.

C. Hotter Ambient (T_{amb}=40^{o}C, RH=50%, Y_{in}= 0.02348)

In this case, Y_{in} (=0.02348) is very high which makes mass transfer rate very low. At the same time, ambient air temperature T_{amb} (=40°C) is quite high, which reduces heat input to inlet air very much thereby increasing the drying efficiency, in general.

(a) Design set of X_{in}, T_{ain} and W_m (X_{in}= 18%, T_{ain} = 49°C and W_m = 50 kg/hr)

Material moisture content at exit from drier, X_{out} (=12.75%), becomes higher than its limiting value of 9% which is not acceptable.

(b) Increased inlet air temperature (T_{Ain})

(i) Since the value of T_{mout} in case of deep bed drier almost reaches to its T_{ain} value, therefore, to bring the moisture content in our acceptable limit, we require tempering process and two stage drying.

(ii) By raising T_{Ain} to 55 °C we can achieve X_{out} to its limiting value of 9 %. But this process has a limitation under which the outlet temperature of the material reached 54.9%.

(c) Decreased inlet moisture content (X_{in})

To overcome the issue of outlet temperature reaching 54.9% I above condition, lower value of inlet moisture content X_{in} (14%) is recommended that shall maintain the acceptable limit both in terms of X_{out} (=8.45%) and T_{mout} (= 48.9°C).

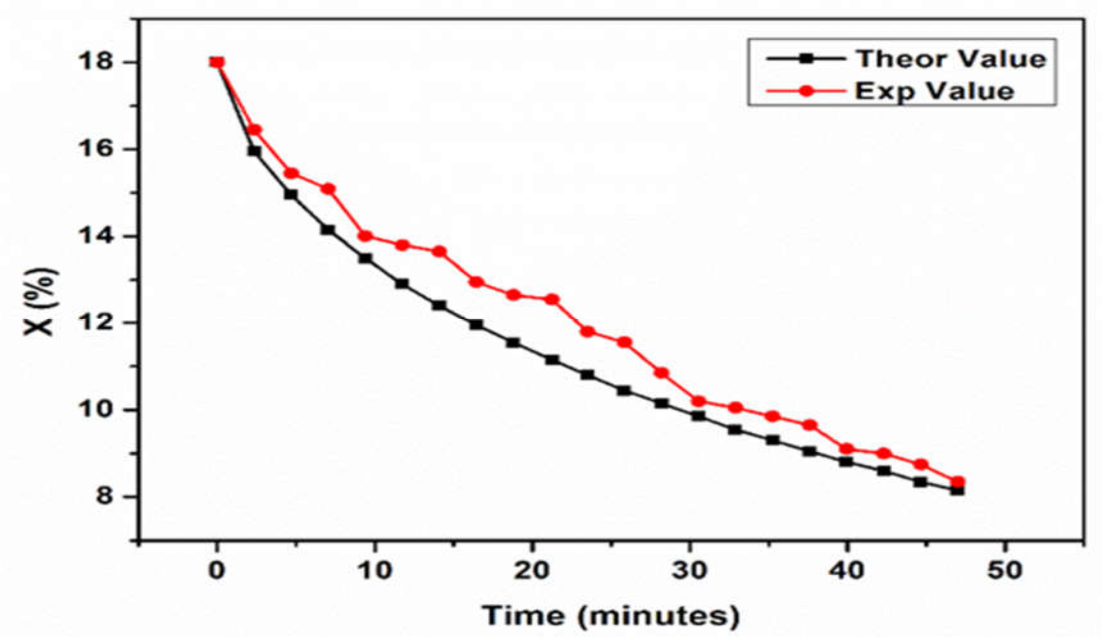


Figure 6.11. Avg. moisture content of the grain vs. time at 50°C, RH 50%.]

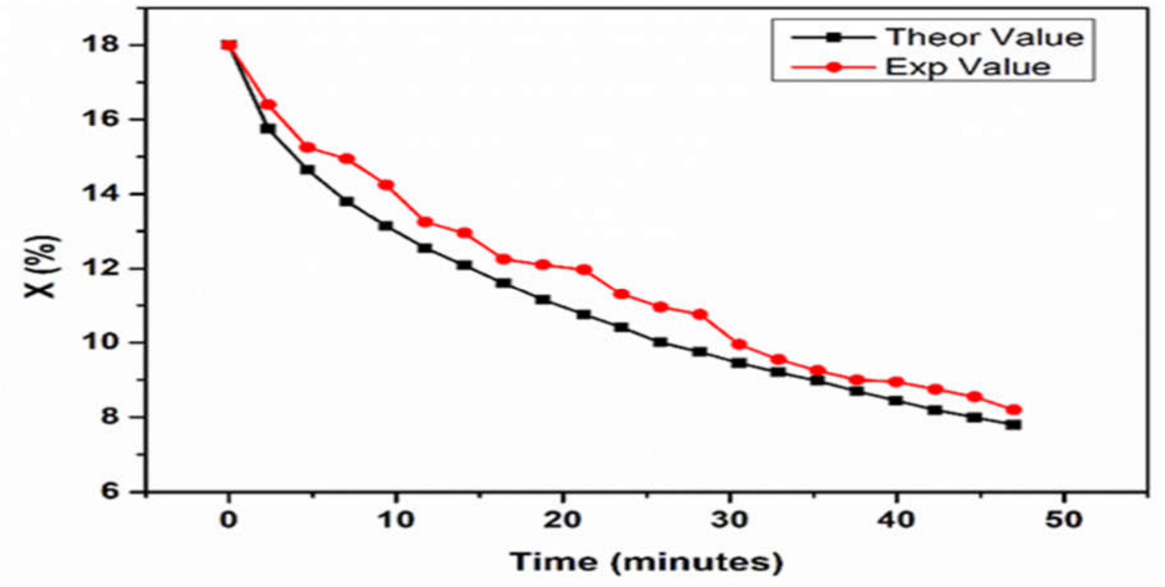


Figure 6.12. Avg. moisture content of the grain vs. time at 55℃, RH 50%

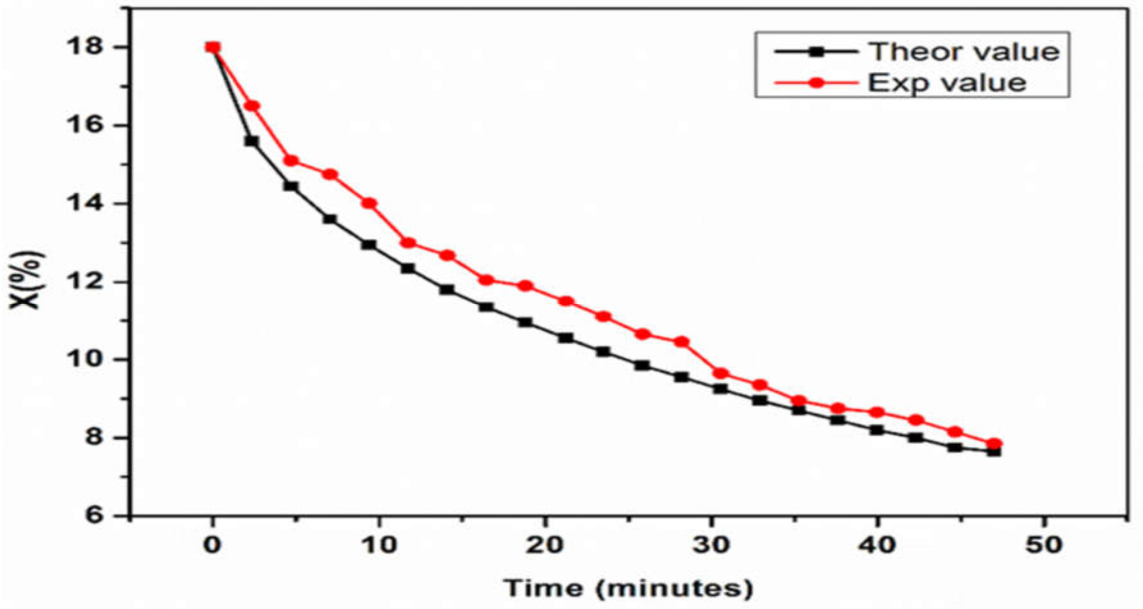


Figure 6.13. Avg. moisture content of the grain vs. time at 60℃, RH 50%

The outcome of the results from the present computer program is validated with the help of experimental values (Fig 6.11-Fig 6.13). The close approximation of the two results in the range of 6% justifies the accuracy of the program.

6.7. Conclusions

Following conclusion are drawn on the basis of mathematical models and experimental validation:

1. The developed mathematical model and computer program for counter flow deep bed drying of spherical particles is well suited to analyze the drying phenomena of canola seeds. Inlet air temperature with 45°C and mass flow rate of 55 kg/h is best suited for drying the canola seeds with 18% moisture content. For higher throughput, the inlet air condition should be 49°C with mass flow rate of 60kg/hr.
2. Temporal variation of Intra-kernel moisture distribution offers a lot of insight for deciding optimum design and performance parameters.
3. In a relatively colder climate (Tamb=25°C and RH=50%), material flow rate can be as high as 65 kg/hr but the drying efficiency goes down to 61%, because more heating of inlet air is needed in this case compared to T_{amb} at 30°C.
4. If we used dryer in a hotter climate having ambient temperature 35 ° C and 50 % RH, the reverse trend prevails, i.e., material flow rate has to remain at a lower level of 45 kg/hr whereas the dryer was designed for 50 kg/hr flow rate.
5. The performance of the dryer is going to be worse in coastal areas with moderate ambient temperature but a high relative humidity than that in a hotter climate. For Tamb=30°C and RH=80%, the material flow rate cannot exceed the value of 19kg/hr and the drying efficiency remains below 24%.
6. For a selected geometry of the dryer, the rating analysis can be used for arriving at improved quality and higher energy efficiency at reasonable level of throughput.
7. The developed model is very general in nature and can be used for studying drying phenomena of any spherical particle. It can be easily extended for the analysis of cylindrical particles.