

Chapter 8

A SEQUENTIAL NUMERICAL TECHNIQUE FOR ANALYSIS OF COUPLED HEAT AND MASS TRANSFER PHENOMENA DURING FLUIDIZED BED DRYING OF PARTICULATE MATERIALS: APPLICATION TO WHEAT DRYING

8.1. Introduction

Drying of particulate materials is an integral component of processing in many fields of engineering including agriculture. Fluidized bed drying of particulate materials has been a continuous subject of investigation, as it renders uniform drying thereby ensuring a high degree of product quality. Food grains need to be dried properly before storage in order to preserve their quality and reduce damage for longer period. Fluidized bed drying has been found to render higher quality of food grains but at a rather large cost. Therefore researchers have been looking for means to make the process further economical, and recirculation of exhaust air has been found to be exclusively suitable on this count.

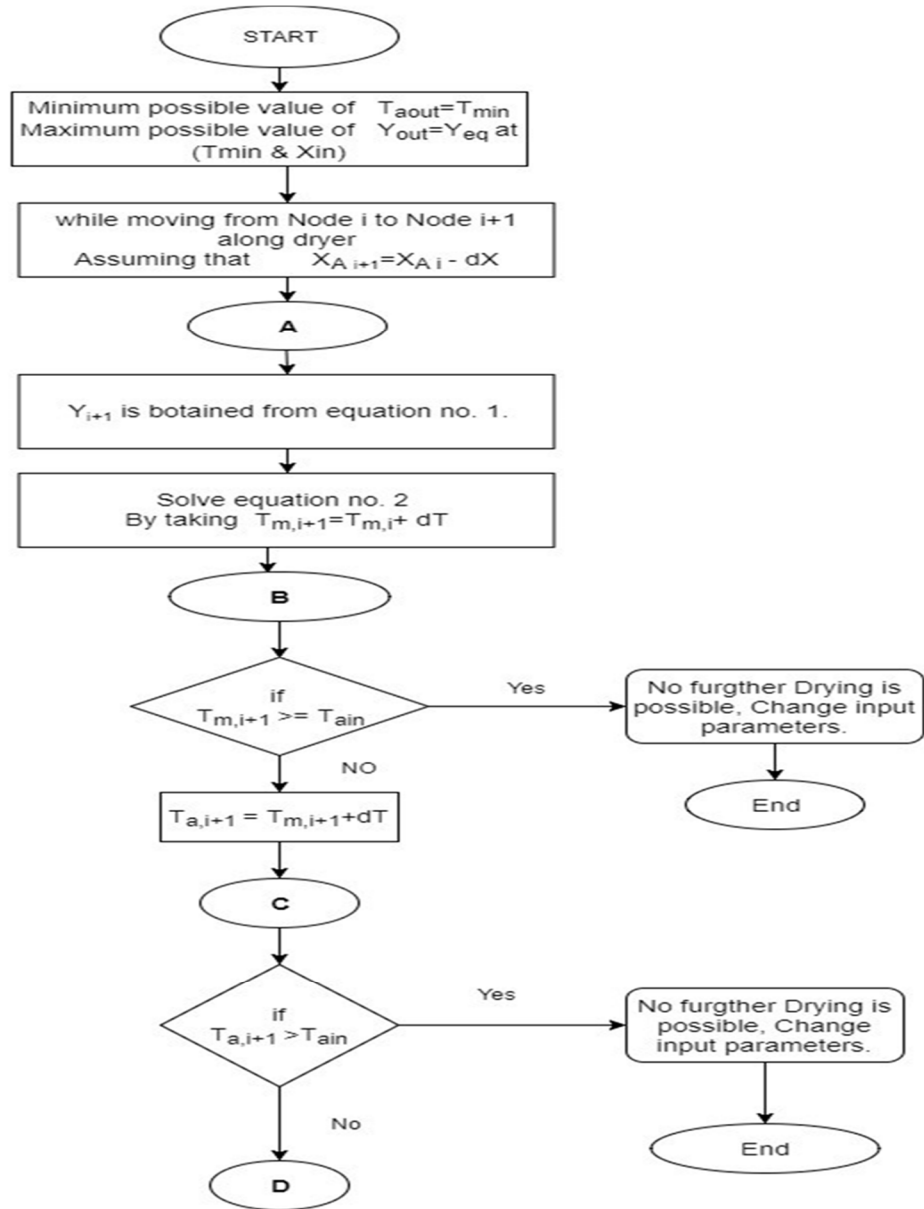
Drying characteristics of wheat is studied with exhaust air re-circulation. It is possible to increase the energy efficiency up to 54%, by re-circulating 88% of exhaust air, in comparison to its value of 33% without air recirculation, at 75% of its design throughput rate thus leading to a very high level of energy economy

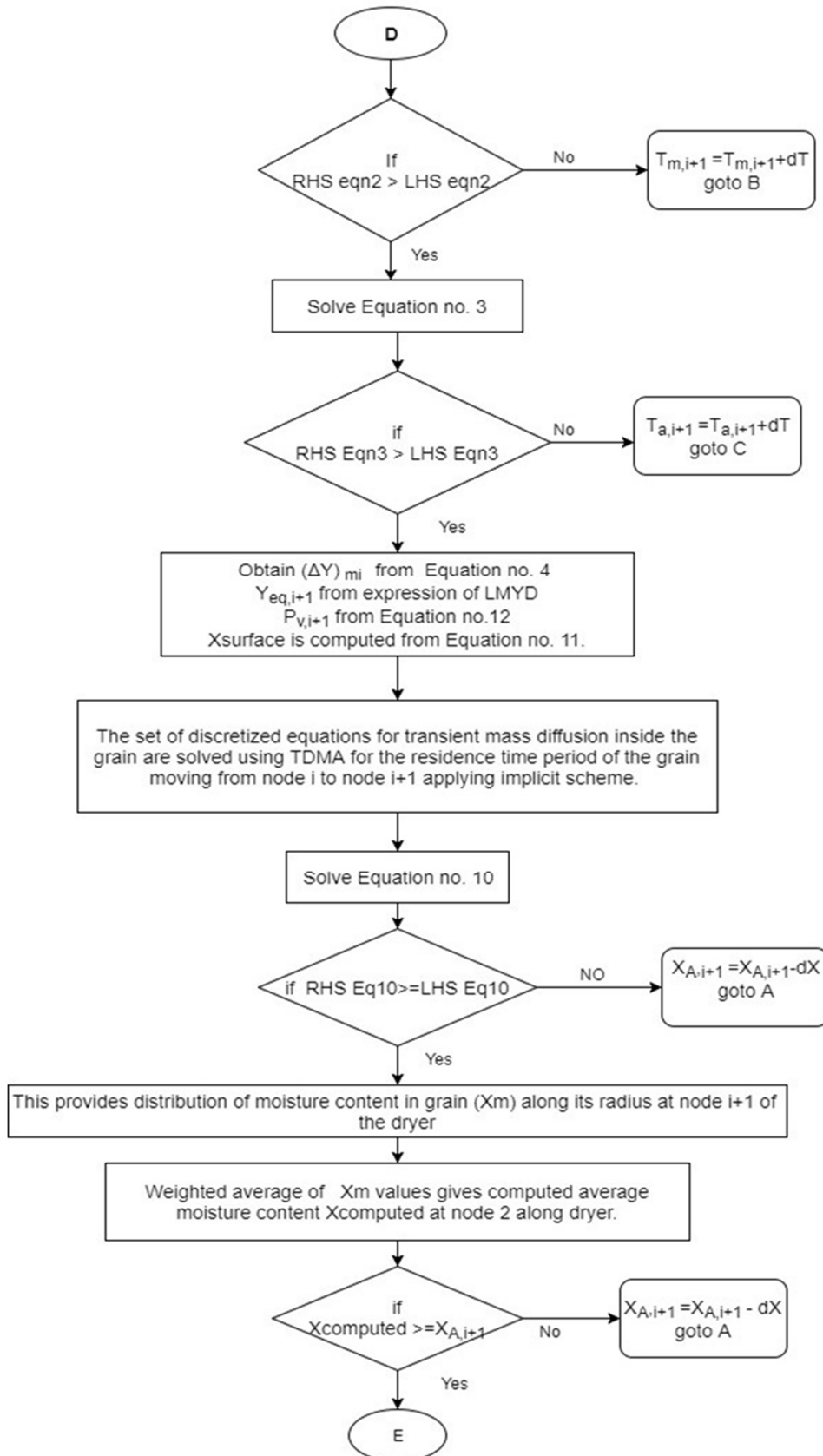
8.2. Numerical Solution Technique

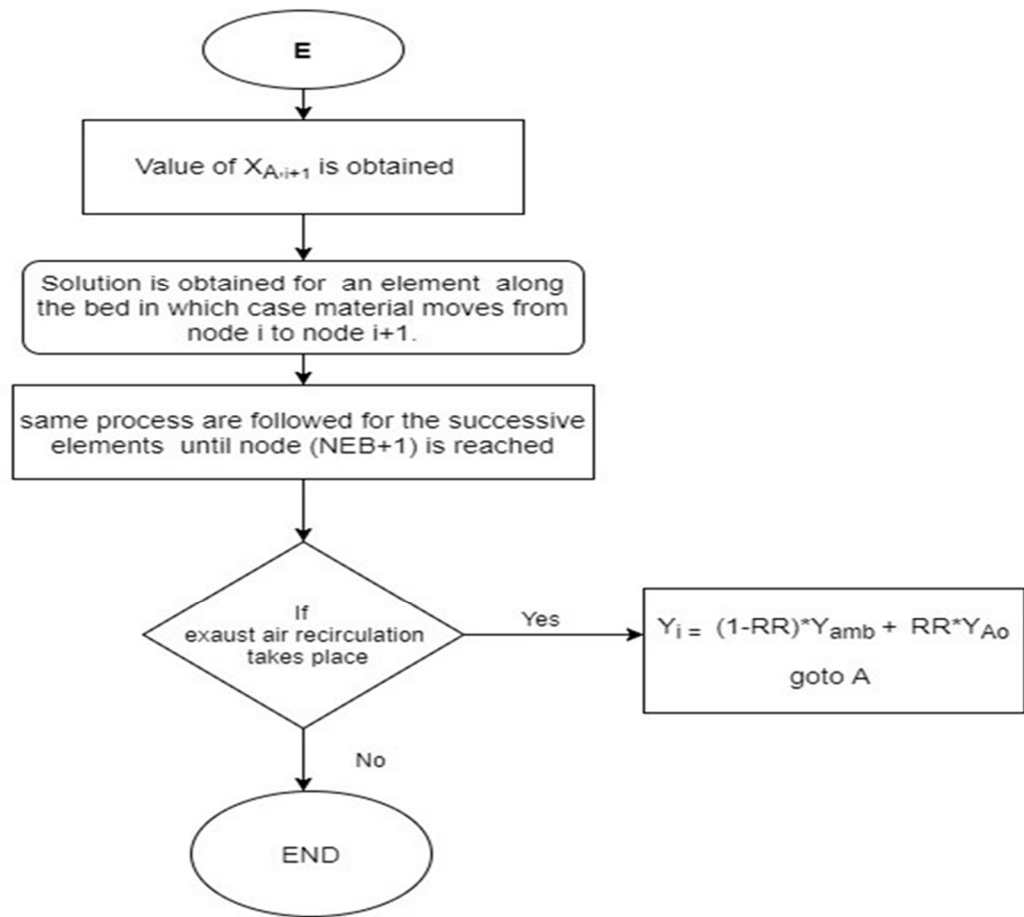
Minimum step sizes, Δx for X and X_m , and ΔT for T and T_M , are selected such that any change smaller than them is of no practical consequence. Beginning from the node 1 in the dryer, an iterative scheme is adopted for the computation of the unknown parameters at the next node along

the dryer length. The scheme is reported below considering inlet and exit of material and air for a general element.

8.3. Detail algorithm for Iterative Scheme







8.4. Results and Discussion

Input Parameters Used for Computation

Dryer geometry :

Length = 1m, Width = 0.15m, Height = 1m

Distributor Plate thickness = 0.003m,

Hole size = 0.002m, Number of holes = 1186

Properties of wheat(soft) [Brooker et al., 1992] [Rafiee et al., 2008] :

$$D_m = 0.004\text{m}, \quad \rho_m = 1190\text{kg/m}^3,$$

$$D_{wg} = 5.68 * 10^{-5} \exp \left[\frac{-35328}{RT_A} \right] \text{m}^2/\text{sec}$$

Recommended maximum values for safe storage over one year for commercial use of wheat are :

$$X_{\text{out}} = 13\text{--}14 \% \text{ (kg/kg;d.b.) and } T_{M_0} = 60^\circ\text{C. [Bala, 2016]}$$

Water diffusivity in air [T. L. Norman et al., 2006] : $D_{wa} = 4.7931 * 10^{-5} * \left[\frac{T^{1.9}}{P} \right] \text{m}^2/\text{sec}$, where

T is in K and P is in Pa

Design set of operating data :

Bed height = 0.1 m

$$X_{\text{in}} = 21\%(\text{kg/kg;d.b.}), \quad T_{\text{Min}} = 30^\circ\text{C}, \quad T_{\text{Ain}} = 60^\circ\text{C},$$

$$W_m = 65 \text{ kg/hr}, \quad T_{\text{amb}} = 30^\circ\text{C}, \quad \text{RH of ambient air} = 50\%, \quad Y_{\text{amb}} = 0.03 \text{ kg/m}^2$$

$$\Delta X = 0.001 \text{ (kg/kg; d.b.)}, \quad \Delta T = 0.1^\circ\text{C},$$

$$U_{\text{mf}} = 1.5 \text{ m/s}, \quad \epsilon = 0.4 \quad RT = 20 \text{ min}, \quad h = 400 \text{ W/m}^2 \text{ }^\circ\text{C}, \quad h_m = 0.3 \text{ kg/m}^2$$

Range of operating variables :

$$T_{\text{amb}} = 20 - 40^\circ\text{C}, \quad \text{RH of ambient air} = 50 - 70\%,$$

$$T_{\text{Ain}} = 60 - 65^\circ\text{C}, \quad X_{\text{in}} = 21 - 23 \% \text{ (kg/kg; d.b.)},$$

$$W_m = 50 - 80\text{kg/hr}, \quad Y_{\text{amb}} = 0.0133 - 0.0235 \text{ kg/kg}$$

$$X_{in} = 21\% \text{kg/kg} \quad W_m = 65 \text{kg/hr} \quad T_{Ain} = 60^\circ\text{C}$$

Drying air inlet conditions reported in this work are such that falling rate drying prevails throughout for all combinations of input variables considered.

Equilibrium Moisture Content

Along with the modified Henderson equation, the empirical Chung equation (Chung) is frequently employed to predict the moisture content values of grains. [Brooker et al., 1992]

The Chung equation has the form,

$$X_{eq} = 0.27908 - 0.04236 * \ln [-(T + 35.662) * \ln (p_v/p_{vs})] \quad (5.58)$$

8.5 Results without Air Recirculation

Figure 8.1. shows the variation in average outlet moisture content with NEB for different values of NEG. The results for NEP=15 and NEP=20 are found to coincide at all values of NEB. Moreover, beyond NEB=25, there is no change in X_o for these two cases. Accordingly, NEB=25 and NEP=15 are selected for further analysis.

The average outlet moisture content in the grain drops along dryer length at a decreasing rate; whereas, the grain temperature increases continuously also at a diminishing rate as depicted in Fig 8.2. Both of these behaviors are in line with falling rate period of drying.

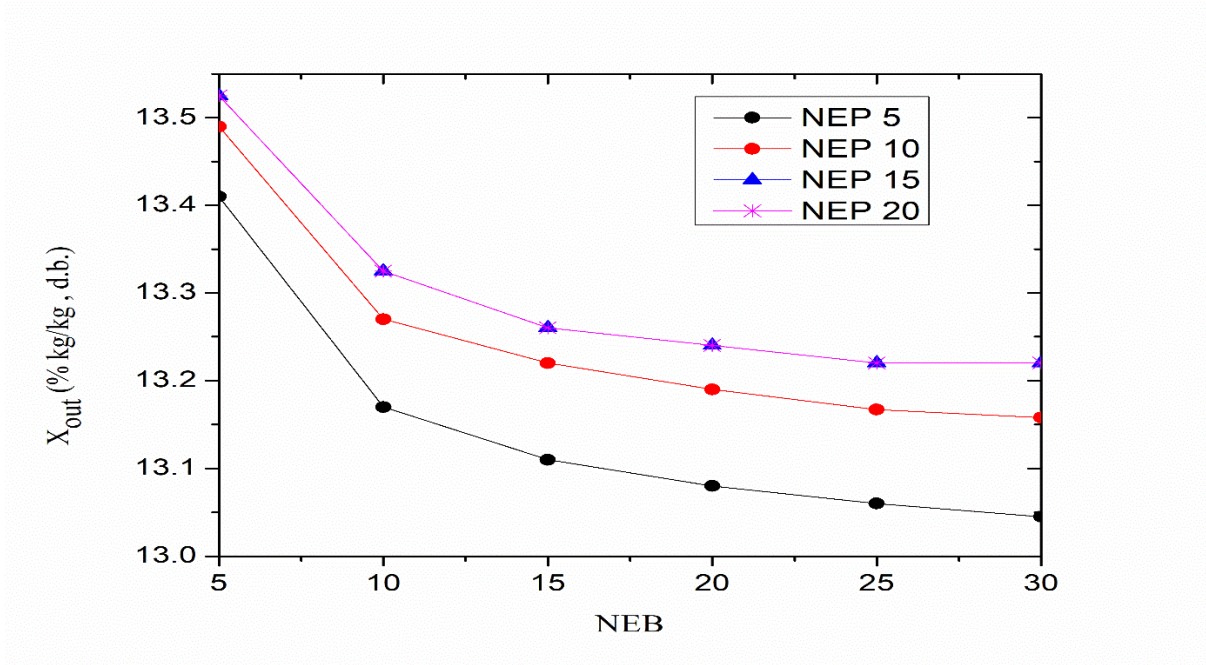


Figure 8.1. X_{out} versus NEB for different values of NEP

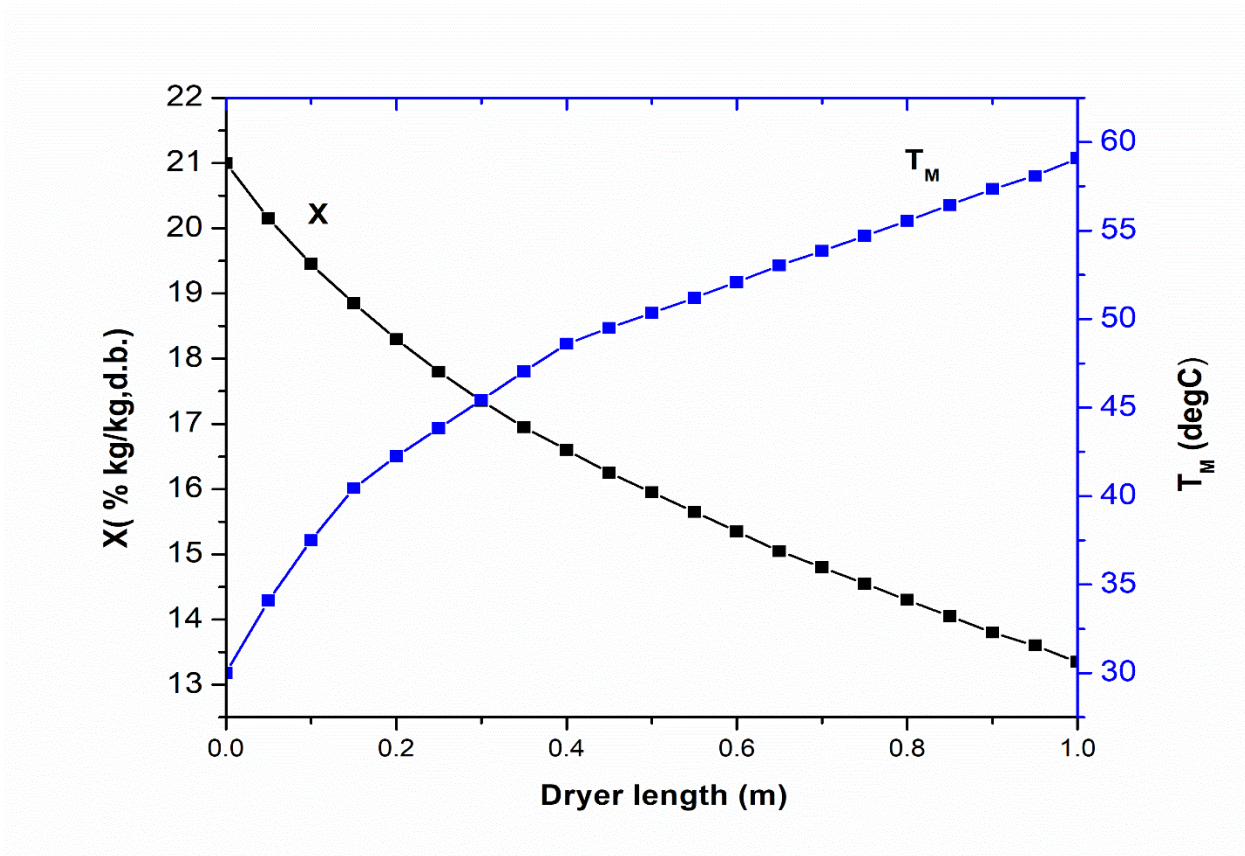


Figure 8.2. Variation of X and T_M with dryer length

Fig.8.3. represents the variation in moisture content of grain at different radial nodes (indicated by R (followed by the node number) along the length of the dryer. Moisture removal rates at the grain surface and intermediate points near the surface are very high in the beginning and go on decreasing with time; whereas, moisture removal rates at the center and intermediate points near the center are relatively smaller initially and go on increasing with time. For radial node NEB7 and node NEB10, a point of inflection is clearly evident. The reason for this behavior lies in diffusivity of water in wheat being very small in comparison to mass transfer coefficient at the outer surface. As expected surface value drops sharply and attains a very low value at the exit.

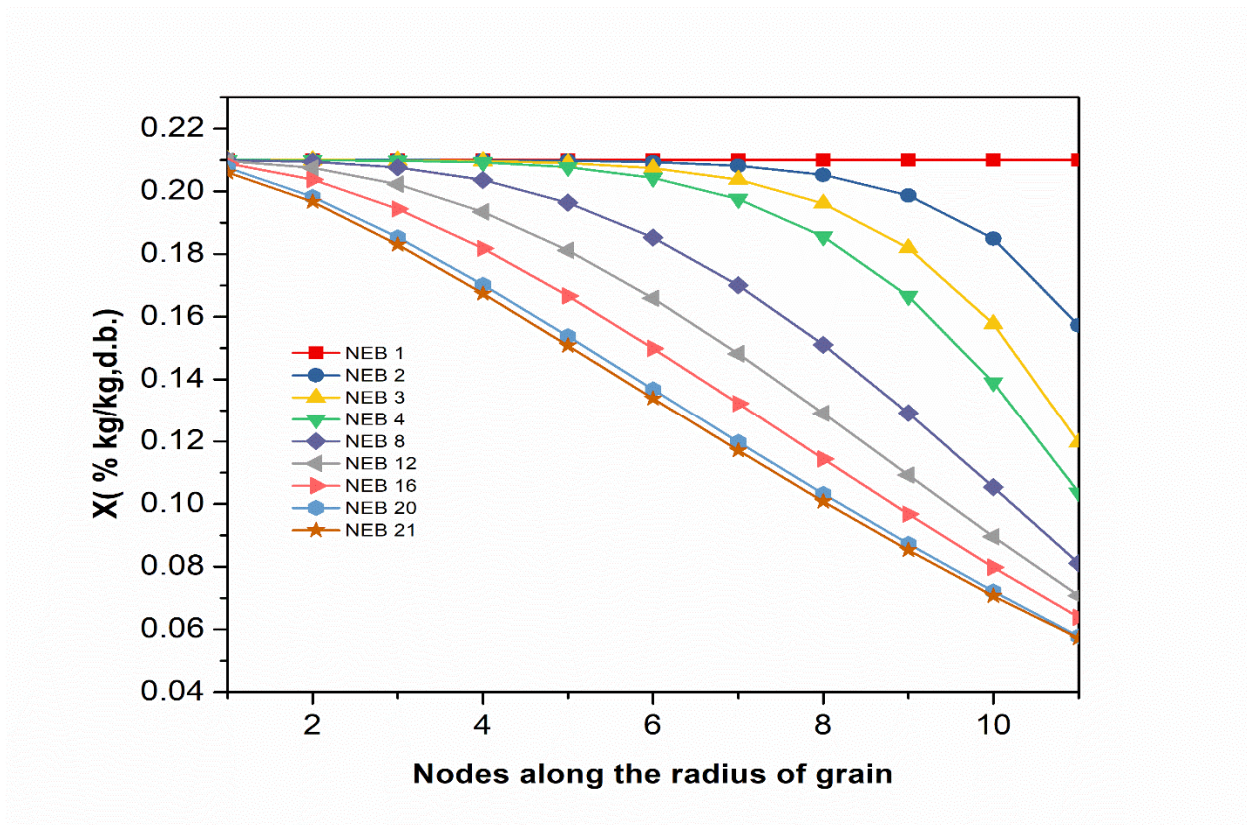


Figure 8.3. Moisture distribution at different radius of grain along dryer length

8.6. Results with air recirculation

Table 8.1 shows the effect of recirculation ratio on different output parameters. By increasing recirculation ratio, drying reduces only marginally but efficiency increases very much. The reason lies in the flow ratio between air and wheat being relatively large for fluidization to take place. For RR value of 18%, the drying efficiency rises up to 41%, while it is only 38.4% for the design case without recirculation. There is not much effect of recirculation on outlet temperatures of material and air. At RR=20%, the exit moisture content of grain from dryer exceeds the acceptable limit of 14 and is marked in bold

Table 8.0.1 Effect of recirculation ratio on output parameters

RR %	Y _i kg/kg	X _{Ao} kg/ kg %	T _{Mo} °C	Air outlet conditions		Eff %
				T _{Ao} °C	RH %	
0	0.0133	13.75	58.5	49.2	24.3	38.4
5	0.0135	13.85	57.4	48.6	25.3	39.0
10	0.0138	13.90	56.8	48.0	26.4	40.0
15	0.0141	13.95	55.7	47.3	27.6	40.6
20	0.0144	14.1	54.7	45.5	28.9	41.1

The effect of variation in air recirculation ratio on average material outlet moisture content and drying efficiency are shown in Fig.8.4 and Fig.8.5, respectively, at different material flow rates.

Acceptable region of 13% to 14% for X_{out} is marked by a rectangle in Fig.8.4. If the material flow rate is reduced to 35 kg/hr, recirculation ratio value of 18% with efficiency reaching beyond 41%. In turn, if material flow rate is increased to 70 kg/hr, X_{out} also reaches to its maximum acceptable limit and hence we cannot re-circulated exhaust in this situation.

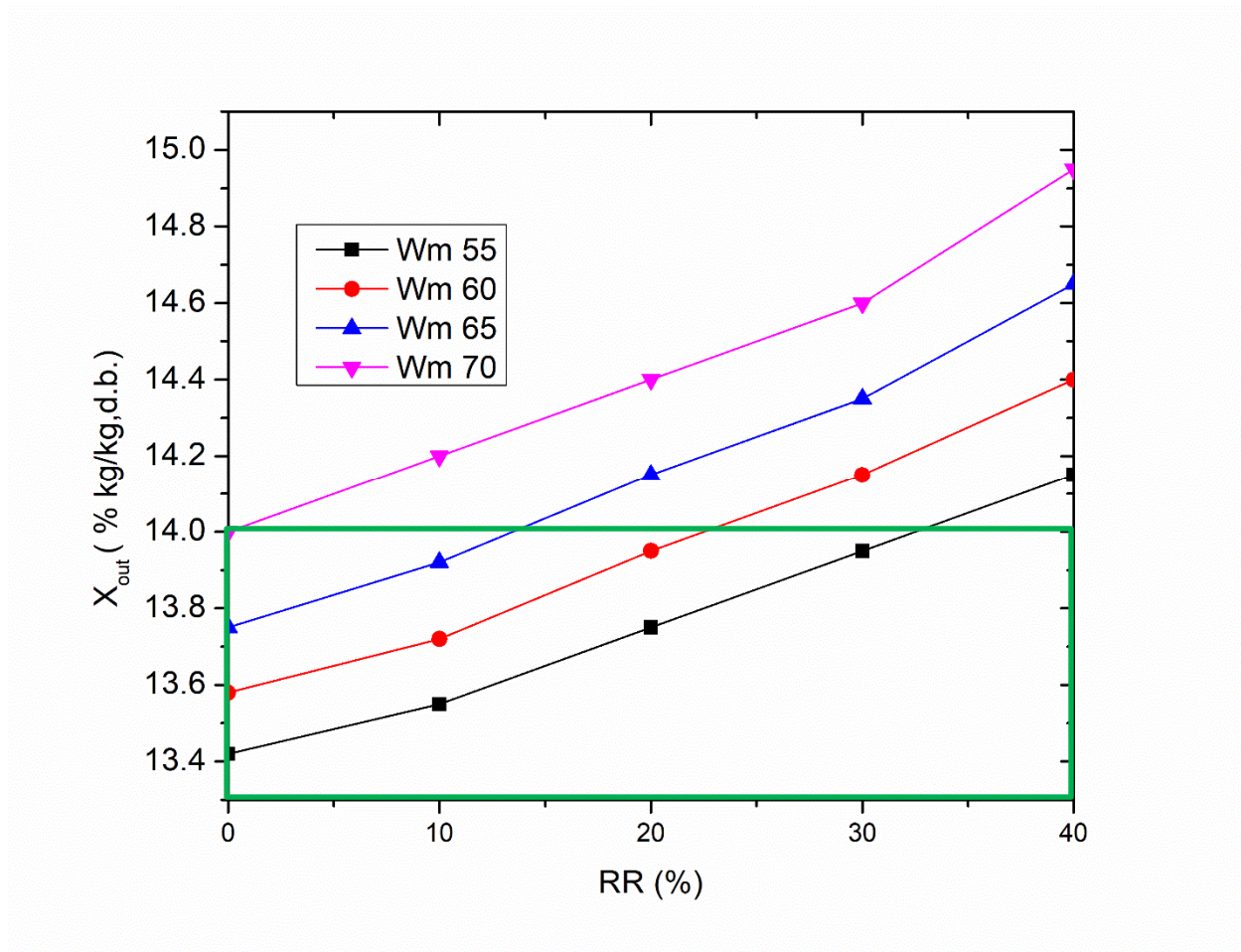


Figure 8.4. X_{out} versus RR at different W_M

From Fig.8.5. It is evident that the drying efficiency, as expected, remains higher for larger flow rate of material. Its rate of increase increases with RR initially and then decreases thereby creating an inversion point which moves towards left for higher material flow rate. The reason for this behavior lies in energy input as heat to inlet air, appearing in the denominator of efficiency

expression, getting smaller for higher RR; and potential for mass transfer, which directly influences the numerator, becoming smaller due to inlet air moisture content rising with increasing RR. Inversion point moves to left for larger flow rates because the diminishing effect of smaller mass transfer potential progressively becomes more dominant.

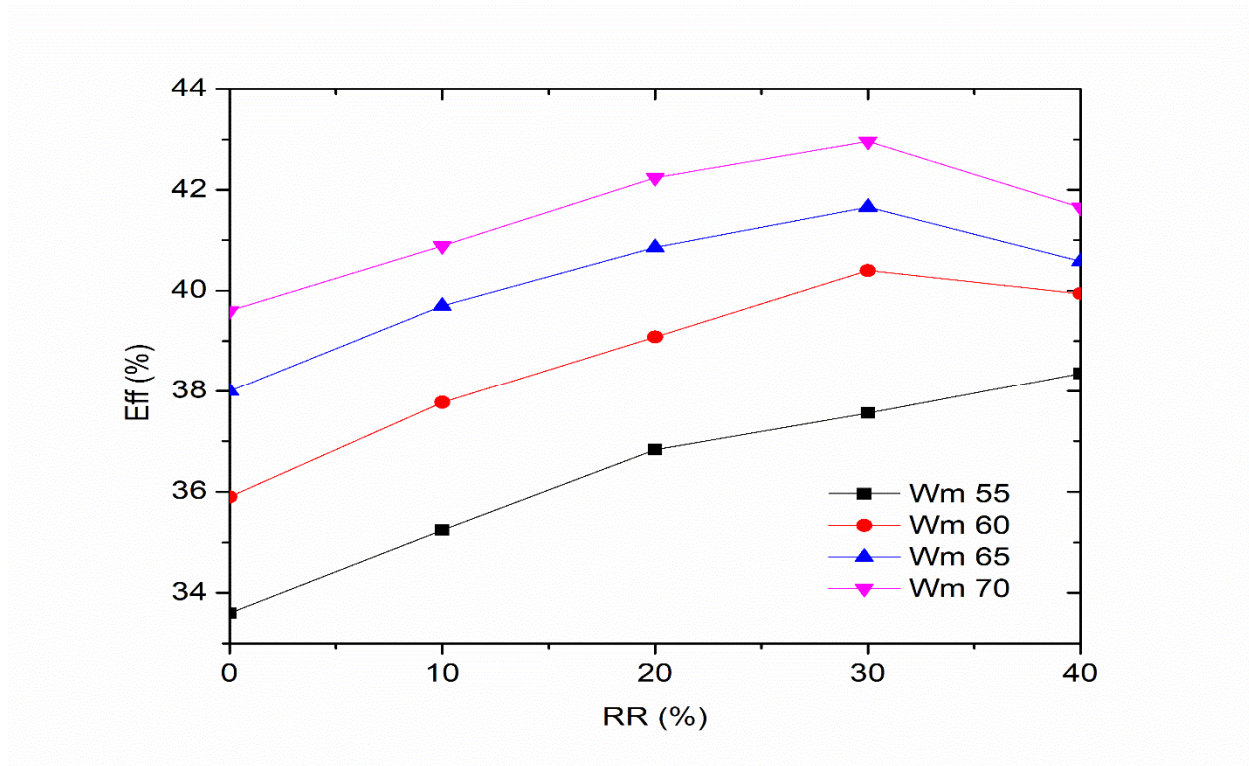


Figure 8.5. Efficiency versus RR at different W_M

Table 8.2 presents the performance of the dryer for off-design conditions of the operating parameters. The values of X_{out} and T_{Mout} for grain exiting from the dryer are reported in the same column for keeping the table size manageable. Similar is the case with the values of T_{Aout} and RH for the outgoing air. Unacceptable points are marked as bold for X_{out} and T_{Mout} .

The following inferences are drawn from the table for achieving acceptable value of X_{out} with maximum drying efficiency in terms of different set of operating parameters which are likely to occur in a year due to varying environmental conditions.

I. Design Ambient Condition

The design set of result is marked with superscript 'D'. It pertains to $X_{in}= 21\%$, $T_{ain} = 60^{\circ}\text{C}$ and $W_m = 65 \text{ kg/hr}$ with 100% of drier useful length without touching limiting values of X_{Aout} and without any recirculation of exhaust air. For design purpose, change in W_m by 5 kg/hr has been considered. 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 lowest output material moisture content without tempering is investigated. Performance of dryer for initial material moisture content values lower and higher than the design one is also reported.

(a). Improvement in drying efficiency

At design input condition, a recirculation ratio of 18%, can lead to drying efficiency of 41%; whereas, design value of efficiency is 38.4%. Arrangement for recirculation of exhaust air involves additional expenditure.

(b). Increase in throughput rate

(i) At design values of X_{Ain} and T_{Ain} , the throughput rate (W_m) can be raised up to 70 kg/hr with $\text{Eff} = 39.6\%$.

(ii) If further increase in throughput rate is desired, then inlet air temperature needs to be raised. The result comes out as $W_m=73\text{kg/hr}$, $T_i=63^{\circ}\text{C}$, $\text{RR}=5$, $\text{Eff}=38.0\%$).

(c). Attaining lowest level of acceptable exit material moisture content In case, one is interested in reaching to a X_{Aout} value lower than the design one (13.75%), may be for storage period greater

than one year, one has to consider smaller value of W_m than design value, since any increase in T_{Ain} is likely to cause T_{Mout} to cross its limiting value of 60°C . For this purpose, W_m values of 60, 55, 50, and 45 kg/hr have been considered. As expected, the percentage of useful dryer length goes on decreasing successively with decrease in W_m and therefore the drying efficiency also drops down continuously from its design level of 38.4%. There is a limit to which W_m can be brought down for reducing X_{Aout} . As evident from the reported data, W_m values of 45 kg/hr and 40 kg/hr lead to same X_{Aout} of 13.25%. The reason lies in equilibrium value of moisture content in air at particle surface reaching to its limiting value of Y_{in} . For reducing X_{Aout} below 13.25%, tempering process needs to be adopted. In this process, the dried product is not allowed to remain

II. Off-design Ambient Conditions

(i) For a colder and dry climate ($T_{amb}=20^\circ\text{C}$, $\text{RH}=50\%$), the dryer performance is much better. With $W_m=40\text{kg/hr}$ and $T_{Ain}=60^\circ\text{C}$, RR can be 75% leading to $\text{Eff}=49\%$. By raising T_{Ain} to 65°C , W_m can be increased up to 56kg/hr, making $\text{Eff}=30\%$.

(ii) In a humid climate with normal temperature such as near coastal areas ($T_{amb}=30^\circ\text{C}$, $\text{RH}=70\%$), RR is restricted to 40% resulting into $\text{Eff}=40\%$ with rest of the input conditions remaining at design level. Much improvement in throughput rate is not possible, because for $W_m=45\text{kg/hr}$ and $T_{Ain}=64^\circ\text{C}$, efficiency drops down to 31% and T_{Mout} reaches to 59°C .

(iii) In a hotter condition ($T_{amb}=40^\circ\text{C}$, $\text{RH}=50\%$), a lower flow rate of material than the design case of $W_m=40\text{kg/hr}$, can only be dried because the exit average grain moisture content crosses its maximum allowable limit. At a reduced flow rate of $W_m=35\text{kg/hr}$, with $T_{Ain}=60^\circ\text{C}$ and $\text{RR}=60\%$, the drying efficiency becomes remarkably high (55%), and this trend should be exploited to its fullest extent. Throughput rate, however can be increased up to 42kg/hr at $T_{Ain}=64^\circ\text{C}$ with a relatively higher efficiency of 40%. Exhaust air recirculation is ruled out in this case as T_{Mout} reaches the limiting value of 60°C .

Table 8.0.2 Dryer performance at off-design conditions

Ambient Air humidity Y_{amb} (Kg/Kg)	X_{Ain} (%)	T_{Ain} (°C)	W_m (Kg/hr)	RR	Useful drying length (%)	Material outlet condition		Air outlet condition			Eff (%)
						X_{out} (%)	T_{mout} (°C)	T_{aout} (°C)	RH (%)	Y_{out} (Kg/Kg)	
Design ambient 0.01329 ($T_{amb}=30^{\circ}C$ RH=50%)	21 ^D	60 ^D	65 ^D	0 ^D	100 ^D	13.75 ^D	58.5 ^D	49.2 ^D	24.3 ^D	0.01826 ^D	38.4 ^D
			40	0	70	13.25	59.3	53.0	18.3	0.01653	25.1
			40	45	70	14.0	53.0	47.8	26.6	0.01858	31.2
			70	0	100	14.0	57	48.4	25.5	0.01841	39.6
			75	0	100	14.35	56.2	47.9	26.4	0.01854	40.68
	18	60	140	0	100	14.0	52.2	45.3	31.7	0.01950	48.16
	23	60	65	0	100	14.85	56.7	47.7	26.9	0.01873	42.14
	Colder ambient 0.00725 ($T_{amb}=20^{\circ}C$ RH=50%)	21 ^D	60 ^D	50	0	85	12.9	59.3	50.7	14.4	0.01149
65 ^D				0 ^D	100	13.3	58.3	48.3	17.6	0.01249	30.8
65			60	0	95	12.8	63.8	53.5	13.5	0.01242	29.9
65			85	0	100	14.0	60.0	50.3	17.1	0.01349	32.5
65			86	0	100	14.1	59.2	49.8	17.5	0.01347	32.4
Humid ambient 0.01877 ($T_{amb}=30^{\circ}C$ RH=70%)	21 ^D	60 ^D	65 ^D	0 ^D	100	14.2	57.6	49.5	30.5	0.02348	36.1
		60	60	0	100	14.0	58.6	50.5	28.8	0.02322	34.0
		65	65	0	100	13.7	63.4	54.8	24.9	0.02384	33.1
			65	22	100	14.0	59.7	51.2	29.8	0.02491	36.4
Hotter ambient 0.02348 ($T_{amb}=40^{\circ}C$ RH=50%)	21 ^D	60 ^D	65 ^D	0	100	14.3	58.0	50.7	34.2	0.02807	52.2
		60	60	0	95	14.2	58.8	51.6	32.5	0.02781	49.3
		61	60	0	100	13.9	59.8	51.9	32.2	0.02798	48.8
		61	61	0	100	14.0	59.7	51.7	32.5	0.02802	49.2

8.7. Comparison between computed and experimental results

Before making comparison between computed results from the theory presented in this paper for continuous plug flow drying with batch drying experimental data, it needs to be emphasized that the two cases become physically identical when the residence time of material inside the dryer is made exactly same for the both of them, with all other parameters such as air temperature and its velocity are kept equal along with dryer geometry. Thus, for a given constant holdup of drying material for continuous flow drying, its flow rate is selected in a manner so that its residence time becomes same as that for the experimental case.

With the above functional equivalence of the two cases, the computed results for dryer geometry used in experimentation are compared with batch drying experimental data, in Figure 8.6 and Figure 8.7 for average moisture content and air of wheat and outlet air temperature of dryer for different drying times. The average moisture content values from computation are very close to those from the experimental ones, the difference lying between 2.3% to 2.7 %, with experimental values of moisture content remaining higher in magnitude. The basic reason for lesser drying during experimentation is due to heat loss from the drying chamber outer surface as it is not insulated whereas theoretical analysis considers no heat loss from the unit. The difference between experimental and theoretical values for T_{Aout} lies between 1.15 to 1.65°C.

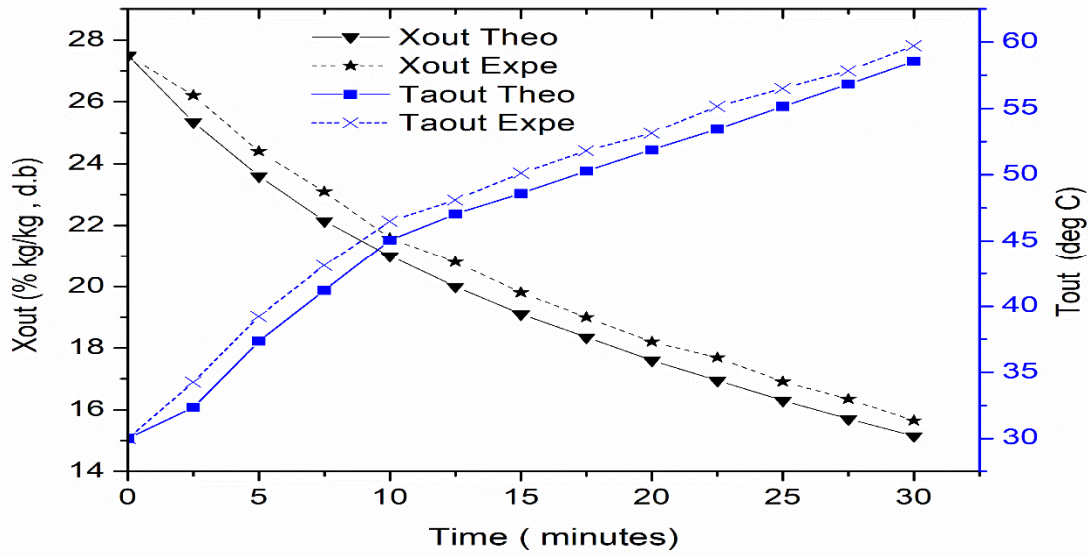


Figure 8.6. Average moisture content and air outlet temperature variation with time at $T_{Ain}=60^{\circ}C$ and $X_{in}=27.5\%$.

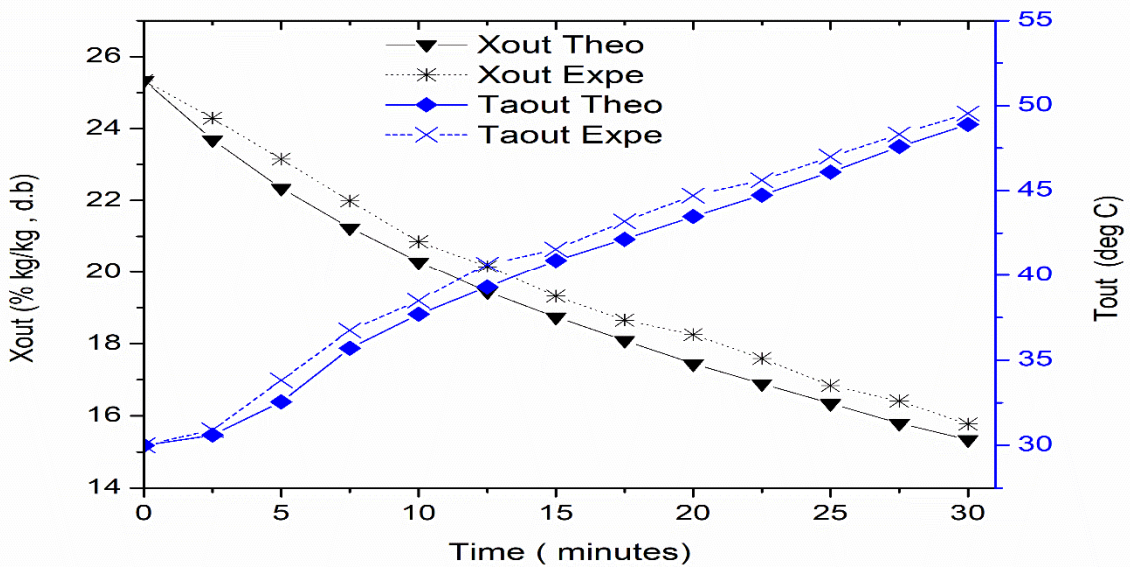


Figure 8.7. Average moisture content and outlet air temperature variation with time at $T_{Ain}=50^{\circ}C$ and $X_{in}=25.4\%$

8.8. Conclusions

- (i) It is possible to analyze the phenomena of coupled heat and mass transfer during fluidized bed drying of spherical particulate materials using an iterative numerical technique for sequential solution of discretized governing equations of overall moisture mass balance, enthalpy balance, heat transfer rate, mass transfer rate; and mass diffusion.
- (ii) The technique provides an insight for efficient utilization of a given dryer geometry and also for designing a new optimum one for attaining desired performance.
- (iii) The developed algorithm can be easily extended to incorporate regular particle shapes other than spherical, such as cylindrical, for achieving more accurate results in specific applications.
- (iv) Results for drying of wheat reveal that it is possible to increase drying efficiency to 41% with 18% of exhaust air re-circulation from its value of 38.4% without air recirculation at its design throughput rate.