Mathematical Modeling and Simulation of Gypsum Drum Dryer

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ABSTRACT: The study aims to solve the problems faced by JK Lakshmi Cement, Kalol. The plant is using wet chemical gypsum as one of the raw materials. The material, being sticky in nature, causes numerous problems in transportation and also overflows the hoppers. The suggested solution of this problem is drying with Inclined Drum Dryer (IDD). The design of IDD is done by generating mathematical model by making heat and mass balance. Two models are generated, One for sizing and one for rating. Both models are converted in to computer codes. Plant requirements are considered as reference and with trial and error method final design is suggested.

Keywords: Mathematical Modeling, Drying of Gypsum, Simulation with coding

1 INTRODUCTION

Inclined Rotary Drum Dryer (IDD) is one of the most widely used drying techniques in industry. Many authors have suggested mathematical model for thermal design of IDD. Most of them however are specific to the product. The earliest approach of such a design is more dependent on actual data generated from working dryers. Myklested [1] is first to develop an expression for final moisture contains of product. Kamke el al. [2][3] has developed a computer code for retention time (Part I) and mass transfer (Part II) for cascading rotary dryer. The problem with this mathematical model is: they are more specific to a dryer and not general. Iguaz et al. [4] proposed a mathematical model for vegetable wholesale by-product by dividing the drum into 10 control volume and applying the heat and mass balance to each control volume. A similar approach of division of control volume is used for analysis of an industrial ammonium nitrate plant by Abbasfard et al. [5]. The study aims to compare data gathered from actual plant with data generated from mathematical modeling. The retention time equation of Foust et al. when used in mathematical model the generated data is closer to actual data than any other model. Fernandes et al. [6] has presented a study of comparison between the industrial and modeling data. Retention time equation of Friedman and Marshall is used for mathematical modeling.

2 DRYER DESCRIPTIONS

A schematic diagram of concurrent dryer assembly is shown in the Fig. 1. The Feeding of material can be done with the help of hopper and belt conveyor assembly. The exhaust air is passing through the cyclone collector and bag collector for collection of residue. The air at 30^{o}C and having moisture contain of 0.001 kg/kg dry air is heated up to 350^{o}C with final moisture contain of 0.001 kg/kg dry air in furnace. The gypsum is entering from inlet chute in the drum with moisture contain of 30 kg/kg dry gypsum and temperature of 30°C. The drum is equipped with straight radial flights for lifting of material.

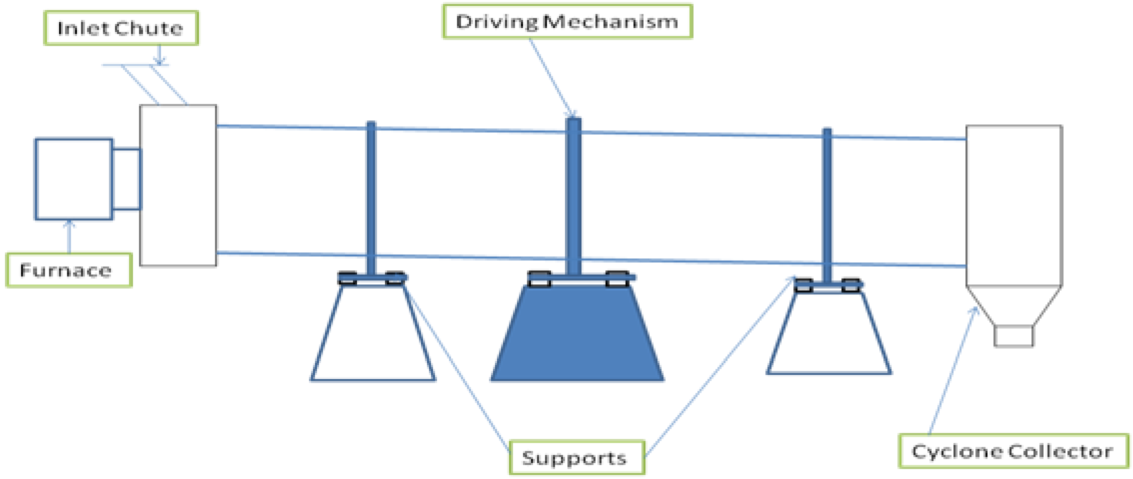
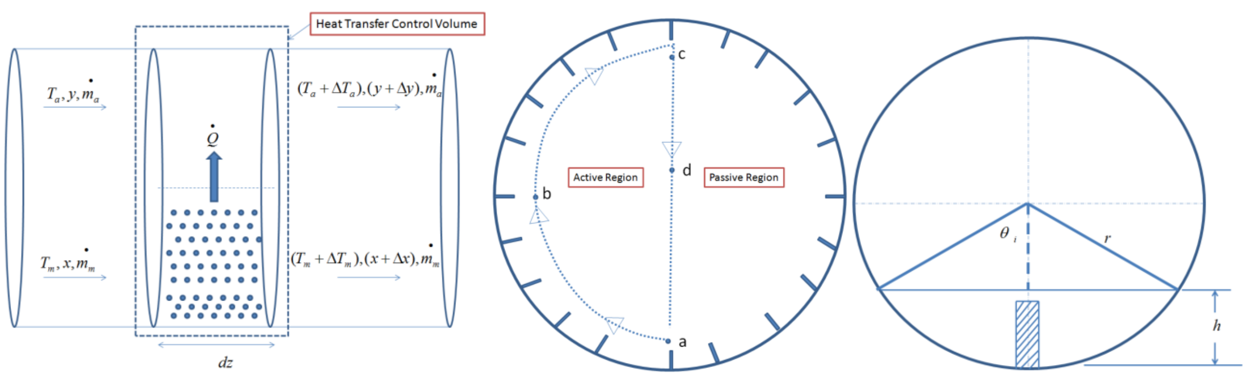


Fig.1 Concurrent Industrial Drum Dryer

3 MATHEMATICAL MODELING

The thermal design of dryer is done by generating two mathematical models. First model, the sizing model is for sizing of dryer. The sizing model provides the 1st approximation of geometry of drum. Second model, the rating model is used for optimizing the dryer by using data generated from first model.



(a) (b) (c)

Fig 2 (a) CV for calculating Heat and Mass Transfer (b) Number of Flights taking part in drying (c) Geometry of a single Flight

3.1 Sizing model

3.1.1 MASS BALANCE

The Gypsum having x_i% moisture is fed with rate of Co kg/hr. Hence the total dry solid in the feed is $\dot{m}_m = Co(1 - x_i)$ and water rate in the feed $\dot{m}_w = Cox_i$. The moisture is reduced to x_o % at the end of drying. Hence the final water rate in the product is $\dot{m} = \left(\frac{x_o \dot{m}_m}{(1-x_o)}\right)$. The total amount of water evaporated is $\dot{m}_e = \dot{m}_w - \dot{m}$.

3.1.2 HEAT BALANCE

The mass flow rate of air required to evaporate the required amount of moisture from product is found by the heat balance as:

$$
\begin{aligned}
TotalheatRequired \\
&= (heatrequiredtoraisetheMaterialtemptosafeexittemp) \\
&+ (Heatsuppliedtoresidualmoisture) \\
&+ (Sensibleheatsuppliedtotheevopratedmoisture) \\
&+ (Latentheatsuppliedtoevopartaedwater)
\end{aligned}
$$

$$\dot{Q}_1 = \left(\dot{m}_m c_m (T_{m,o} - T_{m,i})\right) + \left(\dot{m} c_m \left(\frac{T_{m,o} + T_{m,i}}{2}\right)\right) + \left(\dot{m}_e c_m \left(\frac{T_{m,o} + T_{m,i}}{2}\right)\right) + (\dot{m}_e h_{fg})$$

The heat is lost from the surface of the drum that is nearly equal to 10% of the total heat required. Hence, $\dot{Q}_{loss} = 0.1\dot{Q}_1$. Mass of air required to transfer heat then will be

$$\dot{m}_a = \left(\frac{\dot{Q}_1 + \dot{Q}_{loss}}{c_a(T_{a,o} - T_a)}\right)$$

Diameter of the dryer can be found out by following equation

$$D = 2\sqrt{}(V_{total}/\pi v_c)$$

Where, V_{total} is total quantity of gas inside the drum $V_{total} = V_{air} + V_{water}$ and $v_c$is conveying velocity of air i.e

$$v_c = \frac{6000{d_p}^{0.4}}{(s+1)} \frac{1.2}{\rho_{air}}$$

3.1.3 FLIGHT DESIGN

With reference to Fig. 2 (b and c), the height of flight $h = R(1 - \cos\theta_i)$. Where θ_i is calculated from $\theta_i = 0.321{H_o}^{0.3544}$. Here, Ho is material holdup selected. Similarly, based on the calculated h the length of flight “l” is also selected. The redial angle covered by a single flight can be calculated from geometry i.e. $\theta_n = tan^{-1}\left(\frac{l tan\theta_r}{R}\right)$ hence total number of flight is $N_f = \left(\frac{360}{\theta_n}\right)$.

3.1.4 LENGTH OF DRUM

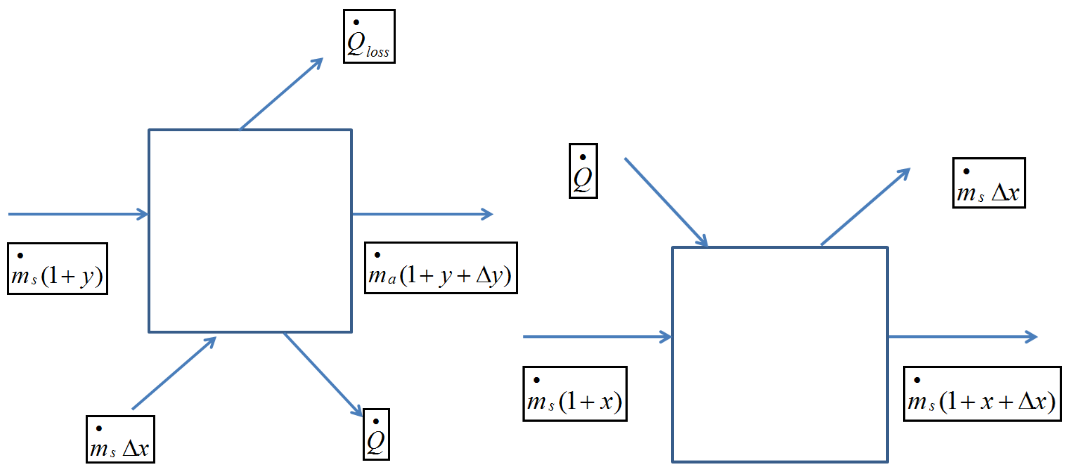
Length of the drum depends on LMTD and total heat transfer rate i.e.

$$L = \left(\frac{\dot{Q}_{total}}{U_a A(\Delta T)_m}\right)$$

$$U_a = K\left(\frac{h_c A_m N_p}{A}\right) \qquad \text{where}\, h_c = \left(k_g \frac{2+\left(0.6Re^{0.5}Pr^{0.33}\right)}{d_p}\right)$$

3.2 RATING MODEL

The rating of drum is modeled by dividing the drum in number of control volumes of length dz and N_p number of practical in each control volume. Fig. 2 (a) shows the control volume for gypsum and Fig. 2 (b) shows control volume for air.



(a) (b)

Fig. 2 (a) Gypsum Control Volume (b) Air Control Volume

Assuming that the initial values of temperature of gypsum and air are $T_{m,i}$, $T_{a,i}$ respectively and moisture contain of 0.3 (w/w) and 0.1 (w/w) respectively, the heat and mass balance is applied at each and every CV in such a way, that the output of one CV is input to the consecutive control volume. The analysis is done with the following equations

$$\Delta T_a = \left(-\frac{\dot{m}_s(c_{p,s}+xc_{p,l})+\dot{m}_a\,\Delta y(h_{fg}+c_{p,v}(T_a-T_s)+\dot{Q}_{loss}}{\dot{m}_a(c_{p,a}+yc_{p,v})}\right)$$

$$\Delta T_a = \left(\frac{\left(hA_p\left\{T_a-T_s+\left(\frac{A_1}{2}\right)\right\}\right)-\left(h_{fg}A_p\left(\frac{P_{sat}}{R_1T_a}-\frac{Py}{(y+0.62)R_2T_a}\right)\right)}{\left(\left(\frac{\dot{m}_p\,v}{fdz}(c_{p,s}+xc_{p,l})\right)-\left(\frac{hA_p(A_2-1)}{2}\right)+\left(\frac{h_{fg}k_mA_p}{2R_2T_s}\left(\frac{dP_{sat}}{dT}\right)\right)\right)}\right)$$

$$\Delta x = \left(-\frac{k_mA_p\,fdz}{\dot{m}_p\,u_{eff}}\right)\left(\left(\frac{P_{sat}}{R_1T_s}\right)-\left(\frac{yP}{(y+0.62)R_2T_a}\right)\right)$$

$$\Delta y = \left(- \frac{\dot{m}_s}{\dot{m}_a} \right) \Delta x$$

3.2.1 *Retention time*

The retention time of dryer is found out with the help of matchett and Sheikh [7] equation as follows

$$\tau = \left(\frac{L\left(N_{rpm} t_{fall} + \delta\right)}{N_{rpm} t_{fall} \left(U_1 + \frac{aD\delta \tan \alpha}{t_{fall}} \right)} \right)$$

4 RESULTS AND DISCUSSION

The rating and sizing models are converted into codes with C++ program. The sizing model code is used for calculation of geometrical parameters and the calculated geometrical parameters are rated with rating model code. The sizing code results are tabulated in Table. 1. The results show that L/D ratio is 8.3 and is within the permissible limit of 5 to 10 and final moisture contains of air and gypsum are within required limits. The final air and gypsum temperature is in good fit with selected range. Hence, the result of sizing model is accepted.

Table 1. Sizing model results

D (m)	**L (m)**	**l (m)**	**N_f**	**x_o (w/w)**	**y_o (w/w)**	**$T_{a,o}$ (ºC)**	**m_a (kg/hr)**
1.88	15.694	0.49	19.31	0.10	0.124	82	9711

The result of sizing model is reselected with nearly L/D ratio of 8 making length of drum as 8 m and diameter of drum as 1 m. The rating model code is then used for rating of drum dryer. The rating model code gives the final selected parameter. The selection procedure is done in this order. Material screening is performed for average particle diameters and 60 % of material is around 0.001 m hence the average particle diameter is selected to be 0.001 m. The code is then used for selection of flight length and number of flights with average particle diameter as 0.001m. Similarly, the code is used for selection of inlet air temperature and RPM of drum each time the previously finalized parameter is made constant. The result of rating code is tabulated with Table. 2.

Table 1. Rating model results and final selected parameters

d_p(m)	**D (m)**	**L (m)**	**l (m)**	**N_f**	**N_{rpm}**	**x_o (w/w)**	**y_o (w/w)**	**$T_{a,o}$ (ºC)**	**$T_{m,o}$ (ºC)**
0.001	1	8	0.51	19	3	0.10	0.16	77.96	63.87

CONCLUSIONS

The sizing and rating analysis of inclined drum dryer for gypsum drying is carried out. It is shown that the sizing and rating model is robust enough to calculate required dimensions of inclined drum dryer.

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Development of a Software for Design of Cyclone Separator: CySep

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ABSTRACT: Cyclone separator is a widely used industrial equipment for separation of solid and gas mixture. Process design of the cyclone affects the separation efficiency to greater extent. Design of cyclone based on Stairmand's cyclone is an iterative procedure. Software developed on user friendly platform can reduce human effort and increase efficiency. In current study, user friendly software 'CySep' is developed to calculate separation efficiency of cyclone separator. Moreover, results obtained from the 'CySep' is compared and found very accurate with already published literature.

1 INTRODUCTION

Cyclone separator is widely used as a gas-solid separator in process industries. Due to stringent environment regulations, it is now mandatory to separate dust particles from exhaust gases. It is also used in industries for the separation of catalyst particles laden with process gas. No moving parts and easy construction makes cyclone separator an economically viable option as a good gas-solid separator (Elsayed et. al. 2010, Funk et.al. 2014, Safikhani et. al. 2011). Cyclone separator separates gas-solid using centrifugal force. Gas-solid mixture enters into the cyclone tangentially, which creates swirling motion, due to which heavy solid particles are directed towards wall of the cyclone and moves downwards (Cortes et. al. 2007). As gas moves further downward more and more solid particles are separated. In cyclone separator, there are two vortices namely inner vortex and outer vortex. Gas-solid mixture, first directed in outer vortex and moves downwards after reaching to the bottom of cyclone gas take inner vortex path as it provides least resistance for gas and relatively pure gas is collected from the top of cyclone separator. Solid particles are collected from the bottom of the cyclone separator which provides least resistance path for solids.

Process design of cyclone separator is relatively easy, but iterative procedure of designing makes it quite cumbersome and less accurate. Design of cyclone is dependent on various factors like, particle size distribution of solids, desired efficiency, as well as pressure drop. Smaller size particles are difficult to separate compared to larger size particles and presence of smaller particles reduces efficiency of cyclone separator. It is recommended to use cyclone above particle size of more than 5 µm as efficiency is better with larger size particles (Elsayed et. al. 2010, Sinnot et. al. 2005). In order to achieve higher efficiency in less number of cyclones, one can not neglect pressure drop aspect. Actual pressure drop within the cyclone, must be less than or equal to maximum allowable pressure drop set by process constraints. By developing user friendly software, we can reduce human efforts and enhance accuracy. For this purpose, Java platform has been selected for programming language. Designer can use this software for designing and simulation. The design of software is based on Stairmand's standard cyclones. In present study, we have limited our focus to efficiency calculation.

2 METHODOLOGY

Designing and simulation is based on Stairmand's standard cyclone. Stairmand has developed eff-ciciency curves for (i) High efficiency and (ii) High throughput cyclones. Design conditions for standards cyclones are tabulated in Table 1, while dimensions of standard cyclones in terms of diameter of cyclone (D_c) are tabulated in Table 2. Diameter for both standard cyclones (High efficiency and High throughput) is 203 mm. Actual design of cyclone is based on these standard cyclones. Scaling Factor (SF) determines deviation from standard cyclone. If SF is near to one, then design is near to standard design. Higher SF values indicate larger deviation from standard (Sinnot et. al. 2005).

In present study, we have taken different data points for efficiency curve manually from elsewhere (Sinnot et. al. 2005) and using Excel as a computation tool, curve fitting is done.

Table 1. Design conditions for Stairmand's standard High efficiency and High throughput cyclones (Sinnot et. al. 2005).

Sr. No.	Design conditions	High efficiency cyclone	High throughput cyclone
1	Test fluid	Air	Air
2	Density difference between gas and solids	2000 kg/m^3	2000 kg/m^3
3	Temperature	20 °C	20 °C
4	Pressure	1 atm	1 atm
5	Volumetric flowrate of gas	223 m^3/h	669 m^3/h
6	Viscosity of test fluid	0.018 mNs/m^2	0.018 mNs/m^2

Table 2. Dimensions of Standard Starimand's cyclones (Sinnot et. al. 2005).

Sr. No.	Dimension	High efficiency cyclone	High throughput cyclone
1	Inlet height	0.5 D_c	0.75 D_c
2	Inlet width	0.2 D_c	0.375 D_c
3	Vortex finder diameter	0.5 D_c	0.75 D_c
4	Total cyclone height	4 D_c	4 D_c
5	Cylinder height	1.5 D_c	1.5 D_c
6	Vortex finder length	0.5 D_c	0.875 D_c
7	Cone tip diameter	0.375 D_c	0.375 D_c

3 DEVELOPMENT OF SOFTWARE

Graphic User Interface (GUI) is developed on the Java. There are two modes in CySep (i) Design and (ii) Simulate. In designing of cyclone, designer has to design equipment based on feed flowrate, particle size distribution, density of solids, density of gas and desired separation efficiency. So, these parameters will become inputs for designing and the final design will give dimension of cyclone and number of cyclones in parallel required to achieve desired efficiency. In simulation of cyclone, designer will get idea whether given number of cyclones would be able to separate solids from gas at desired efficiency at given process conditions or not. For illustration purpose, snapshot of GUI is shown in Figure 1. On left hand side of GUI for design mode, designer has to input variables like volumetric flow rate, density of solid particles, density of gas, required efficiency and particle size distribution. In simulate mode, designer has to input variables like volumetric flow rate, density of solid particles, density of gas, number of cyclone in parallel and particle size distribution. In design mode, 'CySep' will calculate the number of cyclones in parallel required to achieve desired efficiency, achieved efficiency and diameter of cyclone in design mode. While in simulate mode, 'CySep' will calculate achieved efficiency and diameter of cyclone for entered number of cyclones.

For comparison purpose, 'CySep' is compared with the solved example elsewhere (Sinnot et. al. 2005).

3.1 *Problem Statement*

Design a cyclone separator for separation of solid particles form gas stream. Particle size distribution in the inlet gas stream is tabulated in Table 3. Density of solid particles is 2500 kg/m^3. Gas is nitrogen at 150 °C. Operating pressure within the cyclone is 1 atm. Volumetric flowrate of gas is 4000 m^3/h and 80 percent recovery of solids is required. Comparative study of solved example from elsewhere (Sinnot et. al. 2005) and 'CySep' is tabulated in Table 4. Snapshots of results obtained through 'CySep' in design and simulate mode are shown in Figure 2 and 3 respectively.

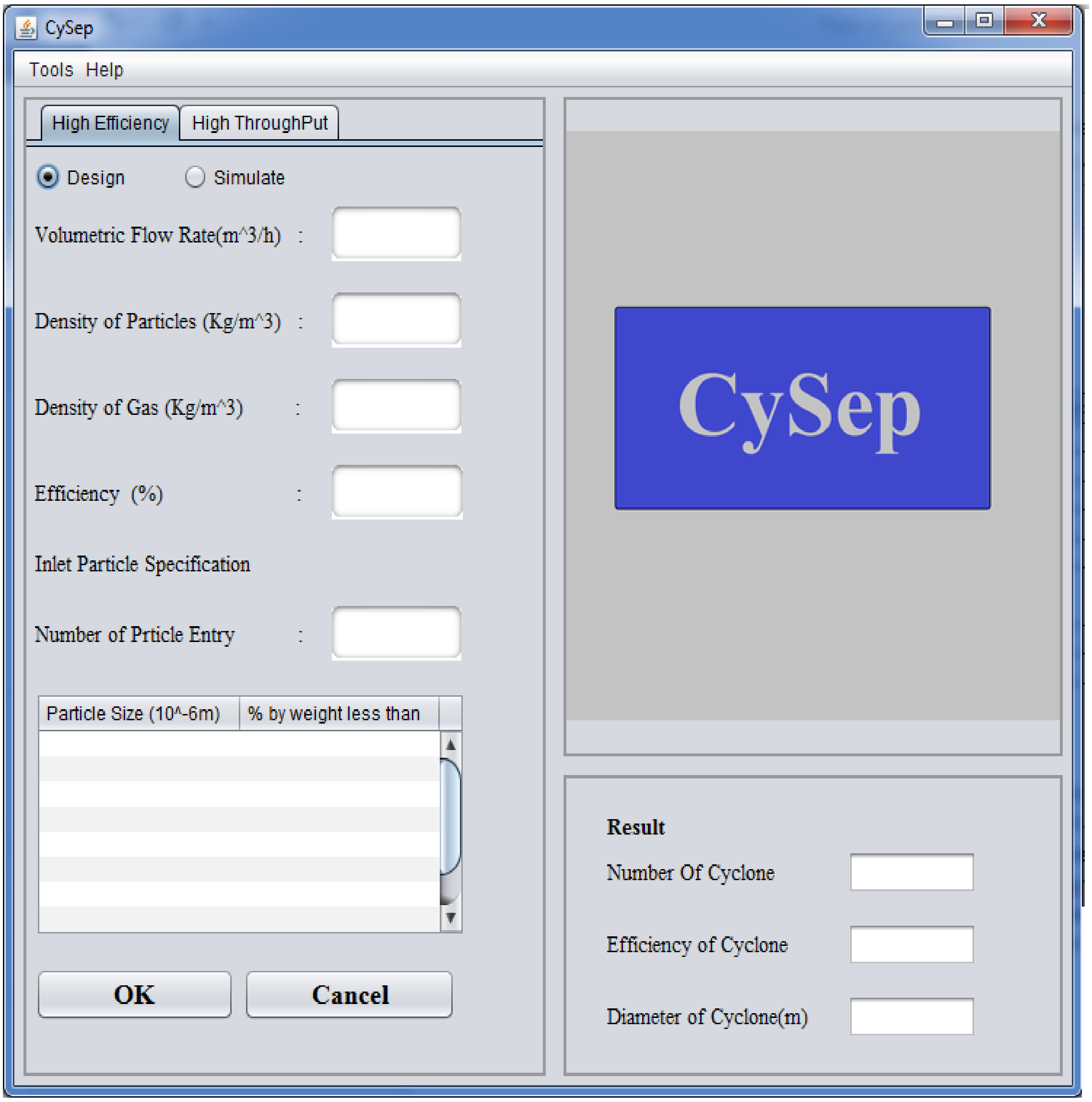

Figure 1. Snapshot of Graphic User Interface of 'CySep'.

Table 3. Particle size distribution of solids.

Sr. No.	Particle size, µm	Percentage by weight less than
1	50	90
2	40	75
3	30	65
4	20	55
5	10	30
6	5	10
7	2	4

In design mode, ‘CySep’ will start iteration with minimum number of cyclones i.e. one. It will initiate loop with the calculation of achieved efficiency with minimum number of cyclones. If desired efficiency has been achieved, then it will break the loop. Otherwise it will increase the number of cyclone by one and continue the iteration till the actual efficiency is equal to or more than the desired one. In the given problem, desired separation efficiency is 80 percent. As per the results obtained in design mode, using a single cyclone having diameter of 0.86 m separation efficiency of 82.649 percent can be achieved.

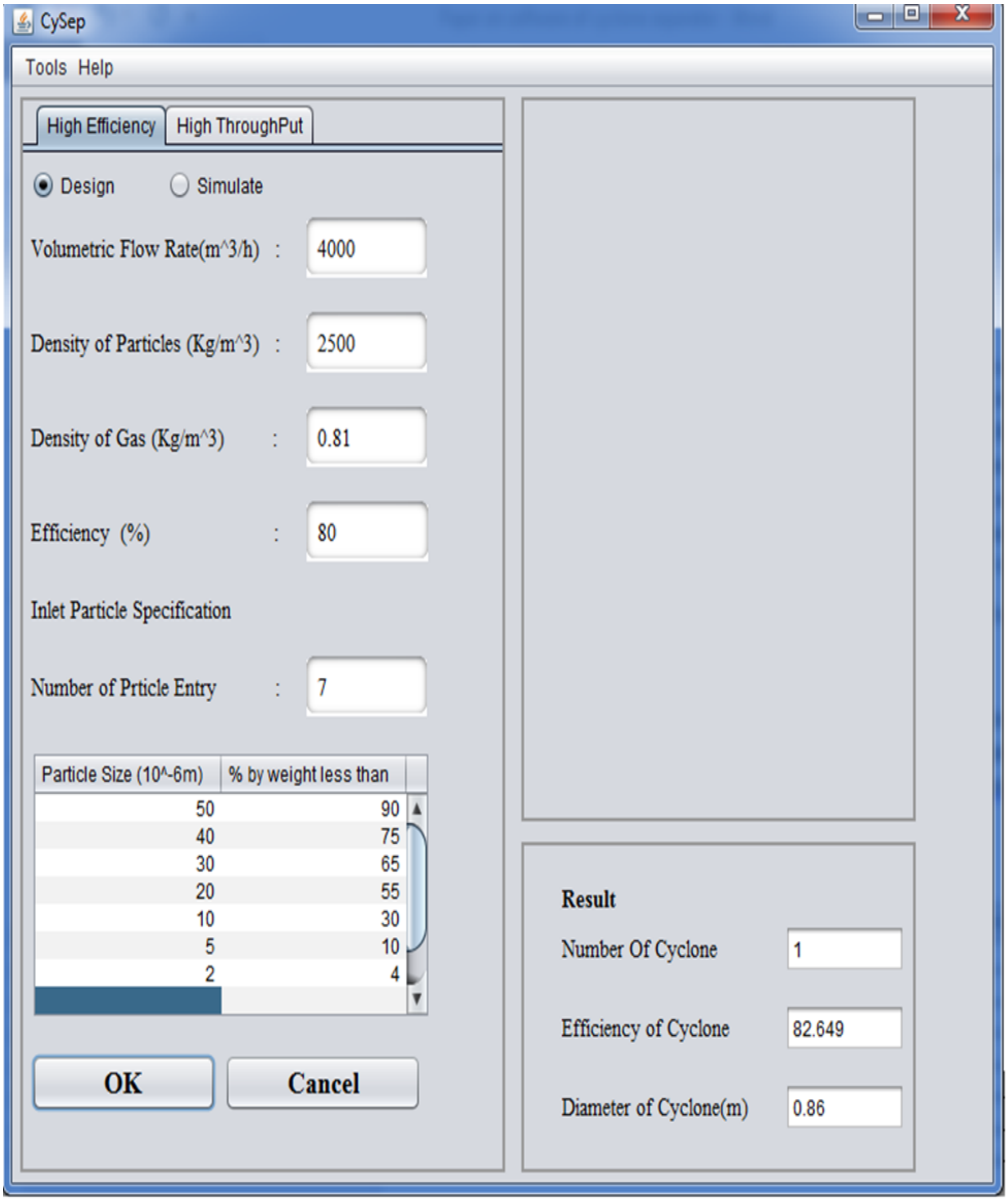

Figure 2. Snapshot of GUI in design mode.

In simulate mode, ‘CySep’ will calculate achieved efficiency for given number of cyclones. In simulate mode, software will not go for iteration. It will directly predict achieved efficiency for given number of cyclones. If we enter four number of cyclones in parallel, then as per the software achieved efficiency is 88.427 percent, which is quite close to already published literature.

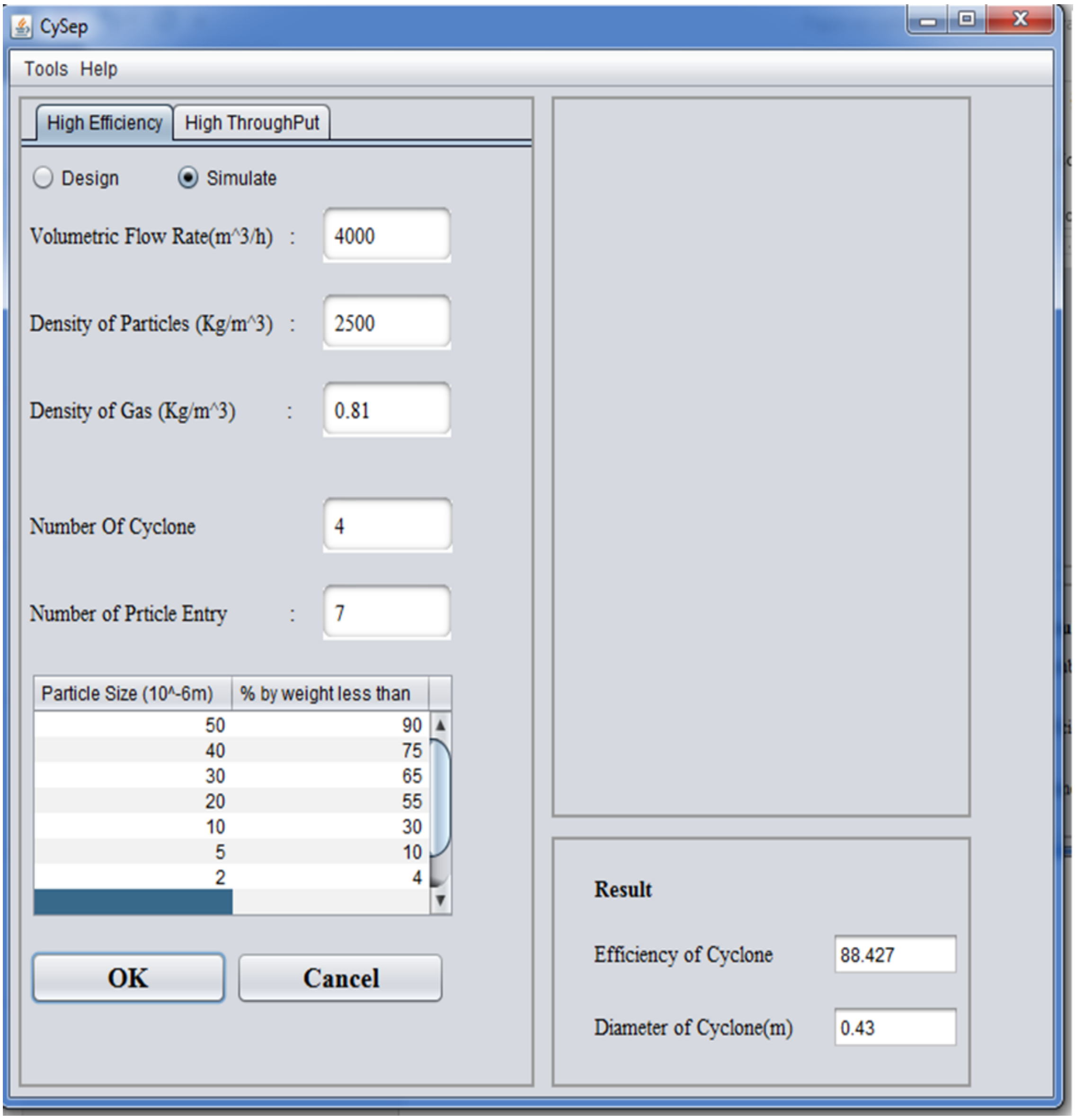

Figure 3. Snapshot of GUI in simulate mode.

Table 4. Comparative study

Sr. No.	Parameter	Results from (Sinnot et. al. 2005)	CySep Design mode	CySep Simulate mode
1	Achieved efficiency	88.7 %	82.649 %	88.427 %
2	Diameter of cyclone	0.42 m	0.86 m	0.43 m
3	Number of cyclone in parallel	4	1	4*

*Number of cyclones in parallel has to be entered by user in simulate mode

4 CONCLUSION

Results obtained on developed software 'CySep' are found to be quite accurate in terms of separation efficiency calculation. Software can reduce human efforts to considerable extent, as designing is an iterative procedure and can also increase accuracy to many folds. Limitation of this software is that pressure drop calculations and other models have not been incorporated. Continuous efforts have been made to modify the software and obtain results which can be readily accepted by industries.

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