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SELECTED PERFORMANCE ANALYSIS OF A ROTARY STEAM TUBE DRYER USING SPREADSHEET SIMULATION

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ABSTRACT
The primary motivation that triggered this study was when a feasible analytical solution amenable to computer spreadsheet programming was sort for, in explaining the physical configuration of the rotary steam tube dryer. An existing rotary steam tube dryer was studied from where analytical derivation of the moisture content distribution, drying rate, mass condensation rate and system efficiency were established. With the derived equations, the developed spreadsheet modules calculate and plot charts, simultaneously, illustrating the variations of the above parameters along the length of the pipe. The results generally show; that the moisture content falls steadily from inlet to outlet of the dryer and that the drying rate has an initial increase before falling along the length of the dryer. The results also show that the rate of steam condensation has an initial steep increase at the beginning of the length of the dryer, which eventually normalizes to steady state as the length advances, while the system efficiency generally increases with increase in length. This developed case was achieved with ordinary Excel array functions without the use of macros and add-ins.
Keywords: Drying, Spreadsheet Simulation, Rotary Steam Tube, Moisture Content

INTRODUCTION
This work is aimed at deriving a spreadsheet model for the performance analysis of a rotary steam tube dryer. The objectives of this exercise are analytical derivation and spreadsheet simulation of the drying rate, determination of the controlling parameters that govern the operation of the dryer and identification of the major factors that control the efficiency of a rotary steam tube dryer. The salient theme of this paper which is basically the removal of a liquid from a solid by evaporation is a simultaneous process of heat and mass transfer. As such, the theory developed in this analysis follows the lines of these two important branches of engineering science. Drying is an operation of great commercial importance in all industrial applications ranging through the food, agricultural, mining and manufacturing sectors. As drying is certainly one of the most energy-intensive operations in industry, performance analysis of the parameters involved will help to improve dryer operations and efficiency.[1]

Many studies have been conducted to model rotary steam tube dryers using transport phenomena principles for mass, momentum, and heat transfer [2], [3], [4] and even using more sophisticated modelling tool.[5] However, their mathematical complexity, computational load, and inability to prove precise predictions on a completely theoretical basis of experimental results make these alternatives still inappropriate for industrial implementation.

On the other hand, in order to conform better to the requirements of modern society concerning working conditions and safety practices, Leena [6] developed control systems to provide opportunities for improving rotary dryer operation and efficiency, focusing on safety. The spreadsheet model of this study not only conforms to the safety measure of modern industrial society working conditions but also arrays the equations of the models into spreadsheet platforms thereby simplifying the otherwise complex mathematical equations and removing the computational burden, as the computer solves the equations with ease.

MATERIALS

Microsoft Excel, which is one of the programmes in Microsoft Office suite, is the most prevalent programme for creating spreadsheets today, and therefore, was used in this exercise. The major reason for using this platform for simulation is because a spreadsheet is simpler and more intuitive to use. One of the goals of this project is to introduce engineers to the spreadsheet as a tool for simulation modelling. Spreadsheets are ubiquitous – almost everybody has one - and files written by one spreadsheet can usually be imported by others. As a result, developers and users can easily pass simulation models from one to another.

To simulate the system, a study of an existing rotary steam tube dryer was conducted and was used to dry silica gel. Silica gel is a granular, porous form of silica made synthetically from acidifying a solution of sodium silicate. Despite the name, silica gel is a solid. Silica gel is most commonly encountered in everyday life as beads packed in a semi-permeable plastic.[7] In this form, it is used as a desiccant to control local humidity in order to avoid spoilage of some goods.[8] Once saturated with water, the gel can be regenerated by heating to about 90-120 °C for some time to dry it.[9]

The schematic cross sectional diagram of the dryer is shown in Fig 1. It is made up of three major parts A, B and C. A and C are respectively the inlet chute and the discharge chamber while B is the steel shell. During any operation, A and C are stationery while B rotates. The dryer also consists of a mixer which has a cylindrical end which is about 3.67m in diameter and 1.57m long. The end of the mixer is connected to the base of a frustum whose tapering end opens into one end of the steel shell. The mixer has spiral blades that transfer the material into the shell.

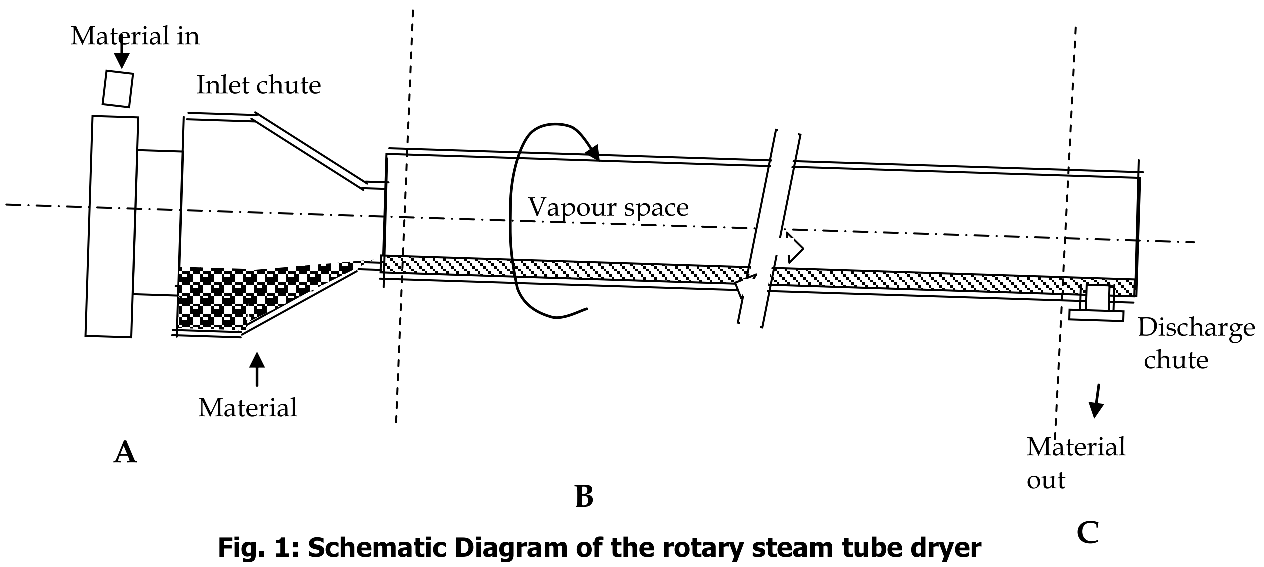


Fig. 1: Schematic Diagram of the rotary steam tube dryer

The steel shell is about 0.0159m thick, 3.05m in diameter and about 30.50m long. It is inclined along its axis at a gradient of 1:48 and rotates about this axis at 3.5 rpm. The rotary motion of the shell is provided by an electric motor coupled to a speed reduction gear to give the low rotary speeds usually encountered in rotary drying practice.

The entire dryer is mounted on elevated stands, partly to enhance removal of the dried product and partly to facilitate maintenance and overhaul of the components. The material to be dried is carried by a conveyor blade into the inlet chute from which it is fed into the mixer by a 1.83m diameter feed screw. At the inlet, the moisture content of material is about 85%. During operation, the material occupies 2% of the dryer volume. The dried product is collected via discharge chutes located between the tube rows at the lower end of the shell.

Contained in the dryer shell are 45 rows of evenly-spaced steam pipes located along the interior of the shell. Each row has three radially-arranged aluminium pipes. Fig 2 illustrates the cross-section of the shell of the steam-tube dryer. The steam pipes are the only source of heat required for drying. The last half of each pipe is covered with radially emanating fins, the intended purpose of which was to increase the heat transfer surface in contact with the material. The fins, which are also of aluminium, are intended for chumming and showering of the material being dried.

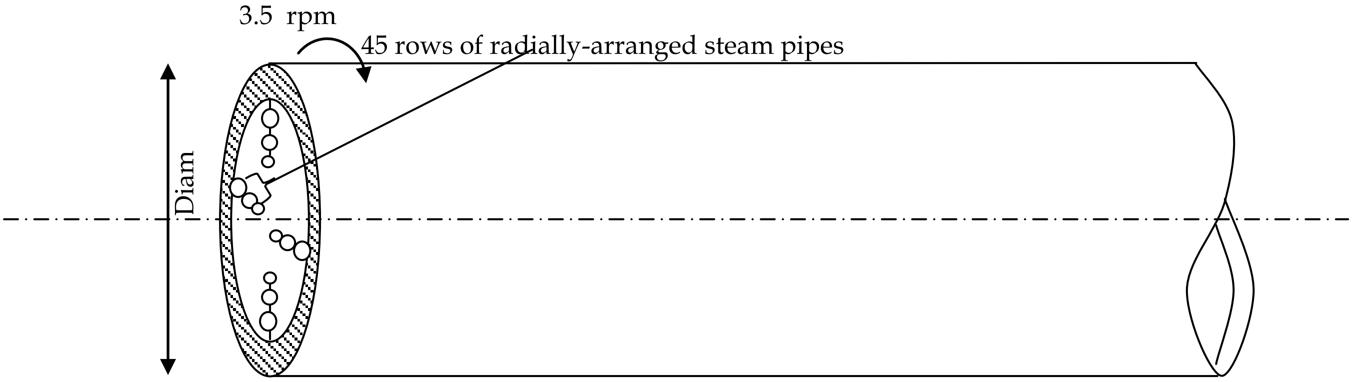


Fig. 2: Cross-section of the dryer shell

The following is the description of the drying process that takes place in the dryer. The saturated steam loses heat to the pipes thereby condensing on the walls. The condensate flows down the pipes with the help of gravity. Heat is transferred to the material from the pipes by conduction and this process is aided by the rotation of the shell as material is thus constantly brought into contact with the hot steam pipes. The rotation also provides some degree of mixing within the material, thereby minimizing radial temperature gradients.

The heat transferred to the material boils off the moisture in the form of water vapour which escapes into the vapour space in the dryer shell. The vapour is ultimately expelled into the atmosphere with the aid of a draw fan located on one side of the inlet chute.

Since the shell is not insulated, some heat is also lost to the atmosphere via the shell surface.

Method

From the description of the dryer, it can be clearly seen that an analytical prediction of the performance of the dryer based on the dryer parameters will be quite difficult. For example, the actual dryer consists of rows of tubes housed in a cylindrical shell with each tube covered with fins for the last half of its length. Therefore, to reduce this rather complex system to a simple system amenable to mathematical analysis, an equivalent steam tube is proposed.

The physical model proposed for the purpose of this analysis has an operation similar to that of the actual dryer. In this case, the steam tubes are replaced by an equivalent tube whose characteristic dimensions are the length, the inner and outer diameters. The length of this model is still the same as that of the actual dryer. However, to be able to obtain the values of the inner and outer diameters, two criteria are used. First is that the volume of steam to be carried by the model should be the same as that of the actual dryer. Second is that, by assuming radial heat flow, the equivalent tube should transfer the same quantity of heat as the component tubes acting together.

Drying Rate and Time

When heat is transferred to a wet solid predominantly by conduction as in the case considered in this paper, the solid approaches boiling point temperature. When the heat for evaporation in the constant rate is supplied by steam and conducted via a wall to the material to be dried, a dynamic equilibrium is established between the rate of heat transfer to the material and the rate of vapour removal from the surface:

$$\lambda \frac{d\omega}{d\theta} = U \Delta T A f_c \quad \ldots \quad (1)$$

where

λ = specific latent heat of evaporation

$d\omega/d\theta$ = drying rate

U = overall heat transfer coefficient

ΔT = Temperature difference between heat transfer surface and evaporating surface;

A = heat transfer area;

f_c = fraction of heat transfer area in contact with evaporating surface.

The falling rate[12] according to capillarity theory can be expressed with fair accuracy over the required range of moisture contents by an equation similar to:

$$\frac{d\omega}{d\theta} = -k_1(\omega - \omega_e) \quad \ldots \quad (2)$$

where

$\frac{d\omega}{d\theta}$ = drying rate at falling rate period;

ω = moisture content at any time;
ω_e = equilibrium moisture content.

k_1 is a function of the constant rate as follows

$$k_1 = \frac{-d\omega/d\theta}{\omega_c - \omega_e}$$

where

ω_c = critical moisture content

From equation of the drying rate,

$$k_1 = -\frac{U\Delta TAf_c}{\lambda(\omega_c - \omega_e)} \cdot (\omega - \omega_e)$$

Hence the falling rate for this case is given by:

$$\frac{d\omega}{d\theta} = -\frac{U\Delta TAfc}{\lambda(\omega_c - \omega_e)} \cdot (\omega - \omega_e) \quad \ldots \quad (3)$$

Since the drying process is considered to take place completely in the falling rate period, the critical moisture content can be replaced by the initial moisture content, ω_o. Therefore,

$$\frac{d\omega}{d\theta} = -\frac{U\Delta TAf_c}{\lambda(\omega_o - \omega_e)} \cdot (\omega - \omega_e) \quad \ldots \quad (4)$$

The drying time can be obtained directly from the equation above by integration thus:

$$\int_{\omega_o}^{\omega} \frac{d\omega}{(\omega - \omega_e)} = \int_0^{\theta} -\frac{U\Delta TAf_c}{\lambda(\omega_o - \omega_e)} \cdot d\theta$$

$$\theta = \frac{\lambda(\omega_o - \omega_e)}{U\Delta TAf_c} \ln \frac{(\omega_o - \omega_e)}{(\omega - \omega_e)} \quad \ldots \quad (5)$$

Moisture Content Distribution and Retention Time

When a solid is dried experimentally, data are usually obtained relating moisture content to drying time. But since the distance along the dryer, corresponding to a particular time, can be obtained, it follows that the moisture content can also be obtained in terms of the distance along the dryer. To be able to establish a relationship between the moisture content and distance along the dryer, another parameter, retention time, has to be taken into account.

The retention time or time of passage of a dryer is the time taken by the material being dried from inlet to outlet of dryer. The time of passage in rotary dryers can be estimated by the following formula.[12]

$$\theta' = \frac{0.19L}{NDS} \quad \ldots \quad (6)$$

where

θ' = time of passage in the dryer, min;
L = dryer length, m;
N = rotational speed, rpm;
S = slope of dryer;
D = diameter of the dryer shell, m.

Having obtained this, attention can now be directed at finding the moisture content distribution. For efficient performance of the dryer, the retention time or time of passage should be equal to the time of drying. Hence by combining Equations 5 and 6,

$$\theta = \theta'$$

$$\frac{\lambda(\omega_o - \omega_e)}{U\Delta TAf_c} \ln \frac{(\omega_o - \omega_e)}{(\omega - \omega_e)} = \frac{11.4L}{NDS} \quad (7)$$

where

L = length of discrete distance along the dryer.

Now,

$$\ln \frac{(\omega_o - \omega_e)}{(\omega - \omega_e)} = \frac{11.4\,U\Delta TAf_c\,L}{\lambda(\omega_o - \omega_e)NDS}$$

$$\frac{(\omega - \omega_e)}{(\omega_o - \omega_e)} = e^{-\frac{11.4\,U\Delta TAf_c\,L}{\lambda(\omega_o - \omega_e)NDS}}$$

therefore

$$\omega = \omega_e + (\omega_o - \omega_e)\, e^{-\frac{11.4\,U\Delta TAf_c\,L}{\lambda(\omega_o - \omega_e)NDS}} \quad \ldots (8)$$

which gives the moisture content in terms of distance along the dryer.

Steam Condensation Rate: In order to obtain a relationship between steam condensation rate and distance along the length of the dryer, there is the need to give a summary of heat transfer process in a dryer.

Saturated steam, coming in contact with the inner wall of the steam tubes losses heat and as such condenses. This latent heat of condensation is conducted radially through the condensate, the wall of the tube, the fins (where applicable) the material being dried, the vapour evaporated from the material, the shell and the ambient air immediately around the shell.

These are:

- the liquid film condensate, R_1
- the wall of the tube, R_2
- the material being dried, R_3
- the finned surface where applicable (since the outer surface of the tube is finned in the last half of the length of the tube), R_4
- the vapour evaporated from the material, R_5
- the shell, R_6
- the ambient air immediately around the shell, R_7

These thermal resistances can be obtained from standard texts and are given by:

R_1 = $\underline{\quad 1 \quad}$

$$R_2 = \frac{h_f(2\pi r_1)}{\frac{\ln(r_2/r_1)}{2\pi k_L \Delta L}}$$

$$R_3 = \frac{d}{k_m A_o f_c}$$

$$R_4 = \frac{1}{h_f h_o}$$

$$R_5 = \frac{1}{0.023 k_v \left(\frac{\rho_v v_v D_i}{\mu_v}\right)^{0.8} \left(\frac{\mu_v C p_v}{k_v}\right)^{0.3} \pi \Delta L}$$

$$R_6 = \frac{\ln\left(\frac{D_o}{D_o - 2t'}\right)}{2\pi k_s \Delta L}$$

$$R_7 = \frac{1}{h_{ab} \pi D_o \Delta L}$$

where

r_1	=	inner radius of tube,
r_2	=	outer radius of tube,
k_L	=	thermal conductivity of tube material (aluminium),
ΔL	=	distance along the length of the dryer,
d	=	depth of material in dryer,
k_m	=	thermal conductivity of material (silica gel)
A_o	=	outside surface area of tube,
f_c	=	fraction of effective surface area of tube,
n_f	=	fin efficiency,
k_v	=	thermal conductivity of vapour in the shell,
ρ_v	=	density of vapour in the shell,
D_i	=	internal diameter of shell,
μ	=	dynamic viscosity of vapour in the shell,
Cp_v	=	specific heat capacity of vapour in the shell,
D_o	=	outer diameter of shell,
t'	=	thickness of shell,
h_{ab}	=	ambient air convection heat transfer coefficient.

The heat due to these resistances can be written as:

$$Q' = \frac{\text{Saturated vapour temperature of supply steam – Ambient air temp.}}{R_1 + R_2 + R_3 + R_4 + R_5 + R_6 + R_7} \quad (9)$$

For heat balance therefore,

$$m\lambda = Q'$$

i.e. $$m = Q'/\lambda \quad \ldots \quad (10)$$

However, the other can be defined as follows:

$$\text{System efficiency} = \frac{\text{Total mass of water evaporated}}{\text{Total mass of condensed steam}} \times 100 \quad (11)$$

In summary, the following equations necessary for modelling the performance of the dryer have been developed. These include:

- the moisture content distribution
- the drying rate
- the mass condensation rate
- system efficiency

The processing of the equations is done over the length of the dryer in steps of unit distance and the variations were studied.

In setting up the model, the first step is to build the model in the spreadsheet using definite values for all parameters and other inputs. This allows one to check the computations and evaluate the correctness of the model. Thereafter, the replacement of the values in the cells that represent random or unknown quantities with formulas that sample these quantities from appropriate distributions is done.

To setup a spreadsheet simulation, generally, each cell in a spreadsheet model can be classified as containing one of three types of quantities:

- *Inputs to the model*. These can be parameters that are part of the model, such as unit costs or mean demand. They can also be the random variables that represent uncertain quantities in the model.
- *Intermediate computations*. These are calculations that are involved in the model.
- *Outputs from the model*. These are the observations on quantities of interest one seeks from the model.

Most models that can be organized in this way can be simulated in a spreadsheet. [10]

Algorithm for Computer Model Simulation

Having carried out an in-depth study on the system and the parameters to determine the performance of the dryer chosen, the algorithm for the computer model was developed and the flowchart of the computer model simulation is shown in Fig. 4.3.

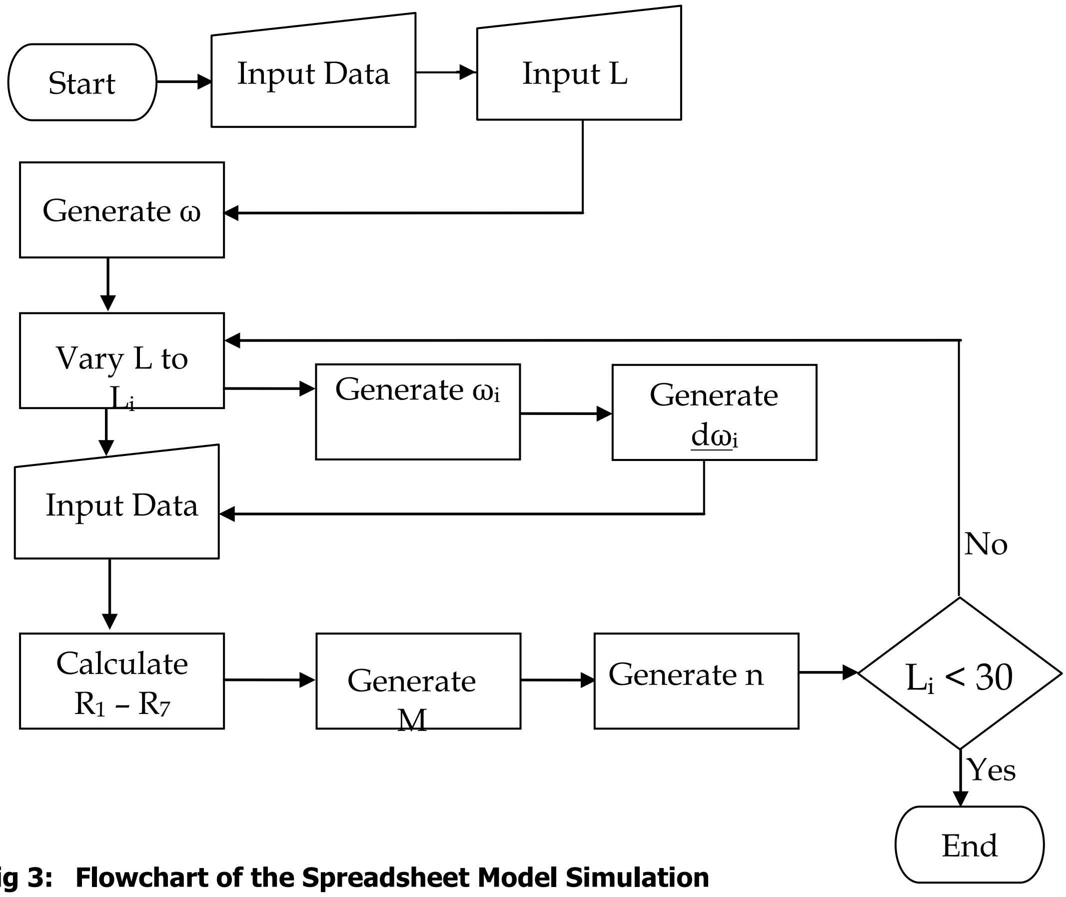


Fig 3: Flowchart of the Spreadsheet Model Simulation

This module is designed to give a quick prediction and estimate of the nature of characteristics that would be expected at any length of the dryer during any drying operation; and of course at the exit. To use, vary the length of the dryer from the "Moisture Content Distribution" module to your choice (from ΔL = 1 to 30m) and observe the automatic calculations of the above four parameters simultaneously from the existing models using the known inputs.

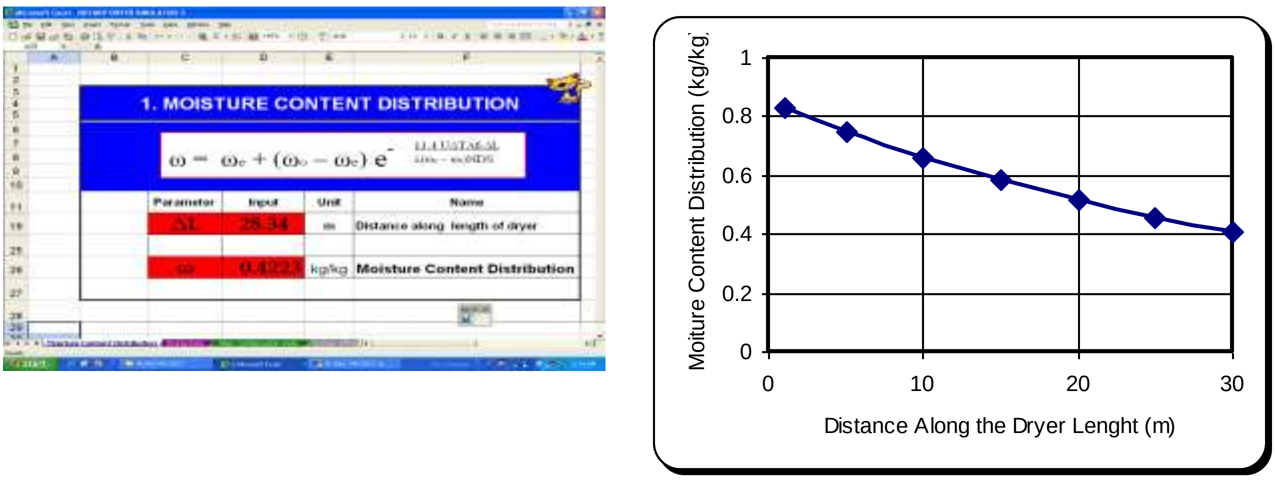


Fig. 4: Spreadsheet Module Interface for Simulating Moisture Content Distribution along the Dryer Length with Resultant Graph Using a Given Input Dataset

To be able to see the pattern of these results, the modules simultaneously plot charts to illustrate the variations of some parameters over the length of the dryer. The first is the plot of moisture content distribution against distance along the length of the dryer. A graph showing the variations of the moisture content with the distance along the length of the dryer is also presented Fig. 4. From the referred figure it can generally be seen that this model predicts falling moisture content from inlet to outlet of dryer, which is as expected.

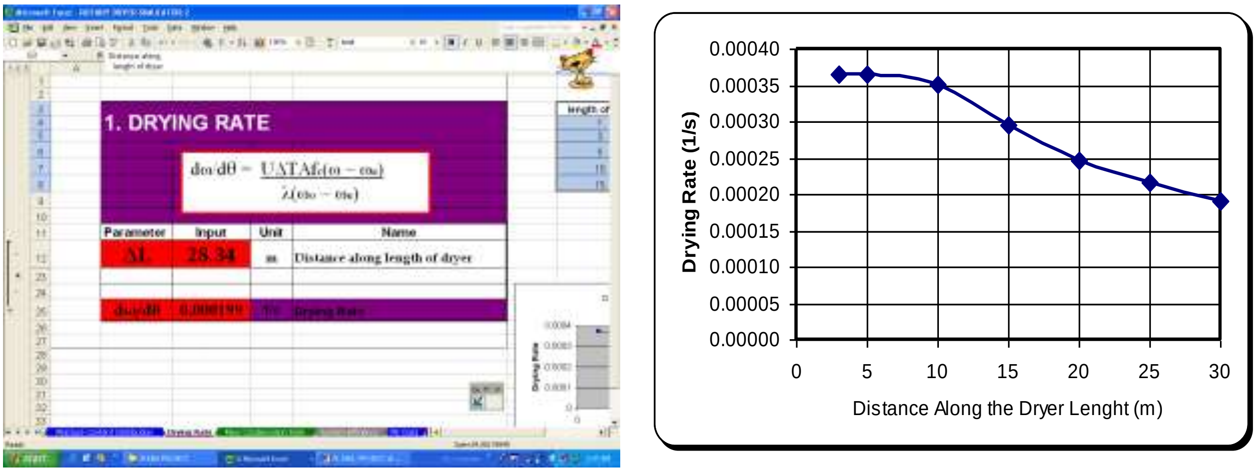


Fig. 5: Spreadsheet Module Interface for Simulating Drying Rate along the Dryer Length with Resultant Graph Using a Given Input Dataset

For the drying rate shown in Fig 5. it can be seen that the initial drying rate increases up to a point and then gradually falls. This is acceptable in theory; as it is shown in [10] that when a solid is being dried, the drying rate first increases and then remains constant (if drying proceeds into the constant rate period) or falls (if drying proceeds in the falling rate period). The first region represents the warming up of the material and in this case a considerable amount of heat is taken up. The second region represents the falling rate period; this is what has been used in this modelling and the result therefore should not be a surprise.

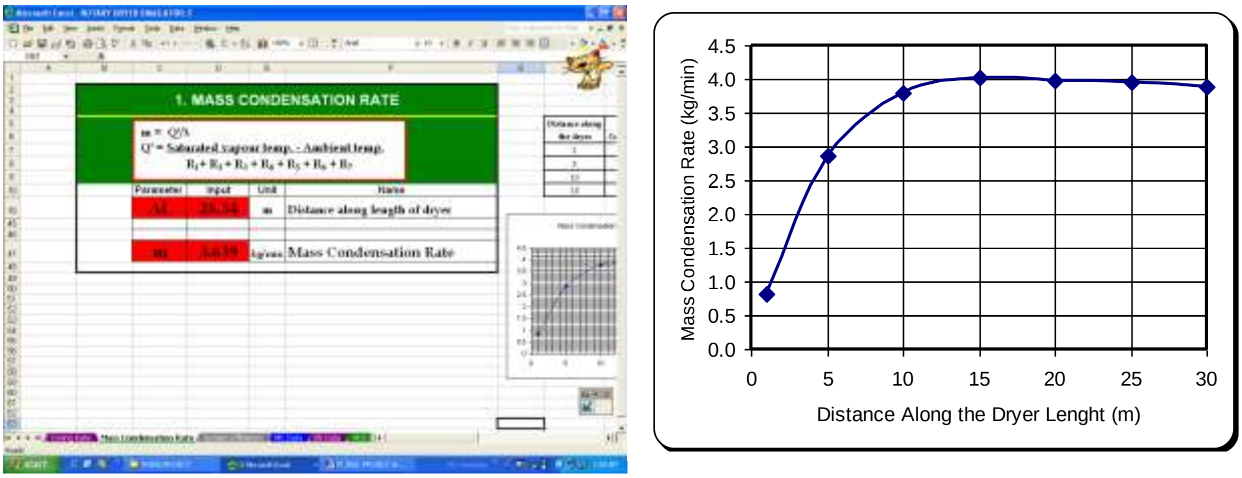
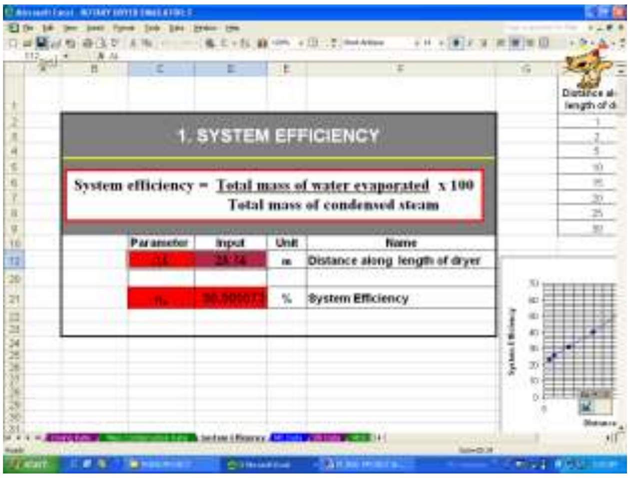


Fig. 6: Spreadsheet Module Interface for Simulating Mass Condensation Rate along the Dryer Length with Resultant Graph Using a Given Input Dataset



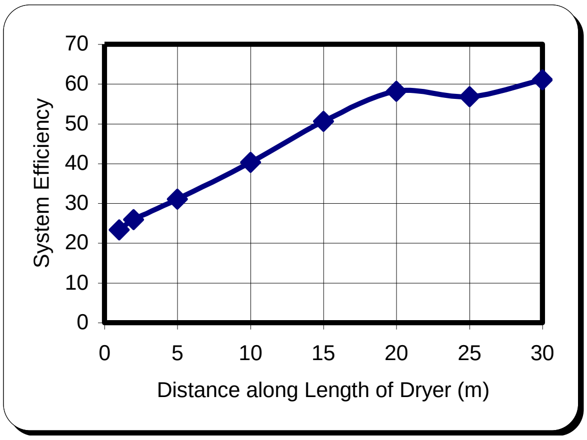


Fig. 7: Spreadsheet Module Interface for Simulating System Efficiency along the Dryer Length with Resultant Graph Using a Given Input Dataset

Fig. 6 shows how the rate of steam condensation goes along the length of the dryer. It has an initial steep increase at the beginning length of the dryer, which eventually normalizes to steady state as the length advances. A single fact can quickly be deduced from the results of Fig. 7; generally, the system efficiency increases with increase in length. This could be a very good result to aid in the choice and selection of this kind of dryer in the market.

CONCLUSION

It can be seen that it is possible with proper analysis and simulation to understand the character and predict the performance of a rotary steam tube dryer. As is obtained in the analysis, the efficiency of the dryer increases with length of the dryer i.e. the greater the distance over which the material will traverse, the greater is the efficiency of the drying operation. Based on cost and other factors, companies may want to use a dryer of greater size to improve on the efficiency of the drying operation.

It can equally be seen that given the available methodology and possibly with the use of appropriate add-ins, spreadsheets can be used to design comprehensive models and run powerful simulations. The analysis in this work should be acceptable as a basis for understanding the behaviour of a rotary steam tube dryer and a reference for managing and controlling the use of a rotary steam tube dryer for drying operations. The designed simulator should be used by companies to understand and predict what to expect during any drying operation. Similarly, the simulator could be useful for educational purposes; for class and conference demonstrations relating to rotary steam tube dyers.

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