NUMERICAL INVESTIGATION ON DRYING OF LARGE COTTON WADS

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Abstract

Seed cotton naturally contains moisture, depending on the climatic conditions. The moisture content plays an important role in ginning processes. High moisture levels (> 7.5% in lint) can cause degradation of lint and ineffective cleaning. In contrast, low moisture levels (< 5% in lint) can result in the development of static charges leading to choking of the system, in addition to increased fiber breakage during processing. Due to climatic variations and variability in cotton drying practices, ginning facilities may have significant expenditures on electricity for running large fans and drying fuel. This paper presents a numerical investigation on drying of large cotton wads under different operational conditions. Cotton drying is a multiphase complex phenomenon involving solid, liquid, air, and vapor. A Computational Fluid Dynamics (CFD) model using an Eulerian multi-fluid volume of fluid approach has been developed. Drying of cotton was a function of porosity, cotton lump shape, size, and density of the cotton in addition to the air flow speed, relative humidity, and air temperature. Each of these physical parameters affected the drying rate uniquely. This study evaluated the effect of conveyance air flow rate and its relative temperature difference from cotton wads. The study and CFD model developed in this paper should be useful for ginning facilities, as well as other engineering applications.

Introduction

Electricity is a major cost for the cotton ginning facilities, accounting for more than 20% of variable cost (Valco et al., 2012), with more than half of the share consumed by centrifugal fans for pneumatic conveying (Funk et al., 2012; Hardin and Funk, 2012). The energy consumed by a centrifugal fan is proportional to the fan speed cubed, while pressure drop is proportional to the fan speed squared, when no material is conveyed. However, the addition of solid material for conveyance increases the pressure drop due to resistance to the solid material, which are not fan speed squared for a given mass flow rate. Different combinations of air velocities and seed cotton mass flow rate were tested for horizontal conveyance in a 20.3 cm (8 in) pipe (Mangialardi, 1977). This study showed that the minimum required air velocity for conveying decreased with mass flow ratio and moisture content. Current recommendations for conveying air velocities for seed cotton are between 17.8 and 25.4 m/s for seed cotton (Baker et. al, 1994). Wide variations in instantaneous material flow rate occur with the feed control systems in cotton gins, and the moisture content of the incoming material can rapidly increase when a wet region in a module is encountered. Using the minimum required conveying velocity for average conditions would result in choking if material flow rate or moisture content increased. Zenz (1949) performed detailed experimental study to characterize the pressure drop per unit length, over a wide range of air velocities and mass flow ratios to convey a variety of materials, showing that pressure drop per unit length decreases with decreasing velocity, reaches a minimum and then increases as velocity is decreased further. Hardin (2014) demonstrated this behavior with seed cotton and developed models for the minimum conveying velocity and pressure drop per unit length.

Seed cotton produced in the fields naturally contains moisture. The moisture content of the seed cotton is an important parameter for the ginning process. The seed cotton having too high moisture content (> 7% fiber moisture content, w.b.) will leave the gin without appropriate cleaning (Cocke, 1974), and will not easily separate into single locks. The condition may choke and damage the gin machinery or entirely stop the ginning process. Seed cotton with too much moisture will also form tight twists known as 'spindle twist' that remain in the ginned lint and degrade appearance. On the other hand, the cotton with too low a fiber moisture content (< 5%) can carry static charges on fibers, which are then attracted to oppositely charged components in the ginning system (commonly condenser rollers) and can choke the gin. Additionally, fiber moisture level below 5% can result in fiber damage during ginning (Childers and Baker, 1978). Dry cotton also requires more force and power to compress than does moist cotton. Ginning above 7% may produce rougher lint, decreased gin capacity, and less effective cleaning. Most researchers report that optimum lint moisture content at ginning is in the 6-7% range. The rate at which cotton lint absorbs or desorbs moisture is an important factor which can be utilized in modeling processing systems (Barker et al., 1990). An efficient and controlled drying process would allow achieving required moisture level in the seed cotton for efficient ginning.

Drying processes are used in wide range of agricultural and industrial applications. Multiple drying approaches, such as solar drying, hot air drying, contact drying, infrared drying, freeze-drying, fluidized bed drying, and dielectric drying, can be used depending on nature of the product to be dried. Experiments are often performed to measure the drying efficiency of different processes in reference to agricultural materials. However, it is expensive and not feasible to conduct enough experiments to describe the possible range of drying methods and parameters. Therefore, numerical simulation tools provide an efficient means to perform critical parametric analysis. There has been a wide application of numerical techniques to simulate drying for the products such as soybean (Rafiee et al., 2008), spraying and evaporation of particles into hot airflow (Huang et al., 2004), vacuum drying of woods (Nadi et al., 2012), and drying of iron ore pellets (Ljung, 2008).

The study presented in this paper focuses on drying by hot air flow over the cotton wads in a pneumatic conveying system. Cotton is a hygroscopic material, which has the ability to attract water molecules. The moisture present in the cotton wads interact with the hot air and leaves in the form of vapor. Mass flow of hot air through the wads is interpreted as flow through porous media. The porous area with defined parameters can be represented as a cotton wad. The numerical model of wet cotton is achieved by patching liquid phase into the porous zone. The CFD simulations base in finite volume method can be complemented by the evaporation model in ANSYS FLUENT (ANSYS Fluent User Guide, 2021). The liquid phase is evaporated from the porous zone and drying process is simulated. The CFD study evaluates effect of relative air velocity and temperature variation on the process of drying. The relative humidity of conveying air was kept constant during the simulation. The CFD studies predict the characteristic behavior of the cotton drying process.

Conveying System and Geometrical Design of Setup

A negative pressure conveying system at the USDA-ARS Cotton Ginning Research Unit, Stoneville, Mississippi is shown in figure 1 (Hardin, 2014). The inlet duct is 3.05 m in length and has 0.254 m diameter. The seed cotton is loaded into a chute above the feed control rollers. The speed of the feed control rollers is adjusted using a variable speed DC motor. A breaker cylinder disperses the seed cotton. A rotary valve (vacuum dropper) is located below the breaker cylinder to minimize air leakage. The parallel flow blowbox is located below the rotary valve. The main conveying duct traverses 7.92 m horizontally. Air velocity measurement ports were used to install pitot tubes. Piezometer rings were used to dampen pressure fluctuations when measuring the differential static pressure in the horizontal conveying section.

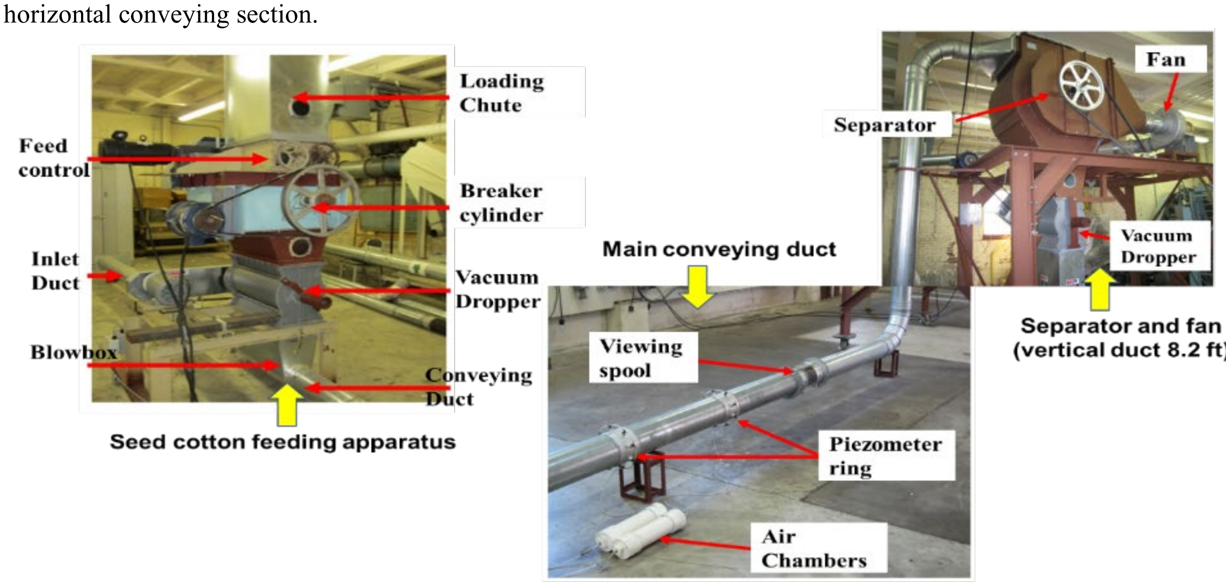


Figure 1. Negative pressure conveying system at USDA ARS, Mississippi (Hardin, 2014).

A clear acrylic viewing spool was installed before the elbow and vertical pipe to observe the cotton flow, as shown in figure 2. The vertical conveying duct was followed by an elbow and transition to a revolving drum separator with a rotary valve at the seed cotton outlet. The centrifugal fan is connected to the separator air exhaust. The fan speed is controlled using a variable-frequency AC drive. The conveying air is exhausted into a settling chamber through a 0.203 m diameter duct.

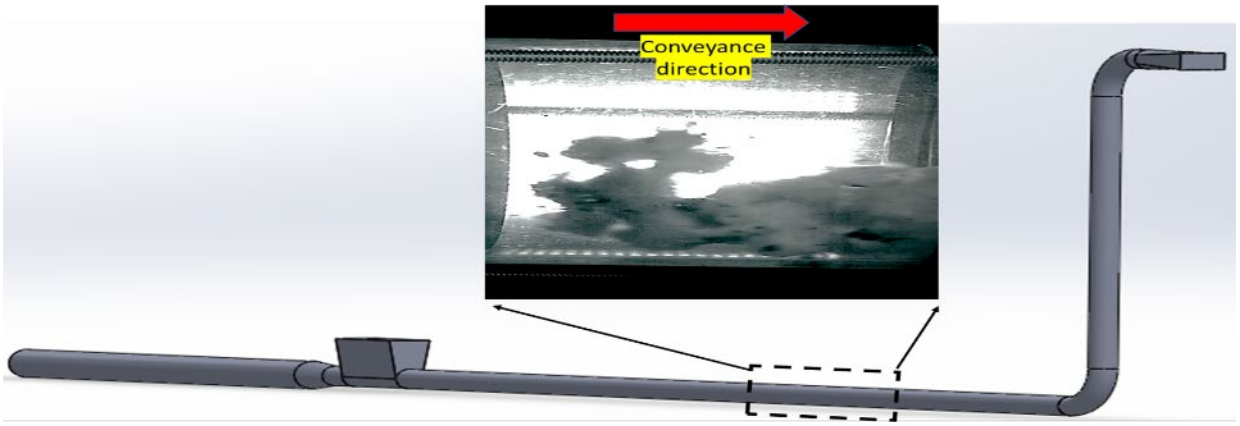


Figure 2. Conveyance of cotton in the conveyer belt.

In the present study, the effect of relative air speed and air temperature variation on drying of cotton wads has been investigated. Therefore, only the horizontal section of the conveyance system was considered for CFD simulations. The stationary cotton wad of maximum size 0.23m × 0.131m × 0.084m in a 3.5 m long straight pipe of diameter 0.2032 m (8 inch) has been shown in figure 3. The cotton wad is located 2.27 m away from the inlet of the pipe.

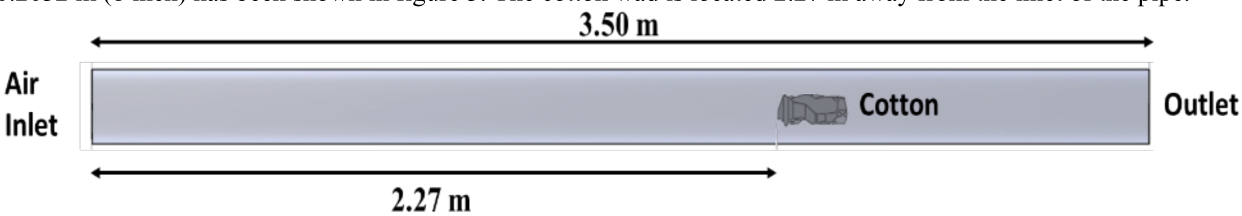
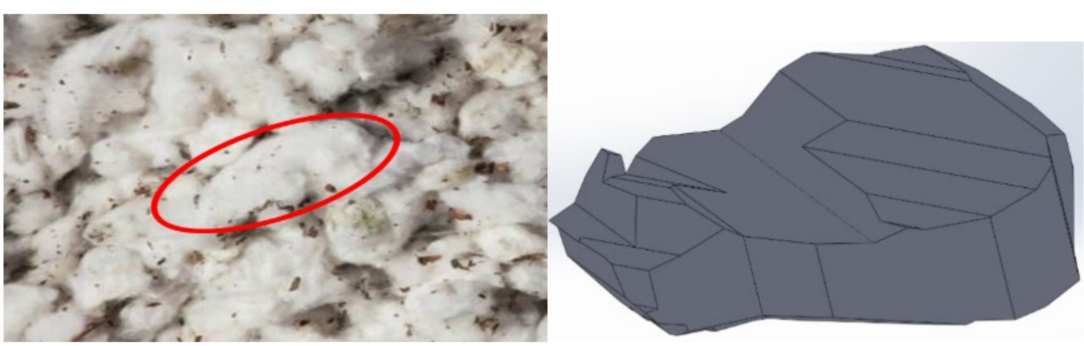


Figure 3. Cotton wad in a conveyer belt pipe

As shown in the figure 2, cotton bolls, along with the sticks, burrs, and leaves form larger cotton wads of different shapes, sizes, packing densities, and structures. Practically, every cotton wad will vary at least slightly.

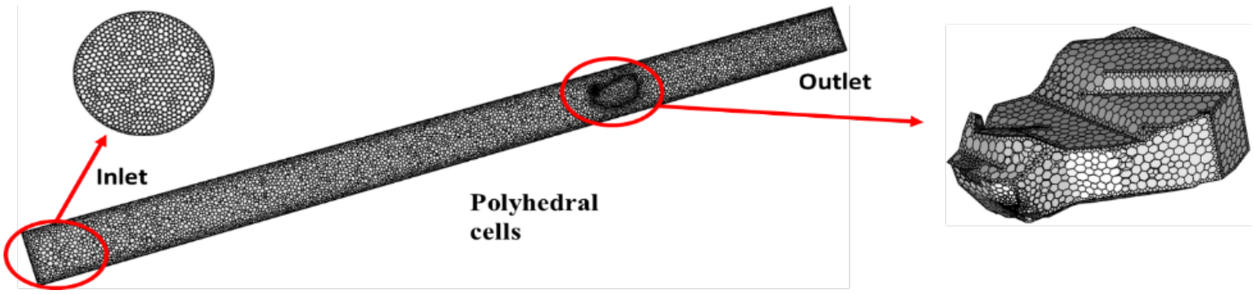
A typical cotton wad in a ginning system is shown in figure 4a (red ellipse). A cotton wad is piece of randomly aggregated bolls and other materials with varying degrees of entanglement among fibers, resulting in inconsistent pore distributions. High fidelity DEM software could be used to prepare cotton wads. However, preparing a typical size wad would require an immense level of effort. Additionally, application of the Finite Volume Method (FVM) would be almost impossible for simulating the drying process. Therefore, an irregular shaped geometric size solid structure was used to simulate the cotton wad, as shown in figure 4b.



(a) (b)

Figure 4. Isometric view of cotton wads (a) Natural seed cotton and (b) geometric cotton.

The meshed view of the conveyance system pipe along with the cotton wad considered for CFD simulations is shown in figure 5, with detailed views of the pipe inlet (a) and the cotton wad (b). At the inlet, outlet, near wall, and air-cotton interface, small size meshes were prepared to accommodate sharp gradients and interface phenomenon. A total of 260630 polyhedral cells were used to simulate cotton drying.



(a) (b)

Figure 5. Meshed (a) horizontal pipe and (b) cotton wad.

Numerical Method

In the process of drying, hot air interacts with the moisture present in the cotton wads. The water receives heat and changes its state to vapor, which leaves the cotton control volume with the hot air. The hot air has been simulated as a continuous phase and the cotton has been simulated as a porous medium. The phases of air, water-vapor and water-liquid are set in the model. The water-liquid is patched and set to 0 m/s into the porous zone. The air phase (included vapor phase to simulate wet air) flows through the porous zone. The CFD simulations have been performed using ANSYS FLUENT 2019R3 (ANSYS Fluent User Guide, 2021). The conservation equations used for the simulations are presented below.

Mass, Momentum, and Energy Conservation Equations for Interacting Phases

The continuity of mass equation for phase q can be represented by equation 1, where $\overrightarrow{v_q}$ is velocity of phase q, density of phase q is $\acute{A}_q$, phase volume fraction is $\pm_q$, mass transfer from phase p to phase q is m_{pq}, mass transfer from phase q to phase p is m_{qp}, S_q is source term considered to be zero in our case (Fluent Theory Guide, 2021).

$$\frac{\partial(\alpha_q\rho_q)}{\partial t} + \nabla.\left(\alpha_q\rho_q\overrightarrow{v_q}\right) = \sum_{p=1}^{n}\left(\dot{m}_{pq} - \dot{m}_{qp}\right) + S_q \tag{1}$$

The fluid-fluid momentum balance for phase q is shown in equation 2, where $\vec{R}_{pq}$ is the interaction force among phases, $\overrightarrow{F_q}$ is the external force on the body, $\vec{F}_{lift,q}$ is the lift force, $\overrightarrow{v_{pq}}$ is the interphase velocity, and τ is the stress tensor. The momentum equation for the phase can be written as:

$$\frac{\partial\left(\alpha_q\rho_q\overrightarrow{v_q}\right)}{\partial t} + \nabla.\left(\alpha_q\rho_q\overrightarrow{v_q}\overrightarrow{v_q}\right) = -\alpha\nabla p + \nabla.\bar{\bar{\tau}}_q + \alpha_q\rho_q\vec{g} + \sum_{p=1}^{n}(\vec{R}_{pq} + \dot{m}_{pq}\,\vec{v}_{pq} - \dot{m}_{qp}\vec{v}_{qp}) + (\vec{F}_q + \vec{F}_{lift,q} + \vec{F}_{vm,q}) \tag{2}$$

Where $\bar{\bar{\tau}}_q$ is the q^{th} phase stress-strain tensor and $\vec{F}_{vm,q}$ is the virtual mass force.

$$\bar{\bar{\tau}}_q = \alpha_q\mu_q\left(\nabla v_q^T\right) + \alpha_q\left(\lambda_q - \frac{2}{3}\mu_q\right)\nabla.\vec{v}_q\bar{\bar{I}} \tag{3}$$

Here, μ_q and λ_q are the shear and bulk viscosity of the phase q and p is the pressure shared by all phases. Equation 2 must be closed with appropriate expressions for the interphase force $\vec{R}_{pq}$. The force depends on the friction, pressure, cohesion, and other effects and is subjected to the conditions that $\vec{R}_{pq} = -\vec{R}_{qp}$ and $\vec{R}_{qq} = 0$. Fluent uses a simple interaction term of the following form:

$$\sum_{p=1}^{n}\vec{R}_{pq} = \sum_{p=1}^{n}K_{pq}(\vec{v}_p - \vec{v}_q) \tag{4}$$

Where K_{pq} (= K_{qp}) is the interphase momentum exchange coefficient.

To satisfy the conservation of energy in Eulerian multiphase applications, a separate enthalpy equation can be written for each phase as:

$$\frac{\partial(\alpha_q \rho_q h_q)}{\partial t} + \nabla.(\alpha_q \rho_q \overrightarrow{u_q} h_q) = \alpha_q \frac{\partial p_q}{\partial t} + \bar{\bar{\tau}}_q : \nabla \vec{u}_q - \nabla . \vec{q}_q + S_q + \sum_{p=1}^{n} (Q_{pq} + \dot{m}_{pq} h_{pq} - \dot{m}_{qp} h_{qp}) \quad (5)$$

Where, h_q is the specific enthalpy of the q^{th} phase, $\vec{q}_q$ is the heat flux, S_q is the source term that includes sources of the enthalpy (e.g., due to the chemical reaction of radiation), Q_{pq} is the intensity of the heat exchange between p^{th} and q^{th} phases, and h_{pq} is the interphase enthalpy (the enthalpy of the vapor at the temperature of the droplets, in the case of evaporation). The heat exchange between phases must comply with the local balance conditions $Q_{pq} = -Q_{qp}$ and $Q_{qq} = 0$.

The Ranz-Marshall correlation was used for solving the heat transfer coefficient h_{pq} between air and water phases. Here κ_q is thermal conductivity, *Nu* is Nusselt number, d_p is particle diameter, *Re* is Reynolds number, and *Pr* is Prandtl number.

$$h_{pq} = \frac{6\kappa_q \alpha_p \alpha_q Nu_p}{{d_p}^2} \quad (6)$$

$$Nu = 2.0 + 0.6 Re^{1/2} Pr^{1/3} \quad (7)$$

ANSYS Fluent Evaporation Model

The momentum equation for the evaporation model used by ANSYS contains a mass transfer expression from liquid state to gas state (evaporation). Mass transfer from gas to liquid state (condensation) is zero in the present case of cotton drying.

$$\frac{\partial}{\partial t}(\alpha.\rho_v) + \nabla.(\alpha.\rho_v \vec{V}_v) = \dot{m}_{l\rightarrow v} - \dot{m}_{v\rightarrow l} \quad (8)$$

Where v is vapor index, α is volume fraction of vapor, ρ_v is vapor density, $\vec{V}_v$ is velocity of gas state, and $\dot{m}_{l\rightarrow v} - \dot{m}_{v\rightarrow l}$ is evaporation rate.

The mass transfer for evaporation starts when the saturation temperature T_{sat} (an input for Fluent) is exceeded by the ambient temperature in certain parts of the domain. Mass transfer is defined as:

$$\dot{m}_{l\rightarrow v} = coeff.\alpha_l \rho_l \frac{(T - T_{sat})}{T_{sat}} \quad (9)$$

Porous Medium Modeling

The porous medium is modeled by the addition of an extra source in the momentum equation. The source consists of two parts, the first is a Darcy law expression and the second is an inertial loss term (Fluent Theory Guide, 2021). For a homogeneous porous medium the source equation is:

$$S_i = -(\frac{\mu}{\alpha} v_i + C_2 . \frac{1}{2} . \rho . |v| v_i) \quad (10)$$

Model Assumptions

The following assumptions were made in simulating the drying of cotton in the conveyance system:

1. A single stationary cotton wad was considered for drying.
2. The cotton wad was considered to have uniform porosity throughout the volume.
3. The moisture was considered distributed equally in entire volume of the porous medium.

4. The conveyance air, cotton, and water content of the cotton, all were considered to have same initial temperature.
5. Heated conveyance air interacts with the moisture (water) of cotton and starts evaporation upon interaction.
6. The pipe walls were considered adiabatic for simulations.

Boundary Conditions

For CFD simulations, the pipe inlet was set to velocity inlet, pipe outlet was set to pressure outlet, pipe walls were considered adiabatic with standard roughness and no slip boundary condition, the cotton-air interface was set as contact regions.

Cotton Drying CFD Simulations

To simulate cotton drying in a conveyance pipe, pressure-based, transient simulations were performed. An inhomogeneous Eulerian approach with Multi-Fluid volume of fluid model was used to solve for the air-water and air-vapor fluids. The air-water interface was modeled using dispersed methodology. The moist air (air-vapor mixture) was considered as primary phase, while water-liquid content of the porous cotton medium was considered as the secondary phase. Heat transfer was obtained using the Ranz-Marshall correlation and mass transfer was obtained using evaporation-condensation models between phase 1 and phase 2. The Schiller-Naumann drag coefficient model was implemented for simulations. The Shear Stress Transport k-w (SST k-w) mixture turbulence model, with low Reynolds number correction was used. Based on the inlet air temperature, the humidity ratio was changed to meet the 50% relative humidity requirement for simulations. The cotton was considered to have 95% porosity and laminar flow (average velocity is assumed low and hence, the flow field is laminar) of air. The viscous resistance offered by cotton was set to 6990000 m^{-2} and inertial resistance was set to 76 m^{-1} in the direction of air flow. The relative viscosity in the cotton zone was solved using Brinkman equations. The convergence limit was set to 10^{-5}.

For cotton drying CFD simulations, the inlet air humidity was fixed to 50%. Drying of cotton was examined for relative air velocities of 0.1, 1.0, 3.0 and 5.0 m/s. The relative velocity is the difference in velocity between air and seed cotton in the conveying system. As the actual value is unknown, a range of likely values was simulated. For each relative air speed, four inlet air temperatures– 20, 66, 121 and 177°C (68, 150, 250, and 350°F)– were examined that span the range of recommended gin drying temperatures. As a result, a total of 16 CFD cases were solved for this parametric study. The saturation temperature varies according to saturation pressure in each computational cell of the simulation domain.

Cotton Moisture Calculation

In general, the moisture content of the cotton wads is calculated on wet basis. The wet basis moisture content (M_w) is described by the percentage equivalent of the ratio of the weight of water (W_w) to the total weight of the material (W_t).

$$M_w = \left(\frac{W_w}{W_t}\right) \times 100 = \frac{W_w}{W_w + W_d} \tag{11}$$

Where W_d is dry weight of the material.

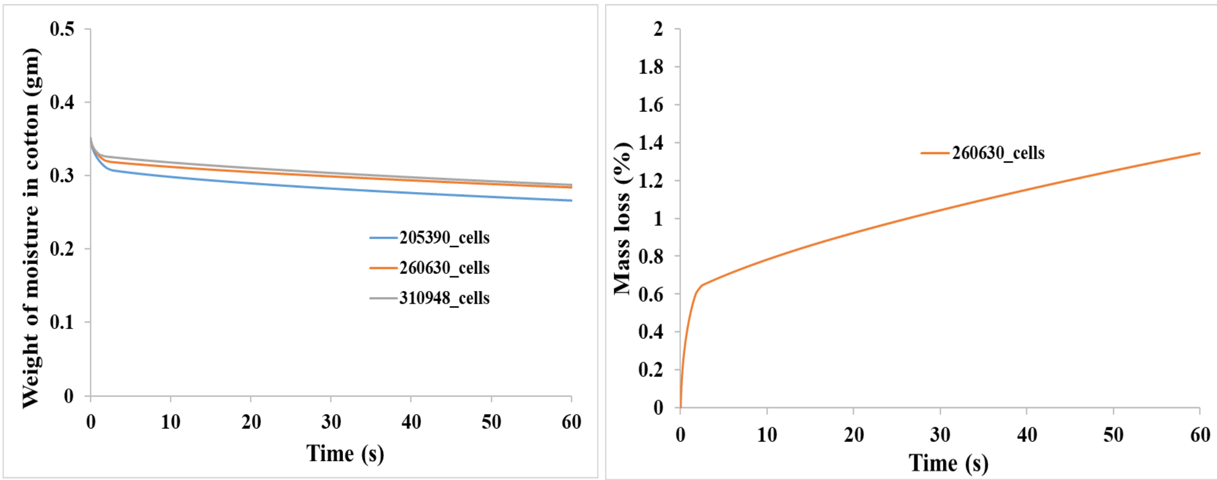
For the study presented in this paper, the total envelope volume of the cotton wad was 1.1612×10^{-3} m^3, the cotton density was 80 kg/m^3, and porosity of the cotton wad was 95 %. The dry weight calculated for 95% porous cotton was 4.6448 gm. At a seed cotton moisture content of 7%, 0.3496 gm of water was patched in the simulated cotton wad. This water volume was considered uniformly distributed following the uniform porosity of cotton wad.

Results and Discussion

Seed cotton naturally holds moisture due to its hygroscopic nature. The level of moisture may be high due to water-cotton contact. For appropriate ginning and maintaining quality of cotton fibers, the moisture level should be optimized to 6-7% fiber moisture content. CFD simulations to investigate the effect of air relative velocity and temperature variations are presented in the following sections.

Mesh Independency Test

The weight of moisture in the cotton is an important factor to understand the rate of drying before and after passing through the pneumatic conveying system. Three mesh sizes, 205390, 260630 and 310948 cells were used to perform the mesh independency test. Simulations were performed for 60 seconds. Mesh independence graph shows that mesh sizes 260630 and 310948 cell numbers perform similar within 5% difference of moisture content (figure 6a). Therefore, the mesh with 260630 cells can be selected for performing further studies. Percentage mass loss of the water from cotton is shown in the figure 6b.

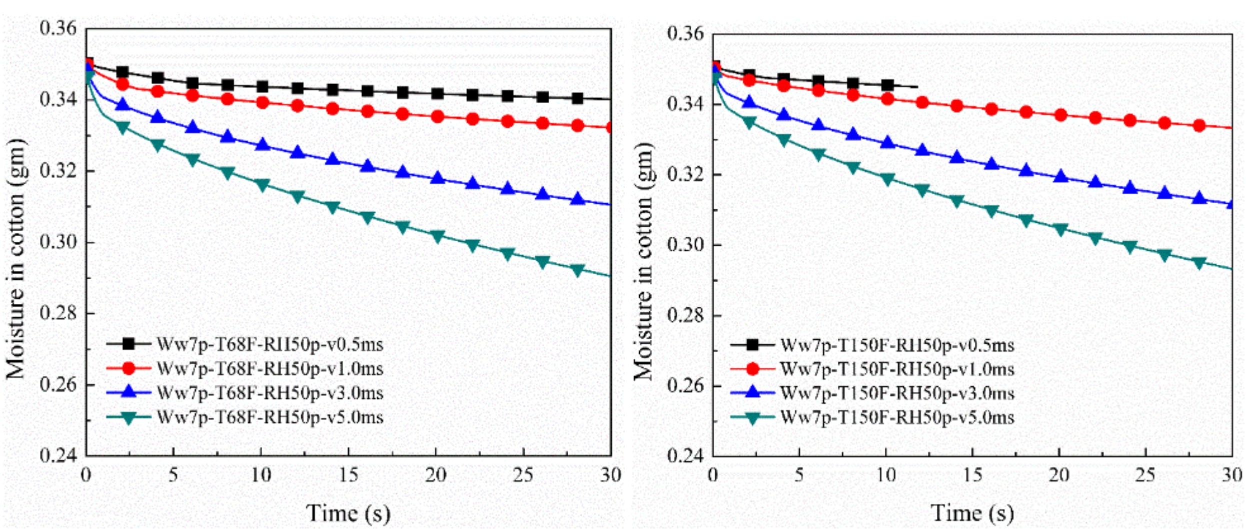


(a) (b)

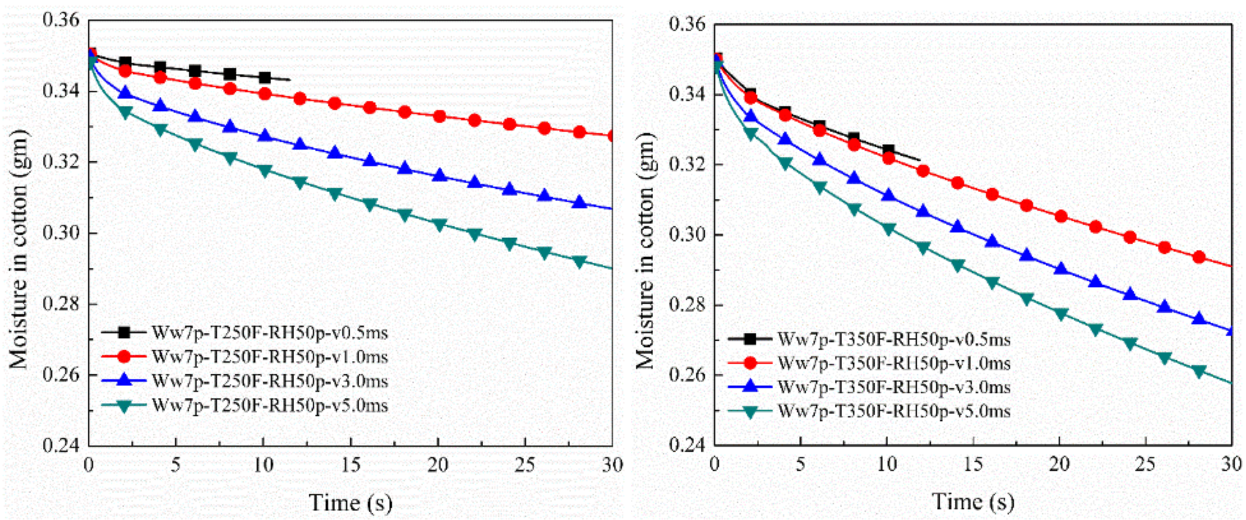
Figure 6. (a) Weight of moisture, (b) percentage loss of mass in the cotton wad.

Effect of Relative Air Velocity on Cotton Drying

In ginning facilities, drying occurs in the pipes used to pneumatically convey the seed cotton to ginning machinery. Large centrifugal fans are used to blow air in the conveying system pipes, which interacts with cotton wads. According to the simulations, the relative speed of air plays a critical role in moisture removal. Higher relative velocity avails more heated air to accelerate the evaporation of water in cotton. Additionally, the vapor phase of water is removed efficiently at higher relative velocities. The effect of relative air velocity on moisture removal from the cotton wad is shown in figure 7. Figures 7a, 7b, 7c and 7d shows the moisture in cotton for air blowing with 50% relative humidity at 20, 66, 121, and 177°C (68, 150, 250, and 350°F), respectively, over the cotton at relative velocities of 0.5, 1.0, 3.0 and 5.0 m/s. In all cases, the moisture in the cotton decreases rapidly at a higher relative air velocities in general. Higher air temperatures also further accelerated moisture removal from cotton wads.



(a) (b)



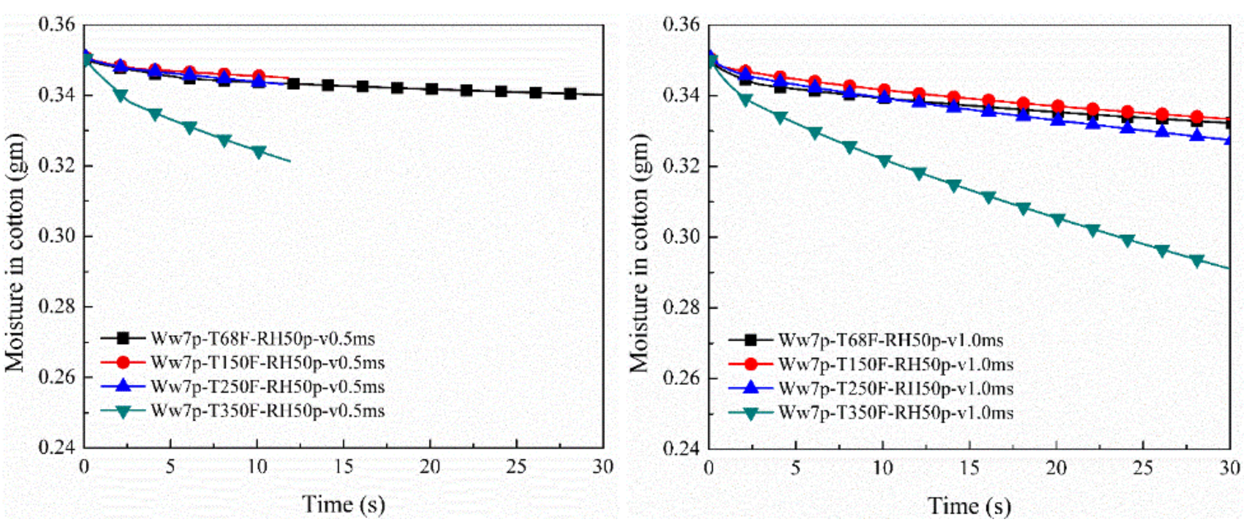
(c) (d)

Figure 7. Loss of moisture from cotton by blowing air at a relative velocity of 0.5, 1.0, 3.0 and 5.0 m/s and air temperature of (a) 20°C (68°F), (b) 66°C (150° F), (c) 121°C (250°F) and (d) 177°C (350°F).

Effect of Air Temperature on Cotton Drying

The temperature of air blown to convey the cotton in the conveyance system plays a critical role in removal of moisture from the cotton. It is generally considered that moisture removal efficiency increases with air temperature. The effect of air temperature on moisture removal from the cotton wad has been shown in figure 8. Figure 8a, 8b, 8c and 8d shows moisture in cotton for air blowing with 50% relative humidity at 0.5 m/s, 1.0 m/s, 3.0 m/s and 5.0 m/s respectively over the cotton at temperatures of 20, 66, 121 and 177°C (68, 150, 250, and 350°F). From figure 8, it can be seen that moisture removal from the cotton wads does not increase in a linear relationship. The rate of moisture removal remains almost the same up to the air temperature of 121°C (250°F). However, as the air temperature is increased to 350°F, the rate of moisture removal increases significantly.

Increasing the relative velocity of air further enhances the moisture removal. The temperature variation shows a step function to characterize the moisture removal. This observation indicates that heat aborbed from heated air is used to increase the sensible and latent heat in the process of vaporization. The rate of evaporation and hence rate of loss of mass in cotton remain low as heat is absorbed by the cotton wads.



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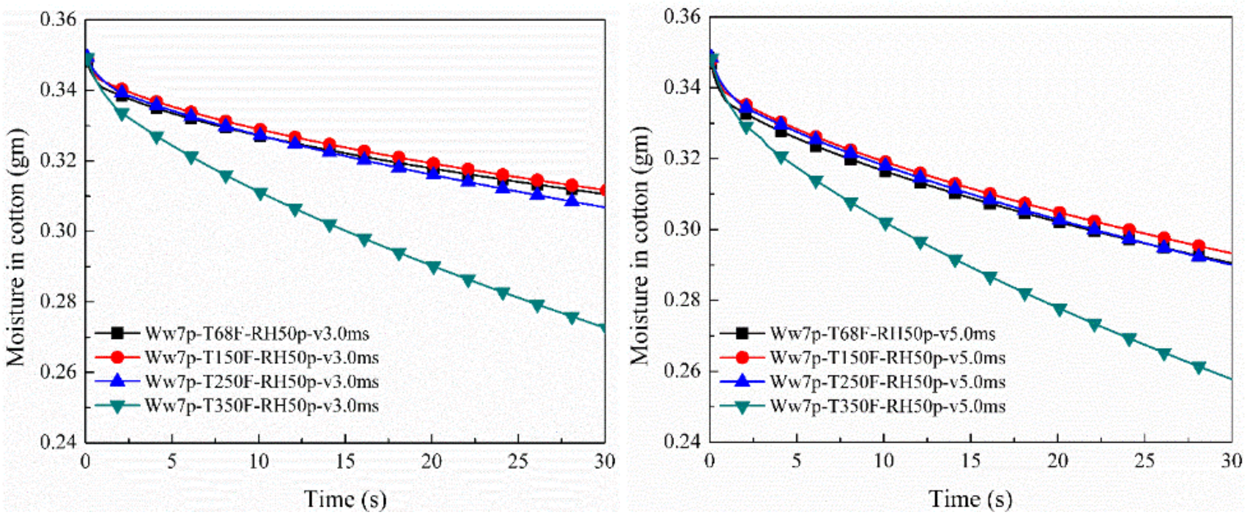

(c) (d)

Figure 8. Loss of moisture from cotton by blowing air at temperatures of 20, 66, 121 and 177°C (68, 150, 250, and 350°F) and relative air velocities of (a) 0.5 m/s, (b) 1.0 m/s, (c) 3.0 m/s and (d) 5.0 m/s.

Conclusion

Ginning facilities use high power centrifugal fans for the conveyance and drying of seed cotton. The harvested cotton from fields usually has different levels of moisture depending on environmental conditions. Cotton gins spend a significant amount of money to convey and dry seed cotton. These costs could be substantially reduced with the development of more efficient systems. This paper presents parametric CFD studies on drying of realistic size cotton wads in an 8-inch pipe. The following conclusions can be drawn from this study:

1. Moisture available in the cotton starts changing its phase from water to vapor, which is removed by the blowing air surrounding the cotton.
2. The moisture removal increases with an increase in relative air speed at any constant temperature. High conveyance air temperature and high relative velocity was the most effective means of moisture removal.
3. Increasing conveyance air temperature at a constant velocity does not accelerate moisture removal linearly. For any given air speed, the temperature variation shows a step function behavior.
4. The lower temperature limit observed in the case of temperature variation studies at constant velocity indicates that heat energy supplied by the heated air upon interaction with wads is used to increase the sensible and latent heat of moist cotton.

The results presented in this paper can be used to further develop and critically analyze the cotton drying systems in ginning facilities.

Acknowledgement

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References

ANSYS Fluent User's Guide. 2021. https://support.ansys.com/AnsysCustomerPortal/en_us/Downloads/Current+Release.

Baker, R.V., E.P. Columbus, R.C. Eckley, and B.J. Stanley, 1994. Pneumatic and mechanical handling systems. In Cotton Ginners Handbook, Agricultural Handbook No. 503. USDA-ARS: Washington, D.C.

Barker, G.L., Baker, R.V., Laird, J.W., 1990. A cotton processing quality model. Agric. Syst. 35, 1–20.

Childers, R.E., Baker, R.V., 1978. Effect of moisture conditioning on ginning performance and fiber quality of high plains cotton. Transcations ASAE 21(2), 379–384.

Cocke, J.B., 1974. Effect of seed cotton moisture level at harvest on ginned lint. Production Research Report No. 157. USDA-ARS: Washington, D.C.

Fluent Theory Guide, 2021. https://ansyshelp.ansys.com/account/secured?returnurl=/Views/Secured/corp/v201/en/flu_th/flu_th.html.

Funk, P, Hardin, R.G., Funk, Paul, 2012. Cotton Gin Electrical Energy Use Trends and 2009 Audit Results. Appl. Eng. Agric. 28, 503–510. https://doi.org/10.13031/2013.42078

Hardin, R.G., 2014. Pneumatic conveying of seed cotton: Minimum velocity and pressure drop. Trans. ASABE 57, 391–400. https://doi.org/10.13031/trans.57.10437

Hardin, R.G., Funk, P.A., 2012. Electricity Use Patterns in Cotton Gins. Appl. Eng. Agric. 28, 841–849. https://doi.org/10.13031/2013.42471

Huang, L., Kumar, K., Mujumdar, A.S., 2004. Computational fluid dynamic simulation of droplet drying in a spray dryer. In Drying 2004- Proc. of the 14th International Drying Symposium, vol. A., pp. 326-332.

Ljung, A., 2008. Drying of Iron Ore Pellets -Analysis with CFD. Thesis, Luleå University of Technology.

Mangialardi, G.J., J., 1977. Conserving energy- reduce volume of air to transport and dry seed cotton. Texas Cotton Ginners Journal and Yearbook 45, no. 1.

Nadi, F., Rahimi, G.H., Younsi, R., Tavakoli, T., Hamidi-Esfahani, Z., 2012. Numerical Simulation of Vacuum Drying by Luikov's Equations. Dry. Technol. 30, 197–206. https://doi.org/10.1080/07373937.2011.595860

Rafiee, S., Keyhani, A., Mohammadi, A., 2008. Soybean Seeds Mass Transfer Simulation during Drying Using Finite Element Method. World Appl. Sci. 4, 284–288.

Valco, T.D., Ashley, H., Green, J.K., Findley, D.S., Price, T.L., Fannin, J.M., Isom, R.A., 2012. The Cost of Ginning Cotton - 2010 Survey Results. In Proc. Beltwide Cotton Conf, pp. 616-619.

Zenz, F.A., 1949. Two-Phase Fluid-Solid Flow. Ind. Eng. Chem. 41, 2801–2806. https://doi.org/10.1021/IE50480A032