DESIGN OF STARCH COATED SEED COTTON DRYERS

Mathew G. Pelletier, Joseph W. Laird and Gary L. Barker
Agricultural Research Service
United States Department of Agriculture

Abstract

A model was developed for the design and analysis of a high temperature tunnel dryer, primarily used with a new cotton ginning product, EASI*flo*® cottonseed (starch-coated cottonseed). This form of cottonseed has emerged as a viable, value-added product for the cotton ginning industry. Currently, little information exists on dryer engineering, which is an essential component and expense for starch-coating cottonseed. In this study, a mathematical computational fluid dynamic model is presented that models the drying process, which can be used as a tool to optimize the design of commercial dryers in place today and in the future.

Introduction

Recent developments in technology have allowed several ginners and cottonseed processors to coat fuzzy (gin-run) cottonseed with starch or other economical products, (Laird, Wedegaertner and Barker, 1998). The resulting product, EASI*flo*® cottonseed, handles very similar to grain, and as an added benefit, does not bridge in bins, conveyors, and other transport equipment. Because of these properties, the market for cottonseed has expanded beyond the oil mills (Wedegaertner and Lalor, 1997). In addition, the starch-coating process is under research as an alternative to flame and acid delinting of planting seed.

Already, the cottonseed coating technology has been successfully transferred to two commercial plants, and several others are in various stages of planning and/or construction. However, the design criteria used to introduce the starch-coating process into the commercial plants originated from empirical data developed by experimental testing (Laird, Wedegaertner and Valco, 1997), and simply from trial and error at the sites. Additional research at these plants is also investigating the starch-coating process to improve other cotton-ginning byproducts, such as gin trash. Each of these processes requires that a very wet starch mixture be applied to the cottonseed or gin trash to help prevent the formation of large agglomerates while drying.

By far, the most expensive part of this process is the rapid drying of the starch coating. Therefore, the objective of this study was to develop and incorporate mathematical models created through computational fluid dynamics, which can be used to rapidly investigate many types of dryer designs. These models can be used to significantly improve dryer design and reduce the fuel costs associated with the belt-conveyor dryers, which are currently being used for coating cottonseed and other cotton gin byproducts. Seed cotton dryers and other gin dryers can also benefit from these models and improve their efficiency.

Double-deck drying conveyors are standard in several industries, ranging from food processing to the feed industry. In a typical double-deck conveyor dryer, the product is transported along on an upper belt, while air blows through the porous bed which is made up by the product thereby providing a drying action. When the product reaches the end of the belt run, it falls directly on to a lower belt. This belt transports the product back through the dryer, allowing it to be exposed to the same type of airflow. The air is typically directed upwards so that the bottom layer is exposed to the hot, dry air first. When the air reaches the upper belts, it has accumulated excess moisture and is less effective at drying the cotton product.

Reprinted from the *Proceedings of the Beltwide Cotton Conference*
Volume 2:1380-1385 (2001)
National Cotton Council, Memphis TN

Currently, two commercial test-bed plants equipped with double-deck dryers are being used to dry starch-coated cottonseed. One of the designs uses a standard, cross airflow that directs the hot air upward through the belts. In this type of dryer, the hot air dries the product sitting on the lower belts much more effectively than the upper belts. The other style was designed using new research that recommended a downward airflow (Laird, et. al., 1997) for improved drying efficiency. As the air pushes through the layer of cottonseed, it presses the product evenly against the wire belt. Air is more uniformly distributed through the cottonseed compared to the upward airflow design. In the upward flow design, microchannels develop as the cottonseed is lifted off the belt by the forced air, resulting in a less uniform exposure for drying.

Due to the very wet nature of this product, several modifications needed to be made to the downward flow dryer configuration. In the initial testing phase, the topmost layer of the seedbed dried quickly while the bottom portion still remained wet. Two mixers were added in the dry to stir the seeds, which reduced the amount of time needed to completely dry the cottonseed.

Because starch-coated cottonseed is a new development, very little design data was available for the requisite engineering parameters, such as resistance to airflow, specific heat, and the time-temperature drying curve relationships. This research developed these missing fundamental engineering parameters that are necessary to generate the computational fluid dynamics models.

Procedure

Significant advances in computational fluid dynamic models have made the modeling of complex processes, such as the stationary deep-bed dryers used in grain drying (Casada et. Al., 1997) (Friesen, 1972) (Thompson et al., 1968)) and double-deck cross-flow conveyor dryers (Khankari and Patankar, 1999) possible.

The wet nature of this process requires the model to take in account not only the evaporation and desorption of moisture from the cottonseed, but also consider the condensation and adsorption effects from moisture-saturated air in the dryer. This model also extends the previous models by including new research that pertains to the adsorption and desorption properties of cottonseed (Barker and Laird, 1997).

Governing Equations

The fluid motion of air is governed by the time-dependant Navier-Stokes equations for an ideal gas, which embodies the conservation of mass, momentum, and energy. For this low-speed application, the incompressible form of the Navier-Stokes equations were used.

Distributed Resistance

The pressure drop across the cottonseed bed is modeled as a distributed resistance in the momentum equations. The equation for the pressure drop for a given flow rate could be characterized by the ASAE D272.1 standard, *Resistance of airflow through grains, seeds, and perforated metal sheets.*

The literature on pressure drop for air-flow through cottonseed has values that were designed for long term storage in terms of 3, 6, and 9 m depths (10, 20, and 30 foot depths) for fuzzy cottonseed (Smith, 1975). There is not however, literature available for either acid delinted or starch coated cottonseed. Additionally there is no information for fuzzy cottonseed in regards to air-flow for very shallow sub-meter depths. Given the lack of available data, experimental values were obtained to provide the necessary pressure-drop-velocity relations for the cottonseed-dryer bed depth of 6.67 cm at a bed packing density of 0.38 gm/cc. These values were chosen as they are the depths and densities that are currently being used in the commercial test plants.

The experimental results showed that the ASAE Standard pressure drop equation does not provide a prediction equation that is independent of depth. As can be clearly seen in figure 1, each depth resulted in a different slope for the ASAE standard pressure drop equation. The performance of this calibration resulted in a coefficient of determination of $r^2 = 0.9976$ with an RMS residual error = 0.181 kPa (0.728 inches water) when tested at a single bed depth. Unfortunately, when the experiment was repeated over a range of bed depths the coefficient of determination dropped to 0.947 with an increased RMS residual error = 0.348 kPa (1.4 inches water) giving an increased spread in the prediction data as detailed in figure 1. To correct this, a new form of the pressure drop equation was developed that would provide better independence of bed depth over the range from 1 to 5 inches; the expected range of bed depths that might be utilized in this type of drying.

Given the deviation between calibrations for each bed depth, an equation that took into account the bed depth was sought. The data set from the experiment was split into two separate parts. The first part was used to develop the calibration equation and the second part was used to provide independent validation of the calibration equation. The results from calibration set is shown in figure 2 and the results from the validation set is shown in figure 3. The coefficient of determination for the new equation resulted in a validation r^2=0.981 with a residual RMS error = 0.158 kPa (0.363 inches water). Given the better performance of this equation over the standard, this equation was chosen for use in the model.

Heat and Mass Transfer

The process of coating the cotton seed produces a very wet product that must then be dried. As the coated cotton seed enters the dryer, the coated seed has an initial moisture content of 65% (wet basis). The drying process of the product in this state is almost completely driven by the starch evaporation rather than the drying of the cotton seed which has not absorbed this moisture internally.

This very wet condition produces a saturated air condition before the air has a chance to exit the bed. This creates the condition for both complete saturation of the air as well as condensation. Thus, for this particular process, the model must take into account both the product's specific and latent heat as well support for both evaporation and condensation.

Mass Transport

In the starch coated seed process, the seeds are at a standard storage equilibrium moisture content ranging from 8-12% moisture content (dry basis, USDA Marketing Report 1020). The seeds are then subjected to a spray deposition process by which a starch water mixture is applied to coat the seeds. This starch water mixture brings the total moisture content of the seeds up above 65% moisture content (dry basis).

In order to characterize and understand the drying process, a sample of the wet coated starch seeds were placed an experimental weighing system constructed by Barker and Laird, 1993, that allowed for continuous weighing of the sample while it was subjected to a flow of constant temperature dry air that was configured to pass around and through the wet coated seeds. The air was set to 100 degrees Celsius with a dew point of -20 degrees Celsius.

Henderson (1976) reported that very wet samples will exhibit a constant-rate drying period that is similar to water pan-evaporation, due to the considerable water content on the surface of particles. It has also been reported that an additive to the water (such as starch) can alter the evaporation rate from pure water (Williamson, 1972), therefore it is expected that in the initial phase of the drying process, the drying characteristics will not match those of pure water, however the prediction equation should be of the same form as reported by Henderson (1976) througout the initial portion of the drying process.

To test this model, experimental data was collected and then used to calculate the true moisture content. The true moisture content was then plotted to compare the true moisture content versus the constant rate drying model's predicted moisture content that was obtained by adjusting the slope to obtain the best fit (figure 2). It was found that the constant rate model did a good job of predicting the drying rate down to 38% moisture content dry basis at which point the model deviated significantly throughout the rest of the drying process. Thus, it was felt that a better model was required.

After the initial constant rate drying phase, the remaining moisture content was found to exhibit a similar drying curve to the drying curves that were reported by Barker, 1996 for gin run cotton seeds albeit with a much faster response due mostly to the pure water evaporation taking place during the initial drying phase. Given the similarities, the same style drying model that Barker utilized was investigated for use with the starch coated cottonseed drying. To characterize the mass transport the classical one dimensional diffusion equation was used (Newman, 1932). The solution to this equation (an infinite series) provides the thin layer drying equation that is based upon the difference between the equilibrium moisture content of the incoming air and the moisture content of the grain. This equation provides a prediction of future moisture content based upon the time between the start of the drying process and when the answer is required at some future time t. This equation depends upon and assumes that the conditions of the incoming drying air do not change throughout the drying process and remain at the same steady state condition from time t=0 to time t where the answer is required.

The main parameter in the equation that is used to tune the equation for various processes is the diffusitvity coefficient D. The value used in this model for the diffusivity coefficient D for starch coated cotton seed is provided from experimental data obtained by utilizing the constant temperature drying technique pioneered by Barker, 1997 with the results of the curve fit shown in figure 3.

In Barker's apparatus, the incoming air is such that the equilibrium moisture content of the air is equal to zero (minus 20 degrees C dew-point). This is a steady state situation in which the incoming air conditions never change. This is the situation that is required by the infinite series expansion of the Newman equation. In the actual cotton seed dryer the air will pick up moisture as it moves through the bed thereby continuously changing the equilibrium moisture content of the air depending upon where in the bed the seeds are. In this situation anyone particular seed, sees a wide variety of conditions as it is transported through the dryer. To account for the continuously changing air states, the model's equation needs to be reformulated so that it is able to respond to continuously changing conditions.

To allow for more flexibility, the solution to the Newman equation was reformulated into a recursive form of the moisture content prediction equation. The recursive form of the equation utilizes a three term approximation. The three term approximation was chosen as Barker (1997) has shown it to correspond well for cotton seed. When utilizing this recursive form of the equation to predict the moisture content, the equation utilized the same diffusivity that was found from the use of the non-recursive version. The results of the prediction are shown in figure 4. It is interesting to note that the recursive form of the equation actually predicts the actual moisture content, for steady state conditions, better than the standard solution does.

Prediction of Product Moisture Content, Air Temperature and Relative Humidity

The model was setup to run the analysis of the double deck dryer in a downward cross flow configuration (figure 7). The model was then tuned to match existing data taken from the experimental commercial pilot plant. Figure 8 shows the moisture content prediction of the cottonseed as the product move through the dryer, while figure 7 shows the air temperature variation. It is interesting to note that the cottonseed is actually dryer 1-2 m (4 ft.) before the exit point of the dryer with a large moisture gradient existing vertically through the seed bed. The cottonseed at the exit point is actually picking up moisture from the air. This is due to the very high relative humidity of the air that is created by the fresh new very wet cottonseeds that are directly above the exit point of the lower level conveyor on the upper conveyor belt (air relative humidities shown in figure 8). This model illustrates that the efficiency of the dryer could be improved by exhausting the first 1-2 m (4 ft.) of air before it passes through the second lower level as this air has already absorbed all of the moisture that it can. By removing this air before it passes through the lower bed, the seeds on the lower bed will no longer pick up unwanted moisture and the dryer will operate at higher efficiencies. This model can now be used to test these and other alternatives such as new dryer designs.

Summary

The mathematical modeling of the cotton seed drying process will allow for many experimental designs to be modeled without the necessity of actually building them. This tool will provide a streamlined method by which to improve existing as well as future starch coated cotton seed dryers. The solution to modeling real starch coated cotton seed dryers dictates the necessity of obtaining several key engineering design parameters. These parameters include the diffusivity and equilibrium moisture content for use in the prediction of the evaporation and drying rate. The resistivity to air flow is required to correctly model the air flow through the porous bed correctly and the specific heat of the cotton seeds is also required for the heat transfer portion of the model.

The requisite data that was not available in the literature was obtained experimentally to provide the necessary engineering design parameters to provide a solid foundation for use in the mathematical model. The data obtained to provide the diffusivity for the prediction of the time-temperature moisture content fit well to the classical solution first proposed by Newman (1932) and later extended to cotton seeds by Barker (1997).

This paper also presents the full derivation of the two-phase fluid flow and mass-heat transport equations that are necessary to provide a model of the starch coated cotton seed dryers. The equations developed in this paper provide the framework from which to model the moisture mass transport from the cotton seed into the air along with the mass convection-diffusion within the air-stream of the humidity gradients that are setup within the cotton seed dryer.

References

Abernathy, G.H., S.E. Hughs, M.N. Gillum, 1994. Improvements of Equilibrium Moisture Content Models for Cotton. Trans ASAE. ASAE, St. Joseph, MI 49085. 37 (2) p561-569.

Anderson, J.D.Jr., 1995. Computational Fluid Dynamics The basics with applications. McGraw Hill, Inc. New York.

Barker, G.L., and J.W. Laird, 1997. Effect of Temperature on the Drying Rate of Gin Run Cotton Seed. Trans ASAE. ASAE, St. Joseph, MI 49085. 40 (4), p891-896.

Casada, M.E., A. Alghannam, and R.C. Dekker, 1997. A Seed Corn Drying Model. ASAE Paper No. 976099, ASAE, St. Joseph, MI 49085.

D271.2. 1985. ASAE Standards. ASAE, St. Joseph, MI 49085

Deen, W.M. 1998. Analysis of Transport Phenomena. Oxford University Press, New York New York 10016.

Ferziger, J.H. 1998. Numerical Methods for Engineering Application. John Wiley & Sons. New York 10158.

Ferziger, J.H. and M. Peric. 1996. Computational Methods for Fluid Dynamics. Springer-Verlag Berlin Heidelberg Germany.

Freisen J.A., 1972. A Dynamic Model for Determining Moisture sorption of Cotton Lint and Seed. Unpublished Ph.D. Dissertation, Mississippi State University.

Henderson, S.M. and R.L. Perry, 1976. Agricultural Process Engineering. The AVI Publishing Co., Inc., Westport Conneticut.

Incropera, F.P. and D.P. DeWitt. 1996. Fundamentals of Heat and Mass Transfer 4th Edition. John Wiley & Sons. New York 10158.

Idelchik, I.E., 1994. Handbook of Hydraulic Resistance, 3rd Edition. CRC Press ISBN 0-8493-9908-4.

Kradangnga, P., 1994. Storage Parameters Determination for Cottonseed. Unpublished Master's Thesis. Mississippi State University, Dept. Agricultural and Biological Engineering. Mississippi.

Laird, J. W., T. C. Wedegaertner, T.D. Valco, and R.V. Baker, 1997. Engineering factors for coating and drying cottonseed to create a flowable product. ASAE Paper No. 97-1015. 13 pp.

Laird, J. W., T. C. Wedegaertner, and T.D. Valco, 1997. Coating Cottonseed for Improved Handling Characteristics. Proc. Beltwide Cotton Conf. Vol 2. p1599-1602.

Laird, J. W., T. C. Wedegaertner, and G.L. Barker, 1998. Water and Starch Rates for Coating Cottonseed. Proc. Beltwide Cotton Conf. Vol 2. p1718-1720.

Newman, A.B. 1932. The drying of porous solids: Diffusion calculations. Transactions of American Institute of Chemical Engineers 27:310-333.

Parker, R.E., and J.A. Friesen, 1968. Thermal Properties of Seed Cotton. ASAE Paper No. 68-301, ASAE, St. Joseph, MI 49085.

Patankar, S.V., 1980. Numerical Heat Transfer and Fluid Flow. Taylor & Francis Washington DC 20005.

Smith, L., 1975. Aeration of cottonseed in storage. Marketing Research Report No. 1020. Agricalutural Research Service's branch of the United States Department of Agriculture.

Tannehill, J.C., D.A. Anderson, R.H. Pletcher. 1997. Computational Fluid Mechanics and Heat Transfer 2nd Edition. Taylor & Francis Washington DC 20005

Thompson, T.L., R.M. Peart, and G.H. Foster 1968. Mathematical Simulation of Corn Drying - a new model. Trans ASAE. ASAE, St. Joseph, MI 49085. 11 (4), p582-586.

Wedegaertner, T.C., and W.F. Lalor, 1997. Whole Cottonseed Research & Promotion Program at Cotton Incorporated. Proc. Beltwide Cotton Conf. Vol 1. P398-399.

Williamson, R.E., 1972. A Simulation for the Dynamics of Evaporating Spray Droplets in Agricultural Spraying. Unpublished Ph.D. Dissertation Mississippi State University.

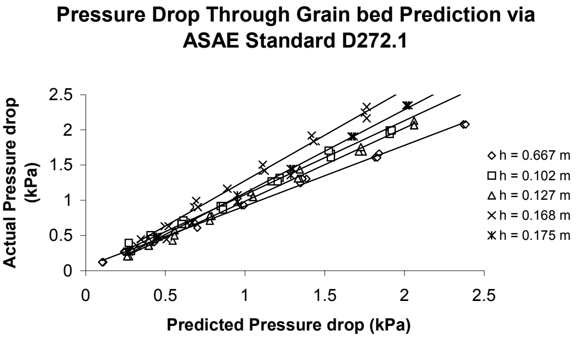

Figure 1: The prediction of pressure drop for various bed depths "h" was calculated by the ASAE D272.1 standard Resistance of Airflow through grains, seeds, and perforated metal sheets (equation 4). The global coefficient of determination for the group produced an $r^2 = 0.974$ with an overall RMS error = 0.113 kPa (0.45 inches water).

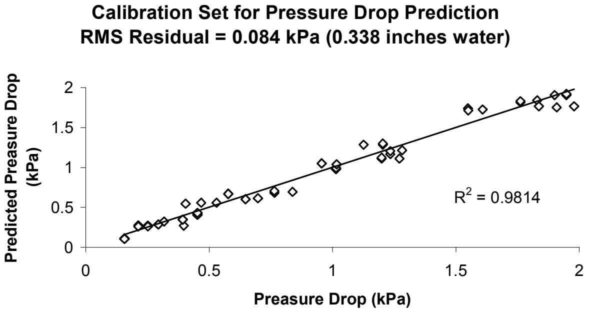

Figure 2: The calibration set for for prediction of the pressure drop to air flow through a porous bed of various depths for starch coated cotton seed utilizing the new derived equation as detailed in equation xx.

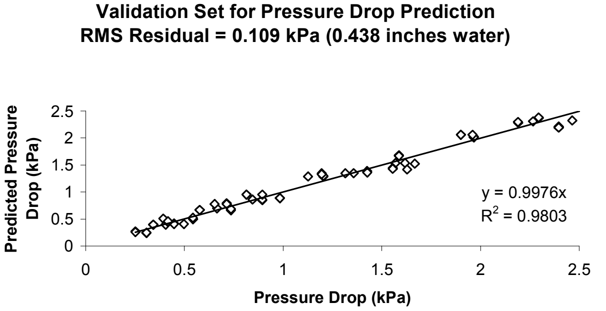

Figure 3: The validation set for prediction of the pressure drop to air flow through a porous bed of various depths for starch coated cotton seed utilizing the new derived equation as detailed in equation xx.

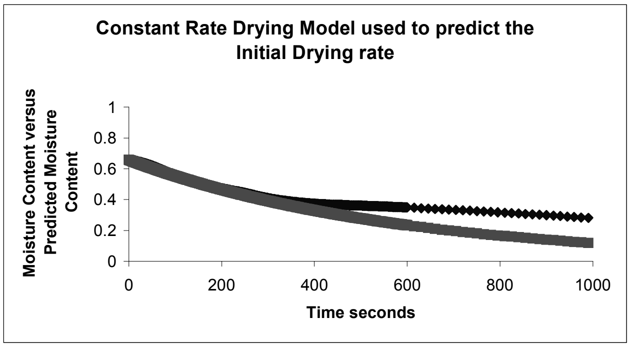

Figure 4: The constant rate drying model used to predict the initial drying rate for the starch coated cotton seeds.

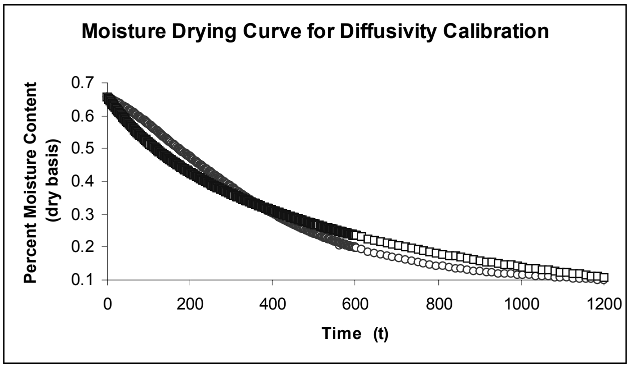

Figure 5: Experimental cotton seed drying curve versus predicted drying curve provides the diffusivity for the model.

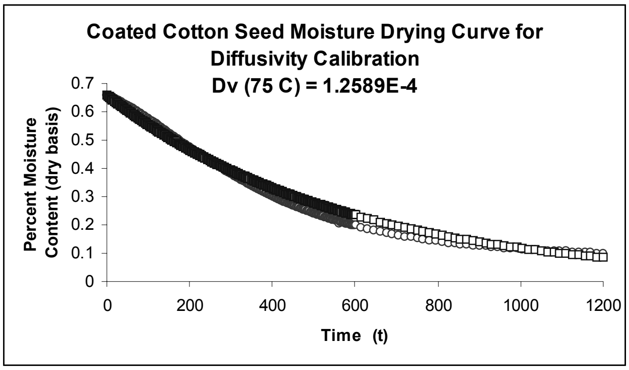

Figure 6: Recursive version of the classic Newman (1932) equation for the prediction of thin-layer drying curve.

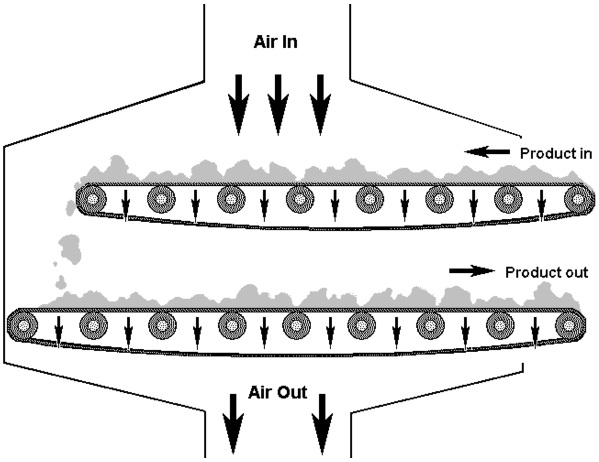

Figure 7: Downflow belt dryer depicting the cottonseed flow and the air-flow.

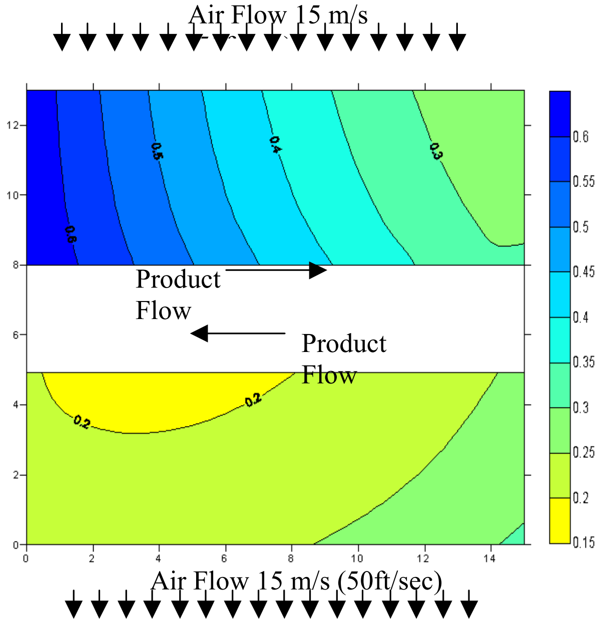

Figure 8: Moisture content prediction by computational model of starch coated cotton seed.

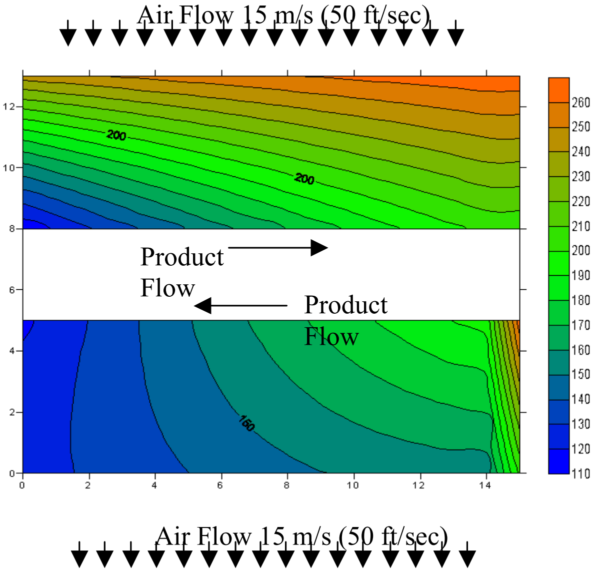

Figure 9: Air Temperature prediction by computational model of starch coated cotton seed.

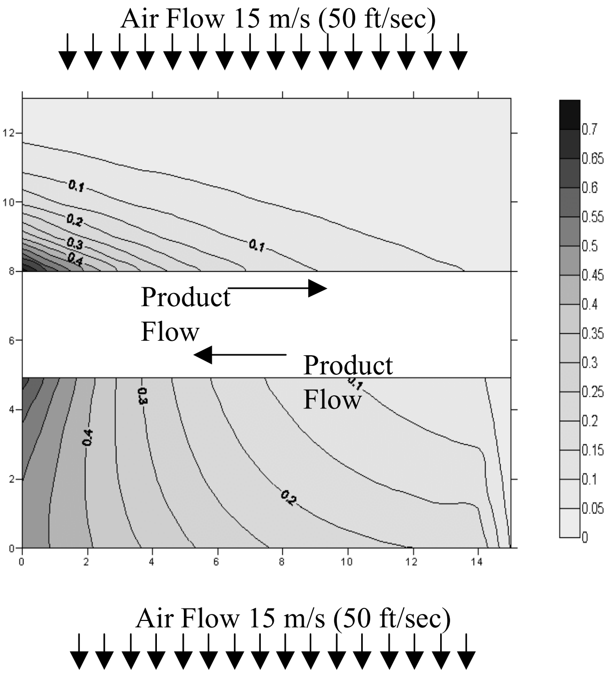

Figure 10: Air Relative Humidity prediction by computational model of starch coated cotton seed.