A CLOSED LOOP TUNNEL FOR DRYING KINETICS RESEARCH

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ABSTRACT

Experimental test equipment for convection drying is proposed. Some improves are considered in order to work with a wide range conditions, less buoyancy air effects, quick response and good stability. The modular design allows to make easy changes and adaptations for particular applications. It is possible to make drying experiments of solids with longitudinal flow, fixed bed in a downward flow and in fluidized bed in an upward flow. The system effects to the performance of the airfoil centrifugal fan were reduced considering square elbows (H/W=1. r/H>1) with 3 long turning vanes and 100% effective duct length. Good airflow pattern is provided to the test chamber. The buoyancy air effect is reduced with a flow deviation into an alternative tunnel while measuring takes place. The closed loop duct, the fast heating response and the isolation of the fiberglass tunnel, allows saving energy and having good temperature regulation. Drying texts of Pinewood were made in order to prove the operation of the closed loop tunnel changing temperature, humidity, and airflow.

INTRODUCTION

It is necessary an adequate experimental drying equipment to investigate the effect of the operational conditions, the mechanism of drying and to establish data for planning.

In order to get the results that can be applied for scale up, some aspects must be taken into consideration. The conditions of drying must be, if possible identical to the conditions anticipated in the industrial unit, the sample must be placed in a similar way in the laboratory unit, the ratios of the surfaces (drying/nondrying) must be identical and the sample must not be too small (Molnár, 1987).

Experimental equipment for drying by convection is, in fact, a controlled climate air duct. The equipment consisted of an air flow rate control section, an air heating control section, an air humidifying section, and a drying test compartment where drying is performed. There are some improvements in order to adjust especial tests.

Generally, the duct is designed to especial applications. There are open and closed loop tunnels. Kiranoudis et. al., (1995) employed a proper laboratory dryer closed loop air tunnel to determine the influence of process variables on the drying kinetics for vegetables. That tunnel was designed to carry out experiments of thorough-type drying. Shishido et. al. (1978), used an open duct test dryer to determinate the diffusivity of moisture within powder refractory brick. They installed an IR-hygrometer and a load cell to measure the surface moisture content of a wet material while hot air pass longitudinally to the sample. It is possible to built versatile equipment for drying by convection, considering that, the tunnels have the same elements. The purpose of this work is to show an experimental closed loop tunnel developed to make drying test in different ways and in a wide range of conditions. The equipment design included some improves that allow to make changes in order to accommodate the particular experimental necessities. The tunnel design considered the recommendation to proper air conduction, to reduce friction and to diminish the construction's cost. (ACGIH, 1988).

PROCEDURE

Experimental design equipment purpose and functions: It was consider a versatile tunnel in order to make different kind of tests. The material to be dried could be placed in a try, in a fixed bed, or like a fluidized bed; in longitudinal flow, through ascendant-descendent flow. A wide range of operation conditions (Temperature, drop pressure, humidity and flow rate) should be possible in drying experiments. The equipment may be proper for mass and heat transfer research in a variety of materials, paste, granulates, fibrous, cut solids in specific shapes. Changes and adaptations should be doing easily. Flow rate uniformity may be ensuring in the drying test compartment. Saving energy, low noise and low vibrations were necessary to work in the laboratory with comfort.

Duct Design Considerations. The ventilation system is designed with specification requirements and performance criteria. The specification requirement prescribes a certain critical dimension and a volumetric flow rate. The performance standard prescribes the function of the system that may choose to adopt.

The design of a ventilation system consists in the creation of a geometrical configuration. The essentials in the design method are selecting a geometrical configuration and predicting its performance based on heat and mass transfer. ASHRAE (1989) describes contemporary practices and design standards that provide excellent guidance to design industrial ventilation systems.

Computing the drop pressure in a duct is the basis of all duct design procedure. The total pressure loss depends on the shape of the fitting and the flow characteristics. The fundamental equations to compute the static pressure (SP) and total pressure (P) change between any two points are:

$$\mathrm{SP}_1 - \mathrm{SP}_2 = \mathrm{VP}_1 - \mathrm{VP}_2 + \mathrm{h}_{\mathrm{LT}} \tag{1}$$

$$\mathrm{P}_1 - \mathrm{P}_2 = \mathrm{h}_{\mathrm{LT}} = \mathrm{h}_{\mathrm{L}} + \mathrm{h}_{\mathrm{LM}} \tag{2}$$

The total head loss (h_{LT}) is made up of frictional losses (h_L) due to friction losses in a constant area ducts and dynamic looses (h_{LM}) result from flow disturbances caused by fittings that change the airflow path's direction area. Frictional losses are due to fluid viscosity and are the result of momentum exchanged among molecules in laminar flow and among particles moving at different velocities in turbulent flow. For fluid flow in conduits, friction loss can be calculated by the Darcy's equation:

$$\mathrm{h}_{\mathrm{L}} = f \cdot \left(\frac{\mathrm{L}}{\mathrm{D}}\right) \cdot \mathrm{PV} \tag{3}$$

In the transitionally rough turbulent zone, the friction factor f is function of Reynolds number (Re) and roughness factors (ε). It could be calculated by the traditional Moody chart or by an equations available for computer solution to the Moody diagram like Churchill's equation. For turbulent flow and low roughness factors can be used the next equation.

$$f = \frac{0.184}{\mathrm{Re}^{0.2}} \tag{4}$$

Dynamic losses result from flow disturbances caused by fittings that change the airflow path's direction or area. These fittings include entries, exits, transitions, and junctions. For easy calculations, dynamic losses (h_{LM}), are assumed to be concentrated at a section and to exclude friction. It can be expressed as:

$$h_{LM} = PV \cdot \sum C \tag{5}$$

There are local loss coefficients (C), for several common fitting (ASHRAE Handbook, 1989).

Air has inertia, once set in motion, air tends to continue in the direction it is moving. It takes energy to make air flow change its directions. The air wants to flow in a straight line. On turns, therefore it crowds against the outside. Then a better airflow design considers a duct elbow that has vane placed at the bend in order to reduce the pressure drop.

The Fan performance may show a lower capacity of performance than manufacturer's ratings. Deficient performance of the fan-system combination is commonly caused by: improper outlet connections, non-uniform inlet flow, or swirl at the fan inlet. An elbow must be often installed near the fan discharge. The loss coefficient of the fan system considers elbow arrangements and a length to establish a uniform velocity profile (effective duct length). Including an adequate length of straight between the elbow and the fan inlet can eliminate the fan inlet effect.

Testing System:

The ventilation system should be tested at the time of initial installation to verify the volumetric and uniformity of flow rate and to get other information that can be compared with the original design data.

Generally, the most important measurement collected when testing a ventilation system is the measurement of volumetric flow rate. This flow was determined using a thermal anemometer. This instrument employs the principle in which the amount of heat removed by an air stream passing a heated object is related to the velocity of the air stream. Commercial instrument use a probe, which consists of two integral sensors: one is the velocity sensor and other is the temperature sensor. Due to small diameter of the probe, measurement can be made directly inside ducts. For rectangle ducts, the procedure is to divide the cross-section into a number of equal rectangular areas and measure the velocity at the center of each one. Thirty-six measuring points was checking.

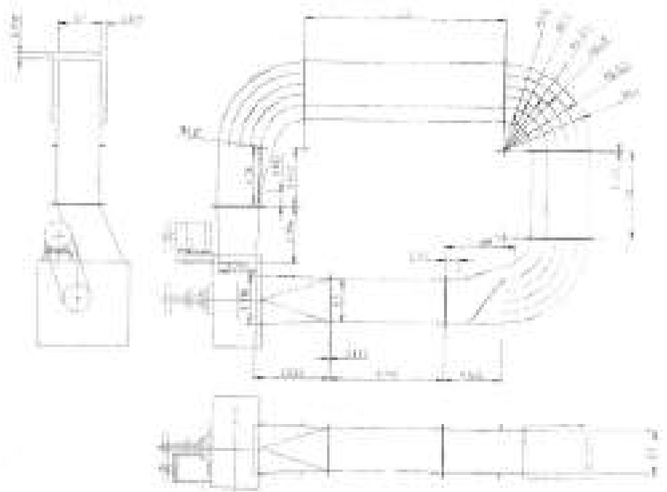


Figure 1. Closed loop tunnel dimensions.

Functionality should be tested in order to ensure the equipment work well. Wood drying is a good way to test the equipment's experimental purpose. The Temperature, humidity, and flow rate conditions should change while the wood drying take place. Two tests were carried out with the same drying schedule in order to evaluate the drying's kinetic reproducibility of *P. pseudostrobus* wood.

Four lumber sections (5.5x20x50 cm) were set in a metal support, in which they could fit exactly, and put in the drying compartment of the dryer. Air condition throughout the experiment was measured on-line. Water losses during drying were determined on-line, by weighing the support with a load cell with an accuracy of ±0.1% of reading.

Air was circulated in the dryer by means of a centrifugal fan with controllable flow rate. The dry bulb temperature of the air stream was measured on-line at various spots of the dryers by means of thermocouples. The air was heated by passing through 3 heating element and a total of 4.5 kW controllable electrical power. The heater could be used separately or together. Air humidity was calculated from dry and wet temperatures. Wicks saturated with water covered the wet bulb thermocouples. Introducing steam, via a distributor devise installed in the dryer's horizontal section, carried out humidifying of hot air. The temperature and humidity were regulated with digital controls.

RESULTS

The closed loop tunnel consisted of nine modules (figure 1): Three rectangular elbows with three turning vanes, two straight rectangular duct, one straight square duct, one fan inlet connection (transition round/rectangular), one plane asymmetric diffuser at fan outlet and two transition square/rectangular. In fact, the rectangular modules include a principal squared duct and a deviation rectangular duct.

Table 1. Fitting loss coefficients.

Fitting	Shape ratios	Coefficient	Min-Max values in tables
Elbow (90°) with three splitter vanes	H/W=1 r/W=1.5 R/W=1	≅0.03	0.03-0.613
Plane asymmetric Diffuser at fan outlet	$\theta=24°$ $A_0/A_b=1.165$	0.12	0.08-0.44
Square elbow with an inlet transition (full radius vanes equally spaced).	L/H=2.66 r/H=1.5	0.28	0.14-0.50
Centrifugal Fan with an outlet duct elbow (inlet direction)	$A_b/A_0=0.858$ $L/L_e=0.928$ $L_e=0.857$	0.16	0.00-5.8

The fittings were made of aluminum. A high pressure-fitting joint was considered, then, an aluminum angle frame was welded to rectangle duct. Unions between fittings were made with screws in order to allow an easy assemble. For closed tunnel design purpose, aluminum has two advantages: smooth roughness (0.03 mm) and lightweight. The first ones allowed less friction losses, while the other allowed easy handle. An adjustable tube support allowed fit the modules in easy way. The identification of the fan used includes the following: An airflow A-SQ type, 1214 size, Class I. Four reasons were considered to choose an airfoil ventilation belt drive: Low noise and vibration level, high efficiency of all centrifugal fan design, good pressure characteristic (0-4" SP), and closed size between outlet fan area and the duct area. A frequency converter is used for speed control of squirrel cage motor, and then a wide airflow range (0.5-7 m/s) is possible.

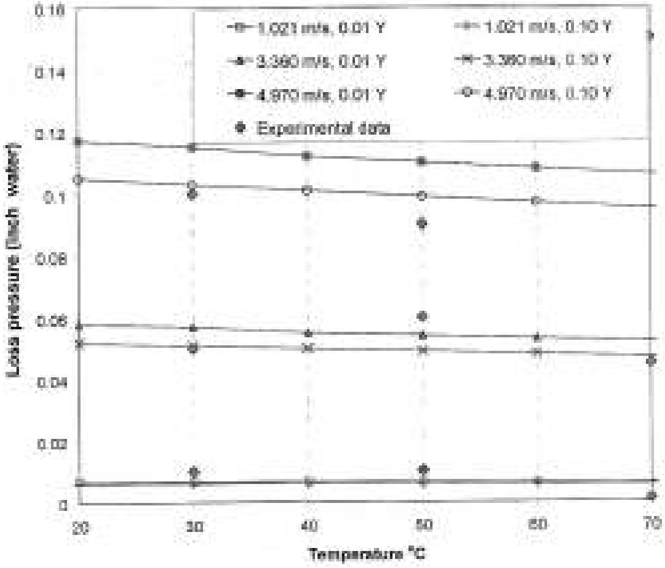
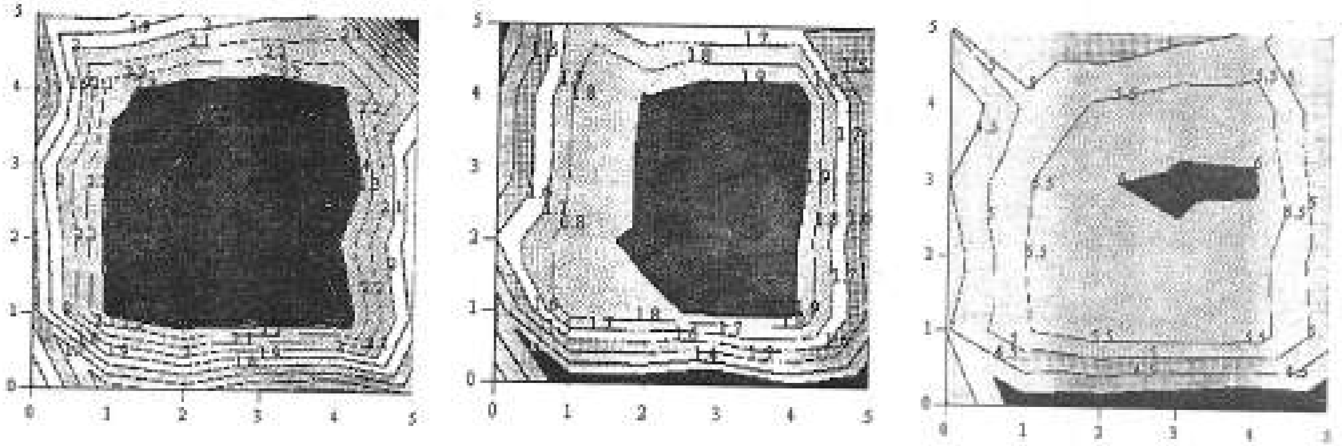


Figure 2. Drop pressure in the tunnel.

The low weight and a fan turning base let the equipment rotate from horizontal to vertical position, then, it is possible to work in longitudinal and thorough flow. The drying test compartment in vertical position let make batch fluidization tests. The buoyancy air effect is reduced with a flow deviation into an alternative tunnel while measuring takes place. It is proper for test in fixed bed in a downward flow and in fluidized bed in an upward flow. In this way, water losses during drying can be measured on-line without taking the sample out of the drying compartment.

Table I presents local loss coefficients for tunnel fittings. It can show minimum and maximum values in tables for the same fitting. By comparing values, it is possible to conclude that the close loop tunnel was designed with low dynamic losses.

The pressure lost at two duct points was calculated with the Darcy's equation. The friction factor was calculated with equation 4. In Figure 2, the calculated loss pressure is plotted at different temperatures, humidities, and airflow. Some loss pressure measured values are plotted for comparison. The experimental values are like the calculated ones.



F40

F20

F60

Figure 3. Flow rate lines (m/s) for three-fan motor speeds, F20, F40, and F60.

The first purpose of duct's design was to obtain uniformity of flow rate. Contour flow rate constant lines for three fan motor speed are plotted versus the cross-section location (Figure 3). The absolute velocity difference increase when the fan motor increase. The centerline contour shows a uniform flow rate area. The wall effects are well noticed. Standard errors were 0.0959, 0.102, and 0.138 respectively for each fan-motor velocity. Good airflow pattern is provided to the test chamber having a maximum standard error 0.15 in the in a wide airflow range (0.5-7 m/s).

The tunnel was isolated to avoid heat losses and substantial temperature differences across the test sections. The moist in the experimental compartment could vary in a wide range (10-100 %HR). A smooth pinewood schedule was chosen to test the equipment operation for drying (Simpson, 1991). One test and its replicate in pinewood were made in order to ensure equipment experimental purpose (Figure 4). The drying kinetics of the test and the replicate are good fitted.

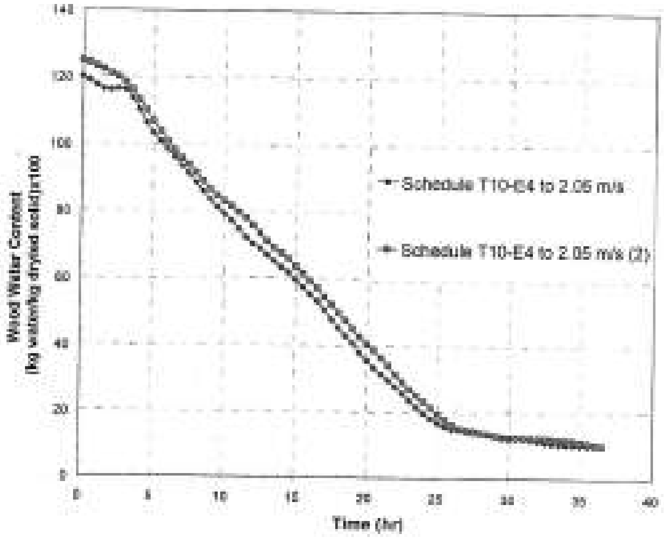


Figure 4. Drying Kinetics for *P. Pseudostrobus*

CONCLUSIONS

A closed tunnel dryer by convection was showed and tested to ensure proper design, good operation, and good function for drying test. The equipment complies with the good airflow pattern and low loss pressure. Long time tests indicated continuous operation with good experimental reproducibility. New characteristics were included: An equipment rotation from horizontal to vertical position and an alternative duct deviation.

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NOTATION

A_0	Duct outlet area	m^2
A_b	Centrifugal fan blast area	m^2
C	Local loss coefficient	dimensionless
D	Hydraulic diameter	m
F	Friction factor	dimensionless
H	Duct height	m
h_L	Friction losses	Pa
h_{LM}	Fitting losses	Pa
h_{LT}	Total head losses	Pa
L	Duct length	M
L_e	Effective Duct length	m
P	Total pressure	Pa
PV	Velocity Pressur	Pa
r	Center duct radius	M
R	Throat radius	M
SP	Static Pressure	Pa
W	Duct width	M
Y	Absolute air humidity	kg moisture/Kg dry air.
Greek Symbols		
θ	Deviation from vertical side	°
ε	Material absolute roughness factor	m
ρ	Fluid density	kg/m^3

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Section IV. Concepts