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ScienceDirect

Energy Procedia 126 (201709) 361–368

Energy Procedia

www.elsevier.com/locate/procedia

72nd Conference of the Italian Thermal Machines Engineering Association, ATI2017, 6-8 September 2017, Lecce, Italy

Experimental investigation on industrial drying process of cotton yarn bobbins: energy consumption and drying time

Giovanni Galoppi[a]*, Lorenzo Ferrari[b], Giovanni Ferrara[a], Ennio Antonio Carnevale[a]

[a] *Department of Industrial Engineering, University of Florence, Via di Santa Marta 3, 50139, Florence, Italy*
[b] *Department of Energy, Systems, Territory and Construction Engineering, University of Pisa, Largo Lucio Lazzarino, 1 – 56122, Pisa, Italy*

Abstract

In the textile industry, the drying process is a time consuming and energy expensive operation that influences strongly the cost of the textile finishing operations. For this reason, the study of innovative techniques plays a key role to decrease the energy consumption, the costs and the environmental impact. After a first mechanical process, the moisture is removed from yarn fibers by a thermal convection dryer that delivers hot air through the material. In this study, the drying process of cotton yarn bobbins is experimentally analyzed. With this aim, an experimental test rig was developed based on the geometry of industrial dryers. The influence of the drying air path and the air working conditions was assessed by performing tests with different configurations, temperatures and pressures. The results were analyzed in terms of drying time and energy consumption as the optimum drying condition is a trade-off between these parameters.

Keywords: drying; experimental tests; cotton bobbin; energy consumption; air conditions influence

1. Introduction

The drying process is one of the most important and crucial operation in several industrial applications [1]. In the textile industry, drying is the stage between dyeing process and the last finishing treatments and requires high amounts

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* Corresponding author. Tel.: +39-0574-831226.
E-mail address: giovanni.galoppi@unifi.it

10.1016/j.egypro.2017.08.246

Nomenclature

Latin letters		*Greek letters*	
cp	Specific heat [kJ/kgK]	η	Efficiency
D	External diameter [m]		
d	Internal diameter [m]	*Subscritps*	
E	Energy consumption [kWh]	*D*	Dried
H	Height [m]	*fan*	Fan
h	Enthalpy [kJ/kg]	*heat*	Heater
$\dot{m}$	Mass flow rate [kg/s]	*in*	Inlet
R_t	Moisture content	*is*	Isentropic
T	Temperature [°C]	*out*	Outlet
t	Drying time [s]	*W*	Wet
W	Weight [kg]		

of energy. In particular, it uses up to 80% of all the energy consumed in the production of textile materials [2] and represents one of the major cost issues among the textile finishing operations. For these reasons, the drying time and the energy consumed must be taken into consideration in order to produce a dried product at minimum cost [3].

Drying of textile yarns consists of two successive operations: a mechanical and a thermal one. Mechanical processes are used to remove the water that is mechanically bound to the fiber and, in general, are based on centrifugal extraction. After the pre-drying, the remaining part of the water is removed by a thermal drying. This process can be performed in several ways, such as convective, contact, infrared or radiofrequency drying [4]. The most widely used drying technique is the convective one that consists of passing a hot air stream through the material to be dried. Heat is transferred from air to the material by forced convection and the evaporated water is carried out.

Since 80's, the research interest on the drying process has grown exponentially. In the literature, there are many investigations on the heat and mass transfer mechanisms in textile fibers with both numerical and experimental approaches. Lee et al. [5] developed a transient two-dimensional mathematical model to simulate the through-air drying process for tufted textile materials showing a closely agreement with experimental results. Li and Zhu [6] developed a model of liquid water, moisture and heat transfer in porous textiles that resulted in good agreement with experimental measurements. The drying process of layered fabrics was modeled by Fohr et al. [7] that found two formulations to estimate the hygroscopic character as function of the diffusion coefficient. Hamdaoui et al. [8] analyzed experimentally the thermal drying of knitted textile fabric at different temperatures and demonstrated that the drying phenomenon follows a polynomial law.

Among the studies on the textile drying, only a few of them dealt with textile bobbins. Akyol et al. [9] determined the thermo-physical properties of a wool yarn bobbin during a convective drying by using an inverse method. In the study of Ribeiro and Ventura [10], who reported an experimental investigation of wool bobbins drying by hot pressurized air, the temperatures in the bobbin were plotted to show the presence of an evaporation front. Akyol et al. [11] evaluated the influence of the thermodynamic conditions on the drying of wool bobbin showing the significant impact of the air pressure and that the process can be described with a logarithmic model. The optimum operating conditions were determined by Akyol et al. [12], who showed the influence of the drying temperature, pressure and mass flow rate on the drying time and the energy consumption. In a more extended work [13], the analyses were performed for different bobbin diameters and it was found a numerical model suitable to simulate the drying behavior.

In this work, the optimum drying conditions of cotton yarn bobbins in a dryer based on a typical industrial configuration were analyzed experimentally. Following the necessity of the textile industries of optimizing the drying process in terms of production costs, the authors performed experimental analyses at different temperatures, pressures and air paths. Before the thermal drying, the mechanical drying was performed with an innovative technique by creating a pressure difference between the external and internal side of the bobbins, which causes a wringing of the bobbins and a significant removal of water. The test rig was designed to perform both mechanical and thermal drying. A measurement system was developed to acquire the main parameters during the drying process. The results showed the influence of the drying conditions on drying time and energy consumption and an optimum solution was found.

2. Test rig and experimental setup

In accordance with the applications in the textile industry, a test rig was built as shown in Fig. 1. The test rig was designed with the aim of performing both the mechanical and thermal drying and acquiring the main parameters during the processes.

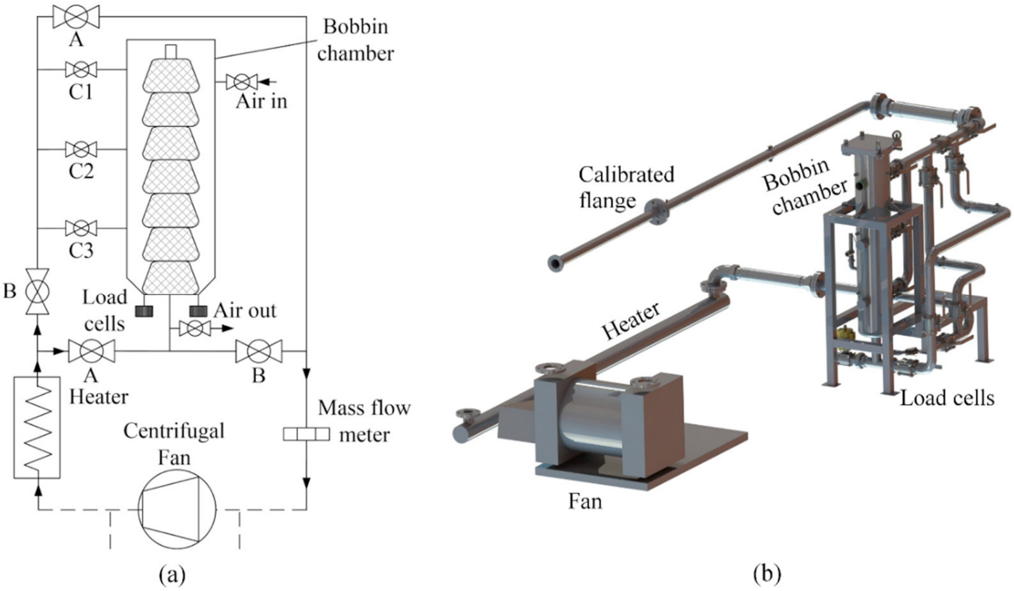


Fig. 1. (a) Schematic view of the test rig; (b) 3D view of the test rig.

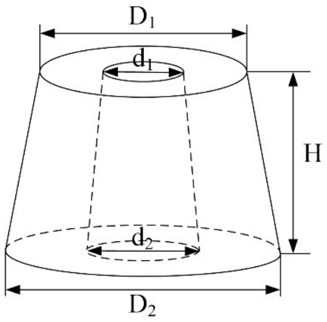
2.1. Thermal drying

To obtain hot air at a desired temperature, an electric heater with a heating capacity of 15 kW was used. The desired temperature at the heater output is set and a PID controller regulates the heater power to keep it constant. A PT100 thermo-resistance was used to measure the output temperature. After the heater, the hot air enters the bobbin chamber, where the bobbins are positioned vertically, one above the other. In this work, seven cotton yarn bobbins were positioned in the chamber. Yarns were rolled on plastic harps with a cone shape, and their schematic view and geometrical dimensions are shown in Fig. 2. The path of the hot air inside the bobbin chamber can be modified by acting on ball valves. As reported in Fig. 1, the air can enter the chamber from either the bottom or the lateral side. By opening the valves A and closing the valves B, the air enters from the bottom and its direction through the bobbins is from inside out; otherwise, the direction is from outside in. In addition, three lateral branches, equipped with ball valves, could be used to change the flow path. By changing the rig configuration it is possible to estimate the influence of the air path on the drying process and to choose the most performing solution. The circulation of the air is assured by a centrifugal fan with a nominal power of 18.5 kW, which can be connected to the rig in two different modes:

- by connecting the outlet of the fan to the inlet of the heater. The fan sucks in the ambient air and delivers pressurized air in the bobbin chamber;
- by connecting the inlet of the fan after the bobbin chamber. The fan sucks in the air inside the chamber and therefore the bobbin chamber is depressurized.

The speed of the fan can be regulated with a variable-frequency inverter.

Theoretically speaking, for a given mass flow rate and inlet temperature, the drying process is as more efficient as lower is the pressure inside the bobbin chamber. By decreasing the pressure, the saturation temperature is reduced and the evaporation of the water inside the bobbins is faster. However, the depressurization can lead to lower mass flow rate and different energy consumptions. The best combination was estimated by an experimental investigation.



Parameter	Value
Internal diameter d_1 (mm)	40
External diameter D_1 (mm)	150
Internal diameter d_2 (mm)	60
External diameter D_2 (mm)	170
Height H (mm)	140

Fig. 2. Bobbin geometry and dimensions.

2.2. Mechanical drying

The test rig was designed to perform the mechanical drying before performing the thermal drying. Unlike the usual method based on the centrifugal extraction, a mechanical wringing was obtained by applying a pressure difference between the external and internal side of the bobbins. In more detail (see Fig. 1), the bobbin chamber was pressurized by using air from an external line (Air in) when all valve are closed (i.e. A, B and C). The increase of the pressure in this process is very slow as the diameter of air inlet is small. After a target value of the pressure was achieved, the air inlet is closed and the equilibrium of pressure across the bobbins was waited. Subsequently, a valve under the bobbin chamber (Air out) is opened and the air is abruptly exhausted. Due to the relative large diameter of this valve, the pressure in the internal part of the bobbins decreases almost instantly. This leads to a strong pressure difference through the bobbins that causes the mechanical wringing. The pressure difference decreases gradually (the velocity depending on the pressure drop) as the air passes from the external to the internal part of the bobbins, up to reaching the equilibrium at ambient pressure.

The main advantages of this method are two. Firstly, both mechanical and thermal drying processes can be performed with the same apparatus, by simply acting on the valves. Secondly, the energy consumption is strongly reduced in comparison to the usual centrifugal extraction that requires a lot of electric energy.

2.3. Measurement system

The test rig was equipped with measurement instruments to acquire the main parameters. The thermodynamic conditions at the inlet and outlet of the bobbin chamber were obtained by measuring the local temperatures and pressures. The temperatures were measured by using T-type thermocouples. The values of the pressure upstream and downstream the bobbin chamber were acquired by using pressure transducers (Setra, -5 to 5 PSID, ±0.1% FSO) with a 4-20 mA output. During the mechanical drying, the pressure inside the chamber is acquired by a specific pressure transducer (Honeywell, 100 psi, 0.1 FS). As shown in Fig. 1, the mass flow rate is measured after the bobbin chamber by using a calibrated flange directly connected to the pipeline. The pressure difference across the flange is acquired by a Setra pressure transducer (-2.5 to 2.5 PSID, ±0.1% FSO). According to the position of the flange, the mass flow rate of the humid air after the drying process is measured. The air mass flow rate at the inlet of the drying process is calculated by subtracting the measured value with the mass water of evaporated from the bobbins. To measure the weight variation of the bobbins and, consequently, the evaporated water mass flow, the bobbin chamber has been placed on a structure supported on four S-type load cells by PCB, each one with 250 lb capacity and 0.1% accuracy.

All signals were acquired by using a National Instruments Field Point and were processed by a software specifically developed in LabView®, which allows to monitor the drying conditions in real time. Moreover, the system can control the opening/closing of the exhaust electronic valves air during the mechanical drying.

3. Analysis

To obtain a homogeneous moisture distribution, the bobbins were kept in a water bath for at least 24 hours. The bobbins were then positioned inside the chamber to start the tests. Before starting the thermal drying process, the water that is mechanical bound to the fibers was removed by the mechanical process. Pressurized air enters the bobbin chamber up to a pressure of 5 bar and then it is exhausted by opening the electric valve. This process is repeated until a significant variation of bobbin weight is no more appreciable. A removal of 25-30% of water was obtained in each test. After that the thermal process started, this being the main focus of the experimental campaign. The experimental tests were carried out at different conditions to asses which configuration could be the best. In particular:

- The influence of the air direction was assessed by carrying out three tests (Fig. 3):
  - CONFIG 1: the air comes from inside and the exit is on the upper lateral branch
  - CONFIG 2: the air comes from inside and the exit is through all the three branches
  - CONFIG 3: the air comes from outside
- The comparison between a pressurized and depressurized chamber was performed by connecting the fan to the plant in different ways, as described previously
- Each configuration was tested at 100°C, 110°C and 120°C. The maximum temperature was suggested by Wiegerink [14] that showed experimentally that the quality index of cotton yarn exposed to drying air temperature of 120°C for 6h is 92%.

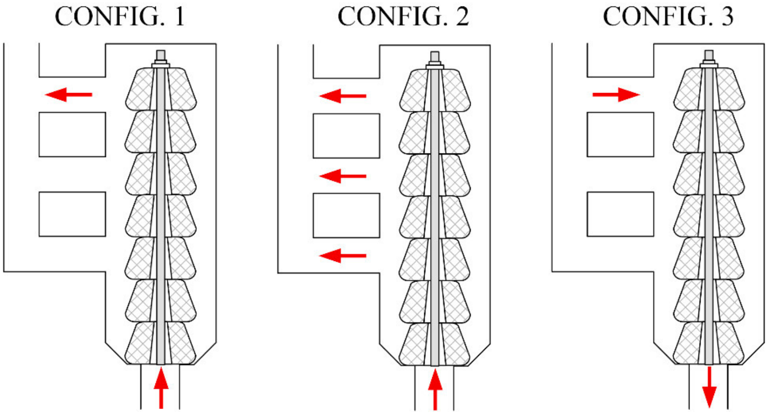


Fig. 3. Different tested configurations of the air direction in the bobbin chamber.

After each test, the energy consumption was estimated from the measured parameters. In particular, the energy consumed by the fan is calculated as:

$$E_{fan} = \frac{\dot{m} \cdot \Delta h_{is}}{\eta_{is}} \cdot \Delta t = \frac{\dot{m} \cdot (h_{out\_is} - h_{in})}{\eta_{is}} \cdot \Delta t \tag{1}$$

where η_{is} is assumed equal to 60% and Δh_{is} is the isentropic enthalpy difference, calculated by the thermodynamic conditions at the inlet and the pressure at the outlet.

The energy consumed by the heater is calculated as:

$$E_{heat} = \frac{\dot{m} \cdot cp \cdot (T_{out} - T_{in})}{\eta_{heat}} \cdot \Delta t \tag{2}$$

where η_{heat} is assumed as 90%. The temperature upstream the heater T_{in} depends on the connection of the fan to the pipeline: in the configuration with a depressurized chamber, T_{in} is the ambient temperature, otherwise it is the temperature after the fan. The temperature at the outlet of the heater T_{out} is the imposed temperature at the inlet of the bobbin chamber. The total energy consumption is the sum of the previous estimated values.

4. Results

The thermal drying behavior of the bobbins is evaluated by showing the trend of the main parameters and the energy consumption. The comparison among the different tested configurations shown in Fig. 3 is reported in Fig. 4

in terms of moisture content R_t:

$$R_t = \frac{W_W - W_D}{W_D} \tag{3}$$

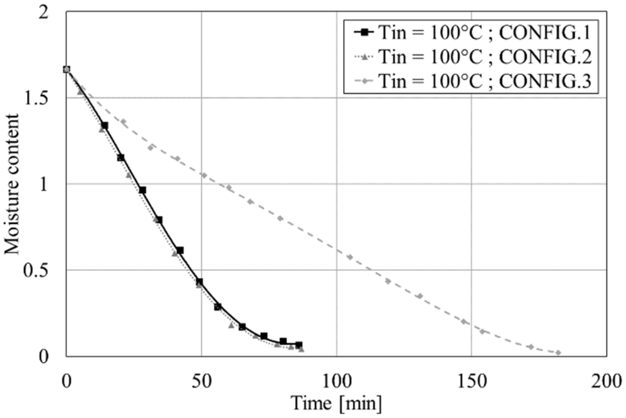


Fig. 4. Moisture content trend at different air directions.

It can be seen that, for a given inlet temperature, the behaviors of CONFIG.1 and CONFIG.2 are almost identical. Therefore, by entering the air from the bottom, the exit of the air through a different number of branches does not have almost any influence on the drying behavior. Conversely, by entering from the lateral side, the behavior is completely different and the drying process is much slower. The different behaviors are justified by considering the mass flow rate and the pressure at the inlet of the bobbin chamber (Fig. 5). By drying from outside in (CONFIG.3), the air compresses the fibers of the bobbins leading to higher pressure losses in comparison to the other configurations, where the fibers tend to be separated. Therefore, the inlet pressure is higher and, consequently, the mass flow rate is lower due to the characteristic curve of the fan. For these reasons, the drying time is much higher.

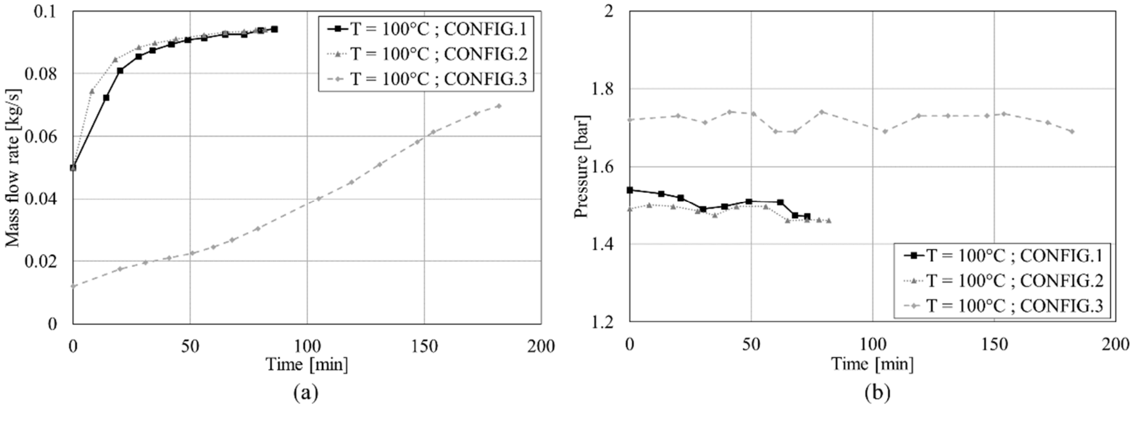
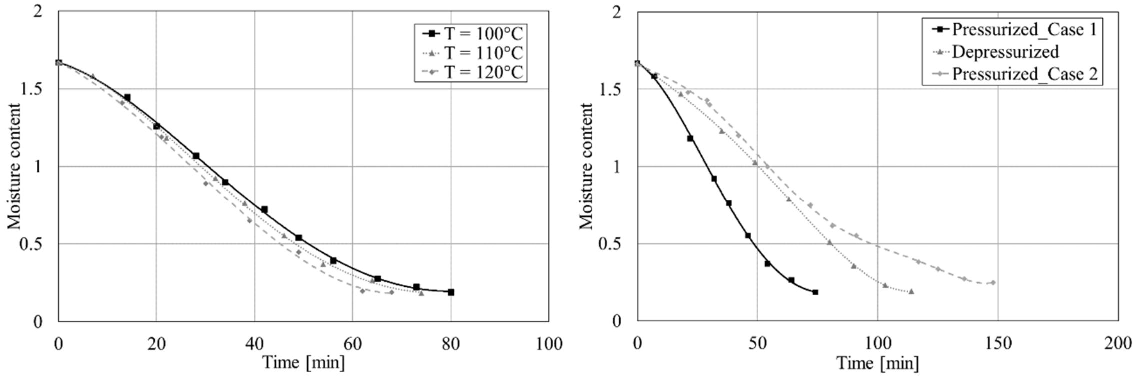


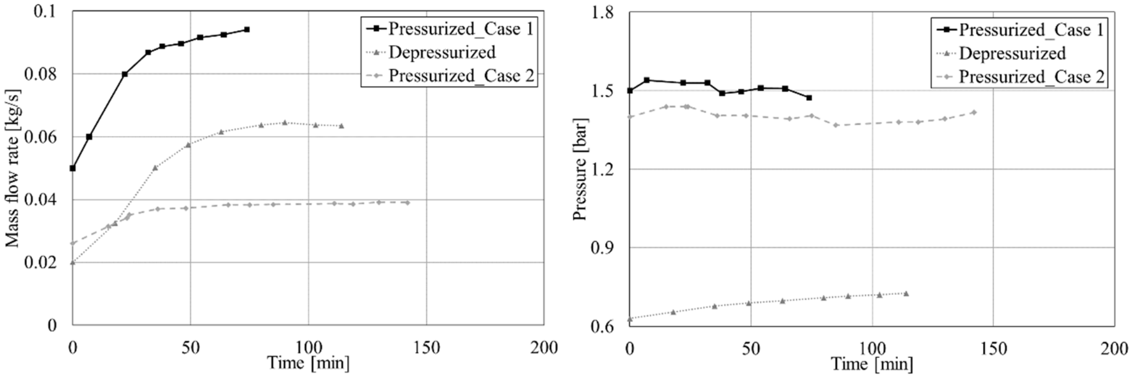
Fig. 5. (a) Mass flow rate and (b) inlet pressure trends at different air directions.

Due to the previous results, only CONFIG.1 was considered for the following tests. Fig. 6a shows the trends at different air temperatures with a pressurized chamber. Each trend presents an initial slower variation of moisture content and a gradual increase of the velocity of the evaporation due to the increase of the temperature inside the chamber. After that, the trend is almost linear up to the final part where the evaporation velocity decreases. Obviously, by increasing the inlet temperature, the moisture removal is faster. The drying time is between 70 and 90 minutes. The influence of the inlet pressure is showed in Fig. 6b, which reports the moisture content trends with 110°C air temperature and different air pressure. The analyzed cases were obtained by depressurizing the chamber and pressurizing it with different fan speed to obtain different values of pressure and mass flow rate: 1.55 bar and maximum 0.092 kg/s for Case 1, and 1.35 bar and 0.04 kg/s for Case 2, as shown in Fig. 7. The moisture removal is faster by pressurizing the chamber at 1.55 bar (Case 1) than depressurizing it, although the drying process should be more efficient with a lower pressure that would decrease the saturation temperature. As shown in Fig. 7a, the mass flow rate is reduced by depressurizing the chamber thus leading to a slower moisture removal. In addition, by pressurizing the chamber at 1.35 bar (Case 2), the mass flow rate is strongly decreased, whereas the inlet pressure is reduced only by 1.55 bar to 1.35 bar (Fig. 7b). For this reason, the drying time is much higher.



(a) (b)

Fig. 6. (a) Moisture content trends at different inlet temperature and (b) different inlet pressure.



(a) (b)

Fig. 7. (a) Mass flow rate and (b) inlet pressure trends at different configurations.

Finally, the influence of the thermodynamic conditions on energy consumption was estimated (Table 1). For a given inlet pressure, by increasing the temperature at the inlet of the bobbin chamber, the energy consumed by the fan is lower due to the reduced drying time, whereas the energy consumed by the heater is higher. The resulting total energy consumption is not very different by varying the air temperature. For this reason, it is worth working with temperatures as high as possible that lead to lower drying time without increasing strongly the energy consumption. In comparison to the case with a pressurized chamber at 1.55 bar (Case 1), with a depressurized chamber the energy consumed by the fan is slightly lower due to the reduced mass flow rate, whereas the energy consumed by the heater is much higher. In this configuration, the air temperature at the inlet of the heater is equal to the ambient temperature, whereas by pressurizing the chamber, the air is preheated by the fan before entering the heater. Globally, the energy consumed by depressurizing the chamber is much higher. Moreover, by pressurizing the chamber, at lower pressure (Case 2) and mass flow rate the energy consumption is reduced. In conclusion, it seems that it is better to pressurize the bobbin chamber, whereas proper inlet pressure and mass flow rate must be chosen as a trade off between the drying time and the energy consumption.

Table 1. Drying time and energy consumption estimated at each experimental test.

Tin [°C]	Pin [bar]	Time [min]	Efan (kWh)	Eheat (kWh)	Etot (kWh)
100	1.55	87	7.93	5.55	13.48
110	1.55	81	7.58	6.6	14.18
120	1.55	73	7.01	7.31	14.32
100	0.65	130	7.35	11.49	18.84
110	0.65	124	6.74	11.57	18.31
120	0.65	119	6.72	12.76	19.48
100	1.35	161	6.55	4.59	11.14
110	1.35	150	5.69	4.95	10.64
120	1.35	141	5.58	5.82	11.4

Conclusion

In this work, the influence of the main parameters on the drying process of cotton yarn bobbins was studied in an experimental test rig based on the common indutrial dryer. Both mechanical and thermal drying processes were performed in the same rig. The mechanical process consists on creating a pressure difference between the external and internal parts of the bobbins leading to obtain a mechanical wrinking that causes a removal of 25-30% of the water. The thermal process was performed by heating the air with an electric heater and by using a centrifugal fan, whereas the test rig was designed to test different air path configurations.

The results showed that the drying time is strongly dependent on the air direction through the bobbins. The best configuration is to dry from inside out as it causes lower pressure drops and, consequently, higher mass flow rates leading to a faster drying process. In addition, the drying time is reduced by entering the air at higher temperatures and by pressurizing the chamber at higher pressure and mass flow rate. The depressurization of the chamber leads to lower mass flow rates. In addition, the total energy consumption is lower by pressurizing the chamber as the drying air is preheated before the heater leading to a reduced energy consumed to heat it. The minimum energy consumption is obtained by pressurizing the chamber at lower pressures, which, however, leads to higher dying time.

In conclusion, the results showed that the optimum conditions are to dry with temperatures as high as possibile and by pressurizing the chamber at pressure and mass flow rate that must be chosen as a trade off between the drying time and the energy consumption.

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