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Investigation of the effect of drying air temperature on drying time by numerical method for textile bobbins

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Abstract. Drying of the yarn bobbins in the textile sector is a very important stage among the textile finishing processes. Because this process takes a lot of time and causes a large amount of energy consumption. In this study, drying times for different drying air inlet temperatures at a constant drying air pressure were determined with the help of mathematical model for textile bobbin drying process. Finite difference method was used in mathematical model solution and the effect of different space and time steps were taken into consideration during the solution.

1. Introduction

The yarn bobbins must be dried after the dyeing process in the textile industry. It is important to perform this process in a short time with minimum energy consumption in terms of efficiency. For this reason, mathematical models have been emphasized for many years for drying processes. It is significant to develop drying methods for designing the drying process to preserve the quality of the products and shorten the drying time with minimum energy consumption [1]. These models generally focus on simultaneous solutions of heat and mass transfer equations. Ribierio and Ventura (1995) studied on an experimental setup where the drying process was carried out by passing hot air both through the inside and outside of the yarn bobbins [2]. In a study by Lee, et al. (2002), a two-dimensional mathematical model was developed for drying of dyed carpet yarns. Hot air was passed parallel to the axis through porous cylindrical media and heat and mass transfer were calculated considering the energy and mass conservation of the environment [3]. Smith and Farid (2004), in their experimental work, they have obtained correlations that allow the drying times of materials to be determined, taking into account the moving boundary theory for cylindrical geometries [4]. In a study by Hussain and Dinçer (2003), a two-dimensional numerical analysis of heat and moisture transfer during the drying of a cylindrical object was performed using the finite difference approach. Temperature and humidity distributions were obtained in humid bodies for different time periods [5]. Barati and Esfahani (2011) considered heat and mass transfer by conduction and convection in order to model the drying process and developed an analytical solution for the mathematical model they created [6]. In the present work, drying times for different drying air inlet temperatures at a constant drying air pressure were determined with the help of mathematical model for textile bobbin drying process.

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2. Materials and methods

The wool yarn bobbins were dried with hot air in the test setup. It passed through the yarn bobbins and the bobbins were dried from only the inside to the outside due to the pressure difference. The volumetric flow rate of the hot air is 500 m^3/h while the temperature and the pressure are 80^{o}C and 1 bar (effective) respectively. The yarn bobbins used in the experiments have an inner diameter of 35 mm and a length of 150 mm.

The wrapped yarn is made up of holes made from polyethylene material that allow air to pass over it. During the tests, 7 thermocouples were placed in the bobbin at even intervals to measure the temperature of the yarn bobbin section (Fig. 1). Akyol et al. (2013) have shown that the temperature change during the length of the bobbin is not important in the experimental study [7]. Therefore, in this study, it is considered that the heat transfer in the bobbin is performed in one dimension in the radial direction.

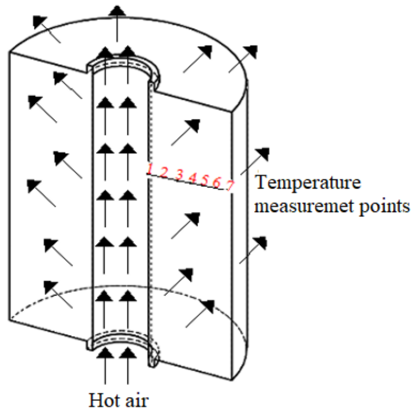

Figure 1. Schematic view of the yarn bobbin used in the experiments and temperature measurement points.

When the mathematical model is written, it is thought that the heat transfer mechanism is realized as follows: Air mass, moving at a specific temperature under a certain pressure has thermal (internal) and kinetic energies. Thermal and kinetic energies are absorbed from the inner surface through the interstices between the yarns by the bulk fluid movement into the bobbin and enter the bobbin volume through spaces between the yarns. Energy can also pass through surfaces by molecular processes. This can happen in two ways: Conduction and mass diffusivity. However, during the passage of the fluid through the material, work is done by pressure and friction forces. Hot air passing through spaces between yarns, collides with yarns and water molecules and transfers some of the energy to them. During the movement, by taking up the evaporating water molecules, the increasing amount of moisture continues to move towards the outer surface while warmed water molecules also undergo forced diffusion [8]. As a result, the mathematical model is expressed as follows:

$$C_{ve}\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(k_e r\frac{\partial T}{\partial r}\right) + P_e(r,T)\frac{\partial T}{\partial r} \tag{1}$$

where: t, T, r, C_{ve}, k_e are respectively: time, temperature, radial coordinate, effective volumetric heat capacity and effective thermal conductivity. $P_e(r, T)$ is the function of temperature and coordinate and can be expressed as:

$$P_e(r,T) = \left(c_{ph}\rho_h + c_{pb}\rho_b\right)V_a \tag{2}$$

where c_{ph}, c_{pb}, ρ_h, ρ_b, and V_a are the specific heat capacity of the dry air and water vapour, density of the dry air and water vapour, velocity of the fluid in the porous body, i.e., in the yarn bobbin respectively. The mathematical model that expresses the physical process is in the form of Eq. (1). The direct problem is solved by the finite difference method in the initial and boundary conditions as follows:

$$r_{in} < r < r_{out}; \quad 0 < \tau < \tau_m$$
$$T(r,0) = T_i; \quad T(r_{in}) = f_1(\tau); \quad T(r_{out}) = f_2(\tau)$$

3. Results and discussion

Firstly, six different situations (Case 1, 2, 3, 4, 5 and 6) have been considered to examine the effect of time and space step on study. First, the model is solved by determining constant time and constant space steps. The time step was chosen as τ=300 s and the space step h=0.00950 m (Case 1). First, to examine the effect of the space step, the space step is reduced to half value at all points and then the model is solved (Case 2). Afterwards, for the effect of the time step, the time step has been reduced to half its value throughout the entire process (Case 3). Finally, the model is solved in various time and space steps to study the combined effect of these two parameters (Case 4, 5, 6). The test duration is 12900 s for all cases.

Table 1. The time and space step values considered in the study for cases 1, 2 and 3.

Case	Time step τ, (s)	Space step h, (m)
1	300	0.00950
2	300	0.00475
3	150	0.00950

Table 2. The time and space step values considered in this study for different time and space step ranges in Case 4.

Time step τ, (s)	Space step h, (m)
100 (between 0-200 s)	0.00475 (between r=0.033-0.0425 m)
200 (between 200-600 s) 300 (between 600-12900 s)	0.00950 (between r=0.0425-0.090 m)

Table 3. The time and space step values considered in this study for different time and space step ranges in Case 5.

Time step τ, (s)	Space step h, (m)
100 (between 0-200 s)	0.00475 (between r=0.033-0.052 m)
200 (between 200-600 s) 300 (between 600-12900 s)	0.00950 (between r=0.052-0.090 m)

Table 4. The time and space step values considered in this study for different time and space step ranges in Case 6.

Time step τ, (s)	Space step h, (m)
100 (between 0-200 s)	0.00475 (between r=0.033-0.052 m)
200 (between 200-600 s) 300 (between 600-4200 s) 100 (between 4200-4500 s) 300 (between 4500-5700 s)	0.00950 (between r=0.052-0.090 m)

100 (between 5700-7200 s)
300 (between 7200-12900 s)

The examined cases are given in Tables 1-4. The convective term P_e, which includes the convection effect of the air, is the function of the temperature. After determining P_e values, three different temperature regions are considered. These regions are as follows: Before evaporation, evaporation, and after evaporation. The P_e values used in this study were taken as 130 W/m^{2}K before the evaporation region and as 66W/m^{2}K in the evaporation region and as 503 W/m^{2}K after the evaporation region. In addition, the effective volumetric heat capacity (C_{ve}) including phase conversion factor and the effective thermal conductivity (k_e) including both mass transport and thermal conductivity are shown in Figure 23. These two thermophysical properties were taken from [1].

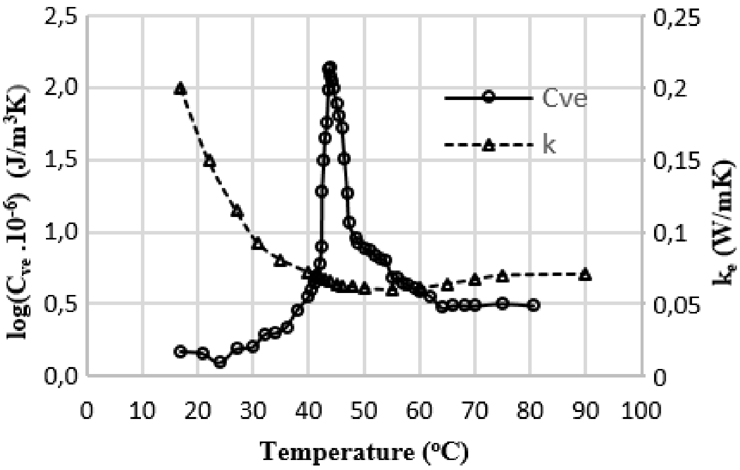

Figure 2. Variation of the effective volumetric heat capacity and the effective thermal conductivity with temperature for wool yarn bobbins (Akyol, 2007).

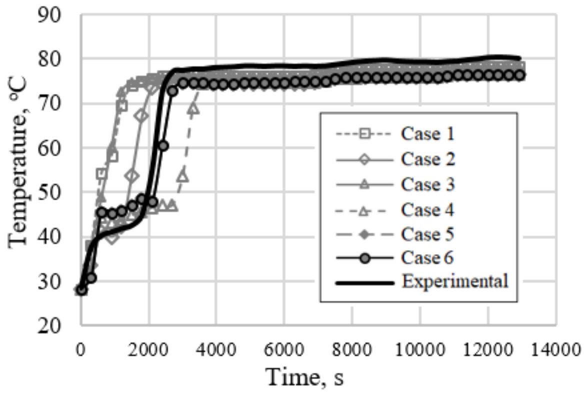

Figure 3. Comparison of experimental results (80°C) and model results (Case 1-6) for temperature measurement point r_2 = 0.0425 m

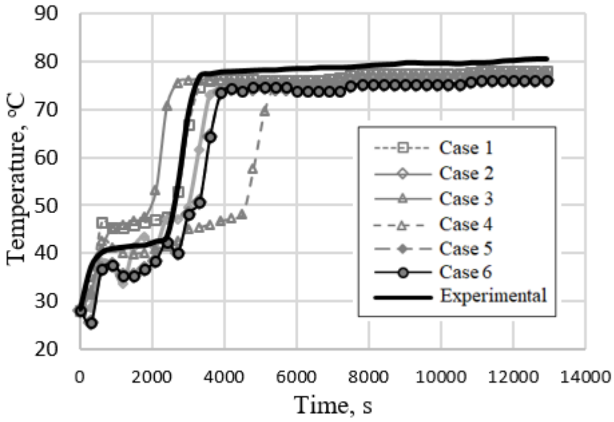

Figure 4. Comparison of experimental results (80°C) and model results (Case 1-6) for temperature measurement point r_3 = 0.0520 m

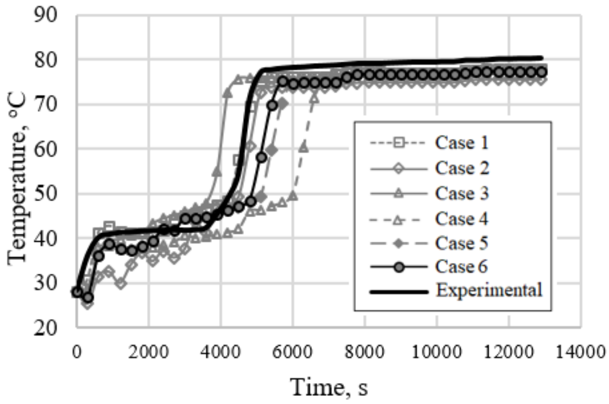

Figure 5. Comparison of experimental results (80°C) and model results (Case 1-6) for temperature measurement point r_4 = 0.0615 m

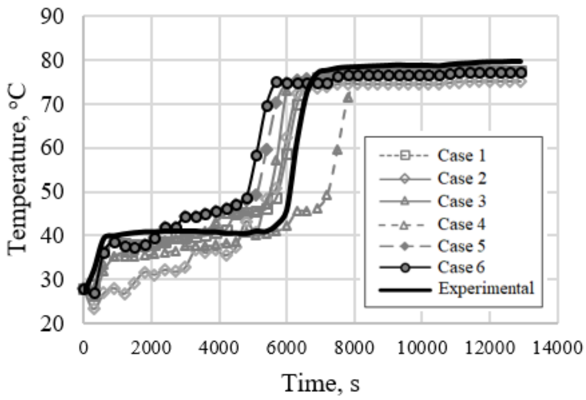

Figure 6. Comparison of experimental results (80°C) and model results (Case 1-6) for temperature measurement point r_5 = 0.0710 m

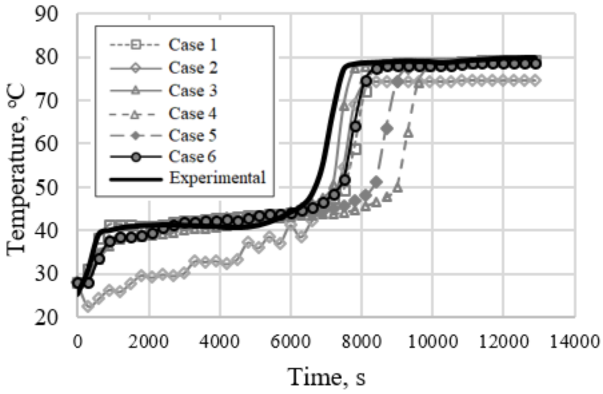

Figure 7. Comparison of experimental results (80°C) and model results (Case 1-6) for temperature measurement point r_6 = 0.0805 m

Figure 3-7 shows the comparison of six various cases (Case 1-6) for different temperature measurement points inside the bobbin with the experimental results. For all cases the inlet air temperature (T=80°C) and the pressure of the drying air (P=1 bar) are constant. When these graphs are examined, it is seen that the case, which provides the best fit with the test results is Case 6. The model results show that it is not a good way to select the time steps at small values throughout the entire process. When the temperature field is examined, it is seen that the biggest faults are near the inner surface where the temperature changes sharply at the beginning of the process and at the inlet and outlet regions to the evaporation temperatures. Case 4, Case 5 and Case 6 (different values of h and τ) were solved by the finite difference method and the results were compared with the experimental results to minimize the errors caused by the numerical solution method. The best result was obtained for Case 6. Therefore, considering the effect of space and time steps in the study, the drying time is estimated for the drying air inlet temperatures of 90°C and 100°C by using the conditions in Case 6 by the help of the mathematical model.

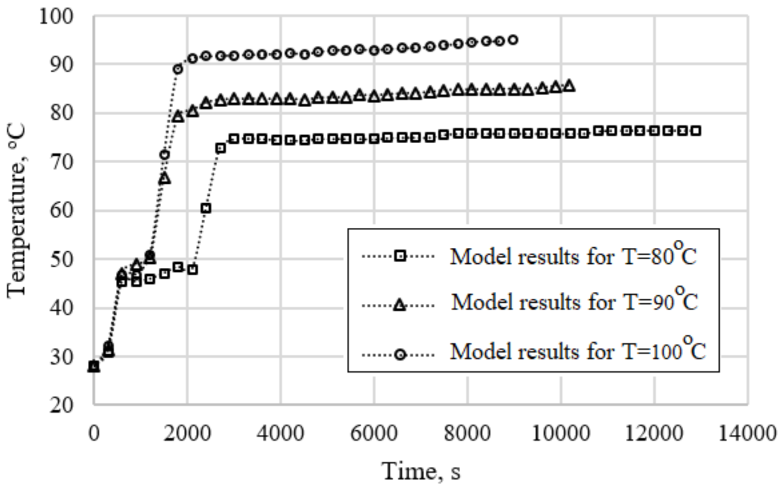

Figure 8. Comparison of model results (T=80°C, 90°C and 100°C) for temperature measurement point at r_2 = 0.0425 m

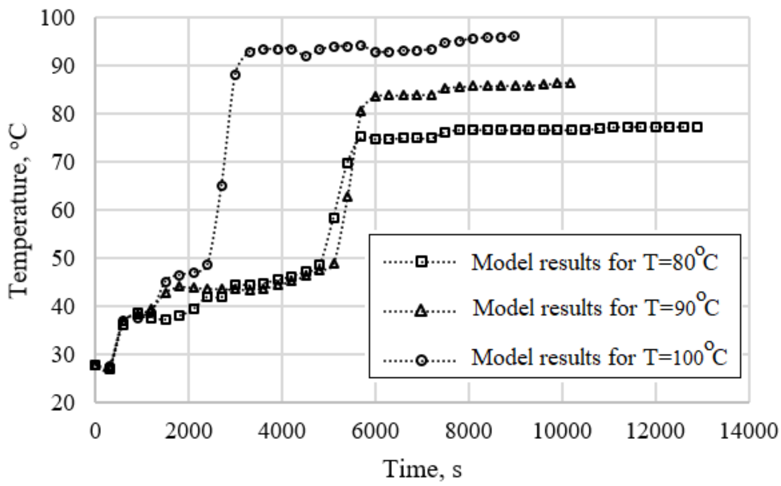

Figure 9. Comparison of model results (T=80ºC, 90ºC and 100ºC) for temperature measurement point at r_4 = 0.0615 m.

Figure 8-10 show the variation of the temperature distribution versus time at three different temperature measurement points inside the yarn bobbin for three different inlet air temperatures. As shown in these figures, the yarn bobbin enters a period of phase transformation which takes place at an approximately constant temperature at which the evaporation takes place intensively after a period of warming. After a point in the yarn bobbin has completely dried, the temperature of this point begins to rise rapidly. The drying time of a specific point in the yarn bobbin can be determined from the mathematical model curves by taking this into account.

In Figure 8, when drying at 90ºC and 100ºC for the 2nd temperature measuring point (r_2 = 0.0425 m), these points appear to dry at almost the same time (1200 s). However, this period at 80ºC is 2100 s according to the model results. Similarly, when Figure 9 is examined for the 4th temperature measurement point (r_4 = 0.0615 m), the drying time of this point for 100 C is 2400 s, while for 80ºC and 90ºC it is approximately 5100 s. The model results for the temperature measurement point 6 (r_6 = 0.0805 m) are given in Figure 10. As seen from the figure, the drying time for 100ºC is approximately 3600 s, while drying time is approximately 6900 s for 90ºC and 7500 s for 80ºC.

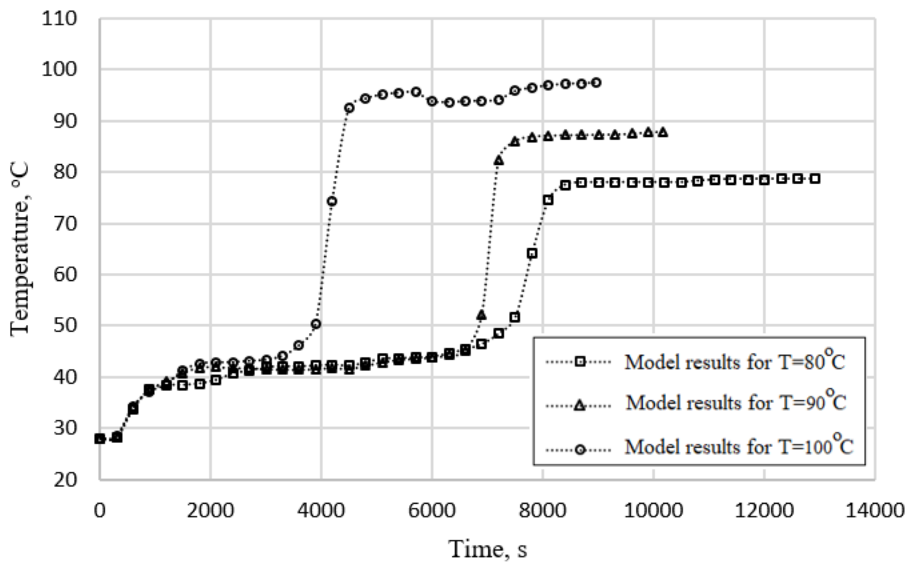

Figure 10. Comparison of model results (T=80ºC, 90ºC and 100ºC) for temperature measurement point at r_6 = 0.0805 m.

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4. Conclusions

As can be seen from the results, the drying times at temperatures of 80°C and 90°C are closer to each other at the temperature measurement points away from the internal points. In this case, according to the mathematical model results it can be said that drying the yarn bobbins at 80°C instead of 90°C may be more economical in terms of energy consumption. However, the drying process at 100°C temperature can be preferred by taking into account the energy consumed due to the shortness of the time.

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