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Sintering of compound nonwovens by forced convection of hot air

C. Staszel [a], S. Sett [a], A.L. Yarin [a,b,*], B. Pourdeyhimi [c]

[a] Department of Mechanical and Industrial Engineering, University of Illinois at Chicago, 842 W. Taylor St., Chicago, IL 60607-7022, United States
[b] School of Mechanical Eng., Korea University, Seoul 136-713, Republic of Korea
[c] 3427 The Nonwovens Institute, Box 8301, North Carolina State University, Raleigh, NC 27695-8301, United States

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ABSTRACT

Sintering and interlocking of model nonwoven materials composed of a mixture of polycaprolactone (PCL) and polyacrylonitrile (PAN) fibers by means of forced convection of hot air through their pores is studied experimentally and theoretically. PCL has a much lower melting point than PAN, and the air temperature was sufficiently high to melt the former, while the latter stayed solid. These molten PCL fibers became a binder and conglutinated the PAN matrix, enhancing stiffness. This was demonstrated by measuring the effect of heat treatment on the resulting Young's modulus of these compound nonwovens, as well as by the corresponding micro-morphological changes revealed by scanning electron microscopy. It was also shown that heating past the melting point of the binding fibers (PCL) would not further increase stiffness of the nonwovens, neither would heating for longer periods of times. A theoretical model describing the heating process was developed and tested experimentally. The model was verified using poly(ethylene terephthalate) PET nonwovens, which revealed good agreement of the data with the theoretical predictions.

1. Introduction

Thermally compressed porous nonwoven mats have become a popular alternative to bulk plastics in the automotive industry. The versatility of these nonwovens produced from low cost recycled fibers is an attractive feature in manufacturing stiff, lightweight porous mats for sound insulation and such load-carrying surfaces as the trunk bottom [1–2]. Thermally compressed nonwovens are also highly formable into complex contours and their cost-to-performance ratio makes them a viable alternative to bulk plastics [1–2].

Porous nonwoven mats containing a mixture of PET fibers and bi-component core–shell fibers with shell of low-melting temperature copolymer of PET and core of PET are used in some automotive applications. Such mixed nonwovens are heated by means of forced hot air convection through the pores. Namely, hot inlet air at constant temperature is pushed to filtrate through the sample at a constant velocity. This inlet air temperature is high enough to melt the lower melting point fibers and interlock the adjacent higher melting point fibers which stay solid [1]. The manufacturing of load-bearing functional fibrous mats is based on conglutination by means of molten low-melting temperature copolymer of PET shell of bi-component fibers. The melting temperature of this copolymer shell is 110 °C or 180 °C depending on the copolymer choice. It is known that the PET matrix fibers experience significant thermal [3–5] and hydrolytic [6–7] degradation at the processing temperatures of 280–300 °C [5]. Thermal degradation occurs due to macromolecular chain scission at the elevated processing temperatures starting at 270 °C [3], reducing the molecular weight of polymer [3,5]. In the case of hydrolytic degradation, moisture present during processing past the glass transition temperatures also induces macromolecular chain breakup [5–7] with a rate several orders higher than in the case of thermal degradation [6]. These forms of degradation have an abrupt adverse effect on stiffness and strength [8–12] and especially on the strength of thermally-bonded nonwovens [9–12]. Therefore, the working temperature range for successful conglutination of the matrix without deterioration of stiffness and strength of individual fibers should be slightly above the melting temperature of the binder shell, either 110 °C or 180 °C (depending on the copolymer used in the shell), while the detrimental overheating should be avoided by a proper temperature control.

The inlet air temperature is important in the case of creating load-bearing fibrous surfaces. In the processes used by the industry, nonwovens are primarily heated under the conditions of a fixed hot inlet air temperature. Prior work by the other research groups has

* Corresponding author at: Department of Mechanical and Industrial Engineering, University of Illinois at Chicago, 842 W. Taylor St., Chicago, IL 60607-7022, United States
E-mail address: ayarin@uic.edu (A.L. Yarin).

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Nomenclature

$c_{p,g}$	specific heat capacity of gas flowing through the nonwoven
$c_{p,s}$	specific heat capacity of nonwoven material (porous medium)
k_g	thermal conductivity of gas
k_s	thermal conductivity of porous medium
L	longitudinal thickness of the porous medium
Pe_{eff}	effective Peclet number, Eq. (13)
t	time
$T(x,t)$	temperature distribution in porous medium
U_g	inlet gas velocity
x	longitudinal coordinate

Greek symbols

α	effective thermal diffusivity of porous medium and gas, Eq. (4)
α_s	thermal diffusivity of porous medium
λ_n	eigenvalues, Eq. (12)
ρ_g	density of gas flowing through nonwoven
ρ_s	density of nonwoven material (porous medium)
σ	related to the specific heat capacities of porous medium and gas, Eq. (3)

been related to heat transfer through porous media, with forced air convection parallel to the porous medium surface [13–21]. Some of these works focused solely on convective heat transfer [13–14], whereas others have also taken into account thermal diffusion under different boundary conditions [16–19]. In addition to these works, analytical solutions of the convection–diffusion equations for species migration have been explored [22]. Although model [22] offers a solution to non-steady state diffusion-convection, albeit under different boundary conditions, it does not account for the effect of porosity. Note also research works devoted to convection–diffusion effect in infinite porous media with a planar heat source [19], and heat transfer through a melting porous medium [21]. In addition, forced air convective heat transfer in non-Darcian filtration flow has been explored [16,17]. In one of these studies, empirical relationships were used to describe non-Darcian effects along with volume averaging techniques to numerically predict two-dimensional heat transfer in porous medium [16]. Notably, much theoretical work has been aimed at forced air convection in porous medium heated by planar heat sources [17–19]. In those cases, constant heat fluxes are introduced along the inlet face or lengths of the samples. Here, we deal with the forced convection normal to the porous medium surface, with the flow going through the sample at constant inlet temperature. This situation did not attract much attention in the past, as to our knowledge. The present model is relevant for the situation studied experimentally in the present work, as well as is closely linked to the industrial context related to creation of load-bearing fibrous surfaces.

The present work aims at forced filtration of hot air through a compound porous matrix, with one material having a low melting temperature, making it a molten binder. In this process, it is important to understand the transient thermal history inside a nonwoven mat due to heating with a constant inlet air temperature. Theoretical model of the thermal process is proposed and compared to the experimental data of the present work.

2. Experimental

2.1. Materials

Two separate experiments were conducted to elucidate the effect of forced hot air convection on the internal structure of polymer nonwoven mats. In the first type of experiments, model PET nonwoven mats of thickness 1.5 cm were heated by forced convection of hot air through them in a setup described in subsection 2.3. These samples were cut as cylinders of the 1.5 cm thickness and diameter 1.7 cm, i.e. these samples were thick, which was useful for measuring temperature inside them and distinguishing it from that of the oncoming hot air flux. The material properties of PET and air are available in [23] and [24], respectively, and the relevant values are listed in Table 1.

Table 1
Physical properties of the gas and nonwoven material used in the experiments.

Gas (air) at 350 °C		Solid skeleton of the nonwoven (PET)	
$c_{p,g}$ [kJ kg^{-1} K^{-1}]	1.009	$c_{p,s}$ [kJ kg^{-1} K^{-1}]	1.040
k_g [W m^{-1} K^{-1}]	0.0314	k_s [W m^{-1} K^{-1}]	0.375
ρ_g [kg m^{-3}]	1	ρ_s [kg m^{-3}]	1385

The average porosity ϕ of the nonwoven mat was measured experimentally. A scanning electron microscope (SEM), Hitachi S-3000 N, was used to image the upper layer on nonwoven facing the flow and then a MATLAB code was used to process the data from the SEM images and determine the porosity of nonwoven mats. Before imaging, samples were sputter coated with 7.5 nm of platinum–palladium and several SEM images of this kind and their processing are shown in Fig. 1.

The original SEM images were converted to black and white in such a way that fibers at the surface are seen alone on the white background as in Figs. 1(b1) and (b2). A MATLAB code was used to calculate the porosity of each sample as follows. The number of white pixels in each image was counted and divided by the total number of pixels in that image (using the processed SEM images). Ten SEM images were taken and processed using this method resulting in the average porosity of $\phi = 0.60$.

In the experiments of the second type, the effect of forced hot air convection on nonwoven mats containing a mixture of polycaprolactone (PCL) and polyacrylonitrile (PAN) electrospun nanofibers was elucidated. These porous nonwoven mats are denoted as PCL–PAN mats. The melting point of PCL is 56–65 °C [25] and that of PAN is 319 °C [23]. The reason for choosing nonwovens different from PET used in the first type of experiments was due to the need to reach the melting point of the binding polymer. Since electrical heating of air was used, it was impossible to reach the melting point of PET, which is 250–265 °C [23]. On the other hand, using PCL, it was possible to heat up the PCL–PAN nonwoven to temperatures high enough for melting PCL nanofibers and conglutinating by them the PAN nonwoven. Such conglutination is of interest to improve the mechanical properties of nonwovens and is reminiscent of the processes used by the automotive industry.

2.2. Electrospinning setup

Electrospinning used to form PCL–PAN nonwoven mats employed a modified setup ramifying from the one described in [26]. In brief, two needles were placed horizontally on the opposite sides of a 35 cm rotating drum (cf. Fig. 2). The needles were attached to a positive DC high voltage source, whereas the drum was grounded. A solution of 15 wt% PCL ($M_w = 80$ kDa) dissolved in a 1:1 ratio (by weight) mixture of dimethylformamide (DMF)