

Modelling of the Through-air Bonding Process

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ABSTRACT

A computational fluid dynamics (CFD) modelling of the through-air bonding process of nonwoven fabric production is reported in this article. In the through-air process, hot air is passed through the fibrous web to heat and melt polymer fibers. Molten polymer subsequently flows to the point of contact between any two fibers to produce a bond. Two different modelling strategies are adapted to produce a comprehensive understanding of the through-air bonding process. In macroscale modelling, a CFD model is developed treating the whole web as a porous media in order to investigate the effect of process parameters. Results reveal that the time required to heat and melt the fibers decreases with the increasing porosity of the web and the velocity of hot air. The CFD modelling technique is then used to analyze the bonding process at a more fundamental level by considering the bonding of individual fibers at microscale. The effects of the fiber diameter, bonding temperature and contact angle between two fibers on the bonding time are investigated. Results show that the time required to bond fibers is weakly related to bonding temperature and fiber diameter. Fiber orientation angle, on the other hand, has significant effect on the progression of bond formation.

INTRODUCTION

The Computational Fluid Dynamics (CFD) technique has become a major tool for the design and development of many engineering systems involving fluid flow and heat transfer. It has been extensively used in the field of aerospace, automotive, biomedical, chemical and many other industrial applications. Its use in textile research and development is however not very common. There are only very few examples of such computational modelling in textile research and development. Gong et al. [1] developed an experimental process for producing through-air bonded three dimensional nonwoven web by applying the CFD technique. Gong et al. [2] in a subsequent article investigated the

distribution of velocity, pressure and temperature inside the bonding chamber and optimized the design. Tafreshi and Pourdeyhimi [3] and Tafreshi et al. [4] investigated the flow dynamics inside hydro-entangling nozzles using CFD modelling. More recently, Hossain et al. [5, 6] reported a CFD model of the airflow and heat transfer through fibrous webs as well as a simulation of the fiber bonding process. These examples alone show that the CFD method can play a vital role in analyzing and improving the nonwoven manufacturing processes.

Manufacturing of nonwoven fabric begins by laying fibers to form a web. The through-air bonding process, involves passing hot air through an unbonded web to heat and melt the polymer fibers. To create a bond of sufficient strength, the web is kept at an elevated temperature for certain amount of time, known as the dwell time. Then, the molten polymer, aided by the reduced viscosity at high temperatures, flows to the contact point of fibers by the surface tension force. Most through-air bonded webs consist of bicomponent sheath-core type polymer fibers, while the core material with a higher melting point provides the structural integrity to the web whereas the sheath polymer with a lower melting point enables the bonding of the fibers together at the point of contact.

Literature survey reveals that the published work on the through-air bonding process is mostly concerned with the experimental study investigating the effects of process parameters on the properties of the nonwoven. Randall [7] reported an experimental study of the effects of process variables such as air temperature, air velocity, dwell time, restraining and carrying mesh size on the mechanical properties of the through-air bonded nonwovens. Randall [8] also studied the effects of binder type, binder fiber content, web basis-weight on the product properties. Kim et al. [9] investigated experimentally the formation of bond and the bonding time for different fiber diameters between two fibers laying orthogonal

to each other. Kim et al. [10] in a follow up article investigated the bond formation and development between two fibers by using a simple computational model and predicted the characteristics shape. However, it failed to predict the bonding time relationship with the fiber diameters as observed in the experiments.

In the present study, the fundamental mechanism of bond formation during the through-air bonding process has been investigated in greater detail using the computational fluid dynamics technique. First a macroscale model is developed in which the web as a whole is modelled as a porous media. Then, a microscale model is developed to study the bond formation between two contacting fibers.

MATHEMATICAL MODEL

Macroscale Model

A macroscopic formulation based on volume averaging is used in the present study. The averaged mass and momentum equations for a single domain based model are given by Beckerman [11]:

Continuity:

$$\frac{\partial(\phi \rho_a)}{\partial t} + \nabla \cdot (\rho_a \mathbf{u}) = 0 \quad (1)$$

Momentum:

$$\rho_a \frac{\partial(\phi \mathbf{u})}{\partial t} + \rho_a (\phi \mathbf{u} \cdot \nabla) \mathbf{u} = -\phi \nabla P + \mu \nabla^2(\phi \mathbf{u}) - \frac{\mu}{k} \mathbf{u} \quad (2)$$

The last term in the momentum equation is due to Darcy's term representing the resistance caused by the fibrous web. The value of permeability k is calculated from a model given by Mao and Russell [12, 13].

The averaged energy equation for air and the porous matrix can be written as

$$\bar{\rho} c \frac{\partial T}{\partial t} + \rho_a c_a \nabla \cdot (\bar{u} T) = \nabla \cdot (k_{\text{eff}} \nabla T) - (1-\phi) \rho_l \Delta h \frac{\partial \gamma}{\partial t} \quad (3)$$

The mean thermal capacitance of the mixture, $\bar{\rho} c$, is defined as,

$$\bar{\rho} c = \phi \rho_a c_a + (1-\phi) [\varepsilon (\gamma \rho_1 c_1 + (1-\gamma) \rho_s c_s) + (1-\varepsilon) \rho_c c_c] \quad (4)$$

The effective thermal conductivity is given as a volumetric average,

$$k_{\text{eff}} = \phi k_a + (1-\phi) [\varepsilon (\gamma k_1 + (1-\gamma) k_s) + (1-\varepsilon) k_c] \quad (5)$$

In addition, the relationship describing melt fraction γ as a function of temperature is given by,

$$\gamma = \begin{cases} 1 & \text{if } T > T_m + \Delta T \\ 0 & \text{if } T < T_m - \Delta T \\ \frac{T - T_m + \Delta T}{2\Delta T} & \text{if } T_m - \Delta T < T < T_m + \Delta T \end{cases} \quad (6)$$

The FLUENT CFD software was used for the solution of the governing continuity and momentum and energy equations.

Microscale modeling

In microscale modeling, two-phase Volume of Fluid (VOF) method is used for the modelling of the air and molten polymer flows. In the VOF method, a single set of momentum equations is shared by phases (here, air and polymer) and volume fraction of each phase is tracked through the computational domain. Molten polymer flows to the contact point because of the surface tension force. Therefore, the momentum equation contains a source term representing the surface tension force. The governing equations for the VOF model are given below:

Continuity:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{u}) = 0 \quad (7)$$

Momentum:

$$\frac{\partial(\rho \bar{u})}{\partial t} + \nabla \cdot (\rho \bar{u} \bar{u}) = -\nabla P + \nabla \cdot (\mu (\nabla \bar{u} + \nabla \bar{u}^T)) + S + F \quad (8)$$

Initially, the fibers are in solid state and obviously the velocity is zero. When the fibers are melted by heat transfer from the flowing hot air, the molten polymer starts to flow. The term S in equation (8) works as a momentum sink to ensure that the fiber velocities in the initial cold state and then in the molten hot state are correctly represented. The surface tension force in equation (8) is represented by F . The force at the surface is expressed as a volume force and is added to the momentum equation as a source term.

Volume fraction equation:

To track the interface between phases a volume fraction continuity equation for the secondary phase (fiber) is solved along with the above equations:

$$\frac{\partial \alpha_q}{\partial t} + \vec{u} \cdot \nabla \alpha_q = 0 \quad (9)$$

where subscript q represents each phase component
Air volume fraction is obtained from the relation

$$\sum_{q=1}^2 \alpha_q = 1.$$

The properties appearing in the transport equations are determined by the presence of the component phases in each control volume. For example, the density is considered to be:

$$\rho = \sum_{q=1}^2 \alpha_q \rho_q \quad (10)$$

RESULTS AND DISCUSSION

Macroscale analysis of through-air bonding

A schematic drawing of a through-air bonding system is shown in *Figure 1*. A nonwoven web is wrapped around a perforated rotating drum, through which the hot air passes radially. To simplify the development of the model, the CFD calculation was carried out on a 60° sector of the drum.

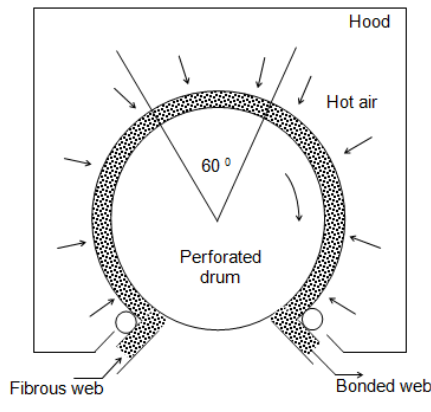


FIGURE 1. A Schematic Drawing of the Through-Air Bonding Process

The computational domain is divided into computational mesh with an average grid size of 1 mm in both the radial and circumferential directions. A uniform inlet velocity and temperature is specified at the inlet boundary. Pressure boundary condition is used at the outlet boundary. The inlet temperature is kept fixed at 140° C. The transient solution is

obtained with a fixed time step of one microsecond [5].

The web is assumed to be made of sheath-core type bi-component fibers of polyethylene (PE) sheath and polypropylene (PP) core with 68 mm web thickness. This is a high loft web which represents an extreme thickness. The calculations are carried out for the air inlet velocity of 1.5, 2.0, 2.25, 2.5 and 3.0 m/s and the web porosity of 0.5, 0.7 and 0.9.

Figure 2(a) gives the simulation results of the temperature distribution inside the web and *Figure 2(b)* shows the corresponding distribution of the melt fraction of fibers. The predicted results are for the porosity 0.9 and air velocity 1.5 m/s. The hot air transfers heat to the web as it flows through it. The fiber temperature rapidly increases to the melting point of sheath polyethylene fiber and the fiber starts to melt. The simulation result shows that it takes approximately 6.6 seconds to heat and melt fibers throughout the web thickness and to reach a steady state condition.

Hossain et al. [5] showed that the time required to melt the fibers through the thickness of the web shows a diminishing linear relationship with the web porosity. This relationship is quite realistic as the increased porosity of the web implies that there is less volume of fibers within the same volume of web to be heated and melted. The volume of the hot air flowing through the web increases with the increasing air velocity which in turn leads to higher convective heat transfer rates to the web consequently resulting in a reduced heating and melting time.

Although, the macroscopic model is very useful in providing information related to the heating and melting time, this model can not provide information regarding the actual bond formation process. A microscale model, which considers the bonding process of individual fibers, is reported in the next section. A detailed account of the micro level modelling can be found in Hossain et al. [6].

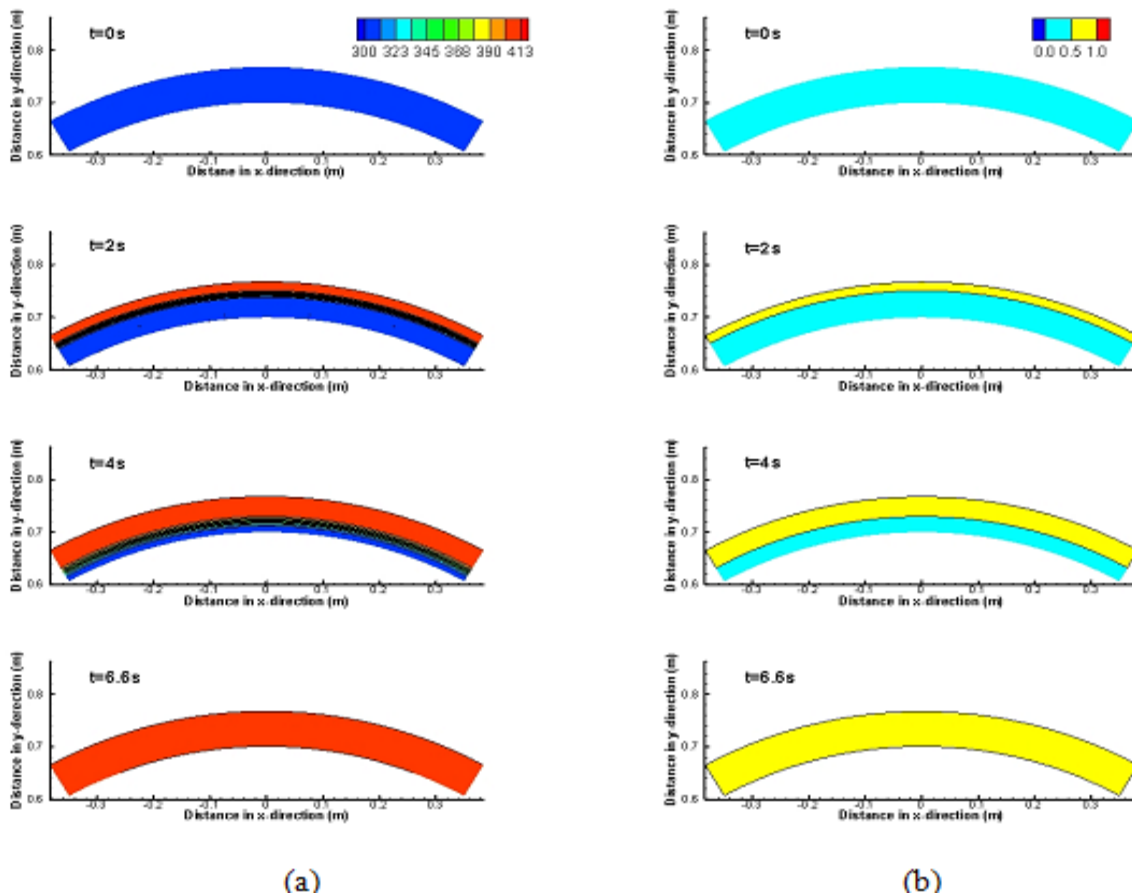


FIGURE 2. (a) Contour plot of temperature of web at different time steps (b) corresponding contour plot of the melt fraction of fibers for a porosity of 0.9 and air velocity of 1.5 m/s.

Microscale analysis of through-air bonding

Stochastic nature of fiber distribution in a web makes it very complicated and resource intensive to generate a realistic computational model for a web specimen. Instead, the formation of a single bond between two fibers is investigated in the present study. In the first instance, bonding of two fibers at a contact angle of 90° , as shown in *Figure 3*, is studied at a bonding temperature of 140°C . Then the effects of the air temperature and the fiber diameter are investigated. Finally, the effect of contact angle between two fibers is investigated.

The development of bond formation between two polyethylene sheath/polypropylene core bi-component fibers is shown in *Figure 4* as a function of time. The molten polyethylene flows to the intersection of two fibers to form a bond. The flow of molten polymer is mainly driven by the surface tension force. In the initial stages of the bond formation, molten polyethylene flows

circumferentially to the contact point. As the bond formation progresses, the molten polyethylene begins to flow along the fiber axis towards the intersection, which then continues to flow to the contact point. This causes a reduction in the fiber diameter in the vicinity of the intersection.

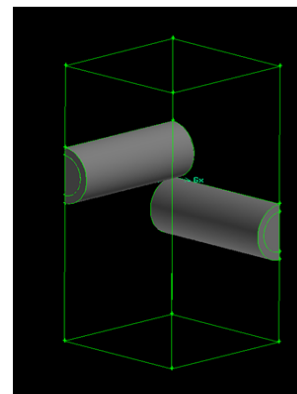


FIGURE 3. Computational domain showing two fibers at 90° contact angle

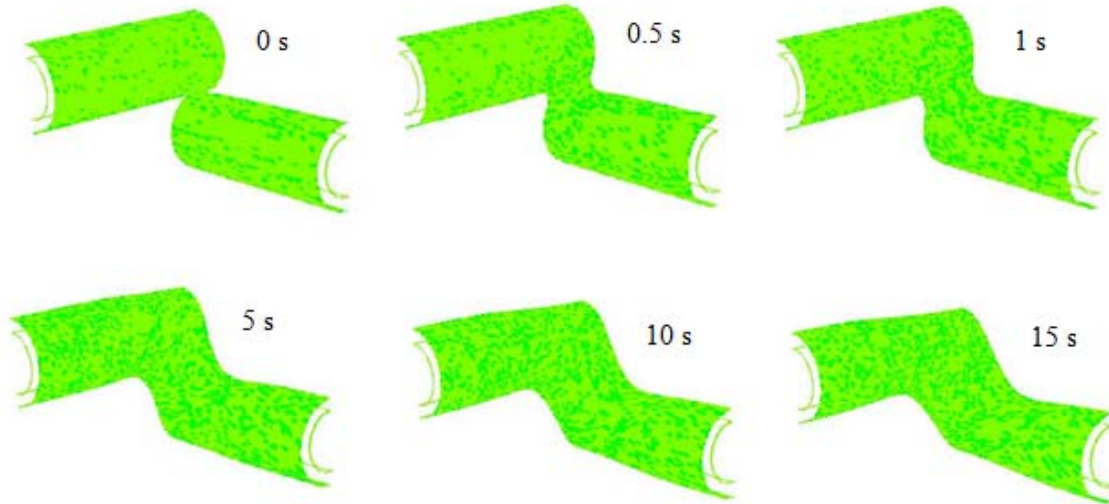


FIGURE 4. Computed shape of bond at different times for the bonding temperature of 140°C.

In order to quantify the progress of bonding, a dimensionless characteristic bond size is proposed as the ratio of the area of the section of the bond on a plane parallel to the axes of the fibers through their contact point to the cross-sectional area of the fibers. This characteristic bond size provides a quantitative comparison of the bonding. Bonding proceeds at a faster rate at the initial stages. This is because the molten polymer flows rapidly to fill up the narrow gap at the contact point of two fibers driven by the high surface tension force. As the bond grows filling the gap at the contact point between the two fibers, the surface curvature increases, consequently reducing the surface tension, which in turn slows down the rate of the bond development.

Comparison of the bond size development with time shows that the air temperature in the range of [130-150°C] and fiber diameter in the range of [15.1-30.3μ] made very little effect on the bonding process. Bonding appears to proceed at a slightly faster rate at higher temperatures. Surface tension force and viscosity are the two most important parameters that control the flow of the molten polymer. When the bonding temperature increases, both viscosity and surface tension force decrease. Overall the reduction of viscosity at higher temperature over compensates the reduction in surface tension force. This results in a small increase of the bonding rate at higher temperatures. The effect of the fiber diameter on the bond size development shows a slight decrease with the increasing fiber diameter. This is in line with the experimental finding of Kim et al. [9].

Effect of the fiber contact angle

The effect of the angle between two fibers on the progression of bonding is also investigated. *Figure 5* shows the computational model involving two fibers with orientation angle of 10°, 20° and 30°. *Figures 6* and *7* show the progress of bonding for these contact angles at 1 and 5 seconds respectively. The characteristic bond size defined earlier has been used to compare the bond size for different fiber contact angles. *Figure 8* shows the development of the bond size with time for different contact angles. The effect of the contact angle on the progress of bond development is found to be significant.

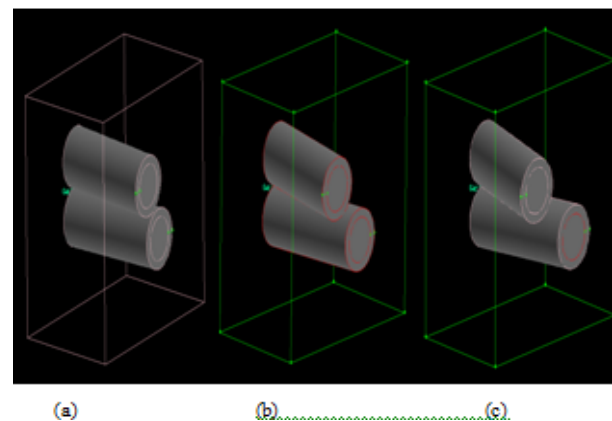


FIGURE 5. Computational domain showing fibers at contact angles of (a) 10° (b) 20° and (c) 30°

The overlap of the fibers at low fiber contact angles is much greater than the overlap at high contact angles. The bonding at smaller contact angles proceeds at a much faster rate because the low contact angle causes a greater amount of polymer to flow in the circumferential direction to the contact point due to the greater fiber overlap. This causes a rapid development of the bond size. As the

orientation angle increases this rate becomes slower. At high fiber orientation angles, the initial fiber to fiber overlap is small and therefore the bond needs to grow with polymer flow not only in the circumferential direction but also in the longitudinal direction which slows down the bond growth rate. These trends are observed in *Figure 8*.

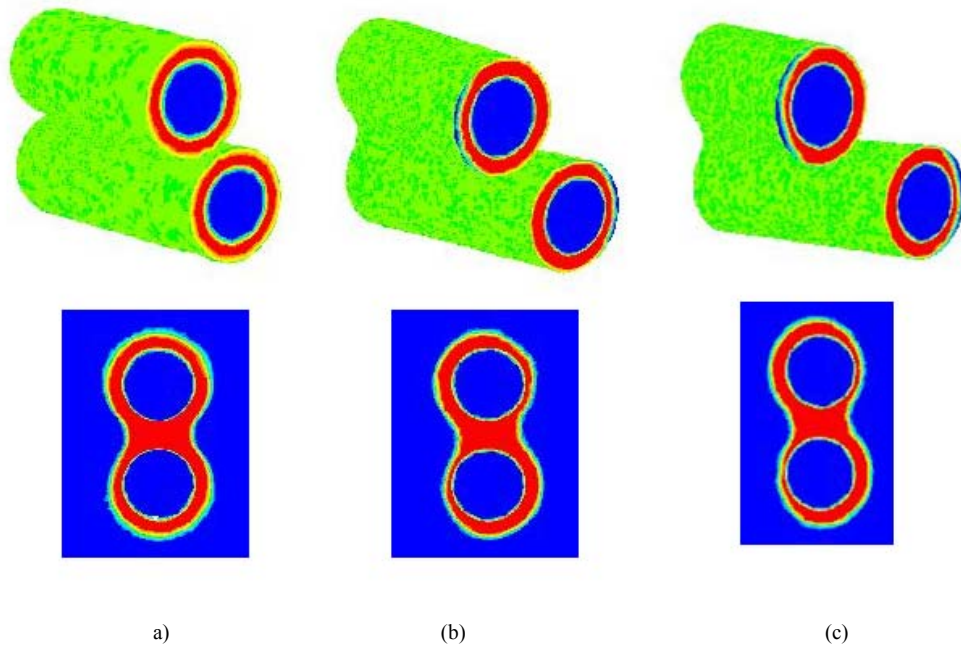


FIGURE 6. Progress of bonding after 1 second. The top row shows three-dimensional view and the bottom row shows cross-sectional view. (a) 10°, (b) 20° and (c) 30° contact angle.

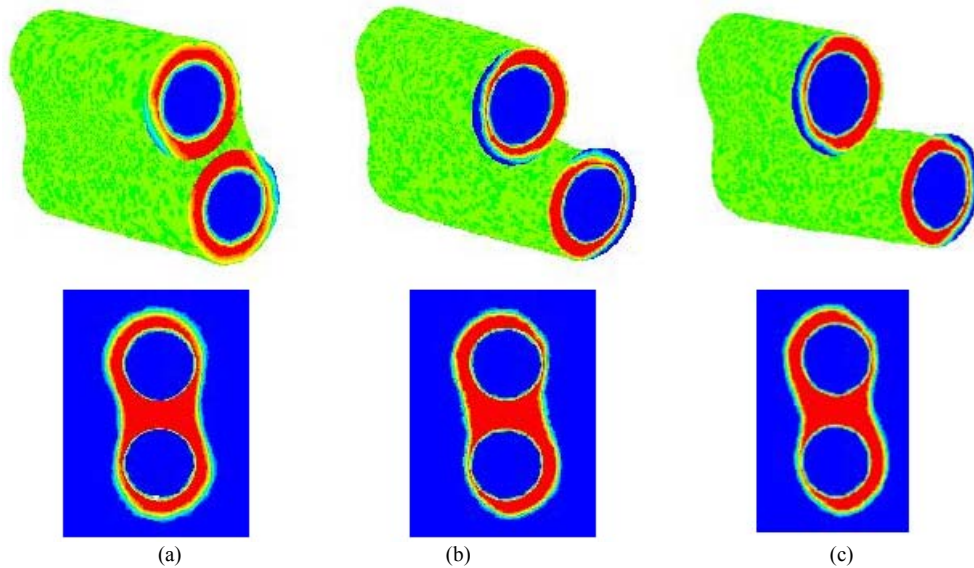


FIGURE 7. Progress of bonding after 5 seconds. The top row shows three-dimensional view and the bottom row shows cross-sectional view. (a) 10°, (b) 20° and (c) 30° contact angle.

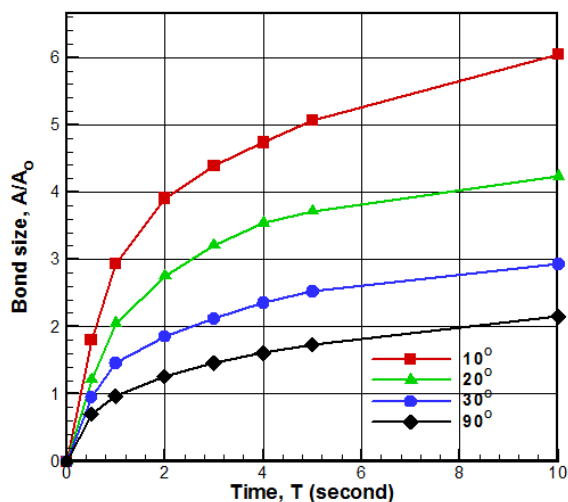


FIGURE 8. The effect of contact angle at different contact angles on the progression of bonding.

CONCLUSION

A computational fluid dynamics study of through-air bonding process of nonwoven fabrics has been presented in this article. The modelling strategy involves macroscale and microscale modelling to analyze the bonding process. In the macroscale modelling, the web has been treated as a porous media and the heating and melting time of fibers within a nonwoven web have been computed. The relevant operating parameters such as the effect of air velocity and web porosity on the melting time of the fibers have been studied. The computational model results indicate that the melting time decreases linearly with the increase of web porosity and decreases nonlinearly with the increase of air velocity. Although the macroscale model has provided useful information, it could not provide information regarding the bond formation process. Then, a microscale model has been developed to study the formation of bond between two fibers. In the first instant, the effect of bonding time on the progression of bond between two fibers at 90° contact angle has been studied. The characteristic bond size has been defined and used in analyzing the process. The computed results show that the formation of bond starts rapidly, but slows down gradually. The effects of temperature and fiber diameter on the growth of the bond have been shown to be small. However, the effect of orientation angle between the two fibers on the growth of bond has been observed to be significant. The rate of bonding decreased sharply with the increase of the fiber contact angle. This is attributed to the greater contact

area between the fibers at low fiber orientation angles.

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NOTATIONS

c	specific heat [J/kgK]
d_f	diameter of fiber [m]
E_a	activation energy [J/mole]
F	surface tension force [N/m ³]
h, H	enthalpy [J/kg]
k	permeability (m ²)
k_{eff}	effective thermal conductivity [W/m ² K]
P	pressure [N/m ²]
R	universal gas constant [J/kgK]
r	radius (m/s)
S	source or sink term [N/m ³]
S_h	source or sink term in the energy equation [W/m ³]
t	time [s]
T	temperature [K]
u	velocity [m/s]
x, y	co-ordinate location

Greek

α	volume fraction
β	fraction of melt of sheath fiber
γ	fraction of melt of sheath fiber

Δh	heat of melting [J/kg]
ε	volume fraction of sheath fiber in the bicomponent fiber
μ	viscosity [kg/ms]
ρ	density [kg/m ³]
ϕ	volume fraction of air (porosity)

Subscripts

a	air
c	core fiber
f	fiber
l	sheath fiber in liquid state
s	sheath fiber in solid state
eff	effective
m	melting

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