THERMO-CHEMICAL SIMULATION OF A COMPOSITE OFFSHORE VERTICAL AXIS WIND TURBINE BLADE

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Abstract

In the present study three dimensional steady state thermo-chemical simulation of a pultrusion process is investigated by using the finite element/nodal control volume (FE/NCV) technique. Pultrusion simulation of a composite having a C-shaped cross section is performed as a validation case. The obtained cure degree profiles for specific points match well with those in the literature. Following the validation case, the proposed numerical technique is applied to the modelling of the pultrusion of a composite blade which has a NACA0018 airfoil cross section. The effects of pulling speed and various set temperature schemes of heating platens on the quality of the composite NACA0018 blade are explored.

Keywords: Pultrusion, Curing, Computational simulation, Finite element analysis, Airfoil.

1. Introduction

A novel concept of a floating offshore vertical axis wind turbine (VAWT) technology based on the *Darrieus* design has conceptually been utilized in the DeepWind Project [1,2]. The main objective of the DeepWind is to develop more cost-effective MW-scale wind turbines through innovative technologies for the sea environment rather than advancing existing concepts (i.e. either horizontal axis wind turbine (HAWT) or VAWT) that are based on onshore technology. Hence increasing the simplicity of the design and the manufacturing techniques as well as reducing the total cost of an installed offshore wind farm is the main challenge of the project. The concept is aiming for the deep water and the large-scale wind turbines. The up-scaling potential of the project is 20 MW wind turbines. It is expected that the structural design can be improved to have higher strength-to-weight ratio for larger chord lengths, e.g. 10-20 m, with deep water offshore floating system (100-1000 m).

The blade cross section for the VAWT can be constant along the length of the blade. In order to manufacture such a composite blade with a constant profile having such a large chord, the pultrusion technology is one of the most efficient and suitable methods. Besides it is a continuous, automated closed-moulding process, it is also cost effective for high volume production of constant cross section parts. The schematic view of the pultrusion process can be seen in Fig. 1. Since it is a continuous process, there is little waste material being produced at the end of the process. It has been widely used for manufacturing highly strengthened and continuous composite structures, e.g. ballistic resistance panels, spars of ship hulls, thin wall panel joiners, door/window frames, driveshaft of vehicles, etc. Besides the potential in producing large blades in one piece which can be directly manufactured over a single block thus reducing production costs, the pultrusion of the whole blade in smaller pieces and then assembling them afterwards in the form of the Troposkien shape is also considered in the DeepWind project. As a consequence the blades may achieve very high stiffness and resistance against aerodynamic loads as well as vibrations. Another viewpoint of the DeepWind Project is that in principle, a production facility can be put on a ship, and the blades can be produced offshore in lengths of kilometres while using a short die length, e.g. 1 m.

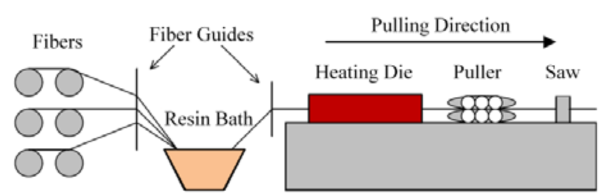


Figure 1. Schematic view of the pultrusion process. Fibers/mats and resin matrix are pulled together in the pultrusion direction by pullers through the heated die and then the cured composite is cut by a saw system.

In literature there have been several modelling studies specific to the pultrusion process. Generally, thermo-chemical analyses, flow simulations and optimization works have been performed by the use of numerical modelling techniques. In order to simulate the pultrusion process, material behaviour, transport phenomena, material properties and process models should be well defined. The material behaviour can be defined with the reaction kinetics and the chemorheology of the resin system. The transport phenomenon involves the heat (and mass) transfer and fluid flow during the pultrusion process. A complete description of the pultrusion process requires a deep understanding of resin flow, heat transfer, pressure, force (pulling, friction forces etc.) as well as residual stress phenomena via corresponding numerical models.

Transient and steady state temperature and cure degree profiles of the composite and the heating die systems during the pultrusion process have been simulated by using numerical techniques such as finite difference methods (FDM) and finite element methods (FEM) with control volume (CV) technique or nodal control volume (NCV) technique [3-16]. The effects of the resin shrinkage and temperature-dependent material properties on the temperature and the cure degree distributions have been discussed in [10, 11] by using the finite element/nodal control volume (FE/NCV) technique. In addition to the theoretical modelling of the pultrusion process for predicting the temperature, experimental studies related with the pultrusion of various composite profiles such as rods, plates, I-beams etc. have been carried out in [17-23]. Die and post die analyses were performed in [23] for temperature and cure degree profiles at the centerline of the composite material. The effects of convection after the die exit were taken into account in the numerical modelling of the post die analysis. The correct prediction of the post die curing and the temperature distribution has vital importance for the numerical simulation of the residual stress during the cooling of the composite (after the exit from the die).

In the DeepWind project, a numerical simulation tool embracing the pultrusion blade manufacturing process is in the process of being developed in order to investigate the effects of the process parameters on the efficiency of the manufacturing process as well as the quality of the pultruded composite VAWT blades/components. The present paper in particular deals with the thermo-chemical modelling of pultrusion of a carbon-fiber/Epon 9420/9470/537 epoxy composite VAWT blade with constant NACA0018 airfoil cross section. A three-dimensional steady state FE/NCV simulation of a C-shaped cross section is initially performed by using ANSYS as a validation case. Following the validation case, a similar modelling strategy has been applied for the NACA0018 airfoil. Since this profile has symmetry along the centerline of the chord, only the half of the airfoil geometry is used for the FE/NCV calculation to reduce the calculation time. Steady-state heat transfer and exothermic reaction (only for the blade) simulations of the die and the blade are performed by using the commercial FE software ANSYS. Steady-state temperature and cure degree profiles of the blade are obtained after performing sequential iterations satisfying convergence. In addition to that the effects of pulling speed and various temperature schemes of the heating platens on the quality of the composite NACA0018 blade are explored.

2. Governing Equations

2.1. Energy Equations

The steady state heat transfer equations in a Cartesian coordinate system for the composite part (Eq. 1) and the die block (Eq. 2) can be written as

$$\rho_c Cp_c \left(u \frac{\partial T}{\partial x} \right) = k_{x,c} \frac{\partial^2 T}{\partial x^2} + k_{y,c} \frac{\partial^2 T}{\partial y^2} + k_{z,c} \frac{\partial^2 T}{\partial z^2} + q \qquad (1)$$

$$0 = k_{x,d} \frac{\partial^2 T}{\partial x^2} + k_{y,d} \frac{\partial^2 T}{\partial y^2} + k_{z,d} \frac{\partial^2 T}{\partial z^2} \qquad (2)$$

where T is temperature, u is the pulling speed, ρ and Cp are the density and the specific heat respectively, k_x, k_y, and k_z thermal conductivities in axial (x), transverse-width (y) and transverse-height (z) direction, respectively. The subscriptions c and d correspond to composite and die respectively. All the material properties used in the simulation are assumed to be constant. The internal heat generation (q) [W/m^3] due to the exothermic reaction of epoxy resin is expressed as

$$q = (1 - V_f)\rho_r Q \qquad (3)$$

where V_f is the fiber volume ratio and Q is the specific heat generation rate [W/kg] due to resin exothermic cure reaction.

2.2. Resin Kinetics

Resin kinetics is an important phenomenon which is related with the exothermic chemical reaction of the resin inside the die. The degree of cure (α) can be written as the ratio of the amount of heat generated ($H(t)$) during curing, to the total heat of reaction H_{tr}:

$$\alpha = \frac{H(t)}{H_{tr}} \qquad (4)$$

The rate of resin reaction, $R(\alpha)$, can be expressed as

$$R_r(\alpha) = \frac{d\alpha}{dt} = \frac{1}{H_{tr}}\frac{dH(t)}{dt} = K_0 \exp(-\frac{E}{RT})(1-\alpha)^n \quad (5)$$

where K_0 is a pre-exponential constant, E is the activation energy, H_{tr} is the total heat of reaction, R is the universal gas constant and n is the order of reaction (kinetic exponent). H_{tr}, K_0, E and n are experimentally evaluated using differential scanning calorimetry (DSC) [13]. The specific heat generation rate, Q (in Eq. 3), is then calculated as [13]

$$Q = H_{tr} R_r(\alpha) \quad (6)$$

By using the *chain rule* the rate of cure degree can be expressed as,

$$\frac{d\alpha}{dt} = \frac{\partial\alpha}{\partial t} + \frac{\partial\alpha}{\partial x}\frac{dx}{dt} = \frac{\partial\alpha}{\partial t} + u\frac{\partial\alpha}{\partial x} \quad (7)$$

$$\frac{\partial\alpha}{\partial t} = R_r(\alpha) - u\frac{\partial\alpha}{\partial x} \quad (8)$$

Since a steady state numerical approach is utilized in this study, $\partial\alpha/\partial t$ is taken as 0.

3. Numerical Implementation

The FE/NCV method [13] is implemented for the pultrusion model of the composite part by using ANSYS parametric design language (APDL). The representation of the FE/NCV can be seen in Fig. 2. CVs are defined at the nodes of each finite element. The degree of cure is solved explicitly for these CVs. The internal heat generation inside the composite is highly nonlinear i.e. it depends on the rate of resin reaction in the energy equation of the composite (Eq. 1). In order to develop a stable and fast numerical procedure the source term (q) in the energy equation is decoupled from the Eq. 1. The *upwind scheme* is used for the discretization of the cure degree ($u\partial\alpha/\partial x$) in the resin kinetics equation to overcome oscillatory behavior in the numerical implementation.

The Peclet number, Pe, is a dimensionless parameter that indicates the degree of convection term ($u\partial T/\partial x$) dominance over diffusion term ($k\partial^2T/\partial x^2$) and given in Eq 9.

$$Pe = u\Delta x\frac{\rho Cp}{k} \quad (9)$$

where Δx is the element size in pulling direction.

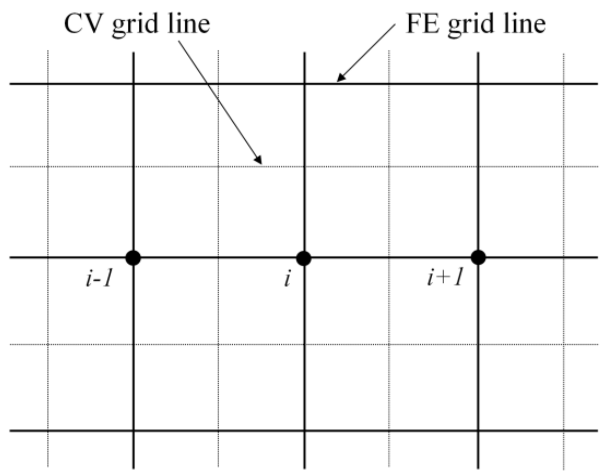


Figure 2. Schematic view of the finite element (FE) and control volume (CV) grids in the pulling direction.

ANSYS has a restriction on *Pe* such that the *Pe* should not exceed 2. Therefore the number of elements or the element size in the pulling direction (x-direction) is determined according to the requirement *Pe*=2. Steady state discretization of the cure degree relation (Eq. 8) discarding the transient term is written in Eq. 10. After obtaining the cure degree for each CV, $R(\alpha)$ and then q are calculated for the energy equation of the composite.

$$u\frac{\alpha_{i,j} - \alpha_{i-1,j}}{\Delta x} = R_r(\alpha) \quad (10)$$

where it is the expression in Eq. 10 which is used in the numerical model in the APDL.

4. Validation Case

4.1. Problem Description

Three dimensional thermo-chemical simulation of pultrusion of a composite having a C-shaped cross section is performed as a validation case. The graphite fiber reinforcement (Hercules AS4-12K) and epoxy resin (SHELL EPON9420/9470/537) system is used for the composite. Chrome steel is used as a material for the die block. The material properties and the resin kinetic parameters are given in Table 1 and Table 2, respectively. Lumped material properties of the composite are calculated by the rule of mixture based on the fiber volume ratio (V_f).

Material	ρ (kg/m^3)	Cp (J/kg K)	k_x (W/m K)	k_y, k_z (W/m K)
Epoxy Resin	1260	1255	0.21	0.21
Fiberglass	2560	670	11.4	1.04
Lumped (V_f = 63.9%)	2090.7	797.27	0.905	0.559
Steel Die	7833	460	40	40

Table 1. Material properties.

H_{tr}(J/kg)	K_0 (1/s)	E (J/mol)	n
324000	191400	60500	1.69

Table 2. Resin kinetic parameters.

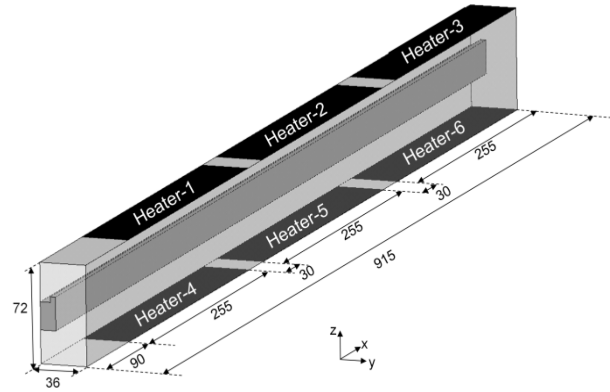


Figure 3. Symmetric pultrusion model geometry for C-shaped composite. All the dimensions are in mm.

The model geometry is seen in Fig. 3. Only half of the cross section has been considered due to the symmetry and an adiabatic thermal boundary condition is applied at the symmetry surface. Three heating platens are placed on the top surface of the die block and the remaining platens are placed on the bottom surface of the die. The corresponding set temperatures of the heaters are given in Table 3. All the surfaces of the die except those on which the heating platens are located are exposed to ambient temperature (27 ^{o}C) with a convective heat transfer coefficient of 10 W/m^2 K. Along the first 90 mm of the die, water-cooled channels are located in order not to have any resin premature gelation at the inlet of the die. The cross sectional details of the die and the composite are seen in Fig. 4. Total of 1948 and 150 structured elements are used for the composite and the die along the pulling direction, respectively. At the die inlet the degree of cure of the composite is equal to zero and the inlet temperature of the composite is taken as the resin bath temperature (□45 ^{o}C). At the die exit, an adiabatic boundary condition is applied to the composite in order to separate the physical domain from the outside since the pultrusion is a continuous process. Perfect thermal contact is applied to the interface boundaries between the die and the composite by using thermal contact elements having a very large heat transfer coefficient (HTC) in ANSYS. The convergence limits for the temperature and degree of cure are set to 0.001 ^{o}C and 0.0001 respectively.

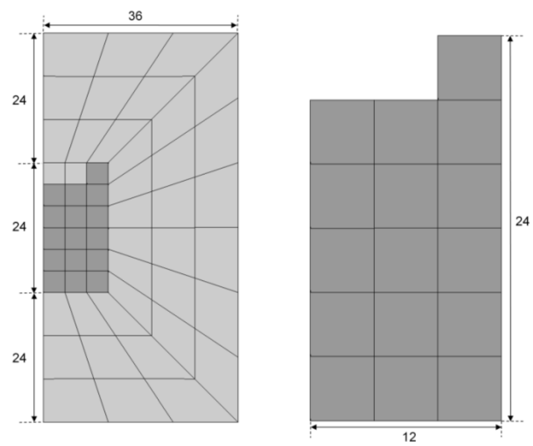


Figure 4. Cross sectional details of the finite elements for the die (left) and the composite (right). All the dimensions are in mm.

Heater 1	Heater 2	Heater 3	Heater 4	Heater 5	Heater 6
105.5	148.5	200.0	115.5	146.5	200.0

Table 3. The set temperatures of the heaters [^{o}C].

4.2. Results and Discussions

The steady state cure degree profiles seen in Fig. 5 are obtained with a pulling speed of 2.299 mm/s and 63.9% fiber volume ratio. It is seen that the results match well with those obtained by using the FE/NCV method in [4,24]. This shows that the utilized numerical scheme is stable and converged to the correct solution. It is seen from Fig. 5 that point A (along the axial direction) has cured before point B since the resin at the die-part interface cures before the center. However the rate of curing of point B is higher than at point A because the contribution of the internal heat generation is higher at the inner region of the composite. In other words, the contribution of the die temperature to the degree of cure is higher than the contribution of the internal heat generation at the die-part interface and the reverse is for the inner regions of the composite. Therefore the cure degree of point B becomes almost the same as the cure degree of point A at the die exit which is around 0.89.

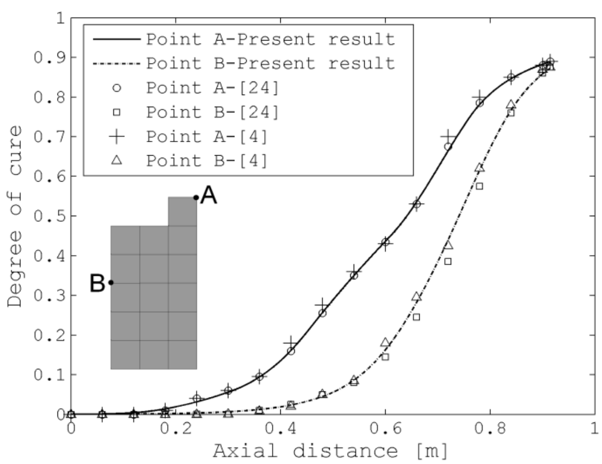


Figure 5. The cure degree profiles for points A and B.

5. Pultrusion of a NACA0018 Profile

5.1. Problem Description

Temperature and cure degree simulations of a composite blade having a NACA0018 airfoil section are performed by using the FE/NCV method. The heater locations are selected as being the same as in the validation case, but in this case only three heating platens are included in the numerical model due to the symmetry. The schematic representation of the model is seen in Fig 6. The cross sectional details of the die and the blade are seen in Fig 7. The same material properties and boundary conditions are used as in the validation case for the die and the composite. Two case studies are examined based on the set temperature of the heaters which are given in Table 4. The set temperatures of the first case study (Case-1) are assumed to be the same as the first three set temperatures in the validation case. For the second case (Case-2), the set temperatures are taken from [23]. In each case, studies with two different pulling speeds, 2.299 mm/s and 3 mm/s, are used. A total of 1948 and 2542 structured elements are used for the composite along the pulling direction in Case-1 and Case-2, respectively.

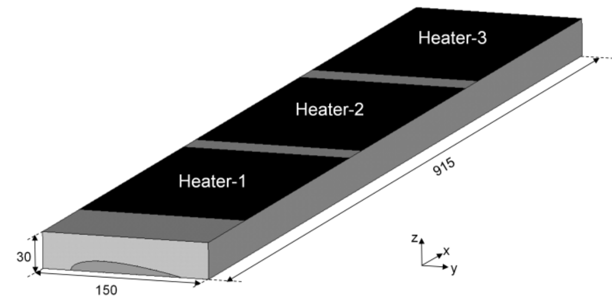


Figure 6. Pultrusion model geometry for NACA0018 blade. All the dimensions are in mm.

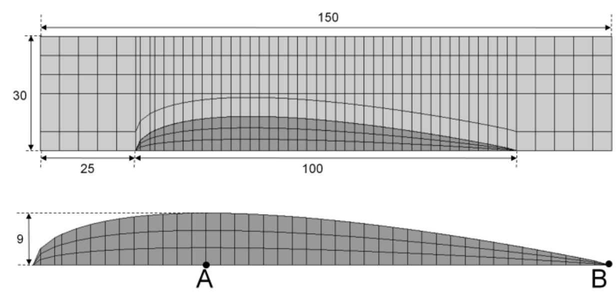


Figure 7. Cross sectional details of the finite elements for the die (the above) and the blade (the below). All the dimensions are in mm.

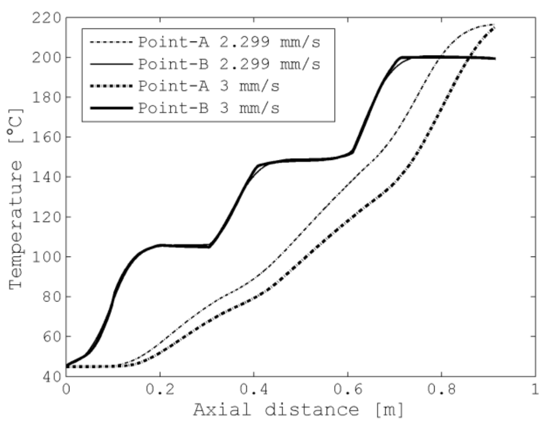
	Heater-1	Heater-2	Heater-3
Case-1	105.5	148.5	200.0
Case-2	171	188	188

Table 4. The set temperatures [^{o}C] of the heaters for the two case.

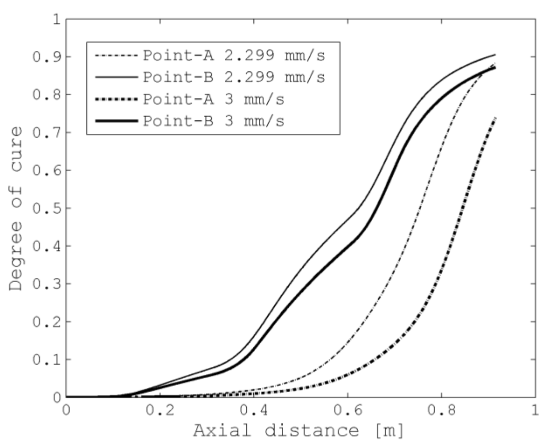
5.2. Results and Discussion

The predicted temperature and cure degree profiles, which are at points A and B (see Fig, 7), for Case-1 and Case-2 are depicted in Fig. 8 and Fig. 9, respectively.

In both cases, i.e. Case-1 and Case-2, although the pulling speed is increased from 2.299 mm/s to 3 mm/s, the temperature at the die-blade interface (e.g. at point B) remains almost the same. This shows that the conductive terms ($k\partial^2T/\partial x^2$) are more dominant at the interface than the convective term ($u\partial T/\partial x$) in the energy equation of the composite blade. On the other hand, the temperature profile at point A shifts right for both case studies due to the increase in speed such that the convective term plays a more significant role at the inner regions. A similar behavior is investigated for the degree of cure distributions by taking the degree of cure equation (Eq. 8) into account. The cure degree profiles at point A shift right further than the point B for two cases as the speed is increased. This indicates that the effect of pulling speed to the cure degree profile at point A is more considerable than the cure degree profile at point B.

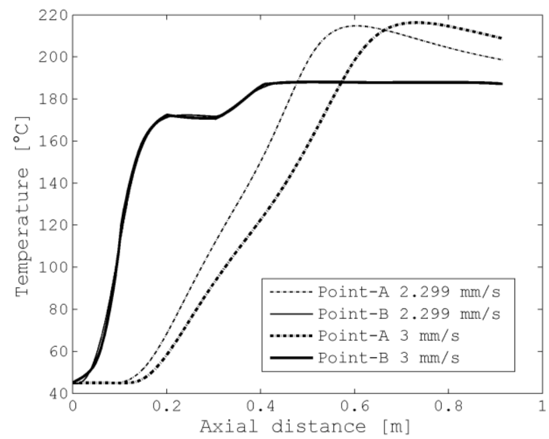


a) Temperature Profiles

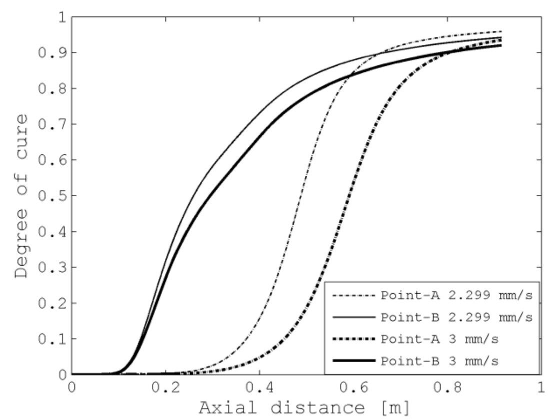


b) Cure degree Profiles

Figure 8. Temperature (a) and cure degree (b) profiles at points A and B for Case-1.



a) Temperature Profiles



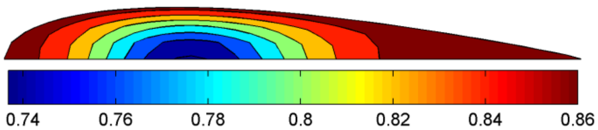
b) Cure degree Profiles

Figure 9. Temperature (a) and cure degree (b) profiles at points A and B for Case-2.

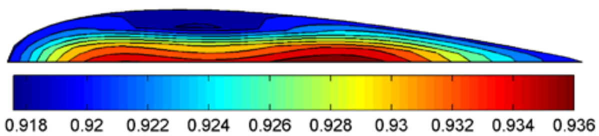
The degree of cure values at the die exit are given in Table 5. It is seen that higher cure degree values are obtained at the die exit for Case-2 since the set temperatures of Case-2 are also higher than for Case-1. In addition to that the cure degree of point A at the die exit is decreased approximately by 16% for Case-1 as the pulling speed is increased, however this decrease is approximately 2% for Case-2. Since point B is located at the interface, the decrease in the cure degree of point B at the die exit is almost the same for both cases, i.e. approximately 2-3%. The cure degree distributions at the die exit are shown in Fig. 10 for both cases with a pulling speed of 3 mm/s. It is seen that the exit cure degree distributions are highly dependent on the set temperature of the heaters. The cure degree of the inner part of the blade cross section is higher than the one at the interface for Case-2, whereas the other way around is obtained for Case-1.

	Point A		Point B	
	2.299 mm/s	3 mm/s	2.299 mm/s	3 mm/s
Case-1	0.88	0.74	0.90	0.87
Case-2	0.96	0.94	0.94	0.92

Table 5. The degree of cure values at the die exit for the two cases with two different pulling speeds.



a) Case-1, pulling speed of 3 mm/s.



b) Case-2, pulling speed of 3 mm/s.

Figure 10. Cure degree distributions at the die exit for Case-1 (a) and Case-2 (b) with pulling speed of 3mm/s. It must be noted that the scales of the figures are not same.

6. Conclusion

In the present work, thermo-chemical simulation of the pultrusion process of a composite NACA0018 blade was studied. In the validation case, the cure degree simulation of a C-shaped composite was performed and the utilized numerical model was found stable and accurate as compared with corresponding results from the literature. Following the validation case, the temperature and the cure degree simulations of the NACA0018 blade was investigated based on the two different set temperature schemes of the heaters (Case-1 and Case-2) with two different pulling speeds. It was observed that higher cure degree values are obtained for Case-2 since the set temperatures of the heaters are also higher than in Case-1. The decrease in the cure degree of point A at the die exit is found as 16% for Case-1 as the pulling speed is increased from 2.299 mm/s to 3 mm/s. On the other this decrease was found as 2% for Case-2. The resin at the inner regions of the composite cured later than the resin located at the die-part interface.

This study shows the significance of the process parameters such as the set temperatures of the heaters and the pulling speed on the quality i.e. cure degree of the pultrusion process of a composite NACA0018 blade. This directly affects the expected mechanical properties of the product as well as the possibility of the defects. Therefore the optimum process parameters have to be found to get desired mechanical properties of the product. This work also motivates for further use of other profiles with different cross sections of VAWT blades with various inner stiffeners, ribs etc.

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