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SPH simulation for short fibre recycling using water jet alignment

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Abstract

This work presents a computational model for a discontinuous fibre composite manufacturing process. The alignment mechanism of this novel process, called the High Performance Discontinuous Fibre (HiPerDiF) method, involves highly coupled fluid-structure interactions. Fibres with a length on the order of a few millimetres are placed in a water suspension, sprayed between two parallel plates and deposited on a moving belt to make an aligned discontinuous fibre tape. This technology can be used as part of a composites recycling process to remanufacture reclaimed fibres into valuable recycled composite feedstock by ensuring a high level of alignment. This work aims to model the alignment mechanism using smoothed particle hydrodynamics in order to inform the design of the industrial machine. The results reveal the influence of jet angle and fibre length on the overall quality of fibre alignment.

1 Introduction

The production of many types of composites such as carbon fibre reinforced composite (CFRP) and glass fibre composites has increased greatly in recent years and looks set to continue to do so in the future, especially as it is more widely adopted in different industries, such as the automotive industry. This is largely due to the excellent mechanical properties the material provides: high strength and stiffness, low density and fatigue and corrosion resistance. However, an increase in production rate creates a significant environmental challenge with regards to manufacturing and end-of-life waste disposal. Furthermore, the use of virgin carbon fibre is expensive and as such the combination of these factors has led to an increase in research into methods that allow composites to be recycled.

Excluding mechanical grinding, which generates low value materials, composite recycling is a two-step process: the degradation of the matrix to reclaim the fibres and their remanufacturing in a new recycled material [32]. Independently of the matrix degradation processes, that might be based on pyrolytic

or solvolytic processes, the reclaimed fibres are in a filamentised, random, low-density-packing (fluffy) form [33]. To obtain a high-performance, and therefore valuable, recycled composite material it is of utmost importance that the fibres are realigned to obtain high fibre volume fraction. One process that has been trialled at the University of Bristol that enables the production of highly aligned, discontinuous composites is the High Performance Discontinuous Fibre (HiPerDiF) method [42]. Using the HiPerDiF method, fibre alignment is achieved by spraying the discontinuous fibres, between 1 mm and 12 mm long, between thinly spaced parallel plates using a water jet, as explained in more detail in Section 2. The HiPerDiF method has been used to remanufacture reclaimed carbon fibres into high performance recycled composites [24] also in combination with natural fibres [23]. Moreover, it is central in the closed-loop recycling of composite materials with thermosetting [26] and thermoplastic [37, 38] matrices. Furthermore the technology allowed the development of a quality control and property assurance methodology for reclaimed carbon fibres [25]. Whilst the process currently produces high quality material, it does so on a laboratory scale. In order to industrialise this process, the throughput must be increased. However, this must be done without degrading the level of fibre alignment. The aim of this work, therefore, is to develop a computational model for the HiPerDiF alignment mechanism that will provide greater insight into the fluid mechanics behind this process and subsequently provide guidelines on the design of an industrial scale composite recycling process. The computational model will be developed using smoothed particle hydrodynamics (SPH). SPH has been chosen due to its excellent ability to model both free-surface flows and cases with large numbers of moving bodies, as will be the case in this project.

SPH is a meshless, Lagrangian method originally developed for astrophysics problems by both Lucy [27] and Gingold and Monaghan [12]. Compared to traditional, mesh-based CFD it is a relatively new method that has found many applications in the area of breaking waves and similar types of problems. There are a few examples of authors using SPH to model flows that contain short fibres. All of these previous works focussed on flows that were more viscous than the fluid of interest in this work such as the works of Kulasegaram and Karihaloo [20] and Deeb *et al.* [8] which looked at self-compacting concrete reinforced with steel fibres or the injection molding process for composites investigated by He *et al.* [17] and Wu *et al.* [41]. The main outcome of this work is the final alignment of the fibres as this is imperative in order to produce material that will have mechanical properties comparable to those that use traditional continuous fibres. There are several works investigating fibre orientation using a variety of methods. It was the focus of the work by Skoptsov *et al.* [36] using SPH to model the injection molding process and Deeb *et al.* [9] using SPH to model self-compacting concrete. A finite volume approach has also been used to study the flow of short fibres through a planar contraction by Khodadadi Yazdi *et al.* [19] whilst an Eulerian based approach was used by Hamalainen *et al.* [15] to study the fibre alignment of a paper-making process, which is a process that has many similarities with the HiPerDiF method.

The HiPerDiF alignment mechanism is a highly coupled fluid-structure in-

interaction problem between the water and the fibres, which in this work are considered to be rigid bodies. There are several methods which can be used to model the rigid bodies with an SPH fluid such as coupling an SPH solver with a finite element solver [10, 13] or with a discrete element method [4, 35]. In this work, the rigid bodies (fibres) are modelled using SPH particles. This is a technique that has previously been used for 2D flow around different shaped disks [40]; 2D flow around circular bodies [16] and flood disaster simulations [1].

This paper presents the details and application of an SPH model of the HiPerDiF alignment mechanism. The remainder of this paper is ordered as follows: Section 2 describes the HiPerDiF technology in more detail, whilst Section 3 outlines the methodology used in the SPH simulations of the HiPerDiF alignment process and Section 4 presents results of the SPH model with initial investigations into the HiPerDiF parameters affecting fibre alignment.

2 HiPerDiF

The High Performance Discontinuous Fibre (HiPerDiF) method is a manufacturing process invented at the University of Bristol to produce highly aligned discontinuous fibre tapes. A diagram of the HiPerDiF technology is shown in Fig. 1.

Figure 1: HiPerDiF composite manufacturing process

The process begins with a low concentration of fibres in a water suspension tank. Fibres are then sprayed through a nozzle towards an array of thinly-spaced parallel plates, known as the alignment head. The momentum change induced by this action causes the fibres to align. After this, they slide on to a moving mesh conveyer belt. This perforated belt allows the water to be extracted by the use of a suction pump without affecting the fibre alignment. This leaves the aligned fibres on the belt, before being fully dried and impregnated with the resin. The alignment of the fibres is crucial to producing commercially

valuable material. As such, it is important to investigate the physics behind the problem in order to better understand the factors influencing the fibre alignment. This alignment process is a highly coupled fluid-structure interaction problem, suitable for analysis using SPH.

3 Smoothed Particle Hydrodynamics

SPH is a meshless Lagrangian method where the spatial discretisation of the state variables is represented by a set of points. These points, or particles, define interpolation points in such a way that the physical values and derivatives of a continuous field are approximated [28]. The interpolation is performed using a kernel function which gives the variable quantities as a weighted average of the neighbouring particles within the size of the kernel support, which is known as the smoothing length. The kernel function has the property of compact support, such that it is zero everywhere except for a finite domain. Therefore in SPH, a function, $F(\mathbf{r}_i)$, can be computed as a sum over neighbouring particles using

$$F(\mathbf{r}_i) = \sum_j \frac{m_j}{\rho_j} F(\mathbf{r}_j) W(\mathbf{r}_i - \mathbf{r}_j, h) \quad (1)$$

where W is the a smoothing kernel function, h is the smoothing length and m_j , ρ_j and $\mathbf{r}_j$ are the mass, density and position of particle j , respectively. This sum includes all neighbouring particles within a radius of $2h$. A large number of different smoothing kernels have been used in the literature. In this work, Wendland's C2 function is used:

$$W(\mathbf{r}_i - \mathbf{r}_j, h) = \begin{cases} \alpha \left(1 - \frac{q}{2}\right)^4 + (2q + 1), & 0 \leq q \leq 2 \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

where $q = |\mathbf{r}_i - \mathbf{r}_j|/h$ and $\alpha = 21/16\pi h^3$ for three dimensions. This formulation can also be used to construct the gradient of $F(\mathbf{r}_i)$, which is given by

$$\nabla F(\mathbf{r}_i) = \sum_j \frac{m_j}{\rho_j} F(\mathbf{r}_j) \nabla W(\mathbf{r}_i - \mathbf{r}_j, h) \quad (3)$$

3.1 Governing equations

The equations governing the particles are the continuity and Navier-Stokes equations, given by

$$\frac{d\rho}{dt} = -\rho \nabla \cdot \mathbf{v} \quad (4)$$

$$\frac{d\mathbf{v}}{dt} = -\frac{\nabla p}{\rho} + \frac{\nu}{\rho} \nabla^2 \mathbf{v} + \mathbf{g} \quad (5)$$

where $\mathbf{v}$ is the velocity, t is time, p is pressure, ν is viscosity and $\mathbf{g}$ is gravity.

In this work, the weakly compressible form of SPH is used. This gives the discretised continuity equation as

$$\frac{d\rho_i}{dt} = \sum_j m_j (\mathbf{v}_i - \mathbf{v}_j) \cdot \nabla W(\mathbf{r}_i - \mathbf{r}_j, h) \quad (6)$$

The right hand side of Eq. (6) is an approximation to $\mathbf{v} \cdot \nabla \rho$ because $\nabla \cdot \mathbf{v} = 0$ as this is incompressible. The momentum equation, Eq. (5), can be discretised as

$$\begin{aligned} \frac{d\mathbf{v}_i}{dt} = & - \sum_j m_j \left[\frac{p_j}{\rho_j^2} + \frac{p_i}{\rho_i^2} \right] \nabla W(\mathbf{r}_i - \mathbf{r}_j, h) \\ & + \sum_j m_j \nu \frac{\rho_i + \rho_j}{\rho_i \rho_j} \frac{(\mathbf{r}_i - \mathbf{r}_j) \cdot \nabla W(\mathbf{r}_i - \mathbf{r}_j, h)}{|\mathbf{r}_i - \mathbf{r}_j|^2 + 0.001h^2} \mathbf{v}_{ij} \\ & + \mathbf{g} \end{aligned} \quad (7)$$

The first term on the right hand side of Eq. (7) is a symmetrical, balanced form of the pressure term, an approximation to $\frac{\nabla p}{\rho}$ which could also be approximated in other ways as described by Price [34]. The second term is the viscosity term proposed by Morris *et al.* [31].

In order to complete the formulation, an equation of state is required to compute the pressures. In this work, the Murnaghan-Tait equation of state, Eq. (8), is used.

$$p = B \left[\left(\frac{\rho}{\rho_0} \right)^\gamma - 1 \right] \quad (8)$$

The value of γ is set to 7 as originally suggested by Cole [5]. The value of B is given by $B = c_0^2 \rho_0 / \gamma$, where c_0 is the speed of sound and is set to a value an order of magnitude greater than the largest velocity expected in the simulation as proposed by Monaghan [29]. This is done to keep the density fluctuations small.

3.2 Surface tension model

Surface tension has the effect of minimising the fluid surface through the attraction of the particles in the surface layer. This is extremely important in this work as it affects the way the fluid interacts with both the fibres and the plates, which could ultimately affect the alignment of the fibres. Therefore, it is important that these effects are captured in the SPH model of the HiPerDiF alignment process. Methods for modelling surface tension within the SPH formulation can be separated into two main categories. The first is based on the continuum surface force (CSF) model introduced by Brackbill [3]. In this method, there is no need to track the interface accurately as the surface forces of the surface tension become volume forces. The surface curvature, however, does need to be calculated. The first use of this method within an SPH framework was presented by Morris [30], where several methods for calculating the surface tension were

shown. However, despite these methods giving good results the need for the surface curvature to be calculated makes their implementation challenging and also normally requires two phases to be present, which is computationally expensive and otherwise unnecessary for modelling the HiPerDiF alignment process. The other category includes methods where the surface tension is represented by a pairwise force between particles. The formulation of the force term is developed based on molecular forces, which are repulsive at short range, attractive at medium range and decay to zero at long range. The force term is given by

$$\mathbf{f}_{ij} = \begin{cases} -\mathbf{s}_{ij} \cos(\frac{3\pi}{4h} |\mathbf{r}_{ij}|) \frac{\mathbf{r}_{ij}}{|\mathbf{r}_{ij}|} & |\mathbf{r}_{ij}| < 2h \\ 0 & |\mathbf{r}_{ij}| > 2h \end{cases} \quad (9)$$

where the coefficient $\mathbf{s}_{ij}$ sets the strength of the surface tension forces. Tartakovsky and Panchenko [39] shows how this force is dependent on the phase the particle is part of and if it is interacting with a solid. They also present analytical relationships that relate the value of this coefficient to the physical surface tension coefficient and contact angle such that $\mathbf{s}_{ij}$ is given by

$$\mathbf{s}_{ij} = \frac{1}{2} \frac{1}{n^2} \frac{\sigma}{\lambda} \quad (10)$$

where n is the average number particle density given by Eq. (11), σ is the surface tension coefficient, which is 0.0728 N/m^2 for water, and λ is given by Eq. (12).

$$n = \frac{\sum_{j=1}^N W(\mathbf{r}_{ij}, h)}{N} \quad (11)$$

$$\lambda = \frac{3}{4\pi^4} [2^7 - 3^2 \times 2^4 \pi^2 + 3^3 \pi^4] \left(\frac{h}{3}\right)^5 \quad (12)$$

3.3 Boundary particles

Implementation of correct solid wall boundary conditions is a complex matter in SPH. There are several methods to achieve this and it is still an active area of research [11]. The main approaches used in the literature can be split into three categories: ghost particles, repulsive particles, and dynamic particles.

Ghost particles are generated outside the system whenever a fluid particle is close to a boundary. This ghost particle has the same mass and density as the fluid particle but the opposite velocity. This means that these particles are not fixed and the total number of particles in the system varies at each time step, which makes implementation more complex.

Repulsive particles, introduced initially by Monaghan [29], are fixed along the boundary and exert a repulsive force on the fluid particles in a form given by the Lennard-Jones potential. However, with this method the motion of the fluid near the boundary cannot be simulated accurately resulting in poor conservation properties [22].

The dynamic particles are SPH particles that are fixed in position or moving with a prescribed motion. Originally proposed by Dalrymple and Rogers [7] and later developed by Crespo *et al.* [6], they satisfy the continuity equation (Eq. (6)) just as the fluid particles do. This method is computationally simple to implement as the calculation for the boundary particles can be included in the same loop as the fluid particles. This is the method used to implement solid wall boundary conditions in this work.

3.4 Modelling the fibres

The fibres are modelled using SPH particles. Each fibre is made up of a number of SPH particles such that the particle spacing on a fibre is half the initial particle spacing of the fluid. This ensures that a fluid particle does not pass through a fibre. The momentum and continuity equation for all particles on all fibres are solved in the same way as for the fluid particles but for each fibre the particles making up that fibre are constrained by rigid body kinematics. So after solving the momentum and continuity equation for the fibre particles, the linear and angular velocities, V and Ω respectively, of each fibre are updated using Eq. (13) and Eq. (14)

$$M \frac{dV}{dt} = F \quad (13)$$

$$I \frac{d\Omega}{dt} = T \quad (14)$$

where M is the mass of the fibre, F is the total force on the fibre computed by summing the contribution from the particles that belong to it, I is the inertia matrix and T is the torque. The force acting on each particle is found from the product of its mass and the acceleration predicted by the SPH discretisation using equation (7), after which all forces and moments are summed for each fibre to find the correct rigid body acceleration. The particles contribution to a fibre are treated as water particles for the purpose of calculating the force of a single particle. In other words, Eqs. (6) and (7) are solved for each fibre particle. Then, the total force on a fibre is calculated by summing the contribution from each particle that belongs to that fibre. The torque is calculated by summing the force on each particle multiplied by the particle's distance from the fibres centre of mass. The fibres are modelled as thin rods meaning that moment of inertia about their length is ignored. The velocities computed using these equations can then be used to update the positions of all of the particles on a given fibre.

The assumption that the fibres can be treated as rigid bodies is supported by bending beam calculations. The drag on fibre can be calculated using Eq. (15) and this force can be used to calculate the maximum deflection on a fibre by modelling the fibre as a thin beam in crossflow. To calculate the drag, the maximum velocity, V , seen in the simulations has been used and the drag coefficient, C_D , has been chosen based on the work of Lindsey [21].

$$D = \frac{1}{2} \rho V^2 S C_D \quad (15)$$

For 3mm long fibres a maximum deflection of 0.20 mm is calculated, which corresponds to 6.6 % of the fibre length. A reasonable assumption for rigid bodies is a maximum deflection no greater than 10 % of the length, therefore the assumption of modelling the fibres as rigid bodies is valid in this instance. This is, however, a conservative calculation as the the fibre slip velocity is less than the jet velocity, which has been used in this calculation.

3.5 Time integration

In this work, the Newmark-beta method [18] is used to integrate the equations in time as done in Hall *et al.* [14]. Values of $\gamma = 1/2$ and $\beta = 1/4$ are used, which gives a constant average acceleration integration and a scheme that is unconditionally stable. The integration scheme is applied to Eqs. (6) and (7) to give:

$$\dot{\mathbf{u}}_{n+1} = \dot{\mathbf{u}}_n + (1 - \gamma)\Delta t \ddot{\mathbf{u}}_n + \gamma \Delta t \ddot{\mathbf{u}}_{n+1} \quad (16)$$

$$\mathbf{u}_{n+1} = \mathbf{u}_n + \Delta t \dot{\mathbf{u}}_n + \frac{1 - 2\beta}{2} \Delta t^2 \ddot{\mathbf{u}}_n + \Delta t^2 \beta \ddot{\mathbf{u}}_{n+1} \quad (17)$$

The Newmark-beta method is implicit so the particle acceleration and density rate of change from Eqs. (6) and (7) are substituted into Eqs. (16) and (17) to perform the time integration and fixed point iteration is carried out to converge to a solution for time level $n + 1$.

3.6 Fluid-Structure coupling

In this application, the fluid and structure represents a highly coupled system. Therefore, it is necessary to ensure that a strongly coupled fluid-structure algorithm is used. The strongly coupled procedure used in this work is presented in Fig. 2.

One iteration of the algorithm consists of computing the new positions and velocities of the fluid particles and the new densities and pressures of all the particles. Then, using the latest values for the fluid variables, new positions and velocities of the fibre particles are calculated. If the positions are converged, then a new time step is initiated. If not, the fluid variables are reset and the latest fibre position and velocities are used to recalculate the fluid values. This is repeated until convergence is achieved, which is measured by the change in the particle postions, such that the iterations are considered converged when the change in particle positions between two successive iterations has reduced to a value close to zero. Typically, in this application, two or three iterations are needed for convergence. This results in a process that is fully implicit, which is important as there is a strong coupling between the fluid and the fibres on a relatively short timescale.

Figure 2: Flowchart of the coupled fluid-structure interaction

3.7 Jet pulse and suction

The HiPerDiF alignment process uses a peristaltic pump to transport the fluid-fibre mixture through the pipes and nozzle. A result of the way the peristaltic pump operates, by squeezing the fluid through a flexible tube using a roller in a circular motion, causes a pulsing effect of the jet. It is therefore important to capture this effect within the computational model. The pulse was timed at 0.025 seconds on and 0.025 seconds off, which is modelled using a clipped sinusoidal function as shown in Fig. 3. The amplitude of the function is calculated so that the overall flow rate matched the values obtained experimentally. It is implemented in the model by setting the velocity of the new nozzle particles according to the value of the function. The final aspect of the alignment head that has been included in the model is the suction used to extract the fluid through the mesh conveyor belt. This suction force is included as a simple ramped pressure force applied to the fluid particles dependent on its distance from the belt. The belt particles are dynamic boundary particles, however they are treated as invisible to the fluid particles in order to allow the fluid particles to pass through the belt whilst allowing the fibres to land on the belt.

Figure 3: Sinusoidal function describing the pulse of the jet

4 Results

The aim of this work is to develop a computational model of the HiPerDiF alignment process in order to facilitate investigation into the main parameters affecting the alignment. Firstly the fluid-structure interaction is validated through comparison to the floating box simulation of Bouscasse *et al.* [2]. Then the current HiPerDiF setup is modelled to demonstrate the efficacy of the model before cases with varying nozzle angle and fibre length are presented.

4.1 Validation of the fluid-structure interaction

Validation of the rigid body formulation was undertaken through comparison to the study of an oscillating floating box by Bouscasse *et al.* [2]. This case consists of a box of dimensions $0.8L \times 0.4L$ whose centre of gravity is shifted horizontally by $0.2L$ in a tank that contains water of dimensions $5L \times 0.7L$. The mass, moment of inertia and Reynolds number are $0.16\rho L^2$, $0.01072\rho L^4$ and 5000 respectively. Bouscasse *et al.* use a δ -SPH method and perform the simulation with a number of different spatial resolutions, however, owing to computational constraints, the coarsest resolution of $L/\Delta x = 100$ is used here. The time evolution of the velocity field is shown in Fig. 4 and the position of the box compares well to those presented by Bouscasse *et al.*. Fig. 5 shows the time history of the centre of gravity of the box compared to the values computed by Bouscasse *et al.*, which quantifies the accuracy of the results presented here with respect to the results in [2] for the same spatial resolution.

Figure 4: Time evolution of oscillating floating box

Figure 5: Time evolution of centre of gravity of oscillating floating box

Table 1: Computational parameters

Parameter name	Value	Units
Initial particle spacing	0.12	<i>mm</i>
Surface tension coefficient	0.0728	<i>N/m</i>
Smoothing length	0.18	<i>mm</i>
Contact angle (plates)	71.0	degrees
Contact angle (fibres)	80.0	degrees
Timestep size	2×10^{-7}	seconds
FSI loop iterations	2	n/a

4.2 Current HiPerDiF setup

Bofore investigating the effect of changing machine parameters on the alignment, the current HiPerDiF setup was simulated in order to demonstrate the efficacy of the whole model. In all the remaining results presented in this section a single nozzle from the HiPerDiF alignment head has been modelled and all other fixed parameters are listed in Table 1. All of the simulations used carbon fibres, which have a density of 1.82 g/cm^3 , an elastic modulus of 200 GPa and a diameter of 0.007 mm. The value for surface tension coefficient is taken from literature for the surface tension for a water-air interface and the the values used for contact angles are an average of the values reported in literature for steel for the plates and carbon fibre for the fibres. The time interval of the jet pulse was determined experimentally, as explained in section 3.7.

The model setup, shown in Fig. 6, consists of two plates and a moving mesh conveyer belt. The front plate has an opening to allow the water/fibre mixture to hit the back plate, which should cause the fibres to drop between the two plates onto the mesh belt and be transported along. In the current setup the nozzle is angled at 45 degrees to both the horizontal and vertical and the fibres are 3mm long carbon fibres. The particles are arranged on the plates as shown in Figs. 7 and 8. These particles are treated as dynamic boundary particles as explained in section 3.3. Each fibre is discretised as a single line of particles, as shown in Fig. 9. The size of each particle on the fibre is the same as the size of each fluid particle. This, along with the length of the fibre, determines the number of particles on a fibre. The particles are introduced into the jet using the initial configuration shown in Fig. 10. A new layer of particles is introduced each time the previous layer has moved by one particle size.

Snapshots from the simulation at different time instances of a single pulse are shown in Fig. 11 and a close up of these time instances with the front plate hidden and the fibres enlarged for clarity, is shown in Fig. 12. This shows the shape of the jet as it impinges on the plate and it is clear to see the effect of the surface tension. It also shows that there is a significant amount of water splashing over the front of the first plate however, most does still fall between the gap. Importantly, all of the fibres drop between the gap. Figure 13 shows the fibres on the belt at the end of the simulation. It is clear just

Figure 6: Setup

Figure 7: Particle arrangement for the plates

Figure 8: Particle arrangement for the belt

from a qualitative analysis, that there is a high level of alignment. However, the alignment can be easily quantified using this computational model, something that is more difficult to achieve experimentally. From this setup there are 64% of fibres aligned within $\pm 3^\circ$ of the belt direction, which is the metric used in the paper by Yu *et al.* [42]. That paper stated an experimental value of 65% of fibres aligned within $\pm 3^\circ$ for the same setup.

Figure 9: A single fibre discretised using particles

Figure 10: Particle arrangement for the particles introduced as the nozzle

4.3 Effect of nozzle angle

Next, the effect of the nozzle angle was investigated. For these test cases the angle of the nozzle to the vertical, θ as depicted in Fig. 6(b), was swept through from 15 degrees to 60 degrees in 15 degree increments. The nozzle angle to the horizontal, ϕ as depicted in Fig. 6(b), was held constant at 45 degrees and the fibres used were 3 mm long carbon fibres. Figure 14 shows the fibres on the belt at the end of the simulation for the four cases. It would appear from these figures that all angles show a high level of alignment of the fibres, suggesting this nozzle angle does not have a large effect in the alignment of the fibres. However, the alignment has been quantified in Fig. 15, and this shows that

Figure 11: Snapshots of the HiPerDiF SPH simulation at different time instances

the shallowest angle has the best alignment and there is very little difference between the other angles. This suggests that more nozzle angles between 0 degrees and 30 degrees should be investigated to see if this trend holds. This also highlights the importance of quantifying the alignment as it is not clear to see this difference in Fig. 14.

4.4 Effect of fibre length

Finally, the effect of the length of the fibres was investigated. It is important to understand the effect of using different fibre lengths for two reason: firstly, a fibre length or a combination of fibre lengths may be chosen in order to tailor the material for a particular application and secondly, the recycled fibres obtained from the supplier may be a variable lengths. In both cases the machine must be designed to obtain a certain quality of material for the given fibres. For these test cases the fibres varied in length from 1.5 mm to 7.5 mm in 1.5 mm increments.

Figure 12: Close up of snapshots of the HiPerDiF SPH simulation at different time instances. The front plate has been made transparent and the fibres have been slightly enlarged for visualisation.

Figure 13: Alignment of the fibres of the current HiPerDiF process

The nozzle angles to both the horizontal and vertical, θ and ϕ , were fixed at 45 degrees. These angles were chosen as they represent the current HiPerDiF setup. Once again, there is a high level of alignment for all the test cases. The percentage of fibres aligned within $\pm 3^\circ$ is shown in Fig. 17. This shows initially the alignment increases as the fibre length increases before reaching a plateau. This reinforces the idea that it is the effect of the fibres hitting the plates that

Figure 14: Alignment of the fibres for different nozzle angles

Figure 15: Percentage of fibres aligned within ± 3 degrees for different nozzle angles

aligns them as the longer fibres are more restricted for the same plate spacing. The decrease in alignment for the longest fibre, 7.5 mm, may be a result of the fibres stacking on top of each other and thus not being transported with the belt properly.

Figure 16: Alignment of the fibres for different length fibres

Figure 17: Percentage of fibres aligned within ± 3 degrees for different length fibres

5 Conclusions

A numerical fluid model for deposition of suspended fibres has been presented based on smoothed particle hydrodynamics. The model includes all fluid-fibre, fibre-fibre and fibre-wall effects and is able to simulate the peristaltic pump, pressure-driven fluid drainage and moving belt. The numerical model has been shown to capture the mechanism behind the fibre alignment in the HiPerDiF process and initial investigations suggest that the primary mechanism is the physical impingement on the plates.

The influence of the vertical impingement angle has been explored, revealing that flat angles are preferable, although the influence is small. A fibre length study has shown that longer fibres align more effectively, until at some point their stacking can potentially reduce alignment again. The SPH approach to fluid-fibre interaction has the potential to be further extended to other composite manufacturing processes such as injection molding and extrusion, as well as continuing to provide more detailed design information for fibre deposition and scaling-up of the process.

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