DEVELOPMENT OF COMMINGLING NOZZLES FOR HYBRID YARN PRODUCTION BY CFD SIMULATION

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Abstract

The production of hybrid yarns is a technology which can be applied to manufacture fiber reinforced thermoplastic composites (FRTC) for technical applications. In this case hybrid yarns consist of reinforcing and multifilament thermoplastic fibers. To reduce the flow paths of the high viscous melt during the consolidation of composites a good mixing is essential. A suitable process to generate hybrid yarns is performed by air jets (so-called air commingling). Different nozzle types like air jet texturing and intermingling nozzles are used depending on the yarn count, the mixing behaviour and the mechanical properties of the initial fibers. The technique of Computational Fluid Dynamics (CFD) is useful to analyse the flow field inside the commingling nozzles. In the frame of this paper the procedure during the simulation is described and related to the commingling process. The concept during the development process of nozzles can be carried out through specific parameter studies. In doing so, the commingling process can be optimized. In this way, the distribution of the individual filaments in the FRTC can be systematically improved.

1. Introduction

Hybrid yarns are yarn structures that consist of different yarn components to archive special yarn properties [1]. One main application field is the processing of hybrid yarns to FRTC. These composites consist of reinforcing fibers (like carbon or glass fibers) and a thermoplastic matrix system. They are meltable under heat, offer good mechanical properties and can be back moulded [2]. A homogenous distribution of the reinforcement and matrix fibres is essential to archive short flow paths. In doing so, the potential for mass applications is given by the reduction of cycle times. The commingling process by air jet mixing nozzles has the capability to offer a homogenous distribution of reinforcing and thermoplastic filaments (like nylon 6 or polyester fibers) in the cross section of the hybrid yarn. During the process both yarn components are opened and mixed by the intermingling nozzle. A good consolidation can be realized by a pre-opening of the sizing of the reinforcing fiber. Therefore, the geometry of the commingling nozzle is essential for the quality (low yarn damage, homogenous filament distribution in the cross section, efficiency) of the commingled yarn. Computational fluid dynamics (CFD) is a method that can be used to analyse the flow field inside the commingling nozzle. Figure 1 shows the procedure during the development of nozzle geometries by using the CFD-technology. This procedure is presented in the following chapters of the paper.

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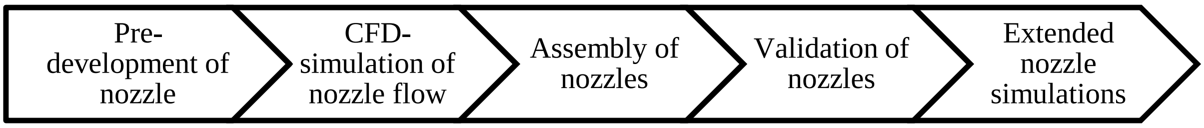

Figure 1. Process chain for the development of nozzle geometries by CFD

2. Materials and methods

2.1Introduction

In this work adapted nozzle geometries are developed that have the capability to manufacture high yarns with high yarn counts. Relevant yarns for FRTC are carbon and glass fibre that are combined with nylon 6 or polyester filament yarns. A suitable process to generate hybrid yarns is performed by air jets [3]. In this process, rapidly moving air in a nozzle generates entanglements in and among the filaments of both components. A test setup for this process consists of godets, a sound box with the mixing nozzle as well as a winder (Figure 2). The single components of both yarns are being fed by separate godet pairs in order to allow the adjustment of the fibre tension as well as the speed of the different yarn components. Both yarn components are inserted through the nozzle with an over feeding rate. This over feeding rate allows the opening and mixing process of both yarn components in the mixing nozzle. Different nozzle types like air jet texturing nozzles and intermingling nozzles are used depending on the yarn count, the mixing behaviour and the mechanical properties. In order to generate a stable mixing-process a good knowledge of the flow behaviour inside the nozzles is essential.

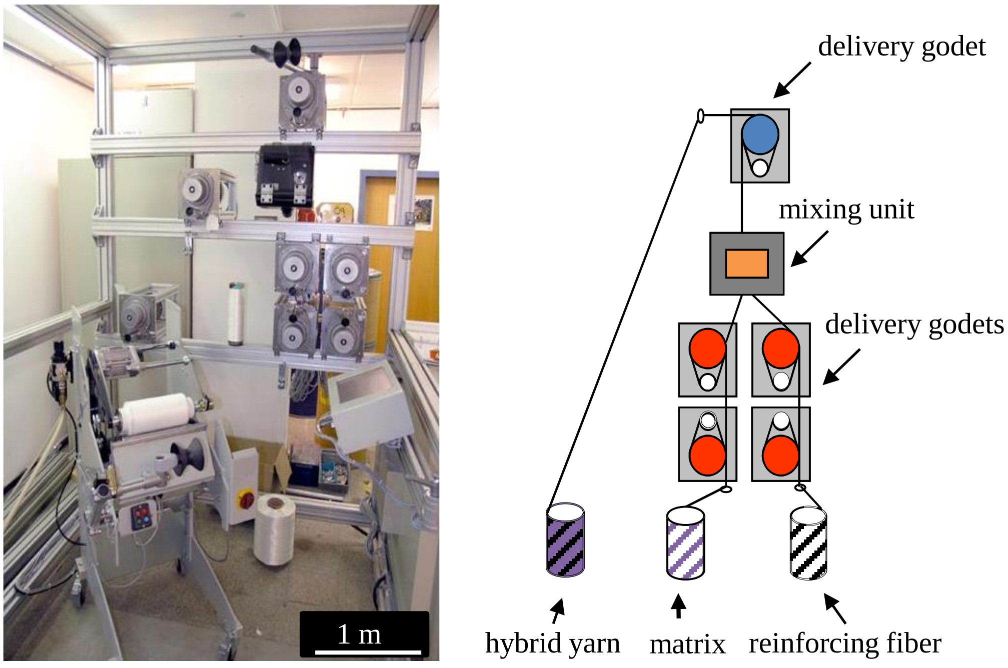

Figure 2. Air commingling plant for the production of hybrid yarns

Due to its small size and the high speed movement of the fibres in the air chamber of the mixing nozzle, it is very difficult to measure and visualize the airflow inside the nozzle. Conventional measuring methods involve including a probe inside of the air jet, which affects the airflow itself and the movement of the yarns. Therefore, a computational approach to analyse the mixing-nozzle is followed. The chosen method for this is simulating the airflow with the CFD-method.

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In contrast to expensive mechanical tests it is possible to do a lot of variation of the process parameters and even changing the geometry with the help of simulation methods. Main benefits are that no parts have to be built and computational costs are much lower and involve less personal. Thus, it is possible to find the best candidate mixing nozzle and the corresponding process parameters to get a stable process. However, simulation results are always only an approximation and have to be validated with real tests to ensure accurate outcome.

Therefore, the most promising nozzle geometries that fit the pre-defined requirements of the nozzle are assembled and validated. The validation is conducted by a test setup and an optical measurement system. The setup consists of a feeding unit as well as clamping devices to mount and position the designed nozzle. A reinforcing roving (carbon fibre) and thermoplastic multi filaments are fed into the pressurized nozzle. During this process the mixing behaviour of both fibres is visualized by means of a high-speed-video (HSV) camera. In doing so, the area of the mixing is shown and conclusions according the hybrid yarn quality are possible. By means of these results modified nozzle geometries are conducted.

2.2Computational fluid dynamics (CFD)

2.2.1 Introduction to CFD

For analysing and solving problems on fluid domains usually CFD approach is used. To describe the pressure, velocity and temperature distributions in a fluid the conservation equations for mass, momentum and energy are expressed and solved on a Cartesian coordinate system in the corresponding x-, y- and z-directions. The resulting Navier-Stokes equation system is shown in equation 1 [4].

$$\rho \frac{du}{dt} = \rho \cdot g_x - \frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left[\eta\left(2\frac{\partial v}{\partial y} - \frac{2}{3}\operatorname{div}\vec{v}\right)\right] + \frac{\partial}{\partial y}\left[\eta\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right] + \frac{\partial}{\partial z}\left[\eta\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right)\right] \tag{1}$$

The Navier-Stokes equations are nonlinear partial differential equations of second order and thus cannot be solved analytically for general problems. Therefore, numerical methods to solve these equations are used. The rising performance and capacity of computers during the last decades have given the CFD-method an additional emphasis.

Even though there are a lot of different numerical methods for solving the Navier-Stokes equations on a given domain. The most often used method is the finite volume method (FVM). It is a fast and efficient method for representing and solving differential equations on discrete points. Around each discrete point a volume is defined and the volume integrals in the Navier-Stokes equations are converted to surface integrals using the divergence theorem. These terms can be written down as fluxes over the surfaces of the volumes and thus form an algebraic approximation of the considered equations.

2.2.2 CFD as a method to develop commingling nozzles

Simulations are useful to reduce development costs. They are much less expensive and a lot of variations can be analyzed in short time. The general approach is based on the three main steps pre-processing, solving and post-processing (Figure 3).

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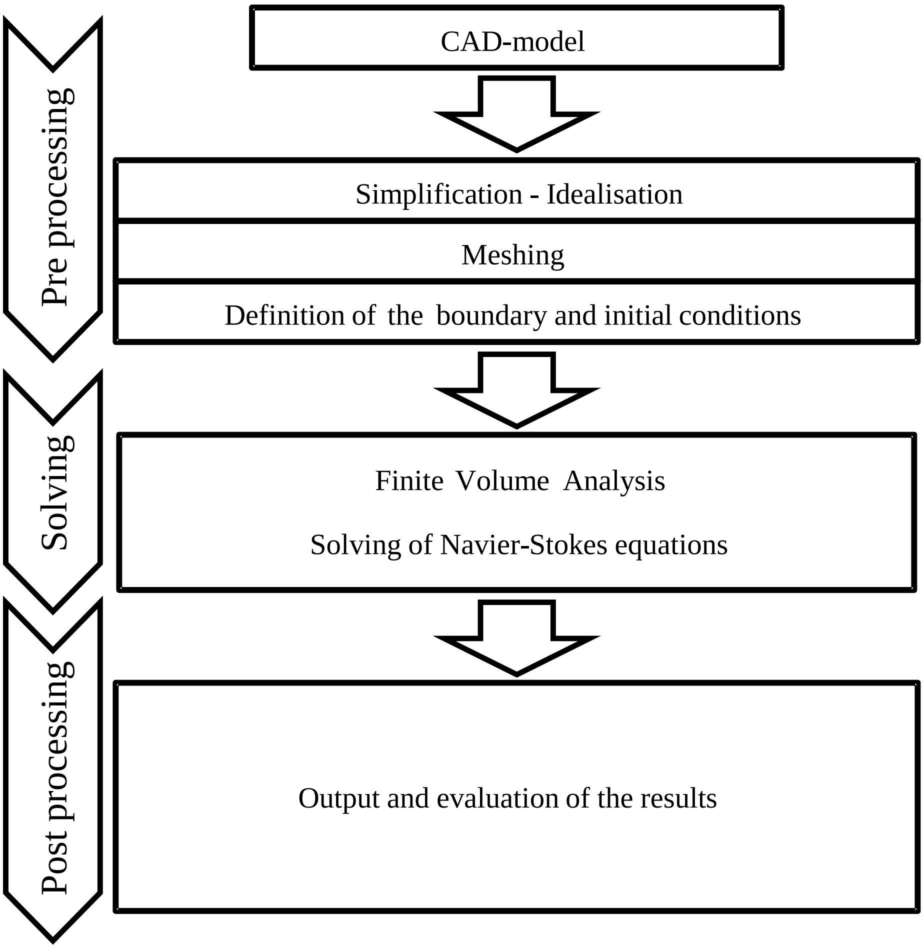

Figure 3. CFD-approach of commingling nozzle

In the pre-processing step the geometry for the fluid domain is extracted from the CAD-model of the mixing nozzle (Figure 4). To be able to build a mesh, the geometry has to be simplified and idealized. For this letterings and small dimension details are removed from the CAD-model. After the mesh has been built, boundary and initial conditions have to be defined. These conditions are chosen according to the corresponding tests.

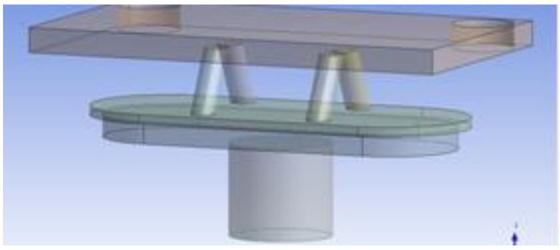

Figure 4. Fluid domain of the commingling nozzle

2.2.3 Nozzle design, meshing and boundary conditions

The designed nozzle with its mounting arrangement and thread guides is shown in Figure 5. The reinforcement and matrix fibers are guided through the thread guiding holes. The guiding is necessary to keep the yarns in the centre of the nozzle. The adapter plate is the holding base of the mixing nozzle and contains the holes for the pressurized air. Spacers are positioned between the rebound plate and the middle plate to leave enough space for the fibers to be mingled.

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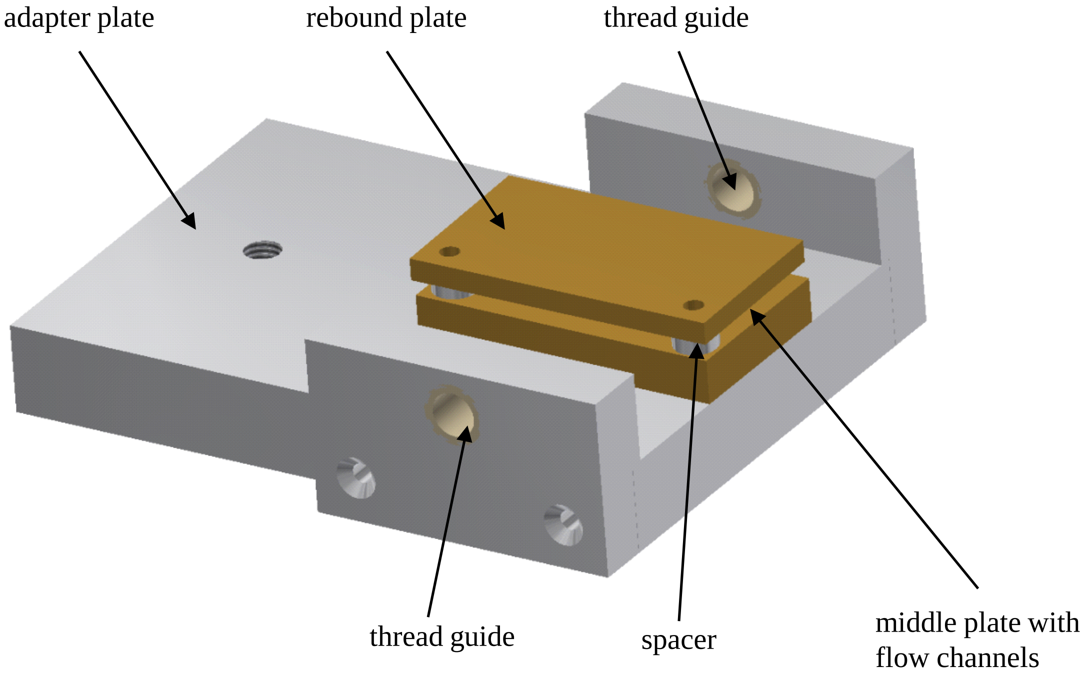

Figure 5. Mounting of the mixing nozzle

3 Results and discussion

Different nozzle designs are compared by CFD-techniques. The parameters that are varied are the position, the diameter and the angle of the flow channels. The result of each analysis is a picture that shows the streamlines of the compressed air inside the nozzle (Figure 6).

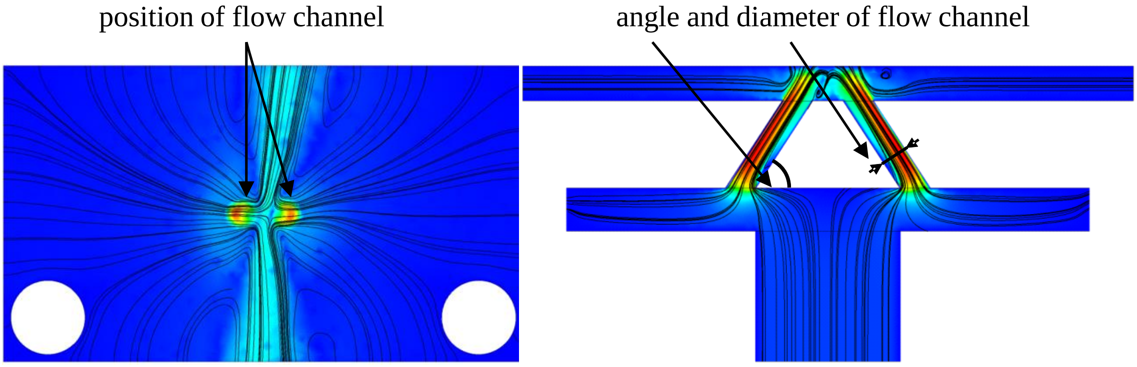

Figure 6. Streamlines inside the nozzle from above (left) and from the front (right)

Based on the characteristics of the streamlines five significant nozzle designs are designed by CAD and later manufactured. The validation of the simulations is realized by means of a HSV-camera. Therefore, a test setup that consists of fiber feeding systems, clamping devices for the nozzle and the HSV-camera is built (Figure 7).

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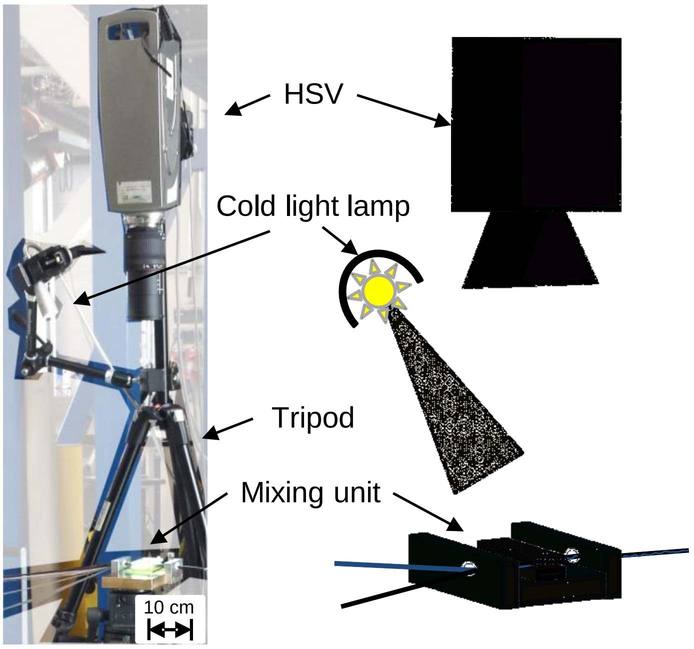
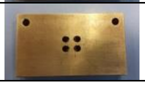


Figure 7. Test setup for the validation of the nozzle CFD-simulations

The validation is performed with a 50 K carbon fibre roving (Sigrafil®, SGL Carbon SE, Wiesbaden, Germany) and 11 times doubled 200 tex polypropylene multifilament yarns (Polisilk S.A., Barcelona, Spain). During these tests the process speed is limited by the feeding system (10 m/min). The range of the pressure inside the nozzle is between 4 and 6 bar. Table 1 gives an overview of the test results of the nozzle validation.

Table 1. Overview of the results of the nozzle validation

Nozzle geometry		Filament damage	Mixing quality of yarn	Yarn position inside the nozzle
Nozzle 1		--	-	--
Nozzle 2		+	-	+
Nozzle 3		+	+	++
Nozzle 4		++	--	+
Nozzle 5		--	0	--
++: very good, +: good, 0: medium, -: bad, --: very bad				

The best result is given by the geometry of nozzle 3 and a pressure of 6 bar. The centering of the hybrid yarn during the mixing process will be realized by further nozzle simulations. Therefore, two additional flow channels at the left and at the right of the middle plate are introduced. According to the description of the procedure during the CFD-simulations (chapter 2.2) further nozzle simulations are conducted. The modified nozzle geometry is shown in Figure 8.

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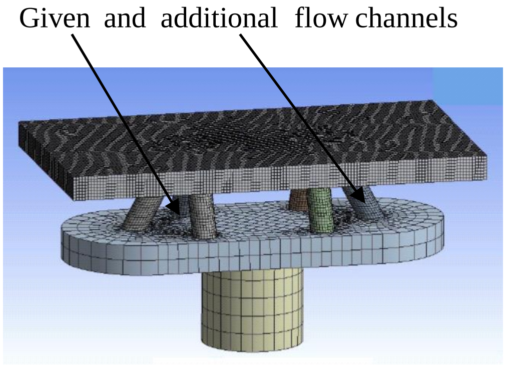

Figure 8. Modified nozzle geometry

The streamlines inside the modified nozzle geometry are demonstrated in Figure 9

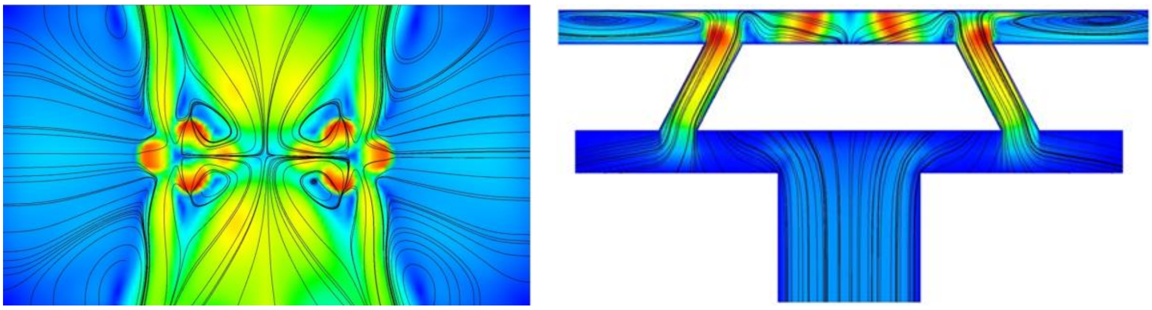

Figure 9. Streamlines inside the modified nozzle from above (left) and from the front (right)

4 Conclusions

The hybrid yarn technology provides a way to efficiently produce thermoplastic FRTC. By using rovings with high yarn count the efficiency of the process can be further increased. The concept during the development process of nozzles that is developed in this paper can be carried out through specific parameter studies. In doing so, the commingling process can be optimized. In this way, the distribution of the individual filaments in the FRTC can be systematically improved. In order to evaluate the fiber distribution in the cross section and to measure the hybrid yarn quality analysis methods as shown in [5] can be used.

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