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MULTIPHYSICS AND MULTIMETHODS PROBLEM OF ROTATIONAL GLASS FIBER MELT-SPINNING

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Abstract. Glass wool manufacturing is a multiphysics problem which requires the understanding of the rotational melt-spinning of ten thousands of viscous thermal slender jets by fast air streams. Due to its high complexity an uniform numerical treatment is impossible. In this work we present a multimethods approach that is based on an asymptotic modeling framework of slender-body theory, homogenization and surrogate models. The algorithm weakly couples melting and spinning phases via iterations. The possibility of combining commercial software and self-implemented code yields satisfying efficiency off-the-shelf. The simulation results are very promising and demonstrate the applicability and practical relevance of our approach for ongoing optimization strategies of the production processes.

Key words. Rotational spinning, viscous thermal jets, fluid-structure interactions, fluid dynamics, structure mechanics, heat transfer, slender-body theory, Cosserat rods, drag models

1. Introduction

A rigorous understanding of the rotational spinning of viscous thermal jets exposed to gravity and/or aerodynamic forces is of interest in many industrial applications, e.g. glass/polymer fiber spinning/tapering [22, 14], pellet manufacturing [8, 21], technical textile production [2, 3]. This work deals with glass wool manufacturing. Rotational spinning processes consist in general of two regimes: melting and spinning. As a representative example we focus on a specific melt-spinning process whose set-up is illustrated in Figure 1. Here, glass is heated in a stove from which the melt is led to a centrifugal disk. The walls of the disk are perforated by ten thousands of tiny holes that are placed equidistantly in a spinning row with tens of rows over height. Emerging from the rotating disk via continuous extrusion, the liquid jets grow and move due to viscosity, surface tension, gravity and aerodynamic forces. There are two air flows interacting with the arising glass fiber curtain: a downwards-directed hot burner flow that keeps the jets near the spinning nozzles warm and thus extremely viscous and shapeable as well as a highly turbulent cold cross-stream that stretches and finally cools them down such that the glass fibers become hardened. These fibers yield the basic fabric for the final glass wool product. For the quality assessment of the fabrics the properties of the single spun fibers, i.e. homogeneity and slenderness, play an important role. A long-term objective in industry is the optimal design of the manufacturing process with respect to desired product specifications and low production costs. Therefore, it is necessary to model, simulate and control the whole process.

The goal of this paper is the first numerical simulation of the whole process, regarding all effects. The manufacturing process is a multiphysics problem whose uniform numerical treatment is impossible because of the enormous complexity.

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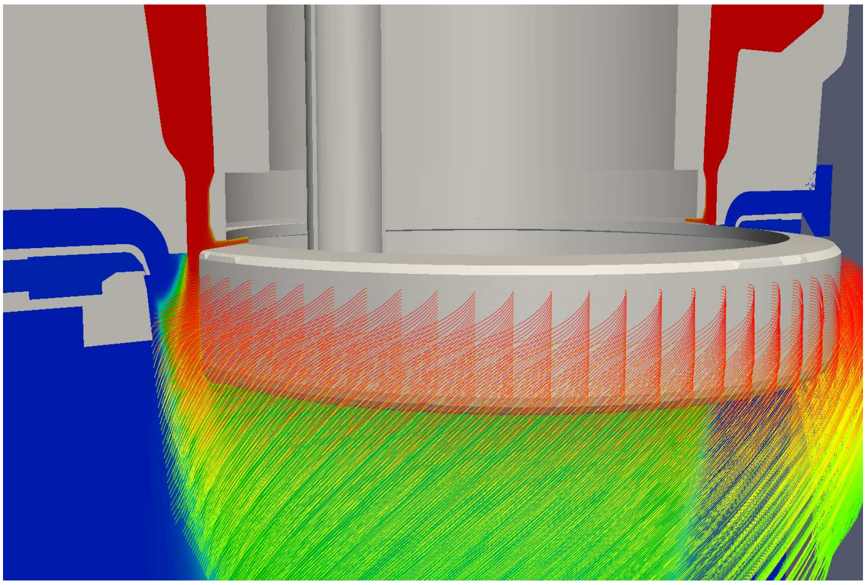

FIGURE 1. Specific rotational melt-spinning process of our industrial partner with 30 000 glass jets. Only every tenth jet is plotted here. The temperatures of air flow and fiber jets are visualized by the color map that ranges from 30°C (blue) to 1500°C (red).

Hence, we follow the idea to handle it as a multimethod problem by deriving adequate models and methods for the separate regimes and coupling them appropriately (see [17] for a similar strategy in the field of nonwoven production). In this sense and contents, the spinning phase has already been modeled and investigated in [3]. In the spinning phase the liquid viscous glass jets are stretched by the surrounding air flow to form long thin fibers of slenderness ratio $\delta = d/l \ll 1$ (with jet diameter d and length l) that lie dense in an arising curtain. To predict the resulting fiber/fabric properties, the fiber-fluid interactions have to be considered. This involves, in principle, the solution of a three-dimensional multiscale-multiphase problem. However, in view of thousands of slender glass jets and fast air streams direct numerical simulation as well as numerical approaches (like embedded domain approaches or immersed boundary methods) are not applicable. Thus, an asymptotic coupling concept has been developed in [3]. Treating the glass jets as viscous thermal Cosserat rods, the multiscale problem is tackled by help of momentum (drag) and heat exchange models that are derived on basis of slender-body theory and homogenization. A robust and efficient weak iterative algorithm makes then the simulation of the industrial spinning phase with its fiber-fluid interactions possible. In that work the melt conditions at the nozzles (i.e. velocity and temperature) and the temperature of the disk wall which act as boundary conditions for glass jets and air flow computations of the spinning phase as well as the disk geometry itself were assumed to be known.

But, in view of the design of the whole manufacturing process the melting phase must certainly be taken into account in modeling and simulation. It deals with the highly viscous melt coming from the stove and creeping in the centrifugal disk to the perforated walls. Melting and spinning phases obviously influence each other. On one hand the conditions at the spinning rows are crucially affected by the melt