CFD Modeling of Fiber Transport and Web Formation Using Fiber-Resolved and Eulerian Approaches

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Motivation

Conventional paper production relies heavily on water to transport the fibers and form the sheets, as the cellulose fibers are dispersed in a water suspension. While this promotes uniform fiber distribution and bonding, the drying step consumes substantial thermal energy, making it a key area for energy reduction. Our approach eliminates water entirely from the process, inspired by the airlaid technique used in the textile industry [1]. This method is already applied in the paper industry for products like napkins. Critical factors include fiber laydown uniformity and orientation, expressed as the Machine Direction (MD) and Cross Direction (CD), with the MD/CD ratio determining sheet strength. Using air as the transport medium avoids the energy-intensive drying process but requires fluid dynamic investigations to optimize the fiber transport and laydown process. CFD simulations provide valuable insights to improve uniformity and fiber orientation, with one of the biggest challenges being the correct mapping of the complex interactions of natural fibers.

Methodology

A fiber-resolved approach is essential for studying orientation. The *Flexible Fiber Model* in Simcenter STAR-CCM+ uses a DEM-based method, representing fibers as chains of cylindrical particles connected by axial and bending springs for representation of the elastic behavior. Since computational effort scales with particle count, initial investigations focus on minimizing segments while maintaining accuracy. This method is suited only for small sections due to the high fiber count. For full-machine simulations, a Eulerian Multiphase Approach is used, which lacks orientation details but provides insights into web uniformity. A tailored drag coefficient correlation is needed, as existing correlations for spherical particles or rigid cylinders do not account for dynamic bending and constantly changing orientation in the flow.

Results

In the first step, a fiber is attached to one end and bent under gravity. Fibers with different numbers of cylinder segments are compared with the Euler-Bernoulli beam theory. Figure 1 shows the deflection profiles and the coefficient of determination.

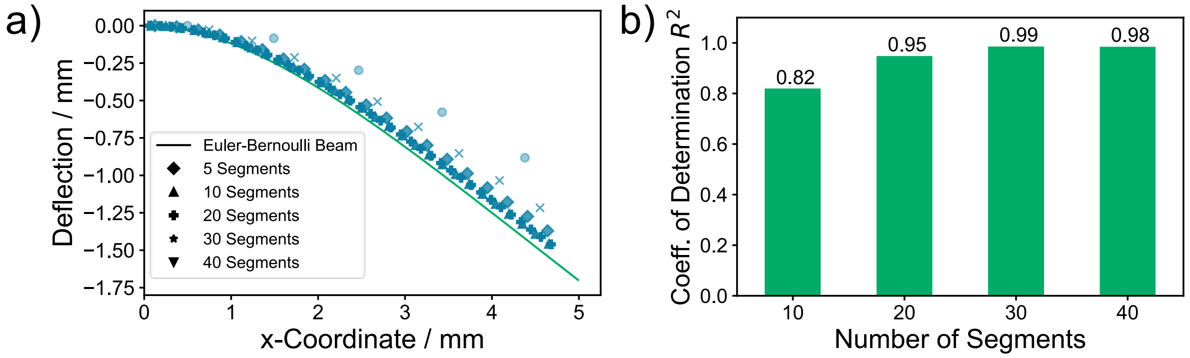

Figure 1: Bending behavior of fibers composed of varying numbers of cylindrical segments compared to the theory of a Euler-Bernoulli beam (a), and the corresponding coefficient of determination (b).

As expected, increasing the number of segments improves accuracy. However, each additional segment increases computational cost, so a trade-off must be made. With more than 30 segments, the coefficient of determination stagnates, and with 20 segments, the deviation is within an acceptable error range of 5 %. Next, the dynamic behavior of a single fiber is analyzed. A fiber is placed in a flow, and its orbiting behavior, such as the *snake turn*, is studied with varying segment numbers [2]. Figure 2 shows the fiber geometry in the airstream.

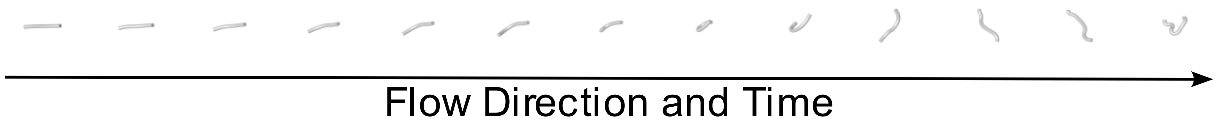

Figure 2: Fiber bending over time in a flow.

These simulations reveal repeating patterns in the fiber's geometry during orbiting, which help to generate a drag correlation. These states are used in single-particle CFD simulations to calculate drag coefficients, which are averaged over the orbiting period. These newly generated drag correlations can then be used in the Eulerian multiphase model to represent fiber-laden fluid flows.

Literature:

[1] Brydon, A. G., Pourmohammadi, A., & Russell, S. J. (2022). Drylaid web formation. In *Handbook of nonwovens* (pp. 89-180). Woodhead Publishing.

[2] Jin, Y., Liu, Y., & Cui, J. (2023). Numerical study on the motion characteristics of an elastic fiber migrating in a cylindrical Couette flow with centrifugal effect. *Acta Mechanica Sinica*, *39*(3), 322423.