Simulation of the oil storage process in the scopa of specialized bees

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ABSTRACT

Several species of specialized bees possess special structures to store and transport floral oils. By using closely spaced hairs at their back legs, the so called scopa, these bees can absorb and release oil droplets without loss. The high efficiency of this process is a matter of ongoing research. Based on recent X-ray microtomography scans from a bee's scopa, we build a three-dimensional geometric computer model. Then, using *NaSt3DGPF*, a two-phase flow solver developed at the Institute for Numerical Simulation, we compute the micro flow in the scopa model. Our calculations reveal the laminar to turbulent air flow in the scopa during flight. Furthermore, we simulate the deformation of an oil droplet in the scopa due to surface tension effects on a microscopic length scale. Our results are in good agreement with measurements for an oil-wetted scopa at steady state which are obtained from X-ray scans. Both simulations are relevant for the understanding of the process of oil absorption and transportation in the real scopa of a bee. Due to the large computational complexity of the problem, massively parallel computations are essential for our simulations.

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1. Introduction

Several species of specialized bees such as Centridini, Tetrapediini, Ctenoplectridae, see Fig. 1(a), have developed structures to store and transport fatty floral oils instead of nectar (cf. Dressler [1], Buchmann [2]). The floral oil is mixed with pollen and fed to the bee's larvae. The advantage of collecting floral oils instead of nectar stems from the oil's much (8 times) higher energy content. The oil is also used for coating breeding cells to prevent water intrusion due to its hydrophobic behavior.

The oil is collected from the flowers by bristles at the front legs of the bees. It is then transferred from the front legs to closely spaced hairs at the bee's back legs, the so called scopa (cf. Fig. 1(b)), to allow for transportation of the oil to the larvae. This transport structure can be used repeatedly and shows a high efficiency of transported oil mass compared to the scopa's weight.

The scopa has a multiscale structure as its size ranges from millimeters to micrometers. It consists of several types of main hairs (cf. Fig. 1(c)) with a length of 2–3 mm and a diameter of

approximately 40 μm. About 20 lateral hairs with lengths of 400 μm and diameters of 5–12 μm branch out from each main hair. In total, the scopa contains about 900 hairs. They form a three-dimensional grid structure in which the oil is stored. Furthermore, the scopa has an oleophilic surface which, beside the geometry, further facilitates oil collection and storage.

The properties of the multiscale microstructure of the scopa are of great practical interest. Man-made structures with an oil storage efficiency comparable to that of the biological role model are not known yet. One application is the oil separation of washing solutions. These solutions occur, for instance, in the process of car engine cleaning. The washing solution can only be given to the wastewater after the oil has been separated out. In practice, expensive steel coalescer are used for the separation process. Structures that increase the efficiency of the process and which are cheaper to produce are intensively searched for. The scopa of bees might be a role model for such future structures. Therefore, its precise properties need to be better understood. As the effects in the scopa take place on a microscopic length scale and are difficult to measure, simulations of the biological system are necessary. But to the authors' knowledge, there have been no simulations of the oil storage process in a bee's scopa so far. Instead of that, numerical simulations in literature primarily focus on the insect's wing design,

(a) specialized bee Epicharis dejeanii

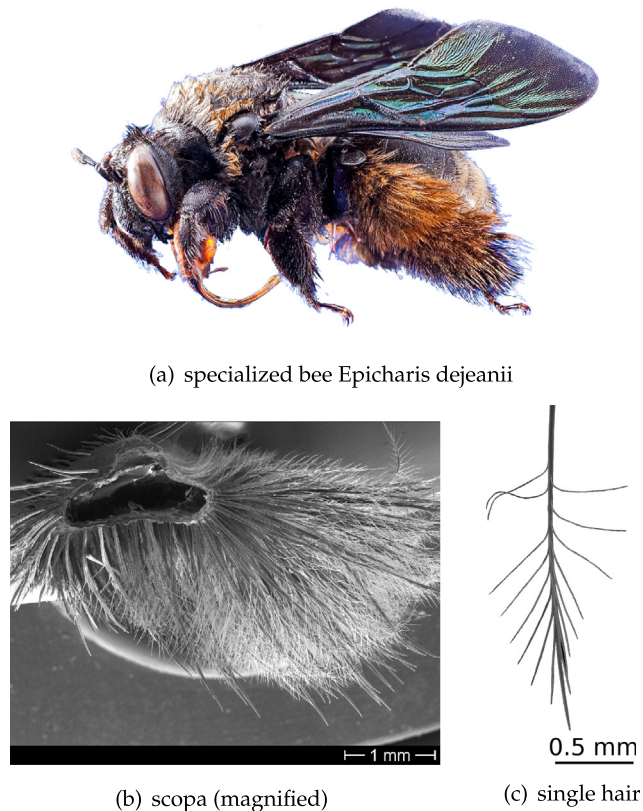(b) scopa (magnified)

(c) single hair

Fig. 1. Photos were taken by the Institute of Crop Science and Resource Conservation (INRES).

see, e.g., Young et al. [3]. In the following, we present the first 3D two-phase flow simulations of an oil droplet within the microscopic scopa.

The remainder of this article is organized as follows: First, in Section 2, we describe the micro-CT measurement of the scopa and the post processing of the measured data necessary to derive a geometric model of the scopa. We then consider the mathematical model for flow dynamics within the scopa. To this end, we state the governing equations and their spatial and temporal discretization used for the two-phase flow solver *NaSt3DGPF* in Section 3. Special focus is given to the boundary conditions on a microscopic length scale. We also explain our domain decomposition approach for parallel computations and discuss the parallel speed-up behavior for the considered problem. In Section 4 we present the simulation results for two specific situations: First, the laminar to turbulent air flow around the scopa's hairs is computed in Section 4.1. Second, in Section 4.2, the deformation of an oil droplet in the scopa geometry is simulated and the outcome is compared to experimental measurements of an oil filled scopa. Finally, in Section 5, we evaluate our findings and give some conclusions.

2. Processing of micro-CT data

The geometric complexity of the scopa is illustrated in Fig. 1(b). In principle, two different approaches are possible to allow for simulations. The structure can either be modeled in a tedious process by hand with a common computer-aided design (CAD) program or it can directly be measured in an experiment from a real scopa by, e.g., a CT scan. The advantage of a CAD modeled geometry is that the surface of the geometry is properly defined and inaccuracies and artifacts due to measurement errors are avoided. On the other

hand, a modeled geometry might not capture all relevant details of the scopa's structure. Nowak et al. [4], for instance, simulate the airflow and the particle deposition in two different geometries of the human lung. While the first geometry is an idealized model, the second geometry bases on a CT-scan and achieves more accurate results.

For this reason, we derive a geometric model from a CT microtomography measurement of the bee species *Epicharis dejeanii* that lives in Southern America. The measurement was performed at the Institute of Textile Technology and Process Engineering Denkendorf (ITV Denkendorf). To this end, the micro-CT *nanotom m* build by GE Sensing & Inspection Technologies GmbH was used. *Nanotom m* has been funded by the Federal Ministry of Education & Research (BMBF) in two projects for the analysis of fiber-reinforced composites and of surface coatings.

The micro-CT consists of an X-ray tube and a digital detector for image capturing. The X-ray tube allows long-time measurements for up to 8 h. Focused on a small target of micrometer size, the X-rays have a power of up to 15 watt. The DXR detector has 3072×2400 pixels with a pixel size of 100 μm. It allows for a scanning resolution up to an accuracy of 0.8 μm. The sensor has a 14 bit color depth so that 16,384 different gray-scale values are used to distinguish small density variations. A CT scan results in a large number of voxel cells which are represented and processed with the software VG-Studio MAX 2.2 by Volume Graphics.

A typical distribution from a micro-CT density measurement is shown in the histogram plot in Fig. 2. The density in each resolved grid cell can have values between 1 and $16{,}384 = 2^{14}$. Thus, there is no natural distinction between solid cells from the scopa cells and the surrounding air cells which renders direct numerical simulations impossible. In the area of medical image segmentation, one viable approach to allow for this distinction is thresholding, see Pham et al. [5] and the references cited therein. We here give the necessary information for its application in a CFD solver. First, a threshold value C has to be chosen such that all voxel cells with a gray-scale value smaller than C are set to air cells. Consequently, cells with a gray-scale value larger than C are identified as a part of the scopa. Fig. 3 compares two different threshold values for the scopa data set. The threshold value C_1 in Fig. 3(a) was deliberately chosen too small so that a larger part of the surrounding volume was identified as a part of the scopa. The same data set is shown in Fig. 3(b) for a different threshold value $C_2 > C_1$. The corresponding geometry occupies less volume and agrees better with the biological data. Since most volume cells of the data set correspond to air, the threshold value is in practice chosen relatively large as indicated by the red vertical line in Fig. 2.
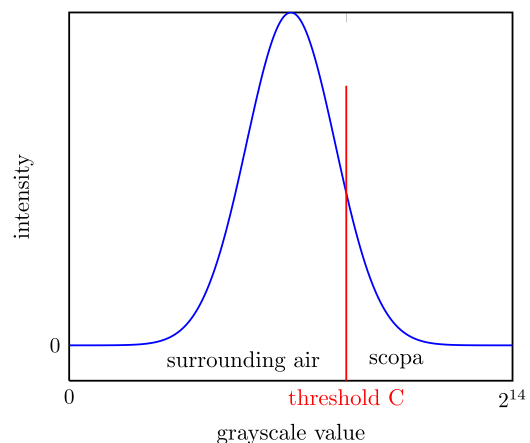

Fig. 2. Histogram with typical distribution of the density values.