Rinse, Sense, Adjust, Repeat: Biomimetic Continuous Process Water Analysis in Washing Machines Based on the Hammerhead Shark’s Olfaction Hydrodynamics

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Domestic household appliances (e.g., washing machines) are major factors in the anthropogenic global energy balance, which is why an efficient control of their energy and material consumption are of great importance in the future. At the same time, most of today’s washing machines can be considered as “black boxes” which lack dynamic analysis techniques for an automated and optimized resource management. Following a biomimetic approach, rapid prototyping methods are combined with high-speed videography and 2D particle tracking. In addition, preliminary work on the functional morphology and hydrodynamic characteristics of the olfactory organ of Sphyrna tudes is utilized to generate a flow channel module suitable for the implementation of diverse state-of-the-art sensor technologies into innovative washing machines. The module’s fluid dynamics are essentially determined by its optimized channel geometry and the fluid’s inflow velocity. Future investigations will reveal whether a precise change of individual hydrodynamic parameters can solely be achieved by a variation of the inflow velocity and whether specific flow profiles can be established to allow for dynamic online analytics of multiple sensors during washing.

1. Introduction

The global energy demand has been rising for decades due to progressive industrialization in combination with steadily growing population numbers and is increasingly causing problems such as supply shortages, depletion of energy resources, or severe environmental impacts.[1] Particularly, energy consumption in buildings is becoming an ever larger factor, which will require more efficient energy and material management in future, whereby the optimization of household appliances (e.g., washing machines) has been identified as an important leverage point.[2] At present, washing machines can be described as a kind of black box in terms of energy and material consumption, which are controlled by a few sensors in combination with the washing program selected by the user (Figure 1a).[3] In addition to other factors like an intelligent (largely automated) operability to avoid use-related errors, innovative systems are currently improved as per the consumption management of the resources used.[4,5] Through the application of recent sensor technology, information on various target substances as well as chemical and physical parameters (e.g., detergent components, microscopic and nanoscopic fibers and dirt particles, pH, temperature, etc.) could be gathered and evaluated online to automate and improve processes such as quality control and consumption optimization during washing (Figure 1b). Nowadays the sensors are placed in different parts of the appliance, mainly according to the access to water and suds, which leads to costs, for example, due to wiring or the requirement of defined housings. Moving toward an autonomous washing machine demands even more sensors. Creating one location where different sensors can be assembled and in parallel providing optimal flow conditions without adding components would be a major step forward due to cost reduction and freedom for the final design. However, both device-specific...
Four criteria are particularly important: 1) the separation of the representative target substances from the main flow and their diversion to the analysis unit, 2) the generation of low, almost constant flow velocities, 3) the maximization of the target-specific residence times to guarantee sufficiently long measuring times, and 4) the generation of the desired flow type (laminar vs turbulent flow). As the detergent drawer of a washing machine represents a replaceable and cost-effective unit that is mostly unaffected by disruptive factors, it might become a suitable location for sensor placement in washing machines, although it currently lacks an optimized flow profile and rarely possesses integrated sensor technology. Interestingly, the same criteria are also fundamental for the functioning of some biological sensory systems, which is why a biomimetic approach is promising to overcome the aforementioned challenges. For example, the perception of environmental stimuli (e.g., blood scents) plays an important role in the life of sharks. In particular, some shark species are able to detect and precisely follow even the smallest amounts of odorants in their pursuit of constantly moving and reorienting prey. This requires that the odorants are efficiently transported to their olfactory epithelium. Some sharks accomplish that using active ventilation mechanisms. Other species, i.e., the smalleye hammerhead sharks (Sphyrna tudes), are obligatory swimmers which utilize their forward swimming movements to create fluid flow through their olfactory chambers. This movement causes a pressure difference between the forward-facing incumbent and the rear-facing excurrent nostrils which act as the driving forces for the fluid flow through the smalleye hammerhead’s olfactory organ and scale up with increasing swimming speeds. To protect their sensory epithelium from damage caused by excessive flow at very high swimming speeds, sharks have evolved both external (e.g., minor and major nasal grooves, Figure 2b) and internal passive regulation mechanisms. During olfaction, the water flow enters the nasal region via the incumbent channel, passes the small sensory channels between the olfactory lamellae, and exits the organ via the excurrent channel. However, this route can be bypassed via apical gaps which interrupt the septum between the incumbent and the excurrent channels at several locations in front of their hairpin bend connection (Figure 2c,d). Following a biomimetic approach, the internal structure of the olfactory organ of S. tudes was abstracted and transferred into three modules, referred to as “Abstraction Level I–III” (ALL–III) (Figure 3a and 4a,b), using both rapid prototyping methods and functional–morphological as well as hydrodynamic characteristics described in preliminary work. Using high-speed videography in combination with 2D particle tracking, the flow profiles of these 3D printed modules were recorded to characterize their hydrodynamic properties. Finally, the suitability of these models for implementation into innovative washing machines was evaluated. The resulting fluid channel design is intended to be used for a sensor support which will help find and develop new washing algorithms with already-existing appliances. The sensor support will be integrated into the detergent drawer which is linked to the circulation path of water supply. An easy integration of state-of-the-art sensors that allow to measure online during the washing process thus is possible. Moreover, the sensor support will be used to combine low-cost sensor concepts from other industries like agriculture with the existing pump in the hydraulic system of a washing machine and also facilitate the transfer of lab-on-a-chip solutions, which yet have to be validated for the washing process.

The ultimate goal of this concept is to achieve a smart, easy-to-implement, and therefore cost-efficient solution toward a resource-efficient “one-button” washing machine.
2. Results and Discussion

2.1. Abstraction Level I: The Emulation of the Olfactory Chamber of Sphyrna tudes

To apply specific sensor devices into the detergent drawers of innovative washing machines, certain requirements are necessary to guarantee their functionality. For example, the fluid flow velocity should be as low and constant as possible, and at the same time, the residence time and frequency of the particles to be detected should be sufficiently high within the designated sensor zone. In this context, the olfactory chamber of the smalleye hammerhead shark (S. tudes) has been selected as an applicable role model for the optimization of the flow profile inside the detergent drawer of washing machines, whose hydrodynamics has already been investigated in detail by Rygg et al. (2013).[18]

The direct emulation of the olfactory chamber into module AL-I revealed that the majority (59%) of all particles tracked took P_\text{B} (zone sequence: Z1–Z4–[Z5–]Z6), followed by P_\text{A} (zone sequence: Z1–Z3–Z5–Z6), with a path frequency of 39% (Figure 5a). P_\text{C} (zone sequence: Z1–Z3 or Z4–Z5–Z2–Z1–Z3 or Z4–[Z5–] Z6), however, can be regarded as a special case that only occurred in 2% of all observations (Figure 5a). This low path frequency on P_\text{C} in module AL-I certainly is a consequence of the extremely small gap openings from Z5 to Z2 in relation to the particle size and the flow direction against an upward inclination within Z2 (see Video 1, Supporting Information), which both tend to favor a particle remaining on P_\text{A} or P_\text{B}, respectively.

The length of the path trajectory of an individual particle, i.e., the standardized total covered distance, increased from P_\text{A} to P_\text{C} as defined earlier. In general, this path-specific increase in trajectory length corresponds with an increase in the degree of branching, i.e., from primary (main channel to primary side channel) or secondary (primary side channel to secondary side channel) junctions, resulting in higher distances to be covered with each additional branching. With the occurrence of recirculation, the average values of s_{\text{tot}} further increased on P_\text{A} and P_\text{C}, whereas the standardized total covered distances between the direct and recirculation path types (see Experimental Section) on P_\text{B} did not differ considerably (Table 1). On P_\text{A} and P_\text{C}, the increase in s_{\text{tot}} on recirculation paths is completely related to the increase in distance caused by the circulation of particles. On P_\text{B}, these differences in s_{\text{tot}} are hardly noticeable, which is

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Figure 2. Anatomy and hydrodynamics in the nasal region of Sphyrna tudes. a) 3D model of the head region of S. tudes reconstructed from high-resolution computer tomography (CT) and magnetic resonance imaging (MRI) scans. The olfactory chambers are shaded red. b) A close-up of the 3D model highlighting the external morphology of the nasal region. c) Streamlines and velocity contours in the olfactory chamber at average swimming speed (0.9 m s\(^{-1}\)). d) Streamlines and velocity contours in the olfactory chamber at maximum swimming speed (1.55 m s\(^{-1}\)). a, anterior; d, dorsal; l, lateral; m, medial; p, posterior; v, ventral. Reproduced and adapted under the terms of the CC-BY license.[18] Copyright 2013. The Authors, published by PLOS.
caused by a lesser amount of performed cycles and by a smaller probability with which individual particles access recirculation paths in the first place (Table 1).

If one compares the zone-specific residence times of particles between the direct and recirculation paths, these time intervals hardly change in five of the six zones of AL-I (Table 1). Only within Z5 (i.e., the prospective sensor zone of AL-I, which functionally but not spatially represents the sensor zone of the biological role model) $t_{\text{zone}}$ showed a threefold increase on recirculation paths (Table 1). From this we conclude that module sections with apparently laminar flow profiles prevented particles from cycling, whereas the majority of particles within turbulent zones is detected on recirculation paths, on which their zone-specific residence times increase with every cycle (Figure 3b, Figure S1, Supporting Information). Independent of the respective module path, the strong positive correlations of $s_{\text{tot}}$ and $t_{\text{tot}}$ with the total amount of performed recirculations per particle further emphasize the aforementioned results (Spearman’s rank order correlation, $s_{\text{tot}}$: $\rho = 0.82$; $t_{\text{tot}}$: $\rho = 0.80$; Figure S2, Supporting Information).

Finally, the particle trajectory velocities were highest in Z1 and lowest in Z2, where particles were more than 86% slower (Table 1). The second lowest values of $v(t)$ could be measured in Z5, especially on recirculation paths (Table 1). In addition to that, the $a(t)$ values of the individual zones in AL-I were very heterogeneous and displayed high variances on both direct and recirculation paths, which is why they should be handled with caution. If one compares the general flow velocity profile of AL-I with that of the biological role model, they look very similar at first glance. Both systems display high flow velocities in their incurrent channels, in the transition areas (large apical gaps) between their incurrent and excurrent channels, as well as in the peripheral areas of their excurrent channels. In contrast to that, low flow velocities prevailed in the hairpin bend regions (Z4) and in the central parts of the excurrent channels (Z5, close to the array of the small apical gaps) in both systems (Table 1, Figure 2c,d and 3). Moreover, these areas are characterized by a turbulent flow, which led to an increased mixing of the tracking or dye particles during investigations (cf. Abel et al.)\[17\].

Finally, the fluid flow of both systems exhibited a decrease in $v(t)$ when the cross-sectional area widened from their incurrent to their excurrent channels, which is in accordance with the principle of continuity of fluid mechanics.\[19\] Thus, it is generally assumed that the formation of the observed flow profile is quite robust and mainly refers to 3D geometry which was transferred from the smalleye hammerhead’s olfactory organ to module AL-I.

However, a closer examination of module AL-I revealed minor differences in fluid dynamics compared with the natural model. First of all, the $v(t)$ values measured in AL-I (0.3–2.2 m s$^{-1}$)
were somewhat higher than those of the natural model (0.1–1.6 m s\(^{-1}\)).\(^{[18]}\) This was mainly due to the higher inflow velocity of module AL-I, which resulted from the high flow rate provided by the submersible recirculation pump (150–800 L h\(^{-1}\)), the performance of which has been chosen according to the specifications of the field of technical application (300–1800 L h\(^{-1}\)) rather than the physiological swimming kinematics of the small-eye hammerhead shark (16.2–28.8 L h\(^{-1}\)).\(^{[18]}\) The higher the inflow velocities, the deeper the oncoming flow penetrated into the system along the incumbent channel. This could easily be observed by comparing the spatial volumes of the near-stagnant recirculation region in the hairpin bend of the small-eye hammerhead shark at different inflow velocities (dark-blue region in the hairpin bend, Figure 2c,d). At average swimming speeds, the volume of the near-stagnant recirculation region is clearly larger compared with the flow profile measured at maximum swimming speeds.
speeds (Figure 2c,d). In module AL-I, this region is completely absent in the hairpin bend due to the even higher inflow velocities (Figure 3b, Figure S1, Supporting Information). In S. tudes, this advantageous mechanism effectively increases the number of sensory lamellae that participate in olfaction at faster swimming speeds, although the detection of chemical cues generally might be more precise in slowly moving sharks due to higher residence times of odorants (cf. Rygg et al.).

The most surprising “potential” deviation between the two systems could be observed inside the small apical gaps within the AL-I flow profile (Z2), where fluid motion promoted a back flow of particles from the excurrent into the incumbent channel (see Video 1, Supporting Information). Presumably, the fluid motion within these small apical gaps is driven by a pressure gradient between the narrow incumbent channel of fast flowing fluid (Z1) and the wide excurrent channel of slow flowing fluid (Z5/Z6) according to Bernoulli’s effect. Should this phenomenon also exist in the olfactory organ of the smalleye hammerhead shark, it would be a hint toward a further passive–adaptive optimization of its sense of smell even at very high speeds of locomotion, where a repeated passage of the sensor would maximize both the residence times and perception probability of chemical stimuli.
Table 1. Descriptive statistics of the particle hydrodynamics within the AL-I module. The data were subdivided according to the path type of individual particles. Particles that passed the module without detour followed a “direct path,” whereas those that performed one or more recirculations travelled a “recirculation path.” To account for module-specific size differences, the $s_{\text{tot}}$ values of each module were standardized using their minimal covered distance on Path A. $a_{\text{tp}}$, particle trajectory acceleration; $s_{\text{tot}}$, total covered distance; $t_{\text{zone}}$, zone-specific residence time; IQR, interquartile range; Max, maximum value; Min, minimum value; N, sample size; $v_{(t)}$, particle trajectory velocity.

| Path type | Parameter | Zone | Path | Median | IQR | Min | Max | N |
|-----------|-----------|------|------|--------|-----|-----|-----|---|
| Direct    | $t_{\text{zone}}$ [ms] | Z1   | –    | 55     | 7   | 45  | 76  | 28|
|           |           | Z2   | –    | 34     | 17  | 9   | 63  | 6 |
|           |           | Z3   | –    | 14     | 7   | 7   | 22  | 15|
|           |           | Z4   | –    | 45     | 35  | 31  | 212 | 16|
|           |           | Z5   | –    | 67     | 66  | 16  | 328 | 18|
|           |           | Z6   | –    | 84     | 31  | 48  | 229 | 28|
|           | $v_{(t)}$ [m s$^{-1}$] | Z1   | –    | 2.2    | 0.3 | 1.3 | 2.5 | 28|
|           |           | Z2   | –    | 0.3    | 0.1 | 0.2 | 0.5 | 6 |
|           |           | Z3   | –    | 1.1    | 0.3 | 0.6 | 1.7 | 15|
|           |           | Z4   | –    | 0.9    | 0.2 | 0.4 | 1.0 | 16|
|           |           | Z5   | –    | 0.8    | 0.3 | 0.5 | 1.0 | 18|
|           |           | Z6   | –    | 1.0    | 0.2 | 0.5 | 1.3 | 28|
|           | $a_{(t)}$ [m s$^{-2}$] | Z1   | –    | −31.8  | 33.4 | −71.0 | 28.4 | 28|
|           |           | Z2   | –    | 0.0    | 24.2 | −34.5 | 54.1 | 6 |
|           |           | Z3   | –    | −17.1  | 70.3 | −125.0 | 387.1 | 15|
|           |           | Z4   | –    | 0.0    | 11.0 | −38.8 | 30.3 | 16|
|           |           | Z5   | –    | 0.0    | 14.0 | −63.7 | 43.5 | 18|
|           |           | Z6   | –    | 6.0    | 12.7 | −8.9 | 52.6 | 28|
|           | $s_{\text{tot}}$ [/] | –    | $P_A$ | 1.0    | 0.1 | 1.0 | 1.1 | 9 |
|           |           | –    | $P_B$ | 1.3    | 0.1 | 1.1 | 1.3 | 13|
|           |           | –    | $P_C$ | 1.8    | 0.3 | 1.6 | 2.1 | 6 |
| Recirculation | $t_{\text{zone}}$ [ms] | Z1   | –    | 47     | 13  | 30  | 78  | 32|
|           |           | Z2   | –    | 31     | 30  | 8   | 79  | 14|
|           |           | Z3   | –    | 23     | 14  | 8   | 101 | 25|
|           |           | Z4   | –    | 53     | 61  | 34  | 114 | 13|
|           |           | Z5   | –    | 182    | 179 | 56  | 515 | 25|
|           |           | Z6   | –    | 74     | 45  | 21  | 238 | 31|
|           | $v_{(t)}$ [m s$^{-1}$] | Z1   | –    | 1.9    | 0.6 | 1.2 | 2.6 | 32|
|           |           | Z2   | –    | 0.2    | 0.3 | 0.1 | 0.8 | 14|
|           |           | Z3   | –    | 0.8    | 0.3 | 0.6 | 1.4 | 25|
|           |           | Z4   | –    | 0.8    | 0.3 | 0.5 | 1.2 | 14|
|           |           | Z5   | –    | 0.6    | 0.2 | 0.4 | 0.8 | 25|
|           |           | Z6   | –    | 0.9    | 0.3 | 0.5 | 1.4 | 31|
|           | $a_{(t)}$ [m s$^{-2}$] | Z1   | –    | −17.7  | 38.4 | −52.7 | 75.9 | 32|
|           |           | Z2   | –    | 0.0    | 0.0 | −88.1 | 26.3 | 14|
|           |           | Z3   | –    | −16.6  | 54.5 | −155.0 | 173.8 | 25|
|           |           | Z4   | –    | −11.4  | 17.5 | −65.9 | 11.4 | 13|
|           |           | Z5   | –    | −0.5   | 3.1 | −10.4 | 17.2 | 25|
|           |           | Z6   | –    | 12.2   | 22.5 | −23.5 | 35.6 | 31|
|           | $s_{\text{tot}}$ [/] | –    | $P_A$ | 1.7    | 1.1 | 1.1 | 3.6 | 11|
|           |           | –    | $P_B$ | 1.3    | 0.3 | 1.2 | 2.0 | 7 |
|           |           | –    | $P_C$ | 2.5    | 0.3 | 2.1 | 4.9 | 14|
2.2. Abstraction Level II: The Design Simplification of AL-I

In a second level of abstraction (AL-II) the design of module AL-I was simplified (Figure 4a). By this, two goals were pursued: 1) a better predictability of the hydrodynamic aspects (e.g., for a facilitated placement of sensors) and 2) a general simplification in favor of manufacturing and maintenance processes. With 63% of all tracked particles, \( P_A \) (zone sequence: Z1–Z2–Z3) clearly had the highest particle frequency in AL-II (Figure 5a). On \( P_B \) (zone sequence: Z1–Z4–Z5–Z6–Z7) and \( P_C \) (zone sequence: Z1–Z4–Z7–Z6–Z3), the particle frequencies were considerably lower with 15% and 22%, respectively. Essentially, these path frequencies strongly depended on the branching angles of primary and secondary junctions, as well as on the Y position of advancing particles in front of such junctions (Figure 4e). Particularly, the smaller the branching angle and lower the Y position of an advancing particle, the higher its probability to deviate from its current path (Figure S3c,e, Supporting Information). Compared with those of AL-I, the branching angles were considerably larger in AL-II (AL-I: 2°–30°; AL-II: 70°–90°).

When comparing the standardized total covered distances of particles on direct paths of modules AL-I and AL-II, they were almost identical. In addition, both modules showed an increase in \( s_{tot} \) for particles of the same module path that have entered recirculation instead of a direct path (Table 1 and 2). In AL-II, however, this could only be observed on \( P_C \), as neither particles of \( P_A \) nor \( P_B \) were able to enter recirculation paths (Table 2). The reason for this is that particles on \( P_A \) and \( P_B \) only pass zones of apparently laminar flow with no recirculation, whereas those on \( P_C \) have to pass Z7 (i.e., the prospective sensor zone of AL-II), which was the most turbulent zone of AL-II, displaying numerous recirculations (Figure 4c). In contrast, any particle within AL-I is capable of performing recirculations, as the respective module paths are not distinctly separated from each other, as this is the case in the modules AL-II (and AL-III) and as all particles in AL-I have a high probability to enter the turbulent zone Z5 (Figure 3b). However, not only the type of flow (apparently laminar vs turbulent) to which a particle is exposed, but also its trajectory velocity and time of exposure to turbulence determine whether it is deflected onto a recirculation path or not. The lower the trajectory velocity and/or the longer the exposure to turbulent flow, the lower is the probability of individual particles to pass turbulences without being deflected onto a recirculation path.

Just as in AL-I, each performed recirculation did not only increase the total covered distance of a particle, but also the zone-specific residence time of the respective particle in AL-II, which was specifically underlined by the strongly positive correlation of these parameters (Spearman’s rank order correlation, \( \rho = 0.82; t_{zone} \): \( \rho = 0.82 \); Figure S2, Supporting Information). Therefore, it was not surprising that particles on paths with long trajectories also exhibited long residence times. If, however, the \( t_{zone} \) values of particles on both recirculation and direct paths are compared with those of AL-I, the corresponding residence times in AL-II zones were generally shorter (Table 1 and 2). This is probably a consequence of the overall channel geometry of AL-II, which highly affects the number of particles being able to reach recirculation path trajectories. Particularly, particles in AL-II mainly pass zones of apparently laminar flow with comparatively high flow velocities, in which they were hardly slowed down by collisions with the channel wall or other particles. Moreover, the fluid flow’s angle of incidence directly in front of Z7 favors a fast passage of this turbulent (sensor) zone. In the end, only particles in Z7 (recirculation path) stood out with \( t_{zone} \) values being nearly as high as the longest residence times of AL-I (Table 1 and 2).

In addition, particles in Z7 also possessed the slowest trajectory velocities within AL-II (Table 2). Independent of the flow channel module under consideration (AL-I or AL-II), the zones with the longest particle residence times displayed very low trajectory velocities. Again, this flow profile characteristic is related to the channel geometry of the given module, although a contribution of additional factors (e.g., inflow velocity) cannot be excluded presently. More precisely, the duct diameter of such zones with low flow velocities increases in comparison with their respective upstream channel sections. Following the principle of continuity of fluid mechanics, the widening of a channel results in a reduction of the flow velocity of the fluid (cf. Vogel). At the same time, the formation of vortices (turbulent flow) is likely to be observed in such areas. In conformity with the Venturi effect, the taper of the channel diameter toward the outlet of the sensor zone led to a renewed increase of flow velocity. Besides geometry, particle-wall and particle-particle collisions also affected the particle trajectory velocities. The less they collided with the channel wall and/or other particles, the higher their measured velocities.

As a general rule, the highest fluid velocities were determined at the main channel sections with the smallest channel diameters (i.e., the incurrent channel of AL-I or the section subsequent to tapering in AL-II).

Finally, the \( A(t) \) values of particles, i.e., the change in particle velocity over time, were heterogeneous on both direct and recirculation paths in AL-II. On average the fluid was neither accelerated nor decelerated inside the sensor zone, whereby the large spread of \( A(t) \) values indicates the existence of velocity changes, which can be explained by both changes in channel diameters (principle of continuity) and fluid-wall interactions (friction or backwater zones).

2.3. Abstraction Level III: The Hydrodynamic Optimization of AL-II

In a third level of abstraction (AL-III) the general hydrodynamic characteristics of AL-II were optimized by both transferring the sensor zone (Z6) to the secondary side channel system to increase the degree of branching in front of it and implementing a second biological principle into the primary side channel system (Z9). The majority of particles within the side channel system followed \( P_C \) and thus passed the slow and turbulent flow within Z6 (i.e., the prospective sensor zone of AL-III). Nevertheless, 88% of the tracked particles in AL-III followed \( P_A \) (zone sequence: Z1–Z2–Z3) without performing any recirculations (Figure 5a and Figure S3, Supporting Information). Similar to that described for module AL-II, only particles that entered AL-III at low Y positions had the possibility to enter the side channel system (Figure S3, Supporting Information). Only 2% of the particles in AL-III took \( P_B \) (zone sequence:
Table 2. Descriptive statistics of the particle hydrodynamics within the AL-II module. The data were subdivided according to the path type of individual particles. Particles that passed the module without detour followed a “direct path,” whereas those that performed one or more recirculations travelled a “recirculation path.” To account for module-specific size differences, the $s_{\text{tot}}$ values of each module were standardized using their minimal covered distance on Path $A$. $s_{\text{tot}}$, total covered distance; $t_{\text{zone}}$, zone-specific residence time; IQR, interquartile range; Max, maximum value; Min, minimum value; N, sample size; $v(t)$, particle trajectory velocity.

| Path type     | Parameter | Zone | Path | Median | IQR | Min | Max | N  |
|---------------|-----------|------|------|--------|-----|-----|-----|----|
| Direct        | $t_{\text{zone}}$ [ms] | Z1   | –    | 7      | 28  | 2   | 58  | 51 |
|               |           | Z2   | –    | 4      | 0.3 | 3   | 6   | 20 |
|               |           | Z3   | –    | 6      | 13  | 3   | 20  | 51 |
|               |           | Z4   | –    | 14     | 29  | 3   | 50  | 31 |
|               |           | Z5   | –    | 50     | 11  | 39  | 64  | 20 |
|               |           | Z6   | –    | 18     | 26  | 7   | 47  | 31 |
|               |           | Z7   | –    | 34     | 9   | 26  | 81  | 11 |
|               | $v(t)$ [m s$^{-1}$] | Z1   | –    | 1.0    | 0.4 | 0.4 | 1.7 | 51 |
|               |           | Z2   | –    | 1.0    | 0.4 | 0.6 | 1.4 | 20 |
|               |           | Z3   | –    | 1.9    | 0.3 | 1.1 | 2.6 | 51 |
|               |           | Z4   | –    | 1.1    | 0.6 | 0.7 | 1.7 | 31 |
|               |           | Z5   | –    | 0.8    | 0.2 | 0.6 | 1.1 | 20 |
|               |           | Z6   | –    | 1.0    | 0.2 | 0.8 | 1.4 | 31 |
|               |           | Z7   | –    | 0.6    | 0.2 | 0.3 | 0.8 | 11 |
|               | $a(t)$ [m s$^{-2}$] | Z1   | –    | 0.0    | 52.3| −590.0 | 1120.0 | 50 |
|               |           | Z2   | –    | 0.0    | 52.3| −250.0 | 500.0  | 20 |
|               |           | Z3   | –    | 153.3  | 156.0| −60.0  | 666.7  | 51 |
|               |           | Z4   | –    | 0.0    | 25.7| −117.5 | 250.0  | 31 |
|               |           | Z5   | –    | −9.5   | 22.8| −28.2  | 18.2   | 20 |
|               |           | Z6   | –    | 28.6   | 54.9| −125.0 | 186.7  | 31 |
|               |           | Z7   | –    | 0.0    | 34.0| −51.3  | 38.5   | 11 |
|               | $s_{\text{tot}}$ [/] | –    | $P_A$ | 1.0    | 0.1 | 1.0  | 1.1   | 20 |
|               |           | –    | $P_B$ | 1.3    | 0.2 | 1.1  | 1.5   | 20 |
|               |           | –    | $P_C$ | 1.7    | 0.04| 1.6  | 1.9   | 11 |
| Recirculation | $t_{\text{zone}}$ [ms] | Z1   | –    | 4      | 3   | 2   | 6   | 9  |
|               |           | Z2   | –    | –      | –   | –   | –   | –  |
|               |           | Z3   | –    | 5      | 2   | 4   | 8   | 9  |
|               |           | Z4   | –    | 42     | 4   | 34  | 50  | 9  |
|               |           | Z5   | –    | –      | –   | –   | –   | –  |
|               |           | Z6   | –    | 43     | 3   | 36  | 47  | 9  |
|               |           | Z7   | –    | 132    | 101 | 31  | 492 | 9  |
|               | $v(t)$ [m s$^{-1}$] | Z1   | –    | 1.1    | 0.1 | 1.0 | 1.4 | 9  |
|               |           | Z2   | –    | –      | –   | –   | –   | –  |
|               |           | Z3   | –    | 2.0    | 0.2 | 1.5 | 2.5 | 9  |
|               |           | Z4   | –    | 0.8    | 0.1 | 0.7 | 0.9 | 9  |
|               |           | Z5   | –    | –      | –   | –   | –   | –  |
|               |           | Z6   | –    | 0.9    | 0.1 | 0.8 | 1.0 | 9  |
|               |           | Z7   | –    | 0.3    | 0.1 | 0.2 | 0.5 | 9  |
|               | $a(t)$ [m s$^{-2}$] | Z1   | –    | 0.0    | 102.5| −410.0 | 207.5  | 8  |
|               |           | Z2   | –    | –      | –   | –   | –   | –  |
|               |           | Z3   | –    | 166.7  | 360.0| −51.3 | 647.5  | 9  |
|               |           | Z4   | –    | −9.3   | 11.4| −27.6| 0.0  | 9  |
|               |           | Z5   | –    | –      | –   | –   | –   | –  |
Z1–Z4–Z9–Z8–Z3), whereas only 10% took P_C (zone sequence: Z1–Z4–Z5–Z6–Z7–Z8–Z3) (Figure 5a, Figure S2, Supporting Information). The very low particle frequency on P_B, even as compared with the already relatively low frequency on P_C, was caused by the extreme size differences of the channel sections at the secondary junction in AL-III (Z4 → Z5 vs Z4 → Z9). Although multiple particles have been directed toward the entrance of Z9, the majority of them was deflected toward P_C, as the diameter of the Z9 entrance (ø 1.0 mm) hardly exceeded the average particle diameter (ø 0.7 mm).

In contrast, the standardized total covered distances in AL-III were the highest amongst all three modules (Table 1, 2, and 3). Here, the differences of s_{tot} between direct and recirculation paths corresponded to an increase in 32% and 48% on P_B and P_C, respectively (Table 3). Just as in AL-II, the highest zone-specific residence times of AL-III could be observed on recirculation paths. Both s_{tot} and t_{zone} again correlated positively with the number of performed recirculations (Spearman’s rank order correlation, s_{tot}: ρ = 0.61; t_{zone}: ρ = 0.80; Figure S2, Supporting Information). In addition, particles passing the sensor zone (Z6), i.e., that have taken path P_C, have spent the longest time within AL-III, closely followed by those passing Z9 (i.e., path P_B) (Table 3). Thereby, the increase in s_{tot} and t_{zone} values within Z6 can be attributed to the increase in the degree of branching in front of the sensor zone and the implementation of Z9, which together altered the module’s flow profile (i.e., the angle of incidence and the particle trajectory velocity) in a way that Z6 could hardly be passed directly by entering particles. In contrast, the inner wall structure within Z9, which was inspired by the geometry of ring tracheids, led to the formation of isolated vortices in the spaces between two adjacent rings, which could retain particles for a considerable amount of time.[24]

As in the previous flow channel modules (AL-I and AL-II), zones with high residence times also exhibited very low trajectory velocities (Table 1, 2, and 3). As opposed to AL-II, however, the trajectory velocities of particles within the sensor zone of AL-III remained more or less constant, showing very small variances of α_{fi}, if at all (Table 3). This generally lowered and stabilized v_{fi} values within the sensor zone, resulting from the aforementioned hydrodynamic optimizations which consisted of decoupling the prospective sensor zone from the comparatively fast fluid flow of the side channel system.

### 2.4. Comparison of the Designated Sensor Zones of the Modules AL-I, AL-II, and AL-III

As described in the previous sections, common features of the designated sensor zones were the presence of turbulences, the occurrence of very long residence times, as well as low and almost constant particle trajectory velocities in comparison with the remaining zones within their respective flow channel module. Taken together, these criteria ensured that a high percentage of the incoming particles were deflected onto recirculation paths and thus forced to stay in the system for longer time periods. In this regard, the occurrence of turbulent flow might be beneficial (e.g., for the homogenization of a respective target substance within the process water through mixing).[23] However, it can also be detrimental to dynamic analyses within a technical process when turbulences grow into significant disturbance variables under certain conditions.

Irrespectively, it has already been shown that the hydrodynamic parameters of AL-I very well resembled those of the natural role model, the olfactory organ of the smalleye hammerhead shark. Comprehensibly, the hydrodynamic characteristics of the AL-I sensor zone were considered to be suitable for the use of sensors in technical applications (Table 4). In particular, virtually every particle is capable of entering AL-I’s sensor zone and besides that has a high probability of being deflected onto a recirculation path within it. Moreover, as mentioned before, the low trajectory velocity hinders particles from leaving the sensor zone, thereby increasing their residence times whose sufficient duration is crucial for a technical transfer. Additionally, the smaller the variation of the particle velocity (a_{fi}) in the sensor zone, the more reliable the implemented sensor technology functions in the technical application.[6]

The basic problem, however, was the high complexity of the natural model, and thus also of module AL-I, which entailed major challenges from an industrial perspective in areas such as production, maintenance, and operability. Therefore, the channel geometry of the module was simplified in a second level of abstraction while still maintaining its bioinspired functional principle. For this purpose, the main flow was clearly separated from the higher-order flows by introducing primary and secondary side channels, from which the primary side channel also contained the sensor zone. However, this led to a deterioration of the hydrodynamic parameters within the sensor zone. First of all, the probability of particles entering both the sensor zone itself and recirculation paths within the sensor zone decreased considerably by 78% and 17%, respectively (Table 4). In general, these phenomena were evoked by the spatial arrangement of AL-II’s main and side channels, which prevented incoming particles with high Y positions from reaching the side channel system. In contrast, t_{zone} of AL-II decreased significantly by 50 ms in comparison with the corresponding value of AL-I (Kruskal–Wallis test, X^2 (2) = 6.84, p < 0.05; Dunn posthoc testing; Figure 5b),
Table 3. Descriptive statistics of the particle hydrodynamics within the AL-III module. The data were subdivided according to the path type of individual particles. Particles that passed the module without detour followed a “direct path,” whereas those that performed one or more recirculations travelled a “recirculation path.” To account for module-specific size differences, the $s_{tot}$ values of each module were standardized using their minimal covered distance on Path A. $a_{ij}$, particle trajectory acceleration; $s_{tot}$, total covered distance; $t_{zone}$, zone-specific residence time; IQR, interquartile range; Max, maximum value; Min, minimum value; N, sample size; $v_{ij}$, particle trajectory velocity.

| Path type | Parameter | Zone | Path | Median | IQR | Min | Max | N |
|-----------|-----------|------|------|--------|-----|-----|-----|---|
| Direct    | $t_{zone}$ [ms] | Z1   | –    | 36     | 38  | 1   | 53  | 32|
|          |           | Z2   | –    | 3      | 1   | 2   | 5   | 20|
|          |           | Z3   | –    | 14     | 1   | 12  | 15  | 20|
|          |           | Z4   | –    | 63     | 23  | 42  | 118 | 15|
|          |           | Z5   | –    | 15     | 2   | 13  | 17  | 4 |
|          |           | Z6   | –    | 27     | 21  | 17  | 42  | 4 |
|          |           | Z7   | –    | 15     | 1   | 14  | 18  | 4 |
|          |           | Z8   | –    | 64     | 27  | 32  | 135 | 15|
|          |           | Z9   | –    | 42     | 4   | 38  | 62  | 11|
|          | $v_{ij}$ [m s$^{-1}$] | Z1   | –    | 0.9   | 0.2 | 0.0 | 2.2 | 32|
|          |           | Z2   | –    | 1.0   | 0.5 | 0.5 | 1.5 | 20|
|          |           | Z3   | –    | 2.1   | 0.1 | 1.8 | 2.3 | 20|
|          |           | Z4   | –    | 0.7   | 0.2 | 0.4 | 0.9 | 15|
|          |           | Z5   | –    | 1.2   | 0.1 | 1.1 | 1.3 | 4 |
|          |           | Z6   | –    | 0.8   | 0.4 | 0.4 | 1.0 | 4 |
|          |           | Z7   | –    | 1.1   | 0.1 | 0.9 | 1.3 | 4 |
|          |           | Z8   | –    | 0.5   | 0.2 | 0.3 | 0.8 | 15|
|          |           | Z9   | –    | 0.7   | 0.2 | 0.6 | 0.9 | 11|
|          | $a_{ij}$ [m s$^{-2}$] | Z1   | –    | 0.0   | 35.9| −142.9 | 2240.0 | 28|
|          |           | Z2   | –    | 92.3  | 375.0| −282.0 | 790.0  | 20|
|          |           | Z3   | –    | 71.4  | 64.0 | −89.2 | 154.3 | 20|
|          |           | Z4   | –    | −6.3  | 13.9 | −29.5 | 24.7  | 15|
|          |           | Z5   | –    | 35.7  | 72.8 | 0.0  | 76.9  | 4 |
|          |           | Z6   | –    | 0.0   | 18.7 | −47.6 | 27.0  | 4 |
|          |           | Z7   | –    | 33.3  | 72.1 | 0.0  | 88.6  | 4 |
|          |           | Z8   | –    | 0.0   | 10.3 | −24.3 | 21.3  | 15|
|          |           | Z9   | –    | −9.8  | 22.5 | −25.0 | 0.0   | 11|
|          | $s_{tot}$ [/] | –    | $P_A$ | 1.1   | 0.03 | 1.0  | 1.2   | 20|
|          |           | –    | $P_B$ | 1.9   | 0.1  | 1.8  | 2.2   | 11|
|          |           | –    | $P_C$ | 2.1   | 0.1  | 2.0  | 2.2   | 4 |
| Recirculation | $t_{zone}$ [ms] | Z1   | –    | 4     | 2   | 2   | 11   | 21|
|          |           | Z2   | –    | –     | –   | –   | –    | – |
|          |           | Z3   | –    | –     | –   | –   | –    | – |
|          |           | Z4   | –    | 64    | 34  | 45  | 123  | 25|
|          |           | Z5   | –    | 15    | 1   | 12  | 18   | 16|
|          |           | Z6   | –    | 218   | 314 | 55  | 624  | 16|
|          |           | Z7   | –    | 14    | 3   | 11  | 18   | 16|
|          |           | Z8   | –    | 51    | 31  | 26  | 127  | 25|
|          |           | Z9   | –    | 179   | 142 | 39  | 596  | 9 |
|          | $v_{ij}$ [m s$^{-1}$] | Z1   | –    | 1.0   | 0.4 | 0.0 | 1.6  | 21|
|          |           | Z2   | –    | –     | –   | –   | –    | – |
|          |           | Z3   | –    | –     | –   | –   | –    | – |
|          |           | Z4   | –    | 0.6   | 0.2 | 0.4 | 0.8  | 25|
|          |           | Z5   | –    | 1.1   | 0.1 | 1.0 | 1.3  | 16|
which resulted from the fact that the sensor zone was not decoupled from the main flow direction within the side channel. Only the significant decrease in particle trajectory velocity as a consequence of the sensor zone’s geometry turned out to be beneficial (Kruskal–Wallis test, $X^2 (2) = 28.71, p < 0.001$; Dunn posthoc testing; Figure 5c), although the associated increase in variation of $a_{fl}(t)$ once more mitigated this advantage.

Finally, a third abstraction step combined the advantages of the previous modules, while, at the same time, eliminating or at least reducing the majority of disadvantages. By implementing the wall structures of ring tracheids to the primary side channel system and shifting the sensor zone to the secondary side channel system, the percentage of recirculating particles was markedly increased within the sensor zone without altering $v_{fl}(t)$ (Kruskal–Wallis test, $X^2 (2) = 28.71, p > 0.05$; Dunn posthoc testing; Figure 5c and Table 4). At the same time, however, the maximum percentage of particles entering the sensor zone was cut in half due to its relocation to the secondary side channel system (Table 4). Depending on the intended sensor technology, a particle density of 10% in the sensor zone can be either advantageous or disadvantageous. If the particle density is too low to guarantee a reliable read-out of the installed sensor, this parameter must be fine tuned in future module versions. In the opposite case, however, the low particle density will not interfere with the measurements and might even offer an advantage when using certain sensors by keeping the background noise low. Regarding the residence time of individual particles within the sensor zone, the hydrodynamic optimization of AL-II led to a significant prolongation of $\approx 60\%$ (Kruskal–Wallis test, $X^2 (2) = 6.84, p < 0.05$; Dunn posthoc testing; Figure 5b), as they moved slowly and likely performed recirculations. Ultimately, when comparing the particle trajectory accelerations between particles of the respective sensor zones, no significant differences could be found (Kruskal–Wallis test, $X^2 (2) = 2.96, p > 0.05$; Dunn posthoc testing; Figure 5d). On average, they experienced neither acceleration nor deceleration. However, the span of the $a_{fl}(t)$ values decreased from AL-I to AL-III (Figure 5d). Accordingly, the sensor zone of AL-III combined the best hydrodynamic characteristics for the application of sensor technology. In future investigations it will therefore be necessary to optimize the AL-III module toward a specifically adjustable flow type (laminar vs. turbulent flow) as a function of the inflow velocity. Moreover, the use of multiple sensor zones per module is conceivable.

### 3. Conclusions

The present biomimetic study showed that an excellent concept from nature, the fluid dynamics in the olfactory organ of the smalleye hammerhead shark, could successfully be transferred into a technical flow channel module and optimized for the use of dynamic online sensory applications in the detergent

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**Table 3.** Hydrodynamic comparison of the biomimetic flow channel modules. The hydrodynamic parameters of the biomimetic flow channel modules AL-I, Al-II, and AL-III are highlighted to compare their potential to meet the intended industrial requirements.

| Parameter | Zone | AL-I | AL-II | AL-III |
|-----------|------|------|-------|--------|
| Maximum percentage of particles entering the sensor zone | 100% | 22% | 10% |
| Percentage of particles entering recirculation paths in the sensor zone | 67% | 50% | 80% |
| Average residence times of particles in the sensor zone [ms] | 182 | 132 | 218 |
| Average particle trajectory velocity in the sensor zone [m s$^{-1}$] | 0.58 | 0.35 | 0.36 |
| Average variation of the particle trajectory velocity in the sensor zone | Small | Large |

**Table 4.** Hydrodynamic comparison of the biomimetic flow channel modules. The hydrodynamic parameters of the biomimetic flow channel modules AL-I, Al-II, and AL-III are highlighted to compare their potential to meet the intended industrial requirements.
drawer of innovative washing machines.\cite{26} Furthermore, its intrinsic flow profile was essentially determined by the fluid’s inflow velocity and the module’s channel geometry, which comprised a sensor zone, whose hydrodynamic characteristics are suitable for the use of a wide variety of sensor technologies. All flow channel modules were created using modern 3D printing processes, which are becoming increasingly relevant for the production and research of fluidic devices. Not only the short time from design to production and the availability of a wide variety of materials (e.g., transparent materials) are significant advantages, but also the fact that there are virtually no limits to design.\cite{27,28} As printing costs are continuously decreasing and printing speeds are increasing, the introduction to the consumer market is rapidly gaining momentum.\cite{29} In future investigations, it will be determined whether a precise change in individual hydrodynamic parameters can solely be achieved by a variation in the inflow velocity and whether specific flow profiles can be established that allow for dynamic online analytics of multiple sensors during washing.

4. Experimental Section

Design and Manufacture of the Flow Channel Modules: Three individual flow channel modules were designed in SolidWorks 2017 and manufactured from transparent photopolymeric material (Clear Resin, Formlabs Inc., Somerville, Massachusetts, USA) using a UV light curing 3D printer (Form 2 SLA, Formlabs Inc.). To avoid an attenuation of its general transparency caused during the chemical removal of the support material, each module was covered by a custom-made lid, comprising an insertable container and connected to the pump via flexible tubing. The essential structures of the olfactory organ of Sphyrna tudes were transferred to a first flow channel module (AL-I, first level of abstraction), the dimensions of which corresponded as detailed as possible to the natural role model. Particularly, the structural geometries of the incumbent and excurrent channels, the apical gap, and the hairpin bend were implemented into this direct reconstruction, ‘biomimicking’ the biological role model as closely as technically possible (Figure 3a).\cite{30,31,24} However, the transfer of the lamellar sensory epithelium, i.e., the actual sensor zone of the biological role model, was foregone with future economic manufacturability in mind and in favor of an improved high-speed video analysis, as the lamellae would have masked the view on the flow profile inside the main channels. To ensure a detailed evaluation of the module’s flow hydrodynamics, AL-I was subdivided into six different zones (Z1–Z6). Here, Z1 corresponded to the shark’s incumbent channel, whereas Z5 and Z6, respectively, formed the turbulent and laminar parts of the excurrent channel (Figure 3b, Figure S1, Supporting Information). Moreover, the apical gaps were arranged into a set of narrow channels (Z2) and a rent channel (Figure 3b, Figure S1, Supporting Information). Moreover, the high-speed flow channel module was provided as a tapering was implemented to build up a pressure gradient between the incumbent and excurrent channel by applying the Bernoulli effect, thereby ensuring flow through the side channel system. Moreover, a prospect sensor zone (Z7) was introduced to the primary side channel system.

Finally, functional optimization was realized in the third level of biomimetic abstraction (AL-III), comprising a total of nine zones (Z1–Z9) (Figure 4b,d). To improve the general hydrodynamic characteristics (i.e., maximization of the target-specific residence times to guarantee sufficiently long measuring times to the sensors) of the prospective sensor zone (Z6), it was incorporated to the secondary side channel system. Simultaneously, a second abstracted biological principle, which was inspired by the ring-shaped wall thickenings of xylem conduits, was implemented into the primary side channel system.\cite{24} These optimizations functioned on the basis of two principles: 1) the fast-flowing fluid bypassed the sensor zone through Z9, where the recirculation zones in the cavities between two adjacent rings facilitated the gliding of the core flow over the cavity fluid (Figure 4b), and 2) the majority of particles within the side channel system was deflected toward the slow and turbulent flow within Z6.\cite{24} It is important to note that the zone numbers of both AL-II and AL-III were neither directly related to the zone numbers of AL-I, nor to the anatomy of the olfactory chamber of S. tudes.

Construction of the Flow Channel Test Setup: The fluid flow optimization experiments were conducted in a small custom-built flow channel (Figure 6a). A 35 × 35 × 35 cm acrylic box was used as a water reservoir, which was covered by a custom-made lid, comprising an insertable container that allowed for an easy exchange of different flow channel modules (Figure 6b). Both the lid and the test container were designed using SolidWorks 2017 and manufactured from polyactic acid (PLA) material (Premium PLA, Formfutura BV, Nijmegen, Netherlands), using a 3D printer (Form 2 SLA, Formlabs Inc., Irvine, California, USA). The inside of the test container resembled the size (18.80 × 9.00 × 6.55 cm) of a standard drawer of a conventional washing machine. In addition, slide-in slots were added to the container design to allow the integration of different test modules into the flow channel. A universal submersible recirculation pump (Silence 1037.008, Tunze Aquarientechnik GmbH, Penzberg, Germany) guided the fluid at a flow rate of 800 L h⁻¹ from the reservoir through a given module, which was mounted into the test container, and back into the tank (see arrows in Figure 6a).

High-Speed Video Recording: To analyze module-specific flows by applying 3D particle tracking, high-speed videos were recorded from the top-view perspective (frame rate: 1000 fps, exposure time: 300 μs) using a high-speed camera (NX4-S1, Integrated Design Tools Inc., Tallahassee, Florida, USA) equipped with a macro lens (Macro-Planar T*2/100 ZF, Carl Zeiss AG, Oberkochen, Germany) together with a high-performance light-emitting diode (LED) cold light source (Constellation 120, IDT Inc.) for illumination. The camera was positioned above the test setup and aligned perpendicular to the mounted flow channel module, whereas the cold light source was installed slightly angled alongside the camera (Figure 6a). The complete system was switched on at least 5 min before the first video recording to ensure the complete establishment of the respective flow profile. From all high-speed recordings, one exemplary video per flow channel module was provided as Supporting Information (Videos 2–4, Supporting Information).

2D Particle Tracking: Ground black pepper (Le Gusto schwarzer Pfeffer gemahlen, 22151070, Teuto Markenvertrieb GmbH, Dissen, Germany) was added to the water reservoir as tracking particles. Individual particle sizes of the trackable pepper platelets varied between 110 × 50 μm and 710 × 340 μm (major × minor axis). A magnetic stirrer placed under the acrylic tank was used to homogenize the fluid-particle suspension. The analysis of the recorded high-speed video material using 2D particle tracking was performed with the open-source platform for image analysis (FIJI) and its built-in manual tracking plugin.\cite{32} In a first step, all possible passages of the particles through the flow channel modules were identified for each module by pre-evaluating the recorded high-speed video material. These pre-evaluations revealed three clearly distinguishable flow paths (P₁, P₂, and P₃) per module, whose lengths increased by definition from P₁ to P₃. Subsequently, 20 particles per passage route were randomly selected and quantitatively tracked. In a separate approach, the first 100 particles entering the module were tracked qualitatively to determine the path frequency distribution (f) of a given module.

Calculation of Particle Hydrodynamics: The particle displacement (sₜ), the trajectory velocity (vₜ), and the trajectory acceleration (aₜ) of individual particles were calculated at any point in time across all video frames, using the respective X and Y pixel coordinates and the following equations

\[ sₜ (t) = \int_v vₜ (t) \, dt \]

\[ vₜ (t) = \frac{d}{dt} sₜ (t) \]

\[ aₜ (t) = \frac{d}{dt} vₜ (t) \]
\[
s(t) = \sqrt{(X(t_{i+1}) - X(t_i))^2 + (Y(t_{i+1}) - Y(t_i))^2}
\]
\[
\nu(t) = \frac{\Delta s(t)}{\Delta t} \quad \text{with} \quad \Delta t = t_{i+1} - t_i = \frac{1}{\text{frame rate}} = 0.001 \text{s}
\]
\[
a(t) = \frac{\Delta \nu(t)}{\Delta t} \quad \text{with} \quad \Delta t = 0.001 \text{s and} \quad \Delta \nu(t) = \nu(t_{i+1}) - \nu(t_i)
\]

Moreover, the total residence time (\(t_{\text{tot}}\)) and the total covered distance (\(s_{\text{tot}}\)) of each particle within a given module were calculated from module entry to module exit using Equation (4) and (5):

\[
t_{\text{tot}} = (n - 1) \Delta t
\]

with \(n = \text{total number of frames per particle tracking}\)

\[
s_{\text{tot}} = \sum_{i=1}^{n} s(t)
\]

In general, all hydrodynamic parameters were calculated according to specific zonation schemes that were established for the individual flow channel modules (Figure 3b and 4c,d). In particular, the position of each particle was assigned to its current zone at any given point in time before the calculation of the hydrodynamic parameters took place. Moreover, the data of all 20 trackings for each module path were subdivided in two groups according to the way an individual particle passed the module. Here, a direct passage was distinguished from tracking trajectories, in which the particles underwent at least one recirculation while travelling through the module. Here, recirculation is defined as the formation of a cyclic section along a particle trajectory that occurs within a single zone of the flow channel module. In contrast, the term loop denotes the formation of a cyclic section along a particle trajectory that spreads across multiple channel zones. To account for module-specific size differences, the total covered distances were standardized using the \(s_{\text{tot}}\) of \(P_x\) of the respective module. Finally, a suitable sensor zone was selected for each flow channel module according to its hydrodynamic characteristics.

Statistics and Data Analyses: Data analysis and statistics were conducted with R 3.3.0 including the additional packages \texttt{car}, \texttt{ggplot2}, \texttt{reshape2}, and \texttt{psych}. Primarily, the calculated hydrodynamic parameters of the 2D particle trackings were analyzed using descriptive statistics. For each module, median, interquartile range, maximum and minimum values of the zone-specific residence times (\(t_{\text{zone}}\)), the trajectory velocities (\(\nu(t)\)), and the trajectory accelerations (\(a(t)\)) were determined. To determine significant differences in \(t_{\text{zone}}\), \(\nu(t)\), and \(a(t)\) between the module-specific sensor zones, Kruskal–Wallis tests were performed together with Dunn tests (posthoc tests with P-value adjustments according to Holm (1979)), after the assumptions for normally distributed data (Shapiro–Wilks test), and homoscedasticity of the variances (Levene test) were checked. For the total covered distance (\(s_{\text{tot}}\)) the same set of descriptive statistics was computed for all three paths within each module. Finally, the number of recirculations performed per particle was correlated with both \(t_{\text{tot}}\) and \(s_{\text{tot}}\) for all predefined module paths by calculating their Spearman’s rank correlation coefficients (\(\rho\)). Positive correlations showed a value for \(\rho > 0.3\), whereas \(\rho < 0.3\) indicated negative correlation. The strength of the correlation was classified in three groups (weak correlations: \(0.3 \leq \rho < 0.5\) and \(-0.5 < \rho \leq -0.3\); medium correlations: \(0.5 \leq \rho < 0.7\) and \(-0.7 < \rho \leq -0.5\); strong correlations: \(0.7 \leq \rho \leq 1\) and \(-1 \leq \rho \leq -0.7\)). Uncorrelated parameters displayed correlation coefficients between \(-0.3\) and \(0.3\). Complete datasets were given in Supporting Information.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

Keywords
2D particle tracking, flow optimizations, high-speed video analyses, sensor applications, Sphyrna tudes

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