EILERS GRADUATE STUDENT FELLOWSHIP
FINAL REPORT

EILERS FELLOW:	Mitsugu Hasegawa
FACULTY ADVISOR:	Hirotaka Sakaue
REPORT PERIOD:	2020
PROJECT TITLE:	Development of a Drag Reduction Technique Using a Microfiber Coating Inspired by Hair-follicles on the Seal
CONNECTION TO ND ENERGY'S RESEARCH AREAS (CHECK ALL THAT APPLY):	**(x) Energy Conversion and Efficiency** **( ) Smart Storage and Distribution** **( ) Sustainable Bio/Fossil Fuels** **( ) Sustainable and Secure Nuclear** **( ) Transformation Solar** **(x) Transformative Wind**

MAJOR GOALS AND ACCOMPLISHMENTS:

List your major research goals and provide a brief description of your accomplishments (1-2 sentences). Indicate the percentage completed for each goal. Please use a separate sheet to share additional details, technical results, charts, and graphics.

MAJOR RESEARCH GOALS	ACTUAL PERFORMANCE AND ACCOMPLISHMENTS	% OF GOAL COMPLETED
Development of microfiber coating for flow control	Fabrication of microfiber coating having a hair-like structure was performed in a laboratory using electrostatic flocking. Correlation between orientation and density of the fabricated microfiber was characterized. The physical aspect of flocking behavior was also investigated. The length of the microfiber coating was successfully controlled from 0.3 mm to 4.0 mm. The prototype of the orientation and density-controlled microfiber coating was also produced. The improvement in orientation and density control in the flocking process is a remaining challenge.	80
Demonstration and characterization of drag reduction technique using a cylinder with microfiber coating	Aerodynamic testing was performed using a cylinder with a microfiber coating with different lengths and positions. Drag impact was evaluated. It is found that: (1) microfiber coating can reduce cylinder drag if the shorter fiber is applied before separation point else if, the longer fiber is applied after separation point; (2) both length and position of microfiber coating play important roles for the drag reduction.	100
Theoretical foundation of drag reduction technique using a microfiber coating	Experimental investigation of flow features of a cylinder with microfiber coating was performed. The flow separation can be delayed resulting in drag reduction if microfiber coating is applied before the separation point. However, it is still questionable why microfiber coating can reduce drag if it is applied after the separation point.	60

RESEARCH OUTPUT:

Please provide detailed information below regarding any output resulting from your research project.

CATEGORY	INFORMATION
EXTERNAL PROPOSALS	National Science Foundation (NSF) proposal is under construction. The proposal will be submitted to fluid dynamics program.
EXTERNAL AWARDS	N/A
JOURNAL ARTICLES	1. *Journal of Fluids and Structures*, Microfiber coating for drag reduction on a cylinder, Mitsugu Hasegawa and Hirotaka Sakaue, Submitted Aug 2020, *Under review.* 2. *Sensors and Actuators A: Physical*, Development of Microfiber Coating for Flow Control: Effects on Microfiber Length in Orientation Control, Mitsugu Hasegawa and Hirotaka Sakaue, May 2020, Vol. 312.
BOOKS AND CHAPTERS	N/A
PUBLIC PRESENTATIONS, SEMINARS, LECTURES	1. Invited lecture at Kanagawa Institute of Technology (Virtual lecture), "Microfiber coatings for bluff body flow control", 2020 November, Japan. 2. 73rd Annual Meeting of the APS Division of Fluid Dynamics (Virtual event), American Physical Society, "Microfiber coating for drag reduction in a cylinder flow", 2020 November, Chicago.

	3. Conference presentation at AIAA SciTech Forum and Exposition 2020, "Investigation of Drag Reduction on a Circular Cylinder using Microfiber Coating by changing its Permeability", 2020 January, San Diego.
AWARDS, PRIZES, RECOGNITIONS	N/A
INTERNAL COLLABORATIONS FOSTERED	Dr. Gianluca Blois, Department of Aerospace and Mechanical Engineering The purpose of collaborative research is to understand the near wake structure of cylinder flow with microfiber coating using particle image velocimetry.
EXTERNAL COLLABORATIONS FOSTERED	Tanaka-Ai USA, Material and Chemical distributor The purpose of collaborative research is to find the potential application of microfiber coating: (1) drag reduction of pipe flow; (2) noise reduction of rotating blade.
WEBSITE(S) FEATURING RESEARCH PROJECT	http://sites.nd.edu/sakaue-lab/microfiber-coating/ The website provides introduction of the research project on microfiber coating for drag reduction.
OTHER PRODUCTS AND SERVICES (e.g., media reports, databases, software, models, curricula, instruments, education programs, outreach for ND Energy and other groups)	The part of the research progresses has been submitted to ND IDEA center for potential patent application.

MAJOR GOALS AND ACCOMPLISHMENTS
(Additional Details, Technical Results, Charts and Graphics)

1. Development of microfiber coating for flow control

Microfiber coating having a hair-like structure was developed using electrostatic flocking. Figure 1 schematically describes the fabrication method of the microfiber coating in the present project. Aligned microfibers were planted over an adhesive layer to anchor the ends of the fibers to the substrate surface. Nylon 6/6, Poly (hexamethylene adipamide) was selected as the material of the microfiber. By using different lengths of fiber filament, microfiber coatings with variable heights were produced. The length of the microfiber coating can be changed from 0.3 mm to 4.0 mm.

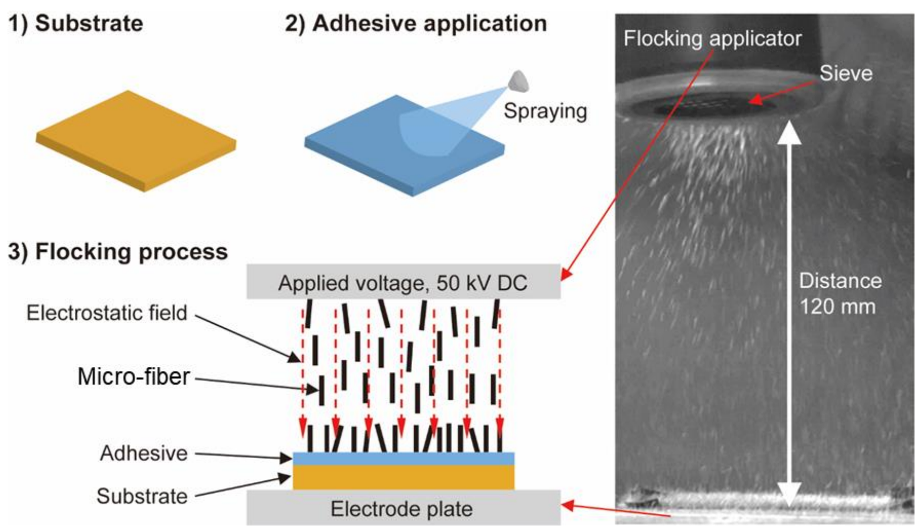

Figure 1: Fabrication process of microfiber coating.

To evaluate the controllability of coating parameters such as density and orientation in the electrostatic flocking, the alignment control of the fibers was characterized. To study the effect of the fiber length and its alignment over an adhesive surface, the microfiber length, k, of 0.54±0.05mm, 0.91±0.03mm, 1.52±0.09mm, and 2.53±0.04mm was used for the flocking. Figure 2 (a) shows the frequency of occurrence of different azimuthal angles for coatings with various microfiber lengths. Figures 2 (b) to 2 (e) show representative microscopic images of the microfiber coatings seen from a lateral view. If the azimuthal angle was between 60° and 90°, the direction of microfibers was said to be well aligned by the fabrication method discussed in section 3.1. The frequency of occurrence of angles between 60° and 90° was 86%, 74%, 64%, and 61% for k = 0.54 mm, 0.91 mm, 1.52 mm, and 2.53 mm, respectively. The best-controlled case, where the most fibers were well aligned, occurred with the shortest fibers. However, regardless of the fiber length, no more than 15% of microfibers had an azimuthal angle, θ_A, less than 30°.

Table 1 summarizes mean surface density of the microfibers. The surface density increases as the microfiber length decreases. It is clearly shown that fiber length also influences the surface density of microfiber coatings as well as the azimuthal angle.

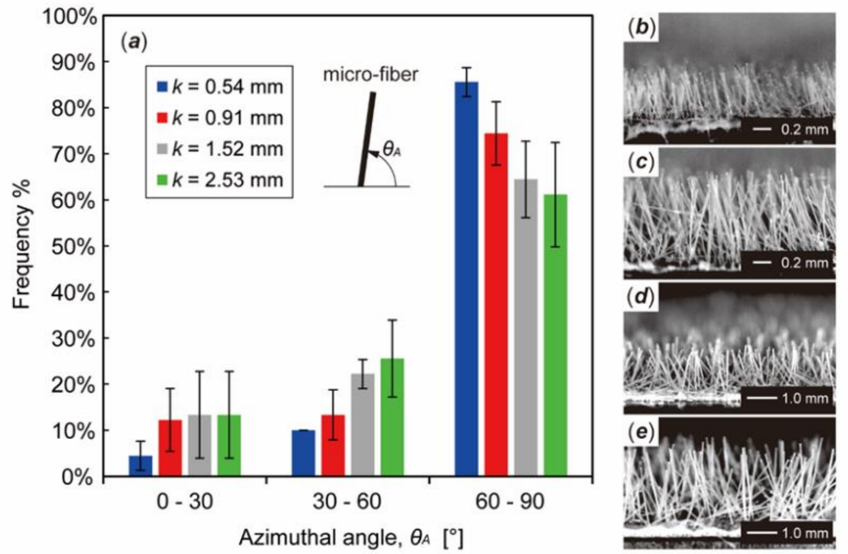

Figure 2: Azimuthal angle of microfiber coatings with various microfiber lengths: (a) frequency histogram; lateral image of (b) k = 0.54 mm; (c) k = 0.91 mm; (d) k = 1.52 mm; and (e) k = 2.53 mm. Error bars represent standard deviation of a data set.

Table 1: Surface density of microfiber coating with various fiber length.

Microfiber length, k [mm]	Surface density, g [fibers per mm^2]
0.54	84 ± 17
0.91	60 ± 13
1.52	14 ± 5
2.53	6 ± 1

Figure 3 shows a correlation between the azimuthal angle and the surface density with respect to the microfiber length. The microfiber length was normalized by the shortest fiber, k = 0.54 mm, given as k/k_{ref}. The azimuthal angle was normalized by the average angle in the case of the shortest microfiber length, f/f_{ref}. Similarly, the surface density was normalized by the average density in the case of the shortest fiber length, g/g_{ref}. As the microfiber length increased, the azimuthal angle was less controlled. Similarly, as the length increased, the surface density was reduced. One can see that the angle and surface density were related with respect to the microfiber length.

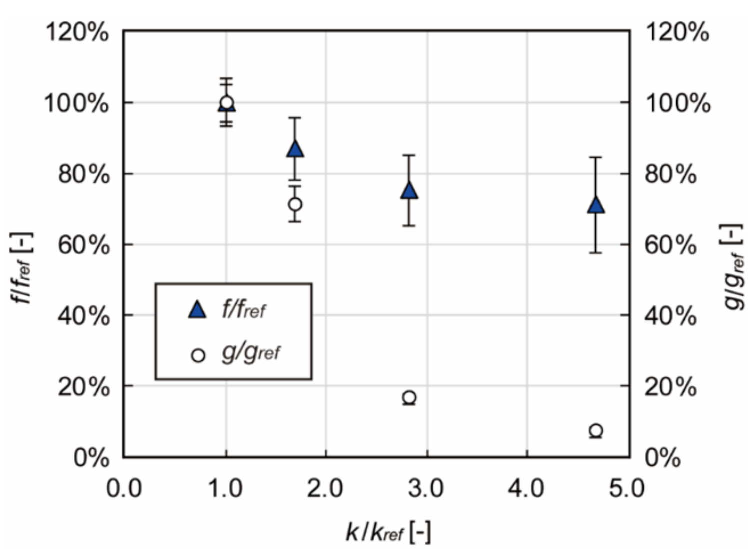

Figure 3: Occurrence of azimuthal angle and surface density of microfiber coatings with respect to microfiber length. Error bars represent standard deviation.

Fast-frame images during the flocking process were captured with a high-speed camera (AX100, Photron, Tokyo, Japan) to evaluate the microfiber alignment in a time-resolved manner. High-speed imaging was used to understand the behavior of a microfiber under an electrostatic field. Figure 4 shows high-speed images focusing on a single microfiber with k = 2.53 mm during flocking. The process shown is described: (1) the fiber travels to the adhesive layer. (t_1 - Figure 4), (2) the fiber lands on the adhesive layer. (t_2 - Figure 4), (3) the fiber oscillates (t_3 to t_9 - Figure 4), and (4) the fiber is aligned almost perpendicular to the surface with $\theta_A > 60°$ (t_{10} - Figure 4).

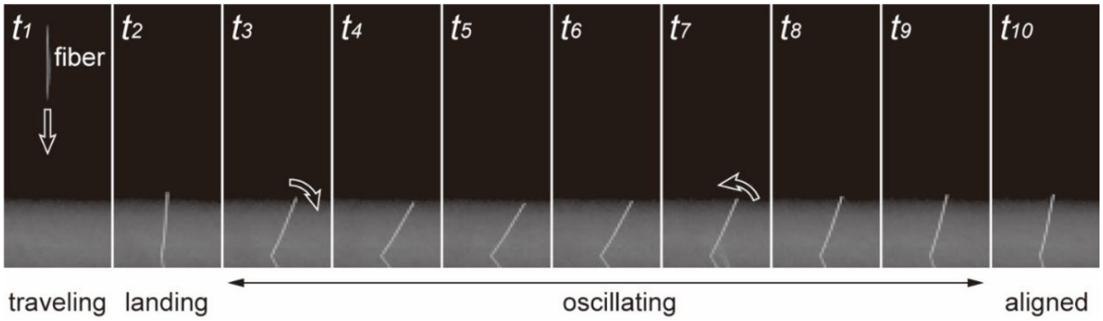

Figure 4: Fast-frame imaging of a single microfiber with k = 2.53 mm during flocking process. The time interval between each frame was 1/3000 s.

The length of microfibers makes a difference in the surface density as shown in Table 1. One of the causes of such a difference is the fiber angle. Inclined fibers occupy more surface area of the adhesive layer as seen from above. This decreases the probability of a traveling fiber landing in an open space without any interaction. This leads to a decrease in the surface density due to the interactions between a new landing fiber and existing inclined fibers on the adhesive layer. Such interactions also lead to the occurrence of more uncontrolled fibers. Since flocked fibers tend to be more inclined if they are longer in length, shown in Figure 3, the surface density decreases as the fiber length increases.

Figure 5 and Figure 6 show the prototype of microfiber coating; density and orientation are controlled, respectively. Figure 5(a) shows the uncontrolled microfiber coating. It is clearly dense and unoriented. While Figure 5 (b) shows a controlled microfiber coating. The density of fiber elements is reduced, and they are well orientated. Figure 6 (a) shows the uncontrolled microfiber coating. It is unoriented. While Figure 6 (b) shows the angle-controlled microfiber coating. The angle is controlled and well orientated.

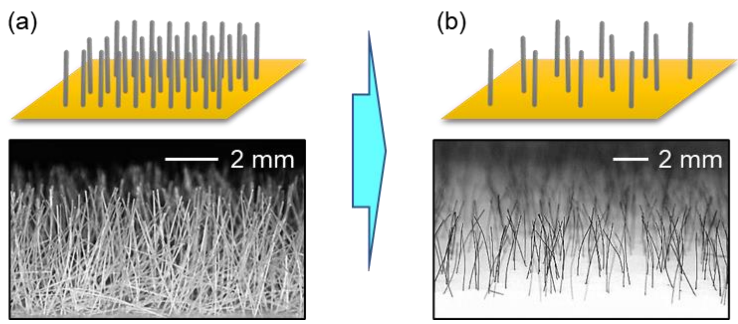

Figure 5: The prototype of density-controlled microfiber coating.

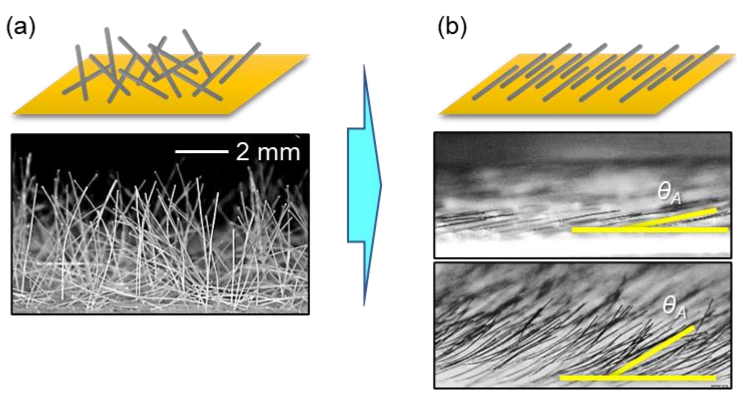

Figure 6: The prototype of angle-controlled microfiber coating.

2. Demonstration and characterization of drag reduction using a cylinder with microfiber coating

Microfiber can reduce cylinder drag, and both the length and position of microfiber coating play important roles in drag reduction. Aerodynamic testing was performed using a cylinder with/without microfiber coating. Figure 7 shows the drag impact for representative cases from the aerodynamic testing campaign. It was found that: (1) Drag decreased if microfiber coating with shorter length ($k/D \leq 1.8\%$) was applied before separation point; (2) Drag also decreased if microfiber coating with longer length ($K/D \geq 3.3\%$) was applied after separation point.

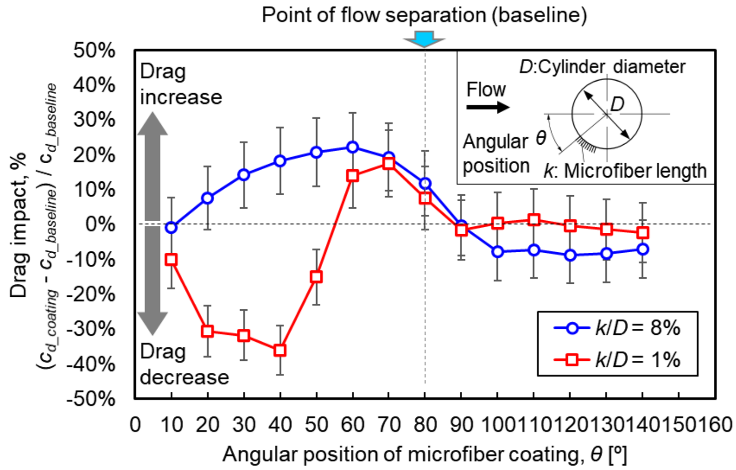

Figure 7: Drag impact, *DI*, by microfiber coating as a function of the coating position on the cylinder. The length of the microfiber coating was 1% and 8% of the cylinder diameter. Error bars represent the combination of the random uncertainty in measurements and the system uncertainty in instruments.

3. Theoretical foundation of drag reduction using microfiber coating

Microfiber coating can achieve two distinctive drag reductions depending on the length and position of microfiber coating: (1) Cylinder drag is reduced if the microfiber coating with a shorter length is applied before the separation point; (2) Cylinder drag is reduced if the microfiber coating with a longer length is applied after the separation point. Figure 8 (a) and (b) show the schematic of both flow control by microfiber coating.

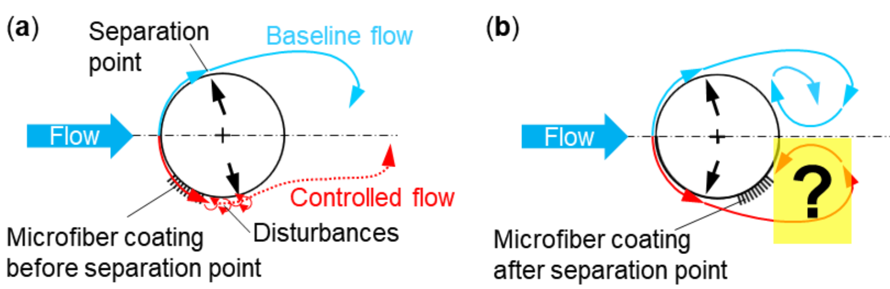

Figure 8: A schematical concept of controlled flow by microfiber coating: (a) Microfiber coating applied before separation point; (b) Microfiber coating applied after separation point.

For the former, the microfiber coating can cause separation delay resulting in drag reduction. The fibrous surface can feed disturbances into the laminar boundary layer. The disturbances induce laminar boundary layer transition resulting in separation delay, as shown in Figure 8 (a). The increase in wetted area over the cylinder surface leads to reducing the pressure drag of the cylinder. Figure 9 shows streaklines around the cylinder. It was shown that microfiber coating delays separation point compared to the bare cylinder.

For the latter, it is still questionable why longer microfiber coating can reduce drag if it is applied to after separation point. There are vortices formed behind the cylinder. Microfiber coating may suppress the formation and shed of the vortices, which impact drag. To identify the mechanism, further investigation on the near wake flow structure will be required.

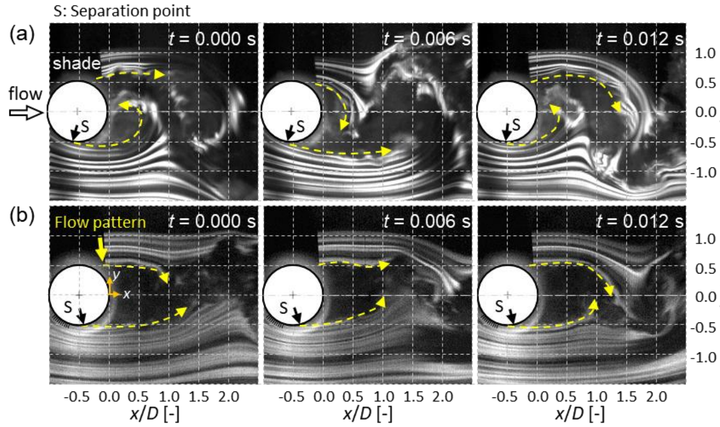

Figure 9: Time series of flow field around the cylinder by smoke flow visualization. **S** indicates the point of flow separation. Comparison of wake flow for (a) bare cylinder, (b) cylinder with microfiber coating at θ = 40°. The length of microfiber is k/D = 1%.