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This is the accepted version of a paper published in *Chemical Engineering Journal*. This paper has been peer-reviewed but does not include the final publisher proof-corrections or journal pagination.

Citation for the original published paper (version of record):

Ghorbani, M., Araz, S A., Talebian, M., Kosar, A., Cakmak Cebeci, F. et al. (2019)
Facile Hydrodynamic Cavitation ON CHIP via Cellulose Nanofibers Stabilized
Perfluorodroplets inside Layer-by-Layer Assembled SLIPS Surfaces
Chemical Engineering Journal
<https://doi.org/10.1016/j.cej.2019.122809>

Access to the published version may require subscription.

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-259752>

Facile Hydrodynamic Cavitation ON CHIP via Cellulose Nanofibers Stabilized Perfluorodroplets inside Layer-by-Layer Assembled SLIPS Surfaces

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Abstract

The tremendous potential of “hydrodynamic cavitation on microchips” has been highlighted during recent years in various applications. Cavitating flow patterns, substantially depending upon thermophysical and geometrical characteristics, promote diverse industrial and engineering applications, including food and biomedical treatment. Highly vaporous and fully developed patterns in microfluidic devices are of particular interest. In this study, the potential of a new approach, which includes cellulose nanofiber (CNF)- stabilized perfluorodroplets (PFC5s), was assessed inside microfluidic devices. The surfaces of these devices were modified by assembling various sizes of silica nanoparticles, which facilitated in the generation of cavitation bubbles. To examine the pressure effects on the stabilized droplets in the microfluidic devices, the upstream pressure was varied, and the cavitation phenomenon was characterized under different experimental conditions. The results illustrate generation of interesting, fully developed, cavitating flows at low pressures for the stabilized droplets, which has not been previously observed in the literature. Supercavitation flow pattern, filling the entire microchannel, were recorded at the upstream pressure of 1.7 MPa for the case of CNF-stabilized PFC5s, which hardly corresponds to cavitation inception for pure water in the same microfluidic device.

Keywords: Hydrodynamic Cavitation; Perfluorodroplets (PFC5); Cellulose Nanofibers (CNFs); Pickering; Microfluidic Device; Layer-by-Layer Assembled

1 Introduction

Cavitation phenomenon has gained much attention in industrial and biomedical applications, due to its potential in the use for environmentally benign cleaning, energy harvesting and cancer treatment [1–3]. Cavitation phenomenon occurs due to a rapid change in static pressure within a liquid, whereupon gas-filled cavities are generated in the low-pressure region. Cavitation bubbles collapse when encountering the high-pressure region, and intense shock waves form, followed by a micro-jet generation from the center of the bubble. Size effects are important in the generation of cavitation phenomenon, and microfluidic systems are suitable platforms for fundamental studies to shed light on microscale cavitation phenomena [4,5]. The major differences between micro- and macro-scale hydrodynamic cavitation lie in cavitation inception, cavitation hysteresis and rapid transition to supercavitation flow pattern and choked flow [4,5]. There are several studies on parameters affecting the generation of cavitation phenomenon. Flow rate, cavitation number [6], Reynold (Re) number and inception of cavitation are the crucial parameters, which assist in understanding cavitation phenomenon [6–9]. Additionally, the working fluid plays an important role. For example, in the case of a mixture of ethanol and water, choking flow conditions could be obtained at very low cavitation numbers [10].

The formation of cavitating flows in microfluidic systems leads to high temperature gradients and enhanced thermal effects [11], and thermal energy generation is possible due to bubble collapse on the wall of microfluidic devices [12]. Recently, it was shown that the generation of cavitation bubbles and collapse of the bubbles are affected by thermophysical properties of the working fluids as well as the surface topology of the channels inside the microfluidic device [13]. Controlling these parameters helped researchers to develop microfluidic devices capable of generating intensified cavitating flows while decreasing the required energy for achieving

the supercavitation flow pattern [14]. As a result, large amount of thermal energy could be generated from a small scale cavitation phenomenon, which could potentially fulfill personal energy needs in environmental friendly fashion.

Inspired by the need for clean energy, the focus in this study is on further intensifying the cavitation phenomenon, in order to generate larger temperature gradients, which is achieved herein by including a new cavitation intensifying strategy. Indeed, cavitation could also potentially be intensified in the presence of rapidly expanding capsules. In this regard, we investigate the potential of particle-stabilized perfluoropentane (PFC5) droplets as cavitation intensifiers. Particle-stabilized droplets are much more stable compared to a surfactant stabilized droplet, because the particles do not easily detach from the O/W interface [15]. This makes particle-stabilized PFC5 droplets promising with the respect to storage stability, because droplets will not merge together into bigger droplets with time. In other words, it is possible to produce a device, where energy can be stored and then released “on demand” in the form of heat.

Here, we present a novel device, which combines a tailored microfluidic channel, ensuring fully developed cavitating flows at very low upstream pressures, together with a new class of cellulose nanofiber-stabilized PFC5 droplets, where the O/W interface is stabilized by the cellulose nanofibers (CNF). By evaluating the energy released from the collapse of the cavitation bubbles, we demonstrate that the CNF-stabilized PFC5 droplets, in combination with the tailored surface roughness of the microfluidics device, represent a unique device in terms of lateral heat release. In addition, as the cellulose nanofibers remain intact after energy release, the particle-stabilized droplets could potentially be regenerated and also stored before being used again.

2 Methods and Materials

2.1 Fabrication of the microfluidics device

All the microfluidic devices were fabricated out of double side polished silicon wafers with a thickness of 380 μm . A schematic of the fabrication protocol [16] is shown in Figure 1A. All the devices employed in this study have small and short side wall roughness elements, as reported in detail in the previous studies of the authors [14]. The microfluidic devices contain two major regions, namely a microchannel followed by an extension (extended channel) downstream of the microchannel. The flow restrictive element induces a sudden drop in pressure due to reduction in cross-sectional area so that small bubbles from the flow restrictive element can be generated due to hydrodynamic cavitation. In addition, the walls of the microchannels are equipped with three pressure sensors to measure the local pressures at the locations (shown as P_1 , P_2 and P_3 in Figure 1B), namely before the entrance of the restrictive element, vena contracta (D_h) and entrance of the extended channel ($5D_h$ - $8D_h$) [17]. Two microfluidic devices with different hydraulic diameters and side wall roughness length were employed in this study. These elements were formed as a structural roughness according to the geometry design. The detailed properties of these devices are listed in Table 1. Meanwhile, the equivalent sand-grain roughness (k_s) was calculated as 5.863 μm using the algorithm presented by Adams et al. [18], which is suitable for low measured roughness values.

Table 1. Dimensions for the different parts of the microfluidic devices

Microfluidic device	Microchannel	Side wall roughness	Side wall roughness
	hydraulic diameter, D_h [μm]	Length	Height

CH1	66	0.3L	0.01D _h
CH2	75	0.5L	0.01D _h

2.2 Surface Modifications of the device

2.2.1 Materials used for surface modifications

Tetraethyl Orthosilicate (TEOS), Ammonia hydroxide solution 25%, 2-Propanol 99.5% (IPA), Poly(sodium 4-styrenesulfonate), average Mw ~70,000 (SPS), Poly(allylamine hydrochloride), average Mw 50,000 (PAH), 1H,1H,2H,2H-Perfluorodecyltriethoxysilane 97% (PFDTs) were purchased from the Sigma Aldrich company. Fomblin Y LVAC 25/6, average molecular weight of 3.300 (PFPE) was purchased from the Solvay company.

2.2.2 Synthesis of silica particles

The modified Stöber method was employed to synthesize monodispersed Silica NPs as described in literature [19]. The zeta potential and diameter of the nanoparticles, which were tuned by the ratio of [TEOS]/[NH₃]_{aq}, were measured using the Dynamic Light Scattering (DLS) technique (Malvern Zetasizer Nano ZS). The silica nanoparticles were synthesized in a bath with [TEOS]/[NH₃]_{aq} ratio of 4. The diameter, PDI and zeta potential of the particles were measured as 100 nm, 0.050 and -37.5 mV, respectively.

2.2.3 Surface modification with the use of silica particles

The silica particle coating in the interior of the microfluidics device was achieved by depositing several layers of PAH and SPS polyelectrolytes as adhesion layers, and then PAH and NPs layers, to achieve the desired rough surface, were formed on the substrates using the layer-by-layer method. In total, 30 bilayers were needed to achieve the desired surface

roughness. The surface tension was adjusted using PFDTs to trap Fomblin YL VAC 25/6 lubricant within the pores of the surface.

2.3 Preparation of Cellulose nanofibers (CNFs)

Never-dried bleached sulfite pulp (Nordic Paper Seffle AB, Sweden) was used to obtain the cationic quaternary ammonium salt modified cellulose nanofibers (CNFs). A 1.32 wt% CNF suspension in water was prepared as previously described [20,21]. The amount of cationic groups residing on the CNF surface was 0.13 mmol per g fiber, obtained by conductometric titration [20,22]. The CNFs have already been characterized in a previous study and had a width of ca. 4 nm and their length was in the micrometer range, which was assessed by TEM [20]. However, bigger fiber aggregates could also be observed with TEM [20].

2.4 Preparation of CNF-stabilized PFC5 droplets

The stock CNF was diluted with MilliQ-water to obtain a 0.28 wt% suspension of CNF. The pH was adjusted to 9.5. To disperse the CNFs, the suspension was treated an ultrasonic liquid processor (Sonics Vibracell W750, U.S.) at an amplitude of 90% for 180 s (using a ½” tip), as previously described [20]. The suspension was brought to room temperature and afterwards 36 g of the attained CNF suspension was mixed with 1 g of PFC5. Afterwards, the mixture was processed for another 60 s at an amplitude of 80% under ice-cooling to obtain the stock suspension of CNF-stabilized PFC5 droplets. The droplets were imaged after ca. 1 h with a Light microscopy (VisiScope, VisiCam 16 Plus camera, VWR, Sweden).

2.5 Characterization

2.5.1 Atomic force microscopy (AFM)

Nanomechanical properties of the thin films and surface topography were assessed by Bruker multimode 8 Atomic Force Microscope (AFM). The height images were captured using NanoAndMore tips with a bending spring constant of 40 N m⁻¹, resonance frequency of 50-

200 kHz, and tip radius of 10-20 nm, and the mechanical properties were assessed using tips with bending spring constant of 200 N m⁻¹ resonance frequency of 500-600 kHz, and tip radius of 25-35 nm. The minimum deformation of the surface in nanomechanical properties evaluation was set as 2-5 nm, and the scan rate was 0.5-1 Hz. The height images of the CNFs were captured (ScanAsyst mode in air) with a Bruker NanoScope V (U.S.A.). A diluted drop of the CNF suspension (ca. 0.003 wt%) was dropped on cleaned silicon-wafer, allowed to settle for 3 min and then removed and dried with nitrogen gas. All images were processed using procedures for plane-fit and flattened.

2.5.2 Scanning electron Microscopy (SEM)

The surface morphology of samples was imaged with the Field Emission Scanning Electron Microscopy (FE-SEM, LEO Supra VP-55). The samples were sputter-coated with a (~10 nm) thick coating of Au/Pd prior to imaging.

2.5.3 Ellipsometry measurements

Woollam Co. M2000 ellipsometry was used to measure and model the thickness and the porosity of the films. The wavelength of the light, which has been used to conduct the ellipsometry measurements, was in the range of 380 to 780 nm (~1.6–3.3 eV). The porosity of the thin film was modeled using the Bruggeman effective medium approximation (EMA) with ellipsometry [23].

2.5.4 Contact angle measurements and contact angle hysteresis

The hydrophobicity of the films was assessed by contact angle and contact angle hysteresis (CAH) measurement using Attension Theta Lite (Biolin Scientific, Finland). 5 µL of distilled water (18.2 MΩ·cm) was accumulated on the tip of the needle and then released on the surface. By increasing and decreasing the volume of water residing on the surface and measuring the maximum and minimum contact angles, the contact angle hysteresis was calculated. The

reported values are the average of three measurements for each sample type.

2.6 Cavitation experiments

The glass wafer on the modified microfluidic devices assists in visualizing flows inside the microfluidic devices. The experiments were conducted by applying different inlet pressures. The inlet pressure was varied from 1 to 7.23 MPa, while the outlet pressure at the microchannel was fixed to 0.1 MPa. The volumetric flow rate was increased with the change in the inlet pressure. Concentration and volume fraction of the CNF-stabilized PFC5 droplets employed in this study have values of approximately 0.027 vol% and 10^8 droplets mL^{-1} at room temperature. Cavitating flows generated in the microchannel were visualized at different regions in the microfluidic devices. The whole steps of the visualization experiments were explained in detail in the previous study of the authors [16].

3 Results and Discussion

3.1 Surface modification by layer-by-layer (LBL) assembled silica nanoparticles

The channels in the microfluidics devices, fabricated using the process flow shown in Figure 1A, went through a surface modification to achieve a rough surface consisting of silica nanoparticles. The coating was prepared by the layer-by-layer method, where polyelectrolytes, as intermittent layers in the build-up of the multilayer coating, were deposited on the surface of the device as shown in Figure 1B. The roughness and surface topography of the coating were assessed using Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) (Figures 1B and C). The average thickness attained from nine points on the thin coating was 110 nm, measured using a profilometer. This value is consistent with the results from ellipsometry (114 nm). The void percentage of the film was estimated as 10% with a mean square error (MSE) of 7% using the Bruggeman effective medium approximation (EMA).

These results were further confirmed with SEM images of the surface at two different magnifications, Figure 1B. The porosities were estimated numerically from the ellipsometry and SEM measurements. Nano and micro-scale roughness of the surface is not only an important parameter that influences the surface energy of the coating, which in turn affects the hydrophobicity, but it also provides pores for the lubricant to penetrate into the coating. AFM height images and results (Figure 1C) proved that these surfaces were rough both on the nano- and micro-scale. The increase in the projected surface is reported as 9% in both scales, and the root mean square is measured as 35.4 nm and 11 nm on the micro- and nano-scale, respectively. The Young modulus of elasticity of the thin film on silicon wafers was 5 GPa, which ensures high durability of the coating under the present working condition.

Static contact angle and contact angle hysteresis measurements reveal the hydrophobic nature of the surface (after the application of the lubricant). The lubricant covers the surface with a very thin layer. As the contact angle of the water droplet and air bubble on a surface are supplementary angles, it can be predicted that the behavior of both of them on this surface is almost the same, and air bubbles have a contact angle of 80° with a low contact angle hysteresis of about 5° , which implies that gas bubbles can easily slide on the surface [24].

Figure 1. Assembly of the microfluidics device. Schematic overview of (A) fabrication process flow for the microfluidic device (B) assembled layers of thin film on the microfluidic device and SEM image of the final thin film (C) 2D and 3D height images of atomic force microscopy representing the nano and microscale roughness of the surface.

Figure 2. Assembly of the CNF-stabilized PFC5 droplets. Particle stabilized droplets were prepared by (A) mixing a CNF suspension in MilliQ water with PFC5 to obtain the CNF

stabilized droplets. (B) Light microscopy image of the resulting CNF-stabilized PFC5 droplets (imaged ca. 1 h after preparation). Droplets were deposited and dried at ambient conditions and imaged using (C) AFM and (D) SEM.

3.2 Assembly of CNF-stabilized PFC5 droplets

The CNF stabilized PFC5 droplet were prepared via a straightforward and simple mixing protocol, where a cationic CNF suspension is mixed with PFC5, whereupon stable micro-sized droplets in a comparatively narrow size distribution are achieved, ca. 1-5 μm in size (Figures 2A and B). The size distribution can be compared with the droplet distribution in surfactant stabilized systems, where the size distribution is typically more polydisperse, ranging over a few orders of magnitude (when the droplets are generated with some types of high energy mixing protocol). The CNF stabilized the O/W interface via a Pickering mechanism as demonstrated in a previous study [25]. In Figures 2C and D, the particle-stabilized droplets were imaged after drying with AFM and SEM, respectively. Interestingly, the capsule structures did not completely collapse under ambient or high-vacuum conditions in the SEM despite that PFC5 will unavoidably evaporate under such conditions. A nanocellulose composite microcapsules at low polymer content in the shell (and initially filled with hexadecane) will completely collapse under SEM conditions [26,27]. Herein, a bulged (half-collapsed) capsule structure was observed, Figures 2C-D, which consisted of a dense CNF layer, see SEM image in Figure 2D.

3.3 Hydrodynamic cavitation measurements

The pioneering studies on hydrodynamic cavitation on microchips have mostly been devoted to the physics of cavitation on the micro-scale [4]. The surface roughness is effective for the generation of cavitation in the micro-scale [13]. The device reduces the required pressure drop for achieving fully developed supercavitation flow patterns. The side wall roughness elements in the channels affect cavitating flows by inducing secondary flows such as turbulent Taylor

vortices, while generating large stable vertical structures, as shown in Figure 3. Therefore, the bubbles keep out of the boundaries, and the vapor phase extends along the length of the channel, which is in line with the previous results [13].

The introduced CNF-stabilized PFC5s generate a highly vaporous cavitating flow, which fills the entire microchannel at a much lower upstream pressure (Figure 3A). To the best of the authors' knowledge, this has not been previously reported [13,14]. According to Figures 3A and B, the droplets give rise to the supercavitation flow pattern at the upstream pressure of 1.7 MPa, while developed cavitating flow with the penetration length of approximately 0.8 mm is observed for the case of water at the pressure of 7.23 MPa. It should be noted that inception of cavitating flow is observed at the upstream pressure of 1.7 MPa for the case of water. The generation of larger cavity clouds (supercavitation), as shown in Figure 3A, leads to intense turbulence due to the collapse of some of the bubbles inside the microchannel, which assists in promoting collapse. Moreover, this pattern results in smaller bubble generation in size [28], while the cavity cloud covers the whole volume of the microchannel, thereby generating large temperature gradient.

Due to the low saturation temperature of these droplets (approximately 29°C), we hypothesize that vaporization will have an additional effect on the flow. Furthermore, the surface tension gradient, induced by the concentration gradient of the dissolved content in the solution, and the generated temperature gradient, substantially reduce the inception pressure for the cavitation phenomenon. As a result, the surface tension effect leads to density gradients, which trigger convective flows in the droplet suspension. These phenomena cause the main flow to be controlled by gravitational forces at low upstream pressure and radial velocity resulting in the slight flow diversion from its regular direction in the extended channel. This flow pattern is observed inside the extended channel for the case of PFC5 droplets and water (Figures 4A

and B) at the upstream pressure of 2.3 MPa. Strong vortices are observed first at the upstream pressure of 2.3 MPa for the case of PFC5 droplet suspension, which are not observed in the case of water at the same upstream pressure. The generated cavitating flow inside the microchannel with PFC5 droplets has a relatively higher mean velocity (45 m/s), which was measured according to the volume flow rate obtained from the experiments, thereby minimizing the buoyancy effects, which is dominated by the surface tension and generated vortices.

Figure 3. The cavitating flow patterns inside the same microchannel (CH1). (A) supercavitation flow pattern at upstream pressure of 1.7 MPa for the case of PFC5 droplets in water (B) developed cavitating flow at upstream pressure of 7.23 MPa for the case of water.

Figure 4. The cavitating flow patterns inside the same microfluidic device (CH1). (A) penetration of twin cavities to the extended channel with a view of the microchannel downstream at the upstream pressure of 2.3 MPa for the case of PFC5 droplets (B) penetration of twin cavities to the extended channel at the upstream pressure of 2.3 MPa for the case water.

PFC5 droplets are also introduced into another microfluidic device (CH2) with a hydraulic

diameter of 75 μm ($D_h = 4A/P$, where A is the cross-sectional area and P is the perimeter of the microchannel) to compare the flow patterns in geometrically different devices (CH1 and CH2) and to characterize cavitating flows with non-dimensional parameters. The two microfluidic devices were optimized with respect to the intense cavitation generation, see details in the previous studies with water and PVA microbubbles [13,14]. Figure 5 shows the comparison between these devices, presented with Re , We and cavitation numbers. Accordingly, the cavitation inception occurs at relatively lower upstream pressure (1.12 MPa) and cavitation number, ($\sigma = (P_{\text{ref}} - P_v) / (0.5 \rho_l V_{\text{ref}}^2)$, where ρ_l is liquid density, P_{ref} is reference pressure, which is the upstream pressure in this study, P_v is vapor saturation pressure and V_{ref} is the reference velocity at the outlet of the microchannel, which was calculated with the use of mass flow rate), (4.28) for CH1 compared to CH2, where the upstream pressure is 1.67 MPa, and σ is 7.28. It should be noted that high values of σ in this study are due to the fact that all of the flow patterns appear at rather low upstream pressures and consequently lower mean velocities inside the microfluidic devices. While Re and We numbers ($Re = \rho v_{\text{ref}} D_h / \mu$, and $We = \rho v_{\text{ref}}^2 D_h / \sigma$, where σ is the liquid surface tension) are almost in the same range for both devices, Re numbers suggest transient flow at the time of the inception.

The cavitation number differences between inception and developed cavitating flows for CH1 and CH2 are 1.34 and 4.17, respectively. This difference in cavitation numbers suggests that more cavitation bubbles are generated inside the smaller channel and intensified cavitating flow leads to the earlier appearance of the supercavitation flow pattern. Moreover, the Re numbers at points A and B (Figure 5) are 7258 and 9745, respectively, which implies that supercavitation arrives at lower Re numbers inside the smaller microchannel with hydraulic diameter of 66 μm (CH1). Although Re and We numbers are lower at point A compared to point B, they are higher for the smaller microchannel at the highest upstream pressure applied

to the microfluidic devices. Thus, the mean velocity at the last stage has higher values for the smaller microchannel despite it having the same pressure magnitude as in the larger microchannel. In addition, very strong vortices are observed in the extended channels for both devices, which implies large pressure variations for PFC5 droplets even at lower upstream pressures. It should be noted that the cavitating flow pattern inside the device having the same hydraulic diameter as CH2 and the same side wall roughness length as CH1 is the same as in CH2, as the corresponding Re number is 9886 at the point B. Therefore, the variations in hydraulic diameter strongly affect the cavitating flow pattern. While supercavitation is observed for the smaller microchannel, hydraulic flip is seen at point B for the larger microchannel once the cavitating flow is developed. This flow pattern happens when the cavity cloud reaches the outlet of the microchannel, and the air flow existing at the extended channel tries to find a way in order to fill the entire boundary of the channel. The backflow observed at point B implies the existence of the air passage replacing the main jet flow from the wall of the microchannel. During this phenomenon, the water jet is separated from the cavitating flow area and this is of great importance in different industrial applications such as hydro-entangling, where uniform fibers form via water jets. To the best knowledge of the authors, hydraulic flip is seen for the first time on the micro-scale.

Figure 5. Cavitation patterns for PFC5 droplets in two different microfluidics devices (CH1 and CH2). The variation of Reynolds and Weber numbers as a function of the cavitation number for the cavitating flow with CNF-stabilized PFC5 droplets. Snapshots of the corresponding flow patterns at points A, B and C of the different curves are included.

In spite of the lower viscosity, sound speed and surface tension of PFC5 droplets compared to water, the supercavitation and hydraulic flip observed in these experiments occur at low upstream pressure for the case of PFC5 droplets.

The potential energy of the bubbles, which is a function of the size of the bubbles and the vapor pressure of the working fluid, transforms into other forms of energy upon collapse. Shock waves, as a result of the bubble burst, can be used in different fields such as pretreatment of biomass [29]. In an attempt to provide insight into cavitation bubble size, bubble diameter variation within a 7 μ s time step is shown in Figure 6. At the points A, B, and C, the size of the bubbles gradually increases and reaches a maximum size of 10.5 μ m in diameter. The size growth can be due to either the expansion of the gases inside the bubbles or flocculation and

coalescences of the small bubbles at points B and C. This growth continues for 3 μs in the extension. The images from the CCD camera show the disappearance of the bubbles, Figure 6 at point D. As can be seen, the rebound bubble size is infinitesimal. As a result, the rebound energy can be neglected, and the shock wave energy is proportional to the initial potential energy of the bubbles before the collapse [30].

Figure 6. The fate of the PFC5 droplets during supercavitation. Bubble radius variations at the upstream pressure of 1.67 MPa inside the extension with shock wave manifestation. The microfluidic device, CH1, was used.

Figure 7. CNFs before and after supercavitation. AFM image of CNF (A) before and (B) after supercavitation.

After the supercavitation and destruction of the Pickering-stabilized droplets, it would be attractive to collect the PFC5 and CNFs and regenerate the CNF-stabilized PFC5 droplets. This is only possible if the cellulosic nanofibers are not significantly modified during supercavitation. We hypothesize that the modification should occur on the surface and in the more assessable amorphous regions of the CNFs, which might decrease the length of the CNFs. In Figures 7A and B the CNF nanofibers obtained after the supercavitation and the starting nanofibers are compared. Evidently, the CNFs have not been shortened and could be reused to create new PFC5 droplets. This constitute a prerequisite to create an efficient, closed-loop device, which can effectively store energy, release it on demand and finally be “recharged” by regenerating the droplets using a simple mixing step.

4 Conclusions

In this study, a new type of droplets, cellulose nanofiber-stabilized perfluoropentane droplets, were tested within a surface tailored microfluidic devices to generate cavitation bubbles in a facile way. The flow pattern with the highest intensity, i.e. supercavitation, was observed at a

low upstream pressure of 1.7 MPa with these droplets, which barely corresponded to the cavitation inception for pure water. Moreover, hydraulic flip, which has not been previously recorded on the microscale, was generated for the larger microchannel in the presence of CNF-stabilized PFC5 droplets. The results also showed that more cavitation bubbles were generated inside the smaller channel configuration, and supercavitation flow pattern arrived earlier due to the smaller difference in cavitation number between the inception and developed cavitating flow in the smaller channel configuration. This outcome implies that the microfluidic device with a smaller hydraulic diameter, possesses the most intense cavitation generation at rather low upstream pressures for the case of PFC5 droplets. As the CNFs are not damaged, droplets can be regenerated; this study proposes an important approach towards a closed-loop device that can store energy, then release and be “recharged” on demand.

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Acknowledgements

Thomas Paulraj is acknowledged for providing help with the AFM and light microscopy imaging. This work was supported by TUBITAK (The Scientific and Technological Research Council of Turkey) Support Program for Scientific and Technological Research Project Grant, 217M869. Equipment utilization support from Sabanci University Nanotechnology Research and Applications Center (SUNUM) is gratefully appreciated.

Authors' contributions

M.G., A.K., D.G. and A.J.S. designed the experiments. A.J.S prepared the PFC5 droplets. F.Ç.C. conceived the idea of SLIPS surfaces by LbL approach with PAH/SPS. A.S.A. and A.J.S. performed the SEM and TEM tests. M.G., A.S.A. and M.T.G performed the experiments and prepared the figures. All the authors analyzed the results, prepared the discussion and reviewed the manuscript.

Declarations of Interest:

None.