THE EFFECT OF PARTICLES ON PERFORMANCE OF FIXED-VALVE MICROPUMPS

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Abstract

Although numerous designs for micropumps have been reported in the literature, very few studies have addressed pumping of anything but pure fluids. In a previous study done in our laboratory, the ability of fixed-valve micropumps to directly transport particle-laden fluids was demonstrated with suspensions of polystyrene microspheres ranging from approximately 3 to 20 μm in diameter without clogging at densities as high as 9000 particles/μl of suspension. In the present study, degassing procedures and a wide range of particle concentration were utilized to better understand characteristics associated with maximum pump performance, defined as the point at which higher driving voltage causes cavitation. Our findings indicate that compared to pure water degassing procedures profoundly affected pumping characteristics for particle suspensions composed of either charged or uncharged polystyrene particles. In addition, degassing durations after which pumping characteristics did not change were found to be approximately 250% longer for particle-laden fluid compared to pure water. Lastly, maximum pump performance was inversely related to particle concentration for low concentrations, to 70 μg/ml for 3 μm diameter microspheres, which, when combined with previous results indicated that higher concentrations result in a concentration threshold beyond which maximum pump performance is not affected. The results of this study serve as a guideline for transport of particle-laden fluids directly through and design of fixed-valve and other types of micropumps.

Keywords: micropump, particles, microspheres, polystyrene, degassing, cavitation

1. Introduction

As interest in microfluidic systems grows, techniques for pumping and dosing of particle suspensions are required for many new applications in industrial production as well as in the fields of biotechnology, environmental testing, and instrumentation for analytical chemistry. In a previous study [1], the ability of micropumps with fixed-valves to directly transport suspensions of particles was demonstrated for polystyrene spheres from 3.1 to 20.3 μm in diameter. Certain other pumping characteristics were also observed. For the concentration range considered pump maximum performance appeared to be unaffected by number density, size, or total surface area, although maximum performance for suspensions was lower compared to pure water. Also maximum performance with suspensions of uncharged particles appeared to be lower than with charged particles. In this study, the role of degassing procedures, and a wider range of particle concentrations were studied in order to better understand pumping characteristics of suspensions.

2. Methods

The type of fixed-valve micropump used in the this study is shown in Fig. 1. Pairs of fixed-geometry inlet and outlet valves were etched in silicon. The pump was driven by a piezoelectric element bonded to a Pyrex cover plate in which a 7 mm square chamber was milled. The depths

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of the valves in silicon and the pump chamber in Pyrex were 400 μm and 30 μm, respectively. A 7 mm square piezoelectric driver element with a thickness of 190 μm was bonded to the 470 μm thick pump membrane. The width of the valve conduits was 114 μm. Two integrated compliance elements were fabricated on the micropump—the trapezoidal chambers between valves shown in Fig. 1. Due to variations in pump performance as determined from the resonance behavior with pure water [1], each series of tests, for which parameters were varied, was performed with the same pump over the shortest period of time possible, always on the same day unless otherwise noted.

Table 1: Suspensions of polystyrene microspheres used in this study. WC identifies microspheres with negative surface charge, types 1-3000 & 1-8000, Interfacial Dynamics, Portland. NC signifies microspheres with no added surface charge, type PS07N, Bangs Laboratories, Fishers, Indiana.

case	type	diameter (μm)	concentration (μg/ml)	number density (1/μl)	surface area (μm^2/μl)
A	WC	3.1	150	9,220	278,000
B	WC	7.9	390	1,420	278,000
C	NC	20.3	1000	215	278,000
D	WC	3.1	3.5	215	6,500
E	WC	3.1	10.5	645	19,500
F	WC	3.1	21	1,290	38,900
G	WC	3.1	35	2,150	64,900
H	WC	3.1	70	4,300	130,000

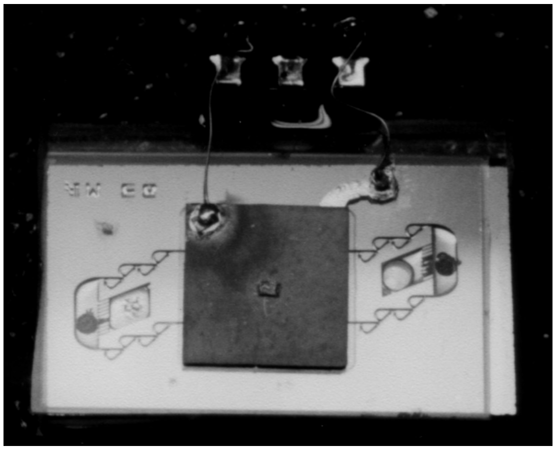

Figure 1: Configuration of a 7-mm square chamber pump with fixed-geometry valves, the design of which is denoted as T45/4x2. The trapezoidal regions between each pair of inlet and outlet valves are compliance chambers (accumulators) utilized to decouple pump oscillations from the load.

Table 1 summarizes the suspensions used in this study. Suspension samples were prepared using de-ionized water filtered at 0.2 μm combined with stock microsphere suspensions to obtain the desired particle concentration. Unless otherwise noted the degassing protocol consisted of evacuation with a vacuum pump (N810.3FT8, KNF Neuberger, Inc. Trenton, New Jersey) rated at 28.5 in Hg for controlled durations while each sample was agitated in an ultrasonic bath (Bransonic 12, Branson Instr. Co., Shelton, Connecticut). This protocol is referred to as protocol #1. Additional details of the procedures for sample preparation, control for aggregation during testing, frequency response signatures for pumps and pump performance tests have been reported earlier [1].

Two issues regarding degassing procedures were addressed. First, the degassing duration was varied to investigate differences between pure water and suspension A of Table 1. Also, the effect of the degassing protocol was investigated to study possible differences in pumping characteristics for charged versus uncharged microspheres using suspensions A–C of Table 1. Lastly, effects of particle concentration were investigated using suspensions D–H of Table 1.

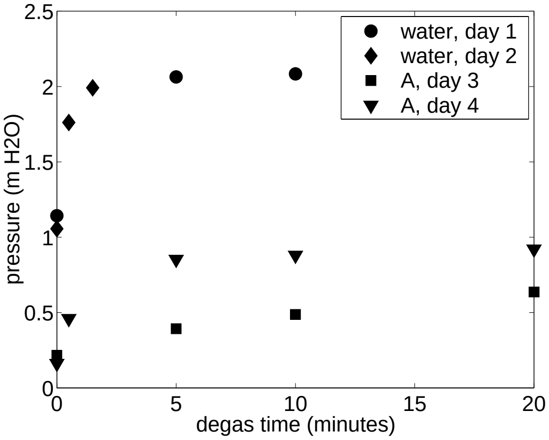

Figure 2: The effect of degassing duration on maximum pump pressure developed at zero volume flow rate for de-ionized water and suspension A.

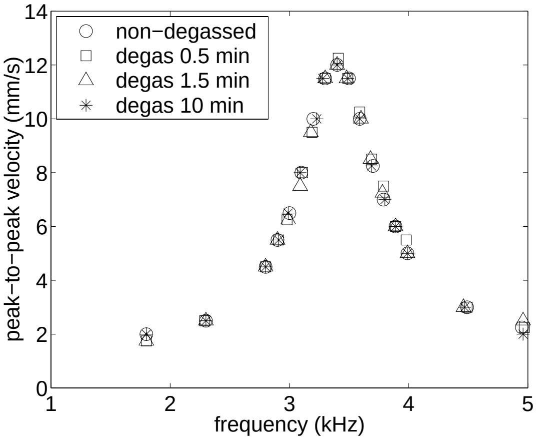

Figure 3: Pump membrane peak centerline velocity versus frequency at 18 V peak-to-peak for pure water for different degassing durations. At this applied voltage pump output was significantly below maximum.

3. Results and Discussion

The effects of varying degassing duration on maximum pump performance for pure water and suspension A are shown in Fig. 2. The figure shows the performance in terms of maximum pressure developed at zero volume flow rate (blocked flow pressure head). Similar results were obtained for maximum volume flow rate developed against a zero pressure head. Maximum performance increased from a minimum when no degassing was performed to an asymptote for longer degassing duration. Both the rate of approach and asymptote level were different for pure water and the suspension. The curve rose faster and to a higher performance limit for pure water. The slower rise time for the suspension compared to pure water, approximately 250% longer, indicated that the particle suspension was more difficult to degas than pure water. Secondly, lower performance with shorter degassing duration for both pure water and the suspension indicated that the amount of gas in the sample was directly responsible for reduced performance. Thirdly, the different maximum performance asymptotes for pure water and the suspension indicated that there was a further effect on performance not accounted for at the same equilibrium vacuum levels. This behavior may be indicative of a higher propensity for cavitation in suspensions due to additional cavitation sites available.

In the case of pure water, there was approximately a 45% loss in performance from the maximally degassed case to the non-degassed case associated with the amount of gas in the sample. However, as shown in Fig. 3 different amounts of gas had no observable effect on pump resonance, a sensitive primary indicator of changes in fluid capacitance [1]. Similar effects were observed for the cases studied with particles. These results showed that the amount of gas involved in reduction of the maximum performance asymptote (lowering of the cavitation point) was small enough to not otherwise affect nominal pump performance, i.e. below the cavitation point. These results provide guidelines for the design of micropumps when characterized and tested with degassed fluids but used with fluids containing differing amounts of dissolved gases.

The strong influence of degassing procedures on maximum pump performance was also observed when polystyrene particles with and without surface charge (controlled during manufacture) were studied. Differences in our previous study [1, Fig. 9], observed to be due to particle types were found in this study to be due to differences in degassing procedures. The two different types of microspheres used in the present study are denoted in Table 1 as NC and WC, respectively. The uncharged particles making up suspension C could not tolerate degassing with ultrasonic agitation without forming aggregates. Therefore, only the de-ionized water making

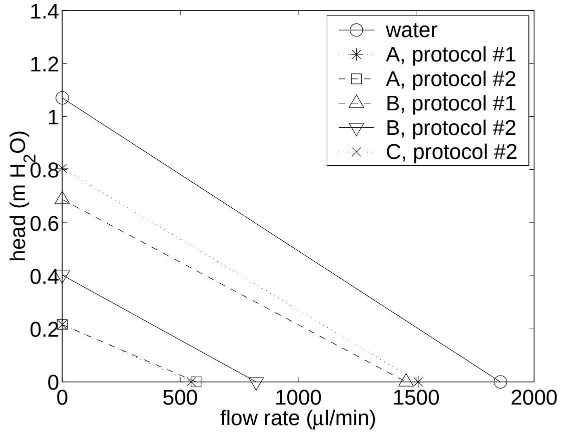

Figure 4: Maximum pump performance for deionized water and various particle suspensions and different degassing protocols, degassed for 10 min.

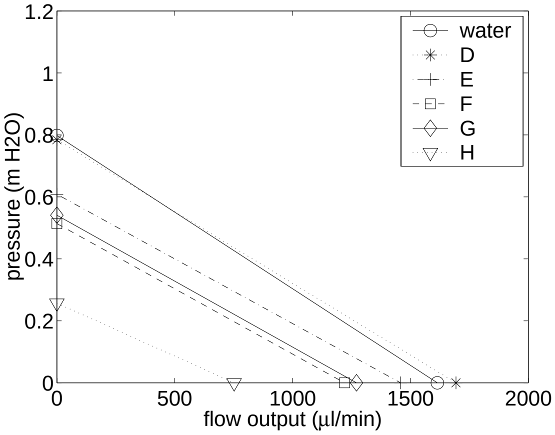

Figure 5: Maximum pump performance for deionized water and various concentrations of 3.1 μm particles, degassed for 10 min.

up the suspension was degassed and the stock non-degassed suspension was added to obtain the desired particle density. Fig. 4 clearly shows, however, that when either type of microsphere was subjected to the alternate degassing procedure, noted in the figure as protocol #2, similar reduced performance resulted, indicating the primary factor was degassing procedure, not particle type.

When suspensions of different particle concentrations were degassed for durations beyond the threshold, maximum pump performance was seen to vary inversely with concentration as shown in Fig. 5 over the range of 3.5 to 70 μg/ml. As expected, the maximum pump performance at the lowest suspension concentration was not significantly different from that of pure water. In our previous study [1, Fig. 9] similar tests at higher concentrations showed maximum pump performance was not influenced by particle concentration, particle size or surface area per unit volume of suspension. The current results along with the previous findings indicate that a threshold exists in concentration beyond which maximum pump performance is not affected.

4. Conclusions

The micropump design with fixed-geometry inlet and outlet valves used in this study was suitable for use in the direct transport of particle-laden fluids. The valves had cross-sectional dimensions of 114 by 400 μm and easily accommodated 20 μm diameter microspheres. This compares to micropumps of similar performance with moving-parts valves that typically have clearances of a few μm. Performance of the fixed-valve pump design was unaffected by particles at all flow rates and pressures below the point of cavitation, which occurred at lower driving voltages with polystyrene microsphere suspensions as opposed to pure water. The diminished maximum performance level with particle suspensions documented in this study can be used as a guide to design micropumps for such applications.

Acknowledgements

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References

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