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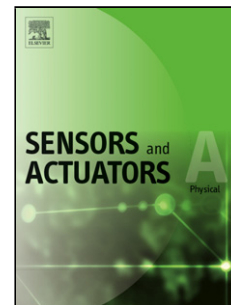
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Electrical-detection droplet microfluidic closed-loop control system for precise droplet production

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To precisely control the size of the droplets is quite important for the application of the droplet microfluidic systems. To date, the size of monodisperse droplets is usually measured by the method of image processing for droplet microfluidics, which requires expensive detection devices such as microscope and high-speed camera. In this paper, an electrical-detection droplet microfluidic closed-loop control system is demonstrated, where the flow rates of fluids are controlled by the pressure-driven microfluidic device and the droplet size can be obtained from the method of electrical detection. The mathematical model of the closed-loop control system is established. Compared with the method of image processing, both the measuring efficiency and accuracy of the droplet size are increased significantly by the electrical-detection method, which can improve the dynamic characteristics of the droplet microfluidic closed-loop control system. In particular, a PI controller is integrated into the closed-loop control system to improve the control precision of the droplet size. By varying the flow rates of the fluids, the effects of the droplet production rates on the dynamic characteristics of the closed-loop control system are studied, and the control precision and stability of the system can be obtained from the experimental measurements.

1 Introduction

Droplet microfluidics has been widely applied for medical, biological and chemical research.^{1–7} In particular, individual droplets with volume ranging from 10 pL to 100 nL are formed in the microchannels, and precise control of the droplet size is quite meaningful for the applications of droplet microfluidic systems.^{8–15} To the best of our knowledge, the method of image processing is mostly used to detect the size of the droplets for droplet microfluidic systems.¹⁶ However, some expensive and sensitive detection devices such as microscope and high-speed camera are required for the method of image processing. More importantly, high resolution images of droplets need to be captured to insure the detection precision of the droplet size, therefore, it is quite complicated and time consuming for the process of image processing, which can affect the dynamic response speed and the stability of the droplet microfluidic systems.¹⁷ In order to improve the measuring efficiency of the droplets, the method of electrical detection has been applied to obtain the droplet size for droplet microfluidic systems.^{18,19} Especially, by fabricating the microfluidic devices with embedded sensing electrodes by 3D printing, the droplet size can be tested by the method of contactless conductivity detection.²⁰ However, compared with the method of contact detection, the magnitude of the capacitance signal can be reduced obviously for contactless detection, which can af-

fect the measurement precision of the droplet size. Based on the principle of the electrical-detection method, the size of the droplets can be calculated. In particular, compared with the method of image processing, both the detection speed and precision can be increased significantly by the electrical-detection method.

For droplet microfluidic systems, the syringe pumps were widely used to supply the flow rates for the system,^{21–24} and by using the computer-tethered syringe pumps to control the flow rates of the two phases, a closed-loop control droplet microfluidic system was established.²⁵ However, due to the flow-rate fluctuations which are induced by the mechanical oscillations of the pump motor,²⁶ the size of the droplets is expected to be a periodic function of time for syringe-pump-driven flows, which decreases the stability of the droplet microfluidic system.^{27,28} Recently, the pressure-driven microfluidic devices have been designed to control the flow rates of the fluids,²⁹ which can greatly reduce the magnitude of flow-rate fluctuations in microchannels.³⁰ Based on the pressure-driven microfluidic device, the closed-loop control droplet generator with real-time feedback control of droplet formation was reported.³¹ In addition, different types of the microvalves were designed and integrated into the droplet microfluidic systems to regulate the flow rates of the fluids,^{32,33} and by changing the opening and closing periods of the microvalves, different volumes of the droplets can be formed in microfluidic devices.³⁴ From the analysis and experimental studies of droplet microfluidics as described above, eventhough some droplet

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