EVAPORATION-COOLING-BASED MICROFLUIDIC TEMPERATURE CONTROL AND ICE GENERATION

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ABSTRACT

We report water-based evaporative cooling for temperature control and ice generation, integrated into a microfluidic device. We opt for water as nontoxic and effective refrigerant. Owing to low pressure (~9.3 kPa) and large surface-to-volume ratio, atomized water droplets evaporate readily, resulting in efficient heat removal. Upon applying vacuum, the temperature decreases at fast as -5.1 ºC/s , and the refrigeration temperature as low as -13.8 ºC is achieved. By using aqueous solution as refrigerant, we also demonstrate ice generation and freezing of biofluid without any external cooling element. Our novel cooling method may contribute significantly to microfluidic chemical and biological assays, where accurate temperature control and cooling/freezing are essential.

KEYWORDS: Microfluidic temperature control, evaporative cooling, on-chip ice generation, freezing of biological samples, vacuum

INTRODUCTION

Precise control of temperature is crucial for various microfluidic applications including biochemical assays [1] (e.g., PCR, protein crystallization), life-science research (e.g., cell damage under freezing, ice-cell interaction) and microfluidic manipulation (e.g., temperature-responsive valve, thermophoresis). In contrast to heating (e.g., Joule heating), cooling is not easy to integrate into a microfluidic device, as currently relying on external, bulky and power-hungry instruments (e.g., Peltier cooling, chilled-water circulation, pressurize-air impingement). Recently, integrated microfluidic cooling using endothermic reaction of laminar stream of refrigerant (e.g., acetone, ethanol, ethyl ether) and gas (e.g., air, nitrogen) was reported [2,3]. However, the use of toxic and flammable refrigerants and pressurized gas tank hampers a wide application of this approach.

Our water-based evaporative cooling method presented here has distinctive advantages over the state of the art. Cooling is effective as water has large latent heat of evaporation [4]. Having large surface-to-volume ratio and exposed to low pressure, water droplets evaporate readily, removing heat efficiently. In addition, water is nontoxic, environmental friendly and inflammable. Cooling is straightforwardly integrated into a microfluidic device as it relies only on a straight-channel microfluidic chip and a laboratory vacuum pump. Notably, our device can generate ice and freeze biological fluids by using aqueous solution as refrigerant. It can be useful for various biological applications including protein-ice interaction study [5] and preservation of biological samples (e.g., cells, enzyme) for long-term storage.

EXPERIMENTAL

Figure 1a shows our experimental setup. A vacuum chamber with an orifice and a reservoir, made of a disposable pipet, are affixed to a plastic chip with a straight microfluidic channel. The reservoir is filled with aqueous refrigerant (DI water, ethylene-glycol solution, BSA solution). The chamber is connected to a vacuum pump. A moisture trap is used to remove moisture from the air before entering the pump. Upon applying vacuum, water, emerged from the through hole, is atomized by the air jet via the orifice, and the resulting water droplets are readily evaporated (Figure 1b). Removing heat by evaporation, temperature inside the vacuum chamber decreases until accumulated aqueous solution freezes into ice (Figure 1c). A microthermocouple (130 μm diameter) was used to measure chamber temperature with minimal disruption of droplet/air flow. A digital pressure gauge was used to monitor chamber pressure. The temperature and pressure data were acquired using DAQ boards and a PC. A digital camera was used to image-capture ice generation and freezing of protein solution inside the vacuum chamber.

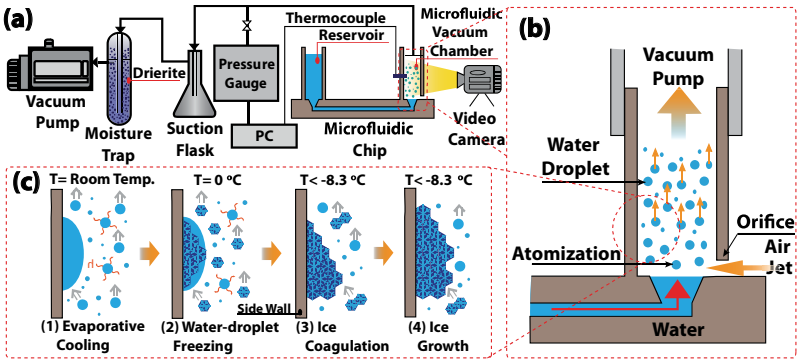

Figure 1: (a) Schematic of experimental setup. For evaporative cooling, an affordable 1/2 hp vacuum pump is used to lower pressure inside the microfluidic chamber (diameter = 4.2 mm, length = 3 cm). (b) Water is drawn from the through hole (diameter = 1.4 mm) and impinged by air jet through the orifice (0.76×0.08 mm^2), resulting in atomization into microdroplets (estimated diameter = ~9.2 μm). (c) The water droplets are evaporated under mild vacuum (~9.3 kPa) , yielding rapid temperature reduction, ice generation, and freezing of biological fluid.

RESULTS AND DISCUSSION

We performed experiments to prove the concept of water-based evaporative cooling. Figure 2a shows temperature inside the microchamber as a function of time when DI water is used. The ambient temperature was ~24 ºC. After vacuum was applied ("Pump On"), temperature decreased sharply and reached the freezing point (0 ºC) in 11.2 s on average, yielding the cooling rate of -2.1 ºC/s. The average of minimum temperatures attained was -12.0 ºC. We observed that water, accumulated on the side wall, froze and the ice grew large enough to obstruct droplet/air flow. As a result, evaporation rate decreased, causing increase in the chamber temperature eventually. Therefore, we tested 20% v/v ethylene-glycol (EG) solution having a lower freezing point (~-10 ºC). Figure 2b indicates stable heat removal and unfluctuating refrigeration temperature as the EG solution did not freeze. On average, the cooling rate was -3 ºC/s, and the minimum temperature was -10.2 ºC. The cooling performance presented here is better than previous work (minimum temperature of -4 ºC and cooling rate of -1 ºC/s [2]). We expect ample increase in the cooling performance if reducing the pressure further (e.g., use a better vacuum pump and/or improve sealing).

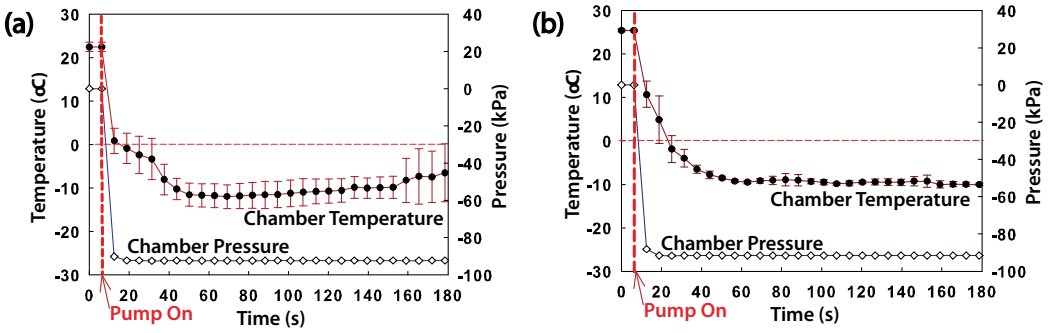

Figure 2: Temperature and pressure in the microfluidic vacuum chamber as functions of time, when (a) DI water (n=3), and (b) 20% ethylene-glycol solution (n=5) are used as water-based refrigerants.

Using the same microfluidic device, ice was produced and biofluid was frozen *in situ*. DI water and 10% w/v BSA solution were used as water-based refrigerants. Figure 3a shows image sequence of ice-generation process in the chamber when water is used for refrigerant. The air jet pushed the atomized water droplets to the side wall, resulting in accumulation on the surface (10.0 s). As the temperature decreased beyond the freezing point, water was frozen (16.0 s). By continual additional of water droplets, the ice grew until it almost blocked the vacuum chamber (43.7 s). As can be seen in Figure 3b, the BSA solution was frozen to almost fill the half of the chamber (50.0 s). We noted that the protein precipitated out as yellowish residue owing to reduced solubility. This is the first report of on-chip freezing of biofluid using the fluid as

refrigerant without any external cooling element. We also tested 20% EG solution (data not shown). As expected from the lower freezing point and undercooling [6], it did not freeze.

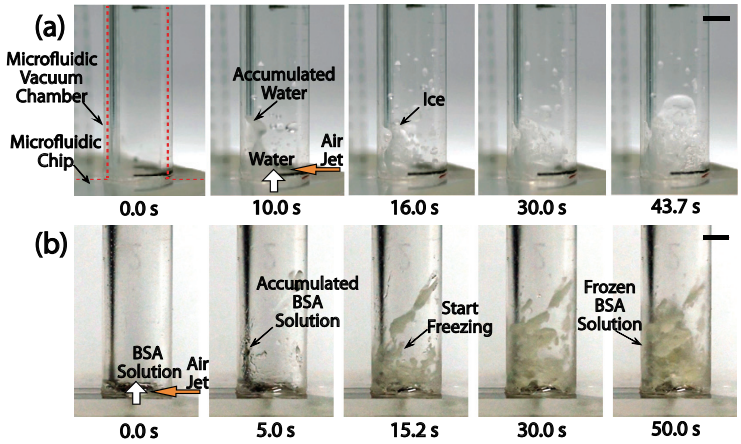

Figure 3: An image sequence of on-chip ice generation and freezing of biofluid. Thermocouple is not installed for better visualization of freezing phenomena (scale bar = 3 mm) (a) DI water was frozen and the ice grew until almost blocking the microfluidic vacuum chamber (ambient temperature = 18.8 ºC, vacuum pressure = 6.3 kPa). (b) 10% w/v protein solution was frozen by evaporative cooling and almost obstructed the chamber (24 ºC, 5.7 kPa).

CONCLUSION

We successfully demonstrated a simple, nontoxic and effective microfluidic cooling method. As based on evaporation of aqueous solution, on-chip ice generation and freezing of biofluid is achieved without external cooling instruments. Mild vacuum employed here (~9.3 kPa) may support a portable vacuum pump for substantial device miniaturization. The vertically attached vacuum chamber used in this work could be microfabricated on-chip in a large number. By tailoring refrigeration condition of each chamber, temperature control in a multiplexed manner could be achieved to realize various microfluidic assays for chemistry, biochemistry and biology in high throughput.

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