The evaluation of heat-transfer cooling performance of PDMS/glass composite lamination interfaced with microfluidic pinnate-like flowpaths

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Abstract.n this paper we present the evaluation results of solar thermal cooling performance of PDMS/glass composite lamination in which the microfluidic flowpaths have been fabricated on the interface between PDMS and glass. The microfluidic flowpaths was designed into pinnate-like and its pattern was transferred onto the surface of PDMS piece through UV flatbed-printer and soft molding, then plasma bonded onto glass, forming PDMS/glass compound window with an area of 10×8 cm^2. The temperature distribution of thus-made device was monitored with IR imager and thermal-couple when DI water with different flow-rates was forced flowing into and out. The results show that this pinnate-like PDMS/glass microfluidic device could significantly realize good heat-transfer, when it was exposed to environmental temperature higher up to 38ºC, the outlet temperature of the flowing water at 5 mL/min could be reduced by 8~10ºC when the inlet flowing water was given at room temperature.

Introduction

As global energy crisis continues to be no bright solutions, there is a highly raising awareness of the energy saving requirement in all areas. The fact that about one-quarter of building energy is wasted by the conventional glazing window[1], has recently prompted quite a number of novel alternative technologies for reducing this overspent[2-3]. Among these, flowing water instead of air between double panes was recently proposed by Chow et al[4-6]. As the much higher thermal conductivity of water could reach to better cooling efficiency than that of air, especially with the extra benefits from the exploitable water heated, and acting as an anti-reflective coat and absorbing infrared short wave radiation in the case of water film[7]. Very recently, along this side Hatton et al[8] did a further step to reduce such bulk flow into milli-or microscale to get more gain in energy balance. Indeed, numerous studies over 3 decades have proven that the mass/heat-transfer of flow in single-phase could be greatly enhanced up to 3-4 orders of magnitude when it's flowing space is reduced from macro to microscale[9-12]. For fully utilizing the microscale effects in thermal managements, the patterns of micorchannel networks, e.g. tree-shaped[13-14],or fractal-like[15], have been presented to optimize the heat-transfer enhancement, the constructal theory proposed by Bejan[16], seems to be a powerful tool for those aims. These previous studies, however, have paid more attentions on the effects of channel geometric sizes within the network entities. Most recently, Hu et al.[17-18] began to consider theoretically the possible significant cooling enhancement of flow within the pinnate leaf-like network, acting the channel network as being the integral part of its embedded matrix[19].

From bio-inspiration, pinnate leaf-like network with scalable series of channels may have less resistant to inner flow compared with vasculature-like network with size identical microchannels, say, diamond-like network[8]. We here purposely make an experimental investigation on the heat-transfer performance of PDMS/glass composite lamination in which the microfluidic flowpaths have been designed as pinnate-like network. Our preliminary evaluation results show that this is a positive direction.

Device design and fabrication

The design is inspired by one of leaf veins networks (LVN): the pinnate channel network. Such patterns were designed with Coreldraw or Auto CAD software. As sample demonstration, two types of such channel arrays, LVN 1: 0.2 mm high and 0.5mm wide, LVN 2: 0.2 mm high and 1.0mm wide, were designed, and theirfabircation was as follow, see Fig. 1

The above patterns were firstly printed using UV flatbed printer (Efi,Gs3250Lx, USA) onto clean Polymethylmethacrylate (PMMA,VH001,Mitsubishi Rayon (Shanghai) Co., Ltd,Japan) template of 0.10 mm thickiness, as the master for negative pattern transferrng, see Fig.1A and Fig.1B. Nextly, polydimethylsiloxane (PDMS, Sylgard184, Dow Corning) layers (4 mm thick) were molded on the above master PMMAs,both spreading over an area of 10×8 cm^2. The PDMS layers were then bonded to cleaned 1/8″glass with plasma oxidized (FEMTO2, DINA Elektronik GmbH, Germany), and baked at 50 ºC overnight (Fig.1C). After connected with housemade interfaces, a syringe pump (LSP02-1B, Baoding Longer Precision Pump CoLtd., China) was used to control the water flow-rate through the channel array interfaced between PDMS/glass composite layers.

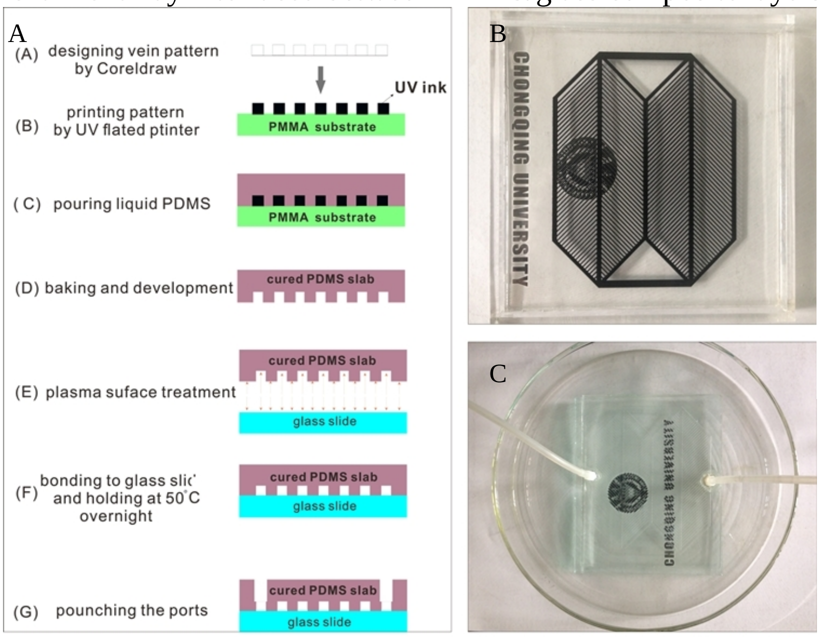

Fig.1 The schematic of fabrication of PDMS /glass composite lamination(A), and PMMA template(B), PDMS /glass composite lamination (C). In (A), the LVN patterns Drawed by Coreldraw (a), then printed on PMMA surface via UV flatbed printer (b), pouring PDMS on PMMA (c), baking (d), surface plasma processing (e), pressing PDMS/Glass together for composite lamination at 50^{o}C vacuum overnight, then pounching (g).

Results and discussions

The fabrication of microfluidic PDMS/glass composite lamination

In order to adaptive to future practical fabrication of microfluidic PDMS/glass composite lamination, we explored a modified technical route to realize wide-area microfabrication, which was now not able to by conventional softlithography. In this fabrication route, commercial UV flatted printer was applied to straightforward print out the designed patterns onto PMMA substrate. The results shown that the minimized wideness of channel could be below 200μm, while the highness could be defined by the layers of ink-printing. Our two channel designs LVN 1, LVN2, spreading on area of 10×8 cm^2 had been successfully transferred into PMMA and then PDMS, as shown in Figure 1. For robust transferring between PMMA and PDMS and then bonding between PDMS and glass, an effective processing could be suggested: evenly coating a solution of lecithin 5% (w/w) on cured UV-ink on PMMA and dry it in vacuum oven at 50ºC for 10min.

The measurement of temperature distribution

For the measurement of temperature changes and distribution of the microfluidic device, a 200 W incandescent light was placed approximaely 15cm away as the thermal source, which could heat the externally surface of the glass side to an higher temperature. Thermal infrared (IR) measurements were made using a FLIR (DT-9875,CEM, china) camera, and 4 K-type thermocouples were attached to the PDMS and glass surfaces to real-time monitoring the temperature change by datalogger (TES-1384,Taiwan,China). The experimental measurement setup was seen as in Fig.2.

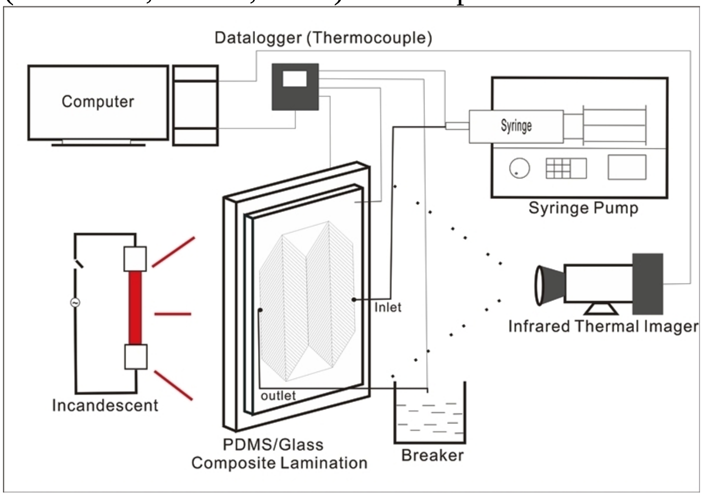

Fig.2 Schematic diagram of the experimental setup for temperature measurement of PDMS/Glass microfluidic composite lamination

Before the experiment measurement, 200W Incandescent lamp installed away 15cm from device for pre-heating PDMS-glass composite device to an initial temperature ranging from 36 to 38 ºC. Then the room temperature (RT, 21ºC) de-ionized water (DI) was pumped through the device inlet at a flow-rate of 0.5/5/15 ml/min, the infrared imager collected the temperature field images on the PDMS surface, and recorded the time spending once the temperature reached steady state judged by the images color and datalogger values. The changes of PDMS surface temperature were visualized using the infrared imager as a function of flow-rate and microchannel dimensions.

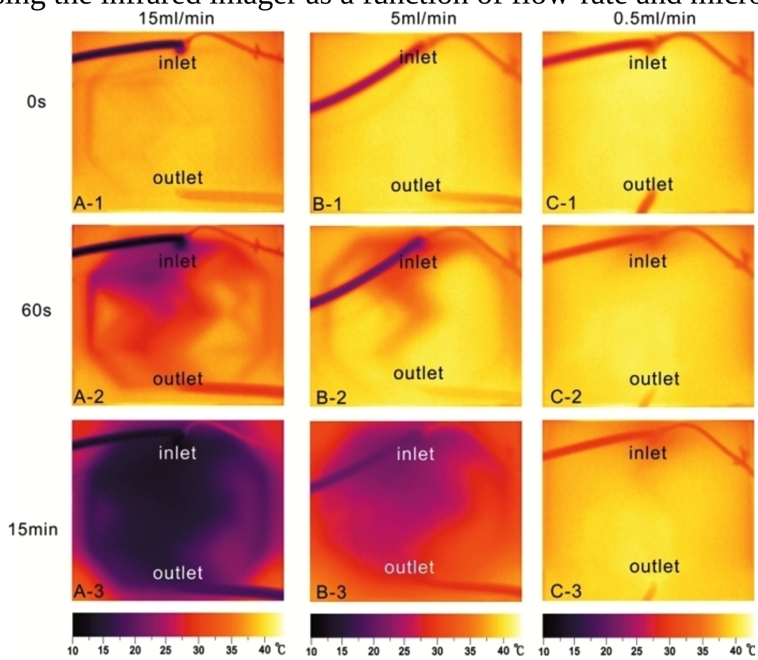

Fig.3 Thermal IR images of the LVN1 PDMS channel layer for input water temperature of 0ºC. Effect of flow rate(up), at steady state (A-3,B-3,C-3), and effect of time(left), at three flow rates (0.5,5,15mL/min). In all images, inlet on up and outlet on down, the flow is from up to down.

From the IR imager recordings, the changes of the cooling effect of device could be obseved (Fig.3). We could see that the LVN2, the 0 ºC water at three different flow rate of 0.5, 5, and 15 ml/min could present different colors at the 0 s and 60 s, and 15min, purple represents low temperature area, and yellow is the high temperature area, under the flow rate of 15 ml/min, the rate and effect of cooling is obviously the best condition , and 0.5 ml/min basically did not change color, at the same time, the time to reach steady state is basically about 10 min for three flow rate.

In order to quantify the cooling effect, we made the curve of the average temperature change, the infrared thermal imager software can real-time collect the PDMS surface average temperature from initial state to the steady state, and temperature that was steady state from entrance to the exit along the center line of the PDMS surface, as the graph shown, the 0ºC water, at 15 ml/min , had the maximum temperature drop from 37 to 16 ºC (as shown in Fig.4), the flow rate of 5 ml/min can reduce to 20ºC, 0 ml/min was no change, even, room temperature water 21ºC at 5 ~ 15 ml/min, temperature could be reduced to 25 ~ 27 from 36 ~ 38 ºC(Fig.4), this temperature is relatively suitable for the life of people. At the same time, from the entrance to the outlet along the center line of PDMS is also maintained a rising trend.

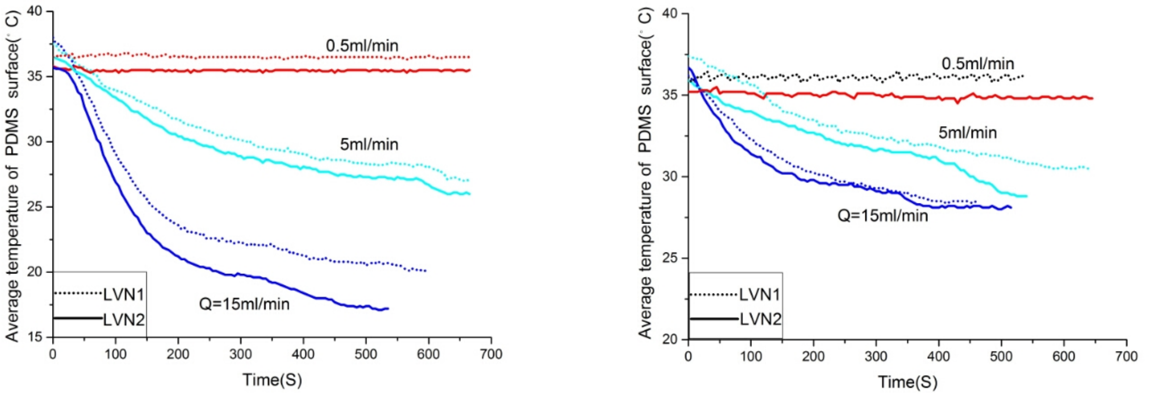

Fig.4 The average temperature of PDMS surface (dash line for LVN1,and solid line for LVN2) as a function of time for input water temperatures of 0ºC (left) and room temperature (right). values experimentally measured are plotted for three flow rates 0.50, 5.0 and 15 mL/min, for the LVN 1 (left) and LVN2 (right) channel layers.

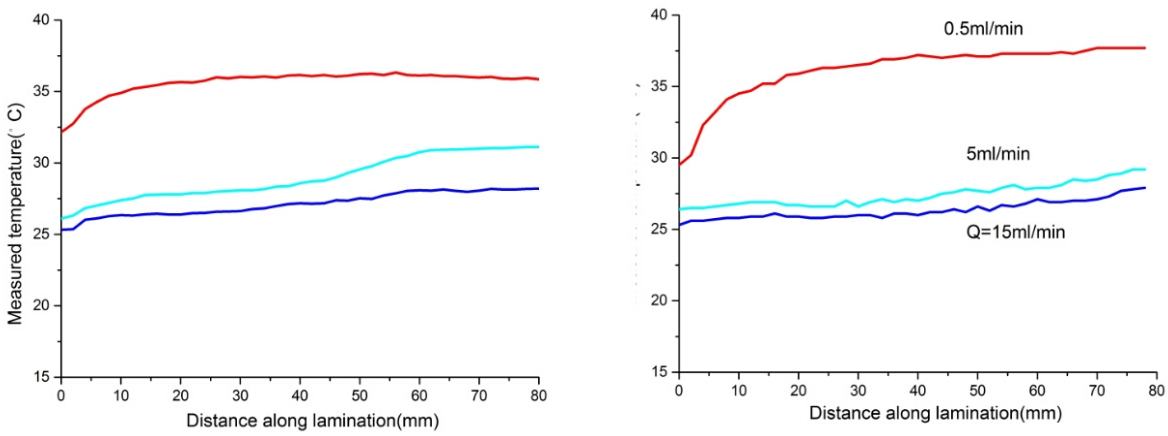

Fig.5 Experimental results for the average temperature across the interior side of the PDMS/Glass ,from inlet to outlet. Values experimentally measured are plotted for three flow rates 0.50, 5.0 and 15 mL/min, for the LVN 1 (left) and LVN2 (right) channel layers. Values of the inlet temperature is RT 21ºC.

Last, we estimated the cooling efficiency of PDMS/glass composite lamination, The energy consumed by raising 1 kg of water by a height of 1 m equals mass ×gravity ×height or 10 J (1 kg ×9.8 N/kg ×1m). If that 1 kg of water is allowed to flow down (by gravity) through the channels of the window at a rate of 15 mL/min (taking 67 min), the power required to maintain the flow is 10 J/67=0.002W; when the area of device is scaled up 10 times than 10×8cm^2, the flow rate is also up to (1/0.1×1/0.8)×15ml/min=187.5ml/min, which could require the power equaling 10J/5=0.07W to maintain the flow. First, a 1 kg of DI water with a specific heat capacity of 4.19 J/gK is heated by~10ºC based on above experiment result, it would absorb 4.19 J/g · K ×1 kg ×10 ºC=42 kJ of thermal energy. Assuming that power be directly related to the work done by an air-conditioning system, it represents a maximum theoretical power saving of 42 kJ/5 min=140 W.

Summary

We present a PDMS/glass composite lamination interfaced with microfluidically pinnate-like flowpaths, and its cooling performance was experiment evaluated. The cooling effect could be compared with that of other similar study while the power cost may be good reduced. Meantime, a straightforward fabrication technique route was explored to adaptive to wide-area microfabrication. Further refined design and detailed analysis is undergoing, the aim is to provide a novel technical way to thermal controlling of building window with more gain in energy balance.

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