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A Venturi microregulator array module for distributed pressure control

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Abstract

Pressure-driven flow control systems are a critical component in many microfluidic devices. Compartmentalization of this functionality into a stand-alone module possessing a simple interface would allow reduction of the number of pneumatic interconnects required for fluidic control. Ideally, such a module would also be sufficiently compact for implementation in portable platforms. In our current work, we show the feasibility of using a modular array of Venturi pressure microregulators for coordinated droplet manipulation. The arrayed microregulators share a single pressure input and are capable of outputting electronically controlled pressures that can be independently set between ± 1.3 kPa. Because the Venturi microregulator operates by thermal perturbation of a choked gas flow, this output range corresponds to a temperature variation between 20 and 95°C. Using the array, we demonstrate loading, splitting, merging, and independent movement of multiple droplets in a valveless microchannel network.

Keywords

Pressure regulator; Micronozzle; Valveless microchannel network

1 Introduction

Pressure-driven flow control systems in lab-on-a-chip devices have long been a compromise between design modularity and ease of implementation. For example, passive flow control schemes relying on capillary forces (Khnouf et al. 2009; Cesaro-Tadic et al. 2004; Xu et al. 2008; Chung et al. 2007; Melin et al. 2004) or centrifugal actuation (Gustafsson et al. 2004; Steigert et al. 2006; Cho et al. 2007; Lai et al. 2004) are attractive, particularly for portable devices, due to their straightforward fabrication and minimal dependence on external supporting infrastructure. But unlike modular reaction or detection components that can typically be swapped into new device designs with little modification, valve dimensions and channel geometries of passive flow control systems must be tailored to application-specific combinations of fluid, substrate, and desired flow pattern. Conversely, fully integrated micropump (Amirouche et al. 2009) and microvalve (Oh and Ahn 2006; Zhang et al. 2007) designs in active flow control schemes are highly modular and can essentially be copied and pasted between device layouts. However, this improvement incurs the costs of increased fabrication complexity and potential structural fatigue associated with moving parts inherent to mechanical components. The tremendous popularity of pneumatically controlled

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microvalves (Unger et al. 2000) is largely attributable to their comparatively simple fabrication through the use of off-chip solenoid valve arrays in place of on-chip actuators. This versatile design has proven suitable for a wide variety of applications but does not scale favorably with increasing numbers of valves due to the individual connection necessary to interface each external control component. Similar scalability considerations apply to direct pressure systems utilizing syringe pumps or external pressure controllers.

The type of flow control selected also determines whether the channel network to be controlled operates as “open” or “closed.” We can think of the majority of microfluidic systems as closed networks in which mechanical barriers push fluid or direct flow. These systems use either integrated or external in-line pumps to displace one or more continuous streams of fluid at prescribed flow rates. In contrast, we refer to an open channel network as a system of microchannels devoid of mechanical valves or seals for directing fluid flow. In this case, flow control relies on specific pressures imposed at key locations. These pressures can result from differences in capillary pressure or centrifugal force in passive flow control systems or applied pressure gradients in actively controlled systems. Open channel networks are ideal for droplet-based systems—characterized by transport of discrete fluid volumes to specific positions at specific times—in which flow rates are typically inconsequential.

Toward development of a modular active flow control platform, we describe the design and demonstrate the application of a multiplexed Venturi microregulator array for droplet manipulation in an open microchannel network via distributed pressure control. Previously published work by our group introduced the Venturi microregulator (Fig. 1c) as a high-resolution pressure controller, readily integrable in existing microfluidic device designs (Chang et al. 2007). The microregulator consists of pressurized gas flowing through a converging–diverging nozzle with a sidearm connected at the nozzle constriction. Modification of the gas temperature using microfabricated heating elements perturbs the flow to enable switching of the sidearm output between positive and negative gauge pressure. The highly modular design potentially allows any number of arrayed Venturi microregulators, each capable of outputting an independently controlled pressure, to share a single pressure input, resulting in a compact unit uniquely suited for active distributed pressure control. Such a unit, directly interfaced to a microfluidic device in a multilayer structure, would require no additional external fluidic connections and possess no moving parts.

2 Materials and methods

2.1 Venturi microregulator array fabrication

The Venturi microregulator array devices consist of an upper glass piece etched with the array geometry anodically bonded to a lower silicon piece patterned with the heaters and four-point resistive temperature detectors (RTDs). Figure 2 shows the fabrication process. The array geometry was etched to a depth of 76 μm in Borofloat glass wafers (700 μm thick, 10 cm diameter) using standard photolithography and hydrofluoric acid wet etch techniques. The isotropic wet etch leads to a rounded trapezoidal channel profile with a lateral etch equal to the depth of the channel. Pressure inlet holes (designated P_{in} in Fig. 1a) were drilled using a high-speed drill press with a diamond-tipped bit (1.5 mm diameter; UKAM Industrial Superhard Tools, Valencia, CA). Smaller sidearm access holes (identified in Fig. 1a) of 0.5 mm diameter were drilled by electrochemical discharge machining.

Heaters and RTDs on the lower silicon piece were patterned in a single metal layer using a standard liftoff process. Bare silicon wafers (550 μm thick, 10 cm diameter) coated with a 100 nm thermal oxide were lithographically processed. Titanium and platinum (300/1000 $\text{\AA}$) were evaporated onto the patterned wafer. The wafer was sonicated in acetone for 10 min to liftoff

unwanted metal. The measured resistances were approximately 2000 Ω (RTDs) and between 50 and 100 Ω (heaters).

The glass and silicon wafers were cleaned, anodically bonded, and diced. In preparation for bonding, the etched glass wafer was cleaned in piranha solution, and both wafers were sonicated in acetone and isopropanol. The wafers were then aligned by eye and anodically bonded at 350°C and 1000 V. After bonding, the wafers were diced to expose the electrical contact pads and to obtain the individual devices. Each device was affixed using standard quick cure epoxy and wire bonded to a printed circuit board. Syringe tips (Part Number 5114-B-90; EFD Inc., East Providence, RI) glued to glass capillaries (2 mm I.D.) were attached to the inlet holes with epoxy (Steel Weld Epoxy; ITW Performance Polymers, Riviera Beach, FL) for interfacing to off-chip connections. Geometric tuning was performed by selectively sealing the tuning ports using the same epoxy.

2.2 Open fluidic network fabrication

The open microchannel network devices also consist of an etched upper glass piece anodically bonded to a lower silicon piece. To generate a geometry containing two distinct etch depths, Borofloat glass wafers coated with chromium and gold (500/5000 Å) were lithographically patterned (Microposit SC 1827; Shipley Co., Marlborough, MA) to expose a set of deep features from which the metal was removed. The wafer was then exposed and developed a second time to pattern a set of shallow features (designated R_{inlet} in Fig. 8c); the metal covering the shallow features was not removed. The wafer was isotropically wet etched in hydrofluoric acid to a depth of 70 μm . The metal covering the shallow features was then etched away. The wafer was etched a second time to achieve a depth of 30 μm in the shallow features and a total depth of 100 μm in the deep features. After stripping the remaining metal and photoresist, inlet holes were drilled by electrochemical discharge machining. The wafer was then cleaned, anodically bonded to a bare silicon wafer, and diced as previously described. Syringe tips and glass capillaries were attached to allow interfacing to the microregulator array device using silicone tubing (1.6 mm I.D.). Channel surfaces were hydrophobically treated before use (Rain-X Original Glass Treatment; SOPUS Products, Houston, TX).

2.3 Device operation

Lab air supply, controlled by a pressure regulator (Model Number 3476A; Matheson Gas Products Inc, Irving, TX), was continuously fed to the gas inlet of the device. The heaters and RTDs on the device were controlled by a DC power supply (Model Number HY5003; Mastech, Hong Kong), two data acquisition boards (PCI-6031E and PCI-6704; National Instruments, Austin, TX), two connector blocks (SCB-100 and SCB-68; National Instruments), a custom signal conditioning circuit, a computer, and a LabVIEW program (National Instruments). To calibrate the thermal sensors, the entire device was heated in a convection oven whose temperature was ramped from room temperature to 100°C. Simultaneously, a current of 3 mA was sent through two leads of the four-point RTDs while the voltage across the other two leads was recorded by LabVIEW. Once converted to resistance, a linear fit of the resistance and temperature data was generated. A proportional-integral control algorithm used in conjunction with this linear fit regulated the voltage across the micro-fabricated heaters, enabling feedback control of each heater ($\pm 0.5^\circ\text{C}$) via the closest RTD. All constriction pressure measurements were serially recorded using an electronic pressure sensor (± 10 Pa, Strain Gage Panel Meter DP25B-S; Omega, Stamford, CT) connected to the sidearm access hole. Measurements were recorded after the constriction pressure stabilized at a steady state value following any change in temperature or inlet pressure. Sealing or unsealing of the other sidearm access holes while measuring the constriction pressure of any one microregulator had no effect on the measurement.

3 Results and discussion

3.1 Geometric design and tuning

Uniform microregulator behavior throughout the array is a critical requirement for distributed pressure control. Any deviation in constriction pressure among arrayed microregulators operated at the same temperature and inlet pressure is almost exclusively attributable to non-uniformities in flow geometry. Because the intended control range of the constriction pressure ($P_{\text{constrict}} \sim 1$ kPa) is two orders of magnitude smaller than the total pressure drop through the Venturi nozzle ($P_{\text{in}} \sim 200$ kPa), inhomogeneities in the etched surface and minor flow perturbations may result in unacceptably large deviations in constriction pressure that are not time-dependent. Minimizing this deviation eliminates pressure gradients between microregulators set at identical temperatures. Although thermally suppressing such deviations is possible by independently setting each microregulator to its respective neutral temperature (i.e., temperature resulting in $P_{\text{constrict}} = 0$), solely relying on this strategy can impose large fixed temperature offsets and drastically reduce the available control range of the individual microregulators. Consideration of flow geometry during device design and incorporation of features enabling post-fabrication tuning of the flow geometry significantly improve constriction pressure uniformity.

Asymmetric flow splitting is one major source of constriction pressure variability. The flow profile through the Venturi nozzle dictates the constriction pressure of a microregulator; therefore, the behavior of individual microregulators will not be identical unless the streamlines through each microregulator are identical. Figure 3a depicts a compact “out-of-plane” flow splitting geometry, in which the flow is forced to the arrayed microregulators immediately upon entering the device. All three components of the velocity vector are nonzero at the point the entering fluid simultaneously impinges on the floor of the device and begins to divide toward each of the four microregulators, rendering the flow particularly susceptible to uneven splitting due to minor perturbations. The geometry in Fig. 3b partially remedies this problem by restricting all flow splitting to the same plane such that the z -dimensional velocity is negligible but necessitates the use of a binary-tree layout to maintain streamline symmetry. Based on simulation data (not shown), the length of channel required to reestablish a uniform velocity profile after a bend or split in a constant cross-sectional area channel of our etch depth (76 μm) and aspect ratio (<0.1) is approximately 2 cm. Because inclusion of a 2 cm straight channel segment upstream of each branch point would make the total area of the device impractically large, we devised an alternative method for geometrically reducing the constriction pressure variability.

Geometric suppression of constriction pressure variability can be achieved by empirical, post-fabrication tuning via additional tuning ports as illustrated in Fig. 3b. The tuning ports function as bleed valves that can be individually sealed to effectively increase the inlet pressure of any one microregulator relative to the others as shown in Fig. 4. Because the tuning process translates the curves of Fig. 4 along the abscissa without changing the shapes of the curves, device calibration enables constriction pressure matching at one inlet pressure. In practice, the tuning procedure is a one-time task after which the constriction pressures remain matched for the lifetime of the device; we have not observed any notable change in constriction pressure matching after 4 months of use.

“In-plane” flow splitting combined with post-fabrication tuning can achieve a 10 times reduction in constriction pressure variability as shown in Fig. 5. Figure 5 also shows the constriction pressure variability of a silicon device fabricated using deep reactive ion etching (DRIE) and anodically bonded to a glass substrate. Whereas our wet-etched glass channels exhibited surface roughness values up to 5%, DRIE typically produces relatively smooth

sidewalls with a surface roughness of $\approx 0.5\%$ (Lee et al. 2007). This reduction in overall surface roughness appears to have no appreciable effect on constriction pressure variability.

3.2 Multiple microregulator operation

The relationship among constriction pressures of arrayed microregulators is best characterized as a series of differences between the microregulator temperature and a reference temperature rather than simply an absolute temperature. As the Venturi nozzle portion of the microregulator is heated, the combined effects of increased gas viscosity and decreased mass flow, cause the constriction pressure to increase. The exhibited linear dependence, as shown in Fig. 6, is identical to the previously reported behavior of a single microregulator. Although the device used to generate the data in Fig. 6 has been geometrically tuned, variability among the constriction pressures of the individual microregulators still exists at any given temperature due to the coarseness of the discrete adjustments permitted by the tuning ports. If we define a set of reference temperatures $\{T_{0,i}\}$ corresponding to the neutral temperature of each microregulator, the microregulator pressures can be perfectly matched by mapping constriction pressure as an offset from $T_{0,i}$, represented as ΔT_i . For the device in Fig. 6, this produces

$$\begin{pmatrix} T_{0,1}=41^{\circ}\text{C} \\ T_{0,2}=63^{\circ}\text{C} \\ T_{0,3}=51^{\circ}\text{C} \\ T_{0,4}=51^{\circ}\text{C} \end{pmatrix}.$$

Thermal crosstalk is an important consideration in designing arrayed microregulators. Thermal diffusion to a microregulator from a neighboring microregulator operated at a higher temperature increases the minimum achievable temperature in the cooler microregulator and consequently decreases the available temperature control range and thus the constriction pressure range. Figure 7 shows that thermal diffusion from heated microregulators may prevent neighboring microregulators from reaching their respective desired constriction pressures. The improved positioning of the heating element along the centerline of the Venturi nozzle in the current microregulator design maximizes heater contact with the gas flow, thereby minimizing heat transfer into the substrate and channel walls. Selective active cooling of the device would enable temperature differentials as high as $108^{\circ}\text{C cm}^{-1}$ to be sustained between microregulators at the expense of increased power consumption. Alternatively, suppression of heat transfer away from the Venturi nozzle by increasing the local thermal resistance of the substrate using backside etching could increase the maximum achievable temperature gradient to $158^{\circ}\text{C cm}^{-1}$ with decreased power consumption at the expense of added fabrication complexity (Yang et al. 2005).

In addition to thermal crosstalk, independent perturbation of the gas flow through any one microregulator should result in minimal upstream interaction that could alter flow through or constriction pressures of other microregulators in the array. Figure 7b depicts the constriction pressures of three microregulators maintained at $\Delta T = 0$ while varying the temperature of the fourth microregulator. Interestingly, the constriction pressure of the neutral microregulators appears to weakly vary opposite to that of the active microregulator. This trend contradicts expected variation from thermal crosstalk, suggesting instead that changing the mass flow rate through one microregulator leads to an opposite change in mass flow rate through the other microregulators and subsequently, an opposite change in constriction pressure. We suspect this may occur due to nonuniform heating in the presence of large temperature gradients, which increases heat transfer into the substrate while decreasing heat transfer into the gas flow and ultimately increases the difference between the heater temperature and the actual temperature of the gas flow.

3.3 Fluid manipulation in open microchannel network

Open channel networks intended for distributed pressure flow control should contain appropriately placed fluidic resistances to maximize pressure gradients achievable in the network. Of particular importance is the configuration of the sample inlet region as depicted for our test device in Fig. 8. The sample inlet is always open such that the pressure at node A_i is equal to atmospheric. Node V_i is connected to the controlled pressure source—in this case, one microregulator in our Venturi microregulator array. This design results in a maximum (or minimum) achievable pressure at node B_i equal to

$$P_{B_i} = P_{V_i}^* \times \frac{R_{\text{inlet}}}{R_{\text{inlet}} + R_{\text{sidearm}}}$$

where $P_{V_i}^*$ is the maximum (or minimum) possible pressure output of the microregulator. As R_{inlet} increases, this maximum approaches $P_{V_i}^*$, corresponding to a closed channel network in the limit as $R_{\text{inlet}} \rightarrow \infty$. Therefore, bounding the interior nodes of an open channel network with large hydraulic resistances shields the interior of the network from the open exterior nodes fixed at atmospheric pressure.

The microfluidic flow control capabilities of the Venturi microregulator array are well illustrated by several operations performed in a separate model device, including droplet loading, movement, splitting, and merging (Online Resource 1 in Supplementary material). Figure 9 shows the sequence of microregulator settings used to carry out each operation. For example, droplet loading involved setting all microregulators to negative pressure until the desired volume of liquid was drawn in through the inlet. The microregulator closest to the loading inlet was then set to positive pressure to shear the droplet away from the loading channel. The small hydraulic diameter of the high-resistance loading channel ($D_h \approx 32 \mu\text{m}$) causes some degree of self-sealing after droplet loading. Because contact angle hysteresis demands a higher pressure to expel this column than to move droplets in the larger main channels ($D_h \approx 117 \mu\text{m}$), the residual liquid further helps to shield the network interior. To prevent undesired introduction of air from disrupting droplet cohesion (Fig. 9: Single droplet loading), the decreasing pressure gradient from node C_1 to node B_1 is reduced as the droplet begins passing C_1 to draw a small amount of liquid into the C_1 – B_1 channel segment. This weak pressure gradient is reversed once half the droplet has passed C_1 to restore the diverted liquid volume to the main body of the droplet. It is important to note that the specific microregulator settings in Fig. 9 are not unique “solutions” for the fluidic manipulations shown. Pressure differences between nodes are responsible for fluid motion; therefore, the pressure at any given node is irrelevant as long as the necessary pressure gradient is maintained.

Barring surface tension effects, the flow rate in any channel segment is zero if and only if no pressure gradient exists down the length of that segment. Because an open channel system does not contain mechanical valves, a zero flow condition in any region of the network is only achieved if the pressures at all bounding nodes are equal. A few specific fluidic manipulations, particularly the simultaneous handling of multiple droplets, highlight the implications of this observation (Online Resource 2 in Supplementary material). Figure 10 shows several images in which one droplet is moved while holding a second droplet stationary. Because the viscosity of the liquid is two orders of magnitude greater than the viscosity of air, nearly the entire pressure gradient in a channel segment containing any portion of a droplet occurs over the length of the liquid column. The pressure distribution in the network is thus dependent on the position of the droplet. In Fig. 10, ΔT_4 is increased as the moving droplet passes node C_2 to match the pressures and prevent flow between nodes B_4 and C_2 , keeping the stationary droplet

still. If the surface tension of the liquid is sufficient, contact angle hysteresis will negate the effect of small pressure differences, suppressing undesired droplet movement even if the pressures at nodes B_4 and C_2 are not perfectly matched.

Consistent with the previously reported behavior of single Venturi microregulators, the response time of the microregulator array for halting droplet movement was approximately 0.8 s when all microregulators were reset to neutral pressure, enabling precise droplet positioning. In the current work, movement of droplets beyond their intended positions was not unusual due to insufficiently rapid manual operator response. Feedback control, coupling electrodes for droplet detection, and automated control of the microregulator array temperatures, would alleviate this problem as well as significantly reduce the duration of each operation. One possible implementation would use electrodes situated around each node as “trip-wires” to detect droplet position (Srivastava and Burns 2006; Cole and Kenis 2009). In this arrangement, the starting position of the droplet and detection of the droplet’s arrival at the desired ending position are necessary to determine the required modifications in the network pressure distribution to perform a given operation. Additional droplet detection electrodes would also be needed at intermediate branch points in complex microchannel networks. Based on droplet acceleration and deceleration times reported in our previous work, operations such as droplet merging and splitting would theoretically require less than 5 s in a fully automated system.

4 Conclusion

Building upon our Venturi microregulator design, we demonstrated the independent operation of multiple arrayed microregulators fed by a single pressure source. By using the array to impose arbitrary pressure distributions across a microchannel network, we demonstrated the ability to use such an array as a modular microfluidic flow controller. Although our current implementation consists of the microregulator array and the controlled fluidic network as two separate devices, Fig. 11 shows a prototype that integrates the two parts into one multilayer structure. In addition to being a challenge in array scaling and maximization of the pressure control range, thermal diffusion presents the primary obstacle to multilayer integration by accelerating evaporation of liquid volumes in the controlled fluidic network due to inter-layer heat transfer. Along with our suggested geometric modifications, a different choice of substrate materials would also likely help to suppress undesired heat transfer. For example, replacement of our Si/glass stack with a glass/PDMS stack ($k_{\text{Si}} = 148 \text{ W m}^{-1} \text{ K}^{-1}$; $k_{\text{glass}} = 1.2 \text{ W m}^{-1} \text{ K}^{-1}$; $k_{\text{PDMS}} = 0.15 \text{ W m}^{-1} \text{ K}^{-1}$) would greatly reduce the overall thermal conductivity of the device, simultaneously decreasing power consumption and thermal diffusion. Addressing these issues will greatly increase the viability and versatility of the Venturi microregulator array as a universal microfluidic flow control platform.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Fig. 1. Multiple Venturi microregulator module. **a** Arrayed Venturi microregulator module investigated in our current work. Four microregulators share one pressure inlet set at a constant inlet pressure, P_{in} , and are numbered 1 to 4 proceeding counterclockwise from the upper left. **b** Dimensions of array geometry. Constriction width is approximately $130\ \mu\text{m}$. Width of sidearm connected to constriction is approximately $86\ \mu\text{m}$. Converging and diverging angles of the nozzles are 30° and 10° , respectively. Etch depth is $76\ \mu\text{m}$. **c** Inset showing single microregulator schematic. Heating the air flow through the converging-diverging channel increases the constriction pressure output through the access hole in the sidearm ($P_{constrict}$)

Fig. 2. Fabrication process flow. Fabrication of the fluidic network uses two etches to generate the deep main channels and the shallow inlet channels, which are labeled R_{inlet} in Fig. 8c

Fig. 3. Alternate microregulator array geometries. **a** Out-of-plane flow splitting geometry. **b** Microregulator array with tuning ports for post-fabrication modification of the flow geometry. Fabricated tuning ports are approximately $86\ \mu\text{m}$ wide. Each tuning port can be sealed to locally increase the pressure in its respective branch

Fig. 4. Plot of constriction pressure behavior with varying inlet pressure at room temperature before (*open symbols*) and after (*filled symbols*) geometric tuning, which allows constriction pressure matching at the desired inlet pressure. The final tuning port sealing configuration of the tuned device is shown. Pressure values are in gauge pressure

Fig. 5.

Graph of variation among the constriction pressures of arrayed microregulators in different device types. All devices were fabricated in glass except for “DRIE, In-plane,” which was fabricated by deep reactive ion etching in Si. All devices were etched to a depth of 76 μm . The inlet pressure of each device was set such that the mean constriction pressure of the arrayed microregulators equaled zero. The standard deviation among the four microregulators of each device was calculated. The average standard deviation of no fewer than three devices is shown for all device types except “DRIE, In-plane,” for which only one device was tested. *Error bars* indicate one standard deviation above and below this average

Fig. 6.

Variation of constriction pressure with microregulator temperature in a geometrically tuned device at $P_{in} = 200$ kPa. Measurements were taken with the indicated microregulator heated to the indicated temperature while all other microregulators were unheated. Although the curves are parallel, they do not perfectly overlap due to the coarseness of the adjustments afforded by the tuning ports. *Error bars* indicate one standard deviation above and below the mean of triplicate measurements. Pressure values are in gauge pressure

Fig. 7.

Effect of thermal and pressure crosstalk. Thermal crosstalk and the lack of active cooling may render low ΔT setpoints unachievable, resulting in the observed nonlinear variation in $P_{constrict}$. This is particularly problematic for microregulators with low $T_{0,i}$ values, where $T_{0,i}$ is the temperature corresponding to neutral pressure output for microregulator i . ΔT_i is the difference between the temperature setpoint of microregulator i and $T_{0,i}$. **a** Tuning port sealing configuration and microregulator designations. **b** ΔT_4 is varied while all other microregulators are maintained at $\Delta T = 0$. **c** ΔT_1 and ΔT_2 are varied oppositely of ΔT_3 and ΔT_4 . This is the maximum achievable pressure difference. *Error bars* indicate one standard deviation above and below the mean of triplicate measurements. All pressure values are in gauge pressure

Fig. 8.

Schematic of fluidic network controlled by microregulator array. **a** Drawing of experimental system. The microregulator array and the controlled microchannel network are separate devices in the current setup. **b** Layout of controlled microchannel network. Nodes A_i are loading ports that are always open to atmospheric pressure. Nodes V_i are connected to the Venturi microregulators. **c** Fluidic resistances and electrical circuit equivalent of inlet region. High inlet resistance, R_{inlet} , and low sidearm resistance, R_{sidearm} , maximize the range of pressures that can be achieved in the network. $R_{\text{inlet}} \approx 180 R_{\text{sidearm}}$ in tested device

Fig. 9.

Images of various droplet manipulations carried out in microchannel network pictured in Fig. 8. *Insets* show configuration of controlling microregulator array; array orientation is identical to microchannel network orientation (i.e., each microregulator connects to the correspondingly positioned outer control node). ΔT_i is the temperature setpoint of microregulator i . *Max Vac* indicates the heaters for that microregulator are turned off to generate maximum vacuum output. *Arrows* indicate direction of negative pressure gradient; *dashed arrows* indicate weak pressure gradient. Images are recolored to enhance droplet visibility. Video of these operations is included in Online Resource 1 (Supplementary material)

Fig. 10.

Moving one droplet while keeping a second droplet stationary. A zero flow condition between nodes B_4 and C_2 must be maintained to keep the upper droplet still. ΔT_4 is increased as the lower droplet moves past C_2 so the pressures at B_4 and C_2 remain matched. A plot of the relative pressure change at node C_2 is shown. Images are recolored to enhance droplet visibility. Video of this operation is included in Online Resource 2 (Supplementary material)

Fig. 11.
Three-layer device integrating Venturi microregulator array and microfluidic network