

Engineering Liquid-Plug Evaporation in Microfluidic Networks: From Vapor and Temperature Mapping to Predictive Lumped-Element Modeling

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Keywords: Lumped-element modeling, Evaporation dynamics, Microfluidics, Vapor transport, Thermosensitive coating, Predictive design, Diffusion resistance

Abstract

Evaporation is a critical yet often overlooked source of error in microfluidic platforms, where nanoliter-scale volume losses can impair metering accuracy and assay reliability. While evaporation has been studied extensively in open configurations (e.g., for droplets on a surface) and in simple systems such as microchannels, fewer studies have characterized evaporation within networked microfluidic circuits with interconnected chambers and channels. In such architectures, evaporation depends on the collective diffusion resistance of multiple pathways rather than a single characteristic length scale. Here, the evaporation of small liquid plugs (100 nL–10 μ L) is systematically investigated within microfluidic circuits. Through controlled experiments and mapping alongside lumped-element modeling, it is shown how channel dimensions determine total vapor-diffusion resistance and the resulting evaporative flux. Results indicate that evaporation rates remain insensitive to contact-line position, provided the system operates in the isothermal, steady-state, and diffusion-limited regime. Furthermore, compact analytical expressions are derived that accurately predict evaporation across diverse designs, including microwell geometries relevant to multi-well plates. This study establishes quantitative design rules for engineering microfluidic circuits with predictable evaporative behavior. It provides a general framework for minimizing volume loss in applications ranging from sample preparation and cell analysis to wearable sensors and portable devices.

1 Introduction

Microfluidics has emerged as a powerful technology enabling the precise manipulation of small liquid volumes within geometrically confined environments, typically in channels with sub-millimeter cross-sections. The inherent advantages of microscale transport enable levels of control, throughput, and integration that are difficult to achieve at the macroscale. In engineering, evaporative microchannels have been investigated widely for thermal management in compact systems, where their high surface-to-volume ratio enables efficient heat removal in power electronics and portable devices [1–4]. In the life sciences, microfluidics has transformed experimental workflows by enabling miniaturized, automated, and highly sensitive assays, resulting in applications such as biochemical assays, point-of-care diagnostics, and sample-preparation workflows [5–10].

Thermal processes are used extensively in sample-preparation workflows, including polymerase chain reaction (PCR), isothermal amplification, enzymatic reactions, and thermal lysis [11–15]. While microfluidic platforms facilitate rapid and efficient thermal cycling due to their high surface-area-to-volume ratio, these same characteristics also make them highly susceptible to evaporation [16]. This factor makes even modest temperature increases sufficient to induce significant evaporation. Also, evaporation may be substantial during long incubation steps, even at 20°C. Therefore, minimizing evaporation is a long-standing challenge in microfluidic and microscale biological assays [17].

While evaporation can be intentionally exploited for passive pumping and flow control in microchannels [18,19], it often results in unwanted volume loss. Moreover, evaporation may compromise the downstream processing by introducing significant quantitative errors [20]. Classic examples include edge effects in microwell plates, where peripheral wells experience increased evaporation, leading to systematic experimental bias [21]. Uncontrolled evaporation is especially problematic when working with very small volumes (sub-microliter), as even modest heating temperatures between 40–60°C can cause complete drying within minutes [22]. In wearable sweat-analysis devices, minor evaporative water loss can markedly elevate biomarker concentrations (e.g., peptides), leading to inaccurate detection [23]. Evaporative volume loss becomes even more pronounced in open microfluidic formats, where liquid interfaces are exposed directly to ambient air, leading to rapid sample depletion or uncontrolled concentration changes [24]. Therefore, optimized and fast sample processing is required to minimize volume loss [25].

To mitigate such evaporation loss, several strategies have historically been employed. Simple approaches include sealing sample chambers with solid lids, adhesive films, or coverslip seals [26]. For example, Choi et al. implemented a mechanical clamping approach that effectively increased the vapor-diffusion resistance of the chamber, resulting in significantly reduced evaporation [27]. Saturating the surrounding air by placing a water bath as close as possible to the sample minimizes the driving force for evaporation [17]. A more complex method involved saturating the surrounding air by fabricating micro-reservoirs from agarose gel [28]. Also, covers made of immiscible liquids, such as mineral oil, were found to be useful for minimizing evaporation [29].

The materials used in the microfluidic device can significantly complicate the evaporation problem. For instance, polydimethylsiloxane (PDMS), one of the most widely used microfluidic materials, is highly permeable to water vapor [30]. Its intrinsic gas permeability enables continuous moisture diffusion through the device walls, thereby accelerating evaporation even under moderate thermal conditions (e.g., 25°C). Several strategies have been proposed to reduce the permeability of PDMS material. One effective approach is to coat PDMS with a vapor barrier, such as parylene [31], or a collagen powder dispersion [32,33]. Another commonly adopted solution is to sandwich the PDMS layer between two glass slides, which effectively suppresses the vapor permeation by considerably increasing the diffusion resistance, thus lowering evaporation loss [34].

Beyond environmental factors such as ambient temperature and relative humidity, geometrical parameters of the fluidic circuit strongly influence the evaporation dynamics. Parameters including channel length, cross-sectional area, and even the shape of liquid menisci can modulate the vapor transport pathway and the effective mass-transfer resistance [35,36]. Most prior studies have focused on open surfaces, sessile droplets, or porous media, where the evaporation dynamic is dominated by complex wetting and interfacial phase-change phenomena [37–40]. In confined geometries, the curvature of the liquid–air interface and liquid meniscus position may alter the local concentration field and, in some regimes, influence the evaporation flux through capillary or interfacial effects [16,41]. Such interfacial effects have been investigated in thin films confined between micropillars, both numerically and experimentally [42,43]. The contact line dynamics were analyzed, and the droplet interfacial temperature was mapped during evaporation by using Infrared Thermography [44]. Far fewer studies have systematically characterized evaporation in non-porous and well-defined geometries (e.g.,

microchannels), where diffusive vapor transport is expected to dominate. Thome et al. developed a theoretical framework for the evaporation of elongated bubbles in microchannels [45], and conducted a thorough comparison with the available experimental database [46]. By integrating ombroscopic imaging and Infrared Thermography, Chauvet et al. demonstrated that, in square capillary tubes, evaporation remains steady when capillary forces keep corner films pinned to the tube entrance but decreases markedly when gravity thins the films and triggers depinning of the contact line [47]. Moreover, evaporation in microfluidic channels has been sparsely investigated, primarily for the simplest case: a single confined microchannel, geometrically characterized and serving as the vapor-diffusion barrier between the liquid chamber and the closed chamber [48].

In contrast, modern microfluidic platforms commonly incorporate complex networked architectures, consisting of interconnected chambers, constrictions, bypass channels, or multilayer pathways [49]. In such systems, vapor must traverse multiple geometrical segments before reaching the bulk environment, and the resulting evaporation rate reflects a distributed network of resistances, rather than a single characteristic length scale. Despite the prevalence of these architectures in biological and diagnostic devices, the relationship between circuit geometry and evaporation rate remains poorly quantified experimentally.

In this study, we combine controlled experiments and theoretical modeling to examine the evaporation of small liquid volumes (~ 100 nL– 10 μ L) confined within a microfluidic chip. Specifically, we focus on regimes where thermal gradients are minimal, and vapor transport is expected to be governed by steady-state diffusion. Extensive measurements were performed using fluorescence-based thermography and liquid–air interface tracking, enabling chip temperature mapping, internal vapor distribution, and characterization of sample volume loss. Moreover, this multimodal approach allows direct evaluation of the assumptions commonly used in analytical models—namely, isothermal conditions and diffusion-limited transport. Finally, we develop a lumped element model based on Fick’s first law to analyze the influence of geometric parameters systematically. By relating measured volume loss to the physical characteristics of the microfluidic circuit, this work provides design rules and a quantitative framework for predicting and controlling evaporation in confined microscale systems. These results are relevant to the design of microfluidic devices for biological assays, thermal processing, portable diagnostics, and wearable devices, where preventing evaporative losses is essential for controlling the sample volume and minimizing errors in downstream processing steps.

2 Materials and Methods

In a typical experiment, a defined volume of deionized (DI) water was introduced into a microfluidic chip and transferred by centrifugation into a designated chamber, ensuring precise liquid positioning. The chip was subsequently placed inside a temperature-controlled heated enclosure, where evaporation proceeded under well-defined ambient conditions. Temperature and relative humidity were monitored continuously using integrated sensors and luminescent coatings, providing real-time feedback to maintain consistent experimental conditions. The following subsections describe the chip design, experimental setup, and analytical methods employed to characterize evaporation dynamics.

2.1 Microfluidic Chips: Design, Fabrication, and Materials

Microfluidic chips were designed using SolidWorks and fabricated via resin-based 3D printing (Detax Medicalprint, Clear–04016) at the Sirris research center. Each chip was rectangular, measuring 20 mm in length, 10 mm in width, and 4.5 mm in thickness. A single microfluidic circuit was designed and patterned onto the surface of each chip with two configurations: *Simple* and *Complex*.

In the *Simple* (Simp) configuration, the microfluidic circuit consisted of a single channel comprising two segments each of lengths L_1 and L_2 and cross-sectional areas A_1 and A_2 , arranged in series. In all the variants, the channels were of equal length, $L_1 = L_2$. We considered three variants of cross-sectional areas: In Simp-#1, both segments possessed the same cross-sectional area ($A_1 = A_2$); in Simp-#2, the second segment was four times wider ($A_2 = 4A_1$); and in Simp-#3, the second segment was four times narrower ($A_2 = \frac{A_1}{4}$) (Figure 1-a). Each *Simple* configuration was 3D printed with two different depths, $H_1 \in \{1, 2\}$ mm. These variations yielded six distinct chip designs (Table 1).

In the *Complex* (Comp) configuration, the circuit included an inlet well with a square entrance ($A_{\text{well } 1} = 9 \text{ mm}^2$, $L_{\text{well } 1} = 2.5 \text{ mm}$) followed by a pyramidal well tapering the cross-section to $A_{\text{well } 2} = 0.015 \text{ mm}^2$ along $L_{\text{well } 2} =$

4 mm. Downstream of the inlet well, a metering chamber is integrated, connected to the well through a microchannel measuring $L_{ch} = 0.60$ mm in length, $W_{ch} = 0.15$ mm in width, and $H_{ch} = 0.10$ mm in depth. The chamber had a constant length of $L_m = 1$ mm. Its depth $H_m \in \{0.2, 0.4\}$ mm, and width $W_m \in \{1, 2, 3\}$ mm were varied across different designs. The vent channel width (W_v) was either varied among $\{0.9, 1.8, 2.7\}$ (designs whose references ended with the suffix A) or kept constant at 0.9 mm (Figure 1-b). Also, the metering chamber was connected to a waste channel with length $L_{waste} = 2$ mm, width $W_{waste} = 0.3$ mm, and depth $H_{waste} = 0.2$ mm. All the variable dimensions for the metering chamber are listed in Table 2.

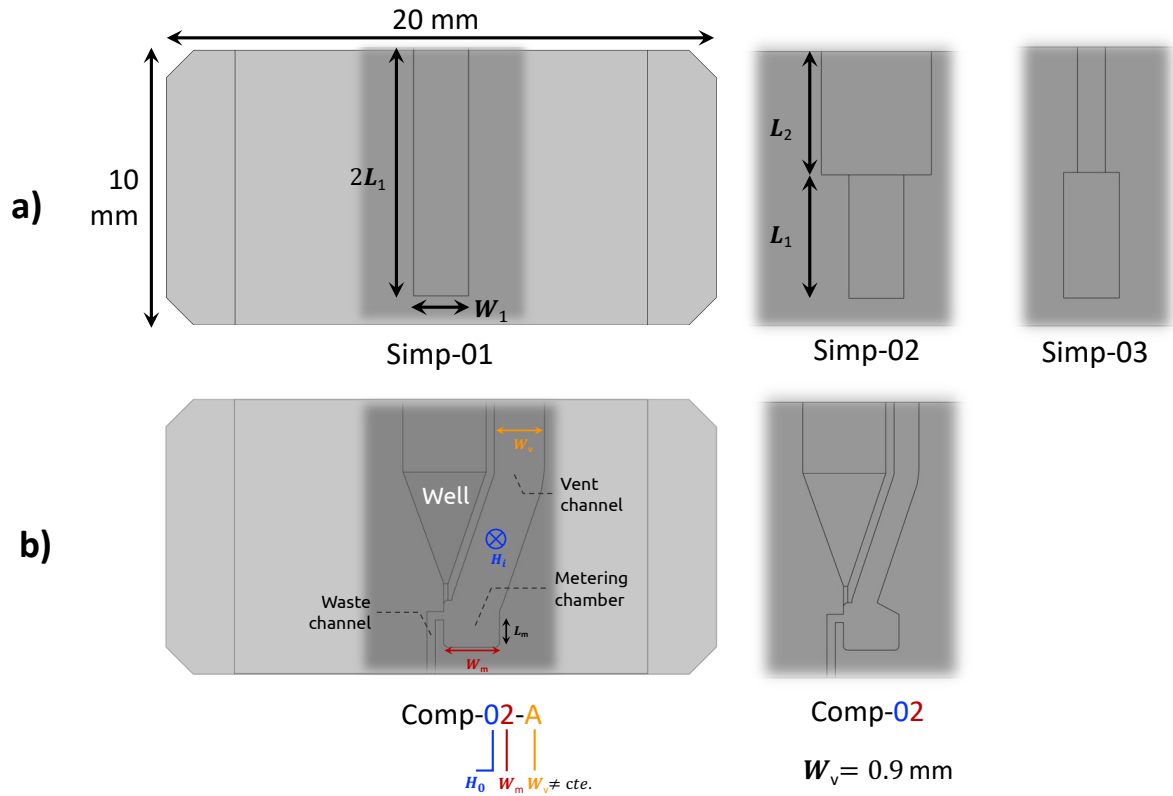


Figure 1: Overview of the microfluidic chips comprising a single circuit designed in two configurations: (a) Simple configurations, consisting of straight channels ($L_1 = L_2$) with uniform or stepped cross-sections ($A_2 = 4A_1$ or its inverse), and (b) Complex configurations, incorporating a pyramidal inlet well connected to a metering chamber via a short microchannel, followed by a waste channel. The metering chamber geometry was varied in width ($W_m \in \{1, 2, 3\}$ mm) and depth ($H_m \in \{0.2, 0.4\}$ mm), while the vent channel width (W_v) was either kept constant at 0.9 mm or varied among $\{0.9, 1.8, 2.7\}$ mm (design references ending with suffix A).

Table 1: Description of channel dimensions implemented in the Simple configurations. All dimensions are given in [mm].

Chip	W_1	H_1	W_2	H_2	$L_1 = L_2$	Data markers
Simp-01	2	1	—	—	$2L_1$	▲
Simp-11		2	—	—		●
Simp-02	2	1	2	2	4.5	▲
Simp-12		2	4	4		●
Simp-03	2	1	0.5	0.5	4.5	▲
Simp-13		2	1	1		●

Table 2: Description of metering chamber and vent channel dimensions in the Complex configurations. All dimensions are given in [mm]. The length of the metering chamber was 1 mm for all the designs.

Chip	W_m	H_m	W_v	Data markers
Comp-01	1	0.2	0.9	■
Comp-11	1	0.4	0.9	■
Comp-02	2	0.2	0.9	●
Comp-02-A	2	0.2	1.8	●
Comp-12	2	0.4	0.9	●
Comp-12-A	2	0.4	1.8	●
Comp-03	3	0.2	0.9	▲
Comp-03-A	3	0.2	2.7	▲
Comp-13	3	0.4	0.9	▲
Comp-13-A	3	0.4	2.7	▲

2.2 Experimental Setup

2.2.1 Centrifugal Bench

A mini centrifugal bench was built to control the rotation of the chips, which were mounted in a Chip-on-a-Disk (COAD) format and inserted into a horizontal disk [8,50] (Figure 2). The rotational speed was able to reach 2500 rpm, $\sim 350 g$ at the highest radial position of the metering chamber ($r = 5 \text{ cm}$).

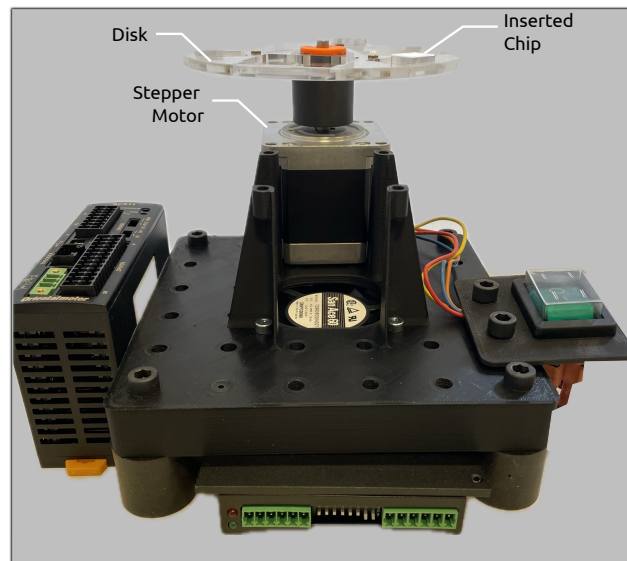


Figure 2: Centrifugal bench assembly in a Chip-on-a-Disk format, built to rotate the chip at accelerations up to 350g.

2.2.2 Controlled Heating Platform

A controlled heating platform was developed to approach isothermal conditions during evaporation experiments while enabling simultaneous thermal and optical monitoring (Figure 3). The chip was placed on a hot plate (VWR 442–1269) and enclosed within a custom assembly of 3D-printed housings. The enclosure walls were printed with 15% infill density, leveraging the internal air gaps as thermal insulation to minimize heat exchange with the surroundings. Local temperature and humidity inside the enclosure were continuously monitored using an Arduino Uno connected to a DHT22 sensor. The measured relative humidity was used to define the far-field vapor concentration boundary condition required to determine the evaporation rate. Where necessary, an additional temperature measurement was obtained directly on the chip using a K-type thermocouple, positioned as close as possible to the chamber of interest.

An optical assembly was positioned inside the enclosure. It comprised a right-angle beamsplitter (Thorlabs C45P integrated with DMLP490) and a right-angle dichroic mirror aligned above the chip. This arrangement allowed illumination of UV LED onto the chip and transmission of emitted light to an external camera (Canon EOS 250D, with an MP-E 65 mm macro lens) located outside the isothermal chamber. An Arduino Mega was programmed to sequentially trigger the light source and synchronize it with the camera trigger via the Canon EOS Utility software. The images were recorded in JPG and 16-bit RAW (CR3) format with a maximum resolution of 24 megapixels.

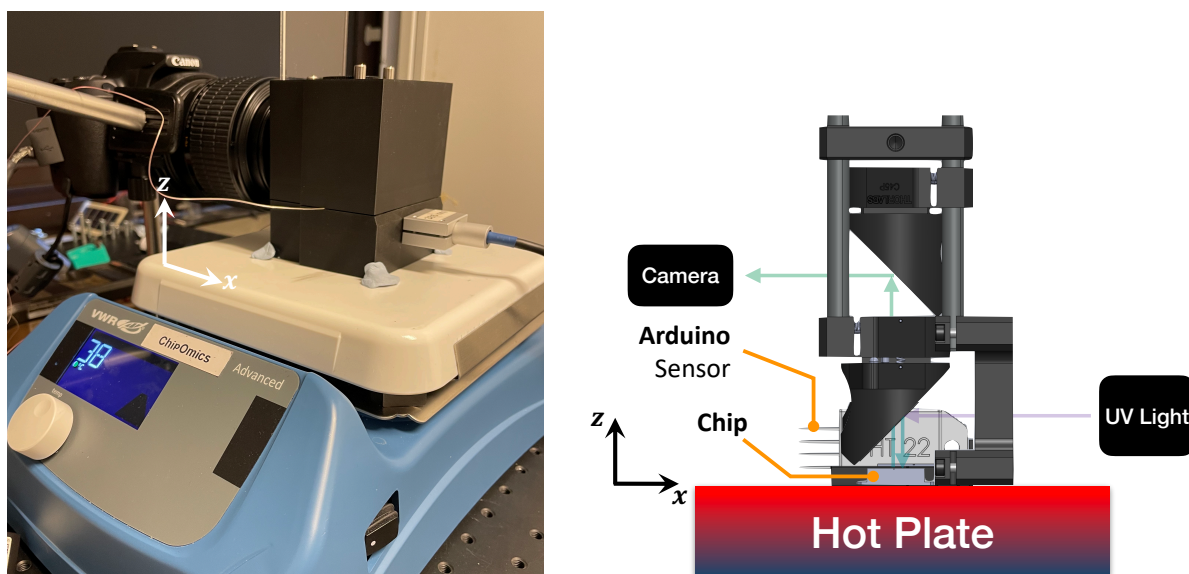


Figure 3: Overview of the controlled heating platform and optical assembly. (Left) Photograph of the experimental setup with the optical assembly positioned above the microfluidic chip inside the printed black enclosure. (Right) Schematic of the optical assembly, demonstrating the chip, Arduino sensor, UV light source, and camera arrangement on the hot plate. The setup directs UV illumination onto the chip and captures the emitted light, while the Arduino monitors environmental parameters (temperature and relative humidity) and synchronizes the imaging.

2.3 Thermo-Sensitive Coating Preparation on Sealing Tapes

Some chips were sealed using a thermo-sensitive coating (TSC); see Table 4. Two different coatings were used. Both comprised a specific fluorescent dye and a binder as summarized in Table 3. For the first TSC, referred to as Ru(Phen), the fluorescent dye was $[\text{Ru}(\text{phen})_3]\text{Cl}_2$ (Ruthenium(II) dichlorotris(1,10-phenanthroline) hydrate (Sigma-Aldrich), and the binder was polyacrylic acid (PAA). For the second TSC, referred to as Eu(TTA), the fluorescent dye was $\text{Eu}(\text{TTA})_3$ (Europium(III) thenoyltrifluoroacetate trihydrate, 95% (Thermo Fisher Scientific) and the binder was polymethyl methacrylate (PMMA). Each coating was prepared by dissolving the dye and binder in ethanol for Ru(Phen) or in toluene for Eu(TTA), and the solutions were stirred until fully dispersed. If sedimentation of undissolved powder was observed, the mixture was subjected to ultrasonic agitation for 5 min to accelerate dissolution and ensure homogeneity of the coating solution.

TSC chips were sealed using a two-layer adhesive tape assembly (Figure 4, left). The first layer was a Nitto double-sided acrylic-adhesive tape of thickness 35 μm . One side of this tape was spin-coated (1200 rpm, 1 min) with 250

μL of TSC solution. The Nitto tape is made of PET, which is permeable to water vapor [51]. This property, combined with the Ru(phen) TSC, enables a combined sensitivity to both humidity and temperature. The second layer (Labelor, 3635E5-38B297, thickness $65\text{ }\mu\text{m}$) was then laminated onto the coated tape. Finally, the protective liner on the other side of the Nitto tape was removed to seal the microfluidic chip, positioning the TSC layer $35\text{ }\mu\text{m}$ from the chip surface (Figure 4, right).

Some other chips, referred to as TSC-free chips (Table 4), did not include a TSC. They were directly sealed with the $65\text{ }\mu\text{m}$ -thick Labelor tape.

Table 3: Description of the prepared thermo-sensitive coatings (TSCs) and their additional sensitivities.

TSC label	Fluorophore	Binder	Fluor./Binder [%wt/wt]	Solvent	Solvent/Binder [wt/wt]	Sensitive to
Ru(Phen)	$\text{Ru(Phen)}_3\text{Cl}_2$	PAA	36.8	Ethanol	4	Temperature and water vapor
Eu(TTA)	Eu(TTA)_3	PMMA	20.9	Toluene	5.4	Temperature only

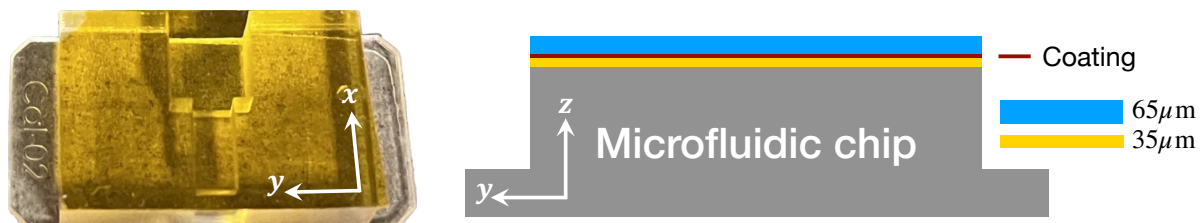


Figure 4: (Left) Top view of the microfluidic chip coated with Ru(Phen) thermo-sensitive coating (TSC) on the sealing layer (Nitto tape). (Right) Schematic illustration of the sealed chip structure showing the Nitto tape (yellow) covering the fluidic circuit and a thicker adhesive tape (blue) laminated on top. The TSC coating (red line) is sandwiched in between.

2.4 Chip Preparation and Testing

Each microfluidic chip was used for several tests. It was cleaned after each use by rinsing with isopropanol and DI water. The microfluidic circuit was then sealed with the adhesive tape. The advancing (a) and receding (r) contact angles were measured for DI water on resin ($\theta_a = 89^\circ$, $\theta_r = 57^\circ$) and Labelor tape ($\theta_a = 102^\circ$, $\theta_r = 72^\circ$). For each test, $8\text{ }\mu\text{L}$ of blue-dyed water was pipetted into the chip, followed by centrifugation at 2500 rpm—either to collect all the liquid at the bottom of the channel in the *Simple* configuration or to select a nanoliter-scale volume into the metering chamber, while routing excess liquid to the waste in the *Complex* configuration [52].

Following centrifugation, the TSC chips were tested by gradually heating them from room temperature in ten successive increments of 5 K each. At each step, the temperature was held for 5 min to allow uniform thermal conduction across its top surface before imaging. The acquired images were subsequently used for TSC data analysis and calibration.

The TSC-free chips used exclusively for evaporation measurements did not include the vapor-permeable PET-based Nitto tape. These chips were heated to a controlled temperature range of 311–313 K (38–40 °C), and the evaporation measurements began once the temperature sensor readings stabilized. Images were captured at 30-second intervals throughout the test duration.

Table 4: Summary of chip preparation and testing conditions for TSC and TSC-free experiments.

Parameter	TSC Test	TSC-Free Test
Chip sealing	35- μm Nitto PET-based tape (vapor-permeable) with spin-coated TSC layer, laminated with 65- μm Labelor tape	65- μm Labelor tape only and without TSC layer

Purpose	Quantitative temperature mapping and qualitative vapor visualization	Quantitative evaporation measurement and model validation
Temperature Range	293 K–323 K (in 5 K increments)	311–313 K (38–40 °C)
Heating Protocol	Incremental heating with a 5-min rest at each step	Constant temperature after stabilization
Imaging Frequency	Once per temperature step	Every 30 s

2.5 Data Analysis

2.5.1 Volume Loss Calculation in TSC-free Tests

Volume loss due to evaporation was quantified by measuring the liquid volume (V) heated within the circuit using Python image processing of the JPG images. To calculate the variations of liquid volume, it was assumed that the shape of the liquid-air interface along the depth of the channel or chamber remained constant throughout the experiment. The liquid volume was determined from the segmented contour area of the liquid phase in the images and converted to physical units using the calibrated pixel size and chamber depth. The dominant uncertainty in the volume measurement arises from the image-processing step used to detect the liquid contour. Assuming that this uncertainty primarily affects the measured contour area N (in pixels), the relative uncertainty in the volume measurement can be approximated as $\delta V/V \approx \delta N/N$. Based on repeated image segmentation and the pixel resolution of the imaging system, the resulting uncertainty in the individual measured liquid volume was estimated to be a maximum of approximately $\pm 5\%$. Each experiment was repeated three times to assess reproducibility.

The evaporation rate was determined by linearly fitting the measured liquid volume versus time for each trial. The error in the evaporation rate was estimated as the standard deviation of the slope estimator obtained from a linear least-squares fit to equally spaced volume measurements. The MATLAB script used to estimate the evaporation rate error is provided in the Supplementary Information.

2.5.2 TSC Data Processing and Calibration in TSC Tests

The TSC images were processed using the MATLAB Image Processing Toolbox. First, CR3 files in RGB format were converted to 16-bit grayscale TIFF images. The Ru(phen)/PAA coating was employed exclusively for qualitative visualization of the vapor distribution within the network. Therefore, the images were used without calibration to map the distribution of relative humidity and temperature within the fluidic circuit. Calibration was performed exclusively for tests involving Eu(TTA) TSC, which served as the purely thermo-sensitive fluorophore. To do so, the temperature measured by the K-type sensor was recorded, and images were acquired after a resting time of 5 min following each temperature adjustment. This resting time was selected based on the characteristic thermal diffusion time of the 3D-printed resin, $t_d = d^2/\alpha$, where $\alpha \approx 10^{-7} \text{ m}^2 \text{ s}^{-1}$ [53]. For a chip thickness of $d = 5 \text{ mm}$, the estimated diffusion time is approximately 5 min, ensuring thermal equilibrium before image acquisition.

For each set of images, a small region ($100 \times 100 \text{ } \mu\text{m}^2$) on the chip was selected as a calibration window, positioned as close as possible to the thermocouple location where the noise generated by the coating was found to be minimal. According to [54], the relationship between fluorescence intensity and temperature can be modeled by

$$\ln\left(\frac{I_{\text{ref}}}{I}\right) = A\left(\frac{1}{T_{\text{ref}}} - \frac{1}{T}\right)^2 + B\left(\frac{1}{T_{\text{ref}}} - \frac{1}{T}\right) + C, \quad \text{Eq. 1}$$

where I_{ref} and I are the emitted intensities at the reference temperature T_{ref} and actual temperature T , respectively, and A , B , and C are setup-dependent coefficients to be adjusted. For each temperature, $\ln\left(\frac{I_{\text{ref}}}{I}\right)$ was calculated, and the calibration coefficients were determined by least-square regression. Equation 1 was then inverted to compute the temperature for each pixel from its emitted intensity I , thereby enabling temperature mapping across the TSC surface.

3 Experimental Results

3.1 Temperature Measurements and Distribution on the Chip

To verify the thermal stability of the experimental setup and the TSC on the chip, temperatures were measured inside the enclosure, at the hot plate surface, and on the 65- μm -thick tape (red layer shown in Figure 4). In addition to the DHT22 sensor, two K-type thermocouples were used: one positioned near the chamber of interest and the other on the hot plate surface. Figure 5-a (left) shows the rise time required for each sensor to reach the final, stabilized temperature when the hot plate was set to 311 K. The comparison between two K-type sensors confirmed that the temperature difference remained below 5 K when the temperature stabilized.

Fluorescence-based thermography was performed on the three *Simple* chip designs coated with Eu(TTA) TSC. Figure 5-a (middle) shows the calibration curve obtained at six temperature points, from which the coefficients in Eq. 1 were determined as $A = 1.1 \times 10^6 \text{ K}^2$, $B = 1.3 \times 10^3 \text{ K}$, and $C = 0$. Figure 5-a (right) displays the microfluidic chip with the Eu(TTA)-coated sealing layer. The embedded K-type thermocouple, used to provide the reference temperature $T_{\text{ref}} = 299.8 \text{ K}$, is also indicated.

Figure 5-b (top) presents representative grayscale snapshots acquired at each calibration temperature. As expected from thermally-induced fluorescence quenching, the images progressively darken with increasing temperature. The processed thermal maps (Figure 5-b, bottom) show that the temperature distribution remains uniform across both the chip surface and the liquid region. The apparent temperature variations at the liquid–gas interface are optical artifacts arising from refraction and reflection effects, and do not represent actual temperature differences.

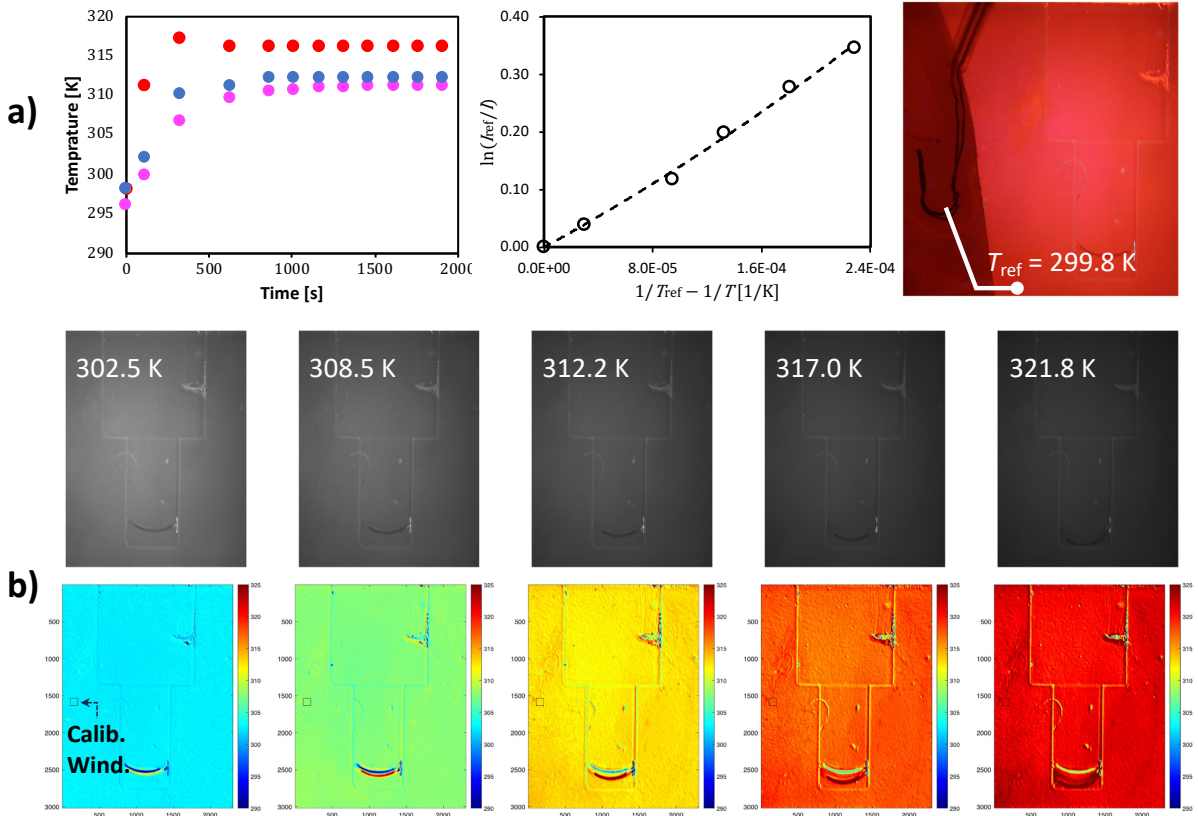


Figure 5: (a) Left: Shows the temperatures measured simultaneously on the chip (blue), hot plate (red), and inside the box (magenta). Middle: Calibration curve of Eu(TTA) TSC fluorescence intensity acquired at six reference temperatures, used to determine the coefficients in Eq. 1. The uncertainty of the temperature measurement was estimated to be $\pm 0.5 \text{ K}$. Right: Microfluidic chip coated with Eu(TTA) TSC. A K-type thermocouple embedded in the chip provides the reference temperature $T_{\text{ref}} = 299.8 \text{ K}$. (b) Top: Representative grayscale fluorescence images recorded at each calibration temperature, showing progressive darkening due to thermal quenching. Bottom: Processed thermal maps reconstructed from the calibrated intensity field, revealing uniform temperature distribution across both the chip surface and the liquid region. The location of the calibration window used for thermal analysis is indicated. Apparent temperature variations observed at

the liquid–gas interface are attributed to optical artifacts (e.g., refraction and reflection at the interface) rather than true thermal gradients.

3.2 Evaporation Tests with *Simple* Configuration

The *Simple* configuration served as a baseline for understanding the fundamental evaporation behavior. Time-lapse imaging showed a consistent and progressive decrease in liquid volume over time (Figure 6-a). The corresponding Python-processed mask is shown, where the background is removed, and the gray contour indicates the metered liquid volume. As shown in Figure 6-b, the results were reproducible across replicates for Simp-01 (left), Simp-02 (middle), and Simp-03 (right). Slower evaporation rates were observed in circuits that included narrow channels or abrupt constrictions in cross-section, likely due to a reduced exposed liquid-air interface and constrained vapor diffusion. In contrast, wider or uniformly large channels facilitated evaporation.

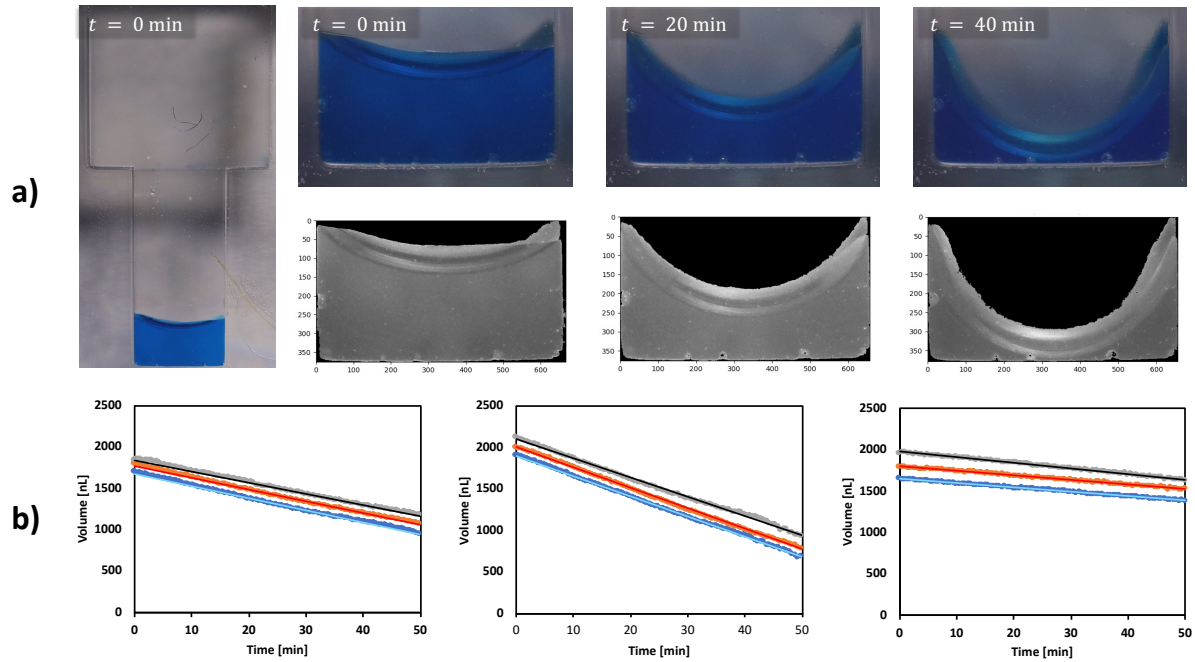


Figure 6: (a) Representative snapshots of design Simp-02 at 0, 20, and 40 min, respectively. The chamber width is $W_1 = 2$ mm for all snapshots. Below each image, the corresponding Python-processed mask is shown, with the background removed, and the contour indicates the measured liquid volume. (b) Reproducibility of evaporative volume loss for designs Simp-01 (left), Simp-02 (middle), and Simp-03 (right) shown over three independent experimental iterations through a linear fit with a coefficient of determination $R^2 > 0.99$. The blue, red, and gray solid lines represent the corresponding linear fits to the measured data in tests 1, 2, and 3, respectively.

3.3 Evaporation Tests with *Complex* Configuration

Similar experiments were performed to evaluate the reproducibility of evaporative volume loss in the *Complex* designs (see Figure 7). Figure 7-a shows representative snapshots of design Comp-03-A at 0, 20, and 40 min. The reproducibility of the measured evaporative volume loss over three independent iterations for designs Comp-03 and Comp-03-A is presented in Figure 7-b, from left to right, respectively. Although the metering chamber has the same cross-sectional area in both designs, the evaporation rate in Comp-03 is reduced by a factor of approximately 1.4 relative to Comp-03-A.

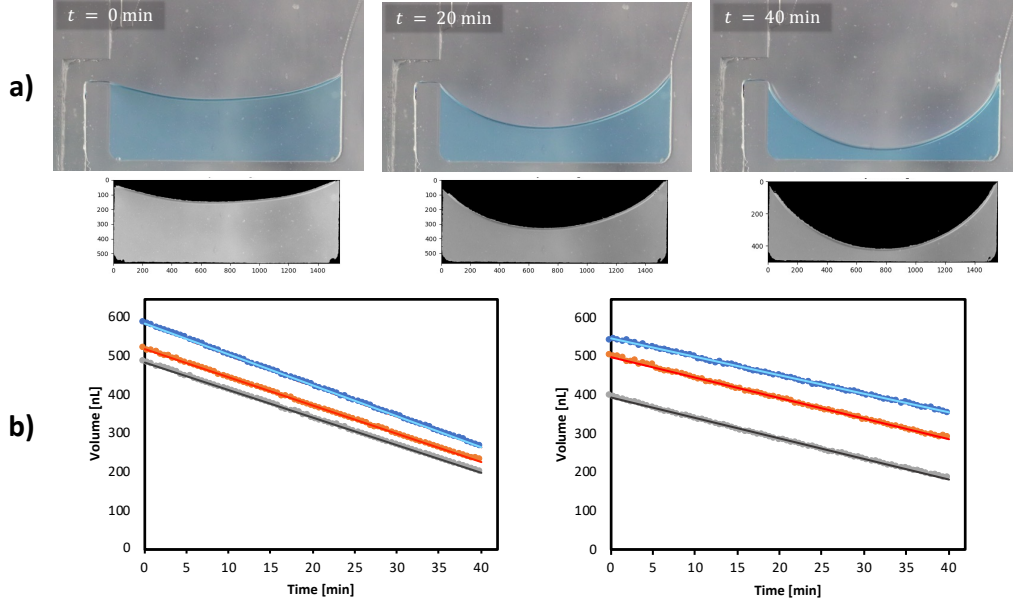


Figure 7: (a) Representative snapshots of design Comp-03-A at 0, 20, and 40 min, respectively. The metering chamber width is $W_m = 3$ mm for all snapshots. Below each image, the corresponding Python-processed mask is shown, where the background is removed and the contour indicates the metered liquid volume. (b) Reproducibility of evaporative volume loss for designs Comp-03 (left) and Comp-03-A (right), shown over three independent experimental iterations through a linear fit with a coefficient of determination $R^2 > 0.99$. The blue, red, and gray solid lines represent the corresponding linear fits to the measured data in tests 1, 2, and 3, respectively.

4 Physical Model and Discussion

4.1 Rationalization of Isothermal Conditions for the Liquid–Chip Evaporation Tests

The temperature shown in Figure 5-a (left) exhibited a gradual increase during the initial heating period. The Arduino DHT 22 sensor and the thermocouple readings reached steady state after approximately 15 min and remained stable within ± 1 K. At steady state, the relative humidity also remained constant within $\pm 2\%$. Once stabilized, the temperature difference between the chip surface in contact with the hot plate and the top surface can be used to discuss the uniformity of the temperature field. The rate of heat flow through the chip, of thermal conductivity $k \approx 0.2$ W m⁻¹K⁻¹, across a surface area $S \sim 10^{-4}$ m², is estimated as

$$q_{\text{chip}} = k \frac{S \Delta T}{d}, \quad \text{Eq. 2}$$

which yields $q_{\text{chip}} \sim 2.5 \times 10^{-2}$ W for the measured temperature difference $\Delta T = 5$ K.

In contrast, the total latent heat required to sustain evaporation from the exposed liquid–air interface is

$$q_{\text{evap}} = \dot{m} L_v, \quad \text{Eq. 3}$$

which yields $q_{\text{evap}} \sim 4 \times 10^{-5}$ W for a mass evaporation rate $\dot{m} \sim 10^{-11}$ kg s⁻¹ and a latent heat for evaporation of water $L_v = 2.44 \times 10^6$ J kg⁻¹ at 311.15 K. The resulting ratio $\frac{q_{\text{chip}}}{q_{\text{evap}}} \gg 1$ indicates that, in response to the temperature gradient, the chip conducts several orders of magnitude more heat than what is consumed by evaporation. Despite that, small temperature gradients on the liquid surface or in the sealing/chip material may still affect the local saturation vapor pressure and, consequently, the evaporation driving force. Thermographic measurements presented in Figure 5-b (bottom) were used to analyze the temperature distribution across the chip, particularly near the liquid–air interface, where the temperature was found to be nearly uniform, with a maximum difference of less than 0.5 K. At the operating temperature of 311 K such a temperature difference results in a variation in saturation vapor pressure of less than 3%. Therefore, the saturated vapor density $\rho_{v,s}$ was assumed to remain constant along the liquid–air interface.

Furthermore, after the initial heating period, no significant difference was observed between the temperatures measured by the K-type thermocouple and the Arduino sensor. This confirms that the DHT22 sensor alone provided reliable measurements of both the ambient thermal environment and chip temperature. Subsequently, the diffusion coefficient of water vapor in air (D) and the saturated vapor density ($\rho_{v,s}$) were obtained from standard thermophysical correlations reported in the literature as functions of temperature [55,56].

These observations justify neglecting heat-transfer limitations in further analysis, allowing the evaporation process to be modeled as diffusion-controlled under an essentially prescribed temperature field and isothermal conditions.

4.2 Modeling Evaporation via Fick's Law and Diffusion Resistance Analysis

The results in Figure 6 reveal that, in the considered regime, the evaporation rate is constant over time and strongly influenced by the channel geometry. Circuits incorporating narrow channels or abrupt constrictions exhibited slower evaporation, likely due to the reduced exposed liquid–air interface and restricted vapor diffusion. Conversely, wider or continuously large channels promoted faster evaporation. These observations can be rationalized by considering the transport of water vapor from the liquid/air interface, through the microchannels, towards the chip outlet(s). Because the chip is positioned horizontally (in $x - y$ plane) on the hotplate, gravity acts strictly parallel to the sub-millimeter chamber depth H_m , while the primary vapor transport occurs horizontally within the plane of the microfluidic circuit. Consequently, any potential buoyancy-driven motion is restricted to a weak vertical recirculation (Rayleigh–Bénard convection rolls [57,58]) cell across the shallow depth of the channel. To quantitatively confirm that this natural convection is negligible, a scaling analysis via the Rayleigh number (Ra) was performed for vapor phase. Using the maximum measured thermal gradient ($\Delta T \approx 1$ K) across the largest chamber depth (0.4 mm) at a baseline temperature of 311 K yields $Ra \approx 10^{-3}$. Consequently, the air inside the channels and chambers likely remained quiescent, so vapor transport occurred predominantly through diffusion rather than convection.

The time to reach a steady-state vapor concentration field in the air scales as the diffusion timescale $t_d = \frac{L^2}{D} \approx 3.5$ s, where $D \approx 2.8 \times 10^{-5}$ m²/s denotes the diffusion coefficient of water vapor in air at $T \approx 311$ K and $L = 10$ mm is a characteristic distance between the interface and the outlet(s). Since this timescale is much shorter than the measured one, it can be assumed that measurements occurred at steady state. In addition, the validity of the continuum-diffusion assumption was verified through the Knudsen number, defined as $Kn = \lambda/L_c$, where $\lambda \approx 65$ nm is the mean free path of air molecules at atmospheric conditions and L_c is a characteristic channel dimension. Using the smallest dimension in the vapor-transport pathways ($L_c = 0.10$ mm) yields $Kn \approx 6.5 \times 10^{-4}$, which is well below the continuum limit ($Kn \ll 0.01$). Therefore, rarefaction effects are negligible, and vapor transport can be accurately described using Fickian diffusion. Moreover, the vapor-transport pathways considered in the present microfluidic circuits are bounded by solid walls and connected to the atmosphere only through a limited number of engineered outlets. Under these confined conditions, the dominant vapor concentration gradients ($\nabla \rho_v$) develop along the pathways linking the liquid–air interface to the vent exits. Multidimensional diffusion effects, which can become important in open evaporating systems [59], are therefore expected to contribute negligibly to the overall vapor-transport resistance. Consequently, the vapor concentration field within each circuit segment is assumed to vary only along the longitudinal coordinate x , while remaining approximately uniform over the cross-section ($d\rho_v/dy, d\rho_v/dz \approx 0$). According to Fick's first law and considering a channel consisting of two consecutive segments with respective lengths L_1 and L_2 and cross-sectional areas A_1 and A_2 , the local diffusion rate of water vapor, expressed as a vapor mass flux in each segment i , is

$$J_i = -D \frac{d\rho_v}{dx}, \quad \text{Eq. 4}$$

where ρ_v is the vapor density, or vapor mass concentration, at position x . Conservation of vapor mass in steady state implies that the product $J(x)A(x)$ is constant with respect to x . Consequently, J is independent of x in each segment of constant cross-sectional area, and the resulting vapor density varies linearly with x . Defining $\rho_{v,12}$ as the vapor density at the junction between two segments, integration of Eq. 4 along each segment yields

$$J_1 = D \frac{\rho_{v,s} - \rho_{v,12}}{L_1}, \quad J_2 = D \frac{\rho_{v,12} - \rho_{v,\infty}}{L_2}, \quad \text{Eq. 5}$$

where $\rho_{v,s}$ corresponds to the saturated vapor density at the liquid surface and $\rho_{v,\infty} = \phi \rho_{v,s}$ represents the reduced vapor density at the outlet determined by the local relative humidity ϕ using the calibrated DHT22 sensor. Mass conservation further implies $J_1 A_1 = J_2 A_2 = \dot{m}$. Solving these equations yields the normalized concentration F between the junction ($\rho_{v,12}$) and the atmosphere at the chip outlets ($\rho_{v,\infty}$)

$$F \equiv \frac{\rho_{v,12} - \rho_{v,\infty}}{\rho_{v,s} - \rho_{v,\infty}} = \frac{1}{1 + \frac{A_2 L_1}{A_1 L_2}}. \quad \text{Eq. 6}$$

This fraction F has been introduced previously in the context of one-sided evaporation and sessile droplets [60]. Herein, for an evaporation problem within a well-defined microfluidic geometry, F provides a direct and intuitive predictor of how strongly the junction density is reduced relative to the vapor density at the liquid interface, and consequently in which segment the vapor gradient is the strongest. In Figure 8 (left) we plot Eq. 6 for three designs yielding $F = 0.2, 0.5$, and 0.8 for Simp-02, Simp-01, and Simp-03, respectively. In chip Simp-02, the ratio $\frac{A_2 L_1}{A_1 L_2}$ is large, so F is small and the junction density remains close to $\rho_{v,\infty}$. The vapor gradient is stronger in the first segment. Conversely, a narrow and/or elongated second segment (small $\frac{A_2 L_1}{A_1 L_2}$ for Simp-03) yields $F \rightarrow 1$, bringing $\rho_{v,12}$ close to $\rho_{v,s}$ and causes a steep vapor gradient along segment 2.

These predictions are supported by the vapor-distribution maps obtained by using Ru(Phen) TSC coatings (Figure 8-right). These measurements were not used for quantitative analysis but rather to support the interpretation of the vapor transport pathways. The pseudo-color maps reveal a clear vapor density gradient along x in luminescence intensity, with more blue regions near the liquid–air interface (high vapor density) and redder intensity toward the outlet (low vapor density). Differences among Simp-01, Simp-02, and Simp-03 directly reflect the geometry dependence of diffusive resistance. Narrower channels exhibit steeper vapor gradients—reflecting higher diffusion resistance—while wider channels maintain more uniform vapor distributions.

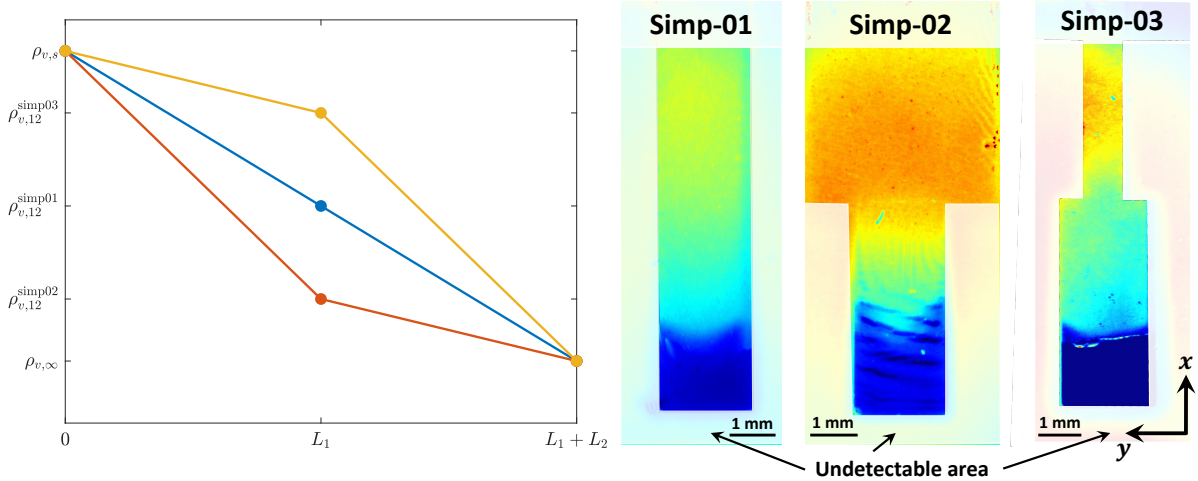


Figure 8: (Left) Predicted fraction $\rho_{v,12}$ from Eq. 6 for three simple designs, showing how channel geometry dictates the junction density and the segment in which the dominant vapor gradient occurs. A small F (e.g., $F^{\text{Simp-01}} = 0.5$) keeps $\rho_{v,12}$ near $\rho_{v,\infty}$, concentrating the gradient in segment 1, whereas a large F (e.g., $F^{\text{Simp-03}} = 0.8$) brings $\rho_{v,12}$ closer to $\rho_{v,s}$, shifting the gradient to segment 2. (Right) At $T \cong 312$ K, Ru(Phen)-based vapor maps confirming the predicted trend—narrower channels exhibit steeper vapor gradients (higher diffusive resistance), while wider channels show more uniform vapor distributions. Pseudo-color maps were not used for quantitative analysis but rather to support the prediction of the vapor transport pathways described by the analytical model (Eq. 6).

The diffusive resistance becomes explicit when substituting Eq. 5 into the mass-conservation condition at the far-field $\rho_{v,\infty} = \phi \rho_{v,s}$. This yields the overall mass-transfer rate of water vapor

$$\dot{m} = \frac{D(1 - \phi)\rho_{v,s}}{\frac{L_1}{A_1} + \frac{L_2}{A_2}}. \quad \text{Eq. 7}$$

In this framework, each diffusion segment i behaves as a lumped element with an associated diffusive resistance $R_i = \frac{L_i}{DA_i}$ analogous to an electrical resistor under Pouillet's law. Consequently, the overall transport process in a *Simple* configuration is equivalent to two diffusion resistances in series, with a total resistance

$$R_{\text{tot}} \equiv \frac{(1 - \phi)\rho_{v,s}}{\dot{m}} = \frac{L_1}{DA_1} + \frac{L_2}{DA_2}. \quad \text{Eq. 8}$$

Thus, R_{tot} can be obtained experimentally from the measured mass-loss rate $\dot{m}$, and theoretically from the geometric sum $\sum_i \frac{L_i}{DA_i}$. The uncertainty propagated from the linear regression used to determine evaporation rate was estimated to be below 3% for most experiments ($R_{\text{tot}} < 200 \text{ s nL}^{-1}$) and below 10% for the highest computed resistance values ($R_{\text{tot}} < 450 \text{ s nL}^{-1}$). The parity plot in Figure 9 shows strong agreement between the measured and calculated total diffusion resistance (relative error < 10%), validating the analytical model for predicting diffusion resistance presented in Eq. 8.

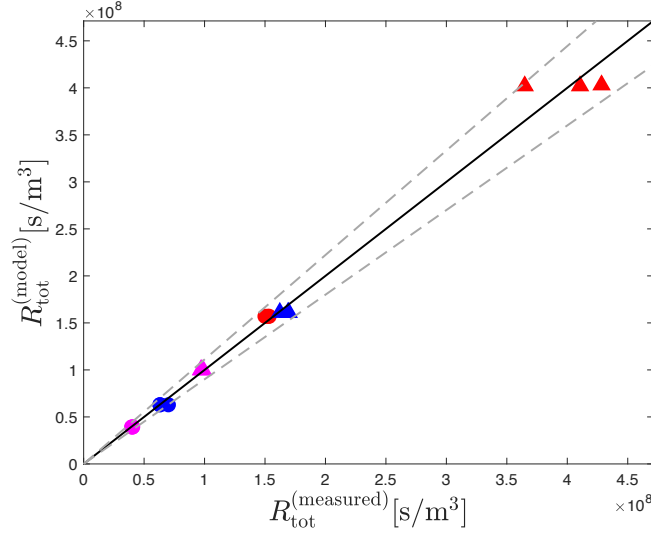


Figure 9: Parity plot compares the R_{tot} derived from the experiments with the values determined from the channel geometry by Eq. 8. The solid line represents the parity line, where experimental and predicted values coincide. Dashed lines represent the lower and upper bounds for a relative error of less than 10%. The propagated uncertainty in the experimentally determined resistance varies with the measured evaporation rate and is estimated to be below 3% for most experiments, increasing to below 10% for the highest computed resistance (Red triangles). The raw measurements used to compute R_{tot} are provided in the Supplementary Information.

Subsequently, the generic form of Eq. 7 can be recast as

$$\dot{m} = \frac{(1 - \phi)\rho_{v,s}}{R_{\text{tot}}} \quad \text{Eq. 9}$$

which provides a framework for evaluating more complex microfluidic networks composed of channels and chambers arranged in series and/or parallel. This formulation remains valid under the following conditions: (i) steady-state conditions with negligible vapor accumulation, (ii) diffusion-dominated transport without significant advective vapor transport [56], (iii) constant temperature and diffusivity, (iv) ideal gas behavior of the vapor phase, and (v) one-dimensional transport through uniform cross-sections in each segment.

4.3 Lumped-Element Modeling of Evaporation in *Complex* Designs

The analysis developed for simple, single- or dual-segment channels lays the foundation for extending the model to more complex geometries using an analogy to electrical-circuit networks and lumped-element modeling (LEM). Having validated the analytical expressions (Eq. 8) for the individual and total diffusion resistances (Figure 9), the complete resistance circuit can be used to predict the evaporation rate directly through the Pouillet's-law analogy. Consequently, the total diffusive resistance of a complex design can therefore be determined using the same series–parallel combination rules applied in circuit analysis (Figure 10).

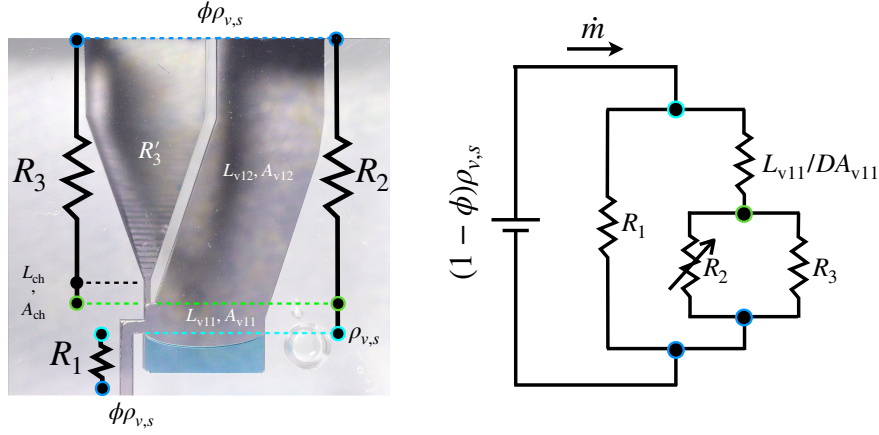


Figure 10: (Left) An annotated Complex microfluidic chip including three distinct diffusion pathways through which vapor escapes from the metering chamber to the atmosphere. Each pathway is modeled as an individual resistance R_1, R_2, R_3 . The segments located above the metering chamber are characterized by their lengths L_{v11}, L_{v12} and cross-sectional areas A_{v11}, A_{v12} , respectively. The resistance associated with the well is modeled as two resistances in series, corresponding to the channel segment (L_{ch}, A_{ch}) and additional well resistance R'_3 . (Right) Equivalent lumped-element representation of the system, where the vapor density difference between the liquid interface and the bulk, $\rho_{v,s}(1 - \phi)$, drives the total mass flow rate $\dot{m}$ through the network of diffusive resistances. The geometrical design is identical for pathways 1 and 3 across all Complex designs, while pathway 2 varies among designs so that the representative resistance R_2 shown is variable.

For the *complex* designs investigated in the present study, vapor can escape through multiple pathways. The corresponding diffusive resistances are therefore combined, such that the total resistance is

$$R_{tot} = \left(\frac{1}{R_1} + \frac{1}{\frac{L_{v11}}{DA_{v11}} + \left(\frac{1}{R_2} + \frac{1}{R_3} \right)^{-1}} \right)^{-1}, \quad \text{Eq.10a}$$

where L_{v11}, A_{v11} correspond to the short segment above the metering chamber and each resistance R_i represents a distinct diffusion pathway. Pathway 1 is the straight waste channel of length L_{waste} and cross-sectional A_{waste}

$$R_1 = \frac{L_{waste}}{DA_{waste}}. \quad \text{Eq. 10b}$$

Pathway 2 is given by

$$R_2 = \frac{L_{v12}}{DA_{v12}}, \quad \text{Eq. 10c}$$

where L_{v12}, A_{v12} correspond to the adjacent segment along the vent channel.

Pathway 3 contains a narrow segment of length $L_{ch} = 0.6$ mm, rectangular cross-section A_3 , followed by an additional resistance R'_3 associated with diffusion along the pyramidal inlet well

$$R_3 = \frac{L_{ch}}{DA_{ch}} + R'_3, \quad \text{Eq. 10d}$$

with

$$R'_3 = \frac{L_{well 1}}{DA_{well 1}} + \frac{L_{well 2}}{D\sqrt{A_{well 1}A_{well 2}}}. \quad \text{Eq. 10e}$$

This analytical expression of R'_3 is obtained as a solution to Fick's equations, as detailed in Appendix A. This is particularly useful for determining the diffusive resistance in multi-well plates whose wells feature pyramidal geometries [61–63].

The theoretical evaporation rate was subsequently calculated from Eqs. 9 and 10a. Finally, the predictions are compared to experimental measurements in the parity plot shown in Figure 11.

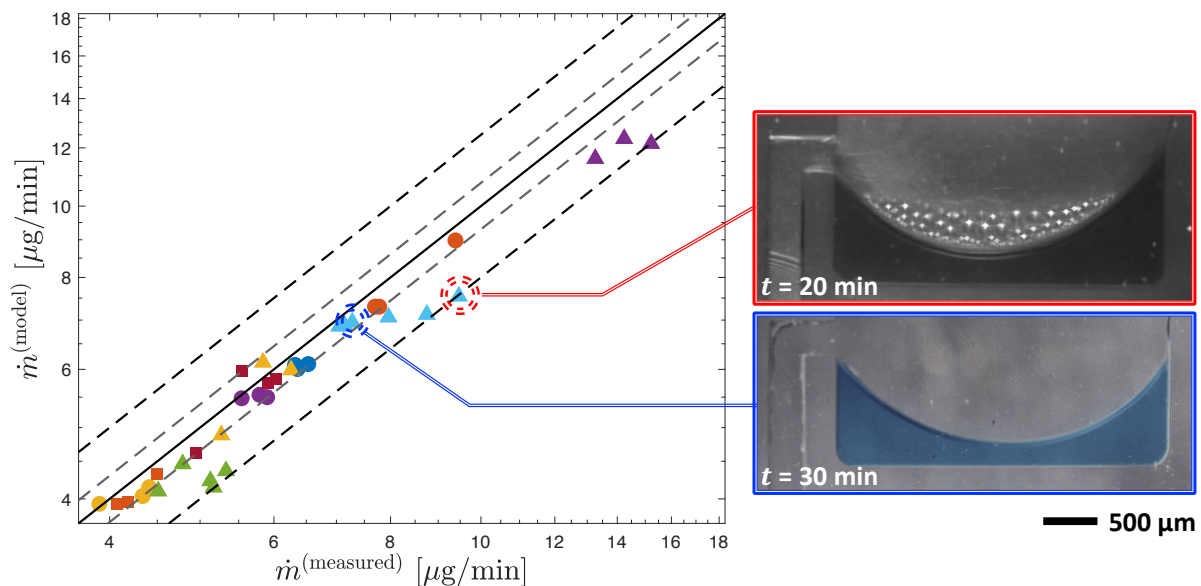


Figure 11: Parity plot comparing the measured and estimated evaporation rates. The solid line represents the parity line, while the gray and black dashed lines indicate relative errors of $\pm 7\%$ and $\pm 20\%$, respectively. Different symbols and colors correspond to different Complex designs presented in Table 2. Notably, the largest deviations from the parity line were observed only in experiments involving condensation for the designs with the widest chamber $W_m = 3\text{ mm}$, whereas condensation-free experiments showed good agreement with the diffusion-limited model. The insets show snapshots of the same chip design from two different experiments: one in which condensation occurred (red) and one without condensation (blue). The propagated uncertainty in the measured evaporation rate is estimated to be below 2% for all experiments. The experimental data underlying the parity plot are provided in the Supplementary Information.

The propagated uncertainty in the experimentally determined evaporation rates was estimated to be below 2% for all experiments. The model predictions are in reasonable agreement with the measurements, yielding relative errors below 7% for all designs with $W_m \in \{1, 2\}$ mm. For the widest chambers ($W_m = 3\text{ mm}$), the experimentally measured evaporation rates were approximately 10–20% higher than the model predictions. This deviation is likely attributed to the onset of condensation on the inner side of the sealing tape along the liquid-air interface (see the inset of Figure 11), which was observed a few minutes after evaporation began. The red inset shows a representative example at $t = 20\text{ min}$. This condensation would have locally increased the concentration gradient of water vapor ($\frac{d\rho_{v,s}}{dx}$), thereby enhancing the diffusive vapor flux away from the liquid surface and introducing a secondary transport mechanism outside the scope of the present evaporation model. In experiments where condensation was prevented, the theoretical and experimental results agreed within 7%. Importantly, tracking the liquid-air interface used to quantify the evaporation revealed that the evaporation flux remained constant even as the contact line receded within the metering chamber (Figure 7a). However, a curved meniscus may alter the local saturation condition through the Kelvin effect [64]. In the present geometry, where the minimum characteristic radius of curvature is on the order of hundreds of micrometers, the resulting correction to the saturation pressure relative to a flat interface is less than 0.01%. Consequently, the assumption of constant saturation vapor density at the liquid-air interface remains valid in the vapor transport and evaporation model. As the characteristic dimensions decrease toward only a few micrometers, capillary pressure and the associated Kelvin correction become progressively more significant and should be incorporated by modifying the interfacial boundary condition for the saturation vapor density.

This confirms the predictive capability of the proposed analytical model for pure solvent systems. While the present study focuses on DI water to isolate the influence of microfluidic geometry on evaporation, it is instructive to consider its extension to complex fluids. For solutions containing dissolved species, evaporation may be altered through changes in the interfacial vapor density. Dissolved solutes reduce the water activity and therefore lower the equilibrium vapor density at the liquid-air interface, thereby decreasing the evaporation driving force. However, for the dilute solutions typically encountered in biological assays, this effect is expected

to remain negligible over most of the evaporation process and becomes significant only after substantial solvent loss, when solute concentrations become strongly enriched near the interface. Additional effects such as concentration polarization may also develop as evaporation progressively enriches solutes near the liquid–air interface [65]. Although these phenomena were not investigated here, the resistance-network framework remains applicable provided that appropriate expressions for the interfacial vapor density and diffusivity are used. Furthermore, future work may extend the framework developed in this study to gas-permeable materials such as PDMS. In such systems, vapor permeation through the device walls could be represented as additional transport resistances connected in parallel with the vapor-diffusion pathways considered here. This extension may provide a unified framework for analyzing evaporation in microfluidic platforms that combine diffusion through gas-filled channels and permeation through surrounding materials.

4.4 Design Guidelines for Evaporation Control

The present results provide several practical guidelines for engineering evaporation in microfluidic circuits. First, the vapor-diffusion resistance increases linearly with pathway length and inversely with cross-sectional area ($R \propto L/A$), indicating that evaporation can be reduced by incorporating longer and narrower vapor-transport pathways. Second, because multiple vapor pathways act as parallel diffusion resistances, the overall evaporation rate may increase substantially when additional vents, outlets, or bypass routes are introduced. Therefore, vapor pathways should preferably be arranged in series rather than in parallel whenever evaporation minimization is desired. Third, introducing narrow segments within the vapor-transport network provides an efficient means of increasing the overall diffusion resistance without the geometrical changes to the liquid carrier chamber. Finally, the experimentally observed insensitivity to contact-line position indicates that evaporation control should primarily focus on engineering the vapor-transport network rather than the liquid-interface geometry.

To ensure that these design rules remain applicable, evaporation should also be maintained in a diffusion-limited regime. This is achieved by operating the microfluidic chip in a thermally stable, enclosed environment, similar to the conditions encountered in laboratory incubators or ovens, while avoiding forced air circulation that may induce temperature gradients and convective vapor transport. The temperature and relative humidity should be monitored in the vicinity of the chip and allowed to stabilize before measurements or operation. Sufficient time should also be provided for the chip to reach thermal equilibrium prior to evaporation measurements. Under these conditions, condensation on the sealing layer is minimized. Since condensation locally reduces the vapor concentration and increases the driving force for evaporation, it can accelerate evaporation and lead to an underestimation of the theoretical diffusion resistance. Together, these design and operating guidelines provide a practical framework for designing and validating microfluidic systems with predictable and tunable evaporative behavior.

5 Conclusions

This study presented a combined theoretical and experimental framework for quantifying the evaporation of small liquid plugs (~ 100 nL– 10 μ L) confined within microfluidic circuits. Systematic experiments on both simple and complex architectures demonstrated that the evaporation rate is predominantly governed by the resistance to vapor diffusion of the channel pathways connecting the metering chamber to the environment outside of the chip.

Fluorescence-based thermography using two different thermosensitive coatings confirmed (i) a uniform temperature distribution across the chip and liquid surface, and (ii) a vapor density gradient dictated by the microfluidic geometry under controlled thermal and humidity conditions—thereby validating the isothermal and diffusion-limited nature of the evaporation process in this context. By integrating the liquid–air interface-tracking within the characteristic regime studied—small plug volumes, fixed chamber geometry, and steady-state vapor diffusion—the evaporation rate was found to be insensitive to contact-line dynamics: neither the position nor the pinning of the liquid meniscus at the chamber edge measurably affected the evaporation flux.

Evaporation in the various geometries was captured by a lumped-element diffusive-resistance model directly analogous to RC electrical circuits. This formulation, derived from Fick's law, provides a practical and interpretable design tool: modest geometric changes—such as vent constrictions or additional diffusion segments—produced substantial and predictable modifications to the evaporation rate. Under diffusion-limited conditions and in the absence of

condensation, the analytical predictions closely matched the measured rates across all tested geometries, including multi-segment pathways, and were corroborated by spatially resolved vapor mapping. Reproducibility tests across a minimum of three independent experimental iterations for each design showed highly consistent volume-loss trajectories, underscoring the robustness of both device fabrication and the measurement methodology.

While the present work focuses on steady-state diffusion of pure water in simple liquid plugs, the framework is general. Future studies may extend it to multi-component mixtures, transient thermal conditions, and more advanced microfluidic architectures. Integration with functional bioassays may further clarify evaporation-driven errors in biochemical and diagnostic workflows.

Author Contributions

Ali Gholizadeh: Conceptualization, methodology, software, data curation, validation, formal analysis, investigation, writing – original Draft, Writing – critical Review & Editing, and visualization.

Howard A. Stone: Validation, formal analysis, writing – critical review & editing (Commentary or Revision), and supervision.

Donato Fontanarosa: Methodology, validation, data curation and software.

Maria R. Vetrano: Methodology, validation, resources, writing – critical review & editing (Commentary or Revision), and supervision.

Tristan Gilet: Conceptualization, validation, formal analysis, resources, writing – critical review & editing (Commentary or Revision), and supervision.

Acknowledgments

The authors thank Denis Vandormael (Sirris) for manufacturing the microfluidic chips, and Gabriel Mazzucchelli, the project coordinator, for his insightful discussions on the application of this work. This research was funded by the Wallonia Public Service (SPW) through the Win2Wal grant 2010126 (ChipOmics).

Appendix A Derivation of the Diffusion Resistance for a Truncated Pyramidal Well

We consider steady, one-dimensional diffusion of vapor along the axial coordinate x through a tapered (pyramidal) well (Figure A.1). Let $\rho_v(x)$ be the vapor mass density [kg m^{-3}] and D the vapor diffusivity in air [$\text{m}^2 \text{s}^{-1}$]. The mass flux $\dot{m}$ [kg s^{-1}] is constant and given by Fick's law in mass form:

$$\dot{m} = -DA(x)d\rho_v/dx. \quad (\text{A. 1})$$

Rearranging and integrating between two interfaces at $x = x_1$ and $x = x_1 + L_{\text{well}}$ yields

$$\rho_{v,1} - \rho_{v,2} = \frac{\dot{m}}{D} \int_{x_1}^{x_1 + L_{\text{well}}} \frac{dx}{A(x)}. \quad (\text{A. 2})$$

Thus, the diffusion resistance is

$$R_{\text{well}} = \frac{1}{D} \int_{x_1}^{x_1 + L_{\text{well}}} \frac{dx}{A(x)}. \quad (\text{A. 3})$$

This expression is exact for any arbitrary geometry. Below, two analytically tractable special cases are presented.

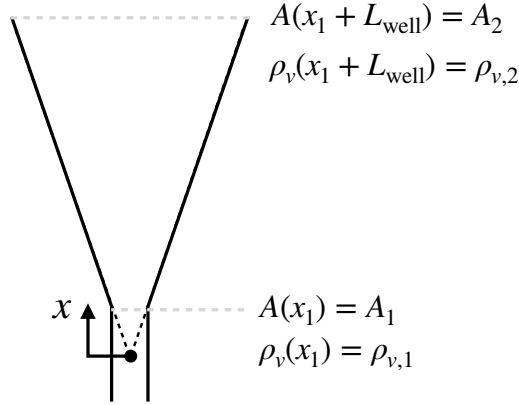


Figure A.1: Schematic of vapor diffusion through a tapered microfluidic well used to derive the total diffusive resistance.

A.1 Particular Solution (i): Linear Scaling of a Characteristic Length (Similar Shapes)

For a pyramidal (linearly tapered) well implemented in this study, the linear dimension—here taken as the side length of a square cross-section—scales linearly with distance from the apex. Placing the apex at $x = 0$ and denoting the side length at $x = x_1$ by w_1 and at $x = x_1 + L_{\text{well}}$ by w_2 , similarity of triangles gives

$$\frac{w(x)}{w_1} = \frac{x}{x_1} \rightarrow w(x) = w_1 \left(\frac{x}{x_1} \right). \quad (\text{A. 4})$$

Since the cross-sectional area of a square section is $A(x) = w(x)^2$, it follows that

$$A(x) = A_1 \left(\frac{x}{x_1} \right)^2,$$

where $A_1 = w_1^2$ and $A_2 = w_2^2$.

Substituting $A(x)$ into the general resistance A. 1 expression yields:

$$R_{\text{well}} = \frac{L_{\text{well}}}{(D\sqrt{A_1 A_2})}. \quad (\text{A. 5a})$$

A.2 Particular Solution (ii): Linearly Varying Cross-Sectional Area (No Shape Similarity)

Although this was not the case in our study, we provide the solution for Eq. A.3 for shapes that are not similar. Assume the cross-sectional area varies linearly between the two ends:

$$A(x) = A_1 + \frac{A_2 - A_1}{L_{\text{well}}} (x - x_0), \quad x \in [x_0, x_0 + L].$$

Substituting into the general resistance expression gives

$$R_{\text{well}} = \frac{L_{\text{well}}}{D (A_2 - A_1)} \ln \left(\frac{A_2}{A_1} \right). \quad (\text{A. 5b})$$

This expression is valid regardless of the shapes at the two ends (triangle to square, etc.), provided that the cross-sectional areas A_1 and A_2 vary linearly between the two interfaces.

Appendix B Supplementary Data

Supplementary data to this article can be found online at doi.org/10.1016/j.icheatmasstransfer.2026.112279.

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