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Design of a Microfluidic Microchannel for Targeted Chemotherapy Drug Delivery

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Abstract: Drug delivery has been significantly advanced through the development of microfluidic technologies, which enable precise manipulation of fluid inflow at the microscale. These systems grease the localized administration of chemotherapeutic agents, thereby reducing systemic toxin in cancer treatment. In this study, a crispy microchannel was designed and anatomized for the controlled distribution of doxorubicin reprised in liposomal carriers. Numerical simulations were performed using COMSOL Multiphysics to estimate key inflow parameters such as velocity distribution, shear stress, and flyspeck circles. The crispy channel figure bettered mixing uniformity and assured smooth inflow while maintaining shear stress within safe physiological limits(0.5 Pa). The optimized design demonstrates implicit for enhanced remedial effectiveness, minimized flyspeck aggregation, and better localized medicine delivery in microfluidic- grounded chemotherapy systems.
Keywords: Microfluidics; wavy microchannel; Chemotherapy; Doxorubicin; Precision drug delivery; Laminar flow.

I. INTRODUCTION

Cancer remains one of the leading causes of mortality worldwide, and chemotherapy continues to be a primary mode of treatment. However, conventional systemic drug delivery often leads to poor targeting, high toxicity, and severe side effects due to the uncontrolled drug distribution within the body [1]. This challenge has encouraged the development of advanced drug delivery systems capable of improving therapeutic efficiency while minimizing adverse effects [2],[3].

Microfluidics has come up as a promising platform for precise and controlled drug delivery due to its capability of manipulating minute fluid volumes in microchannels under laminar flow conditions [4],[5]. Such systems allow enhanced control over flow rate, mixing, and concentration gradients, some of the major parameters for the accomplishment of localized and sustained drug release [6],[7]. In particular, microchannel-based delivery systems have demonstrated potential for site-specific administration of chemotherapeutic agents, improving their bioavailability and therapeutic index [8],[9].

Among all the microchannel geometries, serpentine microchannels provide considerable advantages due to the extended path length, enhanced mixing features, and uniform flow distribution within these channels [10]. The predictable and smooth flow regime within these channels can efficiently ensure stable transport of the drug molecules, which is highly required for precision medicine applications [11]. Further, pH-responsive or nanoparticle-based carriers can be incorporated into such microchannels with the ability to exhibit targeted and stimuli-responsive drug release within tumor microenvironments [12], [13].

This paper focuses on the design and simulation of a serpentine microchannel with an emphasis on precision drug delivery in chemotherapy. The research analyzes laminar flow and diffusion characteristics to establish a relationship between geometry, flow rate, and drug concentration profile. Computational modeling is used in this study to develop the microchannel geometry capable of efficient, predictable, and controlled delivery of anticancer drugs [14], [15].

II. MATERIALS AND METHODS

A. Material

Polydimethylsiloxane (PDMS), a silicone-based elastomer, was employed in this study as the primary material for microfluidic channel design. PDMS was selected due to its excellent biocompatibility, mechanical flexibility, optical transparency, chemical stability, and ease of fabrication, making it highly suitable for drug delivery applications.

B. Geometry design and model setup

Microchannel design is very important for determining the effectiveness of medicine delivery within microfluidics systems. In this work, COMSOL Multiphysics was used to model a windy microchannel in order to achieve smooth and invariant inflow suitable for chemotherapy medicine transport. The wavy shape is opted for because it naturally promotes gentle mixing and provides a longer hearthstone time for the medicine fluid, ensuring that the medicine diffuses evenly before reaching the target point.

Parameter	Symbol	Value	Unit
Channel length	L	4.8	mm
Channel width	W	0.5	mm
Channel height	H	0.5	mm
Amplitude 1	A1	1.0	mm
Amplitude 2	A2	0.35	mm
Extrusion thickness	T	0.5	mm
Number of waves	n	3	-

Table 1. Measurement table

The figure consists of smooth periodic angles with interspersed bends that reduce inflow recession and minimize the chances of congestion, common in straight microchannels. The design parameters, such as channel confines, breadth variations, and material parcels, were named to replicate realistic microfluidic conditions. These values are epitomized in Table 1.

Cross-Sectional Area:

$$A = W \times H = (5.0\times10^{-4})^2 = 2.50\times10^{-7}\ m^2$$

Hydraulic Diameter :

$$D_h = \frac{2WH}{W+H}$$

Since W = H, $D_h = W = 5.0\times10^{-4}$ m (0.5 mm)

Wetted Perimeter :

$$P = 2 \times (W + H) = 2 \times (5.0\times10^{-4} + 5.0\times10^{-4})$$

Channel Volume:

Serpentine Wave Wavelength :

$= 2.0\times10^{-3}$ m (2.0 mm)

$V = A \times L = 2.50\times10^{-7} \times 4.8\times10^{-3} = 1.20\times10^{-9}\ m^3$

= 1.20 µL

$\lambda = \frac{L}{n} = 4.8\ mm / 3 = 1.6\ mm = 1.6\times10^{-3}$ m

C. Flow Simulation in COMSOL

This work models the flow rate and pressure distribution in a wavy microchannel using COMSOL Multiphysics. Water was assumed to be an incompressible fluid with laminar flow. It uses a fixed inlet pressure and an atmospheric outlet condition while considering no-slip walls. The pressure was highest at the inlet, followed by a gradual decrease through the channel due to frictional losses in flow and the curved path. Indeed, the wavy design resulted in a slightly higher pressure drop but enhanced the fluid mixing. The smooth, stable velocity profile ensures controlled and uniform flow for efficient and targeted drug delivery.

D. Meshing and Solver Configuration

Delicacy of meshing plays a significant role in attaining dependable simulation results. In this work, a drugscontrolled mesh was created in COMSOL Multiphysics to precisely capture the inflow movement within the windy microchannel. Since these are the places where subtle variations of velocity and pressure take place due to channel bending, the twisted regions have been paid special attention. A fine mesh was applied along these bends for the accurate calculation of original slants while describing them with a relatively coarse mesh in order to reduce computational trouble without a loss of delicacy.

For better capture of goods near the channel walls, boundary subcaste rudiments were introduced. These thin, structured layers permitted the solver to achieve resolution of variations of shear stress and pressure drop close to the walls, where such small crimes can make great impacts on an inflow profile as a whole. The designed boundary layers were done with a gradational growth rate so that the mesh easily transitions from the wall region into the core of the inflow sphere. Simulation under steady-state conditions was carried out in COMSOL using its stationary solver. A relative forbearance of 1×10^{-6} was kept during the calculations to insure numerical stability and confluence. During calculations, the solver automatically acclimated time-stepping and damping factors in pursuit of smooth confluence. After successful simulation, post-processing was carried out to fantasize important inflow parameters like haste distribution, pressure silhouettes, and wall shear stress. This helped in understanding how the windy figure affects fluid stir, icing a livery, and stable medicine inflow critical demand for precise and safe chemotherapy medicine delivery.

E. Flow Rate and Pressure Analysis

The inflow rate and the distribution of pressure in the wavy microchannel were anatomized using COMSOL Multiphysics. Water was assumed to be incompressible and in laminar inflow as the working fluid. An atmospheric outlet condition was given, with a fixed bay pressure and no- slip walls. The results showed that the pressure was loftiest at the bay and gradationally dropped along the channel due to frictional losses and the crooks in the path. The wavy design caused a slightly advanced pressure drop but bettered fluid mixing. The velocity profile remained smooth and stable, hence assured controlled and livery inflow for effective and targeted medicine delivery.

Volumetric Flow Rate Calculation**:**

$Q = U \times A$

$Q = (6.67 \times 10^{-4}) \times (2.5 \times 10^{-7})$

$Q = 1.667 \times 10^{-10}\ m^3/s$

Flow velocity (U):

To determine the flow velocity:

$U = \frac{Q}{A}$

where Q = volumetric flow rate

Reynolds Number (Re):

The Reynolds number (Re) is used to characterize the flow regime within the microchannel. It is calculated as:

$$Re = \frac{(\rho \times U \times D_h)}{\mu}$$

Where:

- ρ = Fluid density (kg/m^3)
- U = Mean velocity (m/s)
- D_h = Hydraulic diameter (m)
- μ = Dynamic viscosity (Pa·s)

When the mean velocity (U) is expressed in terms of the volumetric flow rate (Q), where U = Q / A, the formula becomes:

$$Re = \frac{(\rho \times Q \times D_h)}{\mu \times A}$$

Assuming water at 25°C (ρ = 997 kg/m^3, $\mu = 8.9\times10^{-4}$ Pa·s):

$Re = (\rho \times Q \times D_h) / (\mu \times A) \rightarrow Re \approx 2.241\times10^9 \times Q$ (with Q in m^3/s) For typical flow rates:

- Q = 1 µL/min → Re = 0.037
- Q = 10 µL/min → Re = 0.373
- Q = 100 µL/min → Re = 3.73 Dean Number (De):

For a serpentine microchannel, the Dean number quantifies the effect of curvature on flow: $De = Re \times \sqrt{(Dh / (2R))}$

$De = Re \times \sqrt{(Dh / (2R))}$

For $R_1 = 1\times10^{-3}$ m:

$De_1 = 1.33 \times \sqrt{(1.333\times10^{-4} / (2\times10^{-3}))} = 0.343$
For $R_2 = 5\times10^{-3}$ m:
$De_2 = 1.33 \times \sqrt{(1.333\times10^{-4} / (1\times10^{-2}))} = 0.153$

Friction Factor (f) :
For laminar flow, the friction factor is given by:

$$f \approx \frac{64}{Re}$$

This relation is valid for Re < 2300, representing fully developed laminar flow. f = 64 / 1.33 = 48.14 f ≈ 48.14
Pressure Drop (ΔP) :
The total pressure drop along the channel is estimated using the Darcy–Weisbach equation: $\Delta P = f \times (L / Dh) \times (\rho U^2 / 2)$ Where:

- f = friction factor
- L = channel length (m)
- Dh = hydraulic diameter (m)
- ρ = fluid density (kg/m³)
- U = average velocity (m/s)

$\Delta P = 48.14 \times (0.05 / 1.333\times10^{-4}) \times (997\times0.01^2 / 2) = 900$ Pa $\Delta P \approx 900$ Pa

F. Drug diffusion and concentration

The prolixity and attention velocity of the medicine within the wavy microchannel were anatomized to understand its transport effectiveness toward the target region. In this study, water was used as a cover for Doxorubicin to observe inflow and prolixity characteristics due to their analogous density at dilute attention. Under laminar inflow conditions, prolixity acted as the dominant medium for molecular transport since turbulent mixing is negligible at the microscale. The draft figure lifted the hearthstone time for the fluid indicating greater molecular prolixity propagating across the tortuosity. The attention profile harvested from COMSOL simulations showed gradual decay of attention from bay to outlet indicating a stable and controllable prolixity process suitable for localized and effective medicine delivery to cancer cells.

G. Validation and performance evaluation

The predicted flow behaviour and pressure distribution with respect to distance were validated against theoretical values for laminar flow in microchannels. The results were consistent with a velocity profile and linear drop in pressure along the length, which confirmed that the COMSOL model was correctly set up. The wavy PDMS microchannel was analyzed for flow stability, pressure efficiency, and the uniformity of diffusion. The model demonstrated smooth and continuous flow with low pressure drop and uniform concentration distribution; therefore the design is applicable for controlled, localized drug delivery in applications for cancer treatment.

III. RESULTS

A. Velocity Analysis in Wavy Microchannel

Velocity magnitude distribution along the wiavy microchannel obtained from COMSOL Multiphysics. The color gradient (blue to red) illustrates variations in fluid velocity where the maximum velocity occurred at the channel centerline while the minimum was observed near the walls. The windy design encourages livery inflow and augmented hearthstone time, suitable for controlled medicine delivery operations.

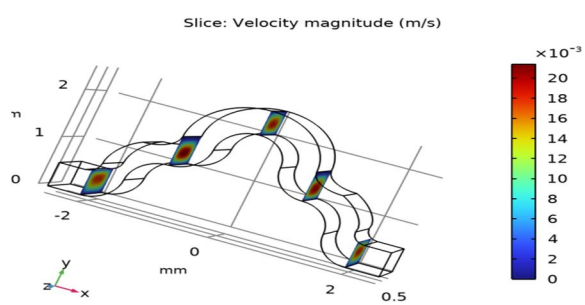

Fig 2. Velocity analysis of wavy microchannel

B. Pressure Distribution

Pressure distribution Figure represents the pressure distribution obtained from COMSOL Multiphysics. The color gradation from red to blue indicates a gradational pressure drop from bay to outlet, as has been attained, which attests to stable laminar inflow. The wavy figure, therefore, will ensure smooth pressure variation with livery inflow, suitable for controlled medicine delivery operations.

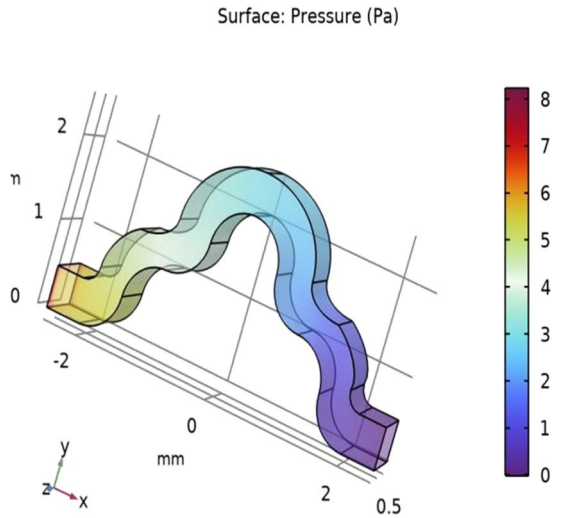

Fig 3. Pressure Distribution

C. Streamline Flow Pattern

This figure shows a full streamline distribution based on velocity magnitude colored through the streamlines. The smooth and continuous flow lines confirm that flow in the wavy channel is stable and laminar. Higher velocity can be observed along the center of the channel and lower velocity toward the channel walls to allow for effective mixing and controlled transport of a drug to achieve ideal conditions in microfluidic drug delivery applications.

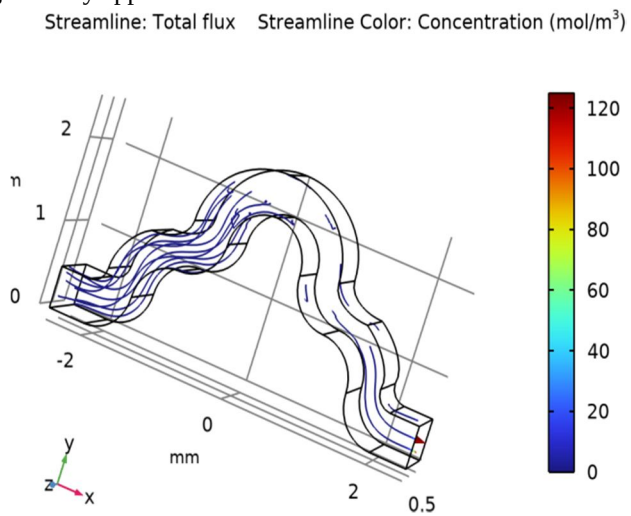

Fig 4. Streamline flow

D. Drug Attention Distribution

This figure represents the medicine's attention profile in the windy channel. The advanced attention regions, in red color, could be seen around the bay, gradationally dwindling, in blue color, along the inflow direction for prolixity and acceleration goods. The smooth grade ensures effective medicine dissipation, icing variable delivery throughout the channel suitable for controlled chemotherapeutic medicine administration operations.

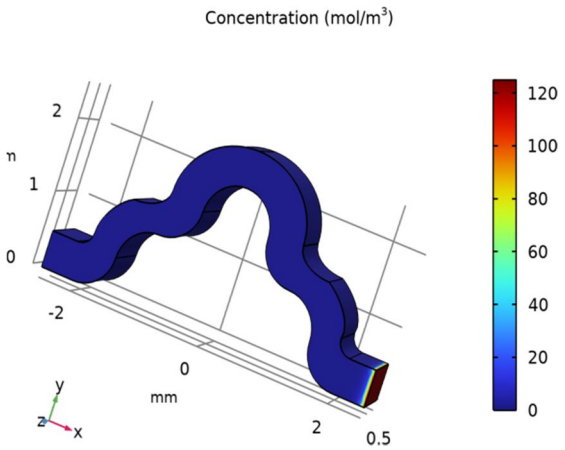

Fig 5. Drug attention distribution

IV. CONCLUSION

The simulation results using COMSOL Multiphysics reveal the effectiveness of the PDMS-based wavy microchannel design for targeted cancer therapy related to drug delivery. The velocity and pressure analyses indicate that the flow rate in the channel is laminar and reliable, which ensures confirmed drug delivery. An increased velocity in the center of the channel flow path and decreased velocities near the wall region serve to enhance the overall time that the drugs remain in the channel, which can improve drug diffusion and interaction with cancer cells. The pressure profile indicated a gradual decrease down the length of the channel confirming smooth flow behavior and minimal pressure loss during fluid flow. The concentration distribution results indicate that the wavy shape allows for a more uniform probability of mixing and prolonging drug delivery while decreasing sudden spikes of toxicity to surrounding healthy tissue and are not desirable in targeting therapy interventions. The wavy shape improved diffusion and allows for contribution to the controlled time dependent localized drug delivery.

Overall the simulation results validate the use a PDMS, serpentine microchannel is reliable, biocompatible, stable, and provides a viable microfluidic platform to conduct cancer therapy interventions with efficient drug delivery, which opens up a new opportunity for continued and future experimentation.

V. ACKNOWLEDGMENT

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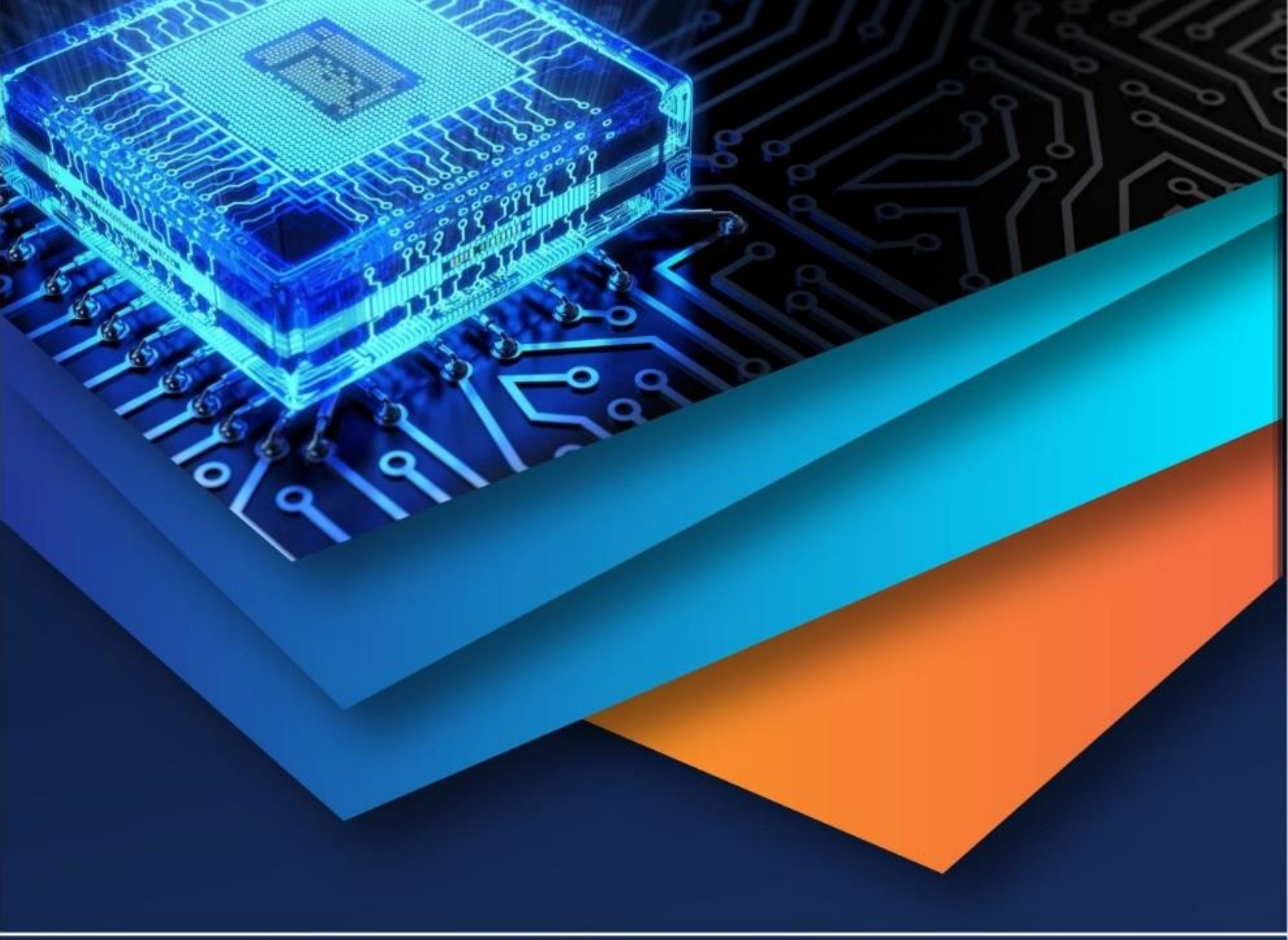

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