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Design and simulation of a multi-range thermal mass flowmeter for liquid flow rate measurement in microchannels

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E-mail: shahrouzi@sut.ac.ir and njodeiri@sut.ac.ir**Keywords:** thermal mass flowmeter, microfluidic, multi-range, flow measurement**Abstract**

The design of advanced thermal mass flowmeters presents a significant challenge in meeting the diverse measurement needs of modern industries, notably in process engineering, micro air vehicles, biomedical, oil and petrochemicals, food, and pharmaceuticals. A key focus is the ability to cover a broad range of flow rates, particularly at lower levels. Employing modern techniques such as microfluidics facilitates the development of flexible thermal mass flowmeters specifically designed for low measurement ranges. This research explores the design and simulation of microscale calorimetric thermal mass flowmeters to address the growing demand for accurate measurements at low flow rates. Critical considerations for these devices include the unique conditions of microfluidic systems, necessitating careful evaluation to ensure the feasibility of fabricating microcalorimetric thermal mass flowmeters. The design considerations can be divided into three categories: microgeometry, transfer phenomena, and range selectivity. Key factors such as geometric parameters in miniature dimensions, temperature and velocity distributions, effects of distributors, and measurement range determinations are scrutinized against constraints like linearity and cavitation. The study centers on measuring flow rates through square microchannels with a hydraulic diameter of 500 μm . A multi-range system allows for comprehensive coverage of the flow rate range while preserving the device's flexibility and ensuring accurate performance. A microchip prototype configured with 1 to 10 flow paths demonstrated the capability to support flow rates from 0 to 100, achieving an R^2 value of 0.98 across temperature differentials of less than 10 degrees, affirming its linearity and precision.

Nomenclature

A	Surface area (m^2)
a	Ratio of surface to volume ($\frac{m^2}{m^3}$)
C_t	Mass flow proportionality constant
D_H	Hydraulic diameter (m)
e	Relative roughness
F	Body force (N)
f	Friction factor
H	Height of channel (m)
H_s	Height of substrate (m)
H_{dis}	Height of distributor (m)
k	Thermal conductivity $\frac{W}{m \cdot K}$
L	Length of channel (m)
L_s	Length of substrate (m)
L_{dis}	Length of distributor (m)

L_{hy}	Hydrodynamic entrance length (m)
L_{th}	Thermal entrance length (m)
$\dot{m}$	Mass flow rate ($\frac{kg}{s}$)
N	Number of flow paths
p	Pressure (Pa)
$\dot{P}$	Perimeter (m)
Q	Heat source (W)
q	Thermal conduction $\frac{W}{m^2}$
R	Electrical resistance (ohm)
T	Temperature (K)
T_U	Upstream temperature (K)
T_D	Downstream temperature (K)
T_H	Heater temperature (K)
T_{in}	Input temperature (K)
T_{∞}	Ambient temperature (K)
T_{out}	Output temperature (K)
u	Flow velocity ($\frac{m}{s}$)
U_m	Average flow velocity ($\frac{m}{s}$)
u_{to}	Turn over flow velocity ($\frac{m}{s}$)
$\dot{V}$	Volume flow rate ($\frac{m^3}{s}$)
W	Width of channel (m)
W_s	Width of substrate (m)
W_{dis}	Width of distributor (m)

Greek symbols

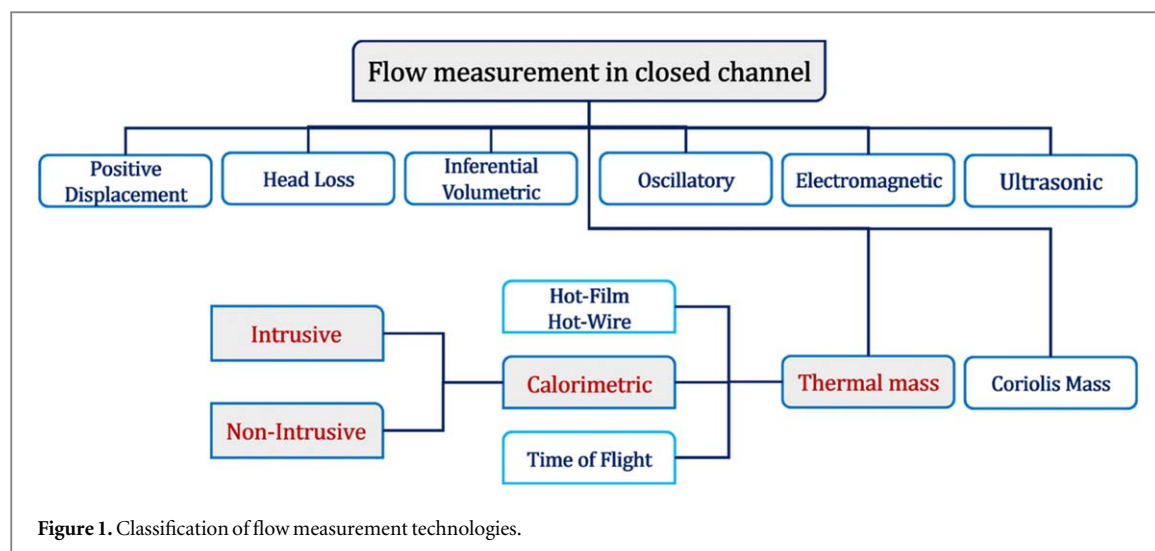
$\dot{\phi}$	Mass flux ($\frac{kg}{m^2.s}$)
ρ	Fluid density ($\frac{kg}{m^3}$)
μ	Dynamic viscosity of fluid ($Pa.s$)
ν	Kinematic viscosity of fluid (m^2/s)
τ_0	Shear stress at the wall (Pa)
α	Thermal diffusivity (m^2/s)
∇	Electrical voltage ($volt$)
ε	Average roughness length (m)

Dimensionless numbers

$Re = \frac{\rho u D_H}{\mu}$	Reynold's number
$Pr = \frac{\nu}{\alpha}$	Prandtl number
$f = \frac{\tau_0}{\rho U_a^2}$	Friction factor
$\frac{\Delta p}{L} = \frac{4f}{D_H} \frac{\rho U_a^2}{2}$	Driving force of fluid flow
$Po = f.Re$	Poiseuille number
$e = \frac{\varepsilon}{D_H}$	Relative roughness

1. Introduction

Flow measurement technology is utilized across various industries to develop and enhance instruments for measuring flow rates. Flowmeters are categorized into distinct groups according to their fundamental



operational principles and significance in industrial applications. The classification of flowmeter types is illustrated in figure 1 [1].

Flow measurement is often based on volume or mass principles, usually, in processes that calculate the flow rate by mass due to the possibility of density being affected by temperature and pressure. Mass flowmeters are divided into two categories: thermal mass flowmeters and Coriolis mass flowmeters [1]. The thermal flowmeter, which is the main subject of the current research, measures the mass rate of flow in an operational range that depends on fluid properties such as thermal conductivity, specific heat capacity, and fluid density (not on the physical state of the fluid). The mass flowmeter incorporates a heater and thermal sensors to establish a link between heat transfer and flow rate. Thermal sensors play a crucial role in various industrial and commercial applications by detecting temperature changes and converting them into electrical signals. Based on these operational principles, thermal mass flow sensors are classified into three main categories: hot-wire and hot-film sensors, calorimetric sensors, and time-of-flight sensors, which assess heater temperature, heater power, and temperature differences under constant temperature and constant power conditions [2, 3]. Technological advancements have made thermal mass flowmeters vital for measuring low flow rates, particularly at the micro and nanoscale. Their application spans various industries, including oil, petrochemicals, food, pharmaceuticals, etc [4, 5]. The growing demand for precise flow measurements of toxic, corrosive, and volatile fluids underscores the reliability and accuracy of these flowmeters. In addition, calorimetric thermal mass flowmeters are classified into two categories: intrusive (direct) and non-intrusive (indirect), whereas in indirect flowmeters, the temperature sensors are not in direct contact with fluid [2].

While the concept of thermal mass flowmeters has been well-established for decades, research efforts to improve their operational capabilities remain ongoing. In recent years, the fabrication of thermal mass flowmeters for liquids has been studied by many scientists [6, 7], some of which will be mentioned below. For instance, Lee *et al* used a sensitive and reliable thermal microflow sensor to detect very low flow rates in the range of $0.1\text{--}100\text{ ml h}^{-1}$ without invasive measurements and contamination, achieving a detection limit of approximately 0.1 ml h^{-1} and an uncertainty of less than 5% [8]. Djuzhev *et al* introduced a measurement system combining calorimetric and anemometric methods, enabling flow velocity measurements from 0.05 to 5 m s^{-1} with a 3% measurement error and a 2% relative standard deviation, noting that sensor placement in a wing-shaped body could enhance signal output [9]. In 2021, Cho *et al* validated a flexible microthermal flow sensor using MEMS technology for both liquid and gas flow measurements, demonstrating versatility across various fluids and flow rates [10]. Additionally, Kim *et al* introduced a disposable microfluidic flow sensor based on a release PET film coated with silicone to achieve a low-cost flowmeter [11]. Ejeian *et al* reviewed recent advancements in MEMS-based current sensors, categorizing them into thermal, piezoelectric, and other types while discussing key challenges and prospects for MEMS flow sensors [12]. In 2018, Chaboki *et al* fabricated a thermal mass flow meter for gases in the range of $0\text{--}500\text{ sccm}$ and investigated the main parameters affecting its performance. In addition, a computer simulation was performed to obtain suitable operating conditions and compare the experimental data with the simulation results. The effect of the flow restrictor and the number of its orifices were studied to determine the appropriate working range of the flowmeter [13]. The recent articles collectively highlight significant progress in calorimetric flow sensing technologies across a range of applications, notably in micro air vehicles (MAVs), aerodynamics, medical implants, and patient monitoring. Zheng *et al* present a flexible calorimetric flow sensor that employs vanadium oxide (VOx) thermistors,

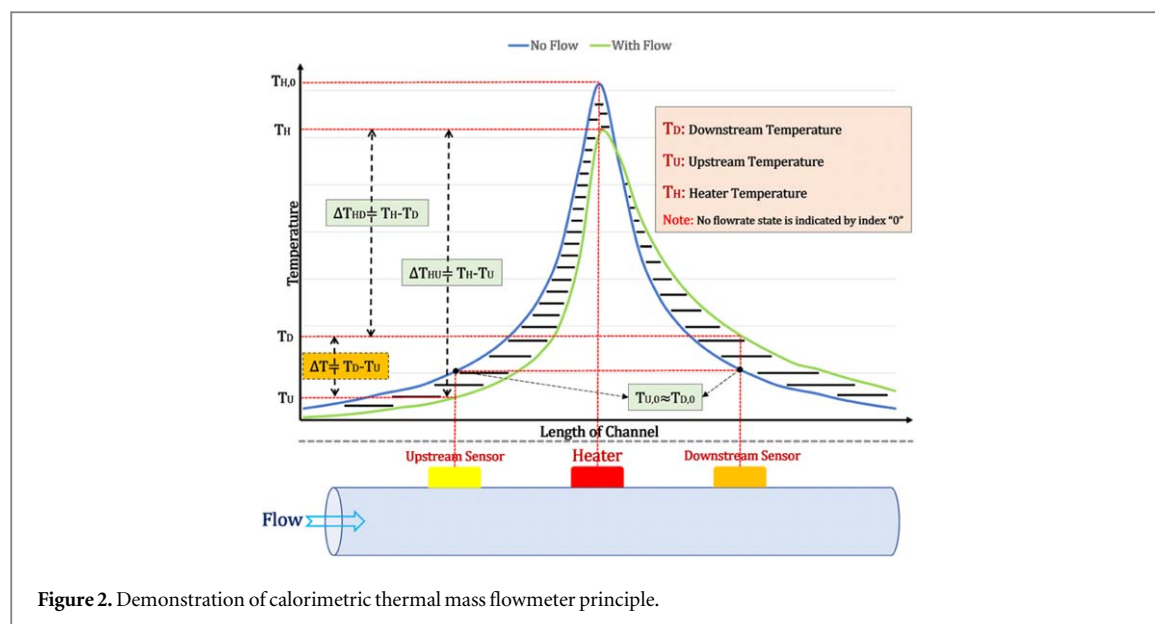
achieving impressive resolutions for measuring flight parameters such as angle of attack and airflow velocity, with experiments confirming high sensitivity and quick response times [14]. In a similar vein, Weiss and Giani create calorimetric microsensors designed to measure wall shear stress in low-speed aerodynamic flows, demonstrating their capability to capture both average and fluctuating stress in various conditions, including laminar and turbulent flows [15]. Vehusheia *et al* investigate microfluidic calorimetric chips aimed at the early detection of infections on implant surfaces, addressing the challenges posed by thermal fluctuations while showing potential for detecting bacterial growth before biofilm formation [16]. Furthermore, Zhang *et al* focus on a PDMS-based MEMS calorimetric flow sensor, highlighting its improved sensitivity and simplified manufacturing process [17]. In another study, Babaelahi *et al* concentrate on optimizing a thermo-resistive flow sensor for monitoring patient respiration, utilizing both analytical and numerical methods to enhance performance [18]. Collectively, these advancements emphasize the promise of calorimetric sensors in improving measurement accuracy and sensitivity across diverse fields, setting the stage for future applications and enhancements. Straighteners, restrictors, and distributors are essential components that stabilize fluid flow, positioned between the fluid inlet and flow rate measurement points to prevent turbulence and maintain laminar flow, which reduces energy loss and enhances measurement accuracy. These devices delay the transition from laminar to turbulent flow by altering cross-sectional areas, particularly at micro scales, where surface roughness and tension can introduce measurement errors [19]. Research by Agrawal in 2009 on a thermal mass flowmeter with a cylindrical restrictor highlighted the importance of flow management [20]. In 2024, Cabrera *et al* noted that 14% of energy consumption in European homes is for domestic hot water, recommending flow restrictors in energy efficiency programs to improve overall efficiency [21]. Additionally, Yang *et al* focused on optimizing a MEMS thermal gas flowmeter to address low mass flow velocity challenges, achieving significant improvements in measurement accuracy [22]. Zhang *et al* examined the effects of flow straighteners on three-phase jet fire monitors using simulations, finding that optimal configurations can enhance outlet velocity and reduce pressure loss [23]. Together, these studies underscore the vital importance of precise flow management with these components in improving measurement accuracy and operational efficiency across a range of applications. Moreover, most thermal mass flowmeters are typically calibrated for specific flow rate ranges, which can limit their versatility. By developing a multi-range and flexible flowmeter, it becomes possible to measure a wide range of flow rates with a single calibration. This innovation addresses the need for greater adaptability in flow measurement, allowing users to efficiently manage varying applications without needing multiple calibrations.

In addition, microfluidics focuses on the manipulation and study of fluids at the microscale, typically in channels ranging from 0.1 to 1000 micrometers, and involves small fluid volumes (nanoliter to picoliter range). Unlike macrofluidics, where larger volumes often lead to turbulent flow, microfluidics is characterized by laminar flow, with surface tension and capillary forces dominating. This allows for rapid reaction times and precise control over fluid dynamics and heat transfer enabling the integration of multiple functions, such as mixing, reaction, and detection, into compact devices. These unique features make microfluidics particularly valuable in biomedical applications and lab-on-a-chip technologies [5].

As mentioned above, the role of the restrictor in fluid flow control through the main sensing channel is indeed pivotal. By regulating the flow rate, the restrictor ensures optimal performance and accuracy of the sensing mechanism, thereby enhancing the overall efficiency of the system. The primary objective of this study is to serve as a comprehensive guide for the design and production of a cost-effective microcalorimetric thermal mass flowmeter (μ CTMF) tailored for liquid applications. The goal is to develop a device that is fully multi-range and adjustable, enabling its utilization across a variety of microsystem applications within different operating ranges. Achieving this multi-range capability involves designing multiple channels and implementing a moving distributor to control the fluid flow through various paths based on the desired range. The simulation involved creating a microchip model using a three-dimensional approach, considering specific assumptions and appropriate boundary conditions. The investigation focused on understanding the parameters influencing flow rate measurements by μ CTMF devices. By conducting a detailed analysis of these parameters, researchers aim to optimize the design and functionality of the flowmeter, ensuring its accuracy and efficiency across different flow rate ranges. Ultimately, the study aims to provide valuable insights for enhancing the performance and versatility of μ CTMF technology for various microsystem applications.

2. Theory

This section discusses the operational theory of μ CTMF and highlights relevant considerations regarding its design. These flowmeters use thermal sensors, typically measure a mechanical variable, such as fluid flow, and convert it into a heat-related variable, like heat transfer or temperature. This conversion process allows the sensor to generate an electrical signal, commonly in the form of voltage, which can be quickly processed and



analyzed by electronic systems. According to such operational principles, thermal mass flow sensors evaluate heater temperature, heater power, and temperature difference in constant temperature or constant power. As shown in figure 2, when the flow does not pass through the channel, the curve of temperature changes along the channel is dome-symmetric. As a result, the temperature difference between the upstream and downstream sensors will be almost zero. As the flow passes, the curve deviates from the symmetrical state (hatched part), and its value will increase or decrease depending on the flow rate. Since conjugated mass and heat transfer occur in the calorimetric principle of flow rate measurements, parameters such as temperature, pressure, velocity, and their interaction will be very significant and influential [2]. In design considerations, the heater is commonly positioned at the center of the microchannel to ensure optimal symmetry. Additionally, as depicted in figure 2, an excessive distance between the sensor and heater can diminish the temperature difference, adversely affecting measurement accuracy. Conversely, the proximity of the sensor to the heater can result in distorted readings attributable to thermal influence on each other. Therefore, a careful trade-off is essential in positioning these components.

Designing a μ CTMF requires careful consideration of microflow dynamics [24, 25]. This paper outlines essential factors such as transport phenomena, simulation criteria, and the characteristics of flowmeters. These general considerations are crucial for ensuring the adequate performance of the μ CTMF in microfluidic applications. By addressing these considerations, researchers can optimize the performance of the μ CTMF for various applications [26, 27]. At the microscale, the elevated surface-to-volume ratio ($a = \frac{A}{V}$) significantly influences surface geometry. Since the hydraulic diameter ($D_H = 4 \frac{A}{P}$) is a crucial geometric parameter in describing transfer phenomena, examining its variations will ensure greater accuracy in the design and analysis of results [28, 29]. Fluid flow at the microscale presents essential considerations due to its differences from the macroscale. The continuum mechanics hypothesis in microscale is often considered in $D_H > 10 \mu\text{m}$ for liquid flow and $D_H > 100 \mu\text{m}$ for gas flow [28, 30]. The study of macroscale fluid mechanics generally starts from the assumption that the fluid can be considered a continuum that changes continuously with the flow [31]. Relative roughness, defined as the ratio $e = \varepsilon/D_H$ where ε represents the average roughness, plays a crucial role in microfluidic systems. In microchannels, surface roughness can have a significant impact on fluid flow behavior and overall system performance. Considering the small dimensions of microchannels, even minor variations in surface roughness can lead to noticeable effects on flow characteristics. Therefore, precise control and optimization of surface roughness are essential to minimize its influence on fluid flow in microfluidic devices [32]. Depending on the substrate material and fabrication techniques used, surface roughness in microchannels, highlighting the importance of addressing this parameter in the design and fabrication of microfluidic systems [33, 34]. Type of fluid, slip condition, entrance length and Reynolds number, diffusion, surface tension and electro-hydrodynamic effects in the microscale each of these can play an essential role in explaining the phenomena [31, 35]. In the present study, a key innovation involves positioning the distributor at the fluid inlet of the microchip. This approach yields beneficial outcomes, including a reduction in the entrance effects of the fluid flow and enhanced multi-ranging capabilities due to its mobility. Furthermore, a prevalent thermal limitation in measuring flow rates using μ CTMF is the phenomenon of cavitation, which is particularly relevant for fluid properties. In this study, the fluid under investigation is water, which can experience cavitation within the temperature difference range of 20–30 °C [2, 36].

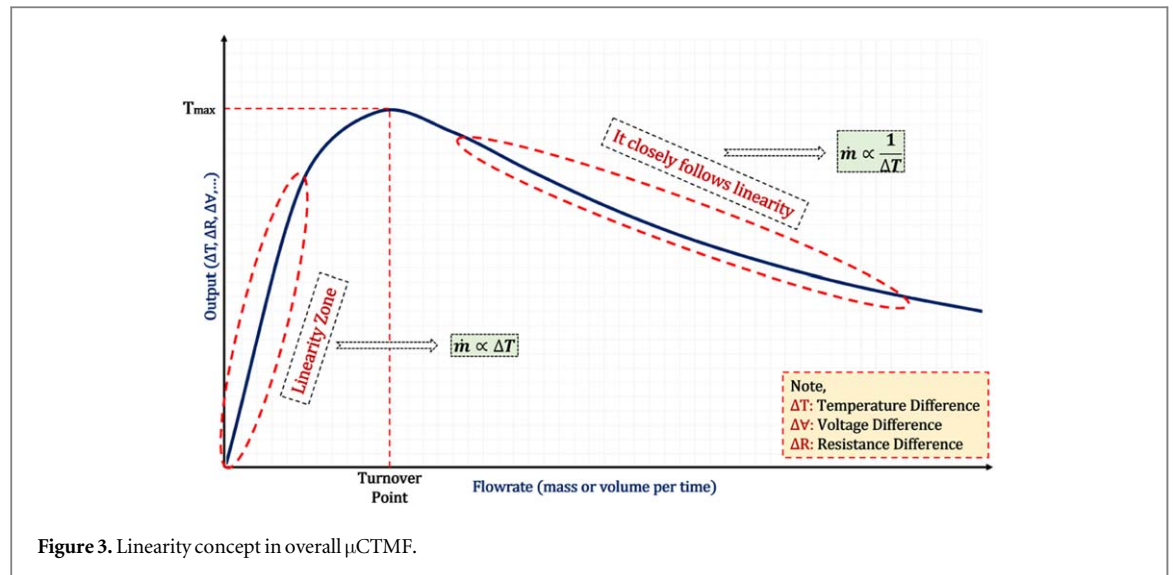


Figure 3. Linearity concept in overall μ CTMF.

In addition, the operational precision and accuracy of the device alongside other characteristics such as repeatability, reproducibility, uncertainty, reliability, and sensitivity are parameters that are evaluated after device fabrication. However, characteristics like rangeability and linearity must be taken into account during the design phase before fabrication, as discussed in detail in this research. Flow measurement ranges are expressed with concepts such as Zero, Span, Turndown ratio, and Rangeability. Establishing a solid relationship between linearity and rangeability is essential for accurately validating the output from measuring devices [19]. Linearity refers to the correlation between the measured variable values and the output signal of the device. Ensuring good linearity allows for precise data validation within the calibration range, enhancing the reliability and accuracy of measurements. By maintaining a linear relationship between input values and output signals, researchers can effectively validate and verify the performance of measuring devices across a wide range of operating conditions. Maintaining linearity in the output signal of sensors with changes in flow rate is crucial for the accuracy of flowmeters. μ CTMF are known for their linear output across various ranges, contributing to their accuracy. By following a linear relationship with flow rate changes, μ CTMF devices can provide precise measurements [24, 36]. Figure 3 illustrates the concept of linearity in the operation of a microchannel thermal mass flowmeter (μ CTMF), demonstrating the relationship between flow rate and output. The graph displays a characteristic curve with a defined linearity zone, where the output closely correlates with the mass flow rate and temperature difference ($\dot{m} \propto \Delta T$). The temperature difference behavior is influenced by the interaction between the heater temperature (T_H) and fluid dynamics. Maximum ΔT is achieved when there is an optimal balance between heat transfer and fluid dynamic, which is specifically affected by the reduction in T_H at increased flow velocities [37]. This non-linear region suggests that at very high flow rates, the output-flow rate relationship becomes more complex, leading to reduced sensitivity to flow changes. The graphical representation effectively highlights the importance of understanding linearity for accurate calibration and operation of μ CTMF systems, ensuring precise flow measurements across various conditions. [1, 4, 19, 24, 38, 39].

In figure 3, the turnover point marks the transition in the behavior of the measured output graph per unit of flow rate, shifting from an ascending to a descending trend at constant power. Preceding the turnover point is the primary area of linearity, where the steeper slope of the line results in more accurate measured outputs from the flowmeter. On the other hand, the area beyond the turnover point demonstrates linearity within a specific range, providing a good approximation for measuring non-zero flow rates. When analyzing the turnover point, it is crucial to consider various parameters such as temperature, velocity, temperature difference, and power, as they significantly influence the phenomena related to measurement based on the calorimetric principle. At the turnover point, the temperature difference reaches its maximum value, and the fluid flow velocity at this juncture represents the end of the linear region. Therefore, the velocities preceding the turnover point, provided they adhere to high-accuracy linearity, effectively determine the conclusion of the measurement range [37].

3. Design and simulation

In this section, the study delves into the assumptions, equations, and considerations pertinent to the simulation and design of a microcalorimetric thermal mass flowmeter (μ CTMF) using COMSOL Multiphysics software. By discussing the transfer phenomena assumptions and flowmeter characteristics across various applications,

researchers aim to design a μ CTMF and analyze its outcomes effectively. To design the μ CTMF and evaluate its performance, it is imperative to initially scrutinize the equations governing the measurement process based on the calorimetric principle. The simulation involves a comprehensive examination of the considerations associated with a fully developed laminar flow of single-phase liquid, ensuring that the final design yields the most precise experimental results [26]. Given that the calorimetric principle involves conjugated heat transfer coupled with fluid dynamics flow, the modeling and analysis of the process are facilitated through the incorporation of momentum and energy balance equations. By integrating these fundamental principles into the simulation, it can obtain a deeper understanding of the measurement process and optimize the design of the μ CTMF for enhanced accuracy and efficiency [29]. The continuity equation and the governing momentum balance equation for a single-phase liquid flow along the microchannel are as follows:

$$-\frac{1}{\rho} \frac{D\rho}{Dt} = \nabla \cdot \mathbf{u} \quad (1)$$

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \mathbf{F} - \nabla \cdot \boldsymbol{\tau} \quad (2)$$

where ρ is the density, $\mathbf{u}$ is the fluid flow velocity, p is the axial pressure of the microchannel, $\mathbf{F}$ is the body forces, and $\boldsymbol{\tau}$ is the viscous stress tensor. The energy balance equations in the conjugate heat transfer process using the thermal calorimetric principle follow equation (3):

$$\rho C_p \mathbf{u} \nabla T = -\nabla \cdot \mathbf{q} + \beta T \mathbf{u} \nabla p + \mu \Phi + Q \quad (3)$$

where q is conduction heat transfer following Fick's law, Φ is viscous heating, and Q is heat source. In equation (3), the simulation results indicate that the contribution of viscous heating is significantly lower than Q (for $Q = 0.05$ W, viscous dissipation $\approx 10^{-7}$), allowing it to be disregarded. This simplification helps streamline the analysis without compromising accuracy. Neglecting the work done by pressure change and viscous heating, the energy balance equation in the microchannel for an axial fluid flow will be as follows:

$$\rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q \quad (4)$$

Based on the stated assumptions, including steady-state conditions, nearly constant density and viscosity, negligible gravitational forces, minimal total derivative of velocity, and negligible slip and viscous dissipation, specific terms in the momentum and heat transfer equations can be disregarded. This simplification allows for a more manageable solution of the equations, facilitating the analysis of the system's behavior under the defined conditions. Before any study, it should be considered that the terms of practical transfer phenomena in the microscale show their behavior. In transfer phenomena, one of the basic concepts that significantly affects some phenomena and conditions is the ratio of surface to volume (a), which is the point of difference between the micro and macro scales. At the microscale, geometric effects become increasingly significant, necessitating careful consideration of various parameters and terms. It can be concluded that the hydraulic diameter, channel cross-section area, temperature, flow velocity, heat source, and pressure should be studied in the analysis and evaluation of the calorimetric flow rate measurement process. Finally, according to all the important topics raised in the design of μ CTMF, a common and low-cost case study with the highest level of operational accuracy and precision was investigated [5, 31]. Figure 4 demonstrates the μ CTMF designed for a wide range of microfluidic applications. To effectively solve the governing equations, it is imperative to establish a set of constants, boundary conditions, and assumptions, all of which are summarized in table 1. This holistic approach not only underscores the importance of the specified parameters but also highlights the intricate interplay between geometry and fluid dynamics in microfluidic systems.

Figure 4 depicts a microfluidic device designed for μ CTMF. The key dimensions of the system are clearly labeled, including the length, width, and height of the microchannel. These geometric parameters are crucial in understanding the fluid dynamics and heat transfer processes within the miniaturized system. The device consists of several core components. The 'Mobile Part' and 'Inlet Distributor' are responsible for introducing the fluid sample into the microchannel. Sensors are strategically placed along the channel to monitor the temperature of the fluid as it flows through the system. A 'Heat Source' is integrated to induce a controlled temperature difference between the upstream and downstream regions of the microchannel. The flow measurement channel operates within a fixed framework where the fluid continually passes through this channel. Essentially, this measurement channel serves as the main pathway for fluid where additional flow paths are effectively opened ($N = 2$ to 10) via the distributor. By measuring the temperature difference across the channel length, along with other parameters like the channel dimensions and fluid properties, the system can calculate the volumetric flow rate of the sample. This calorimetric approach allows for highly accurate flow measurement in microscale fluidic devices, which is essential for many microfluidic applications such as lab-on-a-chip systems, micro-total analysis systems, and other miniaturized analytical devices. The comprehensive

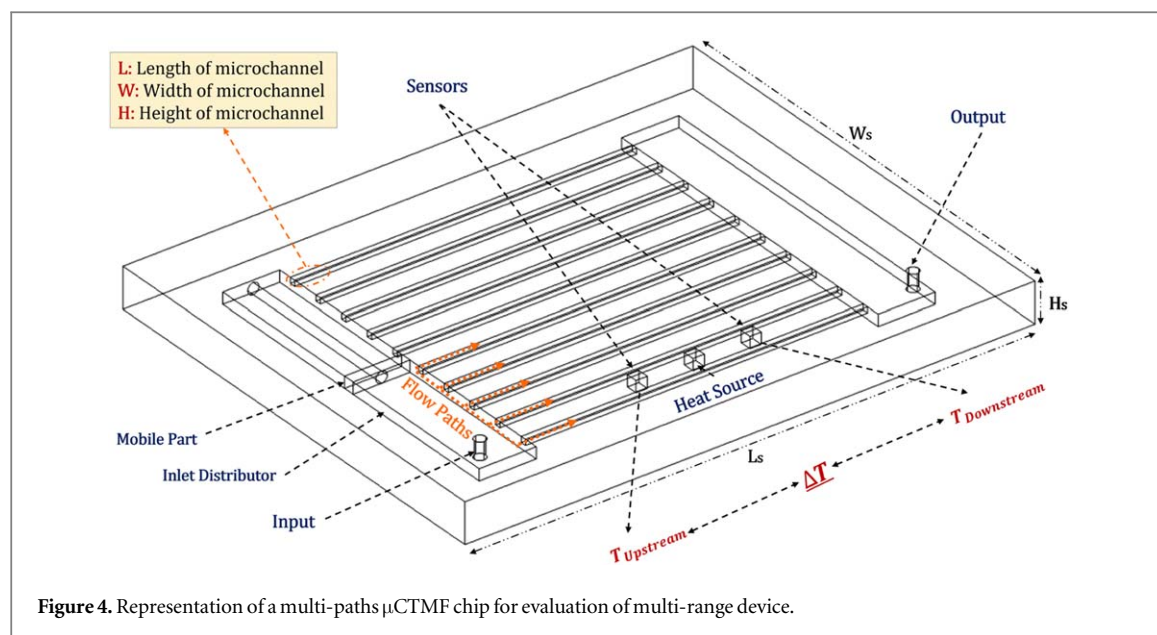


Figure 4. Representation of a multi-paths μ CTMF chip for evaluation of multi-range device.

Table 1. Parameters and conditions related to the design of μ CTMF.

Effective Items	Design Consideration
Type of fluid	Water (liquid)
Hydraulic diameter	$D_H \approx 500 \mu\text{m}$
Cross-section area	Square with side $500 \mu\text{m}$
Substrate	Polymethyl Methacrylate (PMMA)
Input flow rate	$0-100 \mu\text{l min}^{-1}$; $T_{in} = T_{\infty}$
Heat source	$0.05-0.25 \text{ W}$
Number of flow paths	1–10
Substrate dimensions	$L_s = 50 \text{ mm}$, $W_s = 40 \text{ mm}$, $H_s = 4 \text{ mm}$
Distributor dimensions	$L_{dis} = 5 \text{ mm}$, $W_{dis} = 30 \text{ mm}$, $H_{dis} = 1 \text{ mm}$
Channel dimensions	$L = 30 \text{ mm}$, $W = 500 \mu\text{m}$, $H = 500 \mu\text{m}$
Output	$p = p_{atm}$, $T_{out} = \text{Outflow}$

labeling and schematic representation provide a clear overview of the key design elements and working principles of this μ CTMF system.

4. Results and discussion

A selection of critical parameters was identified for the design of the μ CTMF to evaluate the distribution of temperature and velocity. Based on this analysis, recommendations for fabricating a μ CTMF with enhanced precision and accuracy are provided, with detailed discussions of the results. To perform the analysis of the simulation data, approximately 6,000 software runs were conducted, allowing for a more precise and accurate design.

4.1. Channel geometry effect

4.1.1. Hydraulic diameter (D_H) and channel cross-section shape effect

Initially, the importance of the microchannel geometry, including the shape and size of the channels, is assessed, highlighting that the D_H is a vital parameter in the analysis of the results. The dimensions of the channels — length, width, and height — are critical characteristics of microfluidic systems that yield different outcomes depending on the specific application. A detailed examination is performed for each dimension to ensure optimal performance. Table 2 presents how the microchannel dimensions impact the measurement results. As presented in table 2, the length of the microchannel has minimal impact on the device output, making the shortest feasible length the optimal choice. The depth of the microchannel also does not significantly affect the output and is selected based on microscale principles and the measurement range. Conversely, the channel width, due to its proximity to the upper surface where the sensor is located, along with the hydraulic diameter,

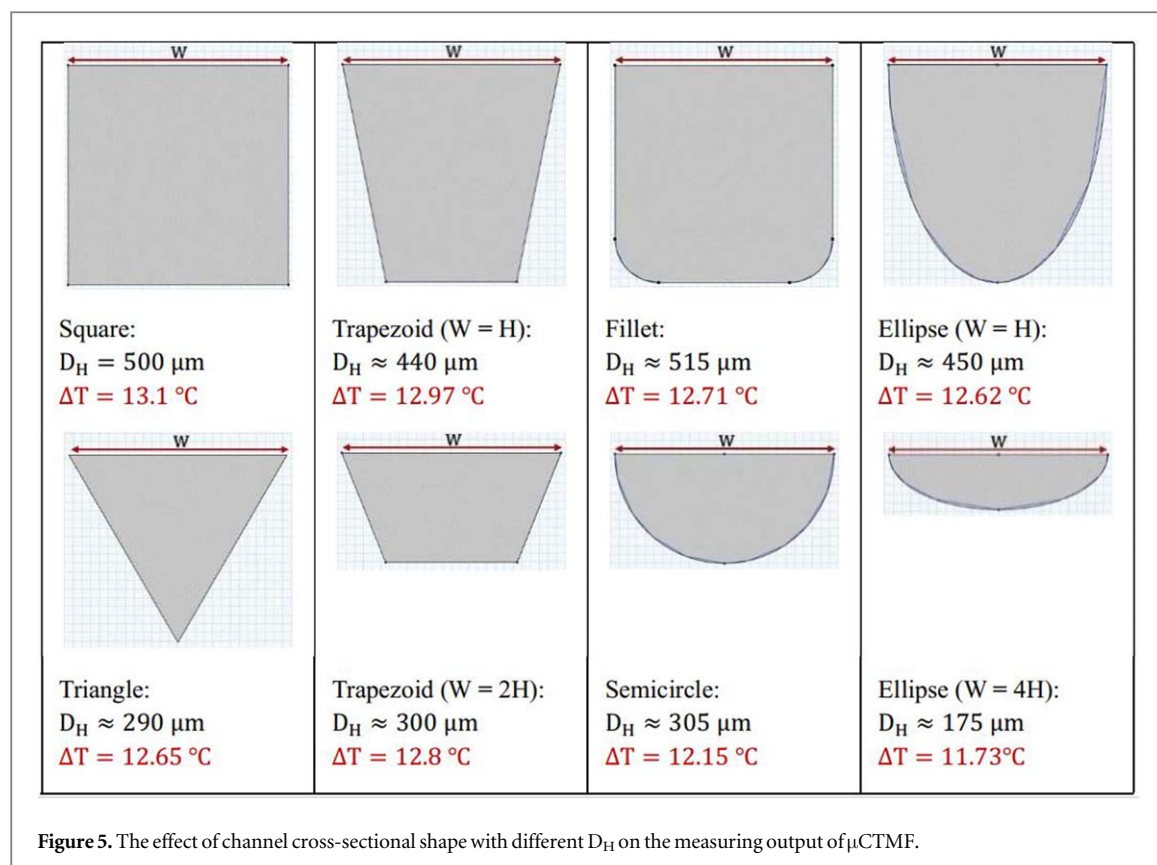


Table 2. Effect of rectangular microchannel dimension on the temperature difference in μCTMF .

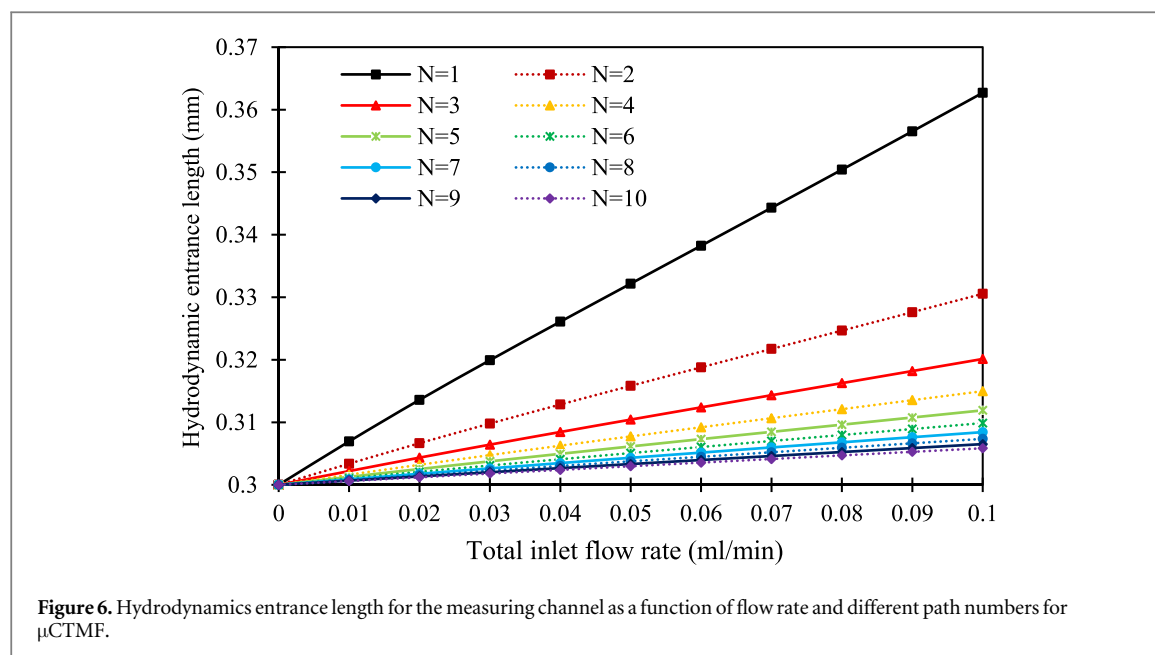
W = H = 500 μm		L = 30 mm, W = 500 μm		L = 30 mm, H = 500 μm		L = 30 mm, W = H = 500 μm	
L (mm)	ΔT (K)	H (μm)	ΔT (K)	W (μm)	ΔT (K)	D_H (μm)	ΔT (K)
30	13.10	1000	13.06	250	12.28	250 μm	12.26
40	13.15	500	13.10	500	13.10	500 μm	13.10
50	13.17	250	13.09	1000	14.4	1000 μm	14.09

influences the output range, i.e., increasing the hydraulic diameter and width leads to an expanded range of fluid flow measurement.

The shape of the microchannel cross-section is a critical parameter for understanding transfer phenomena in microchannels. In experimental microfabrication techniques, diverse cross-sectional shapes can be achieved through methods such as micro-milling. When a ball-end mill is utilized to create a square microchannel, the resulting cross-section resembles a fillet, characterized by its smooth curvature. Conversely, the employment of a V-shaped bit leads to the formation of trapezoidal or triangular cross-sections, highlighting the versatility of micro-milling in producing various geometries for microchannel applications [33, 34]. This research investigates various shapes of channel cross-sections with different D_H and their effects on the overall performance of μCTMF as shown in figure 5. It should be noted that the upper side is maintained at a width of 500 μm for all channels. According to figure 5, the square, trapezoidal, fillet, elliptical, and triangular shapes with dimensions of $W = H = 500 \mu\text{m}$ produce different output values. Among these, the square, triangle, and trapezoid are the most suitable options, in terms of priority. Additionally, it is observed that reducing the depth of the trapezoidal and elliptical shapes results in a decrease in output due to a reduction in D_H . Based on the results, the designed microchannel in this research is square-shaped, featuring a hydraulic diameter of 500 μm as the typical dimension.

4.1.2. Entrance effects

The hydrodynamic entrance length, denoting of fully developed flow, can significantly influence measurements at the microscale; where it can often be negligible compared to the total channel length. An increased entrance



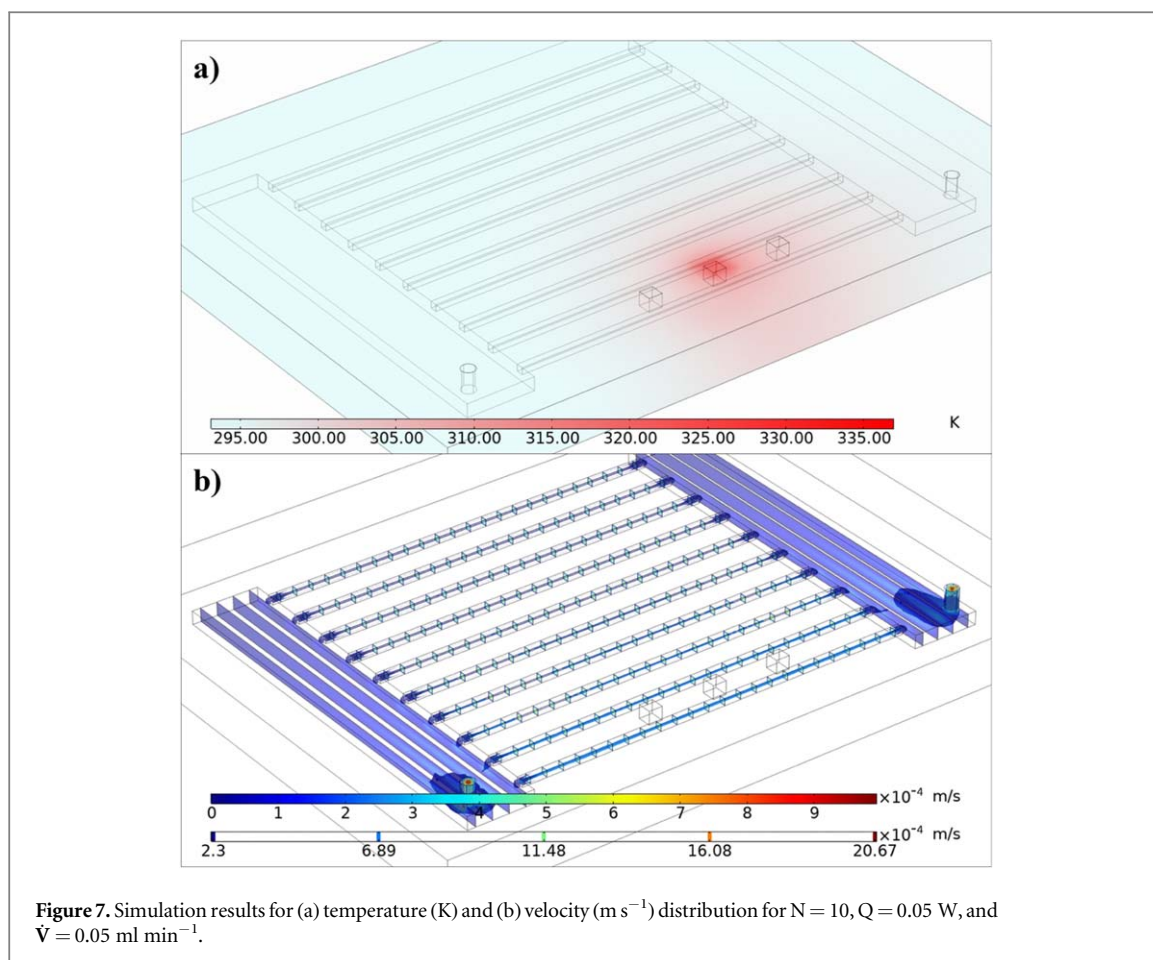
length may elevate the fluid temperature, potentially reaching critical levels that can disrupt μ CTMF stability and accuracy. To enhance device performance, it is essential to minimize this entrance length. One effective solution, given the inherent design constraints, is the incorporation of a distributor at the channel entrance. This distributor reduces flow velocity, thereby slowing heat transfer and preventing temperature spikes. Additionally, it provides significant advantages by allowing mechanical or electrical control over the fluid pathways entering the flow meter. Implementing a distributor with multiple passes to manage fluid flow paths is a strategic approach to optimizing the performance of multi-range devices. This can be achieved through the use of microvalves that selectively open or close specific flow paths, thereby enhancing the system's overall control and versatility. The fluid distributor not only lowers the fluid velocity within the measuring channel but also mitigates the effects of surface roughness, ensuring that the flow remains laminar even at higher flow rates. As illustrated in figure 6, the hydrodynamic entrance length varies with different flow rates and multiple passes. For a channel length of 30 mm, the entrance length measures approximately 0.37 mm. However, by increasing the number of flow paths while maintaining the same flow rate, the entrance length decreases slightly to about 0.30 mm. This reduction indicates that the entrance length does not interfere with fluid flow measurements, as the sensors are positioned sufficiently far from the channel entrance. Overall, these considerations underscore the importance of optimizing the hydrodynamic entrance length to ensure accurate and reliable measurements in microscale applications.

4.2. Effect of microchip fluid flow on transport phenomena

4.2.1. Temperature and velocity distribution

The analysis of the results will commence with a discussion on transfer phenomena, as the performance of μ CTMF relies on the distribution of temperature and velocity during the measurement process. Figure 7 shows a typical distribution of temperature and velocity in the proposed designed microchip.

In figure 7(a), the temperature distribution within the microchip is illustrated, showing that the maximum temperature under the specified conditions ($N = 10$, $Q = 0.05$ W, and $\dot{V} = 0.05$ ml min⁻¹) does not exceed 335 K. Since the fluid (water) does not reach its boiling point, this indicates that the microchip operates at a suitable temperature for effective measurement. Figure 7(b) illustrates the flow velocity distribution within the microchip, highlighting that the highest flow velocity occurs at the center of the microchannel in fully developed flow conditions (approximately 2 mm s⁻¹). As the fluid enters the microchip through the inlet at various flow rates, its velocity decreases in the distributor, which is crucial for maintaining a laminar flow profile. This reduction in velocity allows the fluid to transition into the microchannels at a lower velocity, quickly establishing laminar flow. Such laminar flow is essential for achieving optimal measurement conditions with the thermal mass flowmeter, ensuring precise and reliable readings while minimizing turbulence that could affect the accuracy of the measurements.



4.2.2. Heating power effect

Temperature analysis is crucial in the design and construction of flowmeters while cavitation temperature difference serves as a key limiting factor. Additionally, the specific dimensions of microflowmeters necessitate careful consideration of microscale effects, including cost, accuracy, and durability, all of which depend on suitable operating temperatures for their intended applications. Consequently, the primary concern in the thermal design of these devices is managing thermal power consumption. Figure 8 illustrates the temperature variations resulting from different heat power levels. Increasing heating power from 0.05 to 0.25 W leads to a temperature difference between the sensors ranging from approximately 10 to 40 °C, which is suitable for the measurement range. As observed, higher power correlates with greater temperature differences for the same flow rates. This indicates that increased energy input results in enhanced thermal transfer efficiency, manifesting in larger temperature gradients. The curves demonstrate a nonlinear trend, suggesting that the system's thermal response improves more significantly at lower flow rates before plateauing at higher rates. Moreover, as the flow rate increases, the rate of temperature rise decreases, indicating diminishing returns in heat transfer efficiency at higher flow rates. It is important to note that two fundamental limitations should be considered: the phenomenon of cavitation, where the temperature difference between two points should remain under 20–30 °C, and the boiling point of water at 100 °C. For a flow range of 0–100 $\mu\text{l min}^{-1}$, the designed geometry ensures that temperature differences at heating powers of 0.05 and 0.1 W stay below the cavitation threshold while keeping the maximum fluid temperature below the boiling point. However, at a heating power of 0.25 W the maximum fluid temperature can reach around 440 K which is unacceptable. Consequently, thermal powers of 0.05 and 0.1 W are appropriate for the designed microchip. Specifically, at 0.05 W, the temperature difference between the sensors is within the acceptable range of 0–10 °C, with a maximum fluid temperature of 50 °C, making it the preferred reference heating power for the flowmeter. Additionally, the temperature curve at this power level demonstrates more excellent linearity, which enhances data accuracy.

The maximum temperature difference for the device across various path numbers, as depicted in figure 9, is monitored to avoid cavitation. At a power level of 0.05 W, the maximum temperature difference reaches 30 °C, ensuring that the device's maximum temperature remains below 100 °C, thus preventing bubble formation for water as sample fluid. Consequently, due to the system's geometry, the cavitation—which could introduce uncertainty and diminish accuracy—is effectively avoided in the device. As the flow rate increases, the

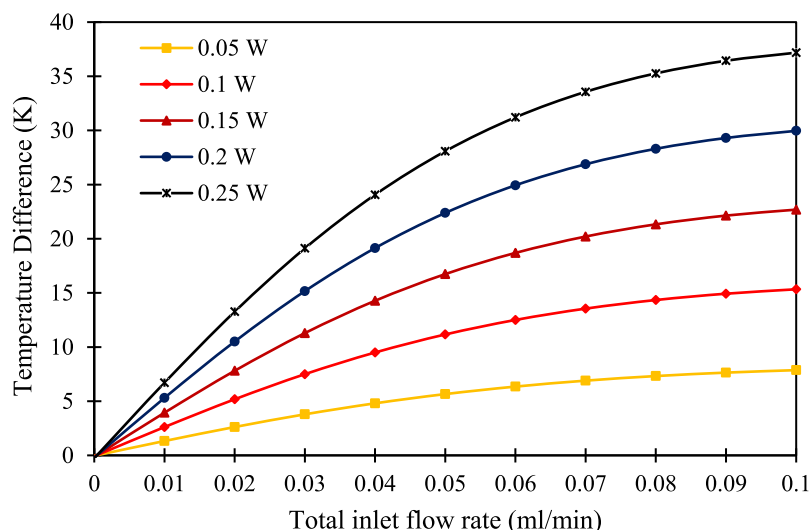


Figure 8. Temperature difference curve regarding flow rate in different heating powers for ten paths.

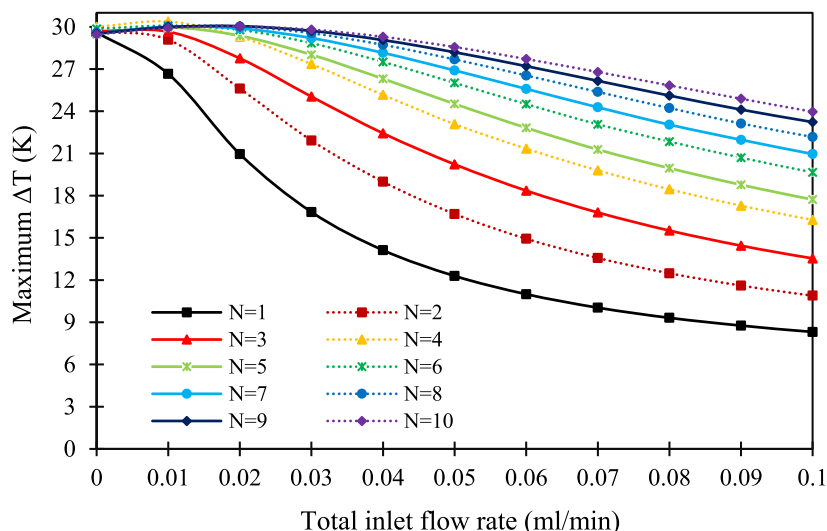
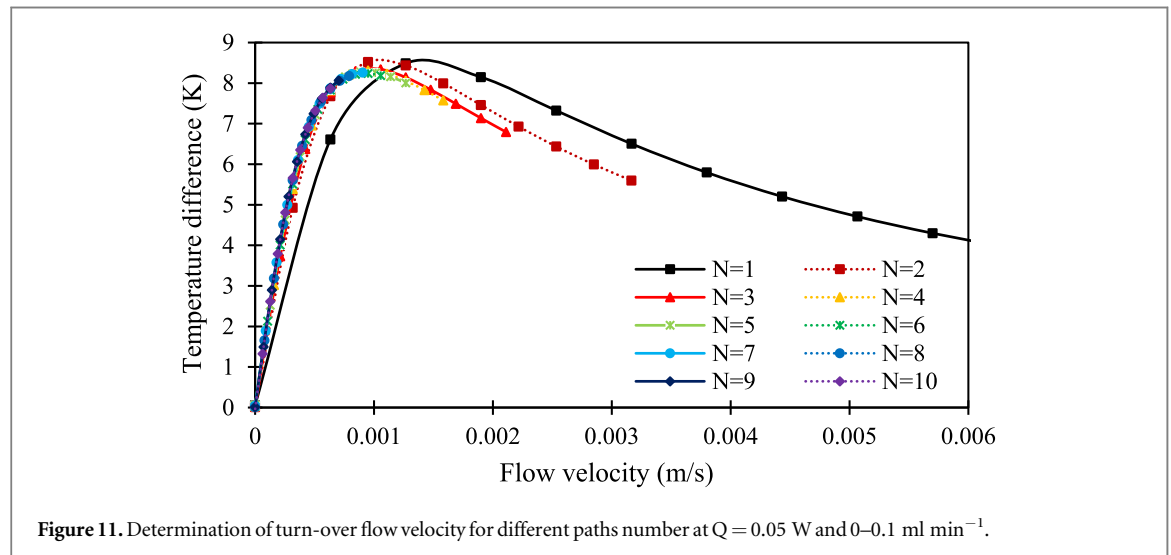
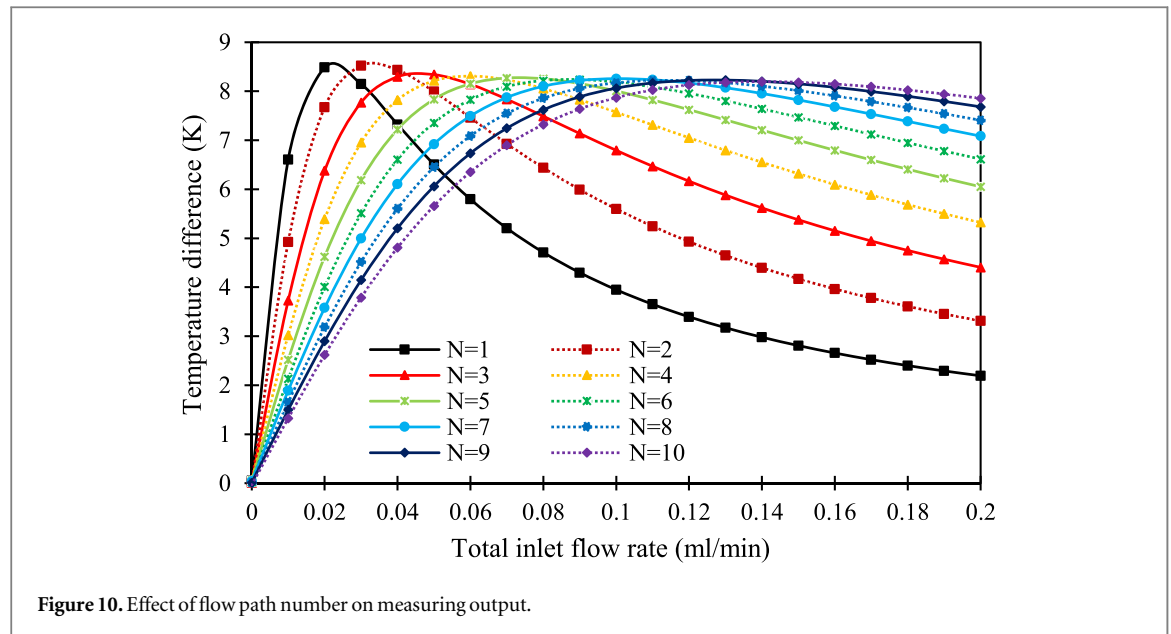


Figure 9. The maximum temperature difference for the number of different paths.

maximum temperature difference generally decreases for all values of N , illustrating an inverse relationship. Specifically, at lower flow rates, there is a more pronounced temperature difference, which suggests that fluid has more time to absorb heat and exhibit greater temperature variation. Conversely, as the flow rate increases, the fluid moves faster through the system, resulting in reduced time for heat transfer and consequently diminishing the maximum temperature difference.

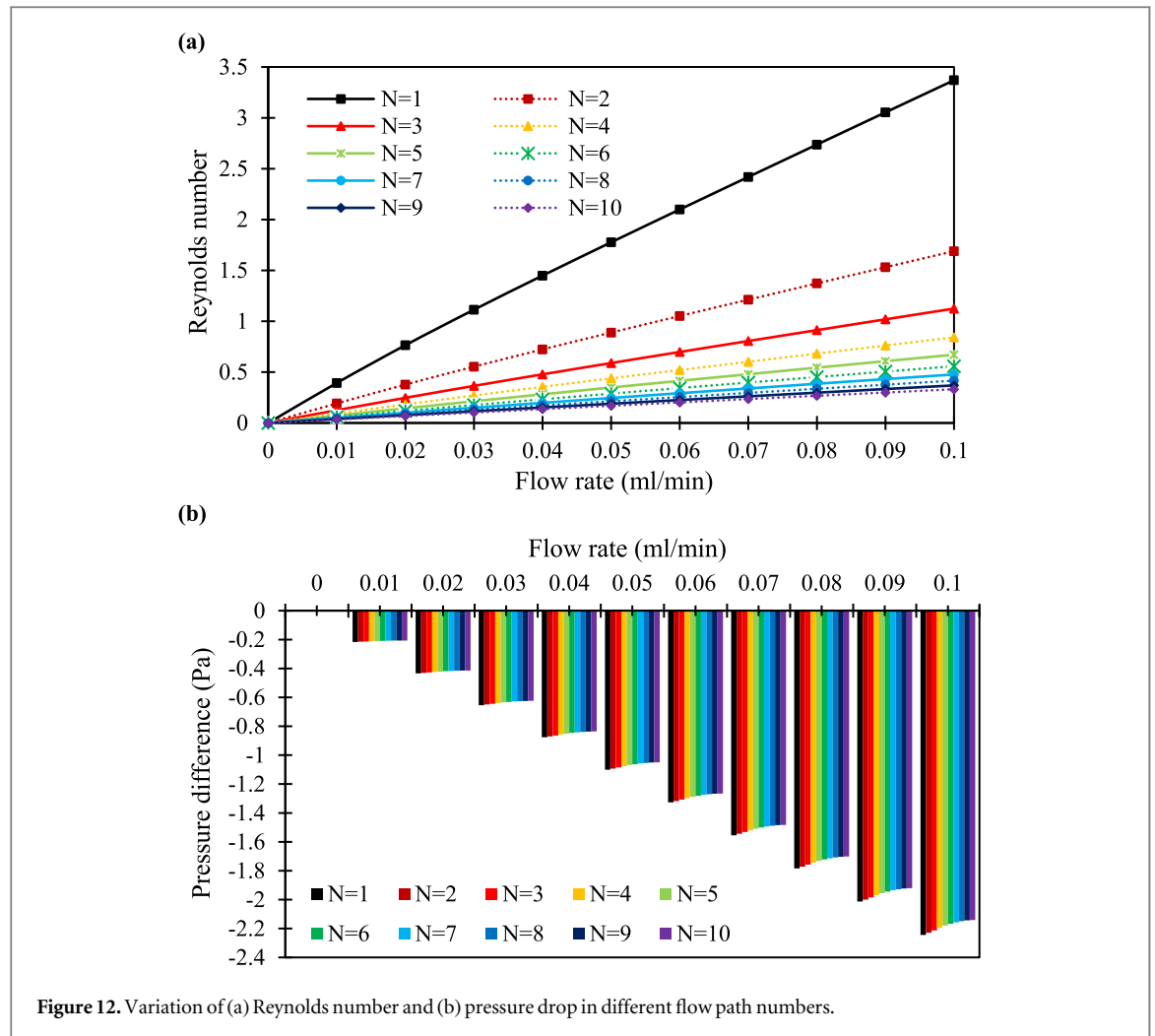
4.2.3. Effect of flow path number

Conjugated heat and momentum transfer are crucial for understanding the measurement phenomena in thermal mass flowmeters. The relationship between temperature difference and fluid velocity across various flow rate ranges is illustrated in figure 10. A vital aspect of the measurement process is the stability of the thermal power consumed; thus, the temperature difference, upstream temperature, downstream temperature, and maximum temperature exhibit a defined trend. As flow velocity increases, the temperature difference initially rises and reaches a peak before gradually declining. At low velocities, all configurations show a significant increase in temperature difference, particularly with $N = 1$ achieving the highest values, indicating that lower flow rates allow for longer interaction times with the heating source, enhancing heat transfer. However, once flow velocity exceeds approximately 0.002 m s^{-1} , the temperature difference begins to decrease for all N values. The curves reveal varying peak temperatures, with higher N values generally resulting in lower peak temperature differences. While low flow velocities facilitate efficient thermal interaction due to prolonged exposure to the



heat source, surpassing a certain threshold hampers the heat transfer rate, leading to a reduction in temperature difference. For instance, the data depicted in figure 10 reveal that at a flow rate of $\dot{V} = 0.01 \text{ ml min}^{-1}$, the temperature difference at the output of a single-channel sensor is 6.6°C , compared with approximately 4.9°C for a 2-channel arrangement. This demonstrates the profound impact of flow channel configuration on measurement accuracy. The trend depicted in figure 10, allows for determining of flow rate based on the observed linearity of temperature difference.

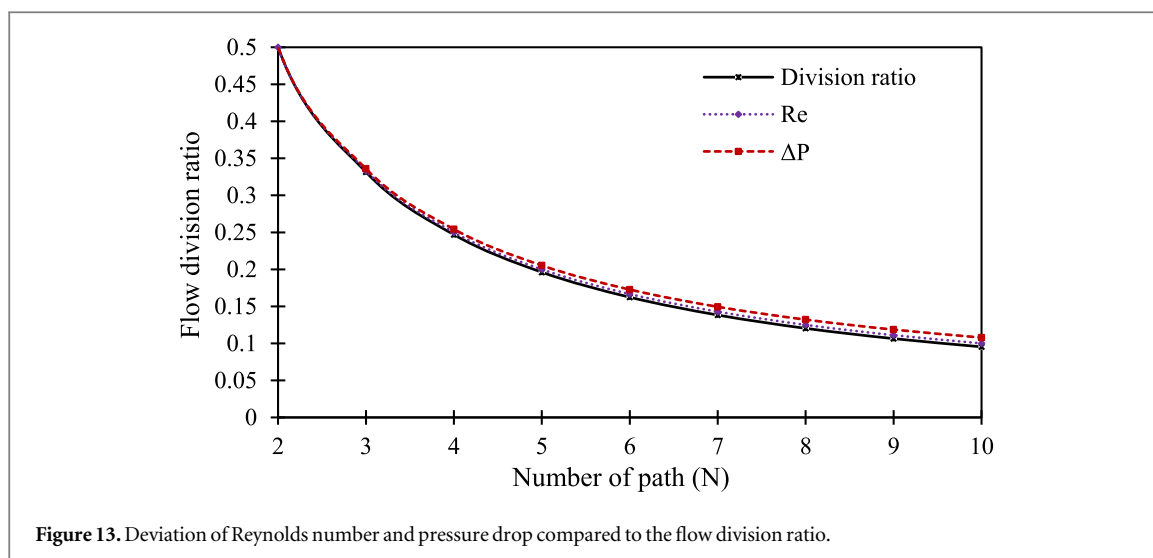
As previously mentioned, with constant power consumption, the temperature change curve about increasing flow rates initially rises before declining. The linearity of this temperature difference curve is maintained at higher flow rates as the number of flow paths increases, delaying the point at which the curve turns. The linear region before this turnover point, which serves as a criterion for defining the flow range, varies with the number of flow paths. For instance, at a flow rate of 0.08 ml min^{-1} , the temperature difference curve has passed the turnover point for up to 6 flow paths, showing a downward trend. In contrast, for more than 7 paths, it has not yet reached the turnover point and continues to show an upward trend. Thus, it can be concluded that utilizing more than 6 channels is advisable for the flow rate of 0.08 ml min^{-1} . The turnover flow velocity point, which defines the linearity range in the measurement process, is roughly 1 mm s^{-1} for various flow paths, as depicted in figure 11. Consequently, based on the geometric characteristics of this study, the flow velocity in the measuring channel should remain below 1 mm s^{-1} to ensure measurement accuracy and uphold linearity. In other words, the more time it takes for the fluid velocity in the measuring channel to reach 1 mm s^{-1} , the greater the measurement range becomes.



4.2.4. Reynolds number and pressure difference

The Reynolds number is a crucial factor in conjugated heat and momentum transfer, mainly due to its substantial influence on laminar and microscale flow. For enhanced design safety, it is essential to maintain the Reynolds number below 10 in microscale scenarios. The friction factor and Poiseuille number are closely tied to the Reynolds number and must be considered in the design and fabrication of flowmeters. The friction factor is influenced by the flow regime and surface geometry, which become increasingly significant at the microscale. The friction factor is influenced by the pressure drop, which serves as a critical driving force in fluid flow. The relationship between the number of paths and the pressure drop indicates that the pressure drop in each microchannel rises with increasing flow rate. Conversely, at a certain flow rate, the pressure drop decreases as the number of paths increases. The friction factor is also affected by pressure and surface roughness, impacting wall stress. Therefore, it is essential to consider pressure drop as a significant factor affecting the friction factor in the design and fabrication of the μ CTMF. Figure 12 illustrates the variations in the Reynolds number and pressure drop within the designed system, confirming alignment with the initial assumptions.

Figure 12(a) illustrates the relationship between flow rate (ml min^{-1}) and Reynolds number for different configurations of parallel flow channels (N ranging from 1 to 10). As the flow rate increases, the Reynolds number also rises, indicating an increase in fluid velocity and turbulent flow characteristics. Notably, for a given flow rate, systems with fewer channels (lower N values) demonstrate significantly higher Reynolds numbers compared to those with more channels. For example, at a flow rate of 0.1 ml min^{-1} , the Reynolds number for $N = 1$ reaches approximately 3.5, while for $N = 10$, it is around 0.5, revealing a marked decrease in turbulence. This trend suggests that as the number of parallel channels increases, the flow is distributed more evenly across the system, resulting in lower overall velocities in each individual channel, which in turn lowers the Reynolds number. Consequently, this indicates that systems with more channels may operate in a laminar flow regime, leading to reduced friction losses. Understanding this relationship is critical in fluid dynamics and system design, as engineers must consider both the flow characteristics and the number of parallel pathways to optimize



performance in thermal and hydraulic systems. By effectively managing these parameters, designers can enhance flow efficiency, minimize energy losses, and tailor systems to meet specific operational requirements.

Figure 12(b) shows the relationship between flow rate (ml/min) and pressure difference (Δp) across a system with varying numbers of flow channels (N , ranging from 1 to 10). As the flow rate increases, there is a consistent decrease in pressure difference for all configurations, indicating an inverse relationship. At lower flow rates, the pressure drop is more pronounced, particularly in systems with fewer channels, such as $N = 1$ and $N = 2$. Conversely, as the number of channels increases, the pressure difference decreases, suggesting that additional channels reduce flow resistance. This trend emphasizes the significance of channel configuration in optimizing system performance, particularly demonstrating that increasing the number of pathways can effectively minimize pressure losses and enhance overall efficiency at higher flow rates.

Increasing the number of flow paths at constant flow rates divides the flow, producing a graph similar to that shown in figure 13. The Reynolds number and pressure drop observed in this design exhibit a similar trend with reasonable accuracy. However, figure 13 indicates that for an exact multi-range flow meter, the fluid flow ratio related to the number of flow paths is not uniform, and this slight variation should be considered in the design to enhance measurement accuracy. Given the significant impact of geometry at the microscale, the resulting deviation can be adjusted according to specific design requirements. Factors such as the placement of inlets and outlets, dimensions of the distributor, and selection of the measuring channel are among the geometric parameters that influence the output. As the number of paths increases, the flow division ratio decreases, indicating a more uniform distribution of fluid across the channels. This trend suggests that adding more pathways allows the system to manage flow distribution more efficiently, resulting in a lower division ratio per channel. Additionally, the Reynolds number decreases with an increasing number of channels, signaling a transition toward laminar flow, which reduces turbulence and promotes stable flow characteristics. Concurrently, the pressure drop diminishes as the number of channels increases, reflecting reduced resistance to flow and minimizing energy losses during fluid movement. This integrated understanding highlights the significance of optimizing the number of parallel paths in fluid system design. By improving flow distribution and reducing pressure drops, engineers can enhance the efficiency and performance of thermal and hydraulic systems.

4.3. Multi-range criteria

Selecting the optimal number of flow paths for a measurement range is crucial for maximizing device performance, as illustrated by the multi-range criteria in the provided figure 14. Key parameters, such as the coefficient of determination (R^2) set at a hypothetical value of 0.99 and the curve slope (CS), play a vital role in assessing the relationship between flow rate and device response. A steeper slope in the line graph signifies a broader range of temperature differences, which helps to reduce measurement errors while maintaining a consistent R^2 value; this ultimately enhances both accuracy and precision. When the number of flow channels is adjusted, the relevant linear calibration coefficient corresponding to the number of channels can be considered — manually or through automated means like a microprocessor — to give the flow rate effectively. The data indicates that the designed microchip achieves remarkable R^2 values across various flow ranges; for instance, in the 10-path configuration, the fluid flow exhibits R^2 values of 0.99 for the 0–0.08 ml min⁻¹ range and 0.98 for the 0–0.1 ml min⁻¹ range, respectively. These high R^2 values reflect strong linearity, demonstrating that the

Flowrate	N=1		N=2		N=3		N=4		N=5		N=6		N=7		N=8		N=9		N=10	
	CS	R ²	CS	R ²	CS	R ²	CS	R ²	CS	R ²	CS	R ²	CS	R ²	CS	R ²	CS	R ²	CS	R ²
0 – 10 $\mu\text{l}/\text{min}$	660.8	0.999	492.4	0.999	373.1	0.999	302.2	0.999	252.2	0.999	213.1	0.999	189.1	0.999	165.4	0.999	149.6	0.999	132.5	0.999
0 – 20 $\mu\text{l}/\text{min}$	471.6	0.961	405.5	0.989	329.7	0.995	276.2	0.998	235.4	0.998	202.9	0.999	180.9	0.999	160.5	0.999	145.9	0.999	131.2	0.999
0 – 30 $\mu\text{l}/\text{min}$	341.1	0.905	327.4	0.964	284.3	0.984	247.6	0.992	216.6	0.995	190.5	0.997	170.7	0.998	154.1	0.999	140.9	0.999	128.1	0.999
0 – 40 $\mu\text{l}/\text{min}$	257.7	0.845	265.2	0.931	24.3	0.966	219.8	0.981	198.4	0.989	176.9	0.993	161.5	0.996	146.6	0.997	135.2	0.998	123.9	0.998
0 – 50 $\mu\text{l}/\text{min}$	199.7	0.789	217.4	0.894	208.5	0.944	194.6	0.968	178.9	0.981	163.4	0.988	151.1	0.991	138.6	0.994	128.8	0.996	119.0	0.997
0 – 60 $\mu\text{l}/\text{min}$	158.9	0.737	180.6	0.856	179.7	0.919	172.4	0.951	161.9	0.969	150.4	0.980	140.7	0.986	130.5	0.990	122.3	0.993	113.8	0.995
0 – 70 $\mu\text{l}/\text{min}$	129.3	0.691	152.0	0.820	156.0	0.894	153.2	0.934	146.6	0.957	138.2	0.971	130.8	0.979	122.6	0.985	115.7	0.989	108.5	0.992
0 – 80 $\mu\text{l}/\text{min}$	107.2	0.650	129.6	0.786	136.4	0.867	136.7	0.915	132.9	0.943	127.1	0.961	121.6	0.971	114.9	0.979	109.3	0.984	103.2	0.988
0 – 90 $\mu\text{l}/\text{min}$	90.31	0.613	111.7	0.753	120.2	0.843	122.6	0.896	120.9	0.928	117.0	0.945	113.0	0.962	107.7	0.972	103.1	0.979	97.96	0.984
0 – 100 $\mu\text{l}/\text{min}$	77.11	0.579	97.20	0.723	106.6	0.819	110.4	0.877	110.3	0.913	107.9	0.937	105.1	0.953	100.9	0.964	97.29	0.972	92.95	0.979
Note:	Minimum Value of R ²						Considered Hypothetical R ²						Suitable Paths							

Figure 14. The number of suitable flow paths in the range of different flow rates.

device performs reliably across different flow rates, which is essential for applications requiring precise measurements. Therefore, thoughtful consideration of these parameters ensures that the selection of flow paths aligns with the intended measurement ranges and supports the overall design and simulation accuracy of the device. By systematically analyzing these factors, engineers can optimize the microchip's performance, thereby enhancing its effectiveness across a variety of applications. This comprehensive approach not only contributes to improved measurement fidelity but also strengthens the device's adaptability to diverse operational contexts.

5. Conclusion

This research concentrates on the design and simulation of a multi-range μCTMF , carefully considering key factors relevant to microfluidic systems across a wide range of liquid flow rates. The initial phase of the study investigates the phenomena and conditions that affect measurement geometry at the microscale, which is crucial for understanding how flow dynamics influence accuracy. By examining guidelines for selecting optimal measurement ranges tailored to specific applications, the research provides a framework for practical implementation. Furthermore, comprehensive design solutions are proposed, emphasizing fundamental principles such as linearity, which ensures a proportional response to flow changes; cavitation management, which mitigates errors caused by vapor formation; and the deployment of a mobile distributor within a multi-path system, enhancing adaptability. These principles are identified as vital for achieving operational accuracy and precision. The designed flow meter functioning at full capacity, covers a range of $0\text{--}80\text{ }\mu\text{l min}^{-1}$ demonstrating a linearity of 0.99. In all results, it was emphasized that the temperature difference should not exceed $20\text{--}30\text{ }^{\circ}\text{C}$ and must remain below the boiling point or surface vapor to prevent cavitation, thereby ensuring that accuracy and precision are not compromised. Ultimately, the findings present a compelling case for developing a multi-range μCTMF , underscoring its potential to significantly improve measurement reliability and versatility across diverse microfluidic applications.

Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

Authors' contribution

H Hosseinzadeh Chaboki: Investigation, Methodology, Software, Data Curation, Visualization, Writing-Original Draft **J Rahbar Shahrouzi:** Conceptualization, Methodology, Formal analysis, Supervision, Writing - Review & Editing **N Jodeiri:** Supervision, Writing - Review & Editing.

Conflict of interest statement

The authors declare no conflicts of interest.

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