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ABSTRACT

This research addresses a critical issue in modern microelectronics, which arises from increased miniaturization and heat generation, necessitating effective temperature control. The study focuses on pulsatile heat pipes, offering a passive and highly efficient heat transfer solution by utilizing fluid and vapor phases within a closed capillary channel. To enhance temperature regulation, microfluidics are employed with integrated separation barriers to improve capacity and efficiency. Altering the flow pattern of liquid and vapor plugs through droplet generation may enhance thermal performance. The study demonstrates the accuracy of the heat transport model through mathematical and empirical data comparison, achieving a remarkable 90.9% accuracy and efficiency. Pulsatile flows, especially in microfluidic systems, exhibit advantages over steady flows, promising avenues for future physics-based research.

I. AN OVERVIEW

Research into innovative technologies that can disperse more power in less space while meeting high-reliability criteria is being driven by the ongoing need for innovative heat transfer techniques to enable miniaturization and power density in electronics.[1] The pulsatile heat pipe (PHP) is a relatively recent addition to the heat pipe family; the original patent was submitted around 30 years ago.[2] For future ground and space applications, PHPs may constitute an alternative to cooling systems due to their ease of construction, capacity to dissipate heat even in microgravity, and compact size.[3] There has been growing interest in droplet microfluidics among researchers and industry professionals over the past two decades, and this has resulted in the publication of several publications detailing both theoretical developments and practical applications.[4]

Miniaturization of electronic components during the past few years has generated increased heat flux.[5] This element, along with strict criteria for aeronautics, transportation, and energy applications, has resulted in difficult problems in thermal management.[6] One of the most exciting developments in cooling technology, for electronic devices, the pulsing heat pipe is an extremely effective passive heat transfer mechanism.[7] As power density in high-performance electronic devices and small-size portable devices grows, thermal properties have become a barrier to further reduction of rising circuit boards, creating an urgent demand for thermal management.[8]

The reduction of mass is one of the current technological design difficulties of many products.[9] To lessen their impact on the environment, this is necessary.[10] Due to the weight savings afforded by synthetic materials, they are increasingly being used in place of metals.[11] Nevertheless, these materials are poor heat conductors, necessitating novel thermal management systems for cooling electronic components.[12] Conditions such as temperature fluxes of several hundreds of W/cm^2, long-term dependability, and very cheap prices for commercial market items are all issues with traditional cooling systems that have arisen as a result of device miniaturization.[13] Because of this, we urgently need cutting-edge new methods of cooling. Heat pipes, specialized devices designed to transport surplus heat to a cooler location, are gaining in popularity.[14]

Microfluidic systems and pulsing heat pipes are two applications of these techniques. Explore fluid dynamics as well, explaining the differences between laminar and turbulent flows and how Reynolds and Capillary numbers play a role. Highlight the significance of phase change phenomena, especially evaporation and condensation, to heat transmission in closed systems. There should be definitions of terms as they are introduced, visual aids for complicated ideas, and comparisons to established standards in the presentation. It is important to highlight the lack of explicit material qualities, experimental dimensions, and a technique when discussing the presentation's flaws. The scientific credibility and readability of the article will be improved by revitalizing these elements. The designers are forced to use synthetic materials that are lighter than metals but have poor heat conductors, necessitating novel approaches to cooling the electronics inside.[15] When compared to other heat pipe designs, PHPs have superior efficiency because of this occurrence.[16]

This research addresses a critical issue in modern microelectronics—maintaining acceptable operating temperatures efficiently while minimizing heat generation. It focuses on enhancing heat transfer through pulsatile heat pipes (PHPs), a passive and highly efficient solution. The study introduces a novel PHP setup called "temperature regulation in pulsed heat pipes with microfluidics (TRPHP-MF)," which improves separation and efficiency by incorporating separation barriers into the channel. The research validates the heat transport model through simulations and real-world data, showing that TRPHP-MF's performance is enhanced by modifying the flow pattern with droplet production. This work emphasizes the importance of physics-based inquiry and cautions against relying solely on empirical correlations in dynamic systems like PHPs. By proposing a practical method to integrate microfluidics into PHPs, this research surpasses previous studies, offering a realistic design improvement with separating barriers. Beyond advancing passive heat transfer solutions, this discovery has the potential to enhance heat transmission in microfluidic systems. It underscores the need for further comprehensive investigations to fully harness PHP-based thermal control solutions.

The main significant contributions to this paper are as follows:

1. For better separation and performance, we developed a novel PHP called temperature regulation in a pulsating heat pipe using microfluidics (TRPHP-MF) that uses dividing barriers built into the channel itself.
2. A change in the flow pattern of the liquid and vapor plugs may lead to enhanced thermal performance in the heat pipe.
3. The heat transport model is validated by a comparison of theoretical and experimental results, which demonstrates its efficacy in enhancing separation while reducing energy use.

The paper is laid out as shown. Section II provides context for the temperature control in a pulsating heat pipe using microfluidics (TRPHP-MF) system. In Sec. III, we develop and analyze the proposed procedure. The simulation analysis and the study's conclusions are illustrated in Sec. IV. Section V presents the study's findings and conclusion.

II. LITERATURE SURVEY

Droplet generation is typically the first and most crucial stage, with results that are steady and predictable.[17] Methods like biochemical testing, click chemistry, and DNA polymerase chain reaction are just a few examples of the many applications that necessitate a tightly regulated droplet formation (DF) process for reliable outcomes.[18]

Cui *et al.*[19] proposed a novel approach to droplet formation in microfluidic systems (DF-MF) with integrated microwave heating. Microwave heating causes an inertial pressure at the contact Laplace, allowing droplet production on demand. Scientists have shown that the power of microwave stimulation and the length between the contact and the junction play a role in droplet formation. Applications needing dynamic tuning of material properties in droplets can benefit greatly from the method's incorporation with microwave detection, which can be used as feedback to govern the supply flow of materials, despite the method's limitations in creating droplets at a high rate.

To select the best polymeric materials for creating flexible pulsing heat pipes, the multi-criteria decision-making (MCDM) model developed by Ordu and Der[20] is presented. Since there are so many different competing materials on the market today, each with its own unique set of qualities, applications, benefits, and downsides, making a decision on which polymeric material to employ requires weighing several factors. Findings from this research lend credence to prioritizing material choices with MCDM methods to improve the selection process. Both business executives and researchers in the academic world who are responsible for choosing polymeric materials would benefit immensely from this study.

According to the review of relevant works, microfluidics-related studies have included temperature measurements. However, they fall short in terms of precision and efficiency at higher levels. Therefore, a more effective system is developed to account for and measure temperatures in microfluidics to facilitate drug injection.

III. TEMPERATURE REGULATION IN A PULSATING HEAT PIPE USING MICROFLUIDICS (TRPHP-MF)

One intriguing alternative to traditional heat pipes is the pulsatile heat pipe (PHP; sometimes named oscillating heat pipe by some writers), which was designed in the early 1990s. A simple capillary tube describes PHP. Figure 1 illustrates this, where the bubbles are regions of vapor that are separated by liquid plugs due to capillarity. When the evaporator and condenser surface temperature is large enough, the bubbles and plugs will migrate back and forth on their own, penetrating both the cooled and heated sections of the tubes (evaporator). Liquid plugs in PHP's evaporator and condenser facilitate convective heat transmission, which works in tandem with latent heat transfer.

The aerospace, transportation, and energy industries demand compact, lightweight, and energy-efficient systems, posing challenges in heat management. Pulsatile heat pipe (PHPs) have emerged as a solution for passive heat transfer in electronic equipment. PHPs harness temperature-induced phase shifts, capillary forces, and liquid motion. They consist of a primary tube with branches, guiding a saturated liquid/vapor mixture through surface tension-induced liquid slugs and vapor plugs. Flow disturbances in condensation and evaporation zones affect thermal gradient transfer.

To create a U-turn on a copper plate using the PHP technique, a square channel is engraved in a copper plate. Figure 1 should provide a comprehensive inventory of system components alongside their roles, enhancing understanding. PHPs excel due to their efficiency and larger dry-out limits compared to other heat pipe designs. They are

FIG. 1. Creating U-turns on a copper plate via a machine-engraved square channel of the PHP.

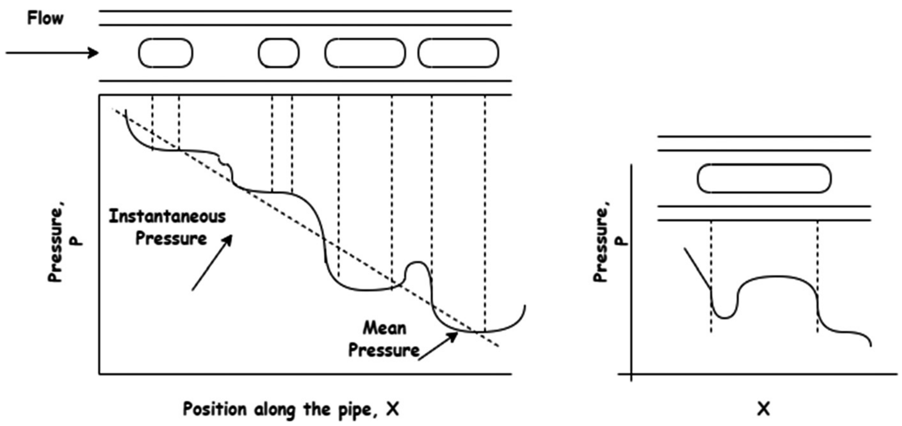

FIG. 2. Reduced pressure.

cost-effective and reliable, with three primary setups. The iterative PHP in Fig. 1 is considered highly effective. This paper focuses on flat plate pulsating heat pipes (FPPHP), featuring a single rectangular or square channel for heat transfer. FPPHP's microtubule heat transfer fluid mode excels in reducing heat gradients, even with modest heat inputs and vertical operation. Figure 2 is commonly used in technical and scientific writing to graphically depict data, concepts, processes, or relationships. Figure 2: reduced pressure in microfluidic systems with a pulsating heat pipe, shows how the implementation of a pulsating heat pipe reduces the pressure within a microfluidic system. This diagram may show how a pulsing heat pipe's heat transfer processes might cause alterations in the microfluidic environment's pressure dynamics, which in turn may affect the behavior of fluids or particles.

Slug flow, a key factor causing phase oscillations in horizontal slug movement, is mitigated by pressure equalization in the channels. Optimal heat sources possess flat surfaces and high surface-to-volume ratios, ensuring efficient thermal contact. However, designing such systems is more intricate than tubular pulsating heat pipes, often requiring complex or costly production methods. While the physical principles governing pulsating heat pipes are well-understood, modeling them is challenging due to process complexity and intensive heat and mass transfer regions. This section aims to elucidate the fundamental phenomena driving heat and mass movement in PHPs, aiding comprehension for subsequent analyses. Slug flow, involving liquid slugs and vapor plugs in capillary channels, is the widely accepted flow pattern in pulsating heat pipes.

Heat and mass transport through liquid films constitute a significant fraction of both processes as it does in other types of heat pipes. For this reason, liquid films must be accurately modeled. Passive heat exchange via the films was formerly assumed to be much weaker, recent simulations using actual film data have revealed otherwise. Further localized calculations and measurement models verified these results. Considering that PHP's oscillation dynamics are governed by mass transfer, this problem takes on utmost significance there.

A. PHP implementation of liquid film dynamics

Oscillations are produced by the principal flow regime inside the PHP, which is analogous to secondary flow in convective boiling. As an alternative, we employ the "bubble" and "plug" terminology of the earliest PHP documentation. It is known as "squeezed bubble flow" or "Taylor bubble flow" and is a common term in hydrodynamics (and more specifically microfluidics). When the gravitational forces that tend to form different layers of fluid moving past one another in horizontal channel segments are outweighed by the capillary forces, a pulsating flow pattern results (Figs. 3 and 4). As a result of this situation, there is a well-known lower bound on the width of the channels themselves

$$c < c_{dr} = 2 * \sqrt{\left(\frac{\varnothing}{f\,(\partial_1 - \partial_v)}\right)}. \tag{1}$$

In Eq. (1), this need is required but not sufficient for PHP oscillation to work. Since the liquid plugs are moving so quickly, their

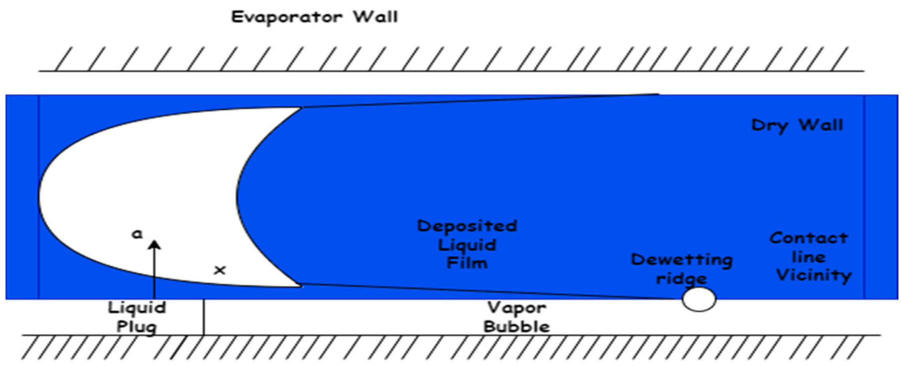

FIG. 3. PHP evaporator liquid film form.

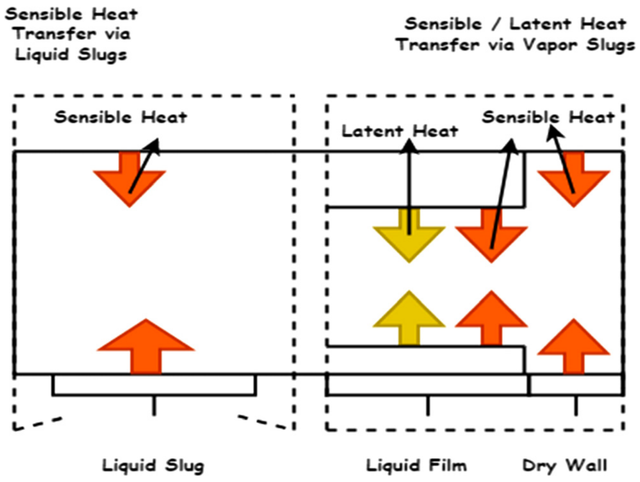

FIG. 4. Correlating heat exchange between zones.

menisci can be torn apart by inertial forces, because of this, PHPs with only one turn (called a single loop) exhibit annular flow in the gravity-assisted domain. This is comparable to the thermosyphon operation

$$\mathrm{FT} = -\beta d\theta L * \frac{\partial u}{\partial q} = 2\theta\mu L\rho C(W o), \tag{2}$$

$$C(W o) = W o * \sqrt{i}\left(\frac{T_o\left(W o\sqrt{i}\right)}{T_1\left(W o\sqrt{i}\right)} - \frac{2}{W o\sqrt{i}}\right)^{-1}$$
$$= 4 + \frac{i}{6} W o^2 + \epsilon\left(W o^4\right). \tag{3}$$

Equations (2) and (3) represent the fluid's axial velocity and the small-eddy approximation $W o$.

Modeling the transmission of momentum and energy inside PHPs requires an accurate assessment of the vapor's thermodynamic condition, which adds another level of complexity. This analysis depends partially on the efforts of an individual who conducted an extensive and comprehensive investigation into modeling approaches for the vapor thermal phase, with a particular focus on the spring responsible for oscillations, by compiling existing literature on PHPs,

$$\mathrm{FT} = 8\,\pi\mu L V + \frac{mV}{3}, \tag{4}$$

$$\Delta \mathrm{p} = \frac{16 * \rho V^2}{D_e * r} L + 5.45 * D_e^{\frac{1}{3}} * C * a^{\frac{2}{3}} * \frac{\varnothing}{d}. \tag{5}$$

In Eqs. (4) and (5), let liquid plug length be L, the numerical coefficient, D_e provides the best approximation to numerical and experimental data related to air bubbles in various liquid mediums. PHP flows typically go below this threshold, allowing just the laminar scenario to be considered. The Richardson annular effect describes the situation in which the velocity is greatest at a distance of C from the wall.

Other authors, however, showed that vapor can be superheated by measuring the fluid temperature at different micro-FPPHP locations, and they highlighted, with long enough vapor plugs, both an overheated region in the exchanger zone and a concentrated thermal region inside the adiabatic zone within a single bubble. As a result, a vapor plug's temperature can fluctuate widely, and small superheated regions can form. Furthermore, they have conducted microgravity testing of their hybrid thermosiphon/tubular PHP

$$\mathrm{F} = C * \varnothing * r * \beta_1 * V^2 * L, \tag{6}$$

$$C = \begin{cases} \dfrac{16}{D_e} & 0 < D_e < 1180. \\ 0.07945 * {D_e}^{0.25} & \end{cases} \tag{7}$$

Consideration of global turbulence's effect is now possible using D_e

$$\frac{d}{dt}(mV) = (p - p_{nxt})S - F - F_{turn} + G, \tag{8}$$

where G is the gravity force. The pressure $p - p_{nxt}$ corresponds to the end of the plug

$$F_{turn} = 0.105 * S * p * V^2 * A_{turn}(\varnothing). \tag{9}$$

$A_{turn}(\varnothing)$ is the nonlinear in Eq. (9).

From Eqs. (6)–(9), it is important to remember that the liquid temperature has no bearing on the vapor bubbles state or the PHP dynamics as a whole when there are enforced values in both the evaporator and condenser sections. When a thermal fluid–solid connection is introduced, both the fluid dynamics and the thermal transfer between both the liquid and the solid must be addressed at each time step. This compounds the difficulty of the situation

$$\frac{\partial T}{\partial t} = D_w * \frac{\partial^2 T}{\partial t^2} + \frac{j}{\partial C}. \tag{10}$$

Equation (10) describes the temperature profile along the inner tube wall.

They demonstrated that with a certain amount of heat input, the subcooling level would increase in the condenser and decrease in the evaporator, revealing a predominant superheating pattern in both regions. The authors claim that at temperatures above saturation, the fluid is a supercooled liquid, whereas at temperatures below saturation, it is a subcooled vapor. When calculating the net energy gain or loss of a pulsing heat pipe, when describing the thermodynamic state of a fluid at a saturated equilibrium, it is important to take into account the transmission of sensible heat (or latent heat in the metastable condition)

$$\Delta \mathrm{pd} = \Delta \mathrm{pd}_0 - \frac{\partial \varnothing}{\partial t} * \mathrm{pd} - e^{i\varnothing t^{-1}}. \tag{11}$$

From Eq. (11), the mathematical expression for flow in a microchannel that is being propelled by a pulsatile differential pressure is pd, where pd_0 is the pressure at zero time, Δpd is the amplitude of the pressure fluctuation, φ is the frequency of the pressure changes, and t is the time elapsed.

When a lump of liquid moves through a capillary tube, divided by two (advancing and retreating) menisci, a slug flow pattern is formed when liquid forms a thin coating on the wall around vapor bubbles. The liquid film appears to be the outcome of a competition between viscosity and capillary forces at a transition region adjacent to the liquid meniscus. The meniscus's thickness is affected by both viscous friction and surface tension forces; the former tends to keep the fluid stationary close to the wall, while the latter reduces the meniscus's size. The capillary count is used to depict this rivalry.

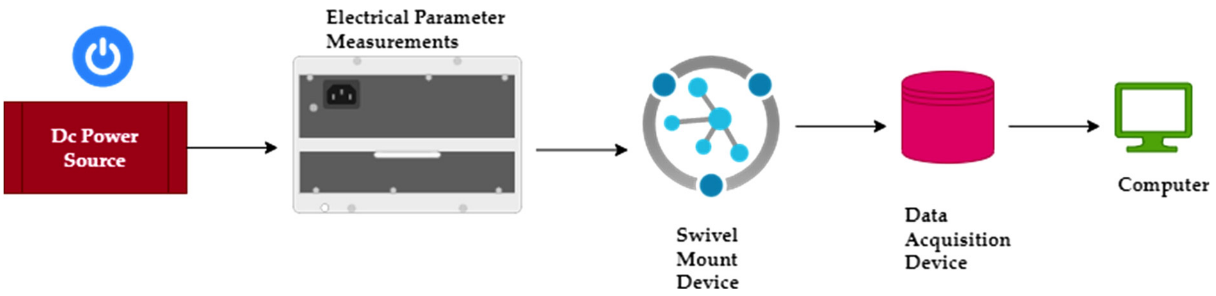

FIG. 5. Schematic diagram.

However, it was repeatedly established in the earliest studies of PHP that this study demonstrates that sensible heat of liquid bodies moving in both the warm and cool PHP sections accounts for a considerable amount of the heat exchanged and that vapor evaporation/condensation mostly leads to slug/plug flow motion as a controller for PHP oscillations. Heat exchanges in pulsating heat pipes (in which it appears that latent heat transfers in both the evaporator and the condenser account for 55%–80% of the total heat transfer) have recently been experimentally proved to be dominated by latent heat.

B. Droplet generation

Over the past two decades, many papers have reported on both basic and applied research in droplet microfluidics, and some businesses, such as Dolomite Bio, have caught up with the progress made in this area. Because the carrier fluid separates each droplet from the others and the channel walls, chemical or biological processes can be carried out within the confines of the droplets, which can serve as microreactors by enclosing cells, particles, or molecules (DNA, proteins). The formation of droplets is dominated by the conflict between interfacial tension and viscous forces at low flow rates (shear force is insignificant), making interfacial tension management, along with flow and geometric condition control, one of the most effective techniques to generate droplets on demand. The interfacial tension between two fluid phases can be adjusted by changing the temperature or by adding surfactants to one or both phases.

Figure 5 shows the schematic diagram. A flat-plate Oscillating Heat Pipe (OHP)'s thermal performance differs between its left and right sides due to inefficient heating. Therefore, the exchanger difference in temperature, heat capacity, and non-homogeneous heat transfer ratio are embraced and determined by calculating from the quasi-steady temperature data to assess the thermal efficiency of the left half, the right half, and the entire flat-plate OHP subjected to non-uniform heating. Thermal resistance was used to determine the temperature gap between the left and right portions of the evaporator.

The initial and critical stage in many applications, such as biochemical screening, click chemistry, and DNA polymerase chain reaction, is the precise and reliable creation of droplets. Passive droplet generation at kHz rates in microchannel networks can be achieved by adjusting pressures and channel geometries, but ensuring precise individual droplet control remains challenging due to design errors, manufacturing defects, and pressure fluctuations. Thermal mediation with embedded heaters simplifies droplet or bubble formation. Microwave heating aids droplet mixing and nanoparticle formation, exploiting the dielectric properties of droplets to selectively apply thermal energy. This note presents a method using external microwaves and controlled heating pulses to generate droplets on demand, studying efficiency in relation to microwave power and explaining the generation mechanism. In contrast to static methods, which often lack empirical correlations, this introduces TRPHP-MF, a novel pulsatile heat pipe (PHP) incorporating microfluidics and separating barriers to enhance efficiency. By manipulating droplet formation, heat transfer in PHPs is optimized, supported by theoretical and experimental validations, emphasizing the innovative potential of this dynamic microfluidic approach. While recognizing the complexity of passive mechanisms and fluid dynamics, further research is needed to assess real-world feasibility and impact (Tables I and II).

IV. RESULTS AND DISCUSSION

The literature review briefly discusses the limitations of model-based conclusions in simulations, focusing on accuracy analysis, efficiency, volume flow rate, and thermal performance. It is crucial to note that the fluid temperature within a pulsatile heat pipe (PHP) cannot be directly equated with the wall temperature measured by thermocouples. This discrepancy arises from the wall's thermal resistance and the method used to attach exterior thermocouples, which reduce accuracy. Fluid motion can manifest in two distinct forms: steady and pulsatile flow, each with unique characteristics and systemic implications.

TABLE I. Comparison analysis of performance.

No. of datasets	Single Loop Pulsating Heat Pipe (SLPHP)	DF-MF	Thermal Fluid Blob (T-FB)	Flat-Plate (FP)-OHP	T-PHP	TRPHP-MF
10	31.01	38.33	35.14	36.56	32.76	49.22
20	35.21	39.45	41.24	20.6	43.65	50.01
30	41.36	34.15	34.19	46.99	54.11	69.1
40	20.21	29.47	43.76	62.62	71.65	52.43
50	42.56	56.33	69.33	69.34	12.98	57.34
60	33.98	47.14	36.54	41.98	47.26	68.44
70	51.54	21.89	56.39	36.41	53.61	75.65
80	67.22	65.25	65.25	59.89	57.98	86.98
90	72.36	82.66	66.15	83.57	79.1	95.09

TABLE II. Material properties and setup dimensions.

Material	Thermal conductivity (W/m K)	Density (kg/m^3)	Specific heat (J/kg K)
Material A	250	2000	800
Material B	150	1800	600
Material C	300	2200	750

Steady flow maintains a consistent speed regardless of the point or time, like water flowing steadily through a pipe. Conversely, pulsatile flow involves periodic velocity and pressure changes, resembling the rhythmic heartbeat. While pulsatile flow occurs naturally in blood vessels, it can be induced in microfluidic systems and exploring its impact on heat transfer and fluid dynamics in setups like pulsating heat pipes holds promise for enhancing system efficiency compared to steady flows.

A. Accuracy analysis

Figure 6 shows the precision test results. The *x* axis and *y* axis of this graph were used to tally up the samples and calculate the precision with which the analysis was performed. The graph presented here was used to count the samples and determine the analysis ratio of accuracy (x axis and y axis). The method may be more accurate over the long run than any other currently used approach.

B. Evaluation of thermal insulation

The process for measuring the thermal insulation analysis ratio is shown in Fig. 7. To better comprehend the relationship between the inclination angle variation (Y axis) and conductivity (X axis), a comparison is drawn between the two. Above, we saw how their similarities can be predicted. Insulating two spaces from one another with a material or method can keep the temperature differences between them and save on energy costs.

C. Examination of volume flow rate

The results of a volume flow ratio test for analyzing flow rates are shown in Fig. 8. It is possible to gain insight into both the (X axis) and the flow rate (Y axis) by comparing and contrasting them. As mentioned previously, a comparison can be drawn between the two.

D. Performance analysis

The benefits of performance evaluation are shown in Fig. 9. The y axis represents the total number of observations, while the x axis displays the various ratios produced through performance analysis. Therefore, to put each hypothesis to the test, a variety of samples were collected at varying ratios. The TRPHP-MF used in this model is a significant improvement over the state of the art.

E. Efficiency analysis

Figure 10 depicts the gains from efficiency analysis. On the x axis are the various ratios obtained through efficiency analysis, and on the y axis is the number of observations. Consequently, several samples were collected at varying percentages to test each hypothesis. This model's TRPHP-MF is a major step forward from previous methods.

Our findings show that the TRPHP-MF model is superior to its contemporaries in every one of these respects. This new feature is said to have been developed in response to the competitive pressure discussed in Sec. IV, with assistance from the proposed model.

V. CONCLUSION

The past two decades have witnessed a surge in the utilization of microfluidic devices owing to their numerous advantages, notably their compact size and versatile capabilities, making them user-friendly even for novices. Typically operating at millimeter scales, they often exhibit low-Re flows characterized by abrupt and reliable onset and cessation. Their micrometer-scale features enable precise manipulation of various particles, including red blood cells, tumors, bacteria, viruses, and micro/nanoparticles. The application of pulsating or oscillating flows in microfluidic systems holds promise in addressing multiple challenges. Coupling an intelligent building system with fluid metals could enable the use of millimeter-scale heating elements for microscale liquid temperature detection, particularly in temperature-sensitive nucleic acid amplification tests. Consequently, this method offers potential beyond microfluidics for detecting micro–macro interactions.

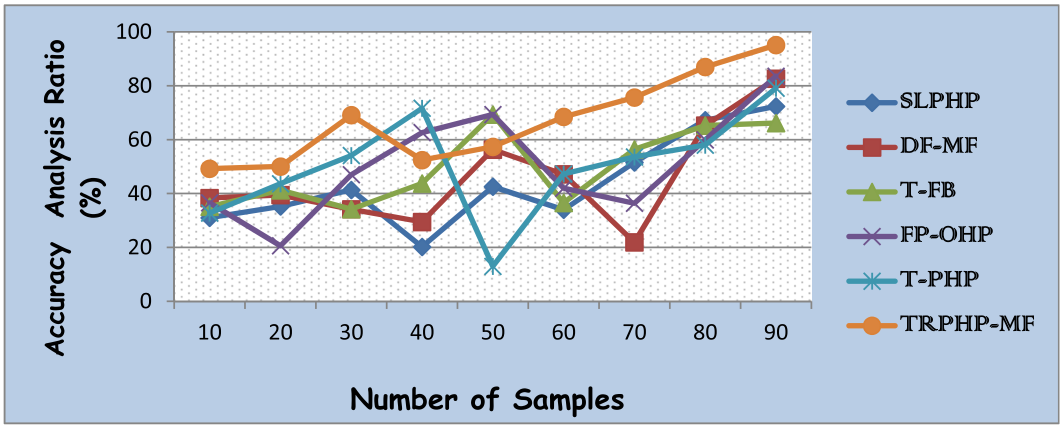

FIG. 6. Accuracy analysis.

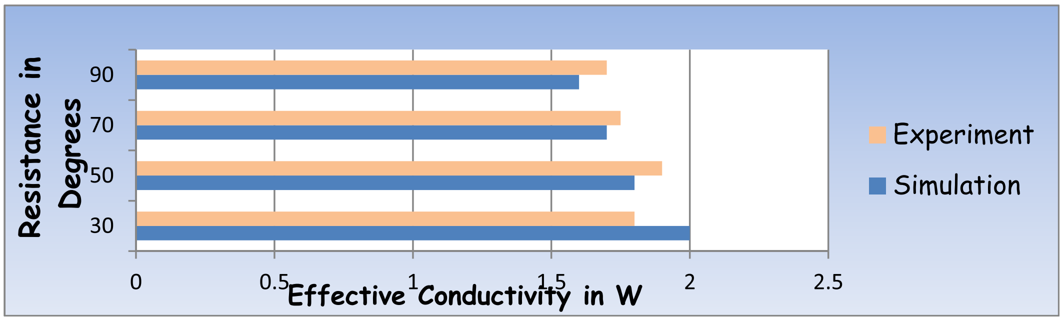

FIG. 7. Thermal insulation.

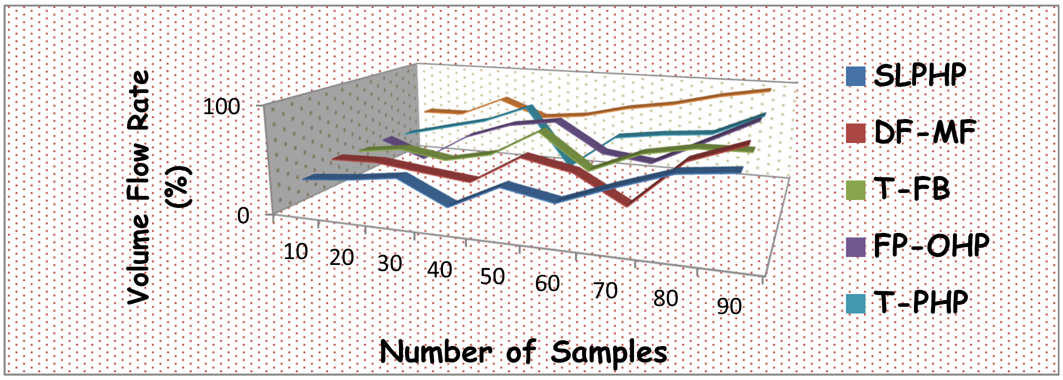

FIG. 8. Volume flow rate.

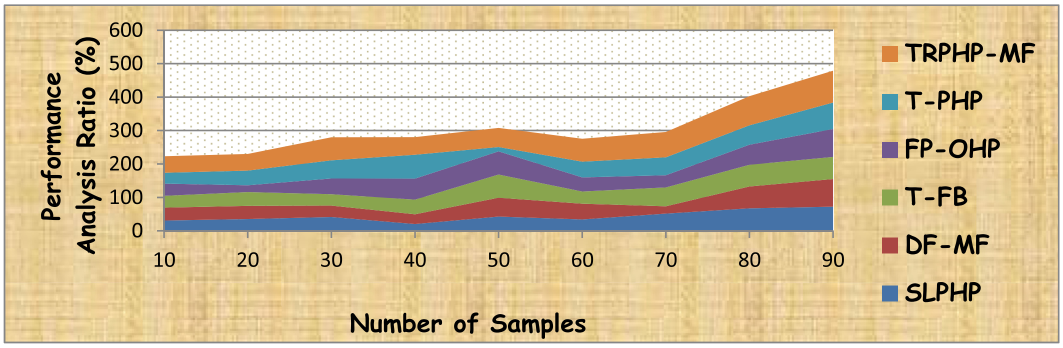

FIG. 9. Performance analysis.

Our work introduces TRPHP-MF, a microfluidic concept achieved by erecting barriers within the flow channel. Vascular waveforms exhibit minimum, maximum, and median blood flow values, with no significant differences observed between cortical and lacunar stroke patients in terms of flow and pulsatility. Heat transfer correlations demonstrate limited predictive capability for the PHP case due to its non-stationary behavior. Accurate modeling appears to rely on dynamic simulation for PHP. Tools supporting predictive simulation are crucial for developing optimized industrial prototypes. To enhance understanding of thermo-fluidic principles in rectangular-channel TRPHP-MF, this paper conducts a comprehensive analysis of theoretical and experimental investigations on thermal and flow characteristics in pulsing heat pipes made from flat plates. This approach achieves improved accuracy and efficiency, with 90.9% and 97.8% performance, respectively. Incorporating pulsatile heat pipe (PHPs) into microfluidic systems is an exciting advancement for efficient heat transfer in modern electronics. PHPs offer a solution to temperature control challenges through passive mechanisms, bolstered by the proposed

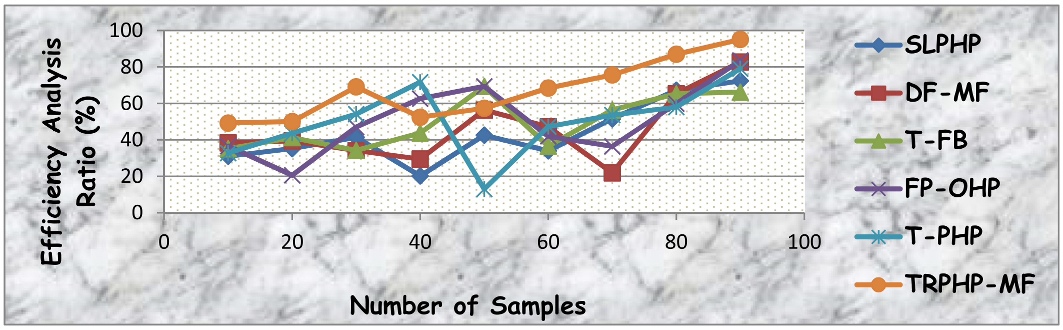

FIG. 10. Efficiency analysis.

Temperature Regulation in a pulsating heat pipe using microfluidics (TRPHP-MF).

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

G. Durga Priyadarsini: Conceptualization (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Resources (equal); Writing – original draft (equal). **Gurunath Sankad:** Conceptualization (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Supervision (lead); Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available within the article.

NOMENCLATURE

FPPHP	Flat Plate Pulsating Heat Pipe
G	Gravity force
L	Plug length
m	Plug mass
PHP	Pulsating heat pipe
p	Pressure
S	Tube cross section
T	Vapor temperature
t	Time
u	Fluid axial velocity
V	Plug velocity
W_0	Womersley number
β	Inclination angle with respect to the horizontal, radians
ρ	Density

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