

Experimental and Mathematical Study of the Capillary Effect in Microflow Inside Polypropylene Hollow Fiber Tubes

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ABSTRACT

Polypropylene (PP) capillary microtubes hold strong potential for use in advanced liquid cooling systems, but their internal flow behavior remains insufficiently understood. Critical factors—such as capillarity, flow regime, and pressure drop—directly influence their thermal performance and practical applicability. Despite their relevance, detailed studies on these parameters in PP hollow fiber microtubes are lacking. This study addresses that gap through a combined mathematical and microscopic investigation of water flow inside PP microtubes with a 0.6 mm inner diameter. Results show that capillary effects are negligible across all tested conditions, contributing only ~0.2% to ~2.7% to the total pressure drop. Moreover, capillary pressure remained largely unaffected by changes in water temperature. The extremely low Knudsen number ($\sim 4 \times 10^{-7}$) confirms continuum flow behavior, justifying the use of classical models like the Reynolds analogy. These findings deepen our understanding of flow dynamics in PP microtubes and support their integration into micro-scale thermal management systems.

Keywords: Microtubes, Microflow, Capillary flow, Polypropylene, Liquid cooling.

1. INTRODUCTION

Capillary microtube technology offers key advantages for heat transfer applications, including high surface-area-to-volume ratio, elevated Nusselt numbers, improved heat transfer coefficients, compact size, and customizable geometry. As a subclass of microchannels, capillary microtubes exhibit distinct internal flow behaviors that critically impact thermal performance. Their confined geometry and small hydraulic diameter promote laminar flow, which, when optimized, can enhance convective heat transfer through boundary layer thinning, increased surface contact, and induced flow disturbances. Understanding and controlling these dynamics is essential for maximizing thermal

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efficiency. Microchannels are widely used in micro heat sinks for electronic cooling (**Zhao et al., 2025; Mohammed and Fayyadh, 2020**), with manifold rectangular fins among the most studied geometries (**Li et al., 2025; Aljubury and Mohammed, 2019; Aljubury et al., 2017**). Recent studies increasingly explore modified internal geometries to generate flow disturbances and improve heat dissipation (**Ma et al., 2025; Cao and Wu, 2025; Liang et al., 2025**), highlighting the importance of manipulating internal flow. Emerging applications include refrigerator evaporators (**Boeng and Stahelin, 2025**) and fusion reactor cooling (**Zhou et al., 2025**), though electronics cooling remains the dominant field (**Weiqiang et al., 2025; Ahmed et al., 2022; Jehhef, 2018**). Microtubes, defined as closed microchannels with a single inlet and outlet, are used in areas like battery cooling (**Bohacek et al., 2019**), heat exchangers (**Jin et al., 2023**), vapor-compression systems (**Ali and Jasim, 2005**), and chemical processing (**Pan et al., 2025**). Despite the potential, research on capillary microtubes in broader thermal systems remains limited, with most studies focused on electronics, leaving many flow–thermal characteristics underexplored. Polypropylene (PP) is a cost-efficient thermoplastic polymer valued for its mechanical strength, resistance to water permeability, high heat distortion temperature, flame retardance and resistance to organic solvents (**Blees et al., 2000**). PP is also notably hydrophobic (**Hussain and Aljalawi, 2022**), a property that influences flow behavior inside capillary microtubes, especially at small scales. Derived from crude oil via propylene polymerization is widely used in chemical engineering sectors such as water treatment (**Waisi et al., 2019**), separation processes of medical drugs, and industrial purification (**Qiu and He, 2022**). When formed into hollow fibers, PP microtubes combine the heat transfer principles of microchannels with the material's inherent advantages. Their smooth internal surfaces reduce friction, while their low density, cost-effectiveness, and thermofluidic compatibility make them suitable for low-pressure and low-temperature heat exchanger applications (**Zarkadas and Sirkar, 2004**). Known as polymer hollow fiber heat exchangers, these systems represent the main practical application of PP microtubes. Their use in heat transfer has been widely examined (**Song et al., 2010; Qin et al., 2012; Zhao et al., 2013; Raudenský et al., 2017; Liu et al., 2018; Aa and Raudensky, 2019**). Despite PP's inherently low thermal conductivity (**Hussein et al., 2024; Thabet and Mobarak, 2016**), several traits make it competitive with metals and other plastics. It can endure high internal pressures (up to 1 MPa) at temperatures up to 80°C (**Kůdelová et al., 2022**) and offers strong chemical resistance and flexibility (**Kůdelová et al., 2022**). Although low wall conductivity has traditionally limited the use of polymeric materials in thermal systems (**T'Joel et al., 2009**), this limitation is significantly mitigated in microtubes due to their extremely thin walls, which lower overall thermal resistance (**Kůdelová et al., 2022**). The flexibility of PP microtube walls presents both opportunities and challenges. On one hand, it allows for intricate and space-saving geometries, crucial in micro-scale devices. On the other hand, it may lead to flow disruptions or blockages at sharp bends during manufacturing or operation. Thus, flow behavior must be carefully monitored in twisted paths, while in straight sections, wall flexibility enhances durability and resistance to external stress. As polymer microtubes gain traction in heat exchanger research, their promising performance has opened the door for broader adoption in heat transfer systems. PP microtubes, in particular, offer design compatibility with conventional metal exchangers in low-pressure/temperature applications (**Astrouski et al., 2020**). Nevertheless, their use in direct liquid cooling for compact systems, such as LED automotive headlight cooling (**Mráz et al., 2022**) and Lithium-ion battery thermal management (**Bohacek et al., 2019**), remains



limited. Further investigation into the fluid dynamics within capillary microtubes is essential to expand their application and fully exploit their potential in modern thermal management systems. Applying PP capillary microtubes in further thermal management applications as a liquid cooling field system requires a deep study of the liquid flow behavior inside them. The capillarity behavior, flow regime, and pressure drop characteristics are crucial factors that affect the widespread engagement of this technology in liquid cooling systems (**Lin and Wen, 2024; Standnes et al., 2024; He et al., 2024**). There is a lack of literature for such specifically focused studies. Therefore, in the present study, a mathematical analysis and microscopic examination of water flow inside PP hollow fiber microtubes were conducted to provide deep insights into capillarity behavior, flow regime, and pressure drop across such microtubes. However, this study focuses on the application of PP microtubes in cooling, where temperature and flow velocity are limited to the ranges listed in Table 3. In addition, the mathematical analysis didn't account for the curved tubing regions.

The novelty of this study lies in its focused investigation of flow behavior within polypropylene (PP) hollow fiber microtubes, a topic previously underexplored despite the growing interest in micro-scale liquid cooling technologies. Unlike past research, this work combines mathematical modeling and microscopic evaluation to quantify the role of capillarity and assess pressure drop characteristics in PP microtubes with a 0.6 mm inner diameter. The boundary conditions were defined using water as the working fluid under various temperature conditions, with particular attention to flow regime characterization.

2. CAPILLARITY BEHAVIOR

In microflow, the most important issues to be checked are the capillary behavior and the flow regime. Any micro-flow characteristics may be subjected to the capillary effects. It depends on both the microtube's material surface energy and the flowing liquid surface tension, according to Young's equation:

$$\cos \theta = \frac{\gamma_S - \gamma_{SL}}{\gamma_L} \quad (1)$$

Where: θ : is the contact angle (in degrees) of the liquid droplet inside the microtube, which is defined as the angle between the tube surface and the tangent line to the droplet surface at the point of intersection with the tube surface, **Fig. 1**; γ_S : is the tube material (or solid material) surface energy (in mN.m^{-1}); γ_L : is the flow material surface tension (in mN.m^{-1}); γ_{SL} : is the solid-liquid interfacial tension (in mN.m^{-1}).

In Eq. (1) above, the contact angle represents the theoretical indicator of the existence of the capillary flow effect inside the microtube. It represents the resultant balance of the cohesive forces between liquid molecules and the adhesive forces between liquid and solid molecules. A contact angle of less than 90° represents the adhesive forces domination and capillary rise flow availability, while a contact angle of larger than 90° represents the cohesive forces domination and an absence of capillary flow.

The surface energy and surface tension are properties of materials, while interfacial solid-liquid tension depends on these properties. The following Fowkes' equation (**Fowkes, 1964**) determines this relation:

$$\gamma_{SL} = \gamma_S + \gamma_L - 2\sqrt{\gamma_S^D - \gamma_L^D} \quad (2)$$

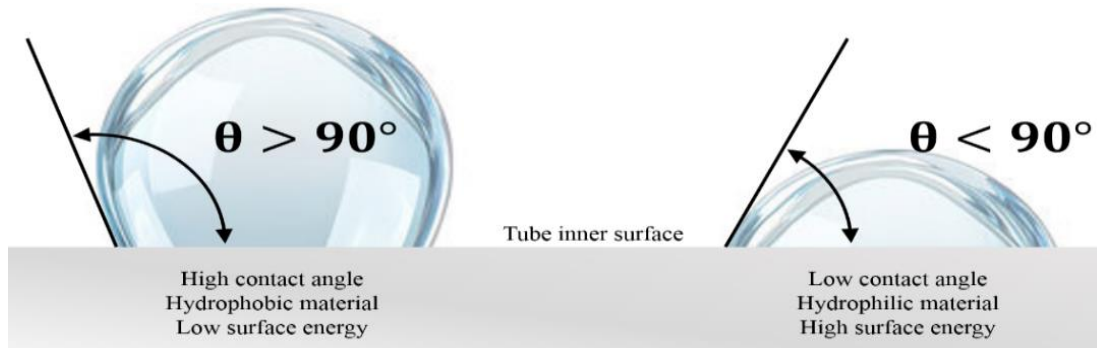


Figure 1. Contact angle between WL droplet and microtube inner surface

Where the superscript D refers to the dispersive (Van der Waals) components of solid surface energy and liquid surface tension. Other components are included in several extended versions of the Fowkes equation, such as polar and hydrogen bond components. However, these components are negligible for PP because it consists of repeating $-\text{CH}_2-\text{CH}(\text{CH}_3)-$ pure hydrocarbon units without polar functional groups that could participate in hydrogen bonding (Van Oss, 1994). Generally, polymers are non-polar materials that have a low affinity for water. Polypropylene fiber is a hydrophobic material with a surface energy of $\sim 30 \text{ mN.m}^{-1}$ (Seraji and Bajgholi, 2022). However, ordinary water has high surface tension ($\sim 72 \text{ mN.m}^{-1}$) (Fleury and Mathieu, 1963; Gianino, 2006; Goldberg et al., 2007) that varies slightly with temperature Fig. 2. The dispersive surface tension component of water is $\sim 30\%$ of the total surface tension (Jordanov and Mangovska, 2009).

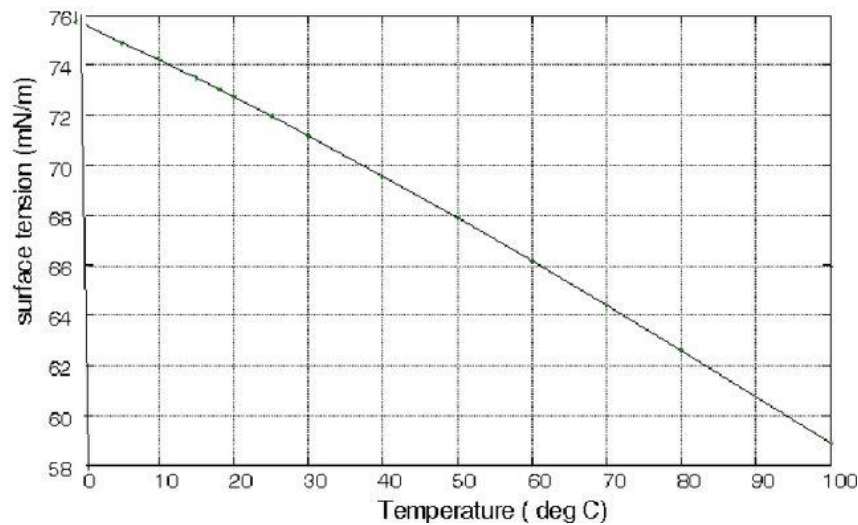


Figure 2. Surface tension of water vs. temperature (Goldberg et al., 2007)

To calculate the effect of capillarity behavior of the PP microtube, the pressure drop due to surface tension is considered to be compared with the applied forced flow pumping pressure. According to the Young-Laplace equation (Sigveland and Skjæveland, 2021):

$$\Delta P_Y = \gamma_L \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \quad (3)$$



Where: ΔP_Y : is the pressure drop due to surface tension (in Pa); R_1 and R_2 : curvature principle radii (in m). For a long cylindrical tube, R_1 equals r , and $R_2 \rightarrow \infty$ (due to the large difference in dimensions). Therefore, Eq. (3) becomes:

$$\Delta P_Y = \frac{\gamma_L}{r} \quad (4)$$

For hydrophobic microtubes, such as PP, the contact angle θ , plays a role in the pressure drop. Therefore, Eq. (4) becomes:

$$\Delta P_Y = \frac{\gamma_L \cos \theta}{r} \quad (5)$$

Capillary pressure causes the pressure drop as a result of capillary effect. To study the effect of this surface tension and pressure drop (or capillarity pressure drops) on the overall flow behavior, the flow pressure drop, ΔP must be determined. For water flow in microtubes (supposed to be laminar), the Hagen-Poiseuille (**White, 2011**) model is applied:

$$\Delta P = \frac{8\mu_w * L * J}{\pi r^4} \quad (6)$$

Where: μ_w : is water dynamic viscosity (in N.s.m⁻²), which varies with temperature; L : is the length of a single microtube path (in m); J : is the volumetric flow rate (in m³.s⁻¹); r : is the inner radius of the tube (in m). The values of water dynamic viscosity are adapted from (**Crittenden et al., 2012**). Note that this simplified analysis is for the estimation of the capillarity role in the liquid cooling systems. Therefore, the flow pressure drop didn't account for the serpentine patterning effect of a single tube. The capillary influence, CI, is determined by the ratio of the capillarity pressure drop to the flow pressure drop:

$$CI = \frac{\Delta P_Y}{\Delta P} \times 100\% \quad (7)$$

The capillarity influence indicates whether or not the capillary flow effectively affects the flow behavior in the microtubes, positively or negatively.

3. HYDRODYNAMIC CLASSIFICATION

In micro-scale conduits, a divergence from the continuum theory towards the slip flow regime is probable. Here, the dimensionless descriptor is the Knudsen number (Kn), which quantifies the relative significance of molecular-scale effects compared to macro-scale dimensions of the system:

$$Kn = \frac{\text{mean free path}}{\text{characteristic length}} \quad (8)$$

The mean free path is the average distance that can be traveled by a molecule can travel before collision. In microtubes, the characteristic length is the inner diameter, which is quite small, causing the Kn to be larger:

$$\text{Where } \left\{ \begin{array}{ll} \text{Kn} \rightarrow 0 & \text{inviscid flow} \\ \text{Kn} \leq 0.001 & \text{continuum theory} \\ 0.001 < \text{Kn} \leq 0.1 & \text{slip - flow} \\ 0.1 < \text{Kn} \leq 10 & \text{transition} \\ 10 < \text{Kn} & \text{free - molecular} \end{array} \right. \quad (9)$$

For liquid water, the mean free path of molecules is 2.5 Ångström, or 0.25 nm at room temperature. The Knudsen number is quite small for liquid flow, even in microtubes of diameters in the hundreds of micrometers. Having said that, it is necessary to determine the Kn number for the liquid flow inside the PP microtubes to confirm the applicability of Reynolds analogy, Navier-Stokes equations, and other mathematical models.

4. EXPERIMENTAL MICROSCOPY

There are many micro details in micro-scale experiments that need to be visualized and studied. The flow inside the PP microtube needs to be visualized to check flow uniformity, surface tension, and capillary flow availability. All these goals are obtained in this work using an educational digital microscope, **Fig. 3** and **Table 1**.



Figure 3. educational digital microscope, utilized in the study

Table 1. Digital microscope specifications

Magnification	40X-1000X
Image sensor	CMOS
Image resolution	Up to 640*480, 1920*1080
Focus range	15mm-40mm
Frame rate	Up to 30 FPS
Available video format	AVI
Adjustable illumination	8 built-in LED diodes
PC interface	USB 3.0/2.0/1.1
Dimensions	14.5cm × 10cm × 5cm
Weight	About 200g

The physical and chemical properties of PP used in the experiments are listed in **Table 2**.

**Table 2.** Physical and chemical properties of the used PP

Property	Unit	value
Density	Kg.m ⁻³	900
Thermal Conductivity	W.m ⁻¹ .K ⁻¹	0.2
Specific heat capacity	J.kg ⁻¹ .K ⁻¹	1920
Young's modulus	GPa	1.3
Poisson's ratio		0.42
Allowable stress	MPa	10

The experimental range and boundary conditions of the analysis are listed in **Table 3**.

Table 3. Experimental range and boundary conditions

Parameter	Unit	Value
Water temperature	°C	0 – 100
Flow velocity	mL.min ⁻¹	350 – 700
Surrounding pressure	Ambient pressure	
Geometry	Long cylindrical tube	
Curvature	Straight tube	

5. RESULTS AND DISCUSSIONS

The analytical solution of the mathematical model presented in this study was implemented to account for the flow behavior inside the PP fiber microtubes individually, i.e., regardless of the application. However, it is a necessary establishment for any further theoretical design, numerical modelling, and experimental investigations. The microflow analysis results show that the utilized microtube dimensions and material properties are consistent with liquid cooling applications. A minimum capillarity effect was found, and a definite continuum theory applicability was confirmed.

5.1 Capillarity Behavior

As expected for hydrophobic polypropylene (PP) fiber microtubes, applying Eq. (1) and Eq. (2) within the liquid temperature range of water results in capillary depression, as shown in **Fig. 4**. The contact angle θ ranges from approximately 152° to 158°, clearly indicating non-wetting behavior. This confirms that passive liquid circulation driven solely by capillary action is not feasible when using PP fiber microtubes with water as the working fluid. Microscopic imaging of stationary water inside the PP microtube further supports this conclusion, as illustrated in **Fig. 5**.

The capillary depression acts as a resistance to the upward flow and as an assistance to the downward flow (**Zhang et al., 2024**). Therefore, for a serpentine pattern with equal upward and downward path lengths, the capillary effect could be completely diminished, which is the case in most of the vertical liquid cooling fields. However, in this analytical determination, the path was suggested to be straight; hence, using Eq. (5), the capillary resistance pressure drop was computed at different water temperatures, **Fig. 6**. It shows that the capillary pressure drops increases with decreasing temperatures, yet, this increment has low sensitivity to temperature increment, **Fig. 7**.

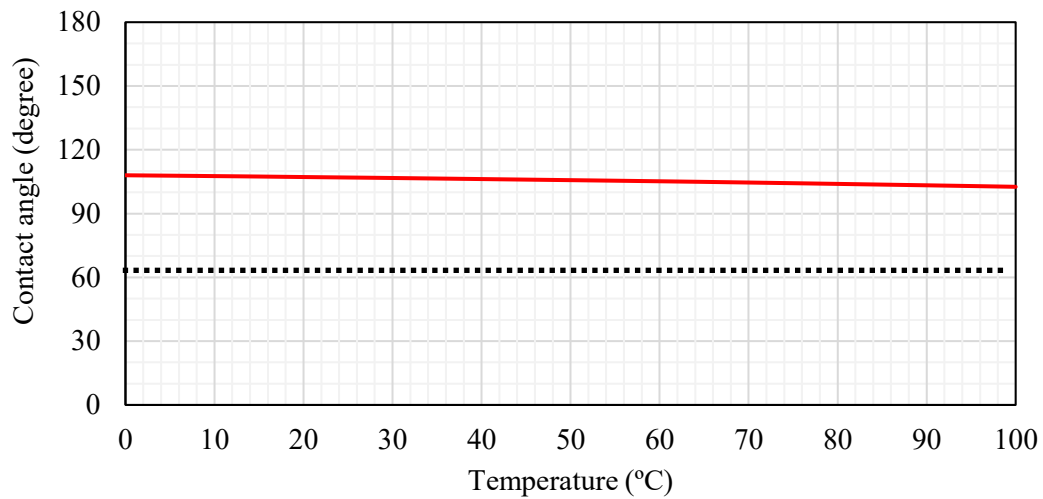


Figure 4. Contact angle of a water drop inside a PP fiber microtube at the liquid phase temperature range

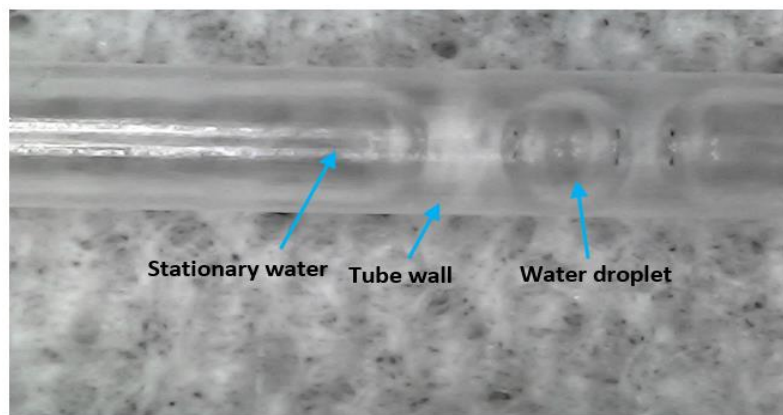


Figure 5. Macroscopy imaging of non-flowing water inside a PP fiber microtube, showing the hydrophobic behavior of PP and the capillary depression.

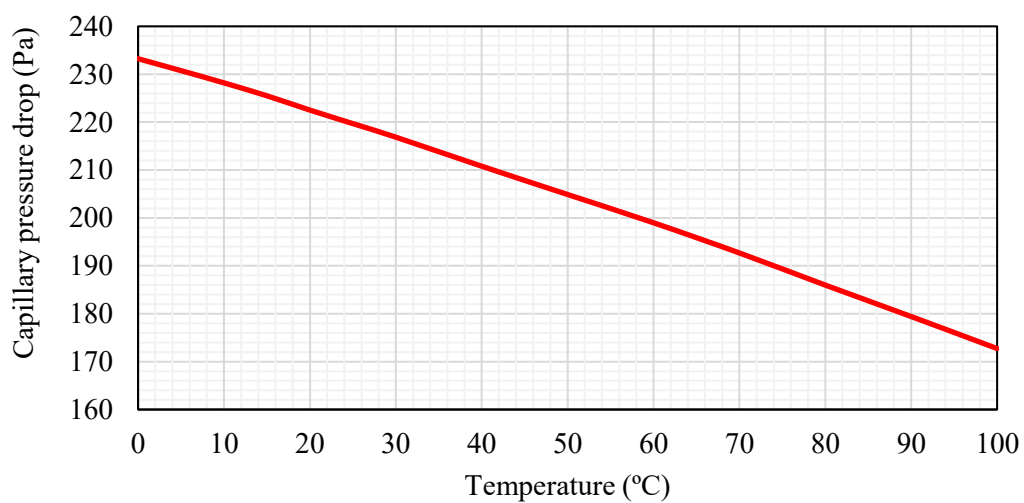


Figure 6. Capillary pressure drop of water inside PP fiber microtubes at the range of liquid phase temperature

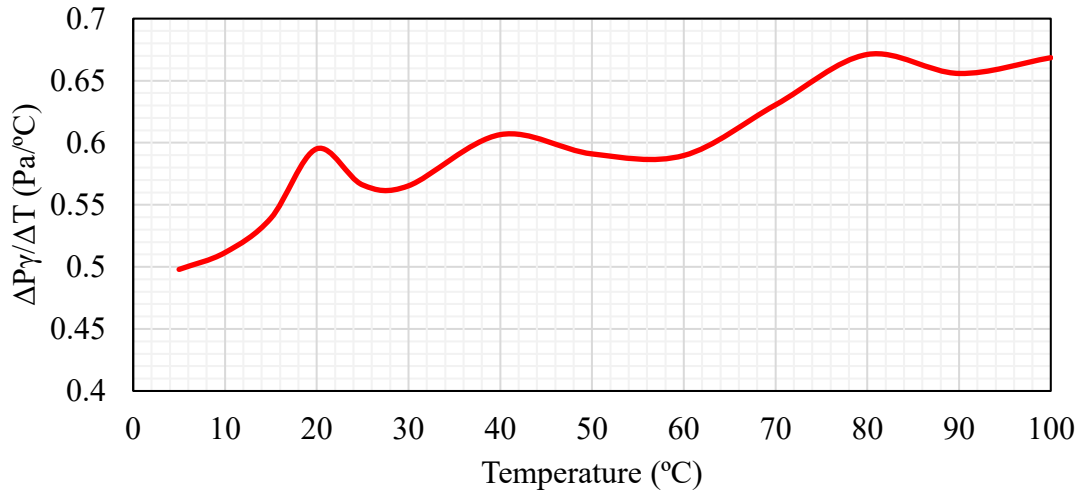


Figure 7. Sensitivity of capillary pressure drop to an increase in water temperature.

The low sensitivity of capillary pressure drop to water temperature indicates that there should not be any concern regarding capillary action to water temperature fluctuations during cooling systems (**Vakilha et al., 2024**). Overall, the effect of this capillary depression behavior is very small compared to the theoretical flow pressure drop of the single microtube. Applying Eq. (6) and Eq. (7), the whole liquid phase temperature range of water yields a negative capillary influence of $\sim 0.2\%$ to $\sim 2.7\%$ for all three flow rate levels, **Fig. 8**.

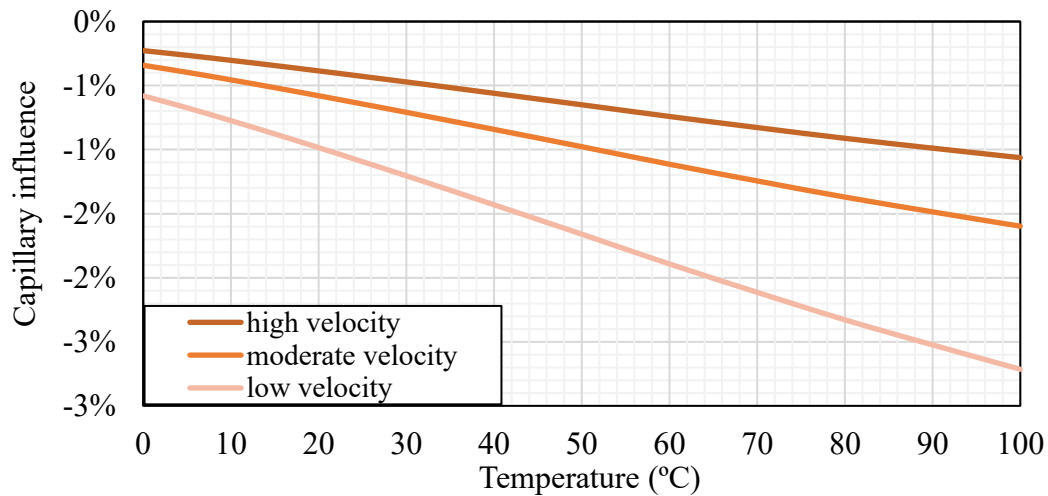


Figure 8. capillary influence of water depression in PP fiber microtubes at all liquid phase temperature range

5.2 Hydrodynamic Classification

For water flow inside microtubes of 0.6mm inner diameter, the Kn number is $\sim 4 \times 10^{-7}$, which is far exceeding the limit of slip-flow consideration (**Lin and Wen, 2024; Cheng et al., 2024**). In fact, even for smaller diameter microtubes, Kn number stays decisively in the continuum regime for liquid water flow, **Fig. 9**. As a result, Navier-Stokes equations and Reynolds analogy are applicable for the mathematical models of liquid cooling systems (**Caltagirone et al., 2024**). Furthermore, since the flow is laminar, viscosity effects are significant, meaning the flow cannot be considered inviscid.

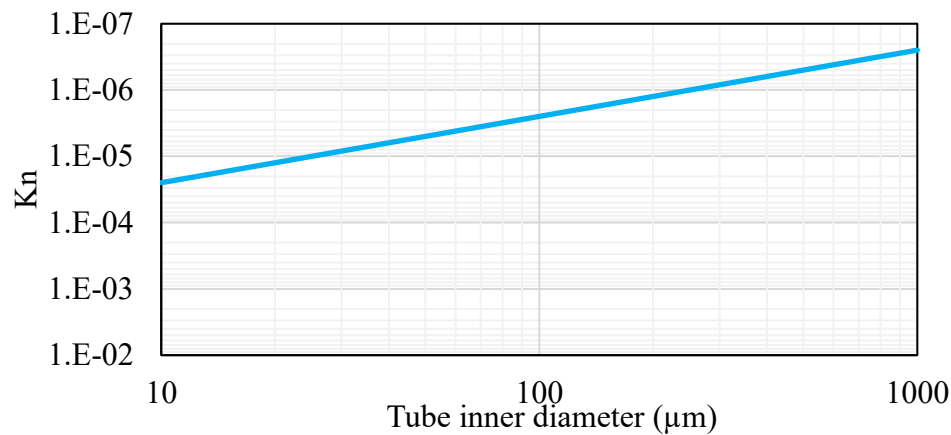


Figure 9. Knudsen number of liquid water flow in microtubes

6. CONCLUSIONS

This study offers a comprehensive evaluation of liquid flow and capillary effects in polypropylene (PP) microtubes with a 0.6 mm inner diameter, shedding light on their potential in micro-scale heat transfer systems. The findings reveal that PP microtubes of this size do not generate significant capillary action when water is used as the working fluid. Capillary pressure drops showed minimal sensitivity to water temperature, indicating stable flow resistance across thermal variations. Across all tested flow rates, the capillary contribution to total pressure drop remained low—between $\sim 0.2\%$ and $\sim 2.7\%$ —demonstrating that capillarity plays a negligible role under the studied conditions. The observed Knudsen number ($\sim 4 \times 10^{-7}$) confirms continuum flow behavior, effectively ruling out slip flow effects and supporting the validity of classical fluid mechanics models like the Reynolds analogy. These results affirm that conventional convective heat transfer theories can be confidently applied to PP microtube systems. In conclusion, PP capillary microtubes with these dimensions exhibit stable, predictable flow characteristics with minimal capillary interference, making them well-suited for integration into microfluidic and heat-sensitive thermal management applications.

NOMENCLATURE

Symbol	Description	Symbol	Description
CI	capillarity influence	WL	Working liquid
L	Length	γ_L	WL material surface tension
J	Volumetric flow rate	γ_S	tube material surface energy
Kn	Knudsen number	γ_L^D	Dispersive surface tension
ΔP	pressure drop	γ_S^D	Dispersive surface energy
ΔP_γ	pressure drop due to surface tension	γ_{SL}	Solid-liquid interfacial tension
R	Radius	θ	contact angle
r	Radius	μ	Dynamic viscosity
v	velocity		

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Credit Authorship Contribution Statement

Amjed Abdulelah: Writing – original draft, Validation, Software, Methodology. Luma F. Ali: Writing – review & editing, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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الخصائص الميكرو تدفقية للماء في الأنابيب الدقيقة المجوفة المصنوعة من البولي بروبيلين

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الخلاصة

يتطلب دمج الأنابيب الشعرية الدقيقة المصنوعة من البولي بروبيلين (PP) في أنظمة التبريد السائل المتقدمة فهماً شاملاً لسلوك التدفق الداخلي داخلها. إذ تلعب المعلمات الرئيسية مثل الخاصية الشعرية، ونظام التدفق، وخصائص فقدان الضغط أدواراً حاسمة في تحديد أدائها الحراري وقابليتها للتطبيق على نطاق أوسع. ومع ذلك، تفقر الأدبيات الحالية إلى دراسات تفصيلية تركز تحديداً على هذه الجوانب داخل الأنابيب الليفية المجوفة المصنوعة من البولي بروبيلين. ولرصد هذه الفجوة، تُجري هذه الدراسة تحليلاً رياضياً وتقيماً مجهرياً لتدفق الماء داخل أنابيب PP دقيقة ذات قطر داخلي يبلغ 0.6 ملم. تكشف النتائج أن تأثيرات الخاصية الشعرية ضئيلة تحت جميع الظروف المختبرة، حيث تتراوح مساهمتها في فقدان الضغط بين حوالي 0.2% و~2.7%. كما وُجد أن ضغط الخاصية الشعرية غير حساس إلى التغيرات في درجة حرارة الماء. ويؤكد رقم كنودسن المنخفض جداً (4×10^{-7}) أن التدفق يقع ضمن نطاق التدفق المستمر، مما يدعم صلاحية استخدام النماذج الكلاسيكية مثل تشابه رينولدز (Reynolds Analogy). وتُقدم هذه النتائج رؤية قيمة حول ديناميكا الموائع في الأنابيب الشعرية المصنوعة من البولي بروبيلين، وتدعم مدى ملاءمتها لإدارة الحرارة في تطبيقات التبريد السائل على المستوى الدقيق.

الكلمات المفتاحية: الأنابيب الماكروية، الجريان الماكروي، الجريان الشعيري، بولي بروبيلين، التبريد بالسائل