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Deviation of macro-micro tubing direct transition in liquid flow comparing to the constructal transition: Experimental study and CFD simulation

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Abstract:
Capillary tubes have growing domain in heat transfer applications. However, complexity of micro pumps and macro-micro constructal optimum transition section impede this growth, especially for polymeric microtubes. In this study, a simplified macro-micro transition section is proposed, analyzed and tested. Three dimensional computational fluid dynamics numerical simulation was conducted to compare between the direct simplified model and the optimal constructal model. In addition, fabrication and experimental testing of the proposed design is done to study the fluid flow behavior in such design and distribution. The numerical results of pressure fields produce comparable pressure drop outcome of the direct transition design. Further, it is notable that the drop in pressure drop increases with increasing flow rate, the fact that encourages utilizing this design for higher flow rates. Moreover, the proposed direct transition design provide a well distributed flow achieved from both the numerical results and experimental measurements. The pressure drop gradient between the central and peripheral branches is very small comparing to the pressure drop. However, this gradient increases with increasing flow rate. The flow velocity of the direct transition was comparable to that of the constructal design. The flow velocity elevation in the direct design increases with increasing flow rate. The numerical simulations consolidated by the experimental results about the fairly approximate flow velocity in the micro-branches in the direct transition design. The suggested design was applied for a liquid cooling vest system successfully and can be applied for several further micro applications.

1. Introduction

Capillary microflow have several applications in heat transfer, such as in thermal management (Meng et al., 2025) and refrigeration (Kareem et al., 2025). It has further application fields in fluids, such as droplet ejection of micropores (Salama et al., 2022) and infiltration of porous media (Lu et al., 2025). In spite of the growing importance of capillary tubes in heat transfer and fluid applications, some issues still represent difficulties in the manufacturing and competence requirements. One of those is the transition from macro to micro dimensions (Herwig and Gloss, 2006; Luo et al., 2007; McNeil et al., 2013) and the uniformity of flow distribution between micro branches (Liu et al., 2010), as well as the pumping mechanisms for microtubes. Capillary

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microtubes technology provides several heat transfer features (Salman et al., 2013; Salman et al., 2015). As a subset of microchannels technology, capillary tubes have large surface area to volume ratio, high Nusselt number, high heat transfer coefficient, compact size and customizable geometry (Aljubury and Mohammed, 2019; Mohammed and Fayyadh, 2020). The microtube as a closed single-input single-output microchannel, has several applications, such as battery thermal management (Bohacek et al., 2019), heat exchangers (Jin et al., 2023), vapor compression refrigeration (Ali and Jasim, 2005) and chemical reactions (Pan et al., 2025). The powerful thermal technology of microchannels is still limited on behalf of applications scope, in addition, there is a lack for wider applications of capillary microtubes in heat transfer. Generally, most research studies in microtubes focuses on using this technology in the enhancement of electronic devices cooling, trapping the promising mathematics of microtubes in heat transfer science within a narrow application.

Microtubes made from polypropylene hollow fibers are used in heat transfer applications taking the advantages of both microchannel theory and special polypropylene characteristics. Due to its low cost, smooth surface, light weight, and some other thermofluids advantages over metals, it was used in alternative heat exchangers for low temperature/pressure applications (Zarkadas and Sirkar, 2004). They are known as polymer hollow fiber heat exchangers, which are the main application in which polymeric fiber microtubes are tested and used. Using polypropylene hollow fibers as thermo-microtubes has a wide interest in literature (Zhao et al., 2013; Raudenský et al., 2017; Liu et al., 2018; Tseng and Raudensky, 2019). In spite of being thermally low conductive materials (Thabet and Mobarak, 2016; Hussein et al., 2024), polypropylene features several characteristics that make them favorable over typical metallic materials. It can withstand high pressure relatively of 40 MPa at high temperatures of 80 °C (Kůdelová et al., 2022). Chemically, polypropylene is corrosion resistant and flexible (Kůdelová et al., 2022). Because of the drawback of low conductivity of polymeric tubes' walls, they are not commonly used in manufacturing of heat transfer applications (T'Joen et al., 2009). However, in micro-scale tubes, the walls are very thin (Kůdelová et al., 2022), which overcomes the effect of the low conductivity on the thermal resistance of the walls.

Capillary flow is excluded in polypropylene microtubes, as in other plastics, due to its hydrophobic nature (Tamim and Bostwick, 2025). As well, the complexity of pumping devices required for micro structures impede the wide spread of this technology in different applications. In order to reduce the complexity of such systems, a simplified organization is suggested in this study by utilizing typical pumping tubing of macro dimensions to feed the cooling fields of the microtubes. However, such structure would require an additional complexity for the transition section from the macro tube to the microtubes. The important consideration is related to the practical manufacturing design. The optimal transition could be settled depending on the constructal theory (Bejan, 2002; Bejan, 2007; Bejan and Sylvie, 2010). However, applying this theory will produce a complex configuration to manufacture. Polypropylene microtubes are manufactured using extrusion mechanisms, which would be very difficult to apply for a constructal distribution design. Therefore, it is necessary to assign a simplified transportation configuration. The new configuration must provide ease of manufacturing without heavily affecting the flow velocities and pressure drop. Such simplification would be very beneficial and encouraging for novel applications of capillary tubes, such as personal cooling systems, coiled heat exchangers (Amori, 2014) and prosthetic cooling application (Ridha et al., 2024; Ridha and Ezzat, 2024a, 2024b).

In this study, an instant direct transition was proposed and studied numerically. In addition, the design was manufactured experimentally and tested to study the deviation from the optimal flow distribution.

2. Scaling limitations

In this study, the macro main tube is with an inner diameter of 3 mm and outer diameter of 5 mm, while the branched microtubes have an outer diameter of 0.8 mm. In order for maximizing the number of branched microtubes and increasing cooling density, the macrotube should transient to as much micro branches as possible. However, the number of micro branches to be formed must not exceed the limit that cause the microtubes to be indented to inside or completely blocked. As a result, the instant transition scaling is:

$$\mathrm{NOB}=\frac{A_{\mathrm{in}}^{M}}{A_{\mathrm{out}}^{m}}=\frac{\pi(R_{\mathrm{in}}^{M})^{2}}{\pi(R_{\mathrm{out}}^{m})^{2}}=\left(\frac{R_{\mathrm{in}}^{M}}{R_{\mathrm{out}}^{m}}\right)^{2} \tag{1}$$

where NOB is the theoretical number of branches for the transition; A_{in}^{M} is the macrotube inner cross-sectional area, mm^2; A_{out}^{m} is the microtube outer cross-sectional area, mm^2; R_{in}^{M} is the macrotube inner radius, mm; R_{out}^{m} is the microtube outer radius, mm.

The flexibility nature of the macro main tube material provides an availability for additional branches. In fact, exceeding the NOB is required to maintain the fitting connection and reduce the spaces between branches. Therefore, the total number of NOB plus one, is considered. In the present case of study, this total number equals 15 micro branches, Fig. 1.

3. Geometrical configuration

Fig. 1 shows the 3D geometry of the proposed direct macro-micro instant transition that studied numerically and manufactured afterward. The expanding bore seen in Fig. 1 at the transition point is a reliable deformation of macro tube wall due to fitting the microtubes inside it. In order to check the losses of such configuration, the optimum transition configuration was modelled depending on the structural theory. However, the optimum branching yields in an even numbers of branches, in which the nearer number in the present case is 16 branches, Fig. 2. The macro-inlet and micro-outlet sections' lengths for both models are identical to normalize the effects of tubing lengths in calculating pressure drops.

The NOB of the constructal model differs from that of the proposed direct transition model by one to fifteen, which corresponds to 6%. Despite that, it still can be compared with as the optimal transition model depending on the hypothesis

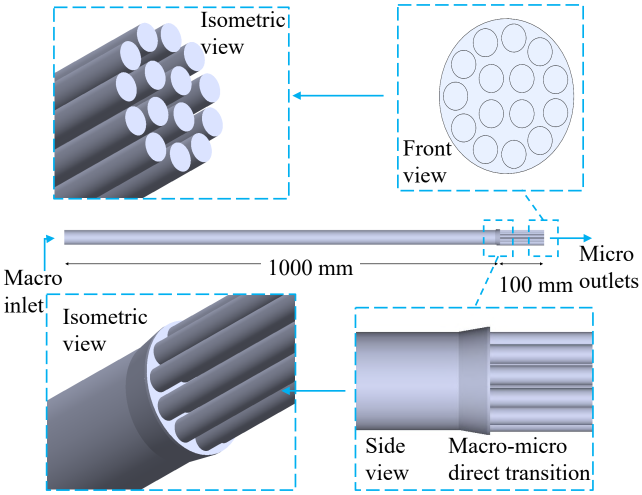

Fig. 1. Macro-micro direct transition proposed design geometry.

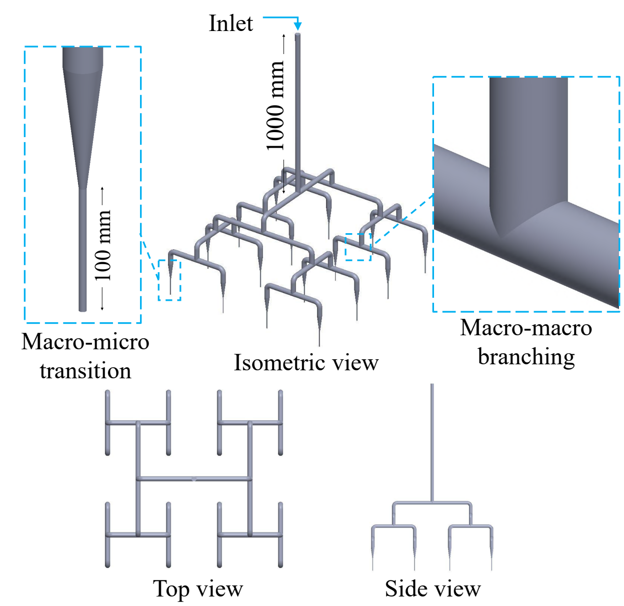

Fig. 2. Optimum macro-micro constructal transition design.

that the proposed model provides an acceptable behavior. In fact, the reason behind not applying the constructal method is the typical extrusion method of plastic microtubes manufacturing, where producing such network is not available.

4. Mathematical model

Steady state simulations is conducted to study the both of transition design models. ANSYS FLUENT software is implemented for these simulations after modelling the designs by SOLIDWORKS software. As it is obvious from Fig. 1 and Fig. 2, the inlet macro section is elongated, which is in order to ensure the fully developed flow entering the branching points. In this specific study, only the fluid flow characteristics are studied, i.e., neglecting the effects of temperature field. This approach is reasonable because the macro-micro transition region exists in-between the pumping facilities and cooling fields and outside both of them, i.e., without heat interaction

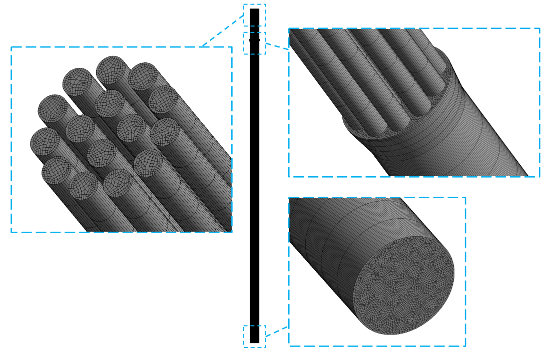

Fig. 3. Numerical simulation mesh of the macro-micro direct transition model.

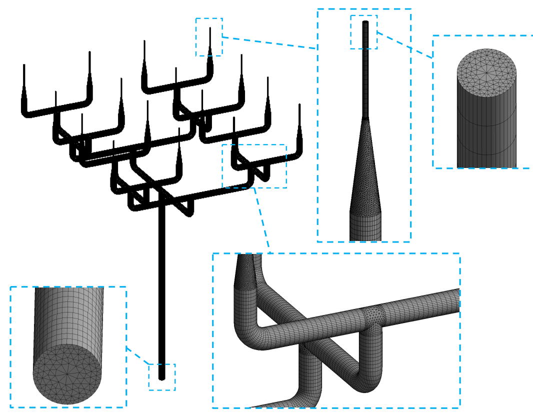

Fig. 4. Numerical simulation mesh of the constructal transition model.

with the hot surfaces nor with condensers. The only heat interaction source is the surrounding ambient, which assumed to be insulated from. In addition, this effect is identical in both designs, thus neutralized.

The governing equations are the Navier-Stocks equations for steady incompressible flow (Ihsan, 2017). The continuity equation:

$$\nabla \cdot v = 0 \tag{2}$$

and momentum equation:

$$\rho_{\text{water}}(v \cdot \nabla)v = -\nabla P + \mu_{\text{water}} \nabla^2 v \tag{3}$$

where ρ_{water} is water density; v is velocity vector; P is pressure; μ_{water} is water dynamic viscosity; $\nabla^2 v$ is viscous term, which is the Laplacian of velocity. The Reynolds numbers that studied here are of range of four inlet velocity speeds, namely: Low (L), Moderate (M) and high (H). This inlet condition is the only boundary condition, while the outlet conditions to be determined through the simulations.

The meshes of both models are shown in Figs. 3 and 4. They are consisting entirely of sweep cells to provide less calculation cost. The elongation of the swept cells is in the direction of flow to minimize its effect. The direct transition model mesh consists of 3,570,355 cells. The average orthogonal quality is 0.94978 and minimum orthogonal quality of 0.47126. The constructal transition model mesh consists of

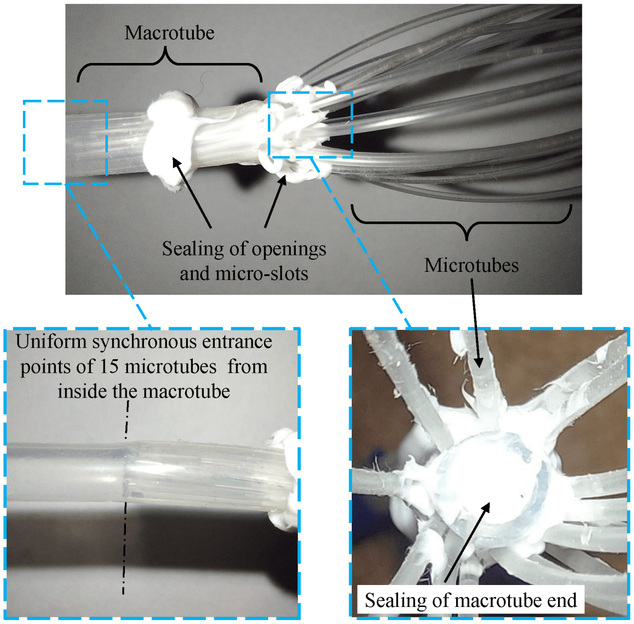

Fig. 5. Macrotube-microtubes transformation manufacturing and entrance point.

1,912,820 cells. The average orthogonal quality is 0.79251 and minimum orthogonal quality of $\sim 2\times10^{-6}$, located only in the curvature regions.

For turbulence modelling, the shear stress transport $k-\varepsilon$ model was employed due to its balance between accuracy and computational efficiency for the type of flow investigated. This model effectively captures adverse pressure gradients and flow separation, making it well-suited for the present simulation. For near-wall treatment, the standard wall roughness model was applied to accurately represent the interaction between the turbulent flow and the wall surface. This approach ensures that the boundary layer development is properly captured, especially in regions where wall effects play a significant role in the overall flow characteristics. The mesh was refined near the solid boundaries to maintain appropriate y^+ values within the valid range for the selected wall function. Additionally, a no-slip boundary condition was imposed on all solid walls, assuming the surfaces are stationary with zero relative motion. This setup reflects the physical constraints of the modeled scenario and supports the accurate prediction of velocity gradients near the wall.

5. Experimental setup

In the present study, polypropylene was selected as the base material for microtube fabrication due to its widespread availability, chemical resistance, and suitability for extrusion-based manufacturing. The main macro tube was used to transfer the working liquid, which is ordinary water, from the uploading main tube to the branched microtubes. This operation can be designed using the constructal theory (Bejan, 2002; Bejan, 2007; Bejan and Sylvie, 2010). This method ensures the even distribution of the liquid between all micro branches. However, manufacturing such design could be complex for plastic extruded tubing, particularly polypropylene, due to its limited formability in precise geometric transitions. Polypropylene, while offering advantages such as chemical resistance and cost-effectiveness, poses manufacturing challenges for intricate constructal structures. In addition, the constructal design demands an additional size. Therefore, an alternative design was proposed for the direct micro-macro transition that is more compatible with polypropylene extrusion processes. The effect of this method on the even distribution was established numerically. The manufacturing of the transition point was done using micro-perforation and polysiloxane, Fig. 5.

To measure the volumetric flow rate through the capillary branches, a bucket and stopwatch method was employed. In this procedure, the outlet of the system was directed into a graduated container, and the time required to collect a known volume of water was recorded using a digital stopwatch with ±0.05 s accuracy. Each measurement was repeated several times to ensure consistency, and the most repeated value was used for analysis. The setup was maintained under steady-state conditions, and care was taken to eliminate air bubbles before each run. The experiments were conducted at room temperature, and the elevation of the outlet was kept constant to avoid gravitational effects on the flow. Each micro branch was tested at all pumping stages. The macro main tube also tested without the transitions section at all pumping stages. This simple yet effective method enabled accurate flow rate estimation, which was subsequently used to evaluate the uniformity of flow distribution across the microtubes.

6. Results and discussion

Several experimental methods were tried to achieve the proposed direct transition connection. The main issues were to keep the instant entrance of the microtubes, best macro-micro fitting, and to prevent leakage. The succeeded method wasn't an easy production proposal, yet it can be simplified with future manufacturing operations. The utilization of silicon wrap was essential for both fixing and leakage prevention. Initially, the new transition point was manufactured individually to be tested mechanically. Afterward, the design applied to the liquid cooling vest connections. Experimentally, the results show a nearly even flow distribution between the micro-branches, Fig. 6, which represents a cooling uniformity requirement where flow velocity affects heat transfer. Further, it is a comfort perception requirement where the wearer do not feel localized stiff sensations.

The additional pressure drop applied by the micro-paths reduce the overall flow rate of the system notably, Fig. 7. Of particular importance is that the flow rate values appear in this section are for different micro-section lengths for experimental and numerical studies, thus, they are non-comparable. However, each of them have its own indication. For a fixed pumping power, the shorter microtube will have a higher flow rate compared to a longer tube because the lower pressure drop, and consequently, the lower wall resistance. The pump has to work harder to maintain the same flow rate in a longer tube, which ultimately results in a lower flow rate.

The grid independence test of the numerical simulation model, presented in Fig. 8, demonstrates a noticeable sensi-

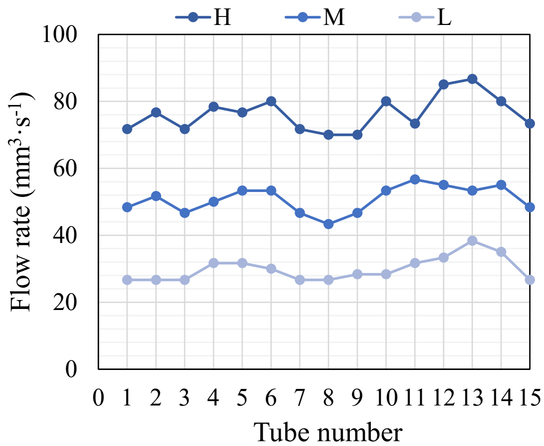

Fig. 6. Experimental measurements of micro flow rates at different inlet macro flow rates.

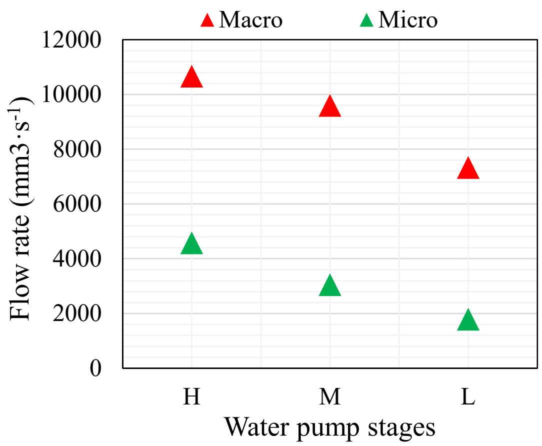

Fig. 7. Experimental measurements of flow rates at macro and micro stages at different water pump stages.

tivity of the pressure drop results to the mesh density, particularly at lower resolutions. As the mesh becomes finer, the variation in pressure drop predictions decreases, indicating improved numerical stability and accuracy. The mesh densities used in the simulations fall within the initial range of the convergence plateau, where further refinement results in only minor changes to the outcome. This suggests that the selected mesh provides a good balance between computational cost and solution accuracy, while still capturing the essential flow characteristics reliably.

The most important issue regarding the macro-micro transition point is the pressure drop of the transition point and the even distribution over all branches. Therefore, the mathematical model applied to focus in this point specifically regardless of other considerations. The goal is to scientifically reason the choice of the simplified direct transition design that is more compact and manufacturable. It is fortunate that it produce encouraging results of pressure drop, Figs. 9 and 10. In fact, the lower pressure drop of the direct design can't be accounted as more optimum design than the constructal design since the branches of the latter is more by 1, as mentioned earlier. In addition the additional distances cut by the water inside the constructal branching section may represent an additional pressure drop sources. However, this comparable pressure drop outcome of the direct transition design is precisely what was required. Further, it is notable that the drop in pressure drop of the direct design in comparison to the constructal design increases with increasing flow rate, the fact that encourages utilizing this design for higher flow rates.

The second important issue of the transition point is the even distribution of water between the micro-branches. It is a well-established that the constructal design provide optimum distribution. In fact, it is the original goal of the constructal theory. However, the numerical simulations results consolidate that the proposed direct transition design provide a well distributed flow, Fig. 11. The pressure drop gradient between the central and peripheral branches is very small comparing to the pressure drop. However, this gradient increases with increasing flow rate.

In a similar manner to pressure drop, numerical simulations show that the flow velocity of the direct transition is comparable to that of the constructal design, Figs. 12 and 13. The appeared flow velocity elevation in the direct design increases with increasing flow rate, Fig. 14.

It is a system performance aspect that the cooling is distributed evenly everywhere in the liquid cooling field. The numerical simulations consolidate the experimental results about the fairly approximate flow velocity in the micro-branches in the direct transition design, Figs. 15 and 16. However, there still a fraction of theoretical variance comparing to the analytical uniform outlet velocity, Fig. 17. In spite of being greater in the direct design and for higher flow rates, it generally represents only tiny fraction of flow velocity.

Although the numerical and experimental studies were conducted using microtube networks of different lengths due to fabrication constraints, both configurations were designed to follow the same geometric principles and flow distribution objectives. The primary focus of the comparison was to assess the uniformity of flow distribution across the micro branches, rather than to match specific flow rate values. The numerical simulation predicted a nearly uniform flow distribution among the outlets, which was consistent with the experimental observations obtained using the bucket and stopwatch method. This qualitative agreement between numerical and experimental results supports the validity of the simulation model in capturing the essential flow characteristics of the system, despite the dimensional differences. Therefore, the numerical model is considered reliable for analyzing flow behavior and guiding design improvements.

For all water pump stages, the macro flow is turbulent at inlet section. However, when entering the micro-section, all studied flow velocities yield laminar flows, where very low turbulences exist, Fig. 18. In microchannels technology, this behavior is typical (Mala and Li, 1999; Barlak et al., 2011; Hamad et al., 2022). This behavior is a lower heat transfer producer. Further, low relative surface roughness are favorable in the laminar flow regime (Everts et al., 2022). However, the high surface area to volume ratio overcome this lack to produce high heat transfer. The serpentine patterning stimulate some turbulences but the long straight paths re-laminate the flow again resulting in an entire laminar flow field that is in

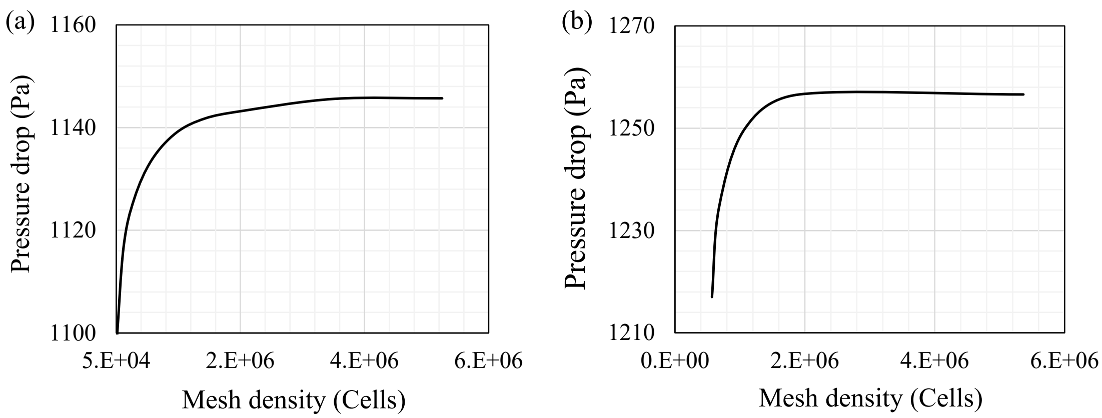

Fig. 8. Grid independence test of the numerical simulation model mesh: (a) Direct and (b) constructal.

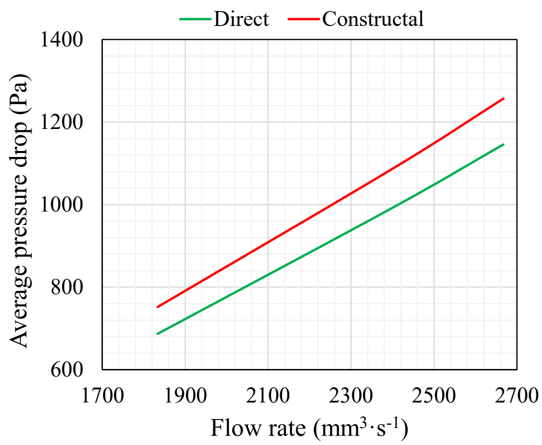

Fig. 9. Numerical results for the average pressure drop of the 10 mm micro-branches of 100 mm macro tube for both the direct and constructal designs.

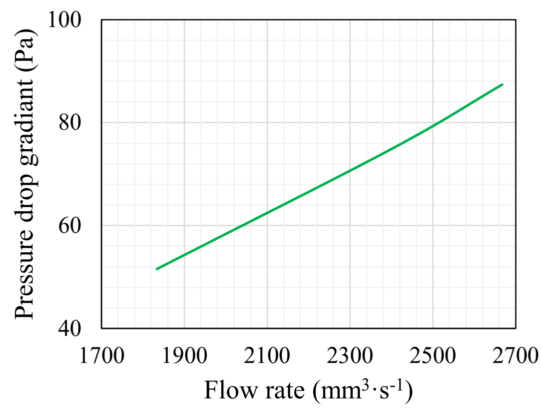

Fig. 11. Numerical results for the pressure drop gradient between the central and peripheral micro-branches of a macro-tube at different flow rates.

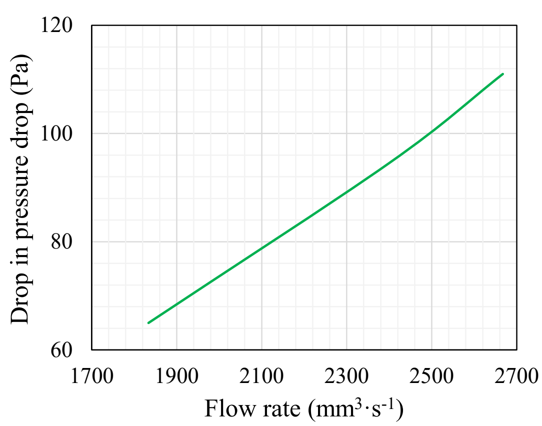

Fig. 10. Drop in pressure drop of the 10 mm micro-branches of 100 mm macro tube direct design comparing to the constructal design.

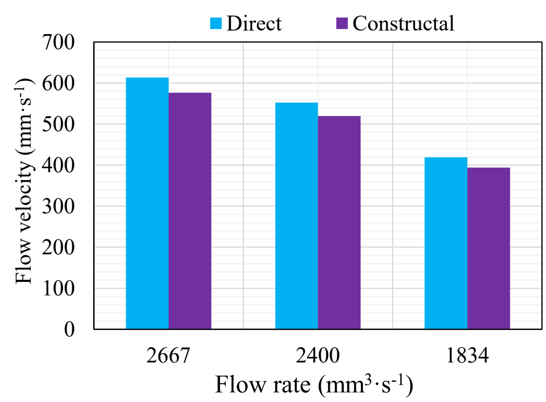

Fig. 12. Numerical results for the average flow velocity of the 10 mm micro-branches of 100 mm macro tube for both the direct and constructal designs.

contact with the hot surfaces.

7. Conclusions

The findings of this study highlight the potential of a simplified macro-micro transition design for capillary tube applications, particularly in polymeric microtubes. The proposed design was successfully fabricated and experimentally tested, demonstrating its effectiveness in facilitating fluid flow distribution. Numerical simulations showed that the pressure drop in the direct transition design is comparable to that of the optimal constructal model. Additionally, the pressure drop decreases with increasing flow rate, making this design advantageous for high-flow applications. The proposed transition section also ensures well-distributed flow, which was achieved

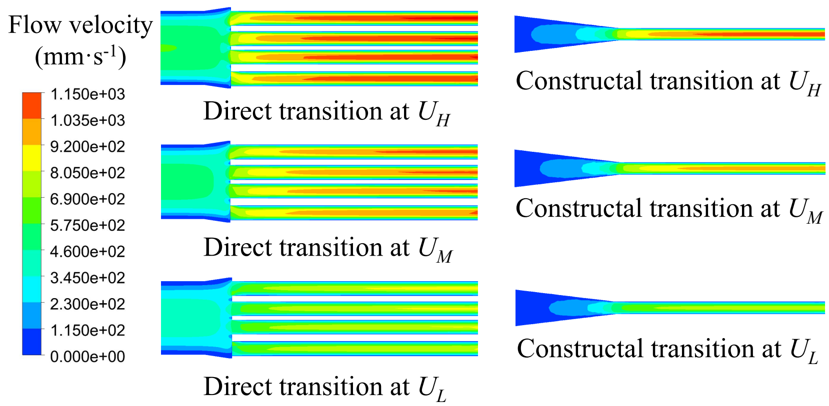

Fig. 13. Numerical results of flow velocity at direct and constructal transition sections for the three water pump stages.

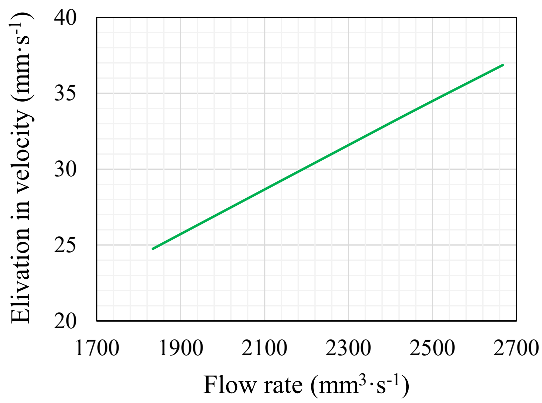

Fig. 14. Elevation in flow velocity of the 10 mm micro-branches of 100 mm macro tube direct design comparing to the constructal design.

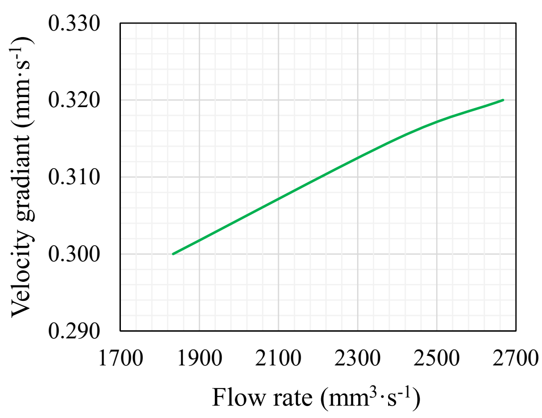

Fig. 15. Numerical results of flow velocity gradient between the central and peripheral micro-branches of the direct transition design.

from both the numerical results and experimental measurements. In addition, it ensures minimal pressure drop gradients between central and peripheral branches, although this gradient increases with higher flow rates. Furthermore, the flow velocity in the direct transition design closely matches that of the constructal model, with velocity elevation becoming more pronounced as the flow rate increases. The consistency betwe-

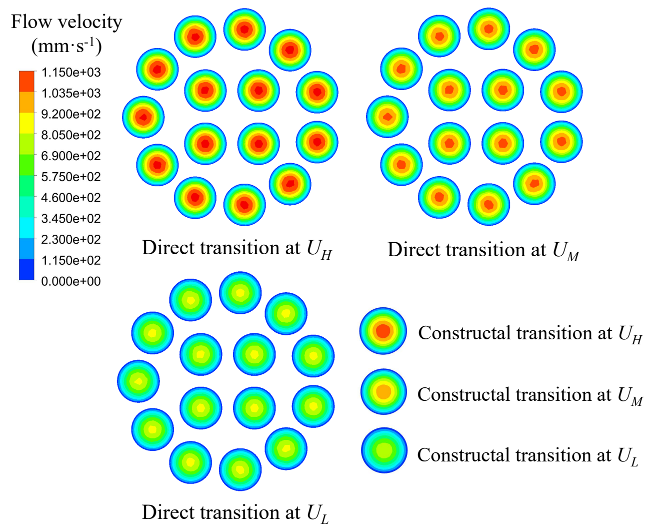

Fig. 16. Numerical results of the outlet flow velocity for the direct and constructal designs at three water pump stages.

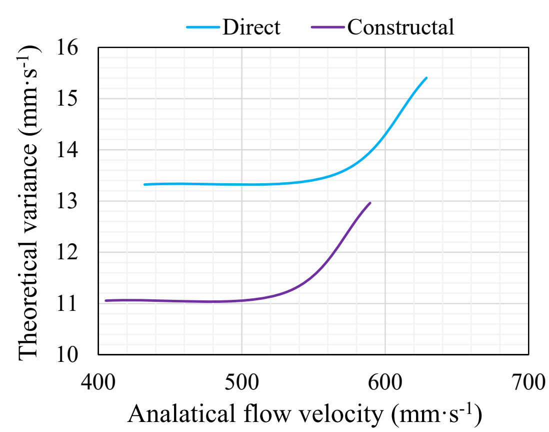

Fig. 17. Theoretical variance of numerical simulation results from the analytical uniform velocity results of the direct and constructal transition designs.

en numerical and experimental results confirms the feasibility of this design for various microfluidic applications. However, it is important to note that the current design has been evaluated under controlled laboratory conditions, which may

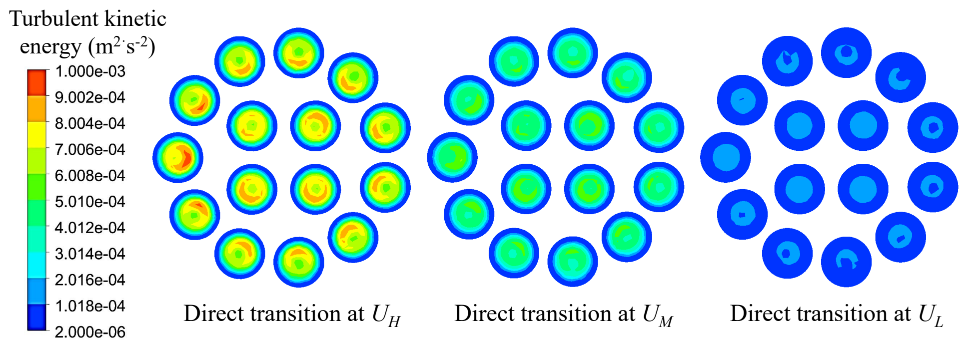

Fig. 18. Numerical results of the turbulent kinetic energy at the outlet section of the direct transition design at the three water pump stages.

not fully capture the variability present in real-world operational environments. Additionally, while the pressure drop performance remains competitive at higher flow rates, further investigation is needed to assess long-term durability, material fatigue, and thermal stability in continuous-use scenarios. Having said that, this design approach offers a scalable and manufacturable solution for engineers working with compact fluidic systems, particularly where simplicity, cost-efficiency, and performance optimization are crucial. Its compatibility with polymer-based fabrication techniques further enhances its applicability in wearable and biomedical devices, where lightweight and flexible materials are often required. Notably, its successful integration into a liquid cooling vest system underscores its practicality and potential for broader applications in micro-scale thermal management systems. The new design of the macro-micro transition section require further study regarding the manufacturing methods without the need for the experimental sealing silicon material. Further, the application of such design is limited to the geometry scales and flow conditions unless further studies consolidate the present study findings in further applications.

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Conflict of interest

The authors declare no competing interest.

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