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Effect of Reynolds Number on the Thermal Resistance and Pressure Drop of a Rectangular Microchannel Heat Sink

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Abstract. Increasing coolant flow in rectangular microchannel heat sinks can enhance cooling performance but also increase pressure drop and pumping requirements, creating a thermo-hydraulic trade-off. This study investigates the effect of Reynolds number on this trade-off for a fixed rectangular microchannel heat sink under steady single-phase water flow. Published numerical and experimental data are analyzed, with a rectangular configuration of aspect ratio AR = 5.180 selected for quantitative evaluation over Re = 200–2000. The thermal-resistance and pressure-drop data are then analyzed using curve fitting and normalization, and normalized thermal-benefit and hydraulic-penalty indicators are introduced to evaluate their combined behavior. The results show that thermal resistance decreases rapidly at relatively low Reynolds numbers but exhibits diminishing improvement as Reynolds number increases, whereas pressure drop continues to rise sharply. A normalized comparison identifies approximately Re = 600–800 as a favorable compromise range for the selected configuration, providing substantial cooling improvement with a relatively limited hydraulic penalty. Although this range is configuration-specific, the proposed normalized framework can be adapted to evaluate Reynolds-number selection in other microchannel thermal-management systems.

Keywords: Reynolds number, rectangular microchannel heat sink, thermal resistance, pressure drop, thermo-hydraulic performance

1. Introduction

The growing heat generation in high power electronic devices and compact engineering systems has led to challenges for the thermal management, which is required to guarantee the reliable operation of the devices [1, 2]. The compact structure, small characteristic dimensions and large heat-transfer area of microchannel heat sinks (MCHSs) make them attractive for high-heat-flux cooling as they enhance heat dissipation [1-3]. Recently, research has also been carried out on structural modifications and optimization approaches to improve the thermal performance of microchannels [4].

Reynolds number depending on coolant velocity affects the flow behavior and heat transfer for a fixed rectangular microchannel. The Reynolds number affects heat-transfer characteristics and flow regimes in rectangular microchannels [5]. In many operation conditions, higher Reynolds numbers are known to improve convective heat transfer [3, 5]. The coupling of thermal and hydraulic

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characteristics has also been reported in microchannel heat exchanger studies, where both heat-transfer performance and pressure drop increase simultaneously with Reynolds number [6].

However, as the Reynolds number increases, the thermal resistance decreases, but the pressure drop and pumping-power requirements increase, resulting in a trade-off between thermal enhancement and hydraulic penalty [3, 6, 7]. Although there are many experimental, numerical and optimization studies on MCHS, it is still important to understand the influence of the operating conditions on the overall thermo-hydraulic performance for practical applications [4, 7]. In particular, many studies address geometric optimization. The thermo-hydraulic trade-off due to Reynolds-number variation alone under a fixed geometry has received less quantitative attention. In addition, thermal resistance and pressure drop differ in both physical dimensions and numerical scales, so they cannot be compared directly. This paper therefore investigates the effect of Reynolds number on the thermal resistance and pressure drop of a fixed rectangular microchannel heat sink using published numerical and experimental data. By introducing normalized evaluation indicators, the study aims to identify a more favorable range of Reynolds numbers and provide a practical framework for evaluating the balance between cooling enhancement and hydraulic cost.

2. Theoretical background

2.1. Reynolds number and flow regime

The Reynolds number is a dimensionless parameter used to characterize the relative importance of inertial and viscous forces in internal flow. For a rectangular microchannel, it can be expressed as:

$$\mathrm{Re} = \frac{\rho u D_h}{\mu} \tag{1}$$

where (ρ) is the fluid density, (u) is the mean flow velocity, (μ) is the dynamic viscosity, and (D_h) is the hydraulic diameter. For a rectangular channel with width (W) and height (H):

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

These definitions are commonly used in microchannel flow studies [8].

In conventional internal flow, Reynolds number is also used to distinguish laminar, transitional, and turbulent regimes. However, the transition criterion in microchannels should be applied with caution because reported critical Reynolds numbers vary with channel geometry, surface roughness, and experimental conditions. Zhao et al. noted that laminar flow is common in microchannels and cited critical Reynolds numbers of approximately 1000–1500 for the conditions considered in their study [8]. Other investigations summarized in the literature show that conventional hydraulic theory can still provide reasonable predictions for single-phase liquid flow in many rectangular microchannels, although deviations have also been reported [9]. Therefore, Reynolds number is used in this study primarily as an operating parameter for comparing flow conditions rather than as a rigid universal criterion for microchannel flow-regime transition.

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2.2. Thermal resistance in microchannel heat sinks

Thermal resistance is commonly used to evaluate the cooling performance of a microchannel heat sink because it relates the temperature rise of the heat sink to the applied heat load. It can be expressed as:

$$R_{th} = \frac{T_{max} - T_{in}}{Q} \tag{3}$$

where (T_{max}) is the maximum temperature of the heat sink, (T_{in}) is the coolant inlet temperature, and (Q) is the total heat input. A lower thermal resistance indicates that a smaller temperature difference is required to remove the same amount of heat and therefore represents better cooling performance [10, 11].

For a given heat load and microchannel geometry, the thermal resistance is strongly dependent on the convective heat transfer between the channel wall and the coolant. Increasing the coolant velocity may improve the convective heat transfer and reduce the maximum wall temperature. This reduces the overall thermal resistance. Gao et al. found that, for a fixed rectangular microchannel configuration, the thermal resistance was rapidly reduced with the increase of Reynolds number from about 200 to 800, while the reduction rate was smaller at higher Reynolds numbers [10]. This behavior suggests that the thermal resistance is a useful parameter for evaluating not only the cooling effectiveness but also the diminishing thermal benefit with further increases in coolant flow rate.

2.3. Pressure drop and pumping power

The pressure drop is the energy loss in hydraulics that occurs when the coolant flows through a microchannel. For the single-phase internal flow, this loss is mainly related to the wall friction, which is influenced by the flow velocity, channel dimensions, surface conditions and flow regime. Experimental studies of rectangular microchannels have demonstrated that classical hydraulic theory can provide reasonable predictions of frictional behavior for many laminar flow regimes [9].

For a fixed channel geometry, increasing Reynolds number implies increasing coolant velocity and flow rate, which in general leads to a higher frictional pressure drop. Seo et al. experimentally found that pressure drop increased with Reynolds number and attributed this trend to increase in mass flow rate and flow resistance [6]. The hydraulic penalty can also be expressed in terms of pumping power,

$$W_{pp} = Q_v \Delta P \tag{4}$$

where (W_{pp}) is the pumping power, (Q_v) is the volumetric flow rate, and (ΔP) is the total pressure drop across the microchannels [10]. Pumping power represents the mechanical power required to maintain coolant flow through the microchannels and therefore provides a direct measure of the energy cost associated with increasing flow rate. This quantity is important for assessing whether additional cooling improvement justifies the corresponding hydraulic demand, forming the hydraulic basis for the thermo-hydraulic trade-off considered later in this study.

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3. Analysis method

3.1. Microchannel configuration and assumptions

The present analysis focuses on the rectangular microchannel configuration referred to as Case 4 in Gao et al. [10]. The selected channel has an aspect ratio of AR = 5.180, with a channel width of W_C = 0.264 mm, a channel height of H_C = 1.366 mm, and a hydraulic diameter of D_h = 0.442 mm [10]. This fixed configuration is used throughout the quantitative analysis so that the influence of Reynolds number can be examined without introducing additional geometric variations.

The coolant is deionized water and is treated as a steady, incompressible, single-phase fluid with no phase change inside the microchannels, consistent with the numerical conditions reported in the source study [10]. The channel geometry and thermal boundary conditions are kept unchanged when different flow conditions are compared. Reynolds number is varied through changes in coolant velocity rather than through changes in channel dimensions. Thermal resistance and pressure drop are therefore compared only within the same configuration and dataset, allowing the observed thermo-hydraulic changes to be primarily associated with variations in Reynolds number.

3.2. Data source and analysis approach

The present study is based on a secondary analysis of published numerical and experimental data rather than new experiments or CFD simulations. The numerical results of Gao et al. are used as the primary quantitative dataset [10]. For the fixed Case 4 configuration defined in Section 3.1, thermal-resistance and pressure-drop data over Re = 200–2000 were extracted from the published figures using an open-source plot-digitization tool. The horizontal and vertical axes were calibrated according to the published scales, and the data points were extracted repeatedly using the same point-selection procedure to evaluate digitization uncertainty. The relative deviation between repeated extractions was kept within approximately 2%. Because the extracted values were reconstructed from published figures, they were treated as approximate data for trend analysis rather than as original raw measurements.

The digitized thermal-resistance and pressure-drop data were further analyzed using empirical curve fitting, with the goodness of fit evaluated using R^2 and RMSE. The fitted relationships were then used to examine the variation of thermal and hydraulic performance with Reynolds number. In addition, normalized thermal-benefit and hydraulic-penalty indicators were introduced to compare the two responses on a common dimensionless basis and to evaluate their thermo-hydraulic trade-off.

Published results from Qu and Mudawar and Seo et al. were used as independent references to assess whether the observed Reynolds-number trends are consistent with those in other single-phase microchannel studies [3, 6]. Because the geometries and operating conditions differ, these studies were used for trend comparison rather than direct comparison of absolute values.

3.3. Thermo-hydraulic performance evaluation

Reynolds number is treated as the primary operating parameter in this study rather than as a performance indicator. The thermal response is evaluated mainly by thermal resistance, R_{th}, while the maximum heat-sink temperature, T_{max}, is used as a supporting quantity. A reduction in thermal resistance at a fixed heat load indicates improved cooling performance [10].

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The hydraulic penalty is evaluated using the pressure drop, ΔP, and pumping power, W_{pp}. These quantities are used to characterize the additional hydraulic and energy requirements which are related to the increase of the coolant flow rate [10]. Thermal resistance and pressure drop are considered the main quantitative responses, while pumping power serves as a secondary measure of the energy required at higher coolant flow rates. Particular attention is paid to whether the reduction in thermal resistance becomes smaller as Reynolds number increases while the hydraulic penalty continues to grow. This comparison provides the basis for the thermo-hydraulic trade-off discussed in Section 4.

4. Results and discussion

4.1. Effect of Reynolds number on thermal resistance

To quantitatively examine the effect of Reynolds number on thermal performance, the rectangular Case 4 configuration reported by Gao et al. was selected, with AR = 5.180, W_C = 0.264 mm, H_C = 1.366 mm, and D_h = 0.442 mm [10]. The thermal-resistance data were digitized from Figure 4(a) of Gao et al. over the Reynolds-number range of 200–2000. For this fixed geometry, the original study reported a rapid reduction in thermal resistance at relatively low Reynolds numbers, followed by a progressively flatter response at higher Reynolds numbers [10].

The digitized data were further analyzed in MATLAB using an asymptotic power-law relation, and the resulting data and fitted curve are presented in Figure 1.

$$R_{th}=0.2412+83.64Re^{-1.227} \tag{5}$$

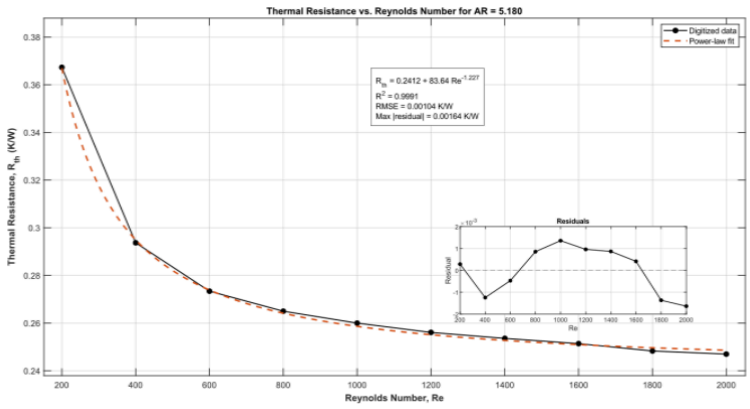

Figure 1. Thermal resistance as a function of Reynolds number for the selected rectangular microchannel configuration with AR = 5.180. The dashed line represents the asymptotic power-law fit

This fit provided a close representation of the extracted data, with R^2 = 0.9991 and an RMSE of approximately 1.04× 10^{-3} K/W. This empirical relation describes the extracted Case 4 data over the investigated Reynolds-number range. The negative exponent indicates that the Reynolds-number-dependent contribution to thermal resistance decreases rapidly as R_e increases, reflecting the diminishing thermal benefit observed at higher flow rates.

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The reduction in thermal resistance is strongly dependent on the Reynolds-number range. From Re = 200 to Re = 800, R_{th} decreases from approximately 0.3673 to 0.2650 K/W, corresponding to a reduction of about 27.9%. In contrast, increasing Reynolds number further from 800 to 2000 reduces R_{th} only from approximately 0.2650 to 0.2470 K/W, an additional reduction of about 6.8%. This demonstrates a clear pattern of diminishing thermal benefit at higher Reynolds numbers.

The observed trend is also consistent with the experimental study of Qu and Mudawar, in which increasing Reynolds number reduced the temperature of a single-phase water-cooled rectangular microchannel heat sink [3]. Therefore, increasing Reynolds number improves cooling effectiveness, but the incremental thermal benefit becomes substantially smaller once the flow rate is sufficiently high. This diminishing return provides the thermal basis for the hydraulic comparison presented in the next section.

4.2. Effect of Reynolds number on pressure drop

To evaluate the hydraulic penalty associated with increasing Reynolds number, the same rectangular Case 4 configuration with AR = 5.180 was analyzed. Pressure-drop data were digitized from Figure 4(b) of Gao et al. over the Reynolds-number range of 200–2000. For this fixed geometry, the original numerical results show a continuous increase in pressure drop as Reynolds number increases [10].

The digitized data were fitted in MATLAB using an empirical power-law relation, and the resulting data and fitted curve are presented in Figure 2.

$$\Delta P = 3.635 \times 10^{-6} Re^{1.487} \tag{6}$$

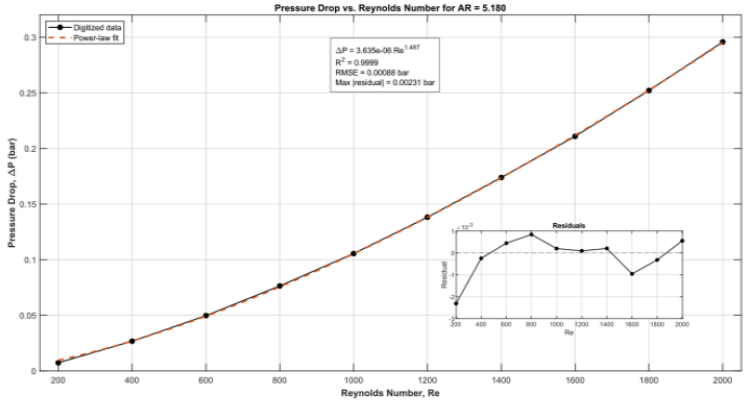

Figure 2. Pressure drop as a function of Reynolds number for the selected rectangular microchannel configuration with AR = 5.180. The dashed line represents the empirical power-law fit

The fitted curve provides a close representation of the extracted data, with R^2 = 0.9999 and an RMSE of approximately 8.8×10^{-4} bar. Since the fitted exponent is greater than unity, the pressure drop increases superlinearly with Reynolds number for the selected configuration and investigated range, indicating an increasingly significant hydraulic penalty at higher Reynolds numbers.

The hydraulic penalty becomes increasingly significant at higher Reynolds numbers. From Re = 200 to Re = 800, ΔP increases from approximately 0.0073 to 0.0764 bar. When Reynolds number is

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further increased from 800 to 2000, the pressure drop rises from approximately 0.0764 to 0.2958 bar, corresponding to an increase of about 287% relative to the value at Re = 800. This behavior contrasts sharply with the thermal response discussed in Section 4.1, where thermal resistance decreased by only about 6.8% over the same Reynolds-number interval.

This hydraulic trend is independently supported by the experimental results of Qu and Mudawar. Their data show that pressure losses increase as Reynolds number rises in a single-phase water-cooled microchannel heat sink. More importantly, the present analysis shows that the hydraulic penalty continues to increase rapidly in the high-Reynolds-number region, where the reduction in thermal resistance has already become relatively limited [3]. This imbalance indicates that further increases in flow rate should not be evaluated solely on the basis of their thermal benefit. Therefore, a combined evaluation of cooling improvement and hydraulic cost is needed to identify a more favorable operating range.

4.3. Trade-off between cooling enhancement and hydraulic penalty

The results of Sections 4.1 and 4.2 reveal an increasingly uneven balance between thermal improvement and hydraulic cost as Reynolds number rises. In particular, increasing Re from 800 to 2000 yields only an additional reduction of approximately 6.8% in thermal resistance, while the pressure drop increases by about 287% over the same interval. This indicates that the thermal benefit becomes progressively weaker at high Reynolds numbers, whereas the hydraulic penalty continues to increase substantially.

Because thermal resistance and pressure drop have different units and magnitudes, their raw values cannot be compared directly. Two normalized quantities were therefore introduced: the normalized thermal benefit, B_T, and the normalized hydraulic penalty, P_H:

$$B_T=[R_{th}(Re_{min})-R_{th}(Re)]/[R_{th}(Re_{min})-R_{th}(Re_{max})] \tag{7}$$

$$P_H=[\Delta P(Re)-\Delta P(Re_{min})]/[\Delta P(Re_{max})-\Delta P(Re_{min})] \tag{8}$$

where $Re_{min}=200$ and $Re_{max}=2000$. In this formulation, both quantities vary from 0 to 1 and represent the fraction of the total thermal improvement and hydraulic penalty accumulated within the investigated Reynolds-number range. Using the fitted relationships obtained in Sections 4.1 and 4.2, the normalized thermal-benefit and hydraulic-penalty curves were calculated over Re = 200-2000 and plotted in Figure 3.

As shown in Figure 3, the thermal benefit increases rapidly at relatively low Reynolds numbers and then gradually approaches saturation, whereas the normalized hydraulic penalty continues to rise. Under an equal-weight criterion based on maximizing B_T-P_H, the largest difference occurs at approximately Re = 665, where B_T = 0.8196 and P_H = 0.1673. Thus, about 82% of the total thermal-resistance improvement available over the investigated range is obtained while only about 17% of the total pressure-drop penalty is incurred. Rather than treating this point as a unique optimum, the broader range of approximately Re = 600–800 is identified as a favorable compromise region for the selected configuration. Within this range, applications that prioritize cooling performance may favor operation toward the upper end, where a larger fraction of the available thermal benefit is obtained, whereas systems with stricter pumping-power constraints may prefer

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operation toward the lower end to limit the hydraulic penalty. For applications requiring a more balanced thermo-hydraulic compromise, operation near the equal-weight point of Re ≈ 665 may provide a reasonable reference.

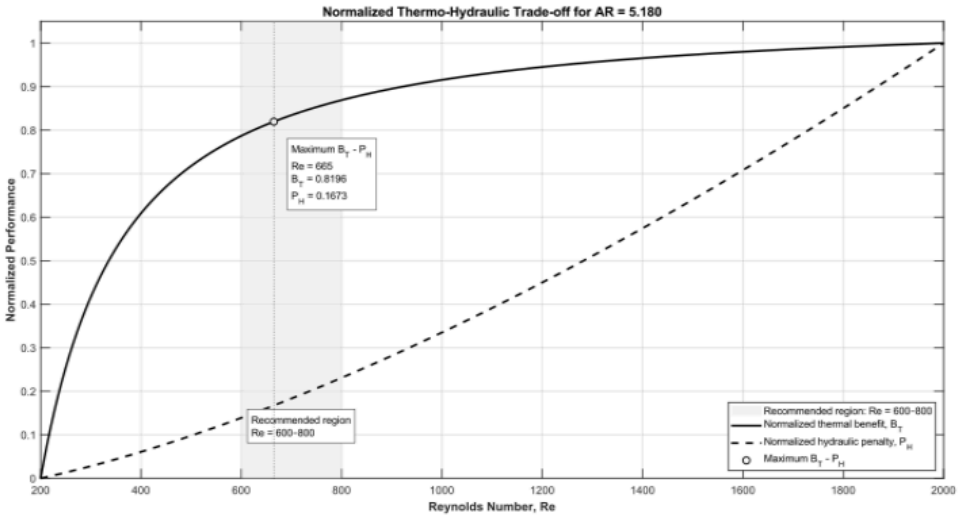

Figure 3. Normalized thermal benefit and hydraulic penalty as functions of Reynolds number for the selected Case 4 configuration with AR = 5.180. The shaded region indicates the favorable compromise range, while the marked point denotes the maximum value of B_T–P_H

This interpretation is further supported by published pumping-power results, which show that thermal resistance decreases rapidly at low pumping power but changes little once W_{pp} exceeds approximately 0.2 W [10]. Experimental studies also report that improved heat-transfer performance at higher Reynolds numbers is accompanied by increased pressure loss [3, 6]. These findings support the conclusion that further increases in Reynolds number may provide limited additional cooling benefit relative to the associated hydraulic cost. The identified range of Re = 600–800 is specific to the selected Case 4 geometry and operating conditions and should not be regarded as a universal optimum. Nevertheless, the normalized thermal-benefit and hydraulic-penalty framework can be adapted to evaluate Reynolds-number selection in other microchannel configurations.

5. Conclusion

This study investigated the influence of Reynolds number on the thermal and hydraulic performance of a fixed rectangular microchannel heat sink under steady single-phase water flow. The results show that increasing Reynolds number can reduce thermal resistance and improve cooling performance, but the additional thermal benefit becomes progressively smaller at higher Reynolds numbers, while pressure drop and hydraulic cost continue to increase. By combining normalized thermal-benefit and hydraulic-penalty indicators, a favorable compromise range of approximately Re = 600–800 was identified for the selected Case 4 configuration. This result demonstrates the importance of evaluating cooling enhancement and hydraulic penalty simultaneously rather than considering thermal performance alone.

Several limitations should be noted. First, the quantitative analysis is based primarily on published numerical data rather than new experiments. Second, only one fixed rectangular microchannel configuration was used for the detailed Reynolds-number comparison. Third, the

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identified favorable range depends on the selected geometry, coolant, and operating conditions and therefore should not be regarded as a universal optimum. Future research may extend this framework to different channel geometries, coolants, and thermal boundary conditions, and may combine experimental measurements with numerical optimization. As microchannel cooling continues to develop for high-power electronics and other compact thermal-management systems, integrated thermo-hydraulic evaluation is expected to become increasingly important for achieving efficient cooling with acceptable pumping requirements.

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