REVIEW ARTICLES

Single-phase convective heat transfer in microchannels*

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Abstract A comprehensive review is conducted on the investigations of the forced single-phase convective heat transfer in non-circular microchannels. The observations and results available in the open literature are inspected and compared for better understanding of the physical nature of the heat transfer performance and providing some lines of future research. There seems to be no unequivocal agreement in the understanding on the relative phenomena and the determination of the heat transfer coefficients in microchannels. The study on the interfacial phenomena and interaction at the interface will be the frontier in this area. Appropriate data reduction and the correlating parameters will be the cornerstone of comparability and evaluation for comprehensive investigations. The selection of correlating parameters will actually be the basis for the better understanding and description of new phenomena.

Keywords: single-phase convection, microchannel, heat transfer, empirical correlation.

As the size of channels diminishes to the order of several hundred to 0.1 micrometer, the fluid flow and heat transfer performance in these microchannels are strongly influenced by the wall effect, and might deviate from the normal situation described by classical theories. Fluid flow and heat transfer characteristics in non-circular channels are usually evaluated from the situations of circular pipes if the diameter D is replaced with a hydraulic diameter, D_h, where the hydraulic diameter is defined as

$$D_h = \frac{4A}{P}. \quad (1)$$

For turbulent flow in channels, this is normally considered rational, however, for laminar flow the use of this length scale induces the inadequacy for predicting flow friction and the heat transfer rate[1,2]. The deviation or inadequacy mainly results from two-dimensional flow and second flow induced by non-circular geometrical configurations. The inadequacy and associated flow influences are reasonably expected in non-circular microchannels. Unlike circular tubes or microtubes, microchannels employed in a wide variety of applications are generally fabricated into different substrates and sealed with cover(s). The geometry of both substrate and microchannel and the structure of microchannel module would cause a series of consequences, including heating/cooling condition of the flow in the channel, thermal effects in the substrate, multichannel configurations, inaccuracy in measuring the microchannel scale (and/or practical length scale variation due to packaging and sealing) and surface performance. Consequently the heat transfer behavior in microchannels should be significantly distinguished from that in circular tubes.

As a well-known term frequently appearing or discussed in literature, microchannel has not been very well defined, or there does not exist a scale range accepted by investigators universally. For convenience and being likely in accordance with the expression by most investigators, the hydraulic diameters of mcirochannels will be limited in the range less than 1000 micrometer hereafter. Single-phase convective heat transfer in microchannels has its unique significance in the development of new technologies and devices for the control of energy transfer and other advanced applications requiring very compact and extremely large heat flux heat exchangers[3,4]. Practical applications involving the thermal control of high-density electronics, bioengineering devices, mini and compact heat exchangers have increasingly utilized microchannels and microstructures capable of unusually high levels of heat removal. For example, the effective cooling of electronic components and de-

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** To whom correspondence should be addressed. E-mail: pxf-dte@mail.tsinghua.edu.cn vices, to dissipate heat in excess of 10^7 W/m^2 at low operating temperatures, is of critical importance for developing ultra large scale integrated circuits. The fundamental and applied research interest in microchannel heat transfer has been increasing and the intense activities have been invariably going on since the earlier 1980s.

From the investigations available in open literature, there seems to be no general conclusion concerning the heat transfer phenomena in microchannels[5~8]. There are several reports indicating slightly higher Nusselt numbers in turbulent flow than those expected. For laminar flow both higher and lower Nusselt numbers were reported. The information in the literature is far from pointing out the unequivocal trends or reasons for such trends. Heat transfer correlations for the average Nusselt number in microchannels in terms of the Reynolds and Prandtl numbers were proposed for laminar and turbulent flow regime as done for the flow in normal sized channels, based on experiments with a range of fluid-substrate combinations, channel dimensions and configurations. Palm[6] concluded that there were still many open questions to be answered before reliable design tools are available in the form of correlating equations for heat transfer of single-phase flow in microchannels. Obot[7] pointed out that there was a need for carefully crafted experimentation aimed at determining pressure drop and heat transfer characteristics, as well as defining the role of transition on heat transfer for single isolated channel geometry. Sobhan and Garimella[8] emphasized that a reliable prediction of the heat transfer was impossible so far, and an additional systematic study was highly needed for carefully considering every parameter influencing transport processes in microchannels.

In the present paper, an attempt is made to conduct a comprehensive review on the investigations of the forced single-phase convective heat transfer in non-circular microchannels.

1 Laminar convection

1.1 Experimental observations

In the earliest research, Tuckerman and Pease[9] experimentally demonstrated that the multi-microchannel heat exchanger designed for electronic cooling could dissipate very high heat density. They noted the heat transfer coefficients for laminar flow through microchannels, having size scale of 50 μm × 300 μm, might be higher than those for turbulent flow through larger, more conventionally sized channels. In the laminar regime, Wu and Little[10] found that the Nusselt number was the function of the Reynolds number with an exponent slightly larger than that in the turbulent regime for microchannels with $D_h = 50 \sim 80$ μm. At lowest Re, the heat transfer results were lower than expected. Harms et al.[11] experimentally demonstrated that the heat transfer results were apparently lower than those obtained using normal correlations for laminar flow at lower Re in rectangular channels having $D_h \leqslant 404$ μm. However, authors considered this deviation to be induced by the flow bypass in the manifold for the multiple channel structure, and by the effect of inlet bend for the single channel design. They concluded that classical heat transfer theories for local Nusselt number would work fine for microchannels.

Contrarily, Rahman and Gui[12] experimentally measured the laminar convective heat transfer in microchannels, and concluded that the Nusselt numbers were higher than those predicted from analytical solutions for developing laminar flow. Recently, Rahman[13] conducted an experimental investigation on the convective heat transfer in microchannels using two different types of microchanneled structures as heat sinks. Further experimental evidences were provided to support the conclusion that the value of average Nusselt number was usually larger than those predicted by correlations for laminar flow in normally-sized channels. The breakage of velocity boundary layer, caused by surface roughness associated with etched channel structure, was believed to be the most important influence enhancing the heat transfer. In the investigation conducted by Cuta et al.[14], it was found that the Nusselt number was substantially larger than the results predicted from the classical laminar flow theory for the rectangular microchannels having hydraulic diameter of $D_h = 425$ μm.

Peng et al.[15] conducted a sequence of experimental investigations on the forced single-phase convection of water in rectangular microchannels having diameter of $133 \sim 367$ μm and found there existed differences in heat transfer performance between microchannels and large channels. They had detailed discussion on the deviation of correlating data.

1.2 Empirical correlations

In available investigations, Peng et al.[15] obtained a great number of experimental data and presented several correlations for convective heat transfer in microchannels. For laminar regime, the heat transfer data were correlated as

$$Nu = C_{h,l} Re^{0.62} Pr^{1/3}, \qquad (2)$$

where $C_{h,l}$, illustrated in Table 1, is an empirical coefficient which was determined from experiments and depended on the microchannel geometric configurations including both the hydraulic diameter and ratio of H/W. Besides the hydraulic diameter, the aspect ratio, H/W, is another important geometrical parameter substantially altering the heat transfer performance. Later, Peng and Peterson[16] conducted an experimental study on the heat transfer of flow through arrays of rectangular microchannels and suggested a laminar convective heat transfer correlation in microchannels as

$$Nu = 0.1165\left(\frac{D_h}{W_c}\right)^{0.81}\left(\frac{H}{W}\right)^{-0.79} Re^{0.62} Pr^{1/3}, \qquad (3)$$

with 367 μm $\geqslant D_h \geqslant$ 133 μm and $900 \geqslant Re \geqslant 80$.

Table 1. Microchannel geometry and coefficients from Peng et al.[15]

Test	W(mm)	H(mm)	L(mm)	D_h(mm)	H/W	$C_{h,l}$	$C_{h,t}$
1	0.4	0.3	50	0.343	0.750	0.0580	0.01340
2	0.3	0.3	50	0.300	1.000	0.0384	0.00726
3	0.4	0.2	50	0.267	0.500	0.0426	0.01660
4	0.3	0.2	50	0.240	0.667	0.0472	0.00926
5	0.2	0.2	50	0.200	1.000	0.0468	0.00696
6	0.3	0.1	50	0.150	0.333	0.0104	0.00483
7	0.2	0.1	50	0.133	0.500	0.0285	0.00939

In his comprehensive comparison and analyses of experimental data in open literature, Obot[7] re-correlated experimental data using classical theories and common dimensionless parameters and gave his recommendation that satisfactory estimates of heat transfer coefficients for smooth microchannels, within the accuracy experimental errors, could be obtained by using either verifiable experimental data or conventional correlations for channels of large D_h. The expressions were given as

$$C_h = Nu/(Re^{1/2}Pr^{0.4}) = 0.14 \qquad (4)$$

and

$$C_{h,f} = Nu/(Re^{3/2} f Pr^{0.4}) = 0.008. \qquad (5)$$

Eq. (4) is for a smooth channel, and Eq. (5) for smooth or rough channels with hydraulic diameter as length scale. It was noted that most data scattered in an appropriate range of the average value predicted by Eq. (4) or (5) with an accepted deviation from classical theory. However, the illustrations still displayed some variable trends from one to another database or experiments for the same or different microchannels.

So far, there exist many valuable observations and measurements for laminar heat transfer, however, popularly accepted correlations and methodologies are highly necessary for accurately predicting the behavior of convective heat transfer in microchannels. At present, it would be better taking both associated experimental results of microchannels available in open literature and the predictions of conventional correlations as referred estimates for practical applications.

1.3 Importance of geometry

From most theoretical and numerical analyses, the geometrical configurations were aware of having significant effects on the convective heat transfer in microchannels, as discussed by Sobhan and Garimella[8]. However, the investigators reached quite contrary conclusions on effects of microchannel geometry. Harms et al.[11] showed that decreasing the channel width and increasing channel depth would provide better heat transfer performance. Bau[17] revealed that channel width might be optimized to reduce non-uniformity of wall temperature. Fedorov and Viskanta[18] numerically analyzed the detailed temperature and heat flux distributions, particularly along the wall surfaces of the microchannel as well as the average heat transfer behavior. Obviously, the width and height result in significant consequence on both flow and heat transfer. Rostami et al.[19] indicated that channel height played an important role in determining heat transfer and there would exist an optimum height minimizing the thermal resistance. They also noted that the thermal resistance was reduced with decreasing substrate and increasing fin thickness. In the experiments of Peng et al.[15] an optimum aspect ratio seems to exist, at which the laminar heat transfer in microchannels reached a peak value. This optimum aspect ratio occurred at approximately $H/W = 0.75$, as shown in Fig. 1. Actually,

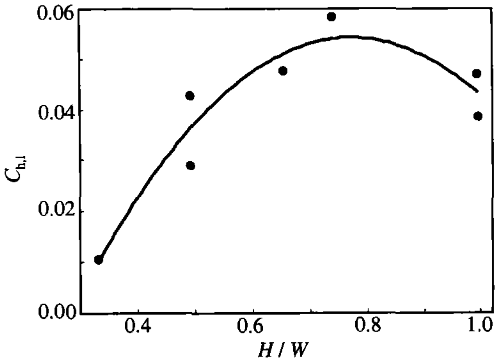

Fig. 1. Variation of coefficient $C_{h,l}$ with H/W[15].

most experimental investigations provided the evidences supporting these experimental observations and theoretical analyses.

However, there are a few investigations showing the less significant influences of microchannel configurations on the heat transfer. A numerical simulation indicated that the effect of microchannel width was much weaker than the analytical predictions[20]. Obot[7] pointed out that H/W and D_h were not important parameters in correlating experimental data.

1.4 Other influences

Besides those normally expected for large channels/tubes and discussed above, some other factors, especially those associated with microchannel configurations, fabrication, microchannel packaging, are certainly convinced to have significant consequence on convective heat transfer in microchannels. In open literature, the discussions and emphases were addressed on the precise measurements, entrance effects, surface roughness, determinations of thermal properties and characteristic parameters such as logarithmic mean temperature difference. Although these probably explicate possible sources of deviations from normal situations for heat transfer performance in microchannels, no consistent conclusions were reached by investigators and there are still new phenomena expected to be of importance for microchannels[6].

2 Turbulent heat transfer

2.1 Flow transition

In open literature it was noted that flow and heat transfer transition in microchannels were different from that in conventional channels and the observations on transition from laminar to turbulent flow were quite different from each other. And also, there is a critical argument on the transition of flow and heat transfer mode[7]. From experimental measurements of both the flow and heat transfer, many researchers observed the flow transition occurring at lower Reynolds numbers. However, some others noted that there were no evidences to support the transition occurring at lower Reynolds number as comparing available data with classical theories. And furthermore, there is an opinion that only laminar flow is possible in microchannels[7]. Obot[7] and Xu et al.[21] attributed the deviation noted by different investigators to the data reduction and dimension uncertainty induced by sealing.

Very few investigations were conducted for understanding the transition heat transfer phenomena, though many researches discussed the flow transition and change of heat transfer modes. At present, the convective heat transfer is highly unclear for transition flow in microchannels. In fact, there was very little information on methods or clear characterizations estimating the occurrence of flow and heat transfer mode transition. No heat transfer correlation proposed is available for this convection in microchannels.

2.2 Turbulent convection

The work of Wu and Little[10] is earliest one in which an empirical correlation was proposed for the turbulent convection in microchannels, expressed as

$$Nu = 0.0022Re^{1.09}Pr^{0.4}, \quad Re > 3000. \quad (6)$$

The most important difference from the conventional correlations is the exponent of Re, and its value is 0.8 for normal situations. Compared with the results of the turbulent heat transfer reported by different investigators in available literature, almost all data were higher than the predictions from conventional correlations, and showed nearly the same trend of Nu changing with Re rather than the results of Wu and Little[10].

The results experimentally obtained by Peng et al.[15] were lower than the others' predictions for $Re > 1000$. They correlated their data and suggested the heat transfer correlation for turbulent flow as

$$Nu = C_{h,t}Re^{0.8}Pr^{1/3}, \quad (7)$$

where $C_{h,t}$ is an empirical coefficient determined from experiments and the values of $C_{h,t}$ are illustrated in Table 1 for different microchannels. As shown in Fig. 2, the empirical coefficient, $C_{h,t}$ was found to be strongly associated with the ratio H/W, where $C_{h,t}$ exhibited a larger value for $H/W = 0.5$ than for 0.75. Obviously, the turbulent convective heat

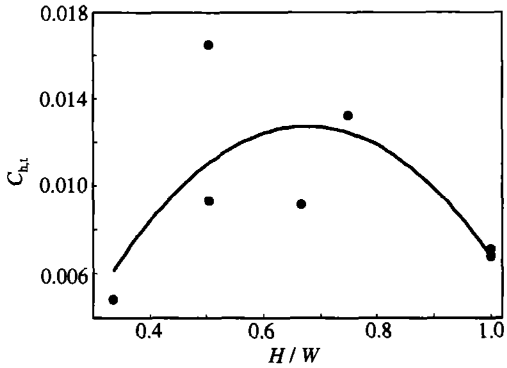

Fig. 2. Variation of coefficient $C_{h,t}$ with H/W[15].

transfer would reach the optimum value when H/W was in the range $0.5\sim0.75$. For turbulent flow through arrays of rectangular microchannels, Peng and Peterson[16] suggested a correlation as

$$Nu = 0.072(D_h/W_c)^{1.15}[1-2.421(Z-0.5)^2] \cdot Re^{0.8}Pr^{1/3}, \qquad (8)$$

where $Z = \{\min(H, W)/\max(H, W)\}$.

Rather than correlating data, more investigators presented their experimental results and tried to explore and/or explain the deviations in microchannels from the classical theories of turbulent heat transfer, as reviewed by Palm[6], Sobhan and Garimella[8]. From their analyses and experiments, Adams et al.[22] concluded that $D_h = 1.2$ was a reasonable lower limit for applicability of standard Nusselt-type correlations to non-circular channels. Obot[7] maintained that the heat transfer could be predicted using classical correlations for large channels. Relatively, the turbulent heat transfer in microchannels is of less importance owing to very small scale. Some researchers even thought that it would be really difficult for the existence of turbulent flow in mcirochannels.

3 Theoretical investigations

The theoretical analyses of heat transfer in microchannels are very limited and mainly focused on the laminar flow[6,8], including numerical simulation using classical theories, modeling and the optimization studies combined conduction in substrates with single-phase convection, and physical understanding of phenomena. Most of available theoretical investigations were conducted to explore the laminar convective heat transfer performance, and the declination was especially made to the theoretical investigations for understanding new phenomena.

Tso and Mahulikar[23~25] employed dimensionless analysis technology to evaluate the importance of thermofluid parameters, and they noted that the Brinkman number, defined as

$$Br = \frac{\mu u_m^2}{k\Delta T} \qquad (9)$$

played a critical role for heat transfer processes in microchannels. This dimensionless number reflects the relative importance of viscous heating to fluid conduction, which is not included in the classical correlations. They conducted a sequence of investigations to account for the effects of Brinkman number on the heat transfer of laminar flow and also on the flow transition in microchannels. From dimensional analysis, they proposed the following correlation of laminar heat transfer[23]:

$$Nu = A'Re^{0.62}Pr^{1/3}f_g(\delta, D_h)Br^d, \qquad (10)$$

where $f_g(\delta, D_h)$ is a function of the geometry of the individual microchannels and microchannel structure (that is, the geometry between two consecutive microchannels), d exponent and A an empirical constant. This correlation is in agreement with the data of Peng et al.[5,15] very well. They noted that Br should be more important in the laminar regime compared to the transition and turbulent regimes. Later, this new type of correlation was supported by their new experimental data[25].

As a unique theoretical analysis for the transition from laminar to turbulent convective heat transfer in open literature, Tso and Mahulikar[24] provided the following two criterions.

For laminar-to-transition boundary,

$$Re_{tr}^{3.4}/Br_{tr} = 3.24\times10^{12}; \qquad (11)$$

for transition-to-turbulent boundary,

$$Re_{tr}^{13.2}/Br_{tr} = 3.38\times10^{42}. \qquad (12)$$

In their investigation, Yang et al.[26] accounted for the effect of electric double layer (EDL) on the heat transfer in microchannels. For rectangular microchannels with shortest side smaller than 40 micrometer, they noted that the EDL effect had significance on the Nusselt number and resulted in lower heat transfer for dilute solutions. Beskok and Karniadakis[27] proposed a physical model including slip flow boundary condition and studied the convective heat transfer of fluid flow in microchannels with Knudsen number greater than 10^{-3}.

Li et al.[28] considered the important significance of the wall effects on the transport processes due to extremely small character scales. A theoretical model, termed as the theory of wall-adjacent layer, was proposed to analyze the effect of geometry on thermal properties of gas flowing in microchannels. The thermal conductivity in a layer very close to the wall would be considerably lower than that in the bulk region due to the gas molecular interaction with the wall. They theoretically derived the thermal conductivity in wall-adjacent layer as

$$\frac{k}{k_b} = 1 - 0.5e^{-1.35y/l}. \qquad (13)$$

The ratio k/k_b varies from 0.5 at the surface to 1 at a distance of three to five times the mean free path of the molecules. Combined with the effect of geometry on the flow and fluid properties for $Kn > 0.005$, the heat transfer relations in terms of Nusselt number in the fully developed laminar flow were deduced as

$$Nu = \frac{5.3846(1 + 3.0807Kn)^2}{1 + 7.1882Kn + 12.7756Kn^2} \quad (14)$$

for constant heating from one-side wall, and

$$Nu = \frac{8.2353(1 + 3.0807Kn)^2}{1 + 7.1882Kn + 13.0260Kn^2} \quad (15)$$

for constant heating from top and lower walls. In Eqs. (20) and (21) Kn is Knudsen number, defined as

$$Kn = \lambda / D_h. \quad (16)$$

4 Discussion

4.1 Difficulties in testing

From the overview of available investigations as discussed above, no unequivocal agreement was reached in understanding the phenomena and determining the heat transfer coefficients in non-circular microchannels. A number of investigators tried to explain the deviation of the experimental observations from the conventional situations and/or to present some new understanding for new phenomena. It is absolutely clear that accurate methodologies are highly necessary for experimental measurements and test procedures and some fundamentals of fluid flow and heat transfer should be identified for microchannels. Considering the small size of microchannels, any inaccurate measurements, including the determination of thermal-fluid parameters and geometrical scale, would result in significant error and deviation.

From authors' experience, the measurements of flowrate, local temperature and pressure, heat input and other quantities were highly uncertain, and close attention must be paid to measurements. These uncertainties accordingly induced serious scatter of the data, perhaps partially resulted in the deviation of experimental observations from the normal cases.

A few investigations have recognized the effects of scale uncertainty on observing and understanding the heat transfer phenomenon in microchannels. Recently, Xu et al.[21] made an attempt to carefully conduct experimental investigation of heat transfer in microchannels and to comprehensively analyze the consequence of any uncertainties in determining microchannel scale on the flow and heat transfer performance. They found that the packaging of microchannels with coverage, besides the non-uniform and difficulty in microscale measurement, induced extra uncertainty of geometrical scale. Additionally, the leakage due to the sealing problem between microchannels also generated big error in determining flowrate through a single microchannel. From careful analyses, they noted that the flow characteristics in microchannels are very well consistent with the classical theories if the above measurement errors did not exist.

4.2 Data processing and correlating

If attention was paid to the data reduction in open literature, it would be easy to note that the methodologies and procedures employed by various investigators in processing experimental data exhibit some inconsistency with each other. The inconsistency of data reduction, for example those in defining some parameters, determining character temperatures and thermophysical properties, makes the comparative evaluations of the published data truly difficult, and has been convinced to be one of important reasons inducing the discrepancy of available results in the literature.

In comprehensively comparative evaluation of the published results conducted by Obot[7], it was exceptionally significant what parameters were chosen to correlate and illustrate the results. By re-correlating the published heat transfer results in microchannels using Eq. (4) or (5), Obot[7] indicated that estimates of heat transfer coefficients for smooth microchannels, being accurate within experimental errors, could be obtained using either conventional correlations or experimental results for large channels. He further noted that the effects of roughness on the heat transfer were much less pronounced than on pressure drop under identical flow conditions.

Obot's work[7] and some others', such as the investigation by Xu et al.[21] strongly demonstrated the critical importance of correlating parameters and methodologies in the process of experimental data, which should be one of the most important aspects for understanding the flow and heat transfer performance in microchannels. As aforementioned, appropriate parameters are critical for describing new phenomena and including the effects associated with geometry on the heat transfer in microchannels. In fact, the problems concerning the correlating and illustrating of the experimental results highly reflect the degree of understanding of fundamental phenomena and getting insight into the physical nature.

4.3 Interfacial influences

Usually, it is expected that there are some unfamiliar phenomena and effects of miniaturization on convective heat transfer in microchannels due to the decrease of scale. One of the most conspicuous alteration for microchannel heat transfer is a dramatical increase in the ratio of solid-fluid interface per unit volume. This would make the interfacial phenomena and interactions occurring at the interface or in interfacial region, which would greatly alter the characteristics of transport processes. The above-mentioned and discussed scale effects, such as electric double layer[26], convection with slip flow condition at the wall[27], variable thermal property induced by gas molecular interaction with the wall[28], and viscous heating[23~25], alter heat transfer mechanism. Though the rather trivial causes discussed in above sections are not negligible, there are also new phenomena being of importance.

The shortage of the knowledge on the interfacial phenomena has seriously impeded the progress in understanding convective heat transfer characteristics in microchannels. Specifically the microscopic interactions between solid and fluid at the interface should play the key role in the transport processes. So far, there is a few researches concerning interfacial transport processes and phenomena. The release of noncondensable gas absorbed at the solid surface of microchannels or existing in bulk liquid was found to affect the convective heat transfer greatly[29]. Yang et al.[26] explored that the existing electric double layer resulted in strong corner and wall effects and altered the temperature field of fluid in the region near to channel wall. In a few of investigations, researchers accounted for the effects of chemical and biochemical reactions, mass penetration, and other interfacial phenomena on flow and heat transfer in microchannels and the application of microchannel heat exchangers[3~8].

4.4 Other considerations

The role of geometrical scale in confined flow passages and the interface phenomena are still highly open questions for the flow and heat transfer, particularly for the heat transfer regime transition in microchannels. Apparently, new physical phenomena are still expected, while available experimental observations are controvertible. No correlation or methodology is available for accurately predicting the convective heat transfer in microchannels or is confidently employed in practical design of microchannel heat exchanger. At present, a reasonable suggestion is to take both associated available experimental results of microchannels and predictions of conventional correlations as reference estimates for practical applications.

Nomenclature

A	Area of microchannel cross-section, (m^2)
A'	Empirical constant in Eq. (16), (-)
Br	Brinkman number defined in Eq. (15), (-)
C_h	Empirical constant in Eq. (4), (-)
$C_{\mathrm{h,f}}$	Emprical constant in Eq. (5), (-)
$C_{\mathrm{h,l}}$	Empirical coefficient in Eq. (2), (-)
$C_{\mathrm{h,t}}$	Empirical coefficient in Eq. (3), (-)
d	Exponent in Eq. (16), (-)
D_h	Hydraulic diameter, (m)
f	Flow friction coefficient, (-)
H	Microchannel height, (m)
k	Thermal conductivity, ($\mathrm{Wm^{-1}K^{-1}}$)
k_b	Thermal conductivity in bulk liquid region, ($\mathrm{Wm^{-1}K^{-1}}$)
Kn	Knudsen number defined in Eq. (22), (-)
l	Spacing distance of parallel plates micro passage, (m)
Nu	Nuseelt number, (-)
P	Wetted perimeter, (m)
Pr	Prandtl number, (-)
Re	Reynolds number, (-)
T	Temperature, (K)
u_m	Average velocity, (m/s)
W	Microchannel width, (m)
W_c	Spacing distance between two consecutive channels, (m)
y	Distance from wall, (m)
Z	$Z=\{\min(H, W)/\max(H, W)\}$, (-)
δ	Critical microchannel dimension in Eq. (16), (m)
λ	Mean free path, (m)
μ	Dynamic viscosity of fluid, ($\mathrm{Nsm^{-2}}$)

Subscripts

b	Bulk fluid
h	Hydraulic or heat transfer
tr	Transition

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