The Review of Studies on Pressure Drop and Heat Transfer in Microchannels

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ABSTRACT: This paper reviews the studies on the pressure drop and the heat transfer in microchannels. Although a lot of studies about the single-phase flow have been done until now, conflicting results are occasionally reported about flow transition from laminar flow to turbulent flow, friction factor, and Nusselt number. Some studies reported the early flow transition due to relatively greater wall effect like surface roughness, but the other studies showed that the flow transition occurred at the Reynolds number of about 2300 and the early flow transition might be due to less accurate measurement of the channel geometry. Also, there have been arguments whether the conventional relation based upon continuum theory can be applied to the fluid flow and the heat transfer in microchannels without modification or not. The studies about the two-phase flow in microchannels have been mostly about investigating the flow pattern and the pressure drop in rectangular channels using two-component, two-phase flow like air/water mixture. Some studies proposed correlations to predict two-phase flow pressure drop in microchannels. They were mostly based on Lockhart-Martinelli model with modification on C-coefficient, which was dependent on channel geometry, Reynolds number, surface tension, and so on. Others investigated the characteristics of flow boiling heat transfer in microchannels with respect to test parameters such as mass flux, heat flux, system pressure, and so on. The existing studies have not been fully satisfactory in providing consistent results about the pressure drop and the heat transfer in microchannels. Therefore, more in-depth studies should be done for understanding the fundamentals of the transport phenomena in the microchannels and giving the basic guidelines to design the micro devices.

Nomenclature

D_h : diameter [m]
f : friction factor
f_{theory} : theoretical friction factor
G : mass flux [kg/m^{2}s]
H : height [m]
Q : volume flow rate [ml/min]
q'' : heat flux [kW/m^2]
Re : Reynolds number
U : sperficial velocity [m/s]
W : width [m]

Subscripts

G : gas phase
L : liquid phase

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1. Introduction

The maximum heat transfer rate, minimum pumping power, and the minimum manufacturing cost have been the most important considerations when the heat exchanger is designed. In the past, the third objective has forced thermal system design in the direction of high-turbulence heat exchangers to take advantage of the high heat transfer coefficient associated with turbulent flow.(1)

However, the great pumping power can be unavoidable to the high-turbulence heat exchangers. The vibration generated by the turbulence can shorten the life of the heat exchanger. Bejan(2) showed that the non-turbulence and the minimum temperature difference can give high efficiency to the heat exchangers. The non-turbulence means the laminar flow regime and it can lead to the low level of vibration. The compact heat exchangers having the micro-sized flow passages can be one of the good alternatives to the conventional heat exchangers.

A lot of attention has been paid to the transport phenomena in the micro geometries because they have a variety of advanced applications in the micro-electro-mechanical systems (MEMS), electronic cooling systems, bioengineering, and others. The application of microelectronics has created an entirely new research area. The evolution of ink-jet printing can be a good example. It showed that the boiling heat transfer is a very important phenomenon in micro head of ink-jet printer.(3) In spite of the brilliant development of micro fabrication, the transport phenomenon in the micro geometries is still one of the unexplored fields in engineering because of the many difficulties in the experiments and the analyses.

The studies on the pressure drop and the heat transfer in the microchannels should be requisites for understanding the fundamentals of the transport phenomena in the microchannels and they can give the basic guidelines to design the micro devices. A lot of studies have been recently done in order to investigate the characteristics of the pressure drop and the heat transfer in the microchannels. Therefore, this paper has objectives to review the previous studies about pressure drop and heat transfer in microchannels and summarize the up-to-date research trend about them.

2. Single-phase flow in microchannels

A lot of the existing studies have addressed the singe-phase flow in microchannels. Table 1 is the summary of the studies on the single-phase flow pressure drop and the single-phase flow heat transfer in the microchannels.

2.1 Pressure drop

Wu and Little(4) tested the trapezoidal channels using nitrogen. They showed that the friction factors for glass channels were three to five times greater than the predicted values and flow transition occurred at Re≅400. Pfahler et al.(5) found that the friction factors were smaller than predicted values and increased with increasing Reynolds number. Choi et al.(6) tested the various circular tubes using nitrogen and found that the friction coefficient was 53 and the Colburn analogy was not valid for the microtubes they tested. Peng et al.(7,8) showed that the flow transition occurred at Re≅200~700 and the transition Reynolds number decreased with decreasing hydraulic diameter. Arkilic et al.(9) performed 2-D analysis with slip boundary condition with helium and gave the relationship between the flow rate and the pressure based on the slip flow boundary condition. Yu et al.(10) tested three kinds of the silica microtubes and proposed the correlations for each flow regime. Peng and Peterson(11) tested the microchannels using the water/methanol mixtures. They showed that the transition oc-

Table 1 Summary of the previous studies on the single-phase flow pressure drop and the single-phase flow heat transfer in the microchannels

Investigators	Geometry	Dimension	Fluid
Tuckerman(19)	Rectangular channel	W=50 μm, H=300 μm	$H_2O^{(H)}$
Wu and Little(4,20)	Trapezoidal channel	W=130~300 μm, H=30~60 μm	$N_2^{(P,H)}$
Pfahler et al.(5)	Rectangular channel	A_c=80~7200 μm^2	n-propanol$^{(P)}$
Choi et al.(6)	Circular tube	D_h=3~81 μm	$N_2^{(P,H)}$
Wang and Peng(21)	Rectangular channel	W=0.2~0.8 mm, H=0.7 mm	H_2O, $CH_3OH^{(H)}$
Peng et al.(7,8)	Rectangular channel	W=0.2, 0.3, 0.4 mm, H=0.1, 0.2, 0.3 mm	$H_2O^{(P,H)}$
Arkilic et al.(9)	Rectangular channel	W=52.25 μm, H=1.33 μm	$He^{(P)}$
Peng and Peterson(22,23)	Rectangular channel	W=0.2~0.8 mm, H=0.7 mm	H_2O, $CH_3OH^{(P,H)}$
Yu et al.(10)	Circular tube	D_h=19~102 μm	N_2, $H_2O^{(P)}$
Peng and Peterson(11)	Rectangular channel	W=0.1~0.4 mm, H=0.2, 0.3 mm	H_2O, $CH_3OH^{(P,H)}$
Adams et al.(24)	Circular tube	D_h=0.10~1.09 mm	$H_2O^{(H)}$
Harms et al.(25)	Rectangular channel	W=25.00, 0.251 mm, H=1.00, 1.03 mm	$H_2O^{(H)}$
Mala and Li(12)	Circular tube	D_h=50~254 μm	$H_2O^{(P)}$
Faghri and Turner(13)	Rectangular channel	D_h=4~100 μm	$He^{(P,H)}$
Tu and Hrnjak(14)	Rectangular channel	D_h=69.5~304.7 μm	R134a$^{(P)}$
Lee and Garimella(15)	Rectangular channel	D_h=318~903 μm	$H_2O^{(P,H)}$
Hwang and Kim(16)	Circular tube	D_h=244~792 μm	R-134a$^{(P)}$

P: pressure drop, H: heat transfer

curred at Re=70~400 and the fully developed turbulent heat transfer was achieved at Re=200~700. Mala and Li(12) investigated the effect of the surface roughness on the single-phase flow pressure drop using the microtubes made of stainless steel and fused silica. They concluded that the friction factors were greater than those predicted by the conventional theory, and the fused silica microtube required greater pressure drop than the stainless steel tube. Faghri and Turner(13) gave the experimental results for the gas flow in the rectangular channels made of silicon wafers. They showed that the friction factors agreed closely with the theoretical values and there was no significant effect outside the bounds of uncertainty on the friction factors. Tu and Hrnjak(14) tested the several microchannels and concluded that when the channel surface roughness was low, even for the smallest channel tested, the laminar friction factor and the critical Reynolds number approached the conventional values. Lee and Garimella(15) showed that at Re≅2000, the experimental results start to deviate from the laminar predictions, indicating the onset of the transition. Hwang and Kim(16) tested three kinds of microtubes with an inner diameter of 0.244 mm, 0.430 mm, and 0.792 mm, respectively. They showed that the early flow transition was not found in microtubes.

There have been a lot of studies on the single-phase flow pressure drop and the single-phase flow heat transfer, but the results are different among them in presenting the transition Reynolds number and the friction factor. Some studies showed that the friction factors were greater than the values predicted by the conventional theory, but others showed that they were smaller. The others gave the result that the friction factor satisfactorily agrees with the conventional theory.

Wu and Little(4) carried out an experimental study with nitrogen in the trapezoidal microchannels made of silicon and glass and presented the result that flow transition occurrs at $\mathrm{Re} \cong 400$. Peng et al.(7) showed in their study that the transition from laminar flow to turbulent flow occurs at $\mathrm{Re} \cong 700$ for $D_h > 267\ \mu\mathrm{m}$. They explained that the intensity of the velocity fluctuation due to the inertial force and viscosity required to initiate the turbulence is smaller than that for the normal flow in large or macro ducts, and any wall effect would easily and quickly penetrate into the main stream fluid zone and influence the entire flow. Mala and Li(12) performed an experimental investigation on flow characteristics with water in the circular microtubes made of silica and stainless steel. They gave the results that the experimental data showed a significant departure regarding the flow characteristics from the predictions of the conventional theory for microtubes with smaller diameters and there might be an early transition from laminar to turbulent flow mode at $\mathrm{Re} > 300 \sim 900$. They mentioned that the presence of surface roughness affects the laminar velocity profile and decreased the transitional Reynolds number.

However, Lee and Lee(17) did not find the early transition in the single-phase flow pressure drop test with the microchannels with a hydraulic diameter of 0.784 mm. Lee and Garimella(15) showed that the flow transition was not so early as in Wu and Little,(4) Peng et al.,(7) and Mala and Li.(12) Obot(18) concluded that there is hardly any evidence to support the occurrence of transition to turbulence for $\mathrm{Re} < 1000$ and the early transition at Reynolds number as low as 400 in Wu and Little(4) and 700 in Peng et al.(7) can be ascribed to possible experimental errors. Hwang and Kim(16) also could not find the early flow transition at $\mathrm{Re} < 1000$. They showed that the flow transition at least down to the diameter of 0.244 mm occurs at $\mathrm{Re} \cong 2000$ or less like the conventional tubes.

There have been controversial results about whether the conventional theory can predict friction factors in microtubes. Wu and Little(4) showed that the friction factors for glass channels were 3 to 5 times larger than smooth-pipe prediction. Pfahler et al.(5) concluded that the product of friction factor and Reynolds number ranges from 73% to 105% of theoretical values for isopropanol and silicon oil and from 81% to 98% for nitrogen and helium. Choi et al.(6) showed that friction factors were

Table 2 The conflicting results between the existing studies about the friction factor of the single-phase flow

Investigator	$f > f_{theory}$	$f \cong f_{theory}$	$f < f_{theory}$
Wu and Little(4)	√		
Pfahler et al.(5)		√	
Choi et al.(6)			√
Peng et al.(7)	√		√
Yu et al.(10)			√
Peng and Peterson(11)	√		√
Mala and Li(12)	√		√
Faghri and Turner(13)		√	
Tu and Hrnjak(14)	√		
Lee and Garimella(15)		√	
Hwang and Kim(16)		√	
Lee and Lee(17)		√	

smaller than those from the conventional fluid theory and the product of friction factor and Reynolds number was 53, instead 64. Peng et al.(7) also gave the result that friction factors were greater than the predicted values but the product of friction factor and Reynolds number was not constant with increasing Reynolds number. Mala and Li(12) showed that measured friction factors were greater than the values from the classical theory. They mentioned that the relative surface roughness might mainly cause larger friction factors of microtubes.

However, Faghri and Turner(13) found through their experimental results that there was a close agreement between the measured friction factors and the theoretical values and the friction factors of gas flow were dependent on Mach number and Knusden number as well as Reynolds number. They gave a different result that for the range of relative surface roughness $0.001 < \varepsilon / H < 0.06$, there was no significant effect outside the bounds of uncertainty on the friction factor for laminar flow. Hwang and Kim(16) showed in their experimental tests that the conventional theory can expect the friction factors well within an absolute average deviation of 8.1%. They concluded that the conflicting results about the friction factors are likely to be due to the less accurate measurement of the geometries of the microchannels and experimental errors. Although many studies have been done as explained, there still exist conflicting results.

2.2 Heat transfer

The studies until the mid-1990s showed that the classical theory can not predict the heat transfer coefficients in micro geometries, but the many recent studies had the different conclusion that it can reasonably predict the heat transfer coefficients in micro geometries. It is true that there are conflicting results among the researchers.

Tuckerman(19) first introduced a microchannel heat sink. He tested the rectangular channels using water as a test fluid and showed that the electronic devices can be effectively cooled with the water flow in the microchannels fabricated on themselves. Wu and Little(20) did a heat transfer test and gave a correlation for Nusselt number in the turbulent regime. Choi et al.(6) measured the Nusselt numbers of the nitrogen gas flow in the microtubes of which inner diameters are less than 80 μm. They found that the measured heat transfer coefficients in laminar flow were smaller than the theoretically predicted heat transfer coefficients and were proportional to the $Re^{1.17}$. Wang and Peng(21) tested the multi-microchannels with the width of 0.2 mm to 0.8 mm and the height of 0.7 mm. They found that the heat transfer in laminar flow was highly affected by the liquid velocity, liquid temperature, and the microchannel size and the turbulent convection started at $Re \cong 1000 \sim 1500$. Peng et al.(8) tested the rectangular microchannels having the hydraulic diameters of 0.133 mm to 0.367 mm. They showed that measured Nusselt numbers of water flow were smaller than the predicted Nusselt numbers and were proportional to $Re^{0.62}$. Also, they found that the laminar heat transfer ceased at the Reynolds number of 400 to 1500. Peng and Peterson(22) investigated the effect of the thermophysical properties and the geometry on the heat transfer. They found that the flow transition and the heat transfer were influenced by the liquid temperature, liquid velocity, Reynolds number, and the channel dimension. Peng and Peterson(23) carried out a test on the single-phase flow heat transfer and proposed the correlations for the microchannels. Adams et al.(24) studied on the turbulent, single-phase flow heat transfer with the circular tubes. Their experimental results showed that the Nusselt numbers for the microchannels were greater than those predicted with the theoretical correlation. They also proposed the correlation to predict the turbulent heat transfer.

Some of the recent studies gave the different results about the heat transfer in microchannels. Harms et al.(25) investigated the single-phase heat transfer of the deionized water in deep rectangular microchannels. They found that the experimentally obtained local Nusselt numbers agree reasonably well with classical theory. Sobhan and Garimella(26) did a comparative study on the existing studies and reached a conclusion that there is no evidence that continuum assumptions are violated for the microchannels. They added that the discrepancies between the existing studies may be due to entrance and exit effects, nonuniformity of the channel dimensions, and the uncertainties and the errors in the instruments. Lee and Garimella(15) tested the five microchannels with the hydraulic diameters ranging 0.318 to 0.903 mm. They found that the heat transfer in the microchannels is satisfactorily predicted with a classical continuum approach.

The literature review of the pressure drop and the heat transfer of single-phase flow shows that the existing studies could not give consistent results. Therefore, it is strongly recommended that in-depth studies should be done to understand the fundamental phenomena in microchannels.

3. Two-phase flow in microchannels

Most of the existing studies have mainly focused on the single-phase flow. There have been only a few studies on two-phase flow pressure drop and heat transfer in microchannels. Table 3 is the summary of the previous studies addressing the two-phase flow pressure drop and the two-phase flow heat transfer in microchannels and microtubes.

3.1 Pressure drop

Moriyama et al.(27) performed an experimental study on the two-phase flow pressure drop in microchannels with the height of 5 to 100 μm with N_2-R113 mixture flow, and found that the two-phase multipliers were smaller for the microchannels. They showed that Lockhart and Martinelli(28) equation with the coefficient $C=0$ gave a good agreement with the experimental values. Mishima and Hibiki(29) tested various circular tubes with an inner diameter ranging from 1 mm to 4 mm using air/water mixture, and proposed the correlation to predict the two-phase flow pressure drop and showed that C-coefficient was dependent on the hydraulic diameter only. Lee and Lee(38) carried out an experimental study on the two-phase flow pressure drop in the horizontal rectangular channels of which height ranged from 0.4 to 4 mm while the channel width was fixed at 20 mm. They proposed the Lockhart-Martinelli type correlation with the modification on parameter C.

3.2 Flow visualization

Triplett et al.(30,31) visualized the flow patterns in the microtubes and the microchannels. They found that the bubbly, churn, slug, slug-annular, and the annular flow patterns were observed, and the existing models overpredicted the void fraction and the pressure drop. Coleman and Garimella(32) also did a visualization test for the microchannels. The surface tension, hydraulic diameter, and the aspect ratio affected the flow patterns of the two-phase flow in the microchannels. Kawahara et al.(33) investigated the flow pattern, void fraction, and pressure drop in the circular tube. They found that the bubbly flow and the churn flow were not observed and void fraction remained low even at high gas flow rates. Serizawa et al.(34) visualized the two-phase flows in the circular tubes using a microscope and showed the several distinctive flow patterns.

Table 3 Summary of the previous studies on the two-phase flow pressure drop and the two-phase flow heat transfer in the microchannels

Investigators	Geometry	Dimension	Fluid	Test ranges
Moriyama et al.(27)	Rectangular channel	W=30 mm H=7~98 μm	N_2/R-113(P)	U_G: 0.1~7.0 m/s U_L: 0.002~0.43 m/s
Peng and Wang(35)	Rectangular channel	W=0.6 mm H=0.7 mm	H_2O(H)	ΔT_{sub}: 40~70℃ v: 1.5~4.0 m/s
Bowers and Mudawar(36)	Circular tube	D_h=2450, 510 μm	R-113(H)	q'' : 0~200 W/cm^2 Q: 0~95 ml/min
Mishima and Hibiki(29)	Circular tube	D_h=1~4 mm	Air/H_2O(P)	U_G: 0.0896~79.3 m/s U_L: 0.0116~1.67 m/s
Raviglururajan(37)	Rectangular channel	W=270 μm H=1000 μm	R-124(H)	q'' : 0~70 W/cm^2 Q: 35~300 ml/min
Triplett et al.(30,31)	Circular tube/ triangular channel	D_h=1.1, 1.45 mm D_h=1.09, 1.49 mm	Air/H_2O(P)	U_G: 0.02~80.0 m/s U_L: 0.02~8.0 m/s
Coleman and Garimella(32)	Circular tube/ rectangular channel	D_h=1.3~5.5 mm	Air/H_2O(P)	U_G: 0.1~100.0 m/s U_L: 0.01~10.0 m/s
Lee and Lee(38)	Rectangular channel	W=20 mm H=0.4~4 mm	Air/water(P)	U_G: 0.05~18.7 m/s U_L: 0.03~2.39 m/s
			R-113(H)	G: 50~200 kg/m^{2}s q'' : 0~15 kW/m^2
Kawahara et al.(33)	Circular tube	D_h=100 μm	N_2/H_2O(P)	U_G: 0.1~60.0 m/s U_L: 0.02~4.0 m/s
Serizawa et al.(34)	Circular tube	D_h=20~100 μm	Air/H_2O(P)	U_G: 0.0012~295.3 m/s U_L: 0.003~17.52 m/s
Hwang and Kim(39)	Circular tube	D_h=244~792 μm	R-134a(P,H)	G: 140~950 kg/m^{2}s q'' : 5~40 kW/m^2

P: pressure drop, H: heat transfer

3.3 Heat transfer

Peng and Wang(35) tested the single-phase flow heat transfer and the boiling heat transfer, and concluded that the heat flux for the microchannels was greater than that for the conventional-sized tubes and the nucleate boiling was intensified. Bowers and Mudawar(36) tested the multitubes and showed that microchannel (D_h=510 μm) had greater CHF than the minichannel (D_h=2450 μm) by 28% at the flow rate of 64 ml/min. Ravigururajan(37) tested the parallel pattern microchannel and the diamond pattern microchannel. He found that the mass quality, mass flux, and the heat flux affected the flow boiling heat transfer of R-124. Also, he showed that the heat transfer coefficient decreased from a value of 12 kW/m^{2}K to 9 kW/m^{2}K at 80℃ when the wall superheat is increased from 10 to 80℃.

Lee and Lee(38) studied the two-phase flow heat transfer for the rectangular channels using R-113. They found that the effect of the heat flux on the heat transfer appeared to be minor and proposed the new heat transfer correlation. Hwang and Kim(39) performed an experimental study on the flow boiling heat transfer in single microtubes with an inner diameter of 0.244, 0.430, and 0.792 mm, respectively. They showed that the existing correlations like Gungor and Winterton,(40) Jung et al.,(41) Kandlikar,(42) Kew and Cornwell,(43) Shah,(44) and Tran et al.(45) failed to predict the two-phase flow heat transfer coefficients in microtubes because the existing correlations did not consider the laminar heat transfer of the liquid-phase flow and increasing surface tension effect in micro geometries. They proposed a new correlation to predict two-phase flow heat transfer coefficients in microtubes in the form of the enhancement model.

Although some studies about the two-phase flow in microchannels have been done until now, they are mostly about the pressure drop of two-phase flow for two-component mixture. More studies should be done to investigate the fundamentals of pressure drop and heat transfer mechanism of two-phase flow which experiences phase-change.

4. Conclusions

Micro fabrication enables us to manufacture the micro thermal systems as well as the flow channels ranging from a few micro meters to a few hundred micro meters. A lot of studies have been done for the fundamental understanding about the transport phenomena in micro geometries. However, they are not so successful in providing consistent results about the pressure drop and the heat transfer in microchannels: Does the flow transition occur earlier in microchannels? Can the conventional theory be applied to get the friction factor and the Nusselt number of the fluid flow in microchannel? The studies about the two-phase flow in microchannels are mostly about the flow patterns and the pressure drop in rectangular channels using two-component, two-phase flow like air/water mixture. They proposed correlations to predict two-phase flow pressure drop in microchannels. A few studies have investigated the characteristics of flow-boiling in microchannels in spite of the inherent experimental difficulties. Therefore, more studies should be done in the future to understand the transport phenomena in microchannels and to give the basic guidelines in designing the micro devices.

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