Impact of secondary flow on the single-phase flow in spiral microchannels: An experimental study

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Abstract
Spiral microchannels have a wide range of applications, such as microscale cooling, fluid mixing and particle sorting, in micro-fluidic devices. The flow characteristics of spiral microchannels play an important role in the design and operation of these devices. An experimental study of the laminar flow characteristics in spiral microchannels is conducted for different Reynolds numbers from 51 to 985. Microchannels have rectangular cross sections and follow Archimedean spiral pathways with different spiral and cross-section parameters. The results show that the pressure drop of the spiral microchannel increases with increasing spiral diameter and aspect ratio, but decreases with spiral pitch and hydrodynamic diameter. In addition, the effect of the spiral and cross-section parameters on pressure drop is evident at the high Reynolds number. Under the influence of additional friction caused by the secondary flow, the friction factor of the spiral microchannel is higher than that of the straight channel, and its value increases with the increase in curvature of the microchannel. The correlation of the Poiseuille number in the spiral microchannel is established on the basis of the experimental results, and 95.3% of the experimental data fall within the error band of ± 18%.

Keywords
Spiral microchannel, pressure drop, friction factor, Poiseuille number, secondary flow

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Introduction
The characteristic of single-phase flow in the microchannel has become increasingly important due to the miniaturization of fluid and thermal systems. The efficiency of heat and mass transfer can be improved in the curved microchannel owing to the secondary flow, which was formed by centrifugal force due to the bending effect. Thus, curved microfluidic channels are widely used in microscale cooling, fluid mixing, and particle sorting.1–3 Research on the straight microchannel provided the basis for studying the flow characteristics in the curved microchannel. Tuckerman and Pease4 proposed the pioneering work of single-phase flow in the straight microchannel. Subsequent researchers investigated the characteristics of single-phase flow in straight microchannels. Peiyi and Little5 investigated the friction factors of various gases in trapezoidal microchannels with hydraulic diameters of 55.81–83.08 μm. Experimental measurements of the friction factors were higher than the conventional prediction because of the considerable relative roughness observed in their work. Peng and Peterson6 studied the effects of geometric configuration on the flow characteristics of water flowing in a microchannel. They concluded that...
the friction factor of a laminar flow can reach the minimum value when the aspect ratio approaches 0.5. Qu and Mudawar experimentally and numerically explored the heat transfer and pressure drop characteristics of a heat sink composed of an array of rectangular microchannels. The experimental results were consistent with numerical predictions, and the variation in pressure decreases with the Reynolds number was attributed to the dependence of water viscosity on temperature. Wu and Cheng investigated the friction factor of deionized (DI) water in a smooth trapezoidal microchannel with hydraulic diameters in the range of 25.9–291.0 μm. The results showed that the cross-sectional aspect ratio considerably affected the friction constant, and the experimental data on friction constants agreed with the analytical solution of Stokes flow theory within ±11%. Steinke and Kandlikar analyzed the friction factor database of the single-phase flow in microchannels. The results showed that the flow theories of Stokes and Poiseuille were applicable to the prediction of the friction factors of a microchannel, but the entrance and exit losses and the developing flow must be taken into account. A novel hierarchical-manifold microchannel with stacked configuration is proposed for the thermal management of high heat flux devices. As a result, the flow maldistribution in these microchannels is reduced with a 28%–32% reduction in the total pressure drop. Another similar investigation with rib columns is carried out by Zhu et al. Compared with smooth microchannel, the microchannel with rectangular rib columns showed a 2.34–3.88 times in the relative friction coefficient, but a 1.69–2.07 times in the relative Nusselt number.

In curved microchannels, when fluid flows along the axial direction, the pressure gradient along the radial direction will lead to continuous fluid circulation and form counter-rotating vortices. The flow along the radial direction is called a secondary flow, which renders the flow characteristics in curved microchannels more complicated than those in straight microchannels. Dean was the first scholar to develop the theoretical analysis of flows in curved tubes. A dimensionless parameter named the Dean number was introduced to characterize the secondary flow. Yang et al. investigated the flow characteristics of a curved microchannel with a central angle between 18° and 186°. They concluded that the friction factor decreased slightly when the curvature radius increased. Wang and Liu performed a numerical study to express the effects of initial conditions, channel curvature, and disturbances on the flow and heat transfer characteristics of curved microchannels. The results indicated that regardless of the size of the curvature, a secondary flow would always be generated in the cross section of the channel, and this phenomenon would moderately increase the friction factor. A series of studies on the flow characteristics of curved rectangular microchannels were carried out by Chu et al. They found that the experimental data were in good agreement with the calculations obtained by the classical Navier–Stokes equations. When the Dean number exceeds 60, the pressure drop of curved microchannels with aspect ratios ranging from 0.1 to 0.2 can be predicted by macroscale flow theory, which is commonly used for straight channel. Xi et al. experimentally studied the flow characteristics of swirl-flow microchannels with different rectangular cross sections by using 30% ethylene glycol solutions. The results revealed that the correlations derived for conventional macro coiled channels could not be used to predict the friction factor of swirl-flow channels. The second law analysis of laminar flow in curved rectangular channels was conducted by Guo et al. They found that the entropy generation caused by the fluid friction was concentrated in the region near the walls, especially in the outer wall. Dai et al. explored the hydrodynamic characteristics of tortuous microchannels by using micro-PIV visualization and 3D reconstruction techniques. The 3D streamlines structures and the secondary flow vectors at the bend of wavy microchannels were determined to understand the complex flow behavior of the channel. Narrein et al. numerically investigated the flow characteristics of a helical microchannel filled with a porous medium. The results indicated that the secondary flow and the porous medium both led to the increase in pressure drop, and the phenomena were accompanied by the thermal performance enhancement of the helical microchannel. The fluid flow characteristics in a rotating rectangular U-shaped microchannel were demonstrated by Sohankar et al. The results showed that an increase in aspect ratio (AR) (for AR > 1) or a decrease in AR (for AR < 1) provided an increase in pressure drop. Nivedita et al. studied the Dean flow dynamics of spiral microchannels for cell analysis. They further investigated the mechanism of the secondary flow and its effect on the flow characteristics of the channel. Subsequently, they defined the correlation to predict the critical Dean number, which has a significant impact on the structural analysis of secondary flows.

From the above literature, extensive research on the flow characteristics of microchannels has been carried out, and the research on curved microchannels has also attracted considerable attention. However, the influence of secondary flow on the laminar flow characteristics of spiral microchannel is rarely studied, and a reliable method to predict the hydraulic characteristics of spiral microchannel is lacking. The present study aims to investigate the effects of geometric parameters and secondary flow on the behavior of laminar flow in spiral microchannels.
Experimental apparatus

The experimental setup used in this study comprises two main loops, namely the gas and working fluid loops, and a data acquisition system, as shown in Figure 1. The main function of the gas loop is to provide power to the working fluid loop, in which the gas used is nitrogen. In the gas loop, nitrogen is supplied by a high-pressure cylinder. The pressure in the gas bottle is adjusted by the pressure relief valve and the precise pressure regulating valve. The working fluid used in the present experiment is DI water. Driven by high-pressure nitrogen, the DI water flows first from the liquid storage tank, then into the liquid filter and the flow meter in sequence. Subsequently, the flow behavior of the working fluid in the spiral microchannel is tested. Finally, the working fluid is collected by a receiver. The test facility is instrumented with differential pressure gage (Rosemount, 3051), precision flow meter (E + H, 83A01-19W0/0), and K-thermocouples to measure pressure drop $\Delta P$, mass flow rate $m$, and temperature of DI water $T$, respectively.

Figure 2 shows the photograph and diagram of the spiral microchannel used in the present study. The test section consists of three components, namely a spiral integrated copper plate, inlet and outlet steel needles (SUS304), and a barium fluoride glass cover plate. The microchannel has an Archimedean spiral structure. The microchannel is ground into a 0.8 mm thick copper plate, using a diamond cutter via a CNC machine. The length and internal diameter of the steel needle are 15 and 0.5 mm, respectively. The cover plate is glued to the copper plate in order to seal the microchannel. The spiral microchannel has a rectangular cross section. The geometry of a spiral microchannel can be characterized by its outermost spiral diameter $D_{sp}$, spiral pitch $P_{i}$, depth of the cross section $a$, width of the cross section $b$, number of turns $n$, aspect ratio $\alpha$, ($\frac{a}{b}$), and hydraulic diameter of the channel ($\frac{4ab}{2a+b}$), $d_h$. The dimensions of the spiral microchannel used in this study are given in Table 1.

Data acquisition

All signals of the differential pressure gage, mass flow meter and thermocouples are recorded by a data acquisition system (Agilent 34980A). The flow rate of the DI water, $\mu$, can be described as follows:

$$\mu = \frac{1000 \times m}{60 \times A_p}$$

(1)

$$A = ab$$

(2)

where $A$ is the sectional area of the microchannel, and $\rho$ is the density of the DI water. The Reynolds number can be expressed as

$$Re = \frac{\mu d_h}{\nu}$$

(3)

where $\nu$ is the kinematic viscosity of the working fluid. The density and kinematic viscosity values are supplied by REFPROP 9.0 of NIST.

The dimensionless parameter named Dean number, $Dn$, is introduced to characterize the secondary flow, and it is expressed as the following equation:

$$Dn = Re \left(\frac{d_h}{D_{sp}}\right)^{0.5}$$

(4)

where $d_h/D_{sp}$ is the curvature of the spiral microchannel. The pressure drop across the spiral microchannel, $\Delta P_{sp}$, is obtained by,
\[ \Delta P_{sp} = \Delta P - \Delta P_{inlet} - \Delta P_{outlet} \]  

(5)

where \( \Delta P \) is the total pressure drop measured by the differential pressure gage, and \( \Delta P_{inlet} \) and \( \Delta P_{outlet} \) are the pressure losses associated with the inlet and the outlet of the test section, respectively.

The fanning friction factor is defined as

\[ f = \frac{\Delta P_{sp}d_h}{2\rho L\mu^2} \]  

(6)

The partial derivative of \( y \) in relation to \( x_i \) represents the sensitivity coefficient of result \( y \) in relation to measurement \( x_i \), and \( y_{\text{min}} \) represents the minima in the operating range.

In accordance with uncertainty analysis, the maximum relative uncertainties of the pressure drop and mass flux are \( \pm 8.7\% \), and \( \pm 3.8\% \), respectively. The maximum experimental uncertainties used to determine \( Re \) and \( f \) are 3\% and 9\%, respectively.

### Results and discussion

Seven series of test sections were carried out to obtain the hydrodynamic characteristics of the spiral microchannel. In the present experiment, the Reynolds number varies from 51 to 985, which means that the flow is in a laminar regime. The spiral microchannel has a longer length than the straight channel. As a result, the ratio of length to diameter of the spiral microchannel is greater than 70. Therefore, the entrance effect can be negligible in the following analysis.\(^9\)

### Pressure drop

The variations in pressure drop versus the Reynolds number of the spiral microchannel with different

![Figure 2](image_url)
parameters of the spiral structure and the cross section are shown in Figures 3 and 4, respectively. In all micro-channels, the pressure drop increases with the increase in the Reynolds number. The Reynolds number measured in the experiment ranges from 51 to 985, with a corresponding pressure drop of 2.1–115.7 kPa. The comparison between spiral microchannels S1 and S2 in Figure 3 shows that the channel with a larger spiral diameter has a higher pressure drop. The effect of the spiral diameter on the pressure drop is not obvious at the small Reynolds number. As the Reynolds number is increased, the difference in pressure drop gradually increases between the channels with different spiral diameters. The effect of the spiral pitch on the pressure drop is obtained by comparing the variations in the pressure drop of the channels S2, S3, and S4, as shown in Figure 3. With the same Reynolds number, the larger the spiral pitch, the smaller the channel pressure drop. Also, when the Reynolds number is increased, the influence of the spiral pitch on the pressure drop becomes increasingly evident.

The channel pressure drop is proportional to the length of the liquid flow. As shown in Table 1, the spiral microchannels S1 and S2 have the same number of turns. When the spiral diameter goes from 20 to 30 mm, the length of the spiral channel increases by 0.5 times. Thus, the pressure drop of the channel increases as the spiral diameter of the microchannel increases. Similarly, when Pi = 3.3, 5.0, and 6.7 mm, the total length of spiral microchannels is 190.2, 128.3, and 97.6 mm, respectively. Therefore, the pressure drop in the channel decreases with increasing spiral pitch.

According to boundary layer theory, the thickness of the velocity boundary layer is inversely proportional to the mainstream velocity in the channel. In this experiment, the velocity boundary layer of the channel is relatively thick at the low Reynolds number. At the same time, under the combined effect of the channel scale, the fluid shear stress on the wall surface is low. The pressure drop of the channel is mainly dependent on the friction pressure drop between the fluid elements or flow layers. In this case, the diameter and pitch of the spiral have negligible impact on pressure drop. When the Reynolds number is further increased, the influence of the inertial force on the flow characteristics becomes increasingly considerable, and the fluid shear stress on the wall increases gradually in the spiral microchannel. The friction pressure drop of the spiral microchannel is greatly enhanced increased by the effect of the friction interaction between the fluid and the wall. As a result, the influence of channel length on the friction pressure drop is gradually manifested. This finding indicates that both the spiral diameter and pitch have a significant influence on the pressure drop of the channel.

Figure 4 depicts the influence of channel cross-section parameters on the pressure drop. A comparison of the changes in the pressure drops of spiral channels S5 and S7 indicates that pressure drop increases sharply when the hydraulic diameter of the channel decreases from 333 to 167 μm. Channel S7 has a pressure drop of 7.6 times that of channel S5 at Re = 225. Subsequently, the influence of the aspect ratio on the pressure drop is determined by comparing the experimental data of channels S6 and S7. Given the same Reynolds numbers, the larger the aspect ratio of the channel, the higher the pressure drops of the channel will be. The difference between the two microchannels increases as the increase in Reynolds number.

According to the classical flow theory and Moody diagram, there is no vortex in the laminar flow regime, so the flow in the straight channel is independent of the
However, because of the Dean vortex generation, the wall roughness has a great impact on the pressure drop even in the laminar flow for the spiral microchannel. In this experiment, all the test sections are processed in the same way, so the mean roughness ($e$) of the channels is basically the same. The relative roughness ($e/d_h$) of the channel increases with the decrease in hydraulic diameter of the channel. The relative roughness of the S5 and S6 channel is 0.5% and 0.2%, respectively. With the increase in roughness, the friction between the channel wall and the fluid is enhanced. At the same time, under the combined effect of the channel scale, the friction pressure drop of channel 5 increases sharply. According to Chu et al., there was no obvious difference in the flow characteristics between the curved microchannel and the straight channel when $0.1 < \alpha < 0.2$. However, the secondary flow has a more obvious strengthening effect on the friction pressure drop when $0.5 < \alpha < 1$. As a result, the spiral microchannel S6 has a higher friction pressure drop.

### Friction factor

Figures 5 and 6 show the variations in the fanning friction factors of the spiral microchannels with respect to the Reynolds number. In general, the friction factor decreases as the Reynolds number increases. At first, the friction factor decreases sharply with the increase in Reynolds number. When the Reynolds number increases to a certain value, the decreasing tendency of the friction factor slows down progressively. In accordance with the Hagen-Poiseuille flow theory, the friction factor of the laminar flow can be expressed as

$$ f = \frac{Po}{Re} $$

where $Po$ is the Poiseuille number. The coefficient of friction is inversely proportional to the Reynolds number. Thus, the friction factor has a changing rule as discussed above with the gradual increase in Reynolds number.

Figure 5 illustrates the effects of spiral diameter on the friction factor. This figure can also be used to compare the experimental data and the calculated result of equation (8), which is a formula used for laminar flows in straight channels. The Poiseuille number can be derived from the following correlation provided by Shah and London:

$$ Po = 24(1 - 1.3553\alpha + 1.9467\alpha^2 - 1.7012\alpha^3 + 0.9564\alpha^4 - 0.2537\alpha^5) $$

where the aspect ratio $\alpha = 1$. As shown in Figure 5, the friction factors of the spiral microchannels can be predicted effectively by equation (8) at the low Reynolds number. When the Reynolds number is increased, the friction factors of the channels with spiral diameters of 20 and 30 mm deviate from the predicted values of equation (8) at $Re = 226$ and $Re = 352$, respectively. In this experiment, the spiral channel has a higher friction factor than the straight channel at the same Reynolds number. The larger the diameter of spiral, the smaller the friction factor. When $400 < Re < 1000$, the friction factors of the channels with spiral diameters of 20 and 30 mm are 49.8% and 34.3% higher on the average than those of the straight channel, respectively.

The influence of the secondary flow on the flow characteristics should be considered in the variation analysis of the friction factors of the spiral microchannel. When the fluid flows through the spiral channel,
the fluid will also flow to the outer channel while flowing along the axial direction of the passage under the action of centrifugal force. Then, the fluid in the center of the channel is subjected to a high centrifugal force due to a high axial velocity. Thus, the central fluid flows to the outer wall of the channel along the radial direction, increasing the pressure on the outer wall of the channel. Subsequently, the outer fluid will flow toward the inner channel wall through the upper and lower wall surfaces under the effect of the radial pressure gradient. A secondary flow is then formed along the radial direction.\textsuperscript{12}

On the one hand, when fluid flows to the outer channel wall from the inner channel in the middle part of the cross section, the fluid elements collide with one another due to the radial flow velocity of the fluid, and additional shear stresses are generated between the fluid elements and the flow layers with different velocities, thereby causing the additional friction loss and the increase of friction factor. On the other hand, additional shear stresses on the channel wall are generated due to the secondary flow along the channel wall surface, which also causes an increase in the friction factor. Further analysis shows that the secondary flow velocity plays an important role in the additional friction loss in the spiral microchannel. Bayat and Rezai\textsuperscript{25} proposed an expression of the secondary flow velocity in curved microchannels based on their experimental research and numerical simulation analysis. The secondary flow velocity can be expressed as

\[ V_{Dn} = 0.031 \left( \frac{\nu}{s} \right) Dn^{1.63} \quad (10) \]

where \( \nu \) and \( s \) are the kinematic viscosity of the fluid and the largest channel dimension, respectively. The variables in equation (10) indicate that the secondary flow velocity depends mainly on the Dean number, which is taken into consideration in this experiment.

The shearing effect of the mainstream on the channel wall is small at low Reynolds number. On the basis of the equation (10), the velocity of the secondary flow is low, and the additional friction in the channel is negligible. Thus, the friction loss in the spiral microchannel depends mainly on the friction between the fluids. Moreover, no obvious difference between the spiral channel and the straight channel can be observed at the low Reynolds number. The Dean number and the velocity of the secondary flow both increase with the increase of the Reynolds number, and the additional friction effect of the secondary flow also increases gradually. Under the influence of additional friction, the friction factor of the spiral microchannel becomes significantly higher than that of the straight channel. The microchannel with a large spiral diameter has a small Dean number at the same Reynolds number, which will lead to a decrease in secondary flow velocity. Thus, the additional friction in the microchannel with a large spiral diameter is less than that of the microchannel with a small spiral diameter. Moreover, the microchannel with a larger spiral diameter has a lower friction factor. Additional friction in microchannels with large spiral diameters can only be observed at the high Reynolds number. In this case, the experimental data of the spiral microchannel will deviate from the curve of the straight channel.

The effect of the spiral pitch on the friction factor is shown in Figure 6. As in Figure 5, the experimental data of the spiral microchannel are compared to the calculations of equation (8) to generate the figure. No significant difference in the friction factors between the spiral channel and the straight channel can be observed at low Reynolds numbers. When the Reynolds number is increased, the curves of the friction factor of the spiral microchannel with spiral pitches of 6.7, 5.0, and 3.3 mm deviate successively from the curves of the straight channel. The larger the spiral pitch, the larger the coefficient of the friction factor of the microchannel will be. When \( 400 < \text{Re} < 1000 \), the friction factors of the channel are 49.8\%, 73.4\%, and 81.4\% higher on the average than those of the straight channel with increased of spiral pitch.

Given the same outermost spiral diameter, the microchannel with a larger spiral pitch has a smaller spiral diameter when the fluid circulates through the same channel length. In this case, both the local Dean number and the velocity of the secondary flow are increased. Thus, the microchannel with a larger spiral pitch has a higher friction factor based on the enhanced additional friction effect.

A summary of the above analyses suggests that the curvature of the spiral microchannel is increased whether the diameter of the spiral is reduced or the pitch of the spiral is increased when the channel has a same hydraulic diameter. Thus, the Dean number of the spiral microchannel is also increased, and the additional friction caused by the secondary flow is strengthened, which leads to the increase of friction factor eventually.

**Correlation equation for the Poiseuille number of the spiral microchannel**

The Poiseuille number is another important parameter used to describe the fluid laminar flow characteristics of channels. Many scholars have systematically studied the Poiseuille number and have proposed their corresponding predicted correlations. Wang and Liu\textsuperscript{14} provided a predicted relation of Poiseuille number for a curved microchannel with a curvature ratio of \( 5 \times 10^{-6} \) and an aspect ratio of 1. The relation can be expressed as
where $P_{oc}$ and $P_{os}$ are the Poiseuille number of the curved channel and the straight channel, respectively. However, different from the channels described above, the spiral diameter of an Archimedean spiral channel changes continuously along the channel, indicating that the values of the Dean number are not constant for the channel. In this study, the Dean number is replaced by the mean Dean number of the spiral microchannel, as follows:

$$Dn_m = \frac{\int Re \left( \frac{d}{D} \right)^{0.5} dL}{L}$$

(12)

The microchannel path can be described as an Archimedean spiral by using

$$R = \frac{D_i}{2} + \frac{P_i}{2\pi} \theta$$  

(13)

where $D_i$ is the innermost spiral diameter of the microchannel, and $\theta$ is the spiral angle. Thus, taking into consideration the equations (12) and (13), the mean Dean number can be expressed as

$$Dn_m = \frac{Re \left( \frac{d}{D} \right)^{0.5}}{L} \int_{R_i}^{R_e} (2R)^{-0.5} \left( 1 + \frac{4\pi^2}{L^2} R^2 \right)^{0.5} dR$$  

(14)

The comparison between the experimental spiral microchannel data and the predicted correlation proposed by Wang and Liu (defined as equation (11)) is presented in Figure 7. In this figure, some of the experimental values placed between the two dashed lines ($\pm 18\%$), as calculated by equation (11). However, large discrepancies between the values predicted by equation (11) and the experimental data are observed, especially for the spiral microchannels with a relatively low aspect ratio. Owing to the large differences in the structural form and the structural parameters of the microchannel, equation (11) cannot predict fully the Poiseuille number of the spiral microchannel in this experiment.

The above analyses imply that the structural parameters of the Archimedean spiral microchannel have an important influence on the flow characteristics of the channel. The mean Dean number is introduced into this study to express the effect of the structural parameters on the Archimedean spiral channel. Equation (9) takes into account the effect of the aspect ratio on the Poiseuille number. The correlation of the Poiseuille number of the spiral microchannel is given by

$$P_{osp} = f(Dn_m, P_{os})$$  

(15)

where the $P_{os}$ can be calculated by equation (9). Then, the experimental spiral microchannel data can be correlated together by multiple nonlinear regression analyses. Here, 150 data sets are correlated by the lstopt 5.0 software with the Levenberg-Marquardt algorithm. The correlation of the Poiseuille number for the spiral microchannel can be expressed as

$$P_{osp} = 793.02 \times Dn_m^{0.31} P_{os}^{-1.90} \text{ for } 6.5 \leq Dn \leq 212.0$$  

(16)

The predictive performance of the correlation (equation (16)) is shown in Figure 8. The results indicate that 95.3\% of the present experimental data can be predicted within $\pm 18\%$, with a standard deviation of 8.5\%. These results are in good agreement with the experimental data.
Conclusion

The flow characteristics of the laminar flow in spiral microchannels are determined and then compared with those in the straight channel. The following conclusions can be derived from the experimental results and analyses:

1. Owing to the effects of the scaling and roughness, the pressure drop of the spiral microchannel increases with spiral diameter and aspect ratio but decreases with spiral pitch and hydrodynamic diameter. In accordance with boundary layer theory, the influence of spiral parameters on pressure drop increases with the increase in the Reynolds number.
2. Due to the additional friction caused by the secondary flow, the friction factor increases with the increasing curvature of the spiral microchannel. Compared to the straight channel, the spiral microchannel can increase the friction factor by an average of 59.7% when $400 < \text{Re} < 1000$.
3. A Poiseuille number correlation for the spiral microchannel is developed by using the mean Dean number, correlating 95.3% of the data within $\pm 18\%$.

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**Appendix**

**Notation**

| Symbol | Description |
|--------|-------------|
| $A$    | sectional area of the channel (m$^2$) |
| $a$    | depth of the channel (m) |
| $b$    | width of the channel (m) |
| $D_{sp}$ | spiral diameter (m) |
| $Dn$  | Dean number |
| $d_h$ | hydrodynamic diameter (m) |
| $f$  | fanning friction factor |
| $L$  | length of the channel (m) |
| $m$  | mass flow rate (g min$^{-1}$) |
| $n$  | number of turns |

| Symbol | Description |
|--------|-------------|
| $Pi$   | spiral pitch (m) |
| $Po$   | Poiseuille number |
| $R$    | spiral radius (m) |
| $Re$   | Reynolds number |
| $v$    | kinematic viscosity (m$^2$s$^{-1}$) |

**Greek symbols**

| Symbol | Description |
|--------|-------------|
| $\alpha$ | aspect ratio |
| $\Delta P$ | pressure drop (kPa) |
| $\varepsilon$ | mean roughness (µm) |
| $\theta$ | spiral angle ($^\circ$) |
| $\mu$ | flow rate (m s$^{-1}$) |
| $\rho$ | density (kg m$^{-3}$) |

**Subscripts**

| Symbol | Description |
|--------|-------------|
| $c$ | curved |
| $exp$ | experimental |
| $i$ | inner |
| $m$ | mean |
| $pred$ | predicted |
| $s$ | straight |
| $sp$ | spiral |