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Two-phase pressure drop of air–water in minichannels

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ABSTRACT

Results of experimental investigations of pressure drop in two-phase adiabatic flow in tubular minichannels are presented. Air–water mixture was used as a working fluid. Eight tubular minichannels with internal diameter $d_w = 1.05 \div 2.30$ mm and the test section length of 300 mm made from stainless steel were used. The investigations were conducted within the range: mass flow rate of water $0.65 \div 59$ kg/h, mass flow rate of air $0.011 \div 0.72$ kg/h, mass fraction of air in the two-phase mixture $x = 0.0003 \div 0.22$, total mass flux $(w\rho) = 139 \div 8582$ kg/(m^2 s). It was found, on the basis of the experimental investigations, that the application of commonly used methods to evaluation of pressure drop in two-phase flow, provided poor results. It is therefore necessary to make some corrections and modifications for the two-phase flow in minichannels correlations.

1. Introduction

At present, an increasing attention is being paid to heat transfer from small elements, which generate large amounts of heat. These elements include above all elements of electronic devices, including microprocessors. The methods used so far for cooling with the employment of gaseous or liquids mediums do not guarantee receive a very large heat fluxes. For this reason, more and more often, the possibilities of heat exchange during phase change of the refrigerant in the flow in channels are used. One should note that the elements in which the cooling process is realized have very small dimensions, and for this reason, the flow of the boiling medium occurs in the so-called minichannels. According to the classification given by Kandlikar [1–4], these are channels with a hydraulic diameter in range of $0.2 \div 3$ mm. With the increase of the flow rate in such channels, an intensive growth of flow resistances occurs. The knowledge of the value of the flow resistance of the medium is important as it facilitates, among others, the selection of the devices which generate the flow.

The designer of a compact evaporator, built on the basis of minichannels, faces an important dilemma at present, which concerns the selection of suitable calculation methods for the flow resistance of boiling mediums in minichannels. The first question which was considered in this problem was: is it possible to use those calculation procedures which have been known for many years and are well-tried with respect to the flow in conventional channels for minichannels.

The paper presents the results of experimental investigations which were conducted to check-out whether the Lockhart–Martinelli and Friedel methods may be used for calculation the two-phase pressure drop also during the flow in minichannels. A mixture of water and air was used as a model medium.

2. Experimental investigations

2.1. Experimental set-up

Fig. 1 presents a schema of the experimental set-up. Water was pumped by a mini-gear pump 2 (D Series Magnetically Coupled Gear Pump manufactured by Tuthill Corporation) and was supplied to the mixing zone 3 and further to the measuring section of a tubular minichannel 4. A system of valves in the instrumentation of the pump 2 controls the water flow rate. Air was supplied by a compressor 1, through a control valve and a system of filters, to a mass flowmeter Coriolis 5 (Promass 80A manufactured by Endress + Hauser). The measuring range of the flowmeter was $0 \div 20$ kg/h and the class of 0.15. It enabled an accuracy of ±0.03 kg/h. The measuring range of the flowmeter could be changed and an increase of the measuring accuracy could be achieved at lower flow rates. The water and air filters were important elements of the experimental set-up which prevent minichannels before its destruction. The pomp as well as the compressor were next to stable construction where test section was fixed. That solution protected main construction from vibrations.

The measuring Section 4 constituted the main element of the test facility. Minichannels with a circular cross section made from stainless steel, with a total length of 500 mm and the internal diameters: 1.05, 1.30, 1.35, 1.40, 1.60, 1.68, 1.94 and 2.30 mm were used.

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Nomenclature

A	cross section (m^2)
C	Chisholm parameter
d	diameter (m)
ΔL	length of test section (m)
Δp	pressure drop (Pa)
Fr	Froud number
g	gravitational acceleration (m/s^2)
j	superficial velocity (m/s)
$\dot{m}$	mass flow rate (kg/s)
Re	Reynolds number
We	Weber number
$(w\rho)$	mass flux (kg/m^2s)
x	mass fraction of gas in two-phase mixture (vapour quality)

Greek symbols

χ	Lockhart–Martinelli parameter
φ	two-phase frictional multiplier
λ	friction factor
μ	dynamic viscosity (Ns/m^2)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

a	acceleration
g	gas phase
go	all mass is assumed as gas only
H	hydrostatic
HOM	homogeneous
l	liquid
lo	all mass is assumed as liquid only
TP	two-phase
TPF	two-phase frictional
w	internal

The total length of the measuring minichannel was divided into three sections: entrance section “a”, the main section “b” and outlet section “c” (in Fig. 1, marked with a, b, c symbols, respectively). The first section was a stabilizing section with the length of 150 mm starting from the inlet cross-section. The second, insulated section “b” with the length of 300 mm was the main measuring section. The last one, outlet section “c” was 50 mm of length. Water which left this section entered tank 10. The method so-called “the method of the filling of the tank” was used to determine the flow rate of water. The description of this method was presented in paper [5], among others. It enabled a precise measurement of very small flow rate of water. The evaluation of the measuring error for the flow rate of water was made comparatively with the use of a Coriolis mass flowmeter. It was found that the uncertainly of this method does not exceed ±5% of the measured value.

The impulse holes were made for the measuring local pressure and pressure drop of the fluid. On the inlet to the measuring section “b”, local pressure of mixture was measured. The piezoresistant sensor with a transducer 6 (Cerabar M PMP41 manufactured by Endress + Hauser) was used for the inlet static pressure measurement. This pressure transducer was the measuring range of 0 ÷ 1 MPa. The accuracy of this pressure transducer does not exceed 0.2% of the measurement range. This gives a pressure measuring uncertainly of ±2 kPa. The pressure drop of the air–water mixtures was measured by a precision differential pressure transducer 7 (Deltabar S PMD75 manufactured by Endress + Hauser), which has an adjustable span. The basic measuring range of pressure transducer was in range of 0 ÷ 500 kPa and its accuracy was 0.075% of measurements. The uncertainly of the differential pressure in the maximal value was ±0.375 kPa.

The temperature of the working medium in the measuring section (b: Fig. 1) was measured using *K* type thermocouple with the diameter of wires ϕ = 0.2 mm, placed on the wall in the inlet, outlet and in the middle of the test section. In the range of 10 ÷ 30 °C individual characteristics of these thermocouples, using the laboratory thermometer having an elementary scale of 0.1 °C were made.

The measuring section was insulated with a 10 mm silicone isolation. The experiment was performed at the room temperature

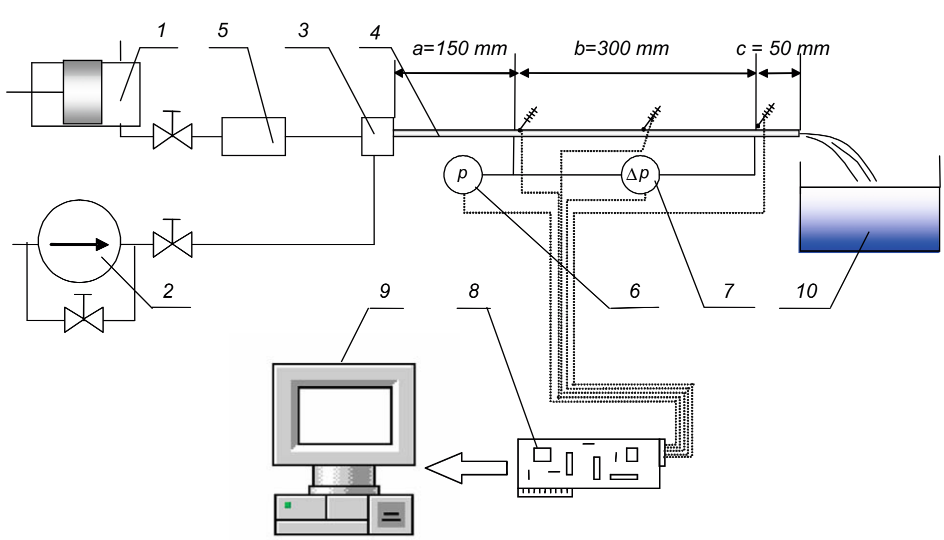

Fig. 1. Schema of experimental set-up 1 – compressor, 2 – pump, 3 – mixing chamber, 4 – minichannel, 5 – mass flowmeter, 6 – pressure transducer, 7 – difference pressure transducer, 8 – measuring card, 9 – PC, 10 – tank, a,b,c – zones of the test section.

and at atmospheric pressure at the tested minichannel outlet. Initial tests of the measuring system showed that the flow of the working medium on the length of the measuring section could be recognized as an adiabatic one. The thermal and physical properties of the fluid were read with the use of [6].

The following values were measured: the flow rate, pressure and temperature, and registered by a data acquisition system, using a measuring board 8 (Fig. 1) type DaqBord 3005 (16 bit., 1 MHz) and PC 9.

2.2. Range of investigations and data reduction

Table 1 presents a list of the measuring ranges of the experimental quantities, including the following: mass flow rate of water - $\dot{m}_l$, mass flow rate of air – $\dot{m}_g$, mass fraction of air in the two-phase mixture – x, superficial velocity of air in minichannel – j_g, superficial velocity of water in minichannel – j_l and total mass flux of mixture – $(w\rho)$.

The determination of a two-phase flow resistance in conventional channels is a difficult question. During a two-phase flow, it is not only the volume fraction of the phases creating the two-phase system that changes, but the shape of the interfacial surface undergoes some changes, as well. On the basis of theoretically derived and empirically verified dependencies, which describe the total pressure drop $\left(\frac{\Delta p}{\Delta L}\right)_{TP}$ in a two-phase flow, it obtains most frequently the following form:

$$\left(\frac{\Delta p}{\Delta L}\right)_{TP} = \left(\frac{\Delta p}{\Delta L}\right)_{TPF} + \left(\frac{\Delta p}{\Delta L}\right)_{a} + \left(\frac{\Delta p}{\Delta L}\right)_{H}, \tag{1}$$

where: $\left(\frac{\Delta p}{\Delta L}\right)_{TPF}$ – frictional pressure drop, $\left(\frac{\Delta p}{\Delta L}\right)_{a}$ – acceleration pressure drop, $\left(\frac{\Delta p}{\Delta L}\right)_{H}$ – hydrostatic pressure drop.

In the case of a two-phase and adiabatic flow through a horizontal channel, the determination of the pressure drop comes down to the determination of a frictional pressure drop only.

2.2.1. Lockhart–Martinelli method (1949)

The frictional resistance of the two-phase mixture flow is expressed as:

$$\left(\frac{\Delta p}{\Delta L}\right)_{TPF} = \Phi_l^2 \cdot \left(\frac{\Delta p}{\Delta L}\right)_{l} = \Phi_g^2 \cdot \left(\frac{\Delta p}{\Delta L}\right)_{g}, \tag{2}$$

where the pressure drop being the result of a single-phase flow of medium (water – l, or air – g) is represented in the form:

$$\left(\frac{\Delta p}{\Delta L}\right)_{l} = \lambda_l \frac{1}{d}\frac{\rho_l j_l^2}{2} \tag{3}$$

$$\left(\frac{\Delta p}{\Delta L}\right)_{g} = \lambda_g \frac{1}{d}\frac{\rho_g j_g^2}{2}. \tag{4}$$

Quantities Φ_l and Φ_g in formula (2) mean factors, which depend of Lockhart–Martinelli parameter χ determined as:

$$\chi^2 = \frac{\left(\frac{\Delta p_f}{\Delta L}\right)_l}{\left(\frac{\Delta p_f}{\Delta L}\right)_g}. \tag{5}$$

Friction factors of single-phase flow λ_l and λ_g are calculated from Hagen–Pouisuille dependence for laminar flow or, for example from Blasius formula – in the case of turbulent flow. Reynolds number, which characterizes the type of flow, is specified with the following formula:

$$Re_{l(g)} = \frac{j_{l(g)} \cdot d}{\nu_{l(g)}}. \tag{6}$$

Superficial velocity of water – j_l or air – j_g, can be determined while assuming that only the selected phase flows through the whole cross-section A of the channel.

$$j_{l(g)} = \frac{\dot{m}_{l(g)}}{\rho_{l(g)} \cdot A}. \tag{7}$$

Fig. 2 presents a diagram in its original version as given by the authors, which allows the determination of corrections Φ_l and Φ_g [7].

Chisholm and Laid (1958) proposed an analytical form of the formulae for the calculation of the correction factors of the two-phase flow resistance in the following form:

$$\Phi_l^2 = 1 + \frac{C}{\chi} + \frac{1}{\chi^2} \tag{8}$$

$$\Phi_g^2 = 1 + C\chi + \chi^2, \tag{9}$$

where C constant is selected depending of the nature of the flow of each of the phases: $C = 5$ (laminar flow of water – laminar flow of air), $C = 10$ (turbulent flow of water – laminar flow of air), $C = 12$ (laminar flow of water – turbulent flow of air) and $C = 20$ (turbulent flow of water – turbulent flow of air).

2.2.2. Friedel's method (1979)

The author made an assumption in the model that the two-phase flow resistance is proportional to the pressure drop which would occur if the whole flowing mass (total mass flow $\dot{m}$ of the two-phase system) was treated as one phase, i.e. as a liquid (water), or as gas (air). The dependence which determines the frictional pressure drop during a two-phase flow can then be expressed as:

$$\left(\frac{\Delta p}{\Delta L}\right)_{TPF} = \Phi_{lo}^2 \cdot \left(\frac{\Delta p}{\Delta L}\right)_{lo} = \Phi_{go}^2 \cdot \left(\frac{\Delta p}{\Delta L}\right)_{go}. \tag{10}$$

For metrological reasons, an approach from the liquid (water) is more suitable and guarantees a smaller measuring error, and for this reason formula (2) takes the following form:

$$\left(\frac{\Delta p}{\Delta L}\right)_{TPF} = \Phi_{lo}^2 \cdot \left(\frac{\Delta p}{\Delta L}\right)_{lo} \tag{11}$$

Table 1
Overall list of experimentally measured quantities.

d_w [mm]	$\dot{m}_g$ [kg/h]	$\dot{m}_l$ [kg/h]	x [–]	j_g [m/s]	j_l [m/s]	$(w\rho)$ [kg/(m^2 s)]
1.05	0.032 ÷ 0.427	1.47 ÷ 18.17	0.0018 ÷ 0.2247	3.7 ÷ 63.9	0.5 ÷ 5.6	587 ÷ 5622
1.30	0.011 ÷ 0.442	2.03 ÷ 34.63	0.0003 ÷ 0.1074	0.9 ÷ 32.0	0.4 ÷ 7.6	481 ÷ 7596
1.35	0.052 ÷ 0.637	2.21 ÷ 30.94	0.0018 ÷ 0.1506	3.6 ÷ 41.8	0.4 ÷ 5.8	455 ÷ 5756
1.40	0.034 ÷ 0.138	0.65 ÷ 35.44	0.0014 ÷ 0.1762	2.8 ÷ 19.3	0.1 ÷ 6.4	139 ÷ 6405
1.60	0.020 ÷ 0.623	4.26 ÷ 59.03	0.0003 ÷ 0.0933	1.1 ÷ 21.9	0.6 ÷ 8.6	683 ÷ 8582
1.68	0.034 ÷ 0.593	1.99 ÷ 58.60	0.0006 ÷ 0.1680	1.7 ÷ 37.3	0.2 ÷ 7.4	280 ÷ 7347
1.94	0.042 ÷ 0.702	1.67 ÷ 47.02	0.0013 ÷ 0.0803	2.9 ÷ 29.4	0.2 ÷ 4.6	174 ÷ 4565
2.30	0.063 ÷ 0.594	2.58 ÷ 53.98	0.0012 ÷ 0.1137	2.3 ÷ 19.9	0.2 ÷ 3.3	172 ÷ 3318

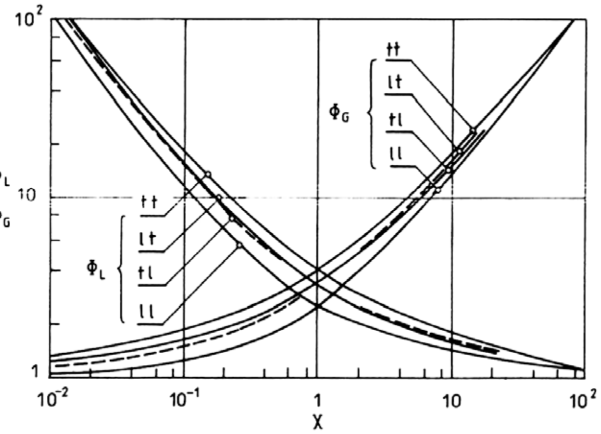

Fig. 2. Dependence of the correction factors ϕ versus the Martinelli parameter χ; Φ_L – two-phase multiplier for the liquid phase, Φ_G –two-phase multiplier for the gaseous phase. $l-l$ laminar flow of water – laminar flow of air; $l-t$ laminar flow of water – turbulent flow of air; $t-l$ turbulent flow of water – laminar flow of air; $t-t$ turbulent flow of water – turbulent flow of air

where:

$$\left(\frac{\Delta p}{\Delta L}\right)_{lo} = \lambda_{lo}\frac{1}{d}\frac{\rho_l j_{lo}^2}{2} \tag{12}$$

$$Re_{lo} = \frac{j_{lo}\cdot d}{\nu_l} \tag{13}$$

$$j_{lo} = \frac{\dot{m}_l + \dot{m}_g}{\rho_l \cdot A}. \tag{14}$$

Friedel proposed correlation for the calculation of the correction factor of the two-phase flow resistance Φ_{lo} on the basis of an analysis of a database of 25,000 of evidence data, as:

$$\Phi_{lo}^2 = \left[(1-x)^2 + x^2\frac{\rho_l\lambda_g}{\rho_g\lambda_l}\right] + \frac{3.24\cdot x^{0.78}(1-x)^{0.224}\cdot\left(\frac{\rho_g}{\rho_l}\right)^{-0.91}\left(\frac{\mu_g}{\mu_l}\right)^{0.19}\left(1-\frac{\mu_g}{\mu_l}\right)^{0.7}}{Fr_{HOM}^{0.045}\cdot We_{HOM}^{0.035}}, \tag{15}$$

where Fr_{HOM} is the Froud number calculated as for a homogeneous flow:

$$Fr_{HOM} = \frac{(w\rho)^2}{d\cdot g\cdot\rho_{HOM}^2}, \tag{16}$$

while We_{HOM} is the Weber number in this model defined as:

$$We_{HOM} = \frac{d\cdot(w\rho)^2}{\sigma\cdot\rho_{HOM}}. \tag{17}$$

The density of the homogeneous mixture is calculated as:

$$\frac{1}{\rho_{HOM}} = \frac{x}{\rho_g} + \frac{1-x}{\rho_l}. \tag{18}$$

2.3. Results and discussion

Experimental investigations of the pressure drop in an adiabatic flow of air–water mixture through tubular minichannels were conducted. The results of the pressure gradients $(\Delta p/\Delta L)_{\text{exp}}$ versus the total mass flux $(w\rho)$, are presented in Fig. 3. This figure includes the results obtained for minichannels with the internal diameters: 1.05, 1.30, 1.35, 1.40, 1.60, 1.68, 1.94 and 2.30 mm.

From all of the results, these were selected, which possess a similar value of the mass fraction of air in the two-phase mixture – x. Fig. 4 presents sample characteristics $(\Delta p/\Delta L) = f(w\rho)$ using the quantity x as a parameter. The results were obtained using one minichannel with diameter d_w = 1.94 mm.

Analogically, from all of the results, these were selected, which possess a similar value of the total mass flux $(w\rho)$. Fig. 5 presents sample characteristics $(\Delta p/\Delta L) = f(x)$ using mass flux $(w\rho)$ as a parameter. The results were obtained using one minichannel with diameter d_w = 1.94 mm.

Characteristics $(\Delta p/\Delta L) = f(w\rho)$ and $(\Delta p/\Delta L) = f(x)$ for the remaining diameters of minichannels appear analogically as in Figs. 4 and 5. The scattering of the points in Figs. 4 and 5 is the result of presence the measuring points with not exactly the same values of the parameter x or parameter $(w\rho)$, respectively. Only these points were accepted where obtained value of parameter $(w\rho)$ or parameter x not exceed ±20% of the value presented in figure. It is evident from an analysis of Figs. 4 and 5 that an increase of

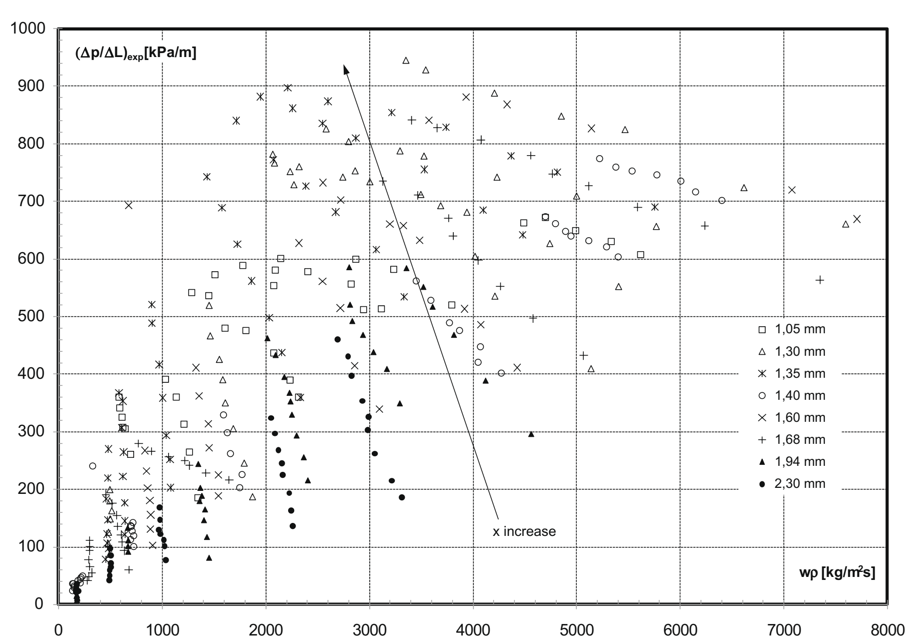

Fig. 3. Pressure gradient $(\Delta p/\Delta L)_{\text{exp}}$ versus total mass flux $(w\rho)$ in minichannels with internal diameters d_w = 1.05 ÷ 2.30 mm for different air fraction x.

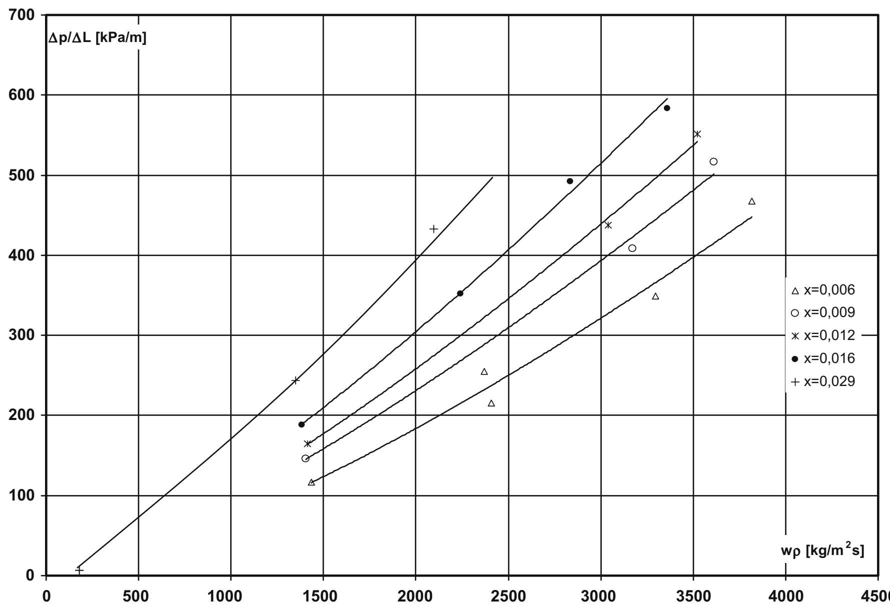

Fig. 4. Sample hydrodynamic characteristics $(\Delta p/\Delta L) = f(w\rho)$ with air fraction x as a parameter for minichannel with internal diameter $d_w = 1.94$ mm.

the total mass flux ($w\rho$), or the fraction of the gaseous phase in the two-phase mixture – x, results in an increase of the resistances of the flow through minichannels.

With the use of the database obtained of 331 data points, an analysis was conducted for the possibility of the application, in minichannels, the classical e.g. the methods of Lockhart–Martinelli and Friedel.

In Eq. (2), which describes frictional pressure drop of the two-phase mixture flow, there occurs correction factor Φ_l^2 for the liquid phase, which is calculated from formula (8). The value of Φ_l^2 factor depends not only of Martinelli parameter χ, but also of the flow characteristics of the liquid and gas phases. This is taken into account by constant C which occurs in Eq. (8). Depending of the nature of the flow of each phase, it can take values in range $C = 5 \div 20$.

Fig. 6 presents the dependencies of experimental correction factor Φ_l^2 of Martinelli parameter χ. The solid lines in the figure denote the theoretical values of correction factor Φ_l^2 counted for the extreme values of C constant, i.e. $C = 5$ and $C = 20$.

The calculation results were compared with the experimental results for the flow of the air–water two-phase mixture. The experimental results covered four ranges, which describe the nature of the flow of each phase, e.g. L–L (laminar flow of water–laminar flow of air), L–T (laminar flow of water–turbulent flow of air), T–L and T–T.

It is evident from the diagrams presented in Fig. 6 that one cannot determine in an explicit manner the influence of the flow of each phase of the two-phase mixture on the value of C. It is evident that the assumption concerning the selection of the value of

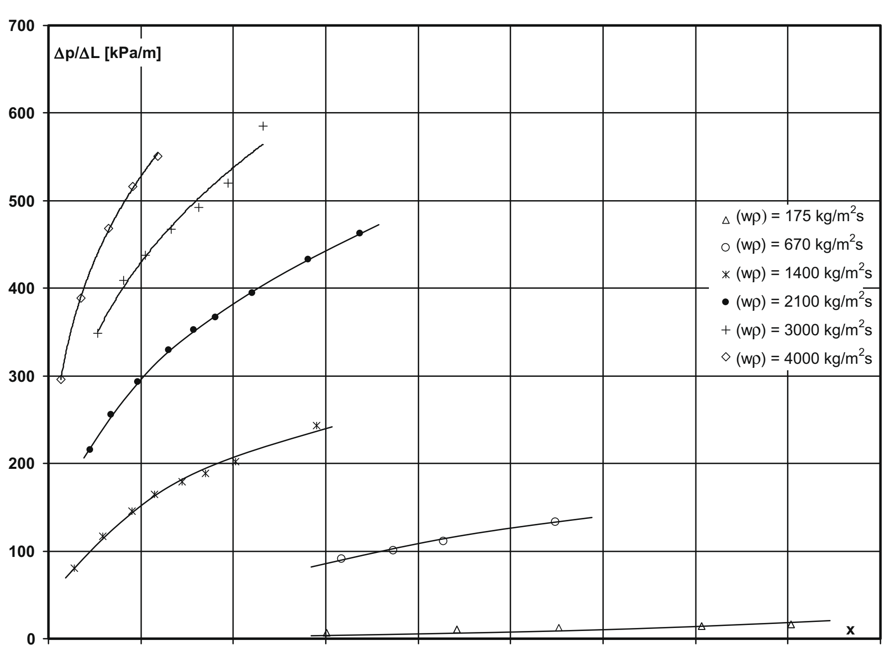

Fig. 5. Sample hydrodynamic characteristics $(\Delta p/\Delta L) = f(x)$ with $(w\rho)$ as parameter for minichannel with internal diameter $d_w = 1.94$ mm.

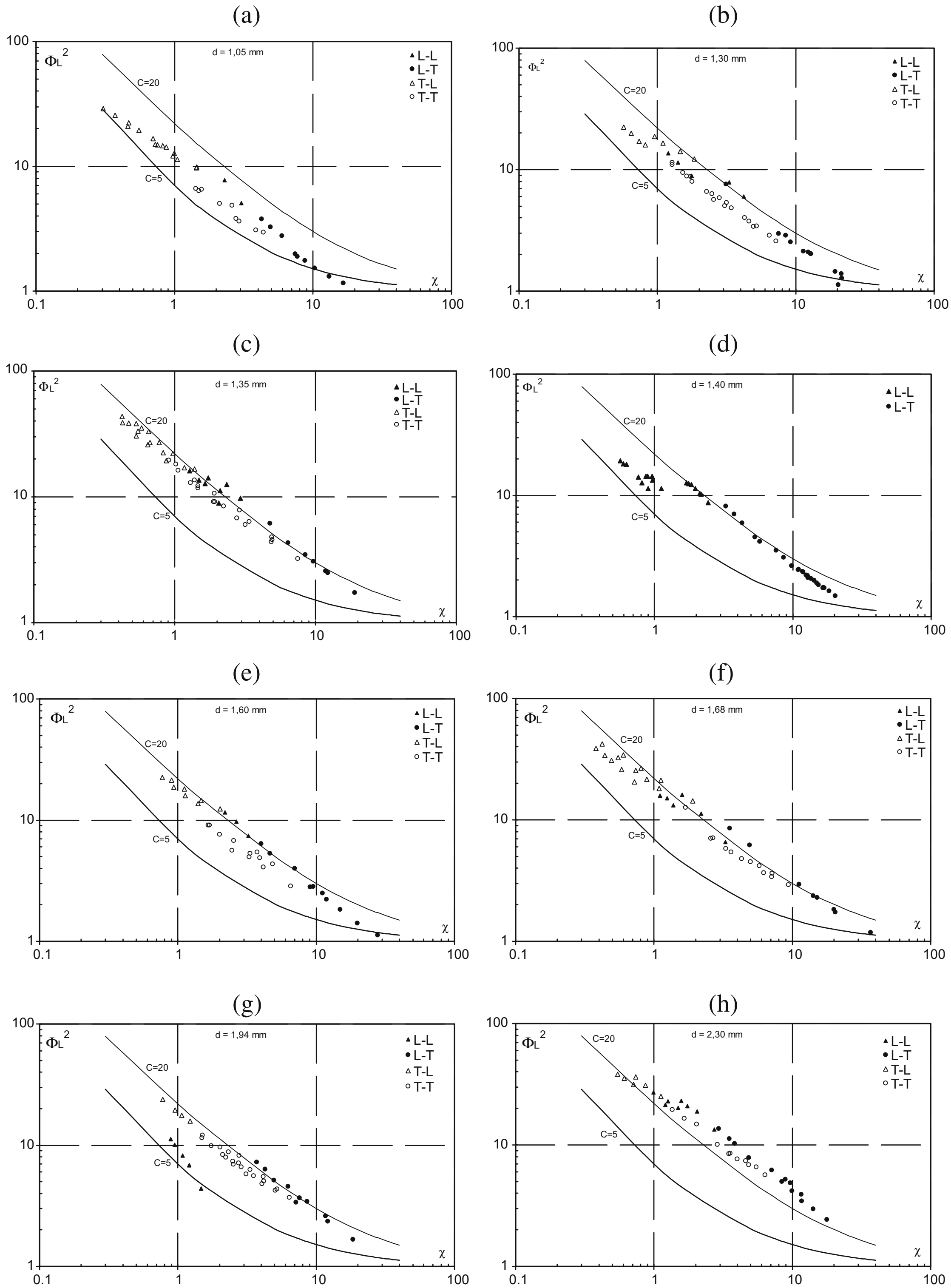

Fig. 6. Comparison of the calculated correction factor Φ_l^2 ($C = 5$ and $C = 20$ – solid lines) and the experimental correction factor Φ_l^2 versus Martinelli parameter χ; *L–L* laminar flow of water–laminar flow of air; *L–T* laminar flow of water–turbulent flow of air; *T–L* turbulent flow of water–laminar flow of air; *T–T* turbulent flow of water–turbulent flow of air.

constant *C*, depending of the nature of the flow of phases, has a theoretical sense only and was not confirmed in the experiment for the minichannels. The value of *C* is variable, in spite of presence only one nature of flow of each phase.

Similar conclusions, on the basis of analogical diagrams obtained from investigations into a two-phase flow of a water–air mixture through minichannels, were made by Kawahara et al. [8,9], Kaminaga et al. [10], Chung and Kawaji [11], Zhao and Bi [12], Pehlivan et al. [13], Triplett et al. [14] or Chen et al. [15].

One can conclude from Fig. 5h, that for a minichannel of diameter $d_w = 2.30$ mm, the value of this constant exceeds boundary value $C = 20$. These problems were also observed by Mishima and

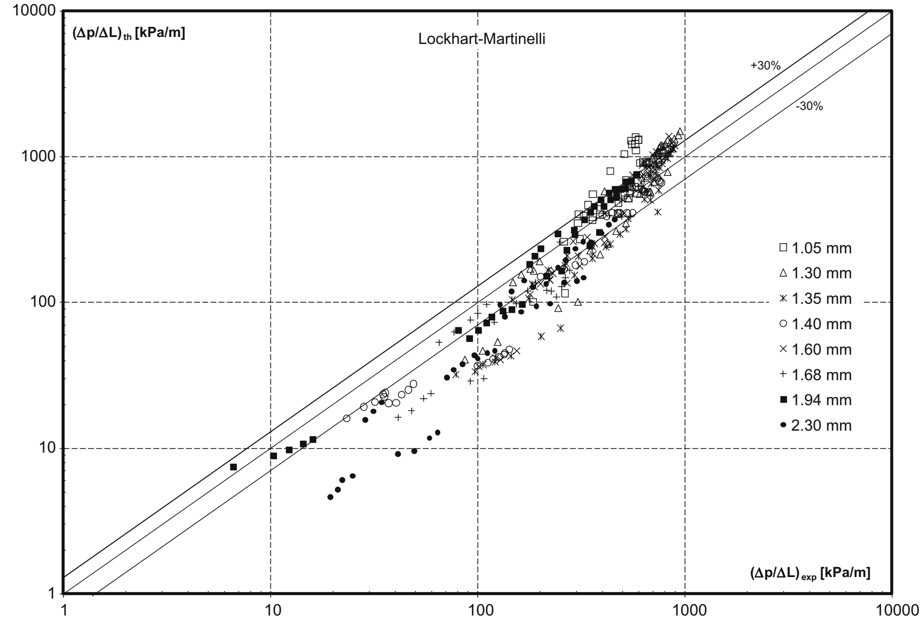

Fig. 7. Comparison of the frictional pressure drop $(\Delta p/\Delta L)_{th}$ described by Lockhart–Martinelli formula with experimental results $(\Delta p/\Delta L)_{exp}$ for different minichannels.

Hibiki [16–18], who proposed that value C be made dependent on the minichannel diameter. There are also proposals by other authors to make value C dependent from the following: Reynolds number, total mass flux ($w\rho$), the confinement number *Co*. A list of different proposals was presented, among others, e.g. by Choi et al. [19], Lee and Mudawar [20]. It is observed that except the proposals to change factor C in Chisholm's Eq. (8), attempts are made to introduce a new dependence for the correction factor Φ_l^2. At present, numerous tests are conducted to examine the dependencies proposed by various authors to be applied for minichannels.

In the further analysis, the results of the calculations of the frictional pressure drop $(\Delta p/\Delta L)_{th}$ determined on the basis of the classical formulae commonly used for conventional channels, with the experimental results $(\Delta p/\Delta L)_{exp}$ obtained for minichannels were compared. Fig. 7 presents the comparison among the two-phase frictional pressure gradient data with the predictions by Lockhart–Martinelli method. It was found that the mean absolute errors for the comparisons are in range of 23.0 ÷ 32.9% for the minichannels with diameter $d_w = 1.35 \div 1.94$ mm. Note that the mean deviation was calculated as $\frac{1}{n}(\sum_n^1 |(\Delta p/\Delta L)_{th} - (\Delta p/\Delta L)_{exp}|/(\Delta p/\Delta L)_{exp}) \cdot 100\%$. It was found that mean absolute error increase with decrease of internal diameter of minichannel. For the above-mentioned range of the tubular minichannel diameters the most of experiment was in range the turbulent flow of water and air (*T–T*), and the laminar flow of water and the turbulent flow of air (*L–T*). Then, for the conventional channels, C constant accepts greater values. In these cases, this corresponds well with the diagrams presented in Fig. 6. Values which were similarly greater, yet not constant, were obtained from the experiment for the minichannel.

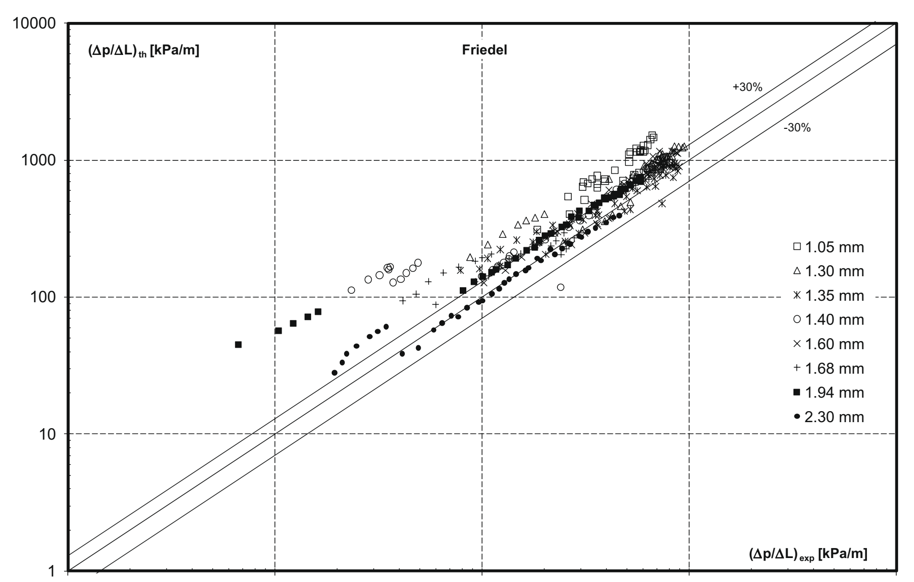

Fig. 8. Comparison of the frictional pressure drop $(\Delta p/\Delta L)_{th}$ described by Friedel formula with experimental results $(\Delta p/\Delta L)_{exp}$ for different minichannels.

It was observed for the remaining range of the diameters of minichannels that deviations are substantially greater: they occur in the remaining flow areas of both phases. It was found that the mean absolute errors for the comparisons are 45.5%, 35.6% and 47.8% for the minichannels with diameter 1.05, 1.30 and 2.30 mm, respectively.

The above-mentioned observations concerning the application of the classical version of Lockhart–Martinelli model for minichannels, indicated limited possibilities of the use of this calculation procedure.

Fig. 8 presents a comparison of the results of calculations according to Friedel's method and experimental investigations. It is evident from the diagram that with an increase of the minichannel diameter, the suitability of the model is better. It is characteristic that the trend of the experiment results is ideally compliant with the model.

For minichannel diameter $d_w = 1.05$ mm, the number of the experiment results, which fall within the range of ±30% did not exceed 5%; for a minichannel with diameter $d_w = 2.30$ mm, the number of the investigations results falling within the above-mentioned range, was as much as 82%. For minichannel diameters of 1.40, 1.94 and 2.30 mm, a significant displacement of a certain number of data was observed. This occurs in the case of the smallest values of the mass flow rate which were applied during the experiments. This also corresponds with the case of a laminar flow through minichannels of both a liquid and a gas. This may give evidence to the sensitivity of this method to the change of the mass flow rate especially when the total mass flux is very small. Papers by other authors confirm the unsuitability of Friedel's method for the calculation of the frictional resistance of the two-phase flow through minichannels. Vassallo and Keller [21] obtained results, depending of the conditions of the experiment, in the range from 5% to 50%. Qu and Mudawar [22], while testing Friedel's model, obtained a mean absolute error which exceeded 350%.

It is evident from the comparative experimental investigations presented above that Friedel's classical method gives poor results for the calculations of pressure drop two-phase flow in minichannels. The error of the method increases when the minichannel diameter decreases.

3. Conclusions

Even though there exist papers which confirm the suitability of classical methods of Lockhart–Martinelli and Friedel for the calculation of the frictional resistance of the two-phase flow in minichannels [23–25], the experimental verification conducted confirms the existence of substantial limitations, including the following:

1. classical correlations of Lockhart–Martinelli and Friedel may serve only for the purpose of an primary estimation of resistances in the adiabatic two-phase flow in tubular minichannels;
2. the need of an introduction of corrections and modifications to the classical method was confirmed by experiments, in order to adapt them to calculations for minichannels;
3. further investigations are necessary in order to check the proposals by other authors concerning the correct determination of two-phase pressure drop in minichannels.

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