Experimental and comparative study on the two-phase pressure drop of air-water mixture in U-bend and straight pipe annuli

To cite this article: R Andrzejczyk and T Muszynski 2018 J. Phys.: Conf. Ser. 1101 012002

View the article online for updates and enhancements.

You may also like

- Evanescent wave absorption sensor with direct-growth MoS2 film based on U-bent tapered multimode fiber
  Zhe Li, Chao Zhang, Yanshun Han et al.

- A novel U-bent plastic optical fibre local surface plasmon resonance sensor based on a graphene and silver nanoparticle hybrid structure
  Shouzhen Jiang, Zhe Li, Chao Zhang et al.

- Tool Texturing for Deep Drawing Applications
  J Hazrati, P Stein, P Kramer et al.
Experimental and comparative study on the two-phase pressure drop of air-water mixture in U-bend and straight pipe annuli

R Andrzejczyk, T Muszynski
Gdansk University of Technology, Faculty of Mechanical Engineering, Department of Energy and Industrial Apparatus, Narutowicza 11/12, 80-233 Gdansk, Poland
e-mail: rafal.andrzejczyk@pg.edu.pl

Abstract. In this paper, the experimental and theoretical analysis of pressure drop in single-phase and two phase-flow were presented for straight and U-bend smooth tube annulus and tube annulus with wire coil insert. Experiments for various boundary conditions were performed. In case of U-tube and straight tube with and without turbulator, tests were made for the water-water and air-water systems. The study covered a wide measuring range, i.e. \( V_w = 9 \times 10^{-5} - 8.87 \times 10^{-6} \) m\(^3\)/s - for water, and \( V_a = 5.55 \times 10^{-5} \) m\(^3\)/s - for air. The test elements were made from a copper pipe with an external diameter of 10 mm and 18 mm and wall thickness 1 mm. The helicoidal vortex generator was made from brass wire with a diameter of 2.4 mm, coil diameter 13 mm and pitch 11 mm. For these geometries, the values of pressure drop and heat flux were determined. Obtained experimental results were compared with correlations from literature. The best coherence with database were obtain for Lockhart-Martinelli and Sugawar et al. models for two-phase flow regime.

1. Introduction
Nowadays, the rapid development of practical engineering applications for mini and micro-devices, micro-systems, advanced material designs, manufacturing electronic microchips increases the demand for better understanding of fluid mechanics [1]. The prediction of single phase and the two-phase pressure gradient is an essential step in the design of a variety of equipment in the power and process engineering, renewable energy systems and heating, ventilation, air conditioning or refrigerating systems. However it should be emphasized that understanding of fluid mechanics are especially very important in case of using different heat transfer enhancement techniques in heat exchangers [2,3]. In case of the most heat transfer enhancement techniques, the heat transfer coefficient enhancement achieved is accompanied by a significant increase in the pressure drop. Therefore properly prediction of heat transfer coefficient as well as pressure drops are mandatory to determine the conditions under which the use of this methods are favorable.

There are many studies in open literature on pressure drop calculation in single phase flow. The most important parameter to determine pressure loses is friction factor \( f \). Most of the works concerned experimental or numerical investigations of this parameter. The literature review of selected works is presented in table 1.

For last few years also many works were made in the field of pressure drops determination in conventional and mini-microchannels with swirl flow inserts such as twisted tapes, coil wires, static mixers et all [8]. The authors in this study focused on experimental investigation in single and two-phase flow in the pipe annulus with wire coil insert.
\[ f = 1.613 \left[ \ln \left( \frac{0.234 \varepsilon^{1.1007}}{Re^{1.1105} + 56.291} \right) \right]^{-2} \]

| Study                        | Re × 10^3 | Re ≤20 | Smooth tubes | Re ≤2000 | 4 Re ≤ 5 × 10^3 | 10^3 < Re ≤ 0.04 | 0.04 < Re ≤ 10^3 |
|------------------------------|------------|--------|--------------|----------|---------------|----------------|-----------------|
| Fang et al. [4]              | 3 < Re < 10^3 | 0.0 < ε < 0.05 | f = 0.3164 | f = 0.184 | f = Re^6.25 | f = 0.53 · ε + 0.094 · ε^0.225 + 88 · ε^0.44 · Re^-1.62 · ε^0.134 |
| Blausius                     | Re ≤ 20 | Smooth tubes | | f = Re^0.25 | | | |
| Moody [5]                    | 4 Re ≤ 5 × 10^3 | 0 < ε < 0.01 | f = 0.0055 \left[ 1 + \left( 2 \cdot 10^{-4} \cdot \varepsilon + 10^{-6} \right) \right]^{1/3} | | | |
| Wood [6]                     | 4 Re ≤ 5 × 10^4 | 10^3 < Re ≤ 0.04 | f = \left[ \log \left( \frac{\varepsilon}{d} \right) + 5.74 \varepsilon^{-0.095} \right]^{2} | | | |
| Sharafeldeen et al. [10]     | 1.4 ≤ Re ≤ 42 | 45 | Air (0.7) | | f = 0.3251 · Re^-0.101 · \left( \frac{\varepsilon}{d} \right)^{0.196} \left( \frac{p_s}{p} \right)^{-0.211} |
| Gunes [11]                   | 3.5 ≤ Re ≤ 27 | 56 | Air (0.7) | | f = 3.970492 · \left( \frac{p_s}{p} \right)^{-0.31182} · Re^{-0.367485} | |
| Slaiman [12]                 | 5.40 | 11 and 14 | Water (2.55-2.98) | | f = 3.6346 · \left( \frac{\varepsilon}{d} \right)^{-0.8912} · Re^{-0.964} \left( \frac{p_s}{p} \right)^{-0.7856} |
| Keklikcioglu and Ozcayyan [13] | 3.4 < Re < 27 | 56 | Air (0.7) | | f = 6.423 · Re^-0.301 \left( \frac{p_s}{p} \right)^{-0.587} \left( \frac{S}{d} \right)^{-0.106} |
| Akhavan-Behabadi et al. [14] | 0.02 < Re < 0.5 | 26.04 | Oil (120 < Pr < 300) | | f = 16.8 / Re^{0.96} |
| Yakut and Sahin [15]         | 5 < Re < 17 | 50 | Air (0.7) | | f = 4.44 · Re^-0.218 \left( \frac{p_s}{p} \right)^{-0.223} |
| Keklikcioglu and Ozcayyan [16] | 2.8 < Re < 27.8 | 56 | Air (0.7) | | f = 72.599 · Re^-0.514 \left( \frac{\varepsilon}{d} \right)^{0.486} \left( \frac{p_s}{p} \right)^{-0.367} |

The two-phase flow multiplier is defined as a ratio of friction pressure drop in the two-phase flow, \( \frac{dP}{dz} \) to the friction pressure drop in the flow of either liquid of as \( \frac{dP}{dz} \).
\[ \Phi^2 = \frac{\frac{dP}{dz_1}}{\frac{dP}{dz_{0}}_0} \] (1)

Generally published predictive methods are limited in validity to specific working fluids and ranges of operating parameters for the data upon which these methods are based, see table 3. It should be emphasized that still there is a need of pressure drop databases covering broad ranges of experimental conditions and a reasonable understanding of the phenomena accompanying are necessary. It is crucial important especially in case of more complicated geometries, e.g. U-bend tubes, coiled tubes, tube with swirl flow devices, displaced enhancement devices [21,22]. In this paper, the comprehensive study of two-phase pressure drop for air-water mixture in tube annulus has been shown. Experimental works were performed for smooth straight and U-bend pipes as well as straight and U-bend pipes with wire-coil inserted for wide measuring range.

| Study | d_b (mm) | Test fluid | \( \Phi^2 \) Correlations |
|-------|---------|------------|-------------------------|
| Lockhart and Martinelli [23] | 1.49-25.83 | Air-water, oils, hydrocarbon | \( \Phi_{ML,LO}^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \) for \( Re_t > 4000 \) \( \Phi_{ML,LO}^2 = 1 + CX + X^2 \) for \( Re_t < 4000 \) \( X = \left( \frac{(dp/dz)_1}{(dp/dz)_0} \right)^{0.5} \) \( C_l=5, C_{l0}=10, C_i=12, C_{i0}=20 \) |
| Mishima and Hibiki [24] | 1.05-4.08 | Air-water | \( \Phi_{M}^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \) \( C = 21 \times (1 - \exp (-0.319/D_e)) \) |
| Sugawara et al.[25] | 0.7-9.1 | Air-water | \( \Phi_{M}^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \) \( C = 21 \times (1 - \exp (-0.333/D_e)) \) |

The primary objectives of the present study are:
I. Providing an experimental database including multiple data points for two-phase total pressure drop during air-water flow at annuli in smooth straight pipe, U-bend pipe and in straight and U-bend pipe with wire-coil inserted.
II. Comparing experimental data with well-known correlations for TFPDs from open literature.
III. Conducting a systematic assessment of predictive techniques for a two-phase pressure drop.
IV. Comprehensive validation influences of mass flux, coiled wire effects for TFPDs.

2. Experimental setup

In order to obtain experimental values of two-phase pressure drop the special experimental facility was done (see fig.1). Construction of the test stand allows to change parameters of water flow as well as air flow parameters. Pressure resistances (AP) were measured using a differential pressure transducer in range 0-3 bar and 0.25 accuracy class made by PELTRON. The volumetric flow rate of water (V_w) was measured with a ROL 16 Rotameter in class 2.5 volumetric flow rate of air (V_a) was measured with a ROL 06 Rotameter in class 2.5. Authors decided to supply all elements from district water system due to the stable temperatures of that source (+/- 0.5 K). Because of high and stable pressure levels in the system (P>4bar), it was possible to achieve turbulent as well as laminar flow conditions. All experiments were performed with steady-state conditions and in each time taken twice for the same thermal flow parameters. The paper presented preliminary study for this reason the measurement accuracy were sufficient. The main purpose of presented study was to find future experimental investigations direction. What is more also the cfd calculation will be done into a future to better understand physic of all phenomena.
Figure 1. Test facility: 1 – U-tube HX, 2 – Tube in tube HX, 3 – differential pressure transducer, 4 – tap water, 5 – air, 6 – cold water control valve, 7 – air control valve, 8 – rotameter, 9 – air compressor.

Figure 2. Turbulator dimensions and cross-section of the apparatus with a view of the helical turbulent element.

Table 4. Uncertainties of selected parameters

| Symbol | Operating range | Uncertainty |
|--------|-----------------|-------------|
| \(V_w\) | \(9 \times 10^{-5} - 8.87 \times 10^{-6} \text{ m}^3/\text{s}\) | Maximum error = 2.5% |
| \(V_a\) | \(5.55 \times 10^{-5} \text{ m}^3/\text{s}\) | Maximum error = 2.5% |
| \(\Delta P\) | 0-200 kPa | Maximum error = 0.5 kPa |
| \(Re\) | 827-18423 | Maximum error = 5.7% |

3. Experimental procedure

Reynolds number at single phase regime was calculated as the mass flow rate through equivalent diameter:

\[
Re = \frac{G \cdot D_e}{\mu}
\]  

(2)

Equivalent diameter depends on the volume of the annulus divided by tube length and circumference.

\[
\text{De} = \frac{4 \cdot V_{sh}}{\pi \cdot D \cdot L}
\]  

(3)

The volume available for the flow of fluid in the annulus, \(V_{sh}\) can be calculated knowing geometrical dimensions of the tested element.

\[
V_{sh} = \frac{\pi}{4} \cdot D^2 \cdot L - \left( \frac{\pi}{4} \cdot d^2 \cdot L + \frac{\pi}{4} \cdot e^2 \cdot L \right)
\]  

(4)

The measured pressure drop is the sum of friction pressure drop (\(\Delta P_{frict}\)), expansion (\(\Delta P_{exp}\)) and contraction (\(\Delta P_{contr}\)) losses due to the headers at both ends of the test section [26]:

\[
\Delta P = \Delta P_{frict} + \Delta P_{exp} + \Delta P_{contr}
\]  

(5)
The pressure drop due to contraction was estimated using a flow model recommended by Hewitt et al. [26] for single-phase flow.

\[ \Delta P_{\text{contr}} = \frac{G^2}{2 \rho} \left[ \left( \frac{1}{C_{\text{con}}} - 1 \right) + 1 - \gamma^2 \right] \] (6)

where \( \gamma \) is the area ratio \( (A_{\text{intake manifold}}/A_{\text{shell}}) \) and \( C_{\text{con}} \) is the coefficient of contraction, which, in turn, is a function of this area ratio:

\[ C_{\text{con}} = \frac{1}{0.639 (1-\gamma)^{0.5} + 1} \] (7)

For the expansion into the header from the test section, the following flow model recommended by Hewitt et al. [26] was also used:

\[ \Delta P_{\text{exp}} = \frac{G^2 \gamma (1-\gamma) \Psi_s \rho}{\rho} \] (8)

where \( \Psi_s \), the separated flow multiplier, is also a function of the phase densities and the quality. In single flow case, those multiplier and quality are equal to unity. The friction factor was calculated as below [27]:

\[ f = \frac{\Delta P}{\left( \frac{\rho \mu^2}{2} \right) \left( \frac{L}{D_e} \right)} \] (9)

The Lockhart-Martinelli parameter was calculated directly from definition as a relation between single phase liquid pressure drop and single phase gas pressure drop [28]:

\[ X = \sqrt{\left( \frac{(dp/dz)_l}{(dp/dz)_g} \right)} \] (10)

The pressure drop for a single-phase flow, can be obtained from the following expression:

\[ \left( \frac{dp}{dz} \right)_0 = f \cdot \frac{G^2}{2 \rho} \cdot \frac{L}{D_e} \] (11)

Finally the pressure drop for two-phase flow was calculated as follow:

\[ \left( \frac{dp}{dz} \right)_{TP} = \Phi^2 \cdot \left( \frac{dp}{dz} \right)_{l} \] (12)

4. Experimental results

It is worth to note that in case of single phase flow (without turbulator and with wire coil insert) experimental correlations have significant difference values of friction factors. In case of smooth tubes (straight and U-bend) only the Swamee and Jain correlation good fits to experimental data. Other experimental correlations underestimating friction factor. In case of single-phase flow with wire coil insert none of the experimental models have a satisfactorily fit to experimental results for friction factor. Nevertheless the best coherency have Keklikcioglu, and Ozceyhan model.
Based on the above analysis, it was decided that in the calculations of two-phase flow resistance were used only correlations for friction factors that had the best coherency with experimental data. As can be seen from calculation results Lockhart-Martinelli (LM) correlation are best fit to experimental data for two-phase air-water flow in smooth pipe annuli. However, for small values of $X$ parameter obtained results are underestimate compare to experimental data. It could be explained by the higher percentage of measurement errors in the obtained results. In case of two-phase flow for annuli with coil wire inserted the best coherency with experimental data was obtained for Sugawara et al correlation. It should be emphasize that this correlation is a modification of LM correlation for small diameter channels and equivalent diameter for annuli with coil wire insert was close to 8 mm.

5. Conclusions
Based on collected experimental data, frictional pressure drop for two-phase flow, single phase flow and single friction factors were calculated. Examination of correlation for single phase friction factor has
shown significant difference of calculation results. As can be seen from calculation results LM correlation are best fit to experimental data for two-phase air-water flow in smooth pipe annuli. In case of two-phase flow for annuli with coil wire inserted the best coherency with experimental data was obtained for Sugawara et al correlation. Undoubtedly, still important is an issue to examine similarities and differences between well-known friction factor correlations to avoid misusing of them. Generally published predictive methods are limited in validity to specific working fluids and ranges of operating and geometrical parameters. Incorrect use of correlation for single phase friction factor could dramatically increase calculation errors especially in case of two-phase flow. To avoid this problems during selecting a given correlation, very important is taking into account its scope of applicability as well as flow and geometrical parameters.

Nomenclature

| Symbol | Description |
|--------|-------------|
| A      | heat transfer area [m²] |
| C      | coefficient in LM parameter [-] |
| C_con  | coefficient of contraction [-] |
| d      | diameter of the inner tube [m] |
| D_e    | equivalent diameter [m] |
| (dp/dz)_T  | pressure drop for two-phase [Pa/m] |
| (dp/dz)_L  | pressure drop for single phase [Pa/m] |
| e      | wire diameter [m] |
| f      | friction factor [-] |
| G      | mass flux [kg/m²s] |
| L      | length [m] |
| p      | wire pitch, [m] |
| ΔP     | pressure drop [Pa] |
| Pr     | Prandtl number [-] |
| Re     | Reynolds number [-] |
| w      | velocity [m/s] |
| V      | volume [m³] |
| V_ab   | volume available in the annulus [m³] |
| X      | Lockhart-Martinelli parameter [-] |

Greek symbols

| Symbol | Description |
|--------|-------------|
| γ      | area ratio [-] |
| Φ²    | two-phase flow multiplier [-] |
| Ψ_s   | the separated flow multiplier [-] |
| ε      | roughness factor [-] |
| μ      | viscosity [Pas] |
| ρ      | density [kg/m³] |

Superscripts

| Symbol | Description |
|--------|-------------|
| a      | air |
| frict  | friction |
| exp   | expansion |
| g      | gas |
| contr  | contraction |
| l      | liquid |
| lt     | laminar/turbulent |
| ll     | laminar/laminar |
| tt     | turbulent/turbulent |
| w      | water |

6. References

[1] Andrzejczyk R, Muszynski T and Dorao C A 2017 Experimental investigations on adiabatic frictional pressure drops of R134a during flow in 5 mm diameter channel Exp. Therm. Fluid Sci. 83 78–87
[2] Andrzejczyk R and Muszynski T 2017 Thermodynamic and geometrical characteristics of mixed convection heat transfer in the shell and coil tube heat exchanger with baffles Appl. Therm. Eng. 121 115–25
[3] Andrzejczyk R and Muszynski T 2018 An Experimental investigation on the effect of NEW continuous core-baffle geometry on the mixed convection heat transfer in shell and coil heat exchanger Appl. Therm. Eng.
[4] Fang X, Xu Y and Zhou Z 2011 New correlations of single-phase friction factor for turbulent pipe flow and evaluation of existing single-phase friction factor correlations Nucl. Eng. Des. 241 897–902
[5] Moody L F 1947 An approximate formula for pipe friction factors Trans. ASME 69 1005–11
[6] Wood D J 1966 An explicit friction factor relationship Civ. Eng 36 60–1
[7] Oke I A, Ojo S O and Adefosun O O 2015 Performance evaluation for darcy friction factor formulae using colebrook-white as reference Ife J. Sci. 17 75–86
[8] Liu S and Sakr M 2013 A comprehensive review on passive heat transfer enhancements in pipe exchangers Renew. Sustain. Energy Rev. 19 64–81
[9] Garcia A, Vicente P G and Viedma A 2005 Experimental study of heat transfer enhancement with wire coil inserts in laminar-transition-turbulent regimes at different Prandtl numbers Int. J.
Heat Mass Transf. 48 4640–51

[10] Sharafeldeen M A, Berbish N S, Moawed M A and Ali R K 2017 Experimental investigation of heat transfer and pressure drop of turbulent flow inside tube with inserted helical coils Heat Mass Transf. 53 1265–76

[11] Gunes S, Ozceyhan V and Buyukalaca O 2010 Heat transfer enhancement in a tube with equilateral triangle cross sectioned coiled wire inserts Exp. Therm. Fluid Sci. 34 684–91

[12] Slaiman Q J M and Znad A N 2017 Enhancement of Heat Transfer in The Tube-Sid of A Double Pipe Heat Exchanger by Wire Coils Al-Nahrain J. Eng. Sci. 16 51–7

[13] Keklikcioglu O and Ozceyhan V 2016 Experimental investigation on heat transfer enhancement of a tube with coiled-wire inserts installed with a separation from the tube wall Int. Commun. Heat Mass Transf. 78 88–94

[14] Akhavan-Behabadi M A, Kumar R, Salimpour M R and Azimi R 2010 Pressure drop and heat transfer augmentation due to coiled wire inserts during laminar flow of oil inside a horizontal tube Int. J. Therm. Sci. 49 373–9

[15] Yakut K and Sahin B 2004 The effects of vortex characteristics on performance of coiled wire turbulators used for heat transfer augmentation Appl. Therm. Eng. 24 2427–38

[16] Keklikcioglu O and Ozceyhan V 2018 Experimental investigation on heat transfer enhancement in a circular tube with equilateral triangle cross sectioned coiled-wire inserts Appl. Therm. Eng. 131 686–95

[17] Muszynski T, Andrzejczyk R and Dorao C A 2017 Detailed experimental investigations on frictional pressure drop of R134a during flow boiling in 5 mm diameter channel: The influence of acceleration pressure drop component Int. J. Refrig. 82

[18] Andrzejczyk R and Muszyński T 2017 The performance of H2O, R134a, SES36, ethanol, and HFE7100 two-phase closed thermosyphons for varying operating parameters and geometry Arch. Thermodyn. 38 3–21

[19] Autee A T and Giri S V 2016 Experimental study on two-phase flow pressure drop in small diameter bends Perspect. Sci. 8 621–5

[20] Mikielewicz D, Wajs J, Andrzejczyk R and Klugmann M 2016 Pressure drop of HFE7000 and HFE7100 during flow condensation in minichannels Int. J. Refrig. 68

[21] Andrzejczyk R and Muszyński T 2016 Performance analyses of helical coil heat exchangers. The effect of external coil surface modification on heat exchanger effectiveness Arch. Thermodyn. 37 137–59

[22] Muszynski T and Andrzejczyk R 2016 Heat transfer characteristics of hybrid microjet - Microchannel cooling module Appl. Therm. Eng. 93 1360–6

[23] Lockhart R W and Martinelli R C 1949 Proposed correlation of data for isothermal two-phase, two-component flow in pipes Chem. Eng. Prog 45 39–48

[24] Mishima K and Hibiki T 1996 Some characteristics of air-water two-phase flow in small diameter vertical tubes Int. J. Multiph. Flow 22 703–12

[25] Kaji M, Sawai T, Kagi Y and Ueda T 2010 Heat transfer and fluid dynamics of air–water two-phase flow in micro-channels Exp. Therm. Fluid Sci. 34 446–53

[26] Hewitt G F, Shires G L and Bott T R 1994 Process heat transfer vol 113 (CRC press Boca Raton, FL)

[27] Sheikholeslami M, Gorji-Bandpy M and Ganji D D 2015 Review of heat transfer enhancement methods: focus on passive methods using swirl flow devices Renew. Sustain. Energy Rev. 49 444–69

[28] Chen J J J and Spedding P L 1981 An extension of the Lockhart-Martinelli theory of two phase pressure drop and holdup Int. J. Multiph. Flow 7 659–75

Acknowledgments
The work presented in the paper was partially funded by statutory activity of faculty of Mechanical Engineering of Gdansk University of Technology.