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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
email: 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*10-5-8.87*10-6 m3/s - for water, and V_a=5.55*10-5 m3/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.

Table 1. Single-phase friction factor correlations

Study	Re × 10^3	ε	f
Fang et al. [4]	3 < Re< 10^5	0.0 <ε <0.05	$f = 1.613\left[ln\left(0.234\varepsilon^{1.1007} - \frac{60.525}{Re^{1.1105}} + \frac{56.291}{Re^{1.0712}}\right)\right]^{-2}$
Blausius	Re≤20	Smooth tubes	$f = \frac{0.3164}{Re^{0.25}}$
	20≤Re≤2000		$f = \frac{0.184}{Re^{0.2}}$
Moody [5]	4<Re<5x10^5	0 <ε <0.01	$f = 0.0055\left[1 + \left(2 \cdot 10^4 \cdot \frac{\varepsilon}{d} + \frac{10^6}{Re}\right)^{\frac{1}{3}}\right]$
Wood [6]	4<Re<5x10^4	10^{-5} <ε <0.04	$f = 0.53 \cdot \varepsilon + 0.094 \cdot \varepsilon^{0.225} + 88 \cdot \varepsilon^{0.44} \cdot Re^{-1.62 \cdot \varepsilon^{0.134}}$
Swamee and Jain [7]			$f = \frac{0.25}{\left[log\left(\frac{\varepsilon/d}{3.7} + \frac{5.74}{Re^{0.9}}\right)\right]^2}$

In the table below an overview of selected works is presented. It should be noted that most of existing studies were made for extensive range of wire coil parameter but for limited range of tube diameter and Prandtl number. Generally, the majority of investigations were made only for air flow. This creates a problem for correct selection correlation for an engineering calculations.

Table 2. Single-phase friction factor correlations for tube with coiled wire inserts

Study	Re × 10^3	d [mm]	Test fluid (Pr)	f
Garcia et. al.[9]	0.8 < Re< 90	18	2.8 < Pr < 50	$f = 5.76 \cdot \left(\frac{e}{d}\right)^{0.95} \cdot \left(\frac{p}{d}\right)^{-1.21} \cdot Re^{-0.217}$
Sharafeldeen [10]	1.4 ≤ Re ≤ 42	45	Air (0.7)	$f = 0.3251 \cdot Re^{-0.101} \cdot \left(\frac{e}{d}\right)^{0.196} \cdot \left(\frac{p}{d}\right)^{-0.211}$
Gunes [11]	3.5≤ Re≤27	56	Air (0.7)	$f = 3.970492 \cdot \left(\frac{p}{d}\right)^{-0.31182} \cdot Re^{-0.367485} \cdot \left(\frac{s}{d}\right)^{-0.157719}$
Slaiman [12]	5-40	11 and 14	Water (2.55-2.98)	$f = 3.6346 \cdot \left(\frac{e}{d}\right)^{0.8912} \cdot Re^{-0.0964} \cdot \left(\frac{p}{d}\right)^{-0.7856}$
Keklikcioglu, and Ozceyhan [13]	3.4<Re<27	56	Air (0.7)	$f = 6.423 \cdot Re^{-0.301} \cdot \left(\frac{p}{d}\right)^{-0.587} \cdot \left(\frac{s}{d}\right)^{-0.106}$
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)	$f = 4.44 \cdot Re^{-0.218} \cdot \left(\frac{p}{d}\right)^{-0.223}$
Keklikcioglu, and Ozceyhan [16]	2.8<Re<27.8	56	Air (0.7)	$f = 72.599 \cdot Re^{-0.514} \cdot \left(\frac{e}{d}\right)^{0.486} \cdot \left(\frac{p}{d}\right)^{-0.367}$

This problem is even more difficult in case of two phase flow conditions. A number of studies has been done concerned at two-phase pressure drop (TFPD) in straight pipe [18] as well as in curved pipe [19]. However, most of the studies were focused on two-phase pressure drop during the flow in circular mini and microchannels [20]. The two-phase flow multiplier is defined as a ratio of friction pressure drop in the two-phase flow, $\left(\frac{dP}{dz}\right)_{TP}$ to the friction pressure drop in the flow of either liquid of as $\left(\frac{dP}{dz}\right)_0$

$$\Phi^2 = \frac{\left(\frac{dP}{dz}\right)_{TP}}{\left(\frac{dP}{dz}\right)_0} \tag{1}$$

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 emphasize, 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.

Table 3. Two-phase frictional pressure gradient correlations

Study	d_h	Test fluid	Φ^2
Lockhart and Martinelli [23]	1.49-25.83 mm	Air-water, oils, hydrocarbon	$\Phi^2{}_{ML\_LO} = 1 + \frac{C}{X} + \frac{1}{X^2}$ for $Re_l > 4000$ $\Phi_{ML\_LO} = 1 + CX + X^2$ for $Re_l < 4000$, $X = \left((dp/dz)_l/(dp/dz)_g\right)^{0.5}$ $C_{lt}=5$, $C_{tl}=10$, $C_{ll}=12$, $C_{tt}=20$
Mishima and Hibiki [24]	1.05–4.08 mm	Air-water	$\Phi^2{}_M = 1 + \frac{C}{X} + \frac{1}{X^2}$ $C = 21 \cdot \left(1 - \exp \cdot (-0.319/D_e)\right)$
Sugawara et al.[25]	0.7-9.1 mm	Air-water	$\Phi^2{}_M = 1 + \frac{C}{X} + \frac{1}{X^2}$ $C = 21 \cdot \left(1 - \exp \cdot (-0.333/D_e)\right)$

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 (ΔP) 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 o6 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 phenomes.

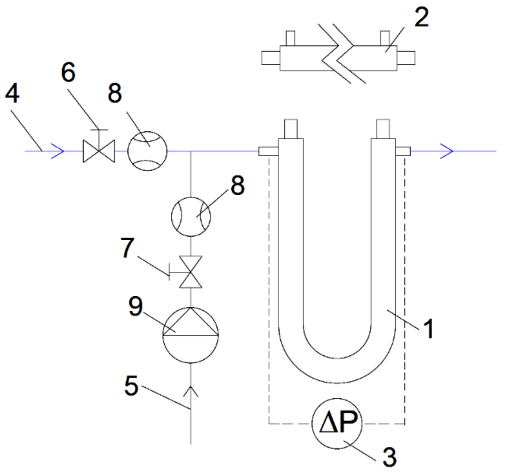

Figure 1. Test facility: 1 – U-tube HX, 2 – Tube in tube HX, 3 – differential pressure transducer , 4 –tap water, 5 –air,6 – cold water control valve, 7 – air control valve, 8 – rotameter, 9 – air compressor

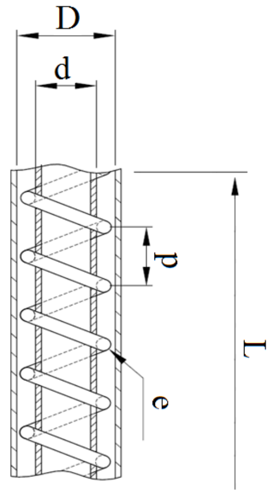

Figure 2. Turbulator dimensions and cross-section of the apparatus with a view of the helical turbulent element

Table 4. Uncertainties of selected parameters

Symbol	Operating range	Uncertainty
V_w	$9*10^{-5}$-$8.87*10^{-6}$ m^3/s	Maximum error = 2.5%
V_a	$5.55*10^{-5}$ m^3/s	Maximum error = 2.5%
ΔP	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:

$$Re = \frac{G \cdot D_e}{\mu} \tag{2}$$

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

$$De = \frac{4 \cdot V_{sh}}{\pi \cdot D \cdot L} \tag{3}$$

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

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

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

$$\Delta P = \Delta P_{frict} + \Delta P_{exp} + \Delta P_{contr} \tag{5}$$

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

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

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

$$C_{con} = \frac{1}{0.639 \cdot (1-\gamma)^{0.5} + 1} \tag{7}$$

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

$$\Delta P_{exp} = \frac{G^2 \cdot \gamma \cdot (1-\gamma) \cdot \Psi_s}{\rho} \tag{8}$$

where Ψ_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]:

$$f = \frac{\Delta P}{\left(\frac{\rho \cdot w^2}{2} \right) \cdot \left(\frac{L}{D_e} \right)} \tag{9}$$

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]:

$$X = \sqrt{\frac{(dp/dz)_l}{(dp/dz)_g}} \tag{10}$$

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

$$\left(\frac{dP}{dz} \right)_0 = f \cdot \frac{G^2}{2 \cdot \rho} \cdot \frac{L}{D_e} \tag{11}$$

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

$$\left(\frac{dP}{dz} \right)_{TP} = \Phi^2 \cdot \left(\frac{dP}{dz} \right)_l \tag{12}$$

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.

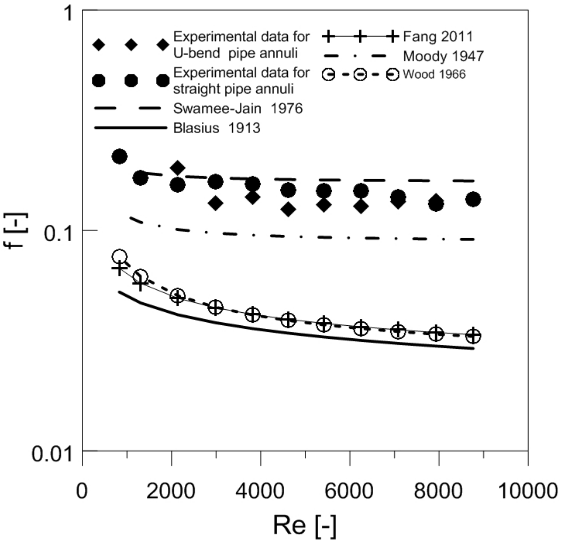

Figure 3. Hydraulic characteristic for annuli without coil wire insert: friction factors vs Reynolds numbers

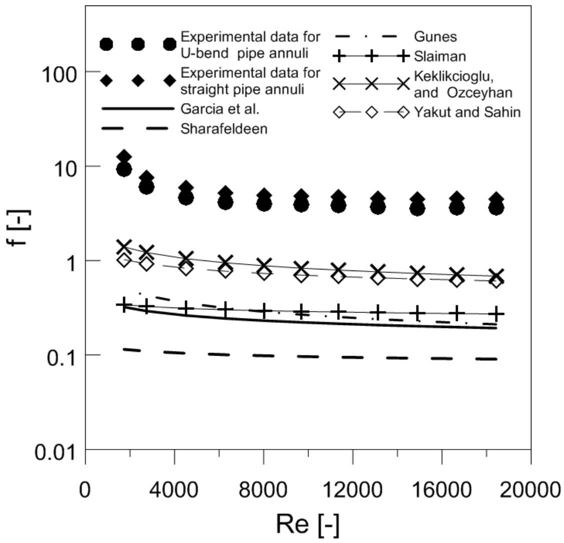

Figure 4. Hydraulic characteristic for annuli with coil wire insert: friction factors vs Reynolds numbers

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.

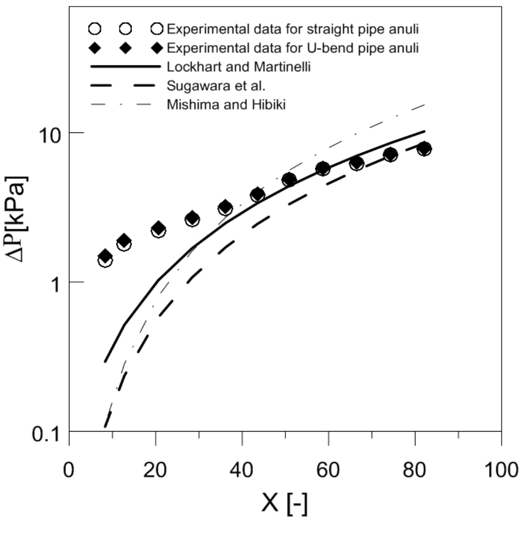

Figure 5. Two phase pressure drop versus Lockhart Martinelli parameter for annuli without coil wire insert

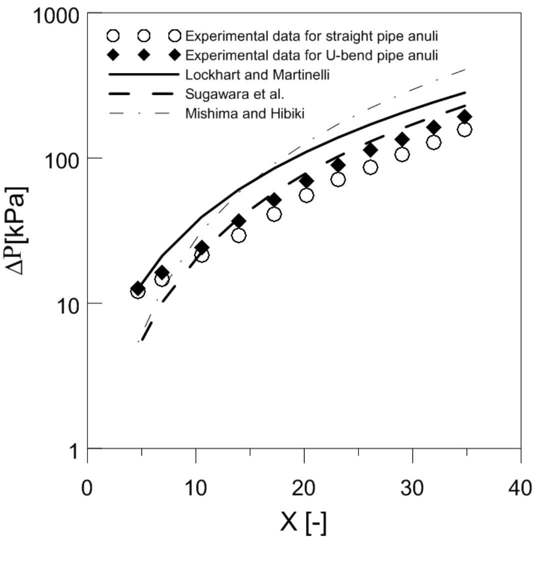

Figure 6. Two phase pressure drop versus Lockhart Martinelli parameter for annuli with coil wire insert

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

A - heat transfer area [m^2]
C – coefficient in LM parameter [-]
C_{con} - coefficient of contraction [-]
d – diameter of the inner tube [m]
D_e – equivalent diameter [m]
$(dP/dz)_{TP}$ – pressure drop for two-phase [Pa/m]
$(dP/dz)_0$ – pressure drop for single phase [Pa/m]
e – wire diameter [m]
f – friction factor [-]
G – mass flux [kg/m^{2}s]
L – length [m]
p – wire pitch, [m]
ΔP – pressure drop [Pa]
Pr – Prandtl number [-]
Re – Reynolds number [-]
w – welocity [m/s]
V – volume [m^3]
V_{sh} – volume available in the annulus [m^3]
X Lockhart-Martinelli parameter [-]

Greek symbols

γ area ratio [-]
Φ^2 two-phase flow multiplier [-]
Ψ_s the separated flow multiplier [-]
ε roughness factor [-]
μ viscosity [Pas]
ρ density [kg/m^3]

Superscripts

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

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