JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535
Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2023.147242
2023, No. 59 (X–XII): 174–182

Real values of local resistance coefficients during water flow through a pipe aerator with filling

Marek Kalenik[1)], Marek Chalecki[2)], Piotr Wichowski[1)], Adam Kiczko[1)], Krzysztof Chmielowski[3)], Martyna Świętochowska[4)], Joanna Gwoździej-Mazur[4)]

[1)] Warsaw University of Life Sciences – SGGW, Institute of Environmental Engineering, Department of Hydraulics and Sanitary Engineering, Nowoursynowska 159, 02-776 Warsaw, Poland

[2)] Warsaw University of Life Science – SGGW, Institute of Civil Engineering, Department of Mechanics and Building Structures, Warsaw, Poland

[3)] University of Science and Technology in Krakow – AGH, Faculty of Drilling, Oil and Gas, Department of Gas Engineering, Krakow, Poland

[4)] Bialystok University of Technology, Faculty of Civil Engineering and Environmental Sciences, Department of Water Supply and Sewage Systems, Białystok, Poland

RECEIVED 14.04.2023 ACCEPTED 23.08.2023 AVAILABLE ONLINE 31.12.2023

Abstract: The paper presents the results of studies on local resistance coefficients (ζ). The study used pipe aerators with filling made according to the Polish patent PL235924. The hydraulic investigations were performed in real working conditions of a water treatment plant in a testing rig built in the Scientific and Research Water Station of the Warsaw University of Life Sciences (SGGW). The investigation encompassed two plastic pipe aerators of an internal diameter 101.6 and 147.6 mm with steel Białecki rings of 12 and 25 mm in diameter. Measurements of pressure difference (Δp) in the investigated aerators were performed at volumetric water flows (Q) selected from the range 2–20 $m^3 \cdot h^{-1}$ with the interval 2 $m^3 \cdot s^{-1}$. The values of ζ were determined according to the PN-EN 1267:2012 standard. The investigation showed that the ζ depends both on an internal diameter of the plastic pipe aerator and the diameter of Białecki steel rings. The values of ζ increase with a decrease of the internal diameter of the pipe aerator and a decrease of the ring diameter.

Keywords: Białecki rings, local resistance coefficient, pipe aerator, pressure difference, volumetric water flow

INTRODUCTION

Due to an increasing potable water stress, anthropogenic impacts and constantly increasing water consumption, water treatment gains a special interest (Malima, Kilonzo and Zuwarimwe, 2022). Therefore, it is important to improve devices and methods used for water treatment in various domestic and industrial applications, as well as a design of water treatment stations with the possible highest capacity and lowest energy consumption (Ojo, Otieno and Ochieng, 2012; Tejada-Tovar, Villabona-Ortíz and López-Barbosa, 2022).

The accessible scientific and technical literature provides little information on hydraulic investigations into working conditions and effectiveness of water aeration as well as rules of design and exploitation of pipe aerators with Białecki rings (Kalenik, Morawski and Stańko, 2006; Kalenik and Morawski, 2007; Kalenik and Morawski, 2009; Kalenik and Morawski, 2013; Kalenik *et al.*, 2017). The pipe aerators occupy little space as they are installed vertically along pipelines supplying water to filters, and they show a high effectiveness of water aeration and are easy in exploitation.

A water flow through the pipe aerator is more complex than through T-fittings (Kalenik, Chalecki and Wichowski, 2020). T-fittings are also used as aerators, i.e. mixers of liquids, and are widely applied not only in water supply systems but also in industrial liquid mixing installations. In the T-fitting, the through-run or divergent water flow is turbulent providing excellent mixing of various liquids (Kuczaj, Komen and Loginov, 2010). Systems with T-fittings are applied in the industry to mix hot and cold water in pipelines of nuclear power plants (Selvam, Kulenovic and Laurien, 2016). The same system is applied for mixing air and fuel in gas turbines or internal combustion engines (Chalet and Chesse, 2010; Sakowitz, Mihaescu and Fuchs, 2014) or for mixing various chemical compounds where mixing quality is an important factor affecting the velocity of chemical reactions. Jet pumps are also applied as aerators, i.e. mixers of liquids, in water treatment plants (Kalenik *et al.*, 2017).

In water supply systems, various water treatment devices and various fittings are applied. They need to be tight in joints, resistant to mechanical and chemical impacts of liquids, cannot corrode and must enable a liquid flow with the lowest possible hydraulic resistance (losses). There are not many technical and research publications concerning the determination of local resistance coefficients (ζ) during the flow of Newtonian liquids in devices and fittings applied in water supply systems (Bassett, Winterbone and Pearson, 2001; Chalet and Chesse, 2010; Csizmadia and Hős, 2014; Li *et al.*, 2014; Sakowitz, Mihaescu and Fuchs, 2014; Wichowski, Siwiec and Kalenik, 2019).

Nowadays, researchers deal mainly with the mathematical modelling of multi-phase flow of various liquids in fittings but not in water treatment devices. First of all, it concerns elbows, T-fittings, diffusors and confusors (Csizmadia and Hős, 2014; Li *et al.*, 2014; Röhrig, Jakirlić and Tropea, 2015). The modelling of Newtonian and non-Newtonian liquid flow uses the CFD (computational fluid mechanics) environment, so-called numerical fluid mechanics (Lin *et al.*, 2005; Ono *et al.*, 2011; Csizmadia and Hős, 2014; Dutta and Nandi, 2015; Athulya and Miji Cherian, 2016; Chowdhury, Alam and Sadrul Islam, 2016; Dutta *et al.*, 2016). The mathematical modelling of flow structures with liquid and solid phases is very difficult as the multi-phase flows depend on many factors and variables (Hellströ̋m Sinha and Smits, 2011; Takamura *et al.*, 2012; Kalenik, 2015; Kalenik and Chalecki, 2018; Wichowski, Siwiec and Kalenik, 2019).

For hydraulic calculations of water supply systems consisting of a water intake, water treatment plant, water tanks and pipeline network, the value of ζ is necessary and it can be determined with use of the accessible literature (PN-76/M-34034, 1987; Liu and Duan, 2009; Csizmadia and Hős, 2014; Li *et al.*, 2014; Li, Wang and Ha, 2015; Pliżga, Kowalska and Musz-Pomorska, 2016; Wichowski, Siwiec and Kalenik, 2019). Various results can be obtained depending on literature sources used to select values of the local resistance coefficient while calculating hydraulic losses in devices of water treatment plants and pipelines. An increase of hydraulic resistance in water supply systems depends on the roughness of materials applied (Wichowski *et al.*, 2021), angles between pipe axes at joints, diameters of devices, as well as the type of a controlling fixtures. Due to that, water supply systems with high hydraulic losses are characterized by higher investment and exploitation costs as they require pumps with higher delivery head which, in turn, require more powerful motors.

In the known constructions of pipe aerators, a cover for removing rings and putting them back into the aerator after chemical cleaning is situated laterally (Kalenik, Morawski and Stańko, 2006). This significantly impedes removal of the rings and refilling the aerator. The aerators cannot remove dissolved gases from water during water aeration due to their construction. Moreover, direct installation in a pipeline makes it impossible to install a vent. Thus, during water aeration, gases and air are pressed into the aerator along with aerated water to filters removing iron and manganese. This increases hydraulic resistance that results in clogging. The installation of a vent to remove gases and air is possible only in the top cover of the filter.

These problems can be eliminated by a pipe aerator made according to Polish patent PL235924 (Kalenik and Morawski, 2020). The aerator consists of a pipe section with filling and has inclined T-pipes on its ends. These T-pipes, in sections coaxial to the pipe section, are equipped with covers that facilitate removal of rings and filling. According to the patent, the top cover of the aerator includes a vent which removes air and gases released from water during aeration and prevents apparent clogging (increase of hydraulic resistance) of filters removing iron and manganese.

Replacement of rings in the pipe aerator is very easy (Kalenik and Morawski, 2020). A tank must be put under the aerator, then a bottom cover is dismounted and the rings fall down from the aerator to the tank. Then the bottom cover is mounted back. The filling of the aerator with rings is also easy: the top cover is dismounted, the aerator is filled with clean rings and the top cover is mounted back.

Currently, the scientific and technical literature does not provide information on how to calculate values of ζ in the pipe aerators with filling made according to Polish patent PL235924 (Kalenik and Morawski, 2020). Thus, the present paper contains a comparative analysis of ζ values in the plastic pipe aerators with Białecki steel rings. The results have been obtained experimentally on the test rig built according to guidelines included in a European standard (PN-EN 1267:2012, 2012). The standard proposes equations and a nomogram to calculate the coefficient for design purposes. The investigation covered two plastic pipe aerators of 101.6 and 147.6 mm in internal diameters, and steel Białecki rings of 12 and 25 mm in diameter.

Usually, pipe aerators used in water treatment plants have internal diameters 100–200 mm (Kalenik *et al.*, 2017). For this reason, the pipe aerator with filling according to Polish patent PL235924 (Kalenik and Morawski, 2020) was made of typical PVC-U PN 10 pressure pipes available on the market and having their external diameter 110 and 160 mm (internal diameter of 101.6 and 147.6 mm, respectively). The PVC-U PN 10 pipes are designed for potable water and glued systems, as they are resistant to acids and bases and characterized by the water pressure strength up to 10 MPa.

MATERIALS AND METHODS

DESCRIPTION OF TEST RIG

To determine real values of the local resistance coefficient (ζ), a laboratory test rig was built in the Scientific and Research Water Station of the Warsaw University of Life Sciences – SGGW. The rig has been designed to investigate hydraulic resistance in pipe aerators with filling and its diagram is presented in Figure 1. Water was forced by a pump (*1*) through a pipeline (*2*) to the rig. At this pipeline (*2*), an Endress+Hauser PROMAG 53P50 electromagnetic water flow meter (*3*) was mounted to measure volumetric flow rate. It also included as a needle valve (*4*) which

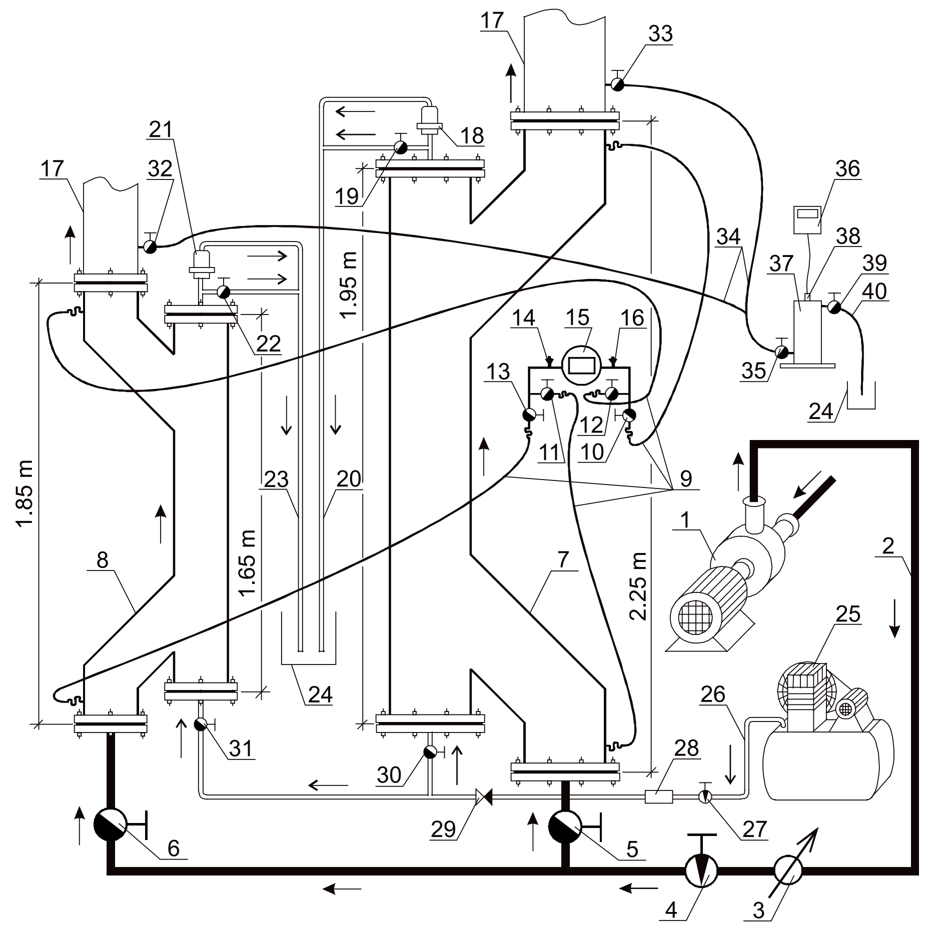

Fig. 1. The test rig used to investigate hydraulic resistance in pipe aerators with filling: *1* = pump, *2* = water supply pipeline, *3* = electromagnetic water flow meter, *4* = needle valve regulating the water volumetric flow, *5*, *6*, *10*, *11*, *12*, *13*, *32*, *33*, *35*, *49* = ball valves cutting off the water flow, *7* = pipe aerator with an internal diameter 147.6 mm, *8* = pipe aerator with an internal diameter 147.6 mm, *9* = impulse hoses, *14*, *16*, *18*, *21* = vents, *15* = piezoelectric pressure difference meter, *19*, *22*, *30*, *31* = ball valves cutting off the air flow, *17* = pipe draining water to the sewerage, *20*, *23* = pipe draining aerated water to the sewerage, *24* = sewerage inlet, *25* = compressor, *26* = air supply pipeline, *27* = needle valve regulating the air flow, *28* = thermal air flow meter, *29* = non-return valve, *34* = hoses supplying the aerated water, *36* = data recorder with display, *38* = electrode measuring the oxygen dissolved in water and water temperature, *37* = tank with overfall, *40* = hose draining the aerated water to the sewerage; source: own elaboration

precisely sets the flow rate of water coming to individual pipe aerators. The aerators had their internal diameters 147.6 mm (*7*) and 101.6 mm (*8*). At the inlet and outlet of the pipe, impulse hoses (*9*) were mounted connected to ball valves (*10–13*).

The hydraulic resistance of the individual pipe aerators was measured with the use of an Endress+Hauser DELTABAR PMD235 piezoelectric pressure difference meter (*15*). The pipe aerators were mounted at the test rig in a vertical position. In the highest points of the measurement system, vents (*14*, *16*, *18*, *21*) were mounted. The air was supplied to the aerators (*7*) and (*8*) from the compressor (*25*), through the pipeline (*26*) where a needle valve (*27*) was mounted to adjust a volumetric flow of air in individual aerators. Values of the volumetric flow were measured with use of an E+E Elektronik EE741 thermal air flow meter (*28*). At the air supplying pipe (*26*), a non-return valve (*29*) was mounted. To measure the oxygen dissolved in aerated water and water temperature, A MERA Hanna Edge HI 2004-2 meter of dissolved oxygen was used, equipped with a data recorder (*36*) with a display and an electrode (*38*) measuring water temperature and quantity of oxygen dissolved in water. The test rig operated in an open system and water flowing out was discharged into the sewer (*17*, *24*).

The measurement ranges of the electromagnetic water flow meter and the piezoelectric pressure difference meter were respectively 0–70 $m^3 \cdot h^{-1}$ and 0–600 kPa. A measurement range of the thermal air flow meter was 0–75 $m^3 \cdot h^{-1}$. The applied electromagnetic flow meter and piezoelectric difference pressure meter had their measurement errors lower than 2% and the thermal air flow meter's one was below 3%, whereas the output current signal was in the range of 4–20 mA. The measurement range of the electrode measuring quantity of the oxygen dissolved in water was 0–45 ppm and its measurement accuracy was ±1.5%. The measurement accuracy of the electrode measuring water temperature was ±0.2°C with a measurement resolution 0.1°C.

During hydraulic resistance tests, the individual pipe aerators (Fig. 1) were filled with 12 and 25 mm steel Białecki rings (Photo 1). A bulk thickness of the rings in the individual aerators was equal to 1 m. The pipe aerator was 147.6 mm in diameter and 2.25 m in height and the pipe aerator 101.6 mm and 1.85 m (Fig. 1).

Photo 1. Steel Białecki rings: a) 25 mm diameter, b) 12 mm diameter (phot.: *M. Kalenik*)

INVESTIGATIONS' METHODS

Measurements of the hydraulic resistance in individual pipe aerators with the steel Białecki rings concerned only a water volumetric flow. Before each measurement series (Fig. 1), all valves on the test rig were closed. The measurements of the hydraulic resistance were performed separately for the 147.6 mm aerator (*7*) and the 101.6 mm aerator (*8*). As each measurement series started, the following valves were opened: *4*, *35*, *39* for all aerators, *5* and *37* for the 147.6 mm aerator (*7*), *6* and *32* for the 101.6 mm aerator (*8*). Then the pump (*1*) and the data recorder (*38*) with the electrode measuring the oxygen dissolved in water and the water temperature were turned on. The distributor of the piezoelectric pressure difference meter (*15*) was connected through impulse hoses (*9*) with the beginning and end of the aerator. As the flow condition stabilized, the following valves were opened on the distributor: *10* and *11* for the 147.6 mm aerator (*7*), *12* and *13* for the 101.6 mm aerator (*8*). Then, the impulse hoses (*9*) and the piezoelectric pressure difference meter (*15*) were vented through vents (*14*, *16*). After the air bubbles had been removed from the measurement set, the first water flow rate Q was set on the electromagnetic water flow meter (*3*) with use of the needle valve (*4*). When the water flow became stable, the pressure difference Δp from the piezoelectric meter (*15*) and the water temperature (T) from the data recorder (*36*) were read. Then, with use of the needle valve (*4*), the next water flow rate Q was set and, when the water flow stabilised again, further readings of the Δp and T were made. As each measurement series was finished, the pump (*1*) and data recorder (*36*) with the electrode (*41*) measuring oxygen dissolved in water and water temperature were turned off.

The measurements of the hydraulic resistance were made for the pre-set values of the Q changing every 2 $m^3 \cdot h^{-1}$ within the range 2–20 $m^3 \cdot h^{-1}$. During measurements, the electromagnetic flow meter (*3*) showed slight pulsations of the Q, evoked by the pump action and affecting also the Δp recorded by the piezoelectric meter (*15*). To eliminate random measurement errors, three measurement series were made for each Q value and the average value calculated by on the results. Hence, 6 averaged measurement series were performed for each aerator.

The ζ values for the plastic pipe aerators with steel Białecki rings were determined from the experimental tests with use of Equations (1) and (2) (PN-EN 1267:2012, 2012):

$$\zeta = \frac{2\Delta p}{\rho v^2} \tag{1}$$

$$v = \frac{10^6 Q}{\pi d^2/4} \tag{2}$$

where: ζ = local resistance coefficient (–), Δp = pressure difference (Pa), ρ = water mass density ($kg \cdot m^{-3}$), v = water flow velocity ($m \cdot s^{-1}$), Q = water flow rate ($m^3 \cdot s^{-1}$), d = internal diameter of the pipe aerator (mm).

RESULTS AND DISCUSSION

Figure 2 presents results of real pressure difference measurements (Δp), i.e. the hydraulic resistance in plastic pipe aerators with steel Białecki rings, related to the water volumetric flow (Q). During the measurements, the Δp in the pipe aerators with filling increased with the increase of the water volumetric flow (Fig. 2) and this tendency is concordant with the literature data (Kalenik, Morawski and Stańko, 2006; Kalenik and Morawski, 2007; Li, Wang and Ha, 2015; Pliżga, Kowalska and Musz-Pomorska, 2016; Wichowski *et al.*, 2021). The lowest hydraulic resistance during the water flow was recorded in the 147.6 mm pipe aerator with 25 mm rings (A4 – Fig. 2), whereas the highest resistance in the 101.6 mm aerator and 12 mm rings (A1). The regression of the measured Δp values was exponential and the determination coefficients (R^2) from sample were equal 1.00. This proves that the hydraulic resistance in the plastic pipe aerators with steel Białecki rings fully depends on the water volumetric flow, internal diameter of the aerator, and diameter of Białecki rings.

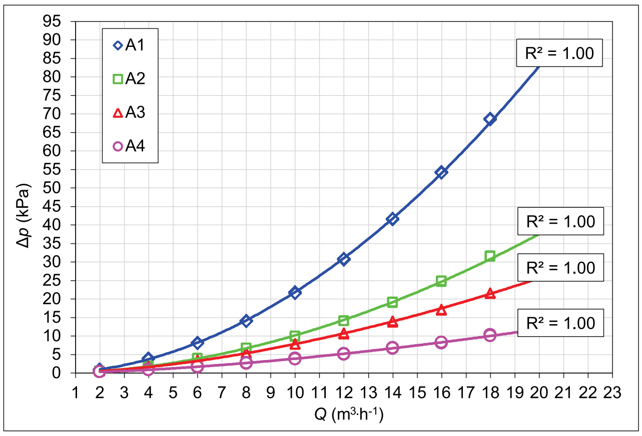

Fig. 2. Relation of the real pressure difference (Δp) vs. water volumetric flow (Q) for plastic pipe aerators with steel Białecki rings; A1 = aerator with internal diameter 101.6 mm and steel rings with diameter 12 mm, A2 = aerator with internal diameter 101.6 mm and steel rings with diameter 25 mm, A3 = aerator with internal diameter 147.6 mm and steel rings with diameter 12 mm, A4 = aerator with internal diameter 147.6 mm and steel rings with diameter 25 mm, R^2 = determination coefficient; source: own study

Using Equations (1) and (2) for the established values of Q and measured real values of pressure difference (Δp) in individual pipe aerators (Fig. 2), local resistance coefficients ζ_{A1m}, ζ_{A2m}, ζ_{A3m}, ζ_{A4m} were determined and presented in Figure 3. Their values for the investigated pipe aerators decreased with the increase of the Reynolds number (Re) (Fig. 3) and it was a correct tendency, concordant with literature data (Costa *et al.*, 2006; Mynard and Valen-Sendstad, 2015). The lowest values of the local resistance coefficient were for the 101.6 mm pipe aerator and 25 mm rings (A2), whereas the highest ones, for the 147.6 mm pipe aerator and 12 mm rings (A3). The regression of the measured ζ values was exponential and the determination coefficients (R^2) from sample were equal 0.93. This proves that in at least 93% of instances the hydraulic resistance depends on Re, i.e. Q, internal diameter of the pipe aerator, and the diameter of Białecki rings, whereas in 7% instances, it depends on the temperature and density of water.

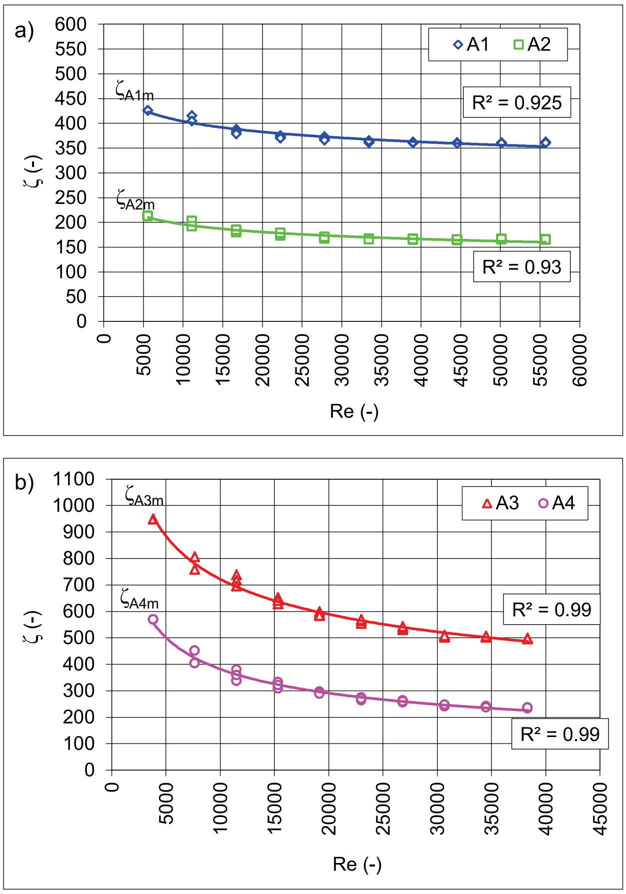

Fig. 3. Relation of the local resistance coefficient (ζ) vs. Reynolds number (Re) for plastic pipe aerators with steel Białecki rings and the internal diameter: a) 101.6 mm, b) 147.6 mm; ζ_{A1m}, ζ_{A2m}, ζ_{A3m}, ζ_{A4m} = measured resistance coefficients for A1, A2, A3, A4 respectively, A1, A2, A3, A4, R^2 as in Fig. 2; source: own study

A functional dependence between the ζ values determined in measurements and Re for the investigated plastic pipe aerators with steel Białecki rings is best described by an exponential mathematical model in the following Equations:

$$\zeta_{A1w} = 832\mathrm{Re}^{-0.0785} \tag{3}$$

$$\zeta_{A2w} = 582\mathrm{Re}^{-0.1182} \tag{4}$$

$$\zeta_{A3w} = 10760\mathrm{Re}^{-0.2934} \tag{5}$$

$$\zeta_{A4w} = 14059\mathrm{Re}^{-0.3915} \tag{6}$$

where: ζ_{A1w} = local resistance coefficient for the pipe aerator with internal diameter 101.6 mm and steel rings with diameter 12 mm (–), ζ_{A2w} = local resistance coefficient for the pipe aerator with internal diameter 101.6 mm and steel rings with diameter 25 mm (–), ζ_{A3w} = local resistance coefficient for the pipe aerator with internal diameter 147.6 mm and steel rings with diameter 12 mm (–), ζ_{A4w} – local resistance coefficient for the pipe aerator with internal diameter 147.6 mm and steel rings with diameter 25 mm (–), Re = Reynolds number (–).

An adjustment evaluation of the exponential mathematical model used to calculate ζ in plastic pipe aerators with steel Białecki rings was performed with the use of a graph (Fig. 4), where the ordinates are the results of calculations from Equations (3)–(6), i.e. calculated values of ζ_w, and the abscissae are the values obtained from ζ_m measurements (Fig. 3). The obtained points were approximated by a linear function crossing the origin of coordinates. Thus, the correctness of choice of the mathematical model was verified by the slope coefficient of the linear function. An analysis of the dependence presented in Figure 4

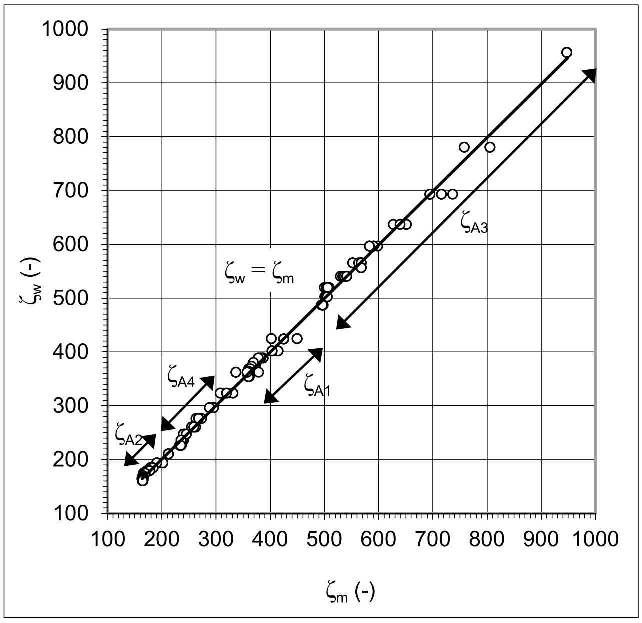

Fig. 4. Verification of the correctness of the exponential mathematical model used to calculate the local resistance coefficient (ζ); ζ_m = measurements values, ζ_w = calculated values, ζ_{A1}, ζ_{A2}, ζ_{A3}, ζ_{A4} = local resistance coefficient for A1, A2, A3, A4 respectively, A1–A4 as in Fig. 2; source: own study

allows to state that the exponential mathematical model well describes reality as the slope coefficient of the linear function is equal to 1.

Table 1 presents a basic statistics for the values of the ζ_m determined in measurements and ζ_w determined from Equations (3)–(6).

Based on a comparison of the average measured ζ_m values with the ζ_w values determined from Equations (3)–(6) (Tab. 1),

Table 1. Basic statistics for the values of the local resistance coefficient (ζ) determined in measurements and from Equations (3)–(6) for the plastic pipe aerators with steel Białecki rings

Local resistance coefficient	Statistics				
	minimum	maximum	average	median	standard deviation
Values determined in measurements					
ζ_{A1m}	359	426	376	366	22
ζ_{A2m}	164	213	176	167	16
ζ_{A3m}	495	948	627	576	141
ζ_{A4m}	233	569	320	281	102
Values determined from Equations (3)–(6)					
ζ_{A1w}	353	423	376	370	21
ζ_{A2w}	160	210	176	172	15
ζ_{A3w}	486	956	627	580	141
ζ_{A4w}	226	556	320	286	99

Explanations: ζ_{A1m}–ζ_{A4m} = local resistance coefficients obtained in measurements, ζ_{A1w}–ζ_{A4w} = local resistance coefficients calculated from Equations (3)–(6).
Source: own study.

one can state that the real values of the local resistance coefficient in the plastic pipe aerators with Białecki rings are identical with those determined from the equations, i.e. $\zeta_m = \zeta_w$.

When designing water treatment stations, a demanded capacity (Q_U) of the system, which is a water volumetric flow (Q), requires a calculation of hydraulic losses, i.e. real pressure differences (Δp), existing in individual devices in a technological line. Based on the calculated hydraulic losses for a treatment station designed, a required useful delivery head (H_U) can be determined. Then, for selected values of Q_U and H_U, a pump required need to be selected from a pump catalogue. Considering the above, if the Re determined by Equation (7) (Wichowski *et al.*, 2021):

$$\mathrm{Re} = \frac{4Q}{\pi d \nu} \tag{7}$$

then Equations (3)–(6) are as follows:

$$\zeta_{A1cal} = 832\left(\frac{4Q}{\pi d \nu}\right)^{-0.0785} \tag{8}$$

$$\zeta_{A2cal} = 582\left(\frac{4Q}{\pi d \nu}\right)^{-0.1182} \tag{9}$$

$$\zeta_{A3cal} = 10760\left(\frac{4Q}{\pi d \nu}\right)^{-0.2934} \tag{10}$$

$$\zeta_{A4cal} = 14059\left(\frac{4Q}{\pi d \nu}\right)^{-0.3915} \tag{11}$$

where: Q = water volumetric flow ($m^3 \cdot s^{-1}$), d = internal diameter of the plastic pipe aerator with Białecki rings (m), ν – kinematic viscosity of water ($m^2 \cdot s^{-1}$).

To check if Δp measured values for the pipe aerators with Białecki rings were identical with those obtained from the Darcy–Weisbach's equation, where the ζ calculated from Equations (8)–(11) had been used, the measured and calculated values of Δp were put into Figure 5 and it was checked if they covered each other. If the Darcy–Weisbach's equation (Wichowski *et al.*, 2021):

$$\Delta p = \left(\sum \zeta + \frac{\lambda l}{d}\right)\frac{8Q^2\rho}{\pi^2 d^4} \tag{12}$$

assumed that $\frac{\lambda l}{d} = 0$, then it would obtain a new form of the Darcy–Weisbach's equation for calculations of the pressure differences Δp_{cal} in the pipe aerators with Białecki rings:

$$\Delta p_{cal} = \left(\sum \zeta_{cal}\right)\frac{8Q^2\rho}{\pi^2 d^4} \tag{13}$$

where: Δp_{cal} = calculated pressure difference in the pipe aerator of the plastic with Białecki rings (Pa), ζ_{cal} = a local resistance coefficient (ζ_{A1cal}, ζ_{A2cal}, ζ_{A3cal} or ζ_{A4cal}) determined from Equations (8)–(11) (–), Q = water volumetric flow ($m^3 \cdot s^{-1}$), ρ = water density ($kg \cdot m^3$), d = internal diameter of the plastic pipe aerator with Białecki rings (m).

Figure 5 presents a comparison of measured Δp values in the pipe aerators with Białecki rings with the values of Δp_{cal} calculated from Equation (13) in relation to Q using ζ_{A1cal}, ζ_{A2cal}, ζ_{A3cal}, ζ_{A4cal}

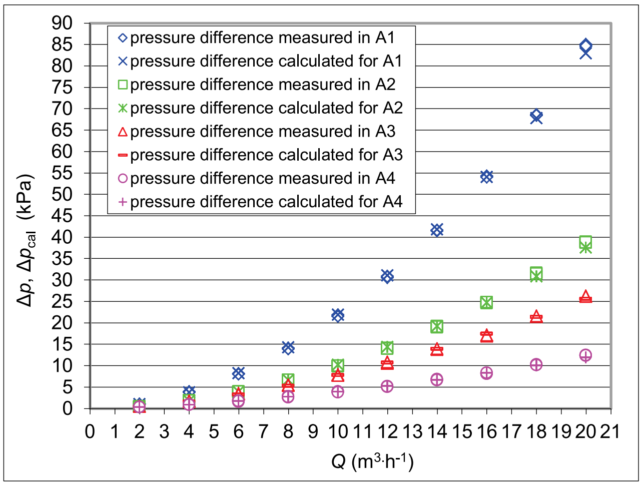

Fig. 5. Comparison of the values of pressure difference (Δp) measured in the pipe aerators with Białecki rings with calculated values of the pressure difference (Δp_{cal}) according to the Darcy–Weisbach's formula (13) in a relation with the water volumetric flow (Q): aerator with internal diameter 101.6 mm and steel rings with diameter 12 mm (A1) and 25 mm (A2) aerator with internal diameter 147.6 mm and steel rings with diameter 12 mm (A3) and 25 mm (A4); source: own study

determined from Equations (8)–(11). An analysis of the relation presented in Figure 5 indicates a very good concordance of Δp_{cal} values calculated from Darcy–Weisbach's Equation (13) using coefficients ζ_{cal} acc. to Equations (8)–(11) with values of Δp measured in the pipe aerators with Białecki rings.

A statistical analysis was performed as well to check if differences between the mean values of the local resistance coefficients obtained in measurements: ζ_{A1m}, ζ_{A2m}, ζ_{A3m}, ζ_{A4m} (Fig. 3) and calculated from Equations (8)–(11): ζ_{A1cal}, ζ_{A2cal}, ζ_{A3cal}, ζ_{A4cal} are statistically significant. At first, the normality of distribution was checked with the use of Shapiro–Wilk test and then the homogeneity of variance with use of Levene test. In both tests for individual groups, the values of calculated probability p_{cal} are greater than the assumed significance level $\alpha = 0.05$. This means that the conditions of normal distribution and homogeneity of variance in the examined groups are satisfied. Then, the *t*-Student test was used for two populations; a zero hypothesis (H_0: $n_1 = n_2$) stated that the mean values are statistically equal, an alternative hypothesis (H_1: $n_1 \neq n_2$) stated that the mean values are statistically different. Calculations of the *t*-Student statistics value $|t_{cal}|$ are gathered in Table 2. Calculations of the normality of distributions, homogeneity and *t*-Student statistics were performed using Statistica.

For the alternative hypothesis, a critical region $|t_{cal}| \geq t_{\alpha=0.05}$ was determined and, for $v = n_1 + n_2 - 2 = 118$ degrees of freedom and $\alpha = 0.05$, i.e. selected 5-percentage risk of error (significance level), the critical value $t_{\alpha=0.05} = 1.980$ was read from tables of the *t*-Student distribution (Oktaba, 1980). Analysis of Table 2 allows to state that $|t_{cal}| \leq t_{\alpha=0.05}$, i.e. the zero hypothesis cannot be rejected. Thus, the differences between the mean values of the local resistance coefficients obtained in measurements: ζ_{A1m}, ζ_{A2m}, ζ_{A3m}, ζ_{A4m} (Fig. 3) and calculated from formulas (8)–(11): ζ_{A1cal}, ζ_{A2cal}, ζ_{A3cal}, ζ_{A4cal}, are statistically insignificant. Hence, the related coefficients are equal to each other, i.e. $\zeta_{ical} = \zeta_{im}$. This is also confirmed by the calculated probability value p_{cal} which is greater than 0.05 (assumed significance level).

Thus, considering the results obtained from the calculations of the pressure difference Δp_{cal} from the Darcy–Weisbach's equation (Fig. 5) as well as the results of calculations of the *t*-Student statistics (Tab. 2), the formulas (8)–(11) can be used to determine the ζ of pipe aerators with steel Białecki rings during design of water treatment stations. Using these formulas, for design purposes, a nomogram has been worked out to determine values of ζ in dependence on water volumetric flow for pipe aerators with the diameter 101.6 mm and 147.6 mm,

Table 2. The *t*-Student statistics differences of the mean values (significant with probability $p < 0.05$)

Local resistance coefficient ζ	Statistic				
	mean	standard deviation	calculated value of the *t*-Student test $\lvert t_{cal}\rvert$	calculated probability value p_{cal}	value of the *t*-Student test read from tables for $p = 0.05$ and $v = 118$ $t_{\alpha=0.05}$ (Oktaba, 1980)
ζ_{A1m}	376.458	22.320	−0.029	0.976	1.980
ζ_{A1cal}	376.481	21.226			
ζ_{A2m}	176.358	15.957	0.231	0.818	
ζ_{A2cal}	176.240	15.143			
ζ_{A3m}	627.494	141.013	0.168	0.867	
ζ_{A3cal}	627.206	140.917			
ζ_{A4m}	320.473	101.856	0.194	0.846	
ζ_{A4cal}	320.175	98.717			

Explanations: ζ_{A1m}–ζ_{A4m} = local resistance coefficients obtained in measurements (Fig. 3), ζ_{A1cal}–ζ_{A4cal} = local resistance coefficients calculated from Equations (8)–(11).
Source: own study.

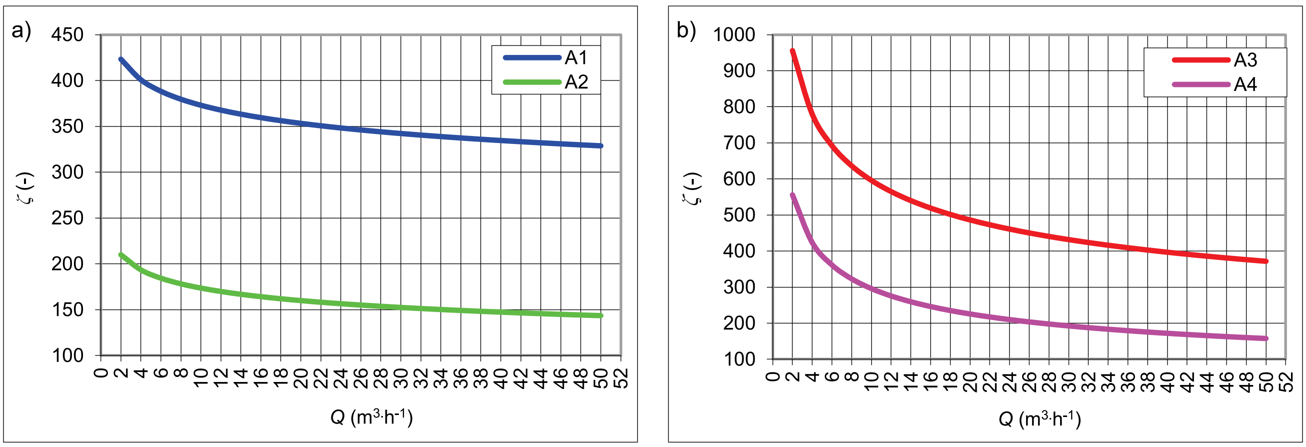

Fig. 6. Nomogram for determining values of local resistance coefficients (ζ) in plastic pipe aerators with steel Białecki rings in a relation with the water volumetric flow (Q): a) aerator with internal diameter 101.6 mm and steel rings with diameter 12 mm (A1) and 25 mm (A2) b) aerator with internal diameter 147.6 mm and steel rings with diameter 12 mm (A3) and 25 mm (A4); source: own study

with steel Białecki rings with the diameter 12 mm and 25 mm (Fig. 6).

The application scope of the Equations (3)–(6) and (8)–(11) as well as that of the nomogram from Figure 6 is limited. The nomogram and formulas can be applied only for the pipe aerators with filling according to the Polish patent PL235924 (Kalenik and Morawski, 2020) where the water volumetric flow cannot exceed 50 $m^3 \cdot h^{-1}$. Such aerators must be filled with Białecki steel rings with diameters 12 and 25 mm and their bulk thickness must be 1 m. Moreover, the pipe aerators must be built of PVC-U PN 10 pressure pipes with the external diameter 110 and 160 mm (internal diameter – 101.6 and 147.6 mm, respectively). The pipe aerator with filling and the internal diameter 101.6 mm must have the height of 1.85 m and that with the internal diameter 147.6 mm – the height of 2.25 m.

Due to that, further investigations are needed in aim to determine local resistance coefficients for pipe aerators according to the Polish patent PL235924, built of typical polyethylene PE-HD 100 PN 10 pressure pipes, available on market, designed for potable water and glued systems as well as filled with plastic Białecki rings.

CONCLUSIONS

1. The local resistance coefficient (ζ) in plastic pipe aerators with steel Białecki rings does not have any constant value and depends on the water volumetric flow. An increase of the water volumetric flow in these aerators evokes a fall in the value of the ζ. The formulas (8)–(11) and the nomogram in Figure 6 can be used during designing water treatment stations to determine real values of the ζ for plastic pipe aerators with steel Białecki rings with internal diameter 101.6 mm and 147.6 mm and with steel rings with diameter 12 mm and 25 mm.
2. The performed investigations showed that the ζ depend both on an internal diameter of the aerator and on a diameter of steel Białecki rings. When the internal diameter of the aerator and Białecki rings decreases, then the ζ increases. However, the coefficient ζ decreases if the aerator's diameter remains the same and the rings' diameter increases; the coefficient ζ decreases as well if the rings' diameter remains the same and the aerator's diameter decreases.

REFERENCES

Athulya, A.S. and Miji Cherian, R. (2016) "CFD modelling of multiphase flow through T junction," *Procedia Technology*, 24, pp. 325–331. Available at: https://doi.org/10.1016/j.protcy.2016.05.043.

Bassett, M.D., Winterbone, D.E. and Pearson, R.J. (2001) "Calculation of steady flow pressure loss coefficients for pipe junctions," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 215(8), pp. 861–881.

Chalet, D. and Chesse, P. (2010) "Fluid dynamic modeling of junctions in internal combustion engine inlet and exhaust systems," *Journal of Thermal Science*, 19(5), pp. 410–418.

Chowdhury, R.R., Alam, M.M. and Sadrul Islam, A.K.M. (2016) "Numerical modeling of turbulent flow through bend pipes," *Mechanical Engineering Research Journal*, 10, pp. 14–19.

Costa, N.P. *et al.* (2006) "Edge effects on the flow characteristics in a 90 deg Tee junction," *Journal Fluids Engineering*, 128, pp. 1204–1217. Available at: https://doi.org/10.1115/1.2354524.

Csizmadia, P. and Hős, C. (2014) "CFD-based estimation and experiments on the loss coefficient for Bingham and power-law fluids through diffusers and elbows," *Computers and Fluids*, 99, pp. 116–123. Available at: https://doi.org/10.1016/j.compfluid.2014.04.004.

Dutta, P. and Nandi, N. (2015) "Effect of Reynolds number and curvature ratio on single phase turbulent flow in pipe bends," *Mechanics and Mechanical Engineering*, 19(1), pp. 5–16.

Dutta, P. *et al.* (2016) "Numerical study on flow separation in 90° pipe bend under high Reynolds number by k-ε modeling," *Engineering Science Technology, an International Journal*, 19, pp. 904–910. Available at: https://doi.org/10.1016/j.jestch.2015.12.005.

Hellstrőm, L.H., Sinha, A. and Smits, A.J. (2011) "Visualizing the very-large-scale motions in turbulent pipe flow," *Physics of Fluids*, 23 (1), pp. 1–5.

Kalenik, M. (2015) "Empirical formulas for calculation of negative pressure difference in vacuum pipelines," *Water*, 7(10), pp. 5284–5304. Available at: https://doi.org/10.3390/w7105284.

Kalenik, M. and Chalecki, M. (2018) "Experimental study of air lift pump delivery rate," *Rocznik Ochrona Środowiska*, 20, pp. 221–240.

Kalenik, M., Chalecki, M. and Wichowski, P. (2020) "Real values of local resistance coefficients during water flow through welded polypropylene T-junctions," *Water*, 12(3), pp. 895–910. Available at: https://doi.org/10.3390/w12030895.

Kalenik, M. *et al.* (2017) "Kinetics of water oxygenation in pipe aerator," *Infrastruktura i Ekologia Terenów Wiejskich*, 2(2), pp. 689–700. Available at: http://dx.medra.org/10.14597/infraeco.2017.2.2.052.

Kalenik, M. and Morawski, D. (2007) "Badanie strat hydraulicznych i skuteczności napowietrzania wody w aeratorze rurowym [Investigations of hydraulic losses and effectiveness of water aeration in pipe aerator]," *Gaz, Woda i Technika Sanitarna*, 12, pp. 14–17.

Kalenik, M. and Morawski, D. (2009) "Badanie skuteczności napowietrzania wody w aeratorze rurowym [Investigations of effectiveness of water aeration in pipe aerator]," *Gaz, Woda i Technika Sanitarna*, 2, pp. 23–26.

Kalenik, M. and Morawski, D. (2013) "Eksperymentalne badania mętności i skuteczności napowietrzania wody w aeratorze rurowym wypełnionym pierścieniami Białeckiego [The experimental research on the turbidity and effectiveness of aerating water in pipe aerator with the Białecki rings]," *Infrastruktura i Ekologia Terenów Wiejskich*, 3(4), pp. 217–227.

Kalenik, M. and Morawski, D. (2020) *Aerator rurowy z wypełnieniem [Pipe aerator with filling]*. Urząd Patentowy Rzeczypospolitej Polskiej. Opis patentowy nr PL 235924. June 25, 2020.

Kalenik, M., Morawski, D. and Stańko, G. (2006) "Experimental investigation of hydraulic resistance in pipe aerators," *Electronic Journal Polish Agricultural Universities*, 9(4), #55. Available at: http://www.ejpau.media.pl/volume9/issue4/art-55.html (Accessed: January 15, 2023).

Kuczaj, A.K., Komen, E.M.J. and Loginov, M.S. (2010) "Large-Eddy Simulation study of turbulent mixing in a T-junction," *Nuclear Engineering and Design*, 240, pp. 2116–2122. Available at: https://doi.org/10.1016/j.nucengdes.2009.11.027.

Li, A. *et al.* (2014) "Study on local drag reduction effects of wedge-shaped components in elbow and T-junction close-coupled pipes," *Building Simulation*, 7(2), pp. 175–184. Available at: http://dx.doi.org/10.1007/s12273-013-0113-z.

Li, Y., Wang, C. and Ha, M. (2015) "Experimental determination of local resistance coefficient of sudden expansion tube," *Energy and Power Engineering*, 7, pp. 154–159. Available at: http://dx.doi.org/10.4236/epe.2015.74015.

Lin, D. *et al.* (2005) "Modeling multi-phase flow using CFD with related applications," *WIT Transactions on Engineering Sciences*, 50, pp. 251–261.

Liu, M. and Duan, Y.F. (2009) "Resistance properties of coal–water slurry flowing through local piping fittings," *Experimental Thermal and Fluid Science*, 33(5), pp. 828–837. Available at: https://doi.org/10.1016/j.expthermflusci.2009.02.011.

Malima, T.P., Kilonzo, B. and Zuwarimwe, J. (2022) "Challenges and coping strategies of potable water supply systems in rural communities of Vhembe District Municipality, South Africa," *Journal of Water and Land Development*, 53, pp. 148–157. Available at: https://doi.org/10.24425/jwld.2022.140791.

Mynard, J.P. and Valen-Sendstad, K. (2015) "A unified method for estimating pressure losses at vascular junctions," *International Journal for Numerical Methods in Biomedical Engineering*, 31, pp. 1–23. Available at: https://doi.org/10.1002/cnm.2717.

Ojo, O.I., Otieno, F.A. and Ochieng, G.M. (2012) "Groundwater: characteristics, qualities, pollutions and treatments: An overview," *International Journal of Water Resources and Environmental Engineering*, 4(6), pp. 162–170. Available at: https://doi.org/10.5897/IJWREE12.038.

Oktaba, W. (1980) *Elementy statystyki matematycznej i metodyka doświadczalnictwa [Elements of mathematical statistics and experimental methodology]*. Warszawa: Państwowe Wydawnictwo Naukowe.

Ono, A. *et al.* (2011) "Influence of elbow curvature on flow structure at elbow outlet under high Reynolds number condition," *Nuclear Engineering and Design*, 241, pp. 4409–4419. Available at: https://doi.org/10.1016/j.nucengdes.2010.09.026.

Pliżga, O., Kowalska, B. and Musz-Pomorska, A. (2016) "Laboratory and numerical studies of water flow through selected fittings installed at copper pipelines," *Rocznik Ochrona Środowiska*, 18, pp. 873–884.

PN-76/M-34034 (1987) *Rurociągi. Zasady obliczeń strat ciśnienia [Pipelines. Calculations of pressure losses]*. Warszawa: Polski Komitet Normalizacyjny.

PN-EN 1267:2012 (2012) *Armatura przemysłowa. Badanie oporu przepływu wodą [Industrial valves. Test of flow resistance using water as test fluid*]. Warszawa: Polski Komitet Normalizacyjny.

Röhrig, R., Jakirlić, S. and Tropea, C. (2015) "Comparative computational study of turbulent flow in a 90° pipe elbow," *International Journal of Heat and Fluid Flow*, 55, pp. 120–131. Available at: https://doi.org/10.1016/j.ijheatfluidflow.2015.07.011.

Sakowitz, A., Mihaescu, M. and Fuchs, L. (2014) "Turbulent flow mechanisms in mixing T-junctions by Large Eddy Simulations," *International Journal of Heat and Fluid Flow*, 45, pp. 135–146. Available at: https://doi.org/10.1016/j.ijheatfluidflow.2013.06.014.

Selvam, P.K., Kulenovic, R. and Laurien, E. (2016) "Experimental and numerical analyses on the effect of increasing inflow temperatures on the flow mixing behavior in a T-junction," *International Journal of Heat and Fluid Flow*, 61, pp. 323–342.

Takamura, H. *et al.* (2012) "Flow visualization and frequency characteristics of velocity fluctuations of complex turbulent flow in a short elbow piping under high Reynolds number condition," *Journal of Fluids Engineering*, 134(10), pp. 101201–101209. Available at: https://doi.org/10.1115/1.4007436.

Tejada-Tovar, C.N., Villabona-Ortíz, A. and López-Barbosa, D. (2022) "Predictive modelling of a rapid stratified bed filter for turbidity removal from surface water," *Journal of Water and Land Development*, 53, pp. 192–202. Available at: https://doi.org/10.24425/jwld.2022.140797.

Wichowski, P. *et al.* (2021) "Hydraulic and technological investigations of a phenomenon responsible for increase of major head losses in exploited cast-iron water supply pipes," *Water*, 13(11), pp. 1604–1623. Available at: https://doi.org/10.3390/w13111604.

Wichowski, P., Siwiec, T. and Kalenik, M. (2019) "Effect of the concentration of sand in a mixture of water and sand flowing through PP and PVC elbows on the minor head loss coefficient," *Water*, 11(4), pp. 828–845. Available at: https://doi.org/10.3390/w11040828.