The development of an empirical equation for determining minor losses due to bends in smooth pipes for irrigation system design

D. Tagwi[1,2*] , A. Senzanje[1], and G. Lagerwall[1]

(1. Bioresources Engineering Programme, School of Engineering, University of KwaZulu-Natal, Pietermaritzburg, 3201, South Africa;

2. Water Resource Development Planning, Department of Water and Sanitation, Head Office, Pretoria, 0001, South Africa)

Abstract: As pipe networks get to shorter lengths or number of bends increases, proportion of losses due to bends increases noticeability, leading to possible over- and under-sizing of pumps, owing to estimations of 30 to 50 pipe-diameters in length of equivalent straight pipe, 10% to 15% and at times 25% of mainline losses as estimated by designers in industry, especially for low operating pressure systems. Without a thorough knowledge of development of the equivalent length, resistance coefficient and valve flow coefficient method, methods do not offer easy, quick, accurate and precise determination of minor losses as bend parameters change in design processes and is addressed by the developed Empirical Equation. Behavioural patterns due to change of individual bend parameters with pressure drop was obtained from bent pipes, Rc (relative radius of curvature) values 13.545, 27.679 and 79.578, experimentally; Short, Standard and Long radius from published data. Key components defining bends, pipe diameter per radius of curvature, Rc and flow coefficient, bend length per pipe diameter ratio (L/D ratio) were then used to derive the Empirical Equation.Derived equation (based on a theoretical 19.05 mm standard radius, k = 0.7395) dynamically determined the best estimate of minor losses due to bend angles 0° to 90° without need of thorough knowledge, finding k for pipe diameters outside experimental and published data also eliminating error. Pragmatic basis for derivation catered for constant parameters (easily measured) and unseen or immeasurable parameters, validating equation. Saturation phenomenon for Rc beyond experimental values was identified with confirmation of the difference between Short and Standard radius bends often confused, by close approximation of k = 0.8976 at Rc = 0.5. Derived Empirical Equation, based on the resistance coefficient method, can satisfactorily be used as a tool in irrigation system design procedures and software for correctly estimating minor losses.

Keywords: pressure drop, friction coefficient, bend radius, relative radius of curvature, minor losses.

Citation: Tagwi, D., A. Senzanje, and G. Lagerwall. 2022. The development of an empirical equation for determining minor losses due to bends in smooth pipes for irrigation system design. Agricultural Engineering International: CIGR Journal, 24(4): 1-19.

1 Introduction

Determination of the secondary losses is critical since the introduction of drip and micro irrigation systems has reduced the operating pressure of the old systems (Chirgwin and Sutton, 2019). With the current and future introduction of low-pressure emitters (operating pressure) and possible use of special bends (unique bends made specifically for an irrigation system or cases of applying the bending

Received date: 2021-11-03 **Accepted date:** 2022-04-10

***Corresponding author: Tagwi, D.,** Bioresources Engineering Programme, School of Engineering, University of KwaZulu-Natal, Pietermaritzburg, South Africa; Water Resource Development Planning, Department of Water and Sanitation, Head Office, Pretoria, South Africa. E-mail: daytontagwi@gmail.com

schedule according to the pipe manufacturing bend limits) in irrigation systems, it is essential that determination of minor losses be as accurate as possible for efficient systems. This will also enable farmers or users to realise a saving in the capital costs, pumping costs, and eventually a green economy.

Considering the different methods used for determining minor or secondary losses in pipe networks, the equivalent length, resistance coefficient and the valve flow coefficient method (Wilson, 2012), the first two methods are ideal for determining pressure drop since they are based on experimental findings to validate them. The valve flow coefficient method is often best used for conversion of coefficients.

Comparing the equivalent length and the resistance coefficient methods, the former though accurate, the pressure drop is likely to be underestimated at smaller pipe diameters than those for which the equivalent length was measured. This is because the flow coefficient (bend length (L) per pipe diameter (D), L/D ratio) decreases as the fittings size increases. The pressure drop would be overestimated at pipe sizes greater than those for which the fitting's equivalent length was calculated (Papavinasam, 2013). The equivalent length method however has the advantage of being very easy to calculate but as a consequence, evaluating small or dynamic pressure losses in pipes is better achieved using the Resistance Coefficient process (Sabet, 2016).

With regards to the published experimental findings, bends are classified into three categories, short radius, standard radius and long radius as described by Dhodapkar *et al*. (2009). In a case the diameter of the elbow is *D*, and the radius is *R*, the outer diameter of a tube with a radius of curvature equal to 1.5 times its outer diameter, or $R = 1.5D$, is referred to as a Long Radius elbow. A standard radius elbow has a radius of curvature equal to the tube's outer diameter, i.e. $R = D$ as also confirmed by Spedding *et al*. (2004). However, in the literature reviewed there seems to be confusion between short and standard radius because the two names are often referred interchangeably (ARC, 2003; Spedding *et al*., 2004; Spellman, 2013; Escudier, 2017; NET, 2022)

To date, the SABI Irrigation Design Manual (South African Norms and Standards) revised edition June 2003 by ARC (2003) for designing irrigation systems when determining the minor losses is on the basis that minor losses are proportional to the velocity head component. This is such that a friction coefficient, k, is multiplied with the velocity head, $\left(k\frac{v^2}{2g}\ [ms^{-1}/ms^{-2}]\right)$, similar to the straight pipe equation considering the Darcy-Weisbach equation (ARC, 2003). The friction coefficients used are the same and do not carry the changing pipe diameter, which is often the case during the design process. This approach was adopted so as not to confuse the designer but lacks the inclusion of the changing L/D ratio and resulting relative radius of curvature, R_c for closer approximation of the friction coefficient. The use of the friction coefficient, k, as a Resistance Coefficient method suffices for one to get the correct pressure drop while undertaking the irrigation design process with changing bend parameters (mainly bend angle, bend length, bend radius and respective flow velocity). This is true, provided the correct k value is used following a thorough understanding of how the friction coefficient was derived (Wilson, 2012).

In practice, not all the k values are given for the change in the relative radius of curvature and pipe diameter. This leaves the designers to estimate the correct friction coefficient from the tables or work with the incorrect coefficients on estimation. In the process this brings about the inaccuracies and uncertainties in the determination of secondary losses in the irrigation system design process. Often estimations of a safety factor of 30 to 50 pipe-diameters in length of equivalent straight pipe, 10% or 15% and up to 25% of the mainline losses (minor losses due to the pipe bends along the main line to the point requiring the most head in the system) in the irrigation system design, is done in the industry to cater for the grey area in the calculation of the minor losses (Savva and Frenken, 2002; Spedding *et al*., 2004).

Avoiding the estimation or inclusion of the minor losses leaves the designer with the risk of a just failing system and the cost on the possible resizing of the pump as this is normally the key component affecting the performance or design of an efficient irrigation system in general experience. The existence or presence of the minor losses and the inaccuracies that are involved in determining them also affect the possible saving on pipe sizes, pumping cost or electricity consumed by the pump sized. This situation calls for a need to have a closer approximation method for the actual energy or pressure lost due to bends. This is also the case for critical operation and at times plant safety in downstream hydraulic valves relief systems (Spedding *et al*., 2004).

The seemingly best method to determine minor or secondary losses due to bends must be based on pragmatic findings validated by experimental results giving a good basis for the design of an irrigation distribution network or system (Yasmina and Rachid, 2015). Despite the accuracy of this method, the main issue would be the need to find a multiplier or coefficient which carries or applies the effect of the changing or transforming bend parameters. This will enable easy and correct assignment of the friction coefficient or equivalent length without a thorough knowledge for the bend parameters in question during the irrigation design process (Pei *et al*., 2016).

To solve this problem, the development of an Empirical Equation is needed to allow for the designers to input the changing bend or specialized bend parameters significantly sensitive to affecting pressure drop or secondary losses. Developing an Empirical Equation for minor losses as a function of the bend parameters requires the breaking up or disaggregating or elaboration of the friction coefficient, k in the expression $\left(k\frac{v^2}{2g}\right)$, which will only need to align or allow for one to effect the changing bend parameters for the correct k value. Of little significance is the roughness of the pipe, and geometry (square or circular tube) which may be ignored (Li, 2003). These, like other dynamic properties (which cannot easily be measured and at times are three- or multi-dimensional in nature) resulting from the introduction of a bend, are at times easily accounted for in the process of determination of the significant measurable bend parameters.

With future developments, the introduction of much lower operating pressure emitters will continue to push for the accurate and precise determination of the secondary losses, requiring designers to move away from estimations. This pushes designers to the extreme of having to accurately calculate minor losses with the use of correct equivalents lengths and coefficients since the major or primary loss determination methods are quite accurate (Wilson, 2012).

Despite the accuracies involved in the use of the traditional methods, there have been limitations in the use of the methods due to their reliance on pragmatic findings, requiring more tests to be done to determine equivalents lengths and friction coefficients (Spedding *et al*., 2004). This means traditional methods are only applicable to the extent of the testing conditions done (ARC, 2003). In contrast, the development of an Empirical Equation as the main aim of the research is not limited to the extent of pragmatic finds. It also has the ease of inserting or inputting in the changing bend parameters catering for the Short, Standard and Long or specialised bends involved during the design process. In essence, pressure drop is determined due to the respective curvature that is the bend Length to Diameter (L/D) ratio with respective flow velocity, replacing the difficulties or complexities in the use of the traditional methods, introducing error. This will enable the designer to arrive at the closest approximate pressure drop due to bending with the use of the correct friction coefficient without a thorough knowledge required. The Empirical Equation will give a simple, easy, and quick mathematical tool for the precise and accurate determination of pressure drop due to bends as well as specialised bends.

The purpose of this research is to develop an Empirical Equation for correctly determining minor losses due to bends in smooth pipes for irrigation design. This will offer a simple, easy, and quick way (mathematical tool) for precise and accurate determination (closest approximation) of minor losses due to bends as well as specialised bends. It is hypothesised that the friction coefficient approaches saturation or a constant as the R_c increases.

2 Materials and methods

2.1 Research site / laboratory

All experimental work was carried out in the HydroLab of the Agricultural Research Council – Institute for Agricultural Engineering (ARC-IAE) accredited laboratory in South Africa.

2.2 Experimental methodology

The build-up of fully developed flow was critical in the determination of pressure loss only due to the bends. Fully developed flow before the bend voided the measurement of any other frictional loss due to secondary effects but only the introduction of the bend in all instances measured. In the measurements done, this was achieved using an inlet and outlet pipe to the bend not less than 151 cm in all cases tested. Additionally, the single phase (water only) supply line was also made at least 2.5 m long and straight before supplying the test configurations. In all the tests undertaken single phase flow (water at room temperature) was used for the tests for simulating the scenarios as in the normal operation of an irrigation system and the test scenarios were repeated five times in each case to learn or ascertain the correctness of the measured values.

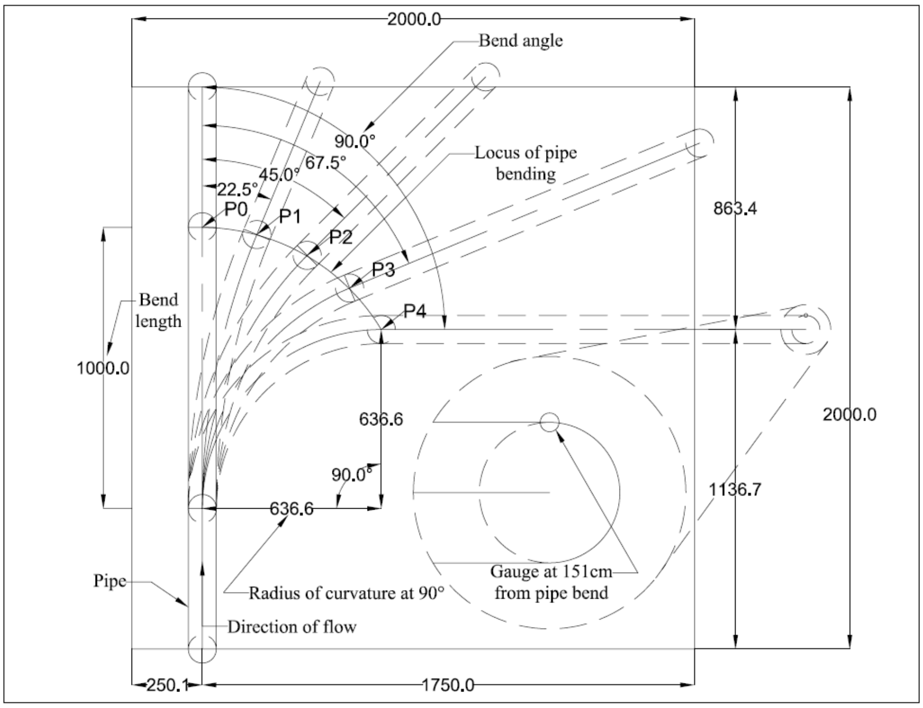

Figure 1 Schematic diagram of experimental test configuration dimensioned in millimeters showing the pipe(s) bend angles tested for varied flow and gauge position

Pressure measurements were then done specifically to determine pressure drop due to the bending introduced, that is, the behavioural change due to the pressure contours shortly after the bend of an open-end pipe to determine the actual pressure drop. The schematic diagram in Figure 1 shows the test configuration of the experimental apparatus used with flexible straight plastic pipes to successively form the required one-meter bend(s) section from 0° to 90° in increments of 22.5°, and subjected to varied supply flow velocities as tabulated in Table 1.

During the experiments, the lowest flow supply to each pipe tested reached the limits when water supplied could not fill the pipe. Just above this flow, the testing of the pipes could be achieved but testing was however done at intervals from 0.0000136 m^3 s^{-1} to 0.0001500 m^3 s^{-1} of the supply line flow velocity rate, which translated to the various flow velocities with the change in pipe diameter (Table 1).

Table 1 Single phase supply flow rate (m^3 s^{-1}) and individual pipe diameter flow velocities (m s^{-1})

Main supply line flow rate with flow meter Outside pipe diameter, 100 mm (OD) Internal pipe diameter, 97 mm (ID)		Actual flow velocity in each pipe (m s^{-1})		
(m^3 s^{-1})	(LPM)	10mm (OD) 8mm (ID)	25mm (OD) 23 mm (ID)	50mm (OD) 47mm (ID)
0.0000136	0.82	0.271	0.0328	0.0079
0.0000273	1.64	0.543	0.0656	0.0157
0.0000409	2.45	0.814	0.0985	0.0236
0.0000545	3.27	1.085	0.1313	0.0314
0.0000682	4.09	1.356	0.1641	0.0393
0.0000818	4.91	1.628	0.1969	0.0472
0.0000955	5.73	1.899	0.2297	0.0550
0.0001091	6.55	2.170	0.2626	0.0629
0.0001227	7.36	2.442	0.2954	0.0707
0.0001364	8.18	2.713	0.3282	0.0786
0.0001500	9.00	2.984	0.3610	0.0865
Flow	Too low flow relative to the pipe size (open channel flow)			
Flow	Too high flow, relative to the pipe size (tests not done)			

The clear polyvinyl chloride (PVC) pipe diameters were taken as given by the manufacturer and verified with Vernier callipers, considering the wall thickness of the pipe. Varied pipe diameters 10 mm (8 mm ID), 25 mm (23 mm ID) and 50 mm (47 mm ID) were individually fed water from a 100 mm (97 mm ID) pipe through a flow meter (ZJ-LCD-M LCD Digital Display Water Flow Sensor Meter, 0.01 LPM, 1% accuracy), to determine the relationship between different flows and pressure drop introduced in each test. Instantaneous measurements of the bend parameters taken include the pressure drop, bend angle and bend radius for the respective flow tested per pipe diameter tested for the one-meter bend.

With the change in bend angle from position P0 to P1 to P2 then P3 and finally P4 (0°, 22.5°, 45°, 67.5°, 90°, respectively) as seen in Figure 1, pressure drop was successively introduced and measured, with change in the bend radii. Changes to the test pipe, radius of curvature and pipe diameter were applied for each fixed length pipe or bend length while the supply flow rate was varied from 0.0000136 m^3 s^{-1} to 0.0001500 m^3 s^{-1} (Table 1), permissible with the pipe diameter to achieve the varied flows and resultant pressure drop.

Pressure drop was measured with the WIKA CPG1500 series precision digital pneumatic pressure gauge (-1 to +5 $\times 10^2$ kPa 0.1% accuracy) taking the average pressure readings for the piezometric pressure from the pipe wall with flowing fluid. The release of the fluid from the test apparatus was not controlled (open-ended). The test set up was performed relative to the atmospheric pressure, allowing for low operating pressure catering for the sensitivity of the pressure gauge used. Since water is relatively incompressible, the assumption was that the normal operation of an irrigation system would be catered for.

The way the pressure drop changed with change in the bend angle for the three pipe diameters was further used to give the mathematical way and manner in which the bend angle alone affected the pressure or friction coefficient in the development of the Empirical Equation. The behaviour of pressure drops with bend angle, as displayed by the results of the three pipes tested, was finally used but linked with the R_c and the L/D ratio in developing the Empirical Equation.

Converting the pressure drop to the friction coefficients was done by removing the $\frac{v^2}{2g}$ term in the pressure drop measured. As a result of the differences in the point of measurement of the pressure drop downstream of the bend for experimental and published coefficients, a manometric correction factor of approximately 0.19 due to the estimated decay of the main pressure head was used. This was relative to the point of pressure measurement, based on initial swirl intensity value of 0.21 seen from the finest fit amid the data and correlation by Kim *et al*. (2014). Correction is due to the different pressure contours or pressure regions as we move downstream of the bend also shown by Jayanti (2011). This showed that in the future tests, pressure drop should be measured at least 50 pipe diameters or more from the bend and based on pressure gradient analysis with 90° bends, least downstream recovery length was found to be 150 times by Azzi and Friedel (2005).

2.3 Theoretical approach to the development of the Empirical Equation

In the development of the Empirical Equation, measurement of the pressure drop due to successive pipe bending was done at R_c values 13.545, 27.679 and 79.578 for the 90° bend to gain an understanding of the parameters leading to the friction coefficients and validation with the experimental work. These are larger than the already published short, standard and long radii. The experimental data obtained was then mathematically associated with the published data for a chosen theoretical 19.05 mm diameter pipe friction coefficient for convention and basis of the Empirical Equation for a standard radius. The theoretical 19.05 mm pipe diameter, Standard radius was used due to the availability of data for comparison from the published and the experimental friction coefficients.

Observations of the behaviour of the individual bend parameters during each test (instantaneous parameters) were noted for association with the change of the resulting friction coefficients. The corresponding experimental data was fitted to establish the various relationships between the different bend parameters over the successive formation of the different bends (0° to 90°). In analysing of fluid problems, the simplest and most desirable method at times is a direct mathematical solution (Farhat and Lesoinne, 2000).

A mathematical relationship which established the relationship between the different bend parameters was finally determined to give the expanded or disaggregated resistance or friction coefficient k, due to the constant and immeasurable quantities (e.g., instantaneous roughness, dynamic viscosity, and kinematic viscosity) included. The actual pressure drop was then found by including the $\frac{V^2}{2g}$ term lastly. This in essence was finally the derived Empirical Equation for a chosen theoretical 19.05 mm diameter pipe friction coefficient.

2.3.1 Dimensional homogeneity and dimensional analysis

Having understood that the pressure drop in all cases can best be expressed as $\left(k\frac{v^2}{2g}\right)$ only with the correct make-up of the parameters to give the correct friction coefficient, k value (ARC, 2003), it is essential that dimensional homogeneity is considered (Fenner *et al*., 2018). Dimensional homogeneity and dimensional analysis needs to be considered for the consistency of both sides of the Empirical Equation. Dimensional homogeneity requires that an equation with quantities on both sides of the equal sign have the same units and this means a dimensionless k value (Fenner *et al*., 2018). The dimensional analysis of an equation has the main advantage of reducing the number of variables in the problem as it combines dimensional variables to form non-dimensional parameters.

2.3.2 Derivation of the Empirical Equation

In all cases in the formation of a bend, there is always a change in the measured bend parameters such that the change is always a function, $f(\theta, D, L, R_e, r, v_d, \rho, \varepsilon, \lambda_d, \mu_d)$, which influences the value of the coefficient to give the correct pressure drop, wherein; θ - bend angle; D - pipe diameter; L - bend length; R_e - Reynolds number; r - radius of curvature; ρ - density; v_d - flow velocity with respective pipe diameter; ε – pipe roughness; μ_d - dynamic viscosity; and λ_d - kinematic viscosity.

Looking at the behaviour of the bend from the experimental findings by Ito (1960), Chisholm (1980), Fitzsimmons (1964), Sekoda *et al*. (1969), Pigott (1950), Keulegan and Beij (1937) as cited by Spedding *et al*. (2004), we can express the pressure loss due to the bend, ΔP (ARC, 2003) as;

$$\Delta P = k\frac{v^2}{2g} \quad (1)$$

Wherein $k = f(\theta, D, L, R_e, r, v_d, \rho, \varepsilon, \lambda_d, \mu_d)$

Considering the related parameters R_e, v_d which speak to the flow in general, it would suffice to have the velocity head numerator term, v^2, only to account for flow in the overall equation (ARC, 2003); (Spedding *et al*., 2004);

then

$$P = f(\theta, D, L, r, \rho, \varepsilon, \lambda_d, \mu_d)\frac{v^2}{2g} \quad (2)$$

Looking at each parameter individually with the exclusion of the relatively constant parameters, $(\rho, \varepsilon, \lambda_d, \mu_d$ which have insignificant influence on the coefficient considering smooth PVC pipe under investigation with water for irrigation design purposes), in the formation of the k value for the conditions desired (Khan *et al*., 2019);

then

$$\Delta P = f(\theta, D, L, r)\frac{v^2}{2g} \quad (3)$$

A mathematical expression which gives us $f(\theta, D, L, r)$ can best estimate the friction coefficient, k value given that θ, D, L, r are known during each design stage of an irrigation system design. This would give the precise and accurate pressure drop friction coefficient, or rather the closest estimate of the k value. Derivation of the Empirical formula took three key steps governed by the relationships found with the main parameters θ, D, L and r with respect to the extent of bending. When broken down, this is mainly due to the bend angle θ, L/D ratio and R_c. Focus will be on the behaviour of the 90 ° bend since a similar effect was seen in the experimental findings across the lower bend angles only at lower magnitudes and translation was also done through the change in the bend angle θ.

Since the value of ΔP is based on the pragmatic or real values from experimental data, it can be agreed that ΔP considers the actual extent of losses (head loss) due to the bend to include the constant and immeasurable parameters. ΔP is made up of the contribution of the complicated issues due to the dynamic pressures differentials within the bend resulting in the energy losses due to change in direction, Dean vortices or vortex formation (Azzi and Friedel, 2005). These result in the generation of the secondary effects with swirl intensity generation as seen by Kim *et al*. (2014).

3 Results and discussion

3.1 Behaviour of the relative radius of curvature with bending

For all the pipe diameters tested, the transition of the bend angle parameters as bending was introduced from 0 ° to 90 °, brought about considerable changes in bend angle (θ) and radius of curvature (r) for the fixed bend length (L) and pipe diameter (D). This brought about the key relationships identified between the different measured parameters θ, D, L, r , essential for the development of the Empirical Equation. The relationship of bend angle with the relative radius of curvature, R_c (R_c = radius of curvature, r / pipe diameter for bend, D, which is unit less) for the fixed bend length for all the pipes tested is expressed graphically in Figure 2.

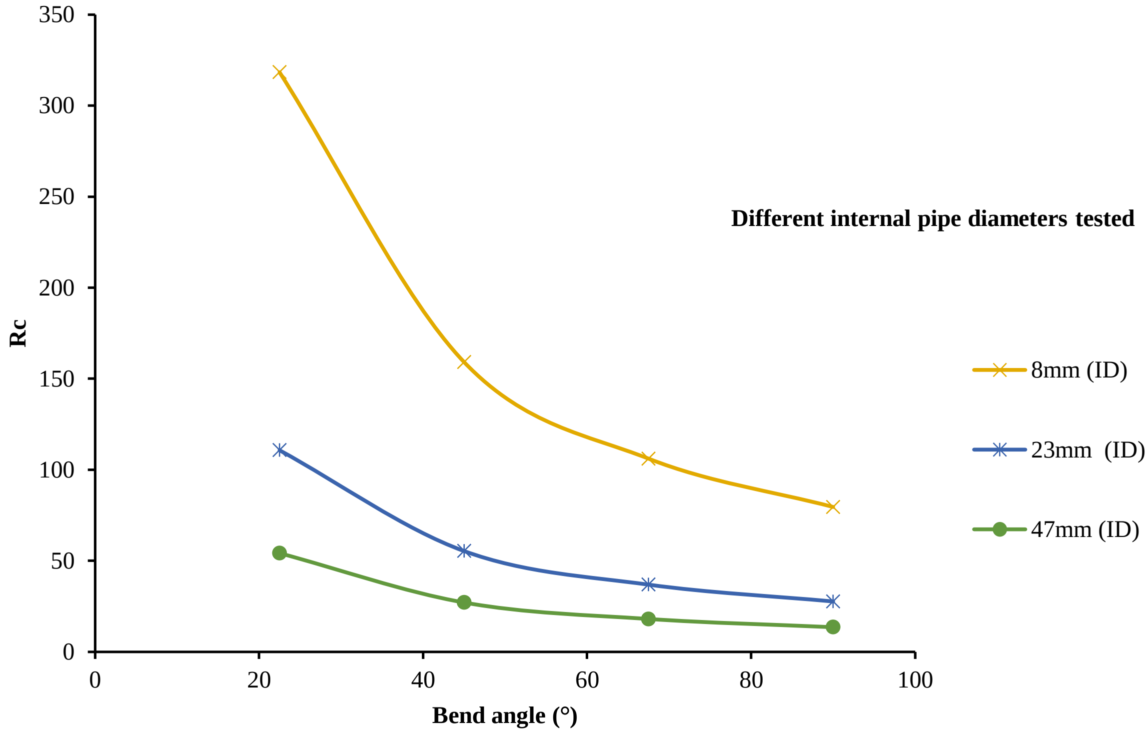

Figure 2 Relationship between radius of curvature (R_c) and bend angle for the 8 mm (ID), 23 mm (ID) and 47 mm (ID) diameter pipes

Generally, it can be seen from each pipe tested that R_c can be increased due to the decrease in the bend angle and the decrease in the pipe diameter. This is because as we approach the straight pipe condition with reduction in bend angle, the radius of the bending approaches infinity as the pipe diameter remains constant. This agrees with the work by Zhan *et al*. (2006). Fundamentally, despite the different pipe diameters used in the tests, the change appeared the same, that is a similar response is seen for the change in R_c for each pipe tested, except on visual analysis there is seen to be a multiplier or scaling-up to combine or overlay the three pipe diameters tested which was also found out by Beck (1960). This relationship was used in expressing the measured results and is further expressed mathematically to combine the individual bend angles to the pipe diameters tested on the last steps of the development of the Empirical Equation.

3.2 Pressure drop for fixed relative radius of curvature with successive bending

On conducting the tests on the pressure drop due to the successive pipe bending with the varied flows, the general trend seen was that the pressure drop increased with the increase in the bend angle and expressed for fixed R_c. These results are graphically shown in Figures 3, 4 and 5 for the varied flows velocities tested.

Generally, as the flow velocity increased with mass flux of the flowing fluid, the consequent pressure loss increased even as bend angle increased (Figures 3, 4 and 5). From the different pipe diameters tested, a general trend is seen on the influence of the bend angle on the pressure drop.

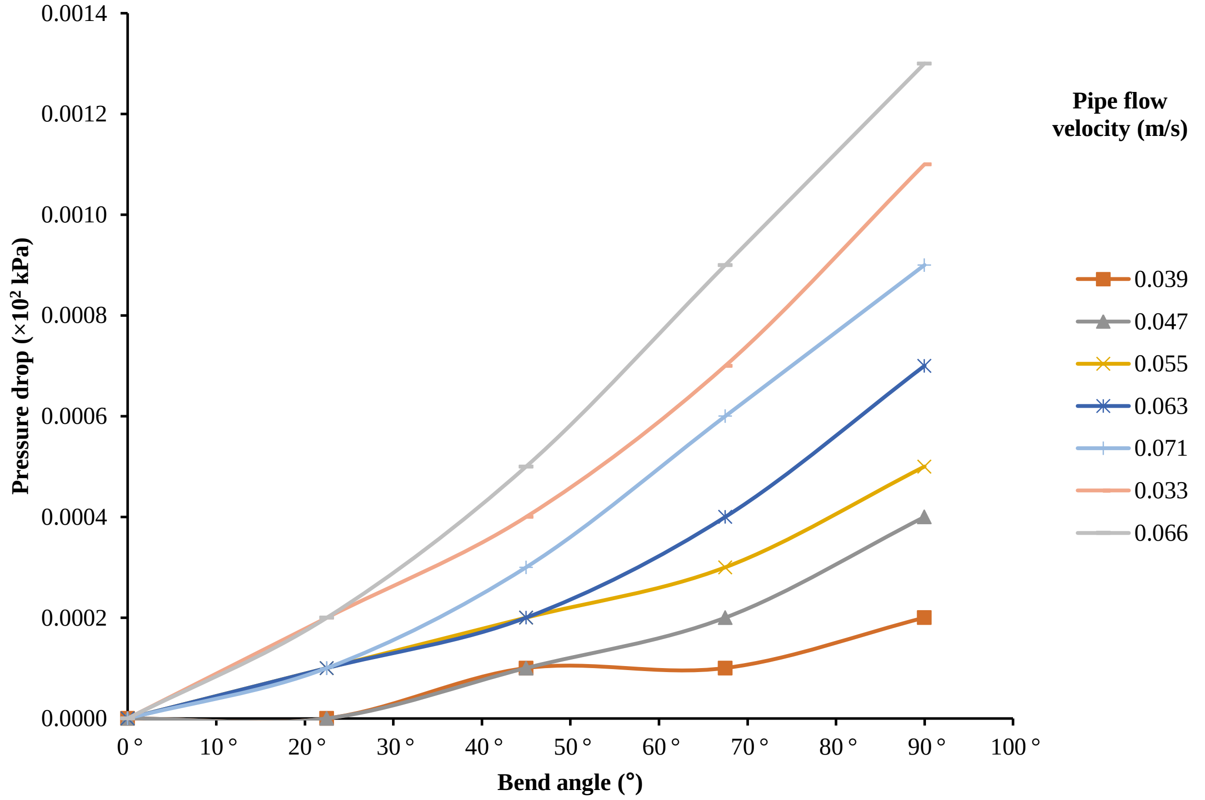

Figure 3 Pressure drop as function of the bend angle for varied single phase flow for the 47 mm diameter pipe for R_c = 13.545

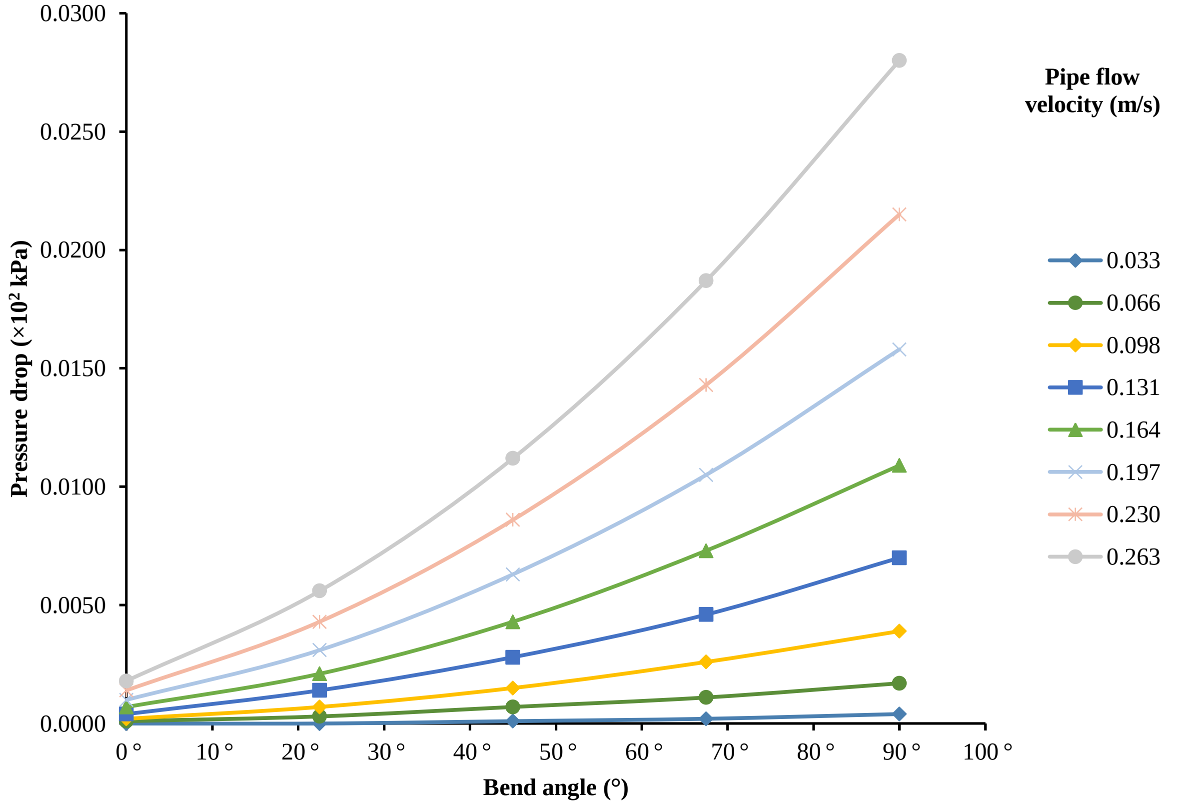

Figure 4 Pressure drop as function of the bend angle for varied single phase flow for the 23 mm diameter pipe for R_c = 27.679

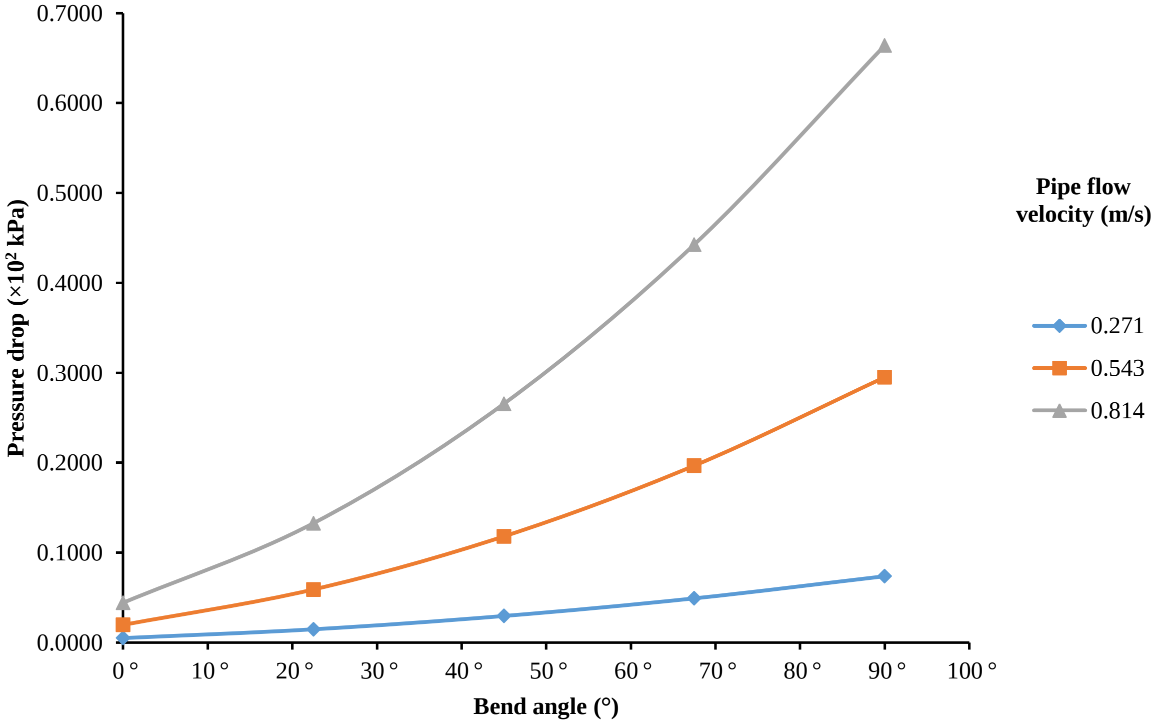

Figure 5 Pressure drop as function of the bend angle for varied single phase flow for the 8 mm diameter pipe for R_c = 79.578

As the pipe diameter increased, the overall pressure drop decreased and lower pressure readings were seen in the larger (47 mm) pipe due to a larger flow cross sectional area compared to all other pipes tested (see Figure 3). Increasing the pipe diameter effectively reduced the flow velocity of the fluid elements resulting in fewer collisions as seen by Sommerfeld and Lain (2015). The smaller pipe diameter (8 mm) expressed fairly large pressure drop readings compared to all the others tested (see Figure 5). Higher flows velocities were also seen with the smaller pipe due to the much-reduced pipe diameter in relation to the 100 mm diameter main supply line wherein the flowmeter was connected for all tests.

3.3 Friction coefficients from the measured pressure drop

The pressure drop measured was found to give an indication of the actual head loss due to the extent of bending involved in each test. To get a better understanding of the pressure drop recorded, it was necessary again to convert the values to a friction coefficient as expressed by other authors: Ito (1960), Chisholm (1980), Fitzsimmons (1964), Sekoda *et al*. (1969), Pigott (1950), Keulegan and Beij (1937) as published by Spedding *et al*. (2004) and also adopted in the Irrigation Design Manual by ARC (2003) for comparison. The friction coefficients as a result of the pressure drop measured for the pipes tested are shown in Table 2. The friction coefficient is seen to be fairly constant in each case especially with the 50 mm and the 25 mm pipe despite the case of the lower flows ignored.

From experimental results, clearly the friction coefficient is relatively constant for the extent of bending involved as for the 90 ° bends in all cases in bold (see Table 2). This is also seen across with the lower bend angles, respectively, and averages thereof at the bottom (see Table 2). The relatively constant nature of the friction coefficients for the head losses is also confirmed by the published results on the 90 ° bends by Spedding *et al*. (2004). The friction coefficients due to the lower levels of bending (bend angle) exhibited a successive decrease which is also later expanded on and shown to have a mathematical relation for all.

Table 2 Friction coefficients, k due to pressure drop against the bend angle for the varied single-phase flows tested with figures in bold used to obtain the average values for closer approximation of the friction coefficients

Bend angle	0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°
Velocity ($m\ s^{-1}$)	Diameter 0.047 m					Diameter 0.023 m					Diameter 0.008 m				
0.033	Too low flow relative to the pipe size, pipe not full					0.0000	0.0000	0.3465	0.6931	1.3861					
0.039	0.0000	0.0000	0.2424	0.2424	0.4834										
0.047	0.0000	0.0000	0.1674	0.3348	0.6714										
0.055	0.0000	0.1231	0.2462	0.3692	0.6166										
0.063	0.0000	0.0943	0.1886	0.3772	0.6609										
0.066						0.0866	0.2599	0.6064	0.9529	1.4727					
0.071	0.0000	0.0745	0.2236	0.4472	0.6714										
0.079	0.0000	0.1208	0.2416	0.4228	0.6647						Flow below tested range				
0.086	0.0000	0.0999	0.2496	0.4494	0.6492										
0.098						0.0770	0.2695	0.5775	1.0011	1.5016					
0.131						0.0866	0.3032	0.6064	0.9963	1.5161					
0.164						0.0970	0.2911	0.5960	1.0119	1.5109					
0.197						0.0963	0.2984	0.6064	1.0107	1.5209					
0.230	Too high flow, relative to the pipe size					0.0990	0.3041	0.6082	1.0113	1.5205					
0.263						0.0975	0.3032	0.6064	1.0125	1.5161					
0.271											0.2536	0.7507	1.5013	2.4955	3.7432
0.543						Too high flow, relative to the pipe size					0.2498	0.7494	1.4975	2.4955	3.7419
0.814											0.2497	0.7484	1.4968	2.4949	3.7421
Average k	0.0000	0.0854	0.2195	0.4001	0.6557	0.0545	0.1765	0.5102	0.8824	1.5143	0.2510	0.7495	1.4986	2.4953	3.7424

3.4 Mathematical relation of pressure drop with change in bend angle

On analysis of the changing friction coefficients with the respective bend angles tested (0° to 22.5° to 45° to 67.5° and finally to 90°) from all the experimental results, a relationship was found to exist for the pressure drop. Generally, the experimental friction coefficient for each test done for the transitional bending 0° to 90° was found to be related to the other flows for the different pipe diameters tested by simply a multiplier to a fitted mathematical relationship for a Linear Model Poly2 as given in Equation 4 using the MATLAB R2014a curve fitting tool for a function $p(\theta)$:

$$p(\theta) = p1 * \theta^2 + p2 * \theta + p3 \qquad (4)$$

Wherein θ = bend angle, with coefficients (with 95% confidence bounds):

$p1 = 4.869e^{-05}$, $p2 = 0.003287$ and $p3 = 0.0493$

Then

$$p(\theta) = 4.869\mathrm{e}^{-05}\theta^2 + 0.003287\theta + 0.0493 \qquad (5)$$

$p(\theta)$ is a result of the gradual decrease in pressure drop as we move from the 90° bend to the straight pipe condition (0°). This equation was used to define the spread of the friction coefficient with the changing bend angle for the developed Empirical Equation.

From Equation 3, $\Delta P = f(\theta, D, L, r)\frac{v^2}{2g}$, the first component of the friction coefficient (bend angle, θ) is considered found in Equations 4 and 5. All that remains is the change due to the D, L and r, the two elements left in development of the Empirical Equation as will be shown. With Equation 5 the relation established, focus was then given to the behaviour of the 90° bend for the rest of the analysis and development of the Empirical Equation with the understanding that the same effect, but different magnitude will be spread to the lower angles of bending in a similar fashion.

It is understood that the key relationship to all bends is the bend length to pipe diameter ratio (L/D) as cited by Spedding *et al*. (2004) and used by Poirier and Geiger (2016). This meant that understanding the influence of diameter coupled with L/D ratio would give the second component of the friction coefficient. Lastly, the third component could be established due to the behaviour of the R_c

which entails r since R_c = radius of curvature, r per pipe diameter, D. The two last components were then combined with the first, $p(\theta)$, completing the friction coefficient. Multiplication was used in almost all instances to combine the different relations observed. This was mainly due to the horizontal and vertical translation (scaling) seen on the friction coefficient with the changing bend parameters to combine or overlay the effect of changing bend parameters.

It was clear that a good understanding of the behaviour or change in each bend parameter could help understand the phenomenon of pressure drop to the bend and thence the resistance or friction coefficient for the different bend parameters as shown in the make of the Empirical Equation.

3.5 Friction coefficient with changing pipe diameter and bend angle

Again, for the fixed R_c, consideration of the 90° bend behaviour was done for analysis of the three pipes diameters tested. This is because the same behaviour occurred but of a lesser magnitude with the decrease in the bend angle and this is catered for in the first relation established, Equation 5. The fixed R_c with bend angle behaviour was plotted for the changing friction coefficient (average friction coefficients used) for each pipe diameter tested as shown in Figure 6. On analysis, this behaviour was also linked (mathematically) to each other and the published friction coefficients by the L/D ratio and the R_c lastly shown.

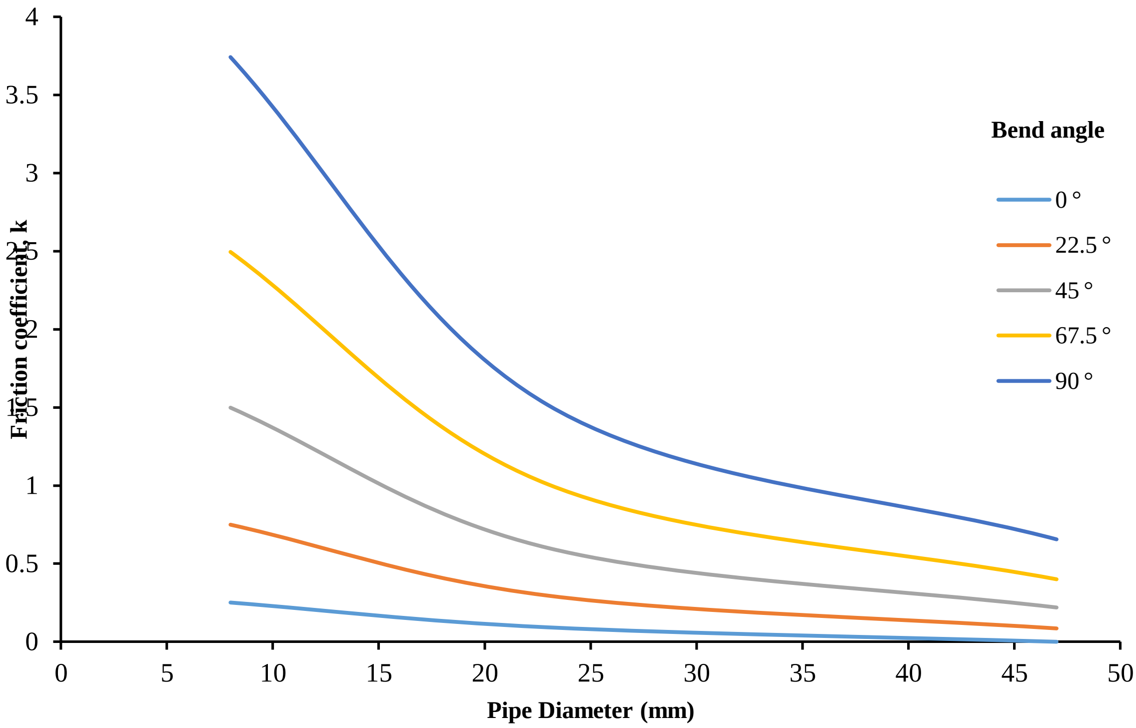

Figure 6 Relationship between friction coefficient and pipe diameter for 0 °to 90 °bend

In general, as the pipe diameter increases the friction coefficient decreased, this again is the case for the lower levels of bending plotted in Figure 6 for the smaller angles. This is because as we increase the pipe diameter until infinity, we approach the straight pipe conditions. Clearly from the graph considering the transition of the friction coefficient with the change in bend angle, mathematically the k is asymptotic (approaches a constant) with increase in the pipe diameter. However, on further visual analysis, the three sets of coefficients used from the results have different pipe diameters with different R_c values gave just three points for analysis. This created a gap in the understanding of the influence of the last two components with fixed pipe diameter and interchangeably the R_c on the 90 °bend for analysis.

Despite this gap, the behaviour of the friction coefficient with fixed pipe diameter was obtained from the published results from literature though with smaller bend length shown graphically in Figure 7 for the Standard and Long radius bends.

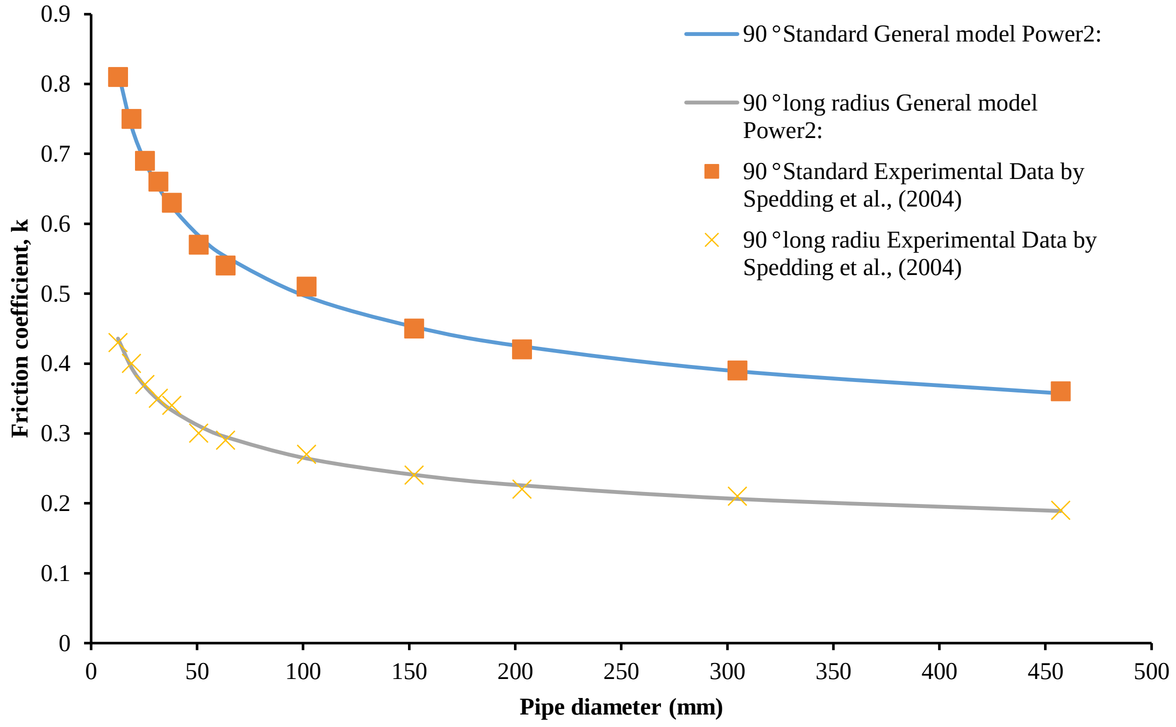

Figure 7 Friction coefficient, k, with change in pipe diameter for fixed R_c at 90 °bend (Spedding *et al*., 2004).

As seen graphically the fitted relationship for the different pipe diameters with a fixed R_c, a friction coefficient relationship is found for the effect of change in pipe diameter only with more data points. The two 90 ° bends, Standard and Long radius bend (two different R_c) are seen to be related with a multiplier or scaling. The difference in the two (Figures 6 and 7) also show the influence on the increase in the bend length. As bend length increases the curve flattens. This is because we approach the straight pipe condition with increase in bend length.

The fitted relationship for the 90 ° bends with each fixed R_c (Figure 7), were then used for the development of the Empirical Equation, again defining the best or closest reference for its basis on the standard radius bend. Using MATLAB R2014a curve fitting tool, this fitted pipe diameter and friction coefficient relation was then expressed for the theoretical standard radius bend as a function $g(D)$ for a General Model Power2 equation:

$$(D) = a * D^b + c \quad (6)$$

Wherein D = respective pipe diameter (in millimeters) with coefficients (with 95% confidence bounds):

$a = 1.487, b = -0.2862, c = 0.09968.$

$$g(D) = 1.487D^{-0.2862} + 0.09968 \quad (7)$$

$g(D)$ defines the departure of the friction coefficient from the standard to the desired pipe diameter. The Empirical Equation was then formulated from a convention from the change in the theoretical friction coefficient (0.7394), emanating firstly from a friction coefficient of the theoretical 19.05 mm Standard radius, with R_c = 1 which was comparable to the experimental tests done as cited by ARC (2003), and Spedding *et al*. (2004).

The choice of convention could equally work with using any known friction coefficient and chosen pipe diameter available for comparison. Though the outside diameter was considered in the published friction coefficients, the choice of using the internal diameter was used in deriving the Empirical Equation. This is due to the fact that the frictional influence is mainly due to the cross-sectional area or hydraulic diameter of the bend despite the pipe wall thickness. In other words when considering the ratio of the pipe diameter to wall thickness for most bends, the wall thickness is normally small for most pipes used in irrigation design.

3.6 Friction coefficient with changing R_c and bend angle

With the above understanding (the translation of the friction coefficient, k, with change in pipe diameter for fixed R_c, Figure 7), this meant that to get to any unknown friction coefficient including the experimental friction coefficient, translation of the friction coefficient through the behaviour of R_c was only need which also entails the influence of changing bend length. The behaviour of the friction coefficient with fixed R_c was obtained also from the several published results, from literature, as shown in Figure 8 and was aligned with the experimental data.

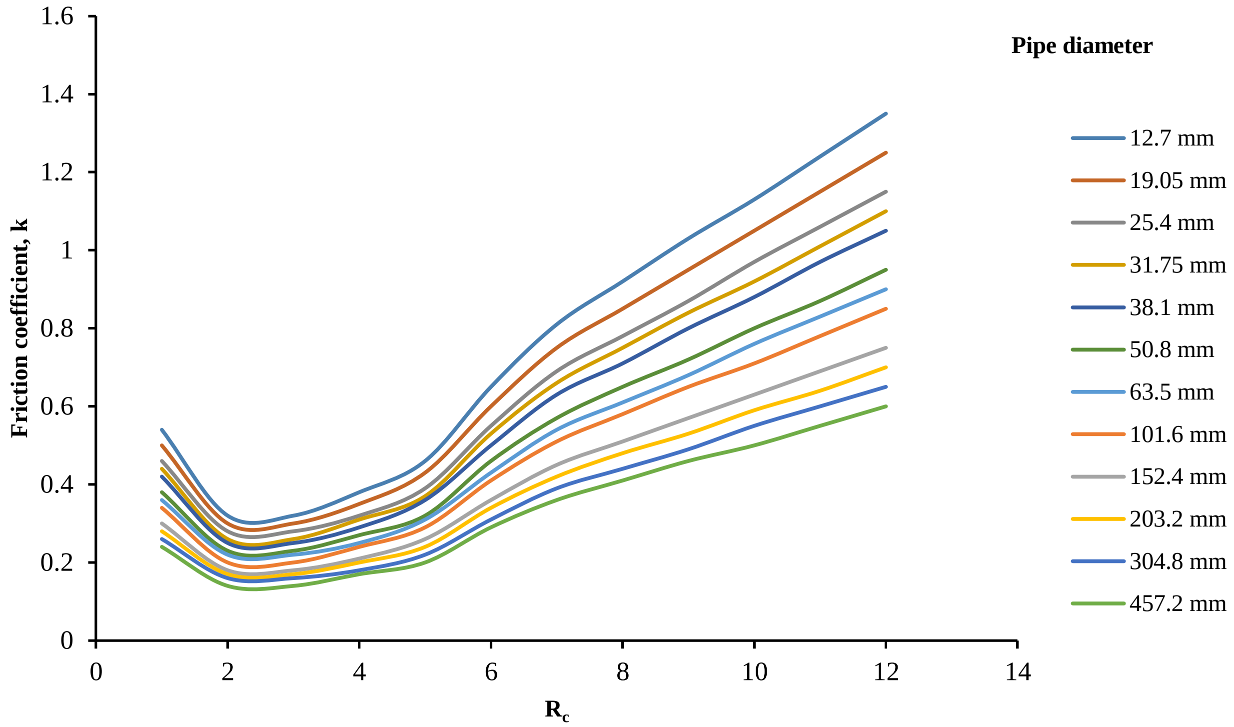

Figure 8 Friction coefficient with change in R_c for fixed pipe diameters for the 90 °bend (Data from Spedding et al. (2004)

Initially the friction coefficient decreases only to increase as R_c increases. This is because a friction coefficient exists for both the straight pipe conditions and the scenario of any bend, giving the two extremes of the friction coefficient (on the left or lower values of R_c and the right or larger values of R_c graphically) and eventually intercept giving the depression seen in Figure 8.

The relationship of the friction coefficient with R_c is seen to be similar for all pipe diameters as seen graphically (see Figure 8). Clearly a multiplier is seen to relate all the different friction coefficients for the changing pipe diameter with fixed R_c. From the analyses of the experimental data patterns and those of the published data (see Figure 8), a fitted relationship was then derived which best explained the translation of the friction coefficient with reference to the chosen theoretical standard radius 19.05 mm bend (convention adopted). This was best expressed by a General Model Rational Function (Equation 9) with respect to the theoretical standard radius 19.05 mm 90 °bend with a function $h(R_c)$:

$$h(R_c) = \frac{(p4*R_c^2 + p5*R_c + p6)}{(R_c^2 + q1*R_c + q2)} \quad (8)$$

Wherein R_c is based on the derived theoretical standard radius 19.05 mm pipe aligned to the experimental data and used as the convention or point of translation or base for determining friction coefficient and is > 0 always (with 95% confidence bounds): $p4 = 4.02, p5 = -11.07, p6 = 29.93, q1 = 18.53, q2 = 11.41$.

Then

$$h(R_c) = \frac{(4.02R_c^2 - 11.07R_c + 29.93)}{(R_c^2 + 18.53R_c + 11.41)} \quad (9)$$

Due to the nature of the rational function derived from the MATLAB R2014a curve fitting tool, it can safely be agreed that the friction coefficient approaches a constant with the inclusion of the experimental data in the fitting (see Table 3), confirming the hypothesis, friction coefficient approaches saturation or a constant as the R_c increases. Generally, the fitted friction coefficients from the measured (average friction coefficients) three experimental results and the published friction coefficients (Short, Standard and Long radius bends) were used for the validation of the derived Empirical Equation (see Tables 4 and 5).

3.7 Composition of the Empirical Equation

On analysis and amalgamation of the various relations found in the experimental data and the published data from literature, the main components to the mathematical build-up of the Empirical Equation were best be described as three main components stated earlier, θ; D, L and r (R_c and the L/D ratio) derived from the relationships observed. The Empirical Equation for the determination of the theoretical dynamic frictional loss coefficient k, that is from 0 ° to 90 °, was then expressed as a single equation with these components:

$\frac{p(\theta)_{wrt\,\theta}}{p(\theta)_{wrt\,90°}}$ – which gives the spread of the friction coefficients over the extent of bending 0 ° to 90 ° as mathematically determined.

$\frac{g(D)_{new\ pipe\ diameter}}{g(D)_{wrt\ 19.05mm,R_c=1,90°}}$ – which institutes the multiplier required for the translating of the theoretical friction coefficient of the 19.05 mm diameter pipe (convention or adopted) to that of the new pipe diameter chosen during the design process, and lastly

$h(R_c)_{wrt\ R_c=new,90°} * g(D)_{wrt\ 19.05mm,R_c=1,90°}$ – which gives the theoretical friction coefficient for the chosen diameter that is the resulting or new R_c for a 90 ° bend founded on the Standard theoretical 19.05 mm diameter pipe friction coefficient.

The combined mathematical relationship for the homogenous equation for the association of the measured parameters gave the theoretical friction coefficient, k of the pressure drop due to each bend parameter. The Empirical Equation is finally shown with the inclusion of the velocity head component (finally the minor or secondary loss required during the design process) and expressed as Equation 12;

$$\Delta P = k * \frac{V^2}{2g} \quad (10)$$

Wherein

$k = f(\theta, D, L, r)$

Then

$$k = \frac{g(D)_{new\ pipe\ diameter}}{g(D)_{wrt\ 19.05mm,R_c=1,90°}} * h(R_c)_{wrt\ Rc=new,90°} * g(D)_{wrt\ 19.05mm,R_c=1,90°} * \frac{p(\theta)_{wrt\,\theta}}{p(\theta)_{wrt\,90°}} \quad (11)$$

And finally

$$\Delta P = \left(\frac{g(D)_{new\ pipe\ diameter}}{g(D)_{wrt\ 19.05mm,R_c=1,90°}} * h(R_c)_{wrt\ Rc=new,90°} * g(D)_{wrt\ 19.05mm,R_c=1,90°} * \frac{p(\theta)_{wrt\,\theta}}{p(\theta)_{wrt\,90°}}\right)\frac{V^2}{2g} \quad (12)$$

With condition

$g(D)_{wrt\ 19.05mm,R_c=1,90°} = 1$ and $\frac{g(D)_{new\ pipe\ diameter}}{g(D)_{wrt\ 19.05mm,R_c=1,90°}}$ remains applicable only when $D = 19.05\ mm$ and R_c remains 1.

The development of the Empirical Equation, named the Dayton Equation, enabled the dynamic determination of the theoretical friction coefficient, k value of any bend (0 ° to 90 °) with respect to

θ, D, L and r for use in the design of irrigation systems as anticipated by Equation 3. This gave a close approximation of the frictional loss due to bending in the comparisons done hereafter (Tables 4 and 5). As postulated, saturation was also seen as R_c increased beyond all experimental values.

3.8 Validation of the Empirical Equation

The theoretical friction coefficients (k values) relationship derived from the experimental data and published (friction coefficients) on development (fitting coefficients) and validation of the developed Empirical Equation are expressed and tabulated in Table 3. Comparison of the specific friction coefficients (experimental and published) is further shown in Tables 4 and 5.

Table 3 Theoretical friction coefficients k, from the developed Empirical Equation (In bold are the published values available from Spedding *et al*. (2004) and those adopted in the Irrigation Design Manual by ARC (2003) and experimental values available from experimental data for comparison and linkage)

R_c / D	0.5	1	1.5	2.6409 (minima)	13.545	27.679	79.578	Scaling
8	1.1165	0.9198	0.4964	0.3926	1.2740	1.9983	2.8948	1.2439
19.05	0.8976	0.7395	0.3990	0.3156	1.0242	1.6065	2.3273	1.0000
23	0.8569	0.7059	0.3809	0.3013	0.9777	1.5335	2.2216	0.9546
47	0.7208	0.5938	0.3204	0.2534	0.8224	1.2899	1.8687	0.8029

From the theoretical friction coefficients above and the analysis done, multipliers exist due to changes in the pipe bends as seen on analysis, which involves a horizontal translation of k with changing R_c and vertical translation with changing diameter. Initially the R_c is seen to decrease but it then increases until constant or saturation creeps in with large R_c values, a concept cited by Blanckaert (2009).

The levels of accuracy of these theoretical friction coefficients determined by the Empirical Equation are much better understood when shown with the comparison of the k values found in the published and experimental data as tabulated in Tables 4 and 5 for validation of the Empirical Equation from the fitting and derivation.

Table 4 Comparison of friction coefficients, k, produced by the Empirical Equation with the published friction coefficients

	R_c = 0.5					R_c = 1					R_c =1.5				
	0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°
Adopted by ARC (2003)	-	-	-	-	0.90	-	0.15	0.30	-	0.75	-	-	-	-	0.40
Spedding *et al*. (2004) for the 19.05 mm pipe	-	-	-	-	-	-	-	0.40	-	0.75	-	-	-	-	0.40
(Larock *et al*., 1999)	-	-	-	-	0.90	-	-	0.35	-	0.75	-	-	0.20	-	0.45
Theoretical coefficients for 19.05 mm pipe	0.060	0.180	0.359	0.598	0.898	0.049	0.148	0.296	0.493	0.739	0.027	0.080	0.160	0.266	0.399

Table 5 Comparison of friction coefficients produced by the Empirical Equation with the experimental data friction coefficients

	Diameter 0.047 m, Rc = 13.545					Diameter 0.023 m, Rc = 27.679					Diameter 0.008 m, R_c = 79.578				
	0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°	0°	22.5°	45°	67.5°	90°
Experimental coefficients	0.00	0.09	0.22	0.40	0.66	0.09	0.29	0.60	1.01	1.51	0.25	0.75	1.50	2.50	3.74
Theoretical coefficients for 19.05 mm pipe	0.05	0.16	0.33	0.55	0.82	0.10	0.31	0.61	1.02	1.53	0.19	0.58	1.16	1.93	2.89
Difference (%)	-100	-48.06	-33.27	-27.02	-20.26	-9.77	-3.84	-2.15	-1.46	-1.24	30.09	29.46	29.43	29.31	29.29

From the comparisons in the two tables (Tables 4 and 5), the derived Empirical Equation has a fairly good estimate of the friction coefficient, k value with the changing bend parameters. Accuracy is seen to be more with the published data due to the multiple testing by many authors. This shows that more testing can be done on the experimental data for the fixed R_c and pipe diameters chosen to reduce the level of error. However, it can be agreed that the *k* values obtained by the Empirical Equation have a reduced level of error due to the fitting of all experimental data (published and tested) in its derived form, giving the closest approximation of pressure drop or head loss as desired for irrigation systems design.

On derivation of the formula, clearly the Short radius was found to be $R = 0.5D$ that is $R_c = 0.5$ with the confirmed theoretical *k* value of 0.898 which is approximately 0.9 as adopted in the Irrigation Design Manual by ARC (2003). No values were given by Spedding *et al*. (2004) with the accompanied confusion in the use of the Short radius when referring to the bend $R = D$ that is $R_c = 1$ which is a Standard radius bend. Generally, the derivation of the Empirical Equation also bridged the gap between the friction coefficients published with the absence of specific bend information and the approximation of coefficients that were not pragmatically found or tested (experimental and published).

4 Conclusions

Flow about any bend follows a very similar flow pattern for all smooth circular pipes relative to the extent of bending or curvature. In all cases there exist multipliers relative to the bend curvature ratio (L/D) and R_c with the change in pipe diameter for the associated bend angles, that is a multiplier due to each changing bend parameter. Due to this phenomenon observed in the flow about the bend, the frictional loss or pressure drop component (minor losses or secondary losses) can thus be easily calculated with the use of the correct multipliers with reference to a convention adopted or a reference theoretical friction coefficient as seen with the derived Empirical Equation.

Derivation of the Empirical Equation, Dayton Equation, allowed for finding the correct friction coefficient with the use of the multipliers mathematically for specific bend parameters, coupled with the velocity head component which can readily be determined. The Empirical Equation bridged the gap between the uncertainties in the use of the various methods and friction coefficients often requiring a thorough knowledge of their development, eliminating error. It allowed for the easy, quick, accurate and precise determination of frictional losses due to bending dynamically from 0 ° to 90 ° for use in the design of irrigation systems (Standard bends and most importantly specialised bends and bends due to bending schedules). Of significant importance, it allowed this through the modification of the friction coefficient with the respective changing bend parameters as postulated, catering for the changes in the bend parameters as seen in the design processes.

A new correlation can safely be said to have been developed in relation to the curvature multiplier and the momentum change due to bending. This is essential with the current and future introduction of low operating pressure emitters and the use of special bends in irrigation systems. The developed Empirical Equation can suitably be used in a spreadsheet or input into irrigation design software for better approximation of minor or secondary loss in the irrigation design process.

Acknowledgments

The authors are grateful to the Agricultural Research Council (ARC) Staff, Mr. Milton Petersen and Mr. Bennet Mdaka, the outgone manager Mr. Felix Reinders, Dr Aluwani Maiwashe - Tagwi, for their constructive comments, suggestions, construction, testing and financial support to this study.

References

ARC. 2003. SABI Irrigation Design Manual (ARC-ILI). Available at:

http://www.agis.agric.za/agric_engineering/pdf/IrrigationDesignPipehydraulics.pdf. Accessed 9 September 2016.

Azzi, A., and L. Friedel. 2005. Two-phase upward flow 90 bend pressure loss model. *Forschung im Ingenieurwesen*, 69(2): 120-130.

Beck, C. 1960. Discussion:“Pressure Losses in Smooth Pipe Bends”. *Journal of Basic Engineering*, 82: 131-140 revised March 1, 1960.

Blanckaert, K. 2009. Saturation of curvature-induced secondary flow, energy losses, and turbulence in sharp open-channel bends: Laboratory experiments, analysis, and modeling. *Journal of Geophysical Research: Earth Surface*, 114: F03015.

Chirgwin, G. A., and B. Sutton. 2019. A low-cost, high-precision drip emitter suitable for low-pressure micro-irrigation systems. *Irrigation Science*, 37(6): 725-735.

Chisholm, D. 1980. Two-phase flow in bends. *International Journal of Multiphase Flow*, 6**,** 363-367.

Dhodapkar, S., P. Solt, and G. Klinzing. 2009. Understanding bends in pneumatic conveying systems. *Chemical Engineering*, 116(4): 46-52.

Escudier, M. 2017. *Introduction to Engineering Fluid Mechanics*. first edition published in 2017: Oxford University Press.

Farhat, C., and M. Lesoinne. 2000. Two efficient staggered algorithms for the serial and parallel solution of three-dimensional nonlinear transient aeroelastic problems. *Computer Methods in Applied Mechanics and Engineering*, 182(3-4): 499-515.

Fenner, T., M. Harris, M. Levene, and J. Bar-Ilan. 2018. A novel bibliometric index with a simple geometric interpretation. *PLoS One*, 13(7): e0200098.

Fitzsimmons, D. E. 1964. *Two-phase pressure drop in piping components*, Hanford Atomic Products Operation.

Ito, H. 1960. Pressure losses in smooth pipe bends. *Journal of Basic Engineering,* 82**,** 131-140.

Jayanti, S. 2011. Bends, flow and pressure drop in. *Thermopedia.DOI 10.1615/AtoZ.b.bends_flow_and_pressure_drop*, 9-89 Article added: 2 February 2011 Article last modified: 16 March 2011.

Keulegan, G. H. & Beij, K. H. 1937. *Pressure losses for fluid flow in curved pipes,* US Government Printing Office.

Khan, M., M. Y. Malik, T. Salahuddin, S. Saleem, and A. Hussain. 2019. Change in viscosity of Maxwell fluid flow due to thermal and solutal stratifications. *Journal of Molecular Liquids*, 288: 110970.

Kim, J., M. Yadav, and S. Kim. 2014. Characteristics of secondary flow induced by 90-degree elbow in turbulent pipe flow. *Engineering Applications of Computational Fluid Mechanics*, 8(2): 229-239.

Larock, B. E., R. W. Jeppson, and G. Z. Watters. 1999. *Hydraulics of Pipeline Systems*. First addition, CRC press: www.crcpress.com.

Li, Z. 2003. Experimental study on flow characteristics of liquid in circular microtubes. *Microscale Thermophysical Engineering*, 7(3): 253-265.

Net, H. W. C. 2022. *GB/T 20801.3-2020: Translated English of Chinese Standard. (GBT20801.3-2020): Pressure piping code -- Industrial piping -- Part 3: Design and calculation [Tips: BUY here & GET online-reading at GOOGLE. Then, if you need unprotected-PDF for offline-reading, WRITE to Wayne: Sales@ChineseStandard.net] [Accessed 18/03/2022]*, ChineseStandard. Page 30. https:// www. chinesestandard.net, .

Papavinasam, S. 2013. *Corrosion Control in the Oil and Gas Industry*. Elsevier: www.elsevier.com: Elsevier Science.

Pei, P., Y. Li, H. Xu, and Z. Wu. 2016. A review on water fault diagnosis of PEMFC associated with the pressure drop. *Applied Energy*, 173: 366-385.

Pigott, R. 1950. Pressure losses in tubing, pipe, and fittings. *Transactions of the American Society of Mechanical Engineers,* 72**,** 679-686.

Poirier, D. R., and G. Geiger. 2016. *Transport Phenomena in Materials Processing*. Second edition, The Minerals, Metals & Materials Society: https://link.springer.com/: Springer International Publishing.

Sabet, M. 2016. *Industrial Steam Systems: Fundamentals and Best Design Practices*. First addition, CRC press www.crcpress.com.

Savva, A. P., and K. Frenken. 2002. Irrigation manual. Planning, Development Monitoring and Evaluation of Irrigated Agriculture with Farmer Participation. Harare: FAO and SAFR.

Sekoda, K., Sato, Y. & Kariya, S. 1969. Horizontal two-phase air–water flow characteristics in the disturbed region due to a 90-degree bend. *Japan Society Mechanical Engineering*, 35**,** 2227-2333.

Sommerfeld, M., and S. Lain. 2015. Parameters influencing dilute-phase pneumatic conveying through pipe systems: A computational study by the Euler/Lagrange approach. *The Canadian Journal of Chemical Engineering*, 93(1): 1-17.

Spedding, P. L., E. Bénard, and G. M. McNally. 2004. Fluid flow through 90 degree bends. *Developments in Chemical Engineering and Mineral Processing*, 12(1-2): 107-128.

Spellman, F. R. 2013. *Handbook of Water and Wastewater Treatment Plant Operations*. 2nd Edition https://www.taylorfrancis.com: Taylor & Francis.

Wilson, H. 2012. Pressure Drop in Pipe Fittings and Valves. Available from https://www.katmarsoftware.com/articles/pipe-fitting-pressure-drop.htm. Accessed 7 September 2016.

Yasmina, L., and L. Rachid. 2015. Evaluation of energy losses in pipes. In *CFM 2015 -22ème Congrès Français de Mécanique*, hal-03446141. Lyon, France, August 2015.

Zhan, M., H. Yang, L. Huang, and R. Gu. 2006. Springback analysis of numerical control bending of thin-walled tube using numerical-analytic method. *Journal of Materials Processing Technology*, 177(1-3): 197-201.