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STUDYING THE SPECIFIC FEATURES AND BENEFITS OF PLASTIC PIPES USED IN FLUID TRANSPORTATION SYSTEMS

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Abstract: *In the present work, a detailed overview of the existing plastic pipes used in fluid transport systems is accomplished, taking into account their specific features and potential advantages. A graphical relationship representing the variation of the coefficient of linear resistance (friction coefficient) on the Reynolds number is presented, obtained by using data provided by manufacturers of such pipes.*

Keywords: *pipes, pipe systems, hydraulic energy loss.*

INTRODUCTION

In designing of different types of pipe systems, pipes made of plastic materials have been increasingly used in recent years. Although this type of pipes has been known to people since the 1950s, it has not been widely used due to some of their disadvantages. However, today the advantages far outweigh the disadvantages and that is why they are superior to pipes produced of steel, asbestos-cement and cast iron. Plastic pipes are lightweight, flexible, durable and versatile.

EXPOSITION

Overview of existing plastic pipes

PVC pipes are generally categorised into four groups: PVC-U unplasticised PVC), C-PVC (chlorinated PVC), PVC-O (molecular oriented PVC) and modified PVC (PolyFab, 2022).

PVC-U stands for unplasticised PVC, which means no plasticiser has been added to the PVC compound. Unplasticised PVC is also known as rigid PVC. PVC-U is the most common PVC type for pipes and fittings including transportation of drinking water, soil and waste, sewage and underground drainage and industrial applications. Pipes and fittings made of PVC-U have many benefits. They are a safe choice for transportation of drinking water, light and easy to handle and affordable. Technical properties include high mechanical performance, high durability, high chemical resistance and resistance to UV exposure. Moreover, PVC-U pipes are 100% recyclable.

C-PVC stands for chlorinated PVC. Pipes and fittings made of C-PVC share many of PVC-U advantages. Both are safe for using drinking water, have high resistance to corrosion, high durability and excellent impact resistance. However, with its higher chlorine content than regular PVC-U, pipes and fittings made of C-PVC can withstand a wider range of temperatures. This has made C-PVC a popular choice for water pipe systems in residential as well as commercial construction. C-PVC is also significantly more ductile than PVC-U. Pipes and fittings made of C-PVC are 100% recyclable.

Molecularly oriented PVC (PVC-O) is the result of a production process that turns the amorphous structure of unplasticized PVC (PVC-U) into a layered structure. PVC-O enhances the many benefits of PVC-U such as resistance to corrosion, preservation of water quality, cost-efficiency and recyclability and an unsurpassed balance between strength, stiffness and flexibility. Pipes made of PVC-O are especially advantageous in terms of hydraulic capacity, ductility, crack propagation and impact and fatigue resistance. This means that PVC-O is an excellent choice for pressure pipes for drinking water. PVC-O is well suited for buried non-potable applications such as irrigation and sewer pumping mains. It is100% recyclable.

Modified PVC (PVC-M, PVC-HI, PVC-A) - this family are thermoplastic alloys formed by the addition of compatible modifying agents to PVC. The modifying agents improve toughness, impact properties and resistance to crack growth that improves the fracture toughness and ductility of the material. This enhanced toughness enables modified PVC pipes to be manufactured with a thinner wall, with subsequent material savings and improved hydraulic properties. The alloying of PVC with modifying polymers achieves improvement in resistance to cracking. The result is the minimization of the effect of stress concentrators such as scratches.

POLYETHYLENE pipes (PE) – in terms of density, they are divided into high density polyethylene (HDPE), medium density polyethylene (MDPE) and low density polyethylene (LDPE) pipes. HDPE and MDPE pipes are widely used in urban gas pipeline and urban water supply pipeline abroad. At present, domestic HDPE pipe and MDPE pipe are mainly used as urban gas pipeline, a small number of them are used as urban water supply pipeline, LDPE pipe is used as agricultural drainage and irrigation pipeline in large amount. HDPE pipe has high strength and rigidity; MDPE pipe has good flexibility and creep resistance besides the compressive strength of HDPE pipe; LDPE pipe has good flexibility, elongation and impact resistance, especially chemical stability and high frequency insulation. PE connecting is by electric melting, butt welding, flange, thread-thread, etc.

The granulate from which polyethylene pipes are produced must be pre-colored in the same color of the final product (the use of colorless PE granulate is prohibited) (Pipelife, 2020).

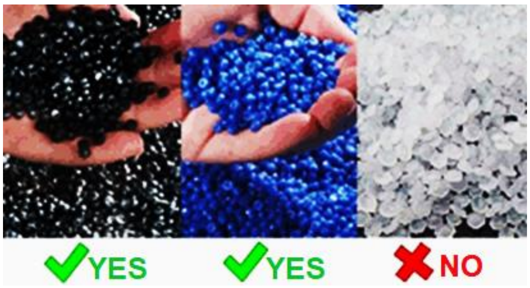
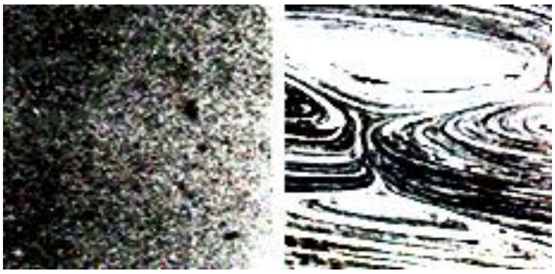


Fig. 1. Illustration of color graining

Only the pre-colored granulate guarantees a homogeneous structure of the manufactured pipes, good long-term pressure resistance and good elasticity of the material. The use of colorless polyethylene and its subsequent coloring during production results in poor homogenization of the material, which is visible only under a microscope (Pipelife, 2020).



Good (homogeneous) pipe structure (in left) produced from pre-colored granulate

Poor (inhomogeneous) pipe structure (in right) produced from colorless granulate colored during extrusion

Fig. 2. Homogeneity of the material of which the PE pipes are manufactured

As a result of poor homogenization, the qualities of PE pipe deteriorate, which leads to a significant reduction in its life, representing a potential possibility for its. In some rarer cases, the mixing of the colorant and granule during extrusion is so poor that in the cross-section of the produced pipe, delaminations are visible to the “naked” eye (Pipelife, 2020).

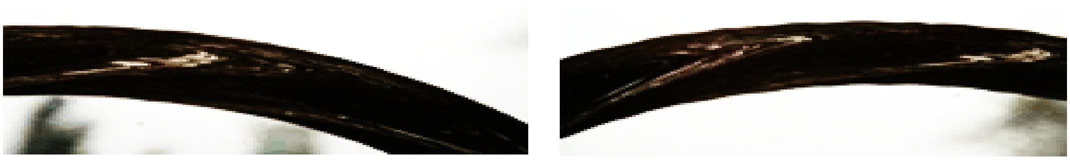
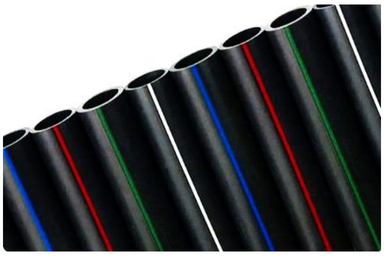


Fig. 3. Cross-section area of poor manufactured PE pipe

Polyethylene pipes come in many different colour options, but each colour is according to the HDPE pipe colour code. The purpose of the different colours on HDPE pipe is to identify the liquid or gas inside the pipe. Usually, the colours used are as follows (Acu-tech, 2018):



Gas: Yellow/Black pipe with yellow stripes
Water: Blue/Black pipe with blue stripes
Green stripe is usually used for rural and irrigation applications.
Red stripe is used for underground high pressure fire mains and is normally supplied in SDR11 or PN16.
Colors meaning may varies depending on manufacturer.

Fig. 4. Sample PE color identification

An important parameter that has to be taken into account in pipe selection is the so-called **SDR** - *Standard Dimensional Ratio*. It is used *to describe the relationship between pipe diameter and wall thickness*, and therefore, *the pressure rating of the pipe* (PE Technical Guidance, 2018):

$$SDR = \frac{Pipe\ Outside\ Diameter\ (Minimum)}{Pipe\ Wall\ Thickness\ (Maximum)} \tag{1}$$

The starting point in designing a PE pipe is the **MRS** (*Minimum Required Strength*) of the grade of PE to be used. The MOP (*Maximum Operating Pressure*) is related to the MRS of the material used; the pipe geometry (SDR) and operating conditions, determined by using following equations:

- when the pipe geometry is known:

$$MOP = (20\ x\ MRS)/\big(C\ x\ (SDR - 1)\big); \tag{2}$$

- when the operating conditions are known:

$$SDR = 1 + \big((20\ x\ MRS)/(C\ x\ MOP)\big), \tag{3}$$

where ***C*** is the ***overall service (design) coefficient***, or ***Safety Factor*** (for PE the minimum value of C is 1,25); MRS is in MPa; (PE100 = 10 MPa, PE80 = 8 [MPa]); MOP is in [bar].

Crosslinked Polyethylene Pipe (PE-X): mainly used for indoor cold and hot water supply and ground radiation heating. There are three kinds of PEX pipes, i.e. a, B and C. PE XA pipe is used for cold and hot water pipeline, oil pipeline, oil tank, chemical pipeline, etc; PE XB pipe is used for heating pipe; PE XC pipe is the most environmentally friendly pipe for ground heating. *Pros:* good temperature & creep resistance, good memory, easy to correct. *Cons:* only metal parts can be used for connection and can not be recycled and reused. *Connection:* ferrule type, clamp type connection and screw thread connection of special metal connection.

Heat Resistant Polyethylene Pipe (PE RT): indoor cold and hot water pipes, especially hot water system. The ideal choice of radiation heating application. *Pros*: excellent temperature resistance, used at -70…90 °C; excellent heat insulation performance, low thermal conductivity; long service life, can be safely used for more than 50 years; chemical resistance and corrosion resistance; good shape memory performance is restored; vibration resistance and shock resistance; the hydraulic characteristics are excellent. *Cons:* cannot be recycled; the overhead span of the pipeline is small and the supporting parts are installed more; due to the influence of the complicated situation such as cross operation during construction, PE-RT pipe is easy to be broken, and the reserved pipe end is flattened, which causes many rehandle. *Connection:* hot melting, electric melting and mechanical connection.

Polypropylene pipes (PP-R): a significant part of all the existing water pipes and heating connection pipes are PPR ones. *Pros*: good temperature resistance, recyclable, environmental protection products, good sanitary performance suitable for transportation of pure water. *Cons:* under the same pressure and medium temperature, the pipe wall is thick and flammable. *Connection*: electric melting, hot melt butt joint, special accessories flange connection and screw connection.

Polybutene Pipe (PB): mainly used in hot water and heating pipe systems. *Pros:* good temperature resistance, good tensile, pressure, impact resistance, low creep, high flexibility, under the same pressure and medium temperature conditions, the pipe wall is the thinnest, belongs to green products. *Cons:* dependence on import, high price, flammable. *Connection:* mainly includes electric melting and hot melt butt joint, and rubber ring sealing butt joint can be used.

ABS Engineering Plastic Pipe (ABS): it is used as sanitary ware downpipe, gas transmission pipe and high corrosion industrial pipeline abroad. Domestic pipe is generally used for indoor cold and hot water pipe, dosing pipe for water treatment, and industrial pipeline with corrosive effect. *Pros:* high strength, impact resistance, can be directly covered with silk, good sanitary performance is suitable for pure water transportation. *Cons:* the bonding curing time is long and flammable. *Connection*: socket connection, flange connection of special accessories and/or threaded connection.

Hydraulic estimations concerning polyethylene (PE) pipes

A main advantage of polyethylene pipelines (PE), compared to the others, is the smaller hydraulic losses obtained during the transportation of fluids. This is due to the great smoothness of the walls of these pipes and the impossibility of formating corrosion and internal deposits, which is of utmost importance for the energy efficiency of fluid transport systems.

There is lack of reliable data on the equivalent roughness of plastic pipes needed for the calculation of the friction coefficient λ. In some cases, manufacturers of plastic pipes, for example, (Akvamont, 2009; Pipelife, 2020; KPS, 2023), provide data on hydraulic energy losses h_V in their catalogs, most often referred to a certain length of the pipeline. However, they do not provide information on whether these losses are experimentally obtained or calculated by applying widely used friction coefficient formulas. Calculations are usually performed using the universal Colebrook-White formula, which for the turbulent regime of motion is recommended as one of the most accurate options for calculating the friction coefficient λ in round cross-section pipes (Popov G., 2019):

$$\frac{1}{\sqrt{\lambda}} = -2\,lg\left(\frac{\Delta}{3{,}7d} + \frac{2{,}51}{Re\sqrt{\lambda}}\right), \quad (4)$$

where $Re = \frac{vd}{\nu}$ is the Reynolds number, related to the flow regime of motion; Δ - pipe wall equivalent roughness [m]; d – pipe outer diameter [m]; v – flow velocity [m/s], ν - fluid kinematic viscosity.

For applying the above equation, it is necessary to know the equivalent wall roughness Δ, which is an unknown parameter. Considering the great technical smoothness of the pipes, some manufacturers (Akvamont, 2009; Pipelife, 2020; KPS, 2023) provide in their catalogs the head losses calculated for the turbulent regime of motion in hydraulically smooth pipes. Often, in such a case, the friction coefficient is determined by using the Blasius formula, which provides satisfactory accuracy up to Reynolds numbers limited in the following range: Re=10^5 (Gujgulov G., Petrov S., 1990):

$$\lambda = \frac{0{,}3164}{Re^{0{,}25}}. \quad (5)$$

For the entire region of turbulent regimes in hydraulically smooth pipes, it is best to apply the Prandl-Nikuradze formula, which, however, is in an implicit form (Popov G., 2019):

$$\frac{1}{\sqrt{\lambda}} = 2\,lg\frac{Re\sqrt{\lambda}}{2{,}51} = 2\,lg\,Re\sqrt{\lambda} - 0{,}8. \quad (6)$$

In case of turbulent regimes in hydraulically smooth pipes applying the Konakov formula enables to obtain results of good accuracy (Popov G., 2019):

$$\lambda = \frac{1}{(1{,}8\,lg\,Re - 1{,}5)^2} = \frac{1}{\left(1{,}8\,lg\frac{Re}{6{,}8}\right)^2}. \quad (7)$$

Polyethylene pipe manufacturers provide values for friction losses most often in tabular or graphical form, with the main values being diameter, flow rate and water flow velocity. Some of them present specially developed nomograms for quick and easy determination of hydraulic energy losses.

Linear head losses per unit length (so-called hydraulic slope) are calculated using the Darcy-Weisbach formula (Popov G., 2019):

$$J = \frac{h_V}{l} = \lambda \frac{1}{d} \frac{v^2}{2g}. \quad (8)$$

In the present work, an attempt is made to clarify how the tabular data provided by the manufacturers in their catalogs are obtained, as for this aim the data given by the manufacturer "Aquamont" (Akvamont, 2009) is used. Based on the tabular data proposed in the manufacturer catalogs, a numerical study of the impact of the friction coefficient on the Reynolds number is accomplished. Head loss data over a 100 m length of pipe are used, given for water velocities starting from 0,5 m/s and up to 5 m/s for pipe diameters in the range 66...277 mm. The equivalent pipe wall roughness depends on the material used in pipe manufacturing and the technology applied. Thus, for the same type of pipes but of different diameters, produced by a given manufacturer, the equivalent pipe wall roughness Δ remains constant, however the relative pipe wall roughness Δ/d varies.

The friction coefficient is determined by using the relative head losses:

$$\lambda = 2g \frac{Jd}{v^2}. \quad (9)$$

The Reynolds number is calculated for water flow of kinematic viscosity: $\nu = 1.10^{-6} m^2/s$.

By using the computational values obtained, the studied relationship $\lambda = f(Re)$ is plotted graphically concerning the pipes of the smallest and the largest (two each) diameters, respectively. The results are presented in fig. 5.

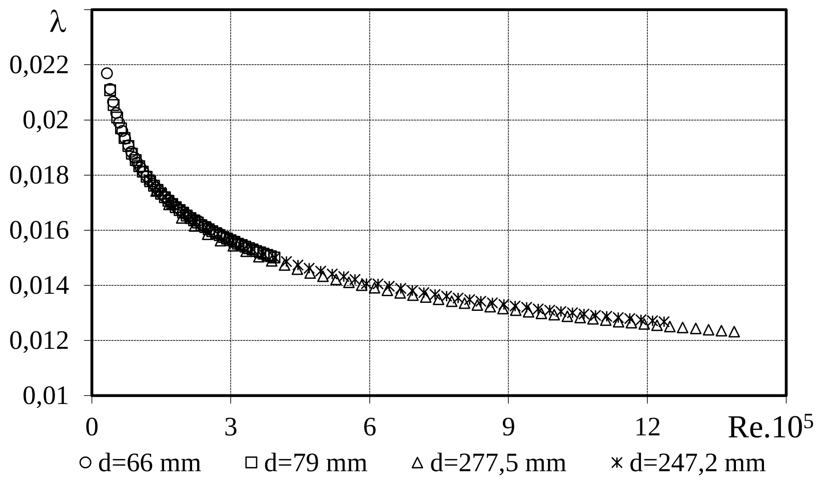


Fig. 5. The relationship $\lambda = f(Re)$ determined by using the data provided by Akvamont.bg

The graph in fig.5 clearly indicates that for the same Re, obtained at different combinations of diameters and velocities, the friction coefficient remains almost constant. This is a reason to state that the friction coefficient does not depend on the relative pipe wall roughness Δ/d, that is involved into the calculation of λ applying the formulas of Colebrook, as well as other authors, valid for fluid flow regimes of motion related to the transition and quadratic regiones. Doubtless, the referred hydraulic energy losses concern turbulent flow regimes at hydraulically smooth pipes, even if $Re > 10^5$.

The analysis of fig.5 demonstrates the presence of good clustering of the values obtained for the friction coefficient around a smooth curve. This is an indirect indication that the values concerning the hydraulic slope J, presented by the manufacturer in (Akvamont, 2009), are obtained based on calculation. The difference in the values of the friction coefficient comparing the two graphs is a reason to consider that the well-known Prandtl-Nikuradze formula, referring to the cases of turbulent flows in hydraulically smooth pipes, is used for its determination. A similar analysis, based on data presented by other plastic pipe manufacturers, is also accomplished. In all available catalogs, head losses are determined theoretically. There is a lack of data on the experimental determination of these losses, which is undoubtedly of both research and practical interest.

For the same flow regimes of motion, the values of the friction coefficient λ is determined. For this purpose, the Prandl-Nikuradze formula in combination with a proper iterative method, is used. In fig.6, it is presented graphically the relationship $\lambda = f(Re)$, determined by applying eq. (6).

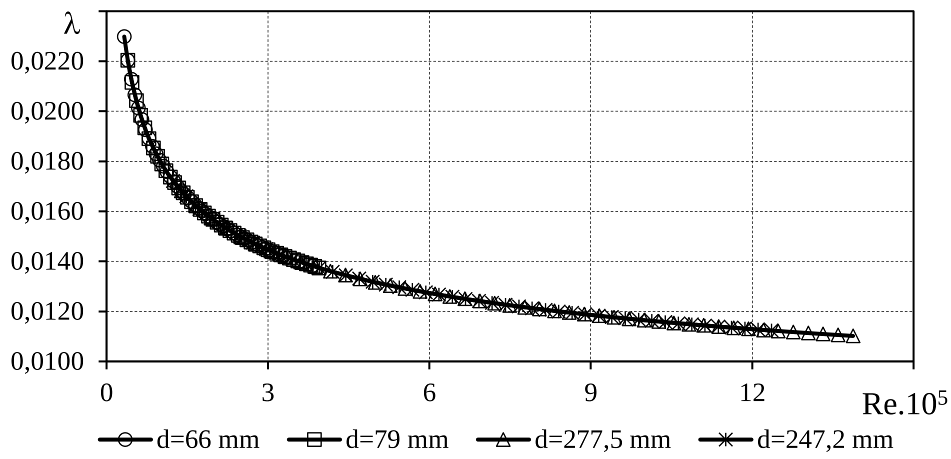


Fig. 6. The relationship $\lambda = f(Re)$ determined by applying Prandl-Nikuradze formula

The comparative analysis of fig.5 and fig.6 provides clear indications about the uniform nature of the curves of the type $\lambda = f(Re)$. This certainly leads to the conclusion that the hydraulic slope data, given in (Akvamont, 2009), concern the case of turbulent flows in hydraulically smooth pipes, where the coefficient λ does not depend on the pipe wall roughness.

CONCLUSION

The overview performed indicates that various types of plastic materials are used in plastic piping systems. These materials display a wide range of properties that are to be taken into account in the designing of such systems. The results of the numerical study performed, unequivocally prove the lack of data on the hydraulic slope of plastic pipes produced by different manufacturers, to be experimentally obtained. The analysis demonstrates that most often the Prandl-Nikuradze formula is used to theoretically determine the friction coefficient, in these pipes for the case of turbulent flows in hydraulically smooth pipes, where pipe wall roughness is not taken into account.

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