Pertanika J. Sci. & Technol. 2(1): 93-105 (1994)
ISSN: 0128-7680

Roughness Coefficient of Micro-irrigation Laterals

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Received 2 July 1993

ABSTRAK

Satu sistem mikro pengairan perlu menyampaikan air dan baja secara seragam ke seluruh ladang. Tetapi kehilangan turus pada paip dan perbezaan paras bumi menyebabkan tekanan air berbeza. Perubahan luahan dan variasi pembuatan penyebar menghasilkan ketidakseragaman pengairan. Untuk memastikan ekonomi yang maksimum rekabentuk hidraul sistem *mikro pengairan* harus dinilai secukupnya pada aras keseragaman yang dikehendaki. Kaedah analisis berkomputer dapat menghasilkan anggaran kehilangan turus yang tepat tetapi masih ramai pereka sistem yang menggunakan pendekatan konvensional kerana lebih mudah walaupun kurang tepat. Kertas ini membentangkan hasil kajian makmal keatas saluran sisi poliethilena berserta berbagai bentuk tonjolan penyebar yang dianalisis serentak. Pereka sistem mikropengairan akan dapat memilih nilai pekali kekasaran Hazen-Williams untuk digunakan dalam menganggar kehilangan turus dengan lebih tepat walaupun menggunakan pendekatan yang konvensional.

ABSTRACT

A micro-irrigation system must apply water and fertilizer uniformly over the entire field. However friction loss in pipes and fittings, and differences in elevation cause water pressure to vary. Discharge variations due to pressure differences and manufacturing variations cause non-uniformity of irrigation. To assure maximum economy, the hydraulic design of the system must be adequately evaluated for the required level of uniformity. This paper presents results of laboratory tests for head loss in smooth polyethylene pipe fitted with insert emitters. The Hazen-Williams roughness coefficients are included in the friction factor-Reynolds number diagrams so that system designers may choose a more accurate friction coefficient to improve energy, water and material use efficiency of a micro-irrigation system.

Keywords: micro/trickle/drip irrigation, pipe flow hydraulics, lateral design, friction factor, roughness coefficient, head loss, emitter barb protrusion

INTRODUCTION

A micro-irrigation system is designed to provide water at the root zone of plants. Water distribution should be as uniform as possible, spatially and temporally, in spite of uneven land slopes and long lateral lines. To assure maximum economy and efficient operation, the hydraulic design of the system must be adequately evaluated and the water emission uniformity be continually assessed throughout the life of the system.

The water distribution network in a micro-irrigation system consists of emitters, laterals, manifolds, submain and main lines. The flow regime throughout the network is hydraulically steady, spatially non-uniform pipe flow with lateral outflows. Pipes are usually PVC and PE, and they are considered to be hydraulically smooth. Head losses are mainly due to pipe friction and changes in elevation. But studies have shown that other factors such as local loss due to emitter barb protrusion at emitter connections to the laterals, sinuous alignment of the flexible lateral pipes and deformation of pipe shape contribute significantly to the total head loss.

The conventional approach in hydraulic analysis of micro-irrigation laterals has been derived from sprinkler irrigation design where pipe sizes and flow rates are large. This approach uses empirical formulae which are not applicable to micro-irrigation due to errors caused by ignoring the effect of water temperature. The formulae do not fit the actual head loss in small diameter polyethylene pipes for the range of Reynolds number normally encountered in micro-irrigation, and should not therefore be used for accurate analysis. But without the convenience of computing facilities, the empirical formulae will still be used by designers of micro-irrigation systems.

HEAD LOSS FORMULAE

The flow regime in lateral lines ranges from the laminar region up to Reynolds number of only about 20,000 due to low velocities and small pipe sizes used. Shear resistance may be evaluated by the Darcy-Weisbach equation or one of several exponential-type friction loss equations such as the Hazen-Williams formula.

The analytical expression for head loss which most accurately fits experimental data is the Darcy-Weisbach equation. It is in a form which can be most easily utilized with the energy equation. It gives a dimensionally correct expression compared to the exponential-type empirical equations. However, its solution requires a knowledge of the resistance coefficient or friction factor for a particular lateral and emitter combination.

Darcy-Weisbach-Blasius Equation

The Darcy-Weisbach equation gives

$$Hf = \lambda LV^2/D2g \quad (1)$$

where Hf is head loss due to friction, λ is friction factor, L is length, V is average flow velocity in the pipe, D is internal pipe diameter and g is acceleration due to gravity. Expressed in terms of total flow in the lateral,

$$Hf = 6.376\ \lambda\ L\ Q^2/D^5 \quad (2)$$

where Hf and L are in metres, Q in l/h, and D in mm.

Pipe friction factor λ can be taken from Blasius equation for smooth pipe,

$$\lambda = 0.3164\ Re^{-0.25} \quad \text{for } Re < 10^5 \tag{3}$$

where Re is Reynolds number. Blasius equation for smooth pipes has been recognized as an accurate predictor of friction factor for plain small diameter plastic pipe (Watters and Keller 1978; Von Bernuth and Wilson 1989). However, in micro-irrigation laterals with insert emitters, the flow regime becomes semi-smooth due to the presence of emitter protrusions (Amin 1990).

In the conventional approach to hydraulic analysis of lateral lines, friction loss due to emitter presence is assessed separately from pipe friction. It is expressed as equivalent length of the lateral (Le) and included in the head loss equation which is then multiplied by a reduction coefficient (F) for multiple outlets to account for reduced flow along the lateral. F depends on the number of outlets and the method used to estimate friction loss in the lateral.

Substituting for λ from Eqn. 3 at 20°C, and $Q=q(L/S)$, Eqn. 2 becomes

$$Hf = 0.4664\ (q/S)^{1.75}\ D^{-4.75}\ F\ (L + Le)^{2.75} \tag{4}$$

where q is the average emitter discharge in the lateral in litres/hour, S is emitter spacing in metres, D is internal diameter in mm, F is reduction coefficient for pipe with multiple outlets, L is lateral length in metres and Le is equivalent length of emitter protrusion head loss in metres.

The conventional approach assumes that emitter discharge q and emitter protrusion head loss Le are known and constant throughout the whole length of the lateral. This assumption is incorrect since emitter discharge is affected by changes in operating pressures. Emitter barb head loss is greater at the upstream end due to higher flow velocities.

Amin and Svehlik (1992) proposed a step by step evaluation of head loss where Darcy-Weisbach equation is used with a combined friction factor for the smooth pipe and the local loss due to emitter connection. Results are more accurate because the effects of temperature changes on emitter discharge and lateral flow rates are also considered. However, without the convenience of computing facilities, designers will still use the conventional approach. Therefore a roughness coefficient that reflects the combined roughness caused by pipe wall as well as emitter barb protrusion should be selected. Thus the Le term in Eqn. 4 can be dropped, and depending on the shape, size and spacing of the emitter protrusion, friction factor λ from other than Eqn. 3 can also be used.

The Hazen-Williams Formula

The Hazen-Williams formula is very widely used in waterworks design. It is most applicable for pipes of 50 mm or larger and velocities less than 3 m/s. The principal advantage of this formula is that the roughness coefficient does not involve Reynolds number, and hence all problems have direct solutions. Due to its simplicity, Hazen-Williams formula has been extended to include plastic micro-irrigation pipes even though they are smaller in diameter with lower flow rates than those normally encountered in other irrigation situations. It is now the most common empirical formula for calculating head loss in a lateral. The Hazen-Williams formula is given by

$$V(m/s) = 0.354\ C\ D(m)^{0.63}\ Sf(m/m)^{0.54} \tag{5}$$

where Sf is the energy slope and C is the Hazen-Williams roughness coefficient. C values range from 150 for extremely smooth and straight pipe to 100 for old riveted steel and 60 for old pipes in bad condition. Small pipes badly tuberculated may have C of 40 to 50.

A more useful expression of Hazen-Williams formula for micro-irrigation with the inclusion of reduction coefficient for multiple outlets F and local losses due to emitter protrusion expressed in equivalent length Le is

$$Hf = 3142.43\ D^{-4.871}\ (Q/C)^{1.852}\ F\ (L + Le) \tag{6}$$

where Q is total flow in l/h and C is the Hazen-Williams roughness coefficient. Substituting the average emitter discharge q=Q/N at the average operating pressure head and the total number of emitters is N=L/S, length L divided by emitter spacing S, the equation becomes

$$Hf = 0.621\ D^{-4.871}\ [(100q)/(SC)]^{1.852}\ F\ (L + Le)^{2.852} \tag{7}$$

Relationship between Friction Factor and Roughness Coefficient

Hughes and Jeppson (1978) expressed Hazen-Williams formula in a form of Darcy-Weisbach equation to identify friction factor λ as a function of roughness coefficient C. A reference temperature of 15.6°C (60°F) was used and the following expression was obtained:

$$\lambda = 1040/(C^{1.852}\ D(in.)^{0.018}\ Re^{0.148} \tag{8}$$

Howell and Barinas (1980) expressed the above in SI units

$$\lambda = 1862/(C^{1.852}\ D(mm)^{0.18}\ Re^{0.148} \tag{9}$$

Manufacturers of pipes for micro-irrigation have always recommended a C value of 150 for the plastic pipe and tubing. However, Watters and Keller (1978) showed that C=150 seriously underestimates pipe friction losses within Re normally encountered in micro-irrigation systems. This has been recognized previously. Howell and Hiler (1974) suggested that C=130 be used for small diameter plastic pipes, D<16 mm. Howell *et al.* (1982) suggested that the best C values for micro-systems are C=130 for 14-15 mm pipe diameter, C=140 for 19-20 mm, and C=150 for 25-27 mm.

Karmeli and Keller (1975) developed a relationship between the C value for a plain tubing (C=150) and a reduced value CE (80<CE<150) that can be used to include the additional friction due to the presence of emitter barbs. But C values less than 100 may place the flow in the complete turbulent rough zone which is independent of Reynolds number. λ would then be a constant for all flow conditions in the pipe. If CE was used, then Eqn. 7 becomes

$$Hf = 0.621\ D^{-4.871}\ [(100q)/(S.CE)]^{1.852}\ F\ (L)^{2.852} \tag{10}$$

When the lateral length is the unknown, then Eqn. 10 becomes

$$L = 0.059\ D^{1.709}\ F^{-0.351}\ [CE.S/q]^{0.65}\ Hf^{0.351} \tag{11}$$

There is little information in the literature on the CE values to be used in the Hazen-Williams formula. Hence there is a need for such values in order to obtain a more accurate estimate of head loss using the conventional approach.

FRICTIONAL HEAD LOSS FOR PE LATERALS WITH INSERT EMITTERS

Attempts to quantify CE were carried out at the University of Southampton and Universiti Pertanian Malaysia (Amin 1990; Mohd Shaharudin 1991; Ramaysh 1992). Results of the study on friction factor for 15 mm ID PE fitted with typical insert emitters at various spacings are shown in *Fig. 1.* For simplicity the ratio of emitter spacing to the internal lateral pipe diameter S/D is used. The lateral was fitted with insert emitters having truncated cone protrusions (Dent 1985; Amin and Svehlik 1992).

Fig. 1 shows that roughness coefficient C varies with emitter spacing and Reynolds number. A plain PE lateral pipe without emitters has C values which range from 120 at lower Re to 140 at Re=20,000. C values for laterals with insert emitters are less than 130 and C decreases with closer emitter spacings. C=125 for S/D=63 to C=100 for S/D=13. However, these results are for 15 mm ID PE and truncated cone emitter protrusion shape of 5 mm depth. In Malaysia, the usual micro-irrigation lateral size is 13 mm. The extent of obstruction to flow by emitter connection is shown in *Fig. 2*, and some of the common protrusion shapes and sizes are shown in *Fig. 3.*

Tests were carried out in the irrigation laboratory of the Dept. of Field Engineering, UPM on four common emitters fitted to 13 mm ID lateral. The emitters were Turbo S.C., Irridelco Flapper, Rain Bug A and Rain Bug B. *Fig. 3* shows their dimensions. For comparison, a micro-jet and a micro-sprinkler were also tested on 13 mm and 15 mm ID PE.

The head loss in a test section fitted with equally spaced emitters was measured at various flow rates through the lateral using differential mercury manometers. Pressure head losses were measured for four spacings of four emitters, and three spacings of a micro-jet and a micro-sprinkler. All tests were conducted without any discharge from the emitters, but flow rates in the lateral were up to Reynolds number of about 30,000.

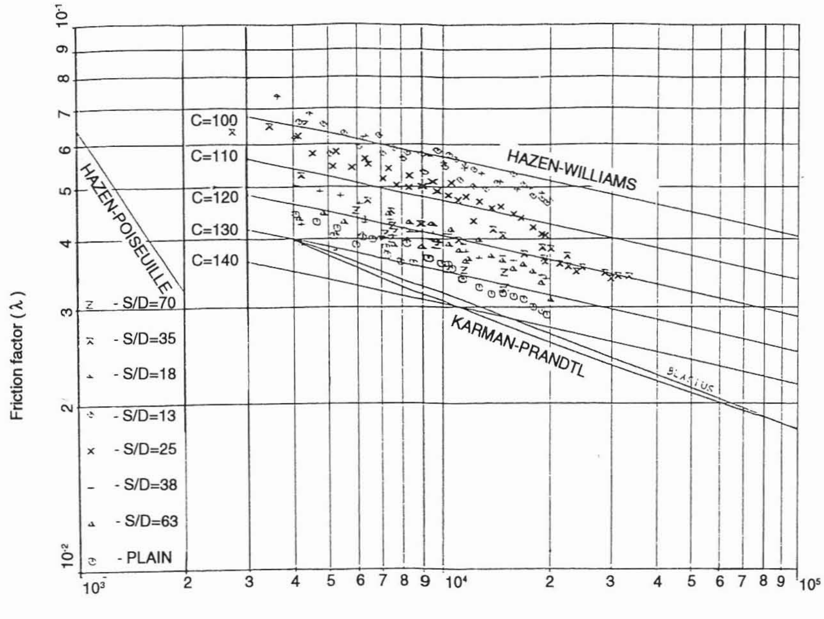

Fig. 1. Hazen-Williams roughness coefficient and friction factor for truncated cone emitter protrusion in 15 mm ID PE at various spacings

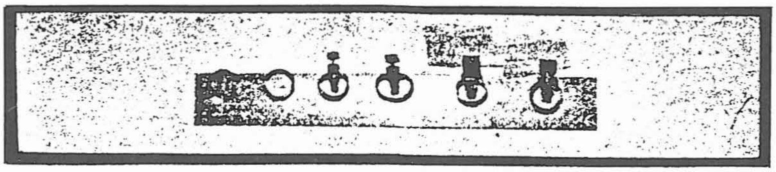

Fig. 2. The extent of obstruction to flow by emitter barb connection to a lateral. A micro-jet and a micro-sprinkler are shown in 13 mm and 15 mm PE

Reynolds number may be expressed in terms of water temperature, using the expression for kinematic viscosity given by Boor *et al.* (1968), as follows

$$Re = 198.7\ Qt\ (1 + 0.03368T + 0.000221T^2)/D \qquad (12)$$

where Qt is the total flow rate in l/h at the upstream end of the lateral, T is water temperature in degrees Celsius and D is internal pipe diameter in mm.

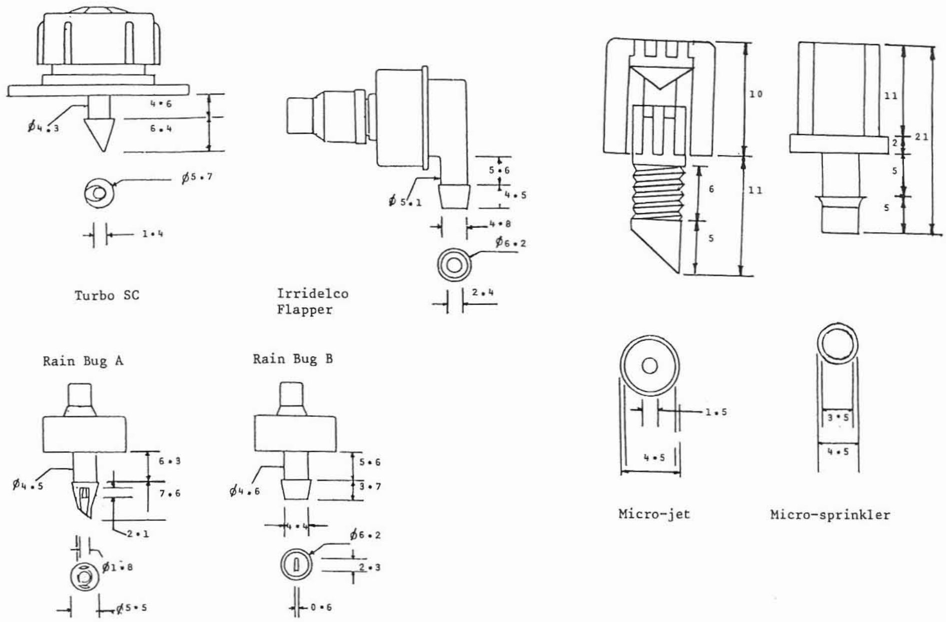

Fig. 3. Typical emitter barb protrusion shapes and sizes

Results of the experiments on head loss in a 13 mm ID trickle lateral fitted with insert emitters at various spacings are expressed as friction factor versus Reynolds number and shown in *Figs. 4-7.* Detailed results are found in Mohd Shaharudin (1991). Test results show that friction loss is more significant in 13 mm ID PE than in 15 mm ID PE. The head loss in a lateral with emitter protrusions increased in the following order: Turbo S.C., Irridelco Flapper, Rain Bug B and Rain Bug A. These data show that friction coefficient not only varies with emitter spacing, but also the emitter protrusion shape and depth in relation to pipe inside diameter, d/D. The head loss is higher with greater turbulence in the wake behind the protrusion caused by the size and shape of the emitter barb connection.

Figs. 1 and 4-7 show that friction factor for semi-smooth flow in a micro-irrigation lateral pipe is almost parallel to the von Karman-Prandtl smooth pipe curve and also to that of Blasius. It can be seen that the data do not fit the Hazen-Williams formula. A wise choice of the coefficient CE for use in Eqn. 10 will result in a better agreement of head loss with Darcy-Wiesbach and λ from the relevant graphs in *Figs. 1 and 4-7.*

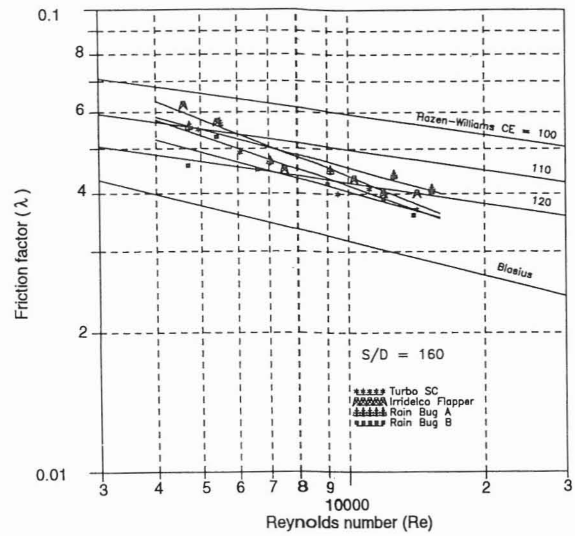

Fig. 4. Friction factor-Reynolds number relationship for 13 mm ID PE with emitters spaced 2 m apart

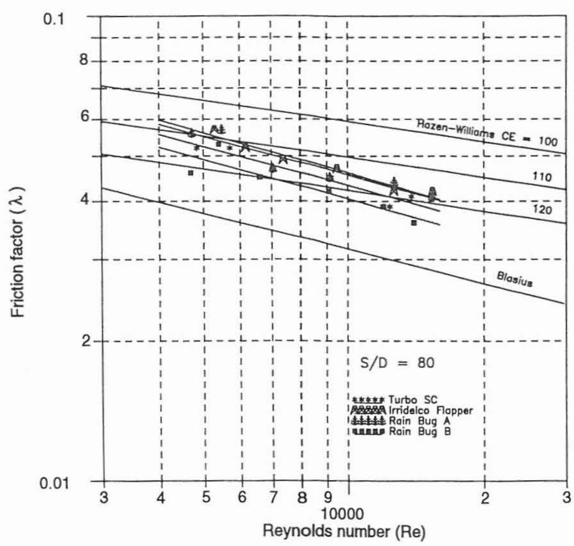

Fig. 5. Friction factor-Reynolds number relationship for 13 mm ID PE with emitters spaced 1 m apart

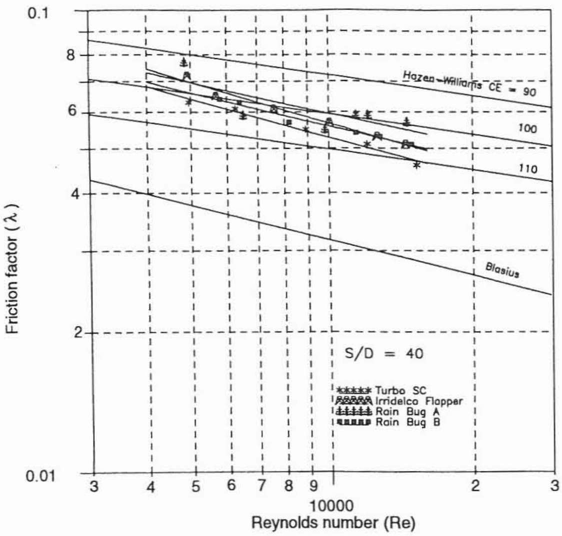

Fig. 6. Friction factor-Reynolds number relationship for 13 mm ID PE with emitters spaced 0.5 m apart

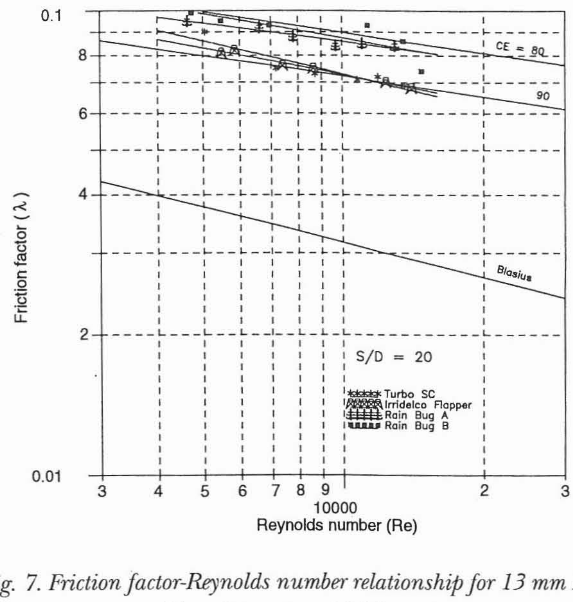

Fig. 7. Friction factor-Reynolds number relationship for 13 mm ID PE with emitters spaced 0.25 m apart

Fig. 8-11 show results of friction factor for micro-jets and micro-sprinklers spaced at 6 m, 3 m, and 1.5 m on 13 mm and 15 mm ID PE in a 30 m test section. Detailed results are found in Ramaysh (1992). The slanted tip protrusion of the micro-jet causes greater head loss than the cylindrical protrusion of the micro-sprinkler in both pipe sizes at the same flow regime. Without emitters, the PE lateral has a C value of 140 at Reynolds number of around 20,000 to 30,000. With micro-jets or micro-sprinklers spaced 6 m apart, CE value was found to be around 130. For a spacing of 1.5 m and at Reynolds number of 20,000, the corresponding CE values decrease from around 120 to 114 for MS15, MJ15, MS13 and MJ13, respectively. Eqn. 9 can be used to convert Hazen-Williams C values to friction factor λ.

These results can be utilized to replace Blasius smooth pipe equation for use in the Darcy-Weisbach head loss equation, or an equivalent CE value can be interpolated for use in the Hazen-Williams formula. However, the equation will be different for each situation, depending on the shape and size of the emitter protrusion, the pipe diameter and the emitter spacing.

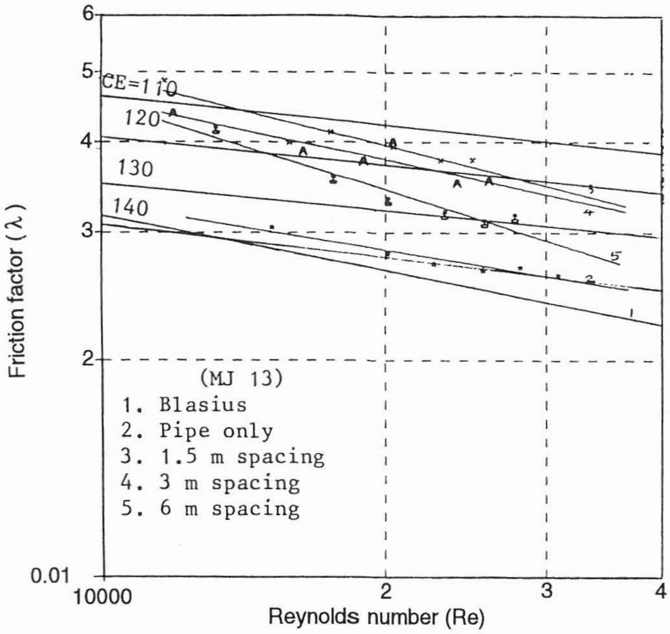

Fig. 8. Friction factor-Reynolds number relationship for 13 mm ID PE with micro-jets at various spacings

Obstruction to flow by emitter barb protrusion is usually large (see *Fig. 2*), and a large head loss is caused by a barb shape which creates great turbulence in its wake. This study has shown that the commonly used C=130 for micro-irrigation laterals is clearly an underestimation of the actual head loss, especially if emitters are closely spaced. Other protrusion shapes should be considered to reduce obstruction to flow as well as to minimize friction loss in the lateral. The trend in the design of emitters, micro-jets and micro-sprinklers should be towards full pressure compensation (discharge exponent x in the emitter flow function $q=kH^x$ equals zero or near 0.0) so that uniform dischargesare obtained irrespective of pressure fluctuations due to friction and elevation changes in the field.

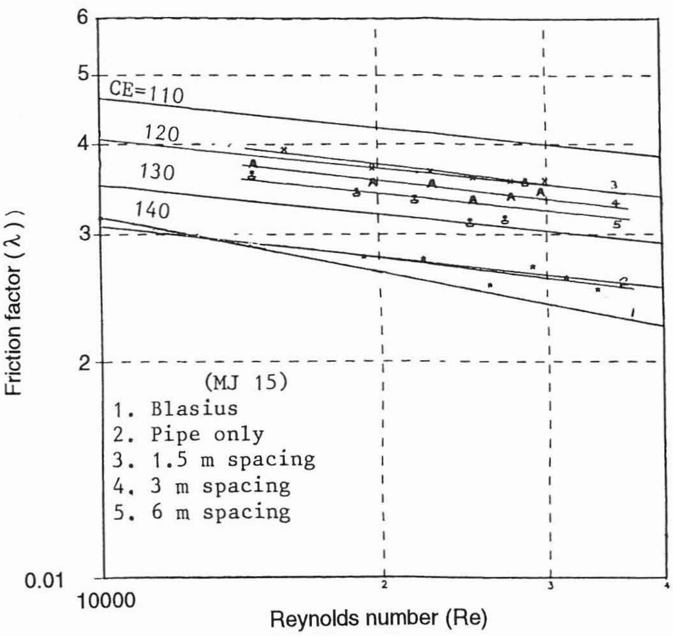

Fig. 9. Friction factor-Reynolds number relationship for 15 mm ID PE with micro-jets at various spacings

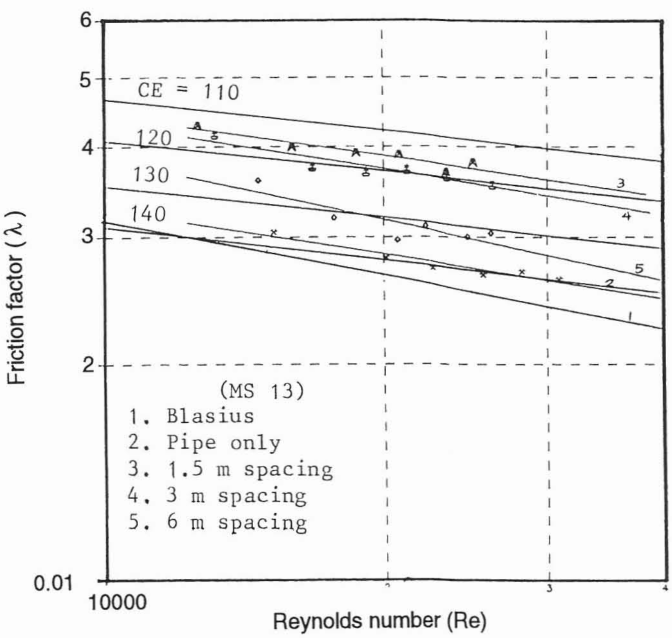

Fig. 10. Friction factor-Reynolds number relationship for 13 mm ID PE with micro-sprinklers at various spacings

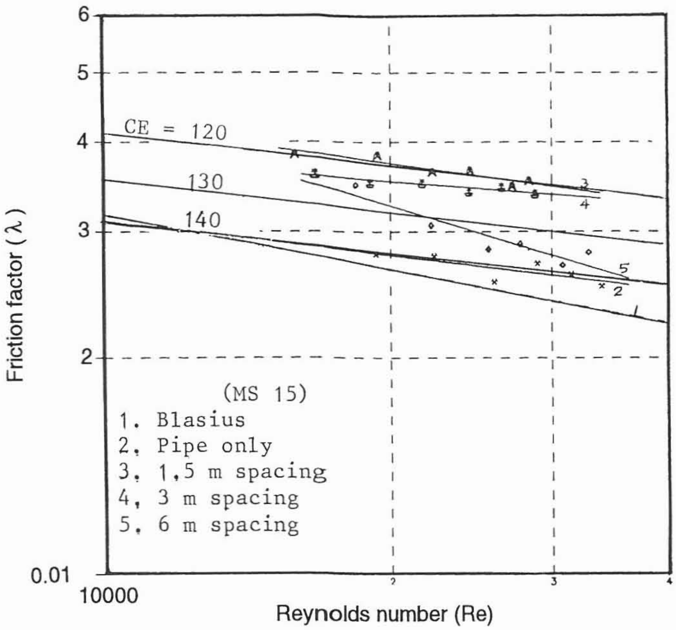

Fig. 11. Friction factor-Reynolds number relationship for 15 mm ID PE with micro-sprinklers at various spacings

SAMPLE PROBLEMS

1. How much is pressure head loss? Lateral is 13 mm ID PE and emitter is Turbo SC with 4 l/h spaced 1 m apart in a 100 m long lateral on flat ground. Assume water temperature to be 30°C.

Using Eqn. 12 for Reynolds number of flow in the lateral, Re=13,500. From *Fig. 5*, the CE value is 120. Using Eqn. 10 and F=0.36 for number of emitters higher than 70, Hf is found to be 3.94 m. Check: Taking CE=120 and converting to friction factor by using Eqn.9, λ=0.0405. Using the Darcy-Weisbach Eqn., one gets Hf=4.0 m.

2. What is an acceptable length of 13 mm PE lateral fitted with Rain Bug A emitters discharging 4 l/h, spaced 0.5 m apart irrigating polybags in a nursery if head loss was limited to 5 m.

Assume water temperature is 30°C and 100 emitters. Qt is 400, Re=13,500. From *Fig. 6*, CE is 100. Using Eqn. 11, one gets L=61.5 m.
Check: Actual no. of emitters is 123, or Qt=492 l/h. From Eqn. 12, at T=30, Re=16,600. From *Fig. 6*, CE=100, hence L=61.5 m.

CONCLUSIONS

Both Darcy-Weisbach and Hazen-Williams equations can be used to estimate the head loss in a lateral with insert emitters. But proper selection of friction factor or roughness coefficient is necessary for a more accurate estimation of the head loss. This paper presents results which can be used as a guide in selecting the correct friction coefficient for use in the conventional approach of hydraulic analysis of micro-irrigation laterals. Other common emitter protrusion shapes and sizes in lateral pipes of different diameters can be studied. Friction loss is reduced to that of the pipe wall only if emitter barb connection was designed such that resistance to flow is minimized.

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