EFFECTS OF FLOW RATE AND PIPE DIAMETER ON WALL CHLORINE DECAY RATES +

تأثير معدل الجريان وقطر الأنبوب على معدل تناقص الكلور

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Abstract:

Wall chlorine decay occurs when chlorine react with the wall material itself and with adhering biofilms. The wall decay constant is mostly a function of pipe characteristics: material, inner coating, age, diameter and presence of attached biomass, therefore wall decay constant (K) is more difficult to determine because it depends on a number of variables. In this study, the continuous flow experiments were performed to determine wall chlorine decay rate and its dependency on water flow rates and pipe diameter. The results show that wall chlorine decay rate can be expressed using first order model and the important parameter which effect on wall decay constant is pipe's material, as flow velocity increases, wall chlorine decay rate increases and as pipe diameter increase, chlorine decay rates decrease.

المستخلص:

يحدث تناقص الكلور (chlorine wall decay) في شبكات توزيع المياه نتيجة لتفاعل الكلور مع مادة جدار (مثل الصدأ) أو مع طبقة الملوثات التي تحيط بجدار الأنبوب. أن تناقص الكلور (chlorine wall decay) في شبكات الجريان يعتمد على عدة عوامل منها نوع مادة الأنبوب وتغليفه الداخلي وعمره الخدمي وقطر الأنبوب....الخ، لذا من الصعب تحديد معاملات تناقص الكلور (chlorine wall decay) لكل أنبوب لارتباطه بعدد من العوامل. أجريت في هذه الدراسة سلسلة من تجارب الجريان المستمر(continuous flow experiments)لتحديد معدل اضمحلال الكلور نتيجة التفاعل مع الجدار واعتماده على سرعة الجريان وقطر الأنبوب الناقل للماء.

أظهرت النتائج بان : (١) معامل اضمحلال الكلور نتيجة التفاعل مع الجدار يمكن تمثيله باستخدام نموذج رياضي من الدرجة الأولى.(٢) بزيادة سرعة الجريان يزداد معدل اضمحلال الكلور (٣) معدل اضمحلال الكلور يقل بزيادة قطر الأنبوب

Introduction:

The chlorine concentration added to the treated water at the entrance of a transport and distribution system does not remain constant during the transport to the consumer tap; it gradually lowers as chlorine reacts in the bulk phase of the water (bulk chlorine decay) and at the wall interface of pipes and tanks (wall chlorine decay).

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Decay may lead to the total disappearance of the disinfectant, thus increasing the probability of microbiological contamination. The effect becomes more relevant in network zones with high water travel times, such as network ends with low consumption [1].

Wall decay occurs when chlorine react with the wall material itself (for example, due to corrosion phenomena) and with adhering biofilms as shown in Fig. (1). The slime layer, or biofilm, represents colonization of the surface by bacteria and other microorganisms. Indeed, biofilms can be found in practically any aqueous environment, forming whenever a solid surface is in contact with an aqueous phase. Initial biofilm formation arises from the inevitable colonisation of surfaces by aqueous phase microorganisms [2]. The wall decay constant is mostly a function of pipe characteristics: material, inner coating, age, diameter and presence of attached biomass [1]. Therefore wall decay constant (K) is more difficult to determine because it depends on a number of variables.

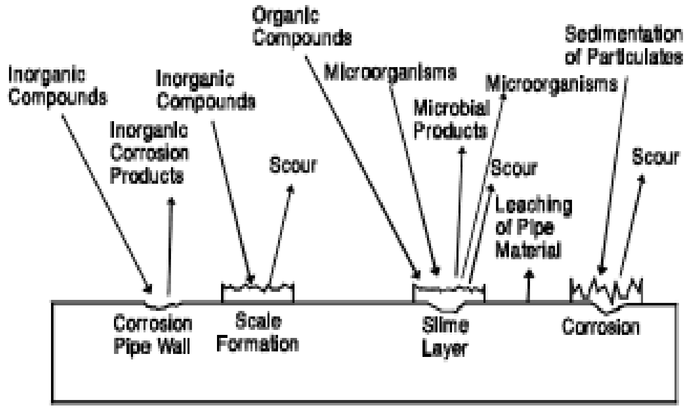


Fig. (1) Schematic of chemical and microbiological transformation at the pipe wall [3]

<u>Theory Review:</u>

Wall Chlorine Decay Kinetics

While flowing through pipes, dissolved substances can be transported to the pipe wall and reacted with its material such as corrosion products or biofilm that are on or close to the wall. The amount of wall area available for reaction and the rate of mass transfer between the bulk fluid and the wall will also influence the overall rate of this reaction. The surface area per unit volume, which can represented by the hydraulic radius, determines the former factor. This factor can be represented by a mass transfer coefficient whose value depends on the molecular diffusivity of the reactive species and on the Reynolds number of the flow [4].

Based on previous works [5,6], it appears reasonable to assume that disappearance of chlorine in water flowing through a pipe is governed by first order kinetics(which mean that the reaction velocity is proportional to the concentration of the chlorine only) . For this model, the rate of chlorine decay can be expressed as [7].

$$\frac{dC}{dt} = -KC \qquad \text{(1)}$$

Where;

$$K = -\frac{K_W K_f}{R_h(K_w + K_f)} \quad \text{.. (2)}$$

Where;

K = Chlorine decay coefficient, (1/T),
K_w = Wall coefficient, (L/T),
K_f = Mass transfer coefficient, (L/T), and
R_h = Hydraulic radius, (L).

$$K_f = \frac{ShD}{d} \quad \text{.. (3)}$$

Where;

D = Molecular diffusivity of solute or dispersion coefficient, (L^2/T),
d = Pipe diameter, (L) and
Sh= Sherwood number, which can be defined as:
$Sh = 0.023Re^{0.83}\ Sc^{0.333}$ for Re >= 2300 .... (4-A)
$Sh = 3.65 + (0.0668(d/L)\ Re\ Sc) / (\ 1 + 0.04[(d/L)\ Re\ Sc]^{0.67})$ for Re < 2300.......(4-B)

Where;

L = Pipe length (L),
Sc = Schmidt number = υ/D,(L/T),
υ = Kinematics viscosity, (L^2/T), and
Re = Reynolds Number.

K_f is typically much higher than K_W. In other words, the transport of material to the pipe wall is much higher than the decay reaction at the pipe wall. Looking at the equation (2) it can be seen that a very large K_f compared to K_w will reduce this equation to approximately.

$$\frac{dC}{dt} = -\frac{K_W C}{R_h} \quad \text{.. (5)}$$

$$K = -\frac{K_W}{R_h} \quad \text{.. (6)}$$

Experiments Procedure:

The rates of wall chlorine decay have been studied employing a pilot scale continuous flow systems. Two systems have been used; the first one which used to study the effect of water flow rate on wall chlorine decay, is the cast iron dead end flow system. While the second was which used to study the effect of pipe diameter on wall chlorine decay rate, is the PVC looped flow system.

1- Chlorine Concentration Measurement

Chlorine concentration was measured by using Hanna chlorine spectrophotometer (HI 93711, Hungary). The range of its measure varies from 0.00 to 2.50 mg/l for free chlorine and from 0.00 to 3.5 mg/l for total chlorine. Chlorine spectrophotometer is a colorimeter instrument uses a photodiode or electric eye to measure the intensity of the sample color. To measure chlorine concentration using this instrument, DPD (N, N-Diethyl-p-

Phenylenediamine) powder is used as chemical indicator according to standard methods for the examination of water and wastewater, 1998.

2- Effect of Flow Rate

The effect of flow rate on wall chlorine decay has been studied using a pilot distribution system. This system consists of cast iron pipe of 109.6 m total length and 18.7 mm diameter as shown in Figs. (2) and (3). Water samples were drawn from seven sampling ports (taps) located a long the pipe.

The flow system was supplied with water using two tanks of 170 l capacity each. The two tanks were arranged in such a way that keeps a constant head for hydraulic pressure and uniform steady flow. The flow rate of water has been controlled using a cock valve fixed at the beginning of the pipe and measured using a measuring jar and a stopwatch (volumetric method). The two tanks were filled with tap water, and then water was chlorinated to obtain initial free chlorine concentration of 25 mg/l. After that, the chlorinated water was left in the tank for five days to remove the effect of initial bulk chlorine decay.

The experimental work of wall chlorine decay rates was conducted for three flow rate(1.7, 3.54 and 5.34 l\sec). For each flow rate, two water samples were drawn from each sampling point as a replication to assure the quality of the results

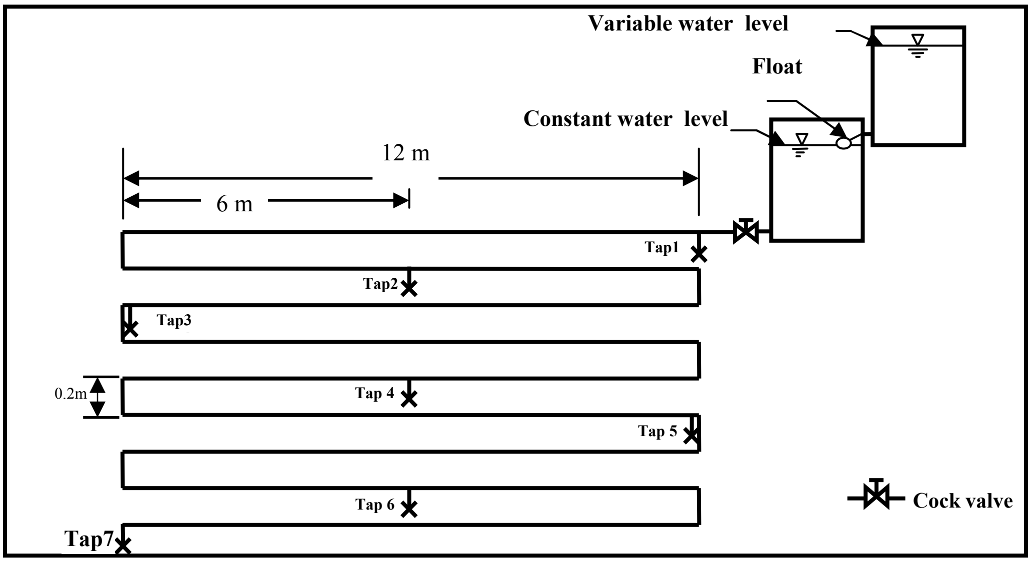
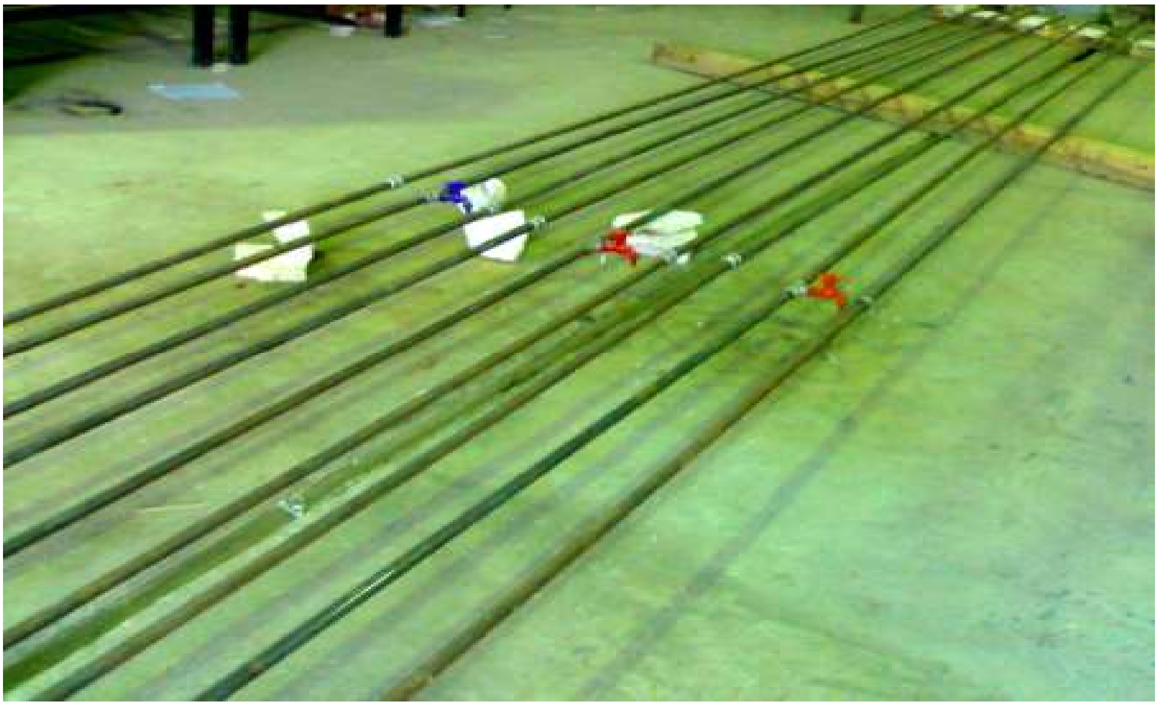


Fig. (2) Schematic diagram of pilot distribution system

(b) Tanks arrangement **(a) Pipes layout**



(c)Sampling points

Fig. (3) Photos of pilot distribution system

3- Effect of Pipe Diameter

In order to study the effect of pipe diameter on wall chlorine decay, two loops of 6m length PVC pipe were made. The first loop consists of 45mm pipe diameter while the second loop consists of 100 mm pipe diameter as shown in the Figs. (4), (5) and (6).

Each of two loop systems has been supplied with water using a water tank of 170 l capacity connected to a pump. The water has been initially chlorinated with 22 mg/l of free chlorine concentration. The chlorinated water was stored for seven days to remove the effect of initial bulk chlorine decay.

The flow rate has been controlled using a cock valve fixed at the beginning of the pipe. Samples of water were taken from the loop end at different time intervals. Duplicated samples were taken for each time intervals to assure the accuracy of chlorine concentration measurement.

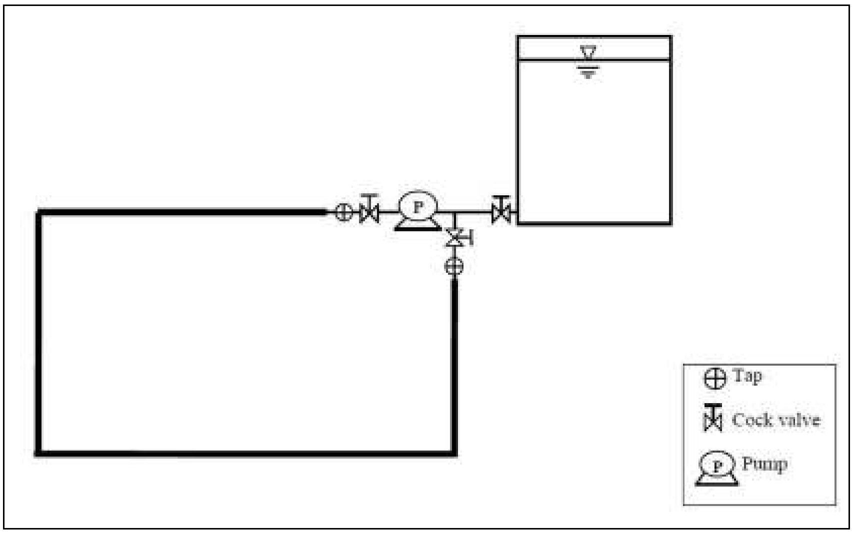


Fig. (4) Schematic diagram of pilot Loop system

Fig. (5) Photo of pilot loop system of 45 mm diameter PVC pipe

Fig. (6) Photo of pilot loop system of 100 mm diameter PVC pipe

Results and Discussion:

1- Dependency of Wall Chlorine Decay on Flow Rates

Three flow rate values; 1.7, 3.54, and 5.34 l/min were adopted. For each flow rate value, residence time was calculated by using the following equation [8] as shown in the table (1):

$$\theta = \frac{\mathbf{A\,x^*}}{\mathbf{Q}} \qquad \text{...(7)}$$

Where;
θ = Residence time (T)
Q = Average volumetric flow rate (L^3/T)
A = Pipe cross-section area (L^2)
x* = Distance from the inlet (L)

Table (1) Chlorine decay results for cast iron pilot distribution system, at different values of flow rate.

Flow rate (l/min)	Tap No.	L(m)	Residence time (sec)	Free chlorine (mg/l)	
Q=1.70	1	0	0.00	18.20	19.00
	2	18.2	176.7	13.0	12.60
	3	36.4	353.4	9.10	8.02
	4	54.8	532.1	2.33	3.01
	5	73.0	708.8	0.93	0.75
	6	91.4	887.5	0.23	0.33
	7	109.6	1064.2	0.10	0.08
Q=3.54	1	0	0.00	19.70	18.90
	2	18.2	84.8	13.91	15.29
	3	36.4	169.6	9.70	9.10
	4	54.8	255.4	3.49	4.91
	5	73.0	340.2	2.30	2.64
	6	91.4	425.9	1.35	1.39
	7	109.6	510.7	0.80	1.0
Q=5.34	1	0	0.00	19.31	18.69
	2	18.2	56.4	15.9	16.70
	3	36.4	112.8	11.5	10.50
	4	54.8	169.9	7.30	7.70
	5	73.0	226.3	5.00	4.40
	6	91.4	283.4	2.06	2.88
	7	109.6	339.8	1.30	1.90

These data (residence time against chlorine concentration) were plotted for each flow rate value, with fitting curves, as shown in Fig. (7). For each flow rate value, the relation between obtained data was best represented by a first order model. The parameters of this model (for the consider flow rate values) are as given in Table (2). Fig. (7) shows that as water flow rate increases, the rate of wall chlorine decay increases. Table (2) declares this result, also, in this table it can noticed that the high chlorine decay for all values of flow rate.

The reason behind this, that the rough surfaces such as ferrous iron can increase problems with biofilms. That is, ferrous iron reacts with chlorine and, reducing the effective concentration of disinfectant in the vicinity of biofilms. Furthermore, rough surfaces contain niches where microbes can grow without exposure to hydraulic shear [9].

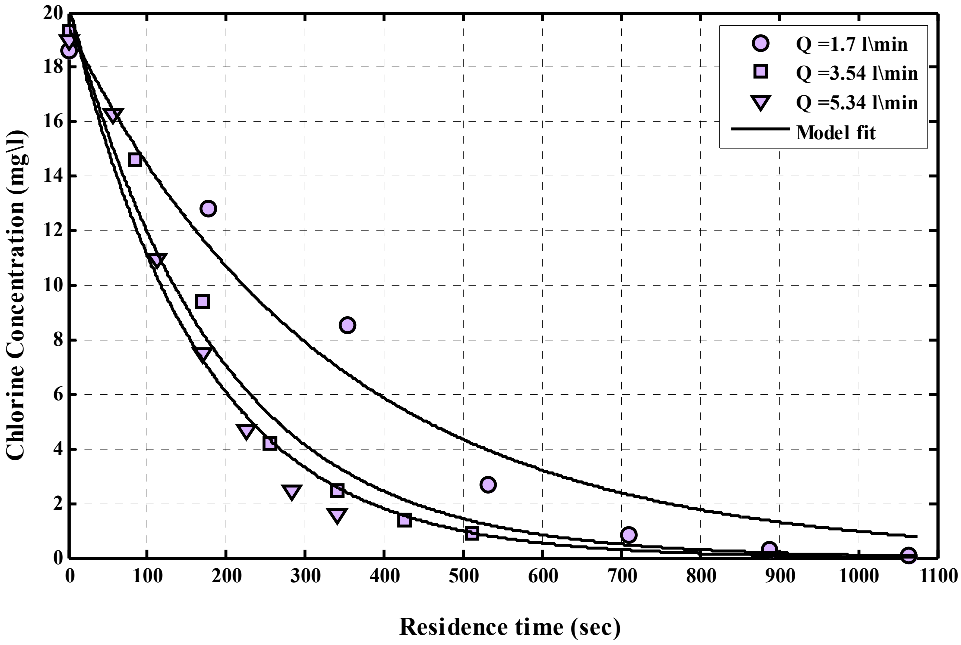


Fig. (7) Variation of wall chlorine decay rate kinetics with water flow rate

Table (2) Variation of wall decay coefficient with flow rate for cast iron pipe of (17.8mm) diameter

Q(L/min)	K(1/day)	K_W (m/day)	R^2
5.34	496.109	2.288	0.9609
3.54	462.931	2.167	0.9715
1.70	275.616	1.254	0.9612

2- Dependency of Wall Chlorine Decay on Pipe Diameter

As well known that the surfaces are accelerated chlorine decay above the level experienced in bulk water [10]. For this reason, studied were conducted on two pilot PVC loops with 45 and 100 mm diameter.

The obtained data (as shown in Tables (3) and (4)) were plotted with fitting curves as shown in Fig.(8). For each diameter value, the relation between obtained data was, also, best represented by a first order model. The parameters of this model are as given in Table (5). Fig. (8) shows that as the pipe diameter increase, the coefficient of chlorine decay rate (K) decrease.

The reason behind the chlorine decays faster in smaller diameter pipelines is that; they have higher surface to volume ratio than those of large diameter mains and reservoirs.

Table (3) Chlorine decay results for PVC pipe loop of 100 mm diameter

Residence time(min)	Free chlorine concentration (mg/l)	
0	9.61	9.59
12	9.5	9.60
32	9.42	9.48
77	8.50	8.10
97	8.00	7.90
116	7.80	7.80

145	7.50	7.20
160	7.25	7.35
195	6.90	6.70

Table (4) Chlorine decay results for PVC pipe loop of 45 mm diameter

Residence time (min)	Free chlorine concentration (mg/l)	
0	9.38	9.42
17	8.70	8.90
34	8.45	8.55
68	8.20	7.80
104	6.90	7.50
126	6.81	6.79
159	6.50	6.50
179	5.70	5.90
199	5.25	5.35

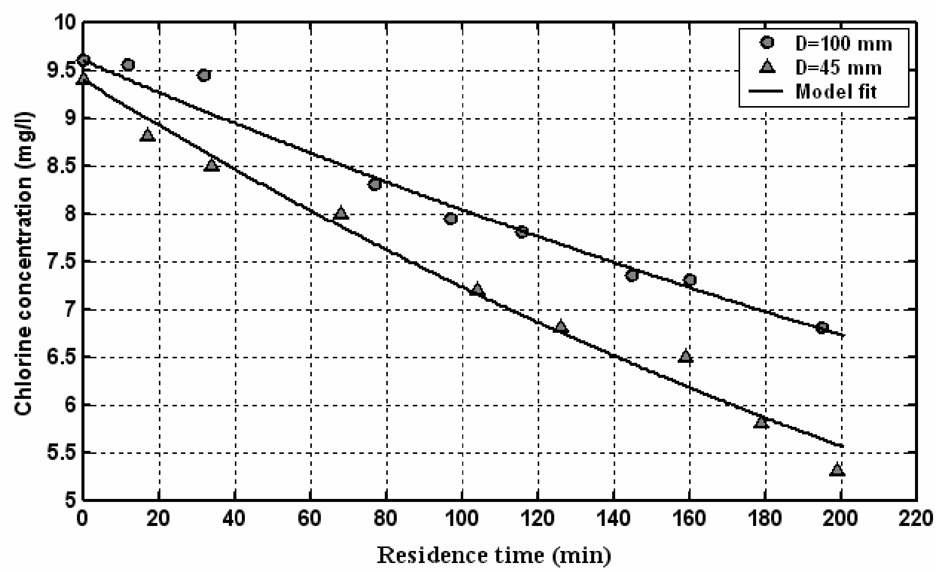


Fig. (8) Variation of wall chlorine decay rate kinetics with PVC pipe diameter

Table (5) Variation of wall decay coefficient with pipe diameter for PVC pipe loop

Pipe diameter (mm)	Hydraulic Radius (Rh)(m)	K (1/day)	K_W (m/day)	R^2
45	0.01125	3.777	0.0423	0.9844
100	0.025	2.566	0.0610	0.9778

Conclusion:

Based on the results of this study the following conclusions can be drawn:

1- Wall chlorine decay rate can be expressed using first order model $\frac{dC}{dt} = -KC$ (which mean that the reaction velocity is proportional to the concentration of the chlorine only), and the important parameter which effect on wall decay constant is pipe's material. The results shown in this study that wall chlorine decay rate coefficient ranged from (496 1\day to 275 1\day) for cast iron pipe, while its range from (3.77 1\day to 2.56 1\day) for PVC pipe

2- As flow rate increase, the wall chlorine decay rates increase. For this study the wall chlorine decay coefficient varies from (496 1\day to 275 1\day) when flow rate varies from (5.34 l\sec to 1.7 l/sec)

3- As pipe diameter increase, wall chlorine decay rates decrease. For this study the wall chlorine decay coefficient varies from (3.77 1\day to 2.56 1\day) when pipe diameter varies from (45mm to 100mm).

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