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Does pressure reduction test have significant effect on evaluating pressure management to reduce physical leakage amount?

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Abstract

Physical leakage flow is positively correlated with water head in water supply network (WSN). Index model is applied to engineering of pressure management in which physical leakage flow is expressed as index of average head in WSN. The paper analyzed three aspects involving flow meter measurement error, water head impact, water flow instability. The result shows that the error of this model is unacceptable from the data of pressure reduction measurement with water flow. Pressure reduction test have meaningless effect on evaluating physical losses reduction unless when it was conducted, users stop consuming water.

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Keywords: Index model; Physical leakage flow; Pressure management; Pressure reduction test; Water head.

1. Introduction

With the growing scale and improvement complexity of urban WSN, water losses in WSN is being given more and more attention [1]. On the other hand, water losses in WSN has caused many administrative problems for administrative staffs [2]. Water losses control is a crucial issue which need to be dealt at the earliest so that the water supply industries can efficiently improve the insufficiency of water supply services [3,4]. Water losses in WSN comprise "apparent losses" and "physical losses or leakage". Physical losses includes the total volume of water losses minus apparent losses. Apparent losses are estimated and therefore the resulting leakage volume may be

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incorrect [5,6]. Managers in water supply industries must therefore verify the results using physical losses assessment. "Water balance", "Minimum Night Flow" and "Pressure based leaking model" are generally used for calculating physical leakage. "Water balance", "Minimum Night Flow" can only calculate Non-Revenue Water (NRW) but cannot accurately calculate physical losses [7,8]. However, although more accurate physical leakage flow can be obtained from pressure based leakage model, it is difficult to determine hydraulic parameter valves because irregular leak points are deeply buried water pipes [9]. Therefore, the paper analyzed whether pressure reduction test has significant effect on evaluating pressure management to reduce physical leakage amount or not for above physical losses assessment.

2. Total water supply amount division in urban WSN

Urban water supply network system is an open system with multiple openings. System input volume should equal to system output volume. This is the basis of water balance analysis. Output volume in network is divided into different categories and the water balance analysis tables are obtained. IWA committees in 1996 provided dividing method that divided water supply flow to focus on analyzing physical losses [10].

IWA water balance analysis is actually based on water volume dividing method that divide the total water supply amount into four categories: Billed Authorized Consumption, Unbilled Authorized Consumption, Commercial Losses, Physical Losses, and the sum of the latter three is Non-revenue water (NRW) [11]. In any steady operation conditions of WSN, as the volume is the integral of flow of time, so total water supply amount is divided into physical losses and water consumptions. Physical losses correspond to physical leakage flow and water consumption correspond to Billed Authorized Consumption, Unbilled Authorized Consumption, Commercial Losses. Basic equation was obtained as follows: Eq. (1)

$$Q_Z = Q_Y + Q_L \tag{1}$$

Where, Q_Z is water supply flow (L/s); Q_Y is water consumption flow(L/s); Q_L is leakage flow (L/s).

3. The current method about pressure management evaluating physical losses reduction

Quantifying pressure management evaluate physical losses reduction in network, which was theoretically achieved by simulative methods with models and field tests methods, or the combined method with the above two methods. Field tests provide data in order to support determination of model parameters. Field tests methods include: pressure reduction test, new water balance analysis after pressure management.

Evaluation methods whose physical losses are reduced by pressure management involve three categories: evaluation before pressure management implementation, pressure reduction test evaluation, evaluation after pressure management implementation. Evaluation before pressure management implementation is that it provide predetermined pressure scheme but the evaluation of physical losses reduction is not conducted; Pressure reduction test evaluation is that leakage flow before and after pressure reduction was respectively obtained through pressure reduction test. The relationship between the leakage flow and water head exponent is determined. Evaluation after pressure management implementation is that the predetermined pressure scheme has been implemented. Physical losses reduction is evaluated by analysis before and after pressure reduction.

4. Analysis about field tests evaluating physical losses reduction

4.1. Pressure reduction test evaluation

Pressure reduction test evaluation usually comprise of pressure reduction test and equivalent leakage point index model. Pressure reduction and rises theoretically need to achieve more than two times. The relation of physical leakage flow and average water head (AZP) as follows: Eq. (2) and Eq. (3). The equivalent leakage coefficient and the equivalent leakage exponent are calculated through testing total water supply amount in each state-of-art of network and average water head (AZP) in WSN.

$$Q_{Li} = K_{net}(H_{AZPi})^n \tag{2}$$

$$\begin{cases} Q_{Y0} + K_{net}(H_{AZP0})^n = Q_{Z0} \\ Q_{Y1} + K_{net}(H_{AZP1})^n = Q_{Z1} \\ Q_{Y2} + K_{net}(H_{AZP2})^n = Q_{Z2} \end{cases} \tag{3}$$

Where, Q_L is physical leakage flow in WSN (L/s); Q_Y is water consumption flow in WSN (L/s); Q_Z is total water supply amount in WSN; K_{net} is the equivalent leakage coefficient in WSN; H_{AZP} is average water head (Free water head); i is serial number of stat of art of network, $i=0$ is before pressure reduction, $i \geq 1$ is after pressure reduction; n is the equivalent leakage exponent.

4.1.1 The actual operability of equivalent leakage index model

The equivalent leakage index model is assumed that it is theoretically correct. The equivalent leakage index model is theoretically verified by the actual measurement data of pressure reduction test. Pressure reduction test can have water consumption flow test and also can have no water consumption flow test through closing all valve in the inlet pipe of consumers. Water consumption flow test include two categories: 1) Water consumption flow was measured in real-time. 2) Water consumption was partially measured.

Water consumption flow in every state-of-art of network can be simply obtained from Eq. (3) with these two methods that pressure reduction test methods with the real-time measurement water consumption flow and without water consumption flow. The possible error of these two methods is that flow meters of all consumers are not accurate when water consumption flow of all consumers is measured in real-time. The values of the partial consumers on inlet pipe are not tightly closed, resulting in the relative small equivalent leakage exponent when pressure reduction test without water consumption is conducted.

The situation commonly exist in the reality: water consumption of the majority of users is not measured in real-time. Many values are closed for pressure reduction test without water consumption, which are difficultly conducted. Therefore, the basic situation about pressure reduction test is that water consumption flow is measured in no real-time. In this case, it is needed to quantify water consumption flow in WSN through a certain method in order to solve Eq. (3).

Water consumption flow in WSN is quantified by component analysis, but the method is still subjective and the results are inaccurate. Another method is that water consumption flow in different state-of-art of network keep equivalence as much as possible, namely: pressure reduction test is conducted in the condition of keeping equivalent water consumption flow, and Eq. (3) is transformed into Eq. (4)

$$\begin{cases} K_{net}(H_{AZP0})^n - K_{net}(H_{AZP1})^n = Q_{Z0} - Q_{Z1} \\ K_{net}(H_{AZP0})^n - K_{net}(H_{AZP2})^n = Q_{Z0} - Q_{Z2} \end{cases} \tag{4}$$

(1) Error analysis based on water supply flow measurement

It is needed to measure water supply flow in pressure reduction test. Water supply flow is measured by flow meters. Accuracy rate of industrial instruments is generally below 1.0 rate (Basic error of the measurement is more than 1%). The highest accuracy rate of 1.0 rate meter is generally 0.5 rate (the basic error of measurement is 0.5%).

It is assumed that the basic error of total water supply amount is 0.5%. The highest error between the two measurements are 1% and total water supply amount account for 80% of the meter range about instrument. So difference error of the right of Eq. (4) account for about 1.2% of total water supply consumption. It is analyzed the maximum measurement error of total water supply amount have effect on physical leakage flow reduction as shown in Table 1.

Table1. The maximum measurement error have effect on physical leakage flow reduction

Physical losses (account for percentage of total water supply amount)	Physical losses reduction	Physical losses reduction（account for percentage of total water supply amount）	the maximum measurement error	The error of physical leakage flow reduction
10%	10%	1%	1.2%	120%
	20%	2%		60%
	30%	3%		40%
20%	10%	2%		60%
	20%	4%		30%
	30%	6%		20%
30%	10%	3%		40%
	20%	6%		20%
	30%	9%		13%

Table 1. shows when physical losses and physical losses reduction in WSN are smaller, the maximum measurement error may cause the error of physical leakage flow reduction to be more. The error even attain 120%. Although physical losses and physical losses reduction is 30%, the measurement error may result in the error of physical leakage flow reduction is still larger, the error even attain 13%. The parameters solved by Eq. (4) have a large method error. From the error analysis point, the left side of Eq. (4) is very small values compared with total water supply amount, named "small amount", where as the right side of Eq. (4) are two "big amount" with significant errors, it is believed that the "small amount" obtained from the difference between two "big amount" is unreliable.

In addition, water consumption flow was calculated by component analysis or water consumption flow of all consumers was measured by pressure reduction in real-time. The two methods also exist problem of "big amount" error about water consumption. The parameters that are obtained from Eq. (4) also exist large method error.

The above analysis was based on the maximum value of the basic error and was the judgment of the most accurate instrument limit that exist the most adverse situation. If the error of measurement is considered as system error, measurement error lesser effect on physical leakage flow than table 1 because the system error have precordial concordance (The errors are respectively large and small when measurement values are large and small). But flow signals of SCADA system in urban WSN always exists conversion problem between the simulation quantity and figure quantity only to possibly further enlarge measurement error of flow; The measures which can reduce the effect of measurement error in engineering carry out more than once pressure reduction, repeated measurement. The parameters optimization are converted to solve overdetermined equations; But the measurement error of total water supply amount cannot ensure precordial concordance of the error. The measurement error of total water supply amount may have significant effect on physical leakage flow reduction, especially is when physical losses is smaller and the range of pressure reduction is also smaller. Pressure reduction test has meaningless effect on evaluating pressure management to reduce physical leakage amount unless all consumers stop consuming water when pressure reduction test is conducted from the above analysis.

(2) Analysis is based on water head that have effect on water consumption flow

Water appliances can be divided into three categories according to water head that have effect on water consumption: volume type; time type; volume and time hybrid type. Water appliances about volume type meet the volume of certain water consumption for requirement and the water head has no effect on the water consumption, such as washing machine water consumption, bath water consumption; Water appliances about time type meet the time of certain water consumption for requirement, the water head has effect on the water consumption and it can be understood the linear relationship between the one second power of water consumption and the water head, such as automatic timing switch automation green irrigation nozzle; Water appliances about volume and time hybrid type meet the volume of certain water consumption for requirement but are slightly affected by the supply water head at the same time.

When all sorts of water appliances simultaneously consume water, water head have lesser effect on water consumption. Water head that have effect on water consumption can is even neglected if water appliances about the time type are little. If it is considered that water head in certain WSN have no effect on consumption, total water supply amount is immediately measured by flow meter when water head is reduced during a period of the relatively stable total water supply amount. It is assumed that water consumption flow is constant before and after pressure reduction, total water supply amount reduction is physical leakage flow reduction, and the test is called the instantaneous pressure reduction. However, the above hypothesis is wrong. The understood of "water head have no effect on water consumption" is based on certain precondition, which assumes that new urban water consumption behavior is formed that consumers adapt to water head variation after a certain period. The urban water consumption behavior is defined as a line combination about water consumption number of consumers along with opening degree size of water consumption orifice of every consumer. "Water head have no effect on water consumption". On the one hand, it involve that the volume of water consumption have no change in a certain period, and on another hand, it involve that water consumption flow have no change after water consumption behavior change. For example, there are 100 green space that need to be sprayed timely by open/close sprayers, ten blocks of green space are permitted to be sprayed with 10min every time, water consumption flow is 100 L/min in each block of green area, the spray in the whole city is completed with continuous 100 min. Later, water supply in the whole city is conducted by pressure reduction, green departments find green water consumption shortage after a few days, then the change of water consumption behavior as follows: twenty blocks of green space are permitted to be sprayed with 20 min each time, water consumption flow in each block of green area is 50 L/min under the low pressure and the spray in the whole city is still completed with continuous 100 min. Before and after the pressure reduction, the spray volume is 100m^3 per day, average water consumption flow about spray is 1m3/min. New urban water consumption behavior is formed by new a line combination among water consumption number of consumers. Urban water consumption behavior has changed through a certain time, there is no reference about the time range for the relevant research, but urban water consumption behavior has not change at least in a short time after pressure reduction, the decreased amount of total supply amount measured by instantaneous pressure reduction test includes the decreased amount of water consumption flow, therefore, simultaneous pressure reduction test is not scientific.

The data of laboratory WSN that was taken for example is used for analyzing the error of instantaneous pressure reduction test, flow change after pressure reduction is shown in Fig. 1.

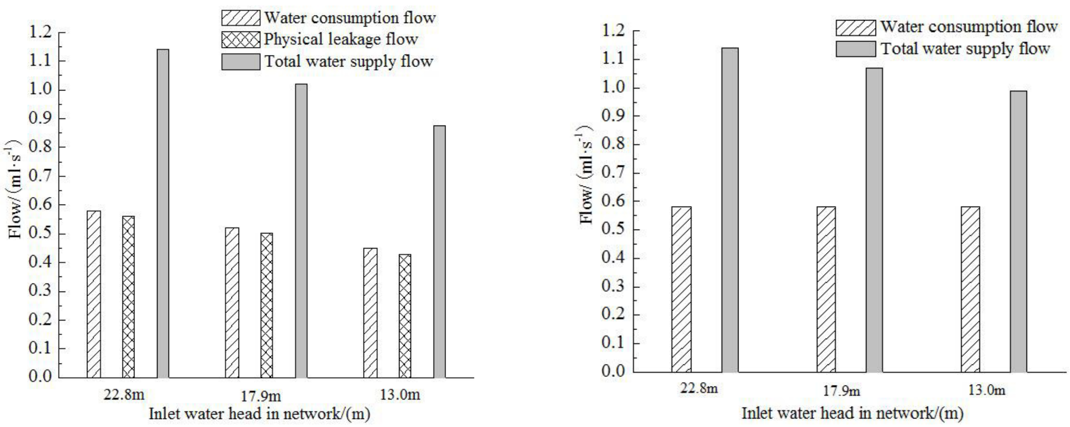

Fig. 1. a) water consumption behavior does not change; b) When water consumption behavior has changed.

Table 2. Water consumption flow have effect on physical leakage flow reduction (water head, m; flow, ml/s).

Inlet water head in network (m)	Total water supply amount (ml/s)	Physical leakage flow (ml/s)	Water head reduction quantity (m)	Physical leakage flow reduction quantity on the basis of water supply change (ml/s)	The actual physical leakage flow reduction quantity (ml/s)	Notes
22.8	1.140	0.560	---	---	---	Unchanged urban water consumption of instantaneous pressure reduction test
17.9	1.022	0.501	4.9	0.118	0.059	
13.0	0.876	0.427	9.8	0.264	0.133	
22.8	1.140	0.560	---	---	---	Urban water consumption behavior occur to change
17.9	1.070	0.489	4.9	0.070	0.071	
13.0	0.988	0.407	9.8	0.152	0.153	

Fig. 1. and Table 2. show when instantaneous pressure reduction solve the quantity of physical leakage flow reduction, urban water consumption behavior has not changed, at this time, water consumption change along with the change of water head. The assumptions that water consumption flow before and after pressure reduction does not change and the quantity of physical leakage flow reduction is replaced by the difference between total water supply amount are wrong. When the quantity of physical leakage flow reduction was solved with the wrong method, the quantity of the flow reduction was much higher than the true flow reduction. Only when after urban water consumption behavior occur to change (the new permutation and combination among opening degree of water consumption orifice of each consumer was completed.) and the water consumption was kept constant (the actual operation is difficult to be adjusted to be completely consistent, resulting in a slight deviation.), the solution that the quantity of physical leakage flow reduction is replaced by the difference between total water supply amount is right.

It was concluded that instantaneous pressure reduction reflect that physical leakage losses reduction is much higher than the actual values unless consumers stop consuming water when instantaneous pressure reduction test is conducted.

(3) Analysis is based on instability of water consumption flow

It is not difficult to be understood that urban water consumption behavior always changes and the change of water head can cause water consumption behavior to change. But the main reason for the change is the social behavior habit. It is whether water head change or not. Urban water consumption behavior at interval 24 hours is bound to change. But water consumption flow is not necessarily same at the same time on different days. If the stability of water consumption flow measured is good, then total water supply amount at the same time on different days can be measured by pressure reduction test, using the difference between total water supply amount of each time to replace the decreased amount of physical leakage flow. This method is called short-term pressure reduction test. If the discrepancy of water head at the same time on different days is very small, the discrepancy of physical leakage flow is very small. The stability of water consumption flow can be expressed by the stability of total water supply amount. It was analyzed to take the measured total water supply amount at District Meter Area (DMA) of LB in CP town for example (Leakage points has been checked and repaired at DMA of LB, the same water head is used every day according to the established scheme of pressure reduction.), the average water supply flow was recorded at each interval 15 minutes, the actual water supply flow was measured as shown in Fig. 2.

The ratio of the standard deviation and the mathematical expectation indicates the discrete coefficient. The discrepancy of the data in first day was larger than the discrepancy of the data in other days as shown in Figure. 2a), the data in remaining six days is selected to calculate discrete coefficient in each moment to take conservative estimate. The data in all six days is used for calculating the discrete coefficient at each moment as shown in Figure 2b). The minimum discrete coefficient in six days in a row is 0.0157 by calculation, which occur at 6:45. The maximum discrete coefficient in six days in a row is 0.1674by calculation, which occur at 14:45. The average value of an all-day discrete coefficient is 0.0636; The smallest discrete coefficient of six Tuesday in a row is 0.0243, which occur at 19:00. The largest discrete coefficient of six Tuesday in a row is 0.1774, which occur at 00:15. The average value of an all-day discrete coefficient is 0.0627.The distribution of the discrete coefficient in all-day is shown in Fig. 3.

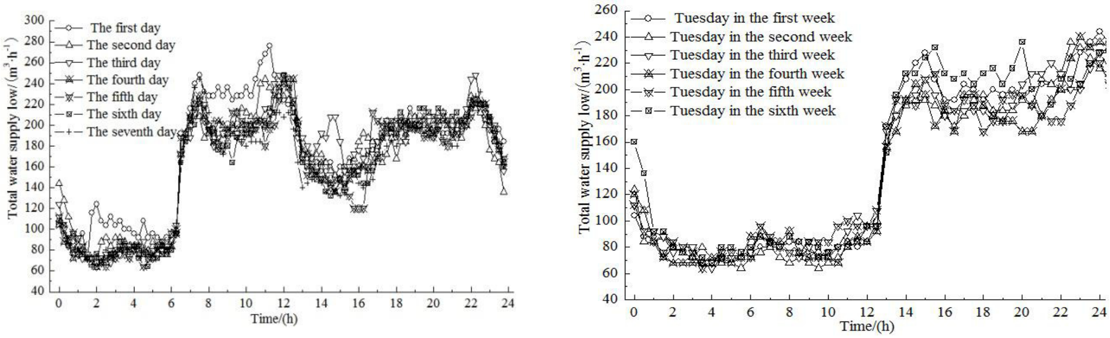

Fig. 2. a) Seven days in a row; b) Six Tuesday in a row

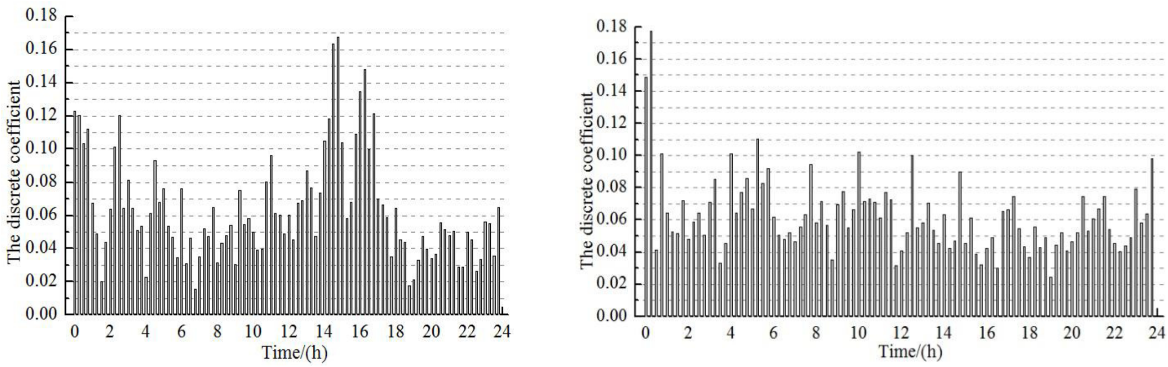

Fig. 3. a) Six days in a row; b) Six Tuesday in a row

The minimum value of the discrete coefficient about the water supply flow in the WSN is 0.0157, which also is 1.2% as much value as the above-mentioned maximum measurement error. Water consumption flow is not stable from the analysis of physical losses reduction. Basic hypotheses about short-term pressure reduction test that "the stability of water consumption flow is good at the same time on different days" is false. It was concluded that short-time pressure reduction test do not reflect that physical leakage flow reduction unless consumers stop consuming water when short-time pressure reduction test is conducted.

In summary, pressure reduction test can not reflect the actual physical leakage flow when pressure reduction test is conducted because total water supply amount has measurement error, water head have effect on water consumption flow and water consumption exist instability unless consumers stop consuming water. It makes that the practical operability of equivalent point index model is poor.

4.1.2 The theory analysis of the equivalent point index model

The equivalent point index model that is obtained by simplifying and quantifying WSN physical losses ideal model have only one independent variable parameter: average water head in WSN (AZP). This model can be basically separated from the hydraulic model in WSN and has been widely used in engineering.

Ideal model assume that different leakage points of physical losses coefficient and exponent heavily exist in WSN. It is the best description of the actual physical losses situation. The model need to be simplified because the ideal model cannot be solved.

It is assumed that equally distributed 2N+1 leakage points in pipeline with unchanged height. Hydraulic gradient is $\mathrm{D}H$ and uniformly decline along pipe length. Average water head is H_{ZAP} , Physical leakage flow in this pipeline as Eq. (5):

$$\begin{aligned} Q_L(\mathrm{V}H) = {} & K_1(H_{AZP} + \frac{N}{2N}\mathrm{V}H)^{n_1} + K_2(H_{AZP} + \frac{N-1}{2N}\mathrm{V}H)^{n_2} + ... + K_i(H_{AZP} + \frac{N-i+1}{2N}\mathrm{V}H)^{n_i} \\ & + ... + K_{N+1}(H_{AZP})^{n_{N+1}} + ... + K_{2N}(H_{AZP} - \frac{N-1}{2N}\mathrm{V}H)^{n_{2N}} + K_{2N+1}(H_{AZP} - \frac{N}{2N}\mathrm{V}H)^{n_{2N+1}} \end{aligned} \tag{5}$$

Where, $Q_L(\mathrm{D}H)$ is physical leakage flow of hydraulic gradient of $\mathrm{D}H$; K_i is leakage coefficient of the i^{th} leakage point; i is leakage points number; n_i is leakage exponent of the i^{th} leakage point.

It is assumed that Eq. (6) is right about this pipeline.

$$\begin{aligned} & K_1 = K_2 = \cdots K_i = \cdots K_{2N+1} = K^+ \\ & n_1 = n_2 = \cdots n_i = \cdots n_{2N+1} = n^+ \end{aligned} \tag{6}$$

Eq. (5) was converted Eq. (7) which is physical losses model.

$$\begin{aligned} Q_L(\mathrm{V}H) = {} & K^+\{(H_{AZP} + \frac{N}{2N}\mathrm{V}H)^{n^+} + (H_{AZP} + \frac{N-1}{2N}\mathrm{V}H)^{n^+} + ... + (H_{AZP} + \frac{N-i+1}{2N}\mathrm{V}H)^{n^+} \\ & + ... + (H_{AZP})^{n^+} + ... + (H_{AZP} - \frac{N-1}{2N}\mathrm{V}H)^{n^+} + (H_{AZP} - \frac{N}{2N}\mathrm{V}H)^{n^+}\} \end{aligned} \tag{7}$$

The equivalent leakage point index model express physical leakage flow as shown in Eq. (8)

$$Q_L(\mathrm{V}H) = K_{net}(H_{AZP})^n \tag{8}$$

Where, K_{net} is equivalent leakage coefficient; H_{AZP} is average head in WSN (Free water head) ; n is equivalent leakage exponent in WSN.

When Hydraulic gradient is $2\mathrm{D}H$ and uniformly decline along pipe length as well as average water head is still H_{AZP} , the physical leakage is shown in Eq. (9):

$$\begin{aligned} Q_L(2\mathrm{V}H) = {} & K^+\{(H_{AZP} + \mathrm{V}H)^{n^+} + (H_{AZP} + \frac{N-1}{N}\mathrm{V}H)^{n^+} + ... + (H_{AZP} + \frac{N-i+1}{N}\mathrm{V}H)^{n^+} \\ & + ... + (H_{AZP})^{n^+} + ... + (H_{AZP} - \frac{N-1}{N}\mathrm{V}H)^{n^+} + (H_{AZP} - \mathrm{V}H)^{n^+}\} \end{aligned} \tag{9}$$

It is proved that only when $n^+ = 1$ and $Q_L(\mathrm{D}H) = Q_L(2\mathrm{D}H)$, no matter what n^+ is, as long as the average head is still H_{AZP} , the equivalent leakage point index model solve invariant physical leakage flow. Thus the equivalent leakage index model is theoretically unreliable. The error of equivalent leakage index model is shown in Fig. 4. It can be seen that the fitting effect of the equivalent leakage point index model in the experimental WSN is very poor because leakage points in experimental WSN are all branch pipe (the pipes after water meter). However, the average water head in WSN is more reflect water head in trunk main; Major physical losses occur at branch pipe in actual WSN. The poorer fitting effect also reflect that the equivalent leakage index model exist larger method error.

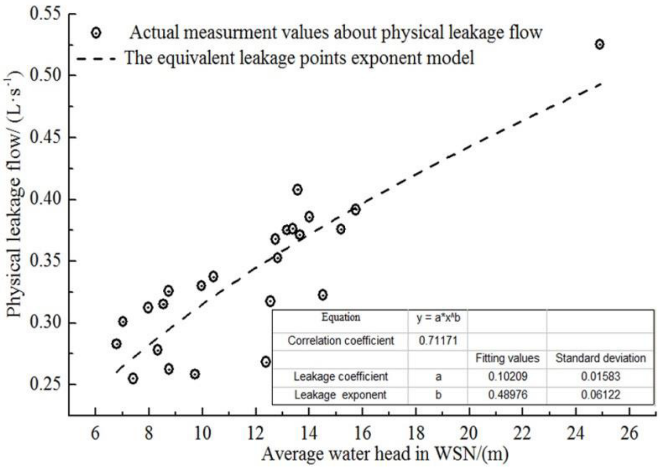

Fig. 4. The fitting by the equivalent leakage index model (series 1).

The equivalent leakage index model exist defect in practical operability and theory according to above analysis. Especially, the practical operability is difficult to meet the engineering application, therefore, pressure reduction test has meaningless effect on evaluating physical leakage flow reduction unless all consumers stop consuming water when pressure reduction test is conducted.

4.2. Evaluation after pressure management implementation

Evaluation after pressure management implementation need pressure management implementation time beyond at least the water balance analysis cycle. Evaluation can be carried out after the pressure management program can be completed and run for a certain time, therefore, it cannot provide decision support for the pressure management.

Evaluation after pressure management implementation is to calculate the difference between the physical losses volume before and after pressure reduction in order to account for the effect of pressure management; but physical losses volume error obtained by water balance analysis is larger. The error that is optimistically estimated account for over 1% of water supply volume. In addition, physical losses control in WSN sometimes conduct leaks repair and pressure management at the same time. Physical leakage reduction is the comprehensive effect between leaks repair and pressure management. Also, new leakage points always increase and leaks may be checked and repaired during pressure management implementation. If the pressure project implementation is conducted for a long time, the current physical losses may be above the physical losses before the pressure management project implementation. Therefore, the evaluation after pressure management implementation is difficult to explain that pressure management can reduce physical losses.

5. Conclusion

Pressure reduction test that evaluate physical losses reduction is meaningless unless all consumers stop consuming water when pressure reduction text is conducted. Pressure management is also hard to explain physical losses reduction through water balance analysis before and after pressure management implementation. Therefore, establishing quantification model of physical losses in WSN is necessary in order to accurately assess that the pressure management reduce physical losses.

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