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LEAKAGE CONTROL OF WATER DISTRIBUTION SYSTEM BY DROP-RESTORE PRESSURE BASED ON VISCOELASTIC MECHANISM

Jinliang Gao[1], Jianxun Chen[2], Wenyan Wu[3], Liqun Deng[4], Kunyi Li[5], Yi Yuan[6]

[1,2,5,6] School of Environment, Harbin Institute of Technology, Harbin, Heilongjiang Province, China
[3] School of Engineering and the Built Environment, Birmingham City University, Birmingham, UK
[4] Shenzhen ANSO Measurement & Control Instruments Co., Ltd., Shenzhen, China
[1] 0000-0002-6662-0187, gjl@hit.edu.cn, [2] 0000-0002-1749-5009, cjianxun877@gmail.com,
[3] 0000-0002-4823-3685, wenyan.wu@bcu.ac.uk, [4] 380317336@qq.com,
[5] 0000-0002-5444-2176, 21b929004@stu.hit.edu.cn, [6] 18292005003@163.com

Abstract

As a common method to control leakage of water distribution system, pressure management has the advantages of reducing energy consumption, reducing the possibility of explosion and avoiding the aggravation of leakage. In recent years, with the popularization of plastic pipe in the world, it is necessary to study its leakage characteristic. Our research group carried out leakage experiments on high density polyethylene (HDPE) pipe, and found that the correlation curve between leakage flow and pressure did not completely coincide in the phase of pressure boost and pressure reduction. The existing FAVAD and exponential leakage models could not explain this phenomenon, which challenges the pressure management theory dominated by a single depressing-pressure process, thus it's necessary to explore pressure management strategies suitable for plastic pipes. Based on the viscoelastic properties of plastic pipe, we established the viscoelastic leakage model and proposed the leakage control method of drop-restore pressure, and verified its feasibility in practical engineering case. The main research objectives of this paper will be firstly to describe the strain response of leakage area in the process of continuous stress application with the Boltzmann superposition principle for HDPE pipe; the Voigt-Kelvin model is used to simulate the creep behavior of viscoelastic material, and a suitable leakage model for viscoelastic pipe is proposed to provide accurate expression of the leakage under the regulation of drop-restore pressure. Secondly, the viscoelastic pipe leakage model is embedded into the pressure-driven analysis model based on non-iterative method, and the pressure-driven viscoelastic leakage model is obtained. Finally, evaluating the proposed leakage model in the practical case. With the minimum of leakage flow as the objective function, the leakage control model of drop-restore pressure is established and solved by particle swarm optimization algorithm to obtain the accurate pressure regulation scheme. After applying the scheme from the optimization, the leakage rate decreases from 37.7% to 16.8% on weekday, which is great impact on leakage control.

Keywords: Pressure management; Leakage control; Pressure-driven viscoelastic leakage model; Drop-restore pressure

1 INTRODUCTION

Pressure management is an effective method to reduce leakage and widely used by scholars and water enterprises. Global pressure reduction or local pressure reduction by using pressure reducing valves and other equipment are two commonly used methods of pressure management. The use of pressure reducing valves for pressure management is common in district metered area[1,2].

Accurate leakage model can be used to reflect the change law of leakage flow with pressure, which is helpful to estimate the benefit of leakage control measures and provide guidance for the formulation of leakage control strategies. With the constant exploration of the leakage law, the leakage model has undergone three stages: orifice outflow model, exponential model and FAVAD model. FAVAD model pays more attention to reflect the area change of leaks and improves the accuracy of leakage model. The three models all prove the positive correlation relationship between the leakage flow and pressure, which builds the foundation for leakage control through pressure reduction. However, in recent years, scholars [3,4] have found that leakage flow is not simply positively correlated with the pressure at leaks, but is affected by the pipe material and the geometry of the leaks. This challenges the conventional awareness of reducing pressure to reduce leakage.

Plastic pipe has the advantages of environmental protection, light weight and high strength, corrosion resistance, smooth inner wall without scaling, easy construction and maintenance, long service life and high cost performance. According to statistics data, from 2010 to 2012, the service length of HDPE pipes with diameter below DN600 in Shanghai accounted for 58% of the total length of commonly used pipes [5]. In recent years, the market share of plastic pipe is expanding, which also provides great impetus for the study of leakage model of plastic pipe.

In this paper, based on the leakage characteristics of HDPE pipe leaks we have studied, the concept of drop-restore pressure to control leakage is proposed. The leakage model in the process of drop-restore pressure was constructed by combining Boltzmann superposition principle and generalized Voigt-Kelvin model. Then, this model was embedded into EPANET hydraulic calculation module, and the pressure-driven leakage model based on viscoelastic theory was established to make the model simulation more close to the real operation. Combined with actual engineering cases, the water network dynamic pressure control model based on drop-restore pressure mechanism was used to calculate the pressure setting at the inlet, and verify the feasibility and effectiveness of the model based on drop-restore pressure mechanism.

2 CONCEPT OF DROP-RESTORE PRESSURE

Our research group has conducted experimental studies on three typical leaks of PE pipe: axial crack, circular leak and circumferential crack [6]. The results show that PE pipe has the following characteristics in the process of pressure boost and pressure reduction:

(1) Under the same leak shape and size, the pressure-leakage flow curve does not coincide between the pressure boost process and the reduction process;

(2) Under the same pressure, leakage flow in the pressure reduction process is higher than that in the pressure boost process;

(3) When the traditional leakage flow-pressure relationship is used to fit the experimental data, the leakage index in the pressure-boost process is generally higher than that in the pressure reduction process.

The leakage flow-pressure relationship curve of the same pressure does not coincide in the pressure boost stage and the pressure reduction stage, which means that the leakage can be reduced when the pressure operation mode is changed. The leakage can be reduced under the same operation pressure by choosing the pressure operation mode reasonably.

Taking the leakage pipe of PE pipe (DN50) with 30mm length axial crack as an example, the leakage characteristic in the process of pressure reduction and pressure boost is analysed. The experimental results are shown in Figure 1, and the conclusion could be drawn as follows:

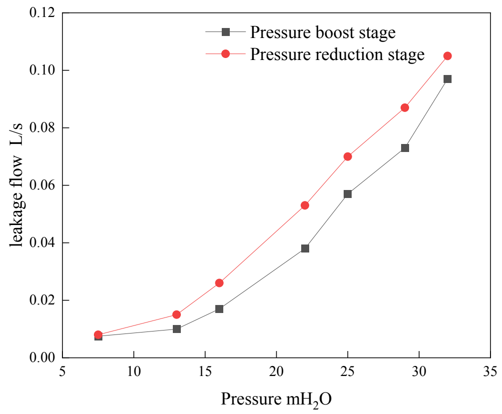


Figure 1. The relationship curve between leakage flow and pressure under pressure boost and pressure reduction stage

(1) Under the same pressure, the leakage flow in the process of pressure reduction is basically greater than that in the process of pressure boost. For example, when pressure is 21.6mH_2O, the measured leakage flow of reducing pressure process is 53.84mL/s, and the leakage flow of pressure boost is 41.57mL/s, which is 23% higher than that in the process of pressure boost.

(2) According to the exponential leakage model, the model obtained from the pressure boost process is $q = 0.003h^{2.32}$, and the model obtained from the pressure reduction process is $q = 0.143h^{1.92}$. It can be seen that the leakage index of the pressure boost process is larger and more sensitive to pressure.

Based on the analysis of the above experimental result, it can be considered that when the pressure is constant, the operating pressure can be adjusted to the initial water supply pressure by lowering the pressure first and then gradually increasing the pressure, so as to achieve the purpose of reducing leakage without changing the operation pressure. Thus, the concept of drop-restore pressure leakage control is introduced, which refers to the adjustment process of first reducing the water supply pressure and then gradually increasing the water supply pressure to the original water supply pressure to achieve the ultimate goal of reducing the leakage flow.

3 LEAKAGE MODEL CONSTRUCTION BASED ON DROP-RESTORE MECHANISM

In the water supply network, the pipe material includes steel, concrete, ductile iron and high density polyethylene material. The stress-strain relationships of the first three materials are linear viscoelasticity. However, the stress-strain relationship of high density polyethylene is viscoelastic, and the strain has a certain lag after the stress application, which is characterized by pressure, time and temperature. In order to model the leakage characteristics of high density polyethylene pipe (HDPE), we used the structural equations to represent physical phenomena that assume linear-viscoelastic behaviour, and apply the Boltzmann superposition principle to describe the change of strain with stress.

3.1 Boltzmann superposition principle

Since the change of leak area is not only related to instantaneous pressure but also to historical pressure, in order to characterize the dynamic change of leak area, Boltzmann superposition principle[7] was used to quantify the change of leak area under pressure variation in the whole process.

According to Boltzmann superposition principle: when the strain is small, the continuous stress actions can be regarded as mutually independent and the strains can be simply added linearly, shown as in equation (1):

$$\varepsilon(\mathrm{t}) = \sigma(t)J_0 + \sum_{\mathrm{i}=1}^{\mathrm{m}} J(\mathrm{t}-\tau_{\mathrm{i}})\Delta\sigma_{\mathrm{i}} \tag{1}$$

The total strain generated by continuous stress application can be expressed as:

$$\varepsilon(\mathrm{t}) = \sigma(\mathrm{t})J_0 + \int_0^{\mathrm{t}} \sigma(\mathrm{t}-\alpha)\frac{\mathrm{d}J(\alpha)}{\mathrm{d}\alpha}\mathrm{d}\alpha \tag{2}$$

where J_0 is instantaneous creep compliance(m^2/N), $\sigma(t)$is the stress at time t (N), $J(\alpha)$is the creep function and τ_{i} is the time constant.
In equation (2), the total strain corresponds to leak area, and the stress corresponds to the operating pressure of the pipe network.

3.2 Voigt-Kelvin model

Creep function is introduced into equation (2). Creep occurs in viscoelastic pipes such as polymer or metal, that is, under a constant pressure, the leak area increases gradually with time. The creep behaviour of viscoelastic pipe under operating pressure was simulated by Voigt-Kelvin model[8].

Among viscoelastic models, the standard linear body model can describe the transient elasticity and hysteresis effect of viscoelastic materials due to its simple creep function expression. In this paper, the creep compliance formula of the standard linear body is introduced:

$$J(\mathrm{t}) = J_0\left[1+\beta\left(1-\exp^{-\lambda\mathrm{t}}\right)\right] \tag{3}$$

Where, $J(\mathrm{t})$is the creep function at time t, β is constant which ranges from 0.1 to 0.9, and λ is constant which value is $0.5\mathrm{min}^{-1}$.

3.3 Construction of viscoelastic leakage model

The above application of Boltzmann superposition principle and the formula of standard wire creep flexibility present the strain in mathematical form, provide one method for the dynamic simulation of leak area.

The circumferential stress of viscoelastic pipe can be calculated by equation (4):

$$\sigma(\mathrm{t}) = \frac{P(\mathrm{t})(D_0-\mathrm{e})}{2\mathrm{e}} \tag{4}$$

Where P is the inner pressure of pipe(MPa), D_0 is exterior diameter of pipe(mm) and e is the thickness of pipe wall(mm).

Substituting equation (3) and equation (4) into equation (2), the total strain of viscoelastic material under ideal state can be obtained as shown in equation (5):

$$\varepsilon(\mathrm{t}) = \frac{(D_0-\mathrm{e})}{2\mathrm{e}}J_0\left[P(\mathrm{t}) + \beta\cdot\lambda\int_0^{\mathrm{t}} P(\mathrm{t}-\alpha)\exp^{-\lambda\alpha}\mathrm{d}\alpha\right] \tag{5}$$

For the actual water supply system, water pressure is in most cases discrete, so a discrete total strain formula is needed. Substituting equation (3) and equation (4) into equation (1), the follow equation (6) could be obtained.

$$\varepsilon(\mathrm{t}) = \frac{(D_0-e)}{2e}\cdot J_0\left\{P(t) + \sum_{\mathrm{i}=1}^{\mathrm{m}}(P_{\mathrm{i}}-P_{\mathrm{i}-1})\left[1+\beta\left(1-\exp^{-\lambda(\mathrm{t}-\tau_i)}\right)\right]\right\} \tag{6}$$

Where τ_i is time constant, P_{i} and $P_{\mathrm{i}-1}$ （MPa） are the pipe pressure in i period and $\mathrm{i}-1$ period, respectively.

The discrete leakage area formula (equation (8)) can be obtained by combining orifice outflow equation (shown as equation (7)) and equation (6):

$$Q = A_{\mathrm{r}} C_{\mathrm{d}} \sqrt{2\mathrm{gH}} \tag{7}$$

Where Q is leakage flow(m^3/h). A_{r} is leak area(m^2), C_{d} is leakage coefficient and H is water head of leak(mH$_2$O):

$$A_r(\mathrm{t}) = K\frac{(D_0 - e)}{2e} \cdot J_0 \left\{ P(t) + \sum_{\mathrm{i}=1}^{\mathrm{m}} (P_{\mathrm{i}} - P_{\mathrm{i}-1})\left[1 + \beta\left(1 - \exp^{-\lambda(\mathrm{t}-\tau_i)}\right)\right] \right\} \tag{8}$$

Where $A_r(\mathrm{t})$ is leak area in t period.

Substitute equation (8) into the equation (7) to obtain the discrete leakage model as equation (9).

$$Q(\mathrm{t}) = C\frac{(D_0 - e)}{2e} \cdot J_0 \left\{ P(t) + \sum_{\mathrm{i}=1}^{\mathrm{m}} (P_{\mathrm{i}} - P_{\mathrm{i}-1})\left[1 + \beta\left(1 - \exp^{-\lambda(\mathrm{t}-\tau_{\mathrm{i}})}\right)\right] \right\} \sqrt{2gH(t)} \tag{9}$$

Where $Q(\mathrm{t})$ is the leakage flow in t moment(m^3/h), $P(t)$ is the pipe pressure(MPa), C is combined coefficient, τ_{i} is time constant.

3.4 Construction of pressure drive viscoelastic leakage model

In the water network model, the diffuser of EPANET node attribute is often used to simulate leaks, and the outflow of diffuser depends on the pressure at the junction. Considering the relationship between flow rate and pressure at diffuser junction, diffuser can realize pressure driven analysis of water supply system. The generalized equation of diffuser flow is shown in equation (10):

$$q_j^{avl} = C_d\left(H_j^{avl} - H_j^{min}\right)^{\gamma}; H_j^{avl} \geq H_j^{min} \tag{10}$$

Where C_d is flow coefficient, $H_j^{avl}$and H_j^{min} are actual pressure and minimum supply pressure at junction j, respectively, and γ is one empirical value.

Based on the research of leakage control mechanism of drop-restore pressure, the research results were applied to the water supply network model. For viscoelastic pipe, it is assumed that the leakage area and strain are linearly dependent, and the pressure at the leak is equal to the operating pressure in the pipe. Based on these two assumptions, the viscoelastic leakage model (equation (9)) is embedded into the EPANET pressure-driven demand model considering the pressure boost and pressure reduction state of the pipe in the previous period.

In the existing studies, the leakage coefficient is determined by fitting the historical leakage flow and pressure data according to pressure driven demand model proposed by Wagner[9]. The circular iterative method is used to determine the leakage coefficient, and it is assumed that the leakage coefficient of every junction is equal and of a certain value, and this resolution is so imprecise. For viscoelastic materials such as HDPE, the leak area depends not only on the instantaneous pressure but also on the historical pressure. Therefore, the leak area should change dynamically with pressure, not a constant value, and the leakage coefficient is not equal at every junction.

According to equation (8) and equation (10), the expression of leakage coefficient can be obtained as follow:

$$C = \sqrt{2g} \cdot C_d \cdot K\frac{(D_0 - e)}{2e} \cdot J_0 \left\{ P(t) + \sum_{\mathrm{i}=1}^{\mathrm{m}} (P_{\mathrm{i}} - P_{\mathrm{i}-1})\left[1 + \beta\left(1 - \exp^{-\lambda(\mathrm{t}-\tau_{\mathrm{i}})}\right)\right] \right\} \tag{11}$$

Where K is the coefficient used to describe the relationship between leak area and strain, and the meanings of other symbols, see above.

It can be seen from equation (11) that the leakage coefficient is only a function of pressure and time, and other parameters can be determined according to the pipe characteristic. The leakage coefficient corresponds to the diffuser coefficient in EPANET. Assuming that leak occurs in every junction of the water supply network, the diffuser coefficient is assigned to every demand junction with the change of instantaneous pressure and historical pressure, and the average leakage flow at night on weekdays is checked to obtain the pressure-driven viscoelastic leakage model.

4 CASE STUDY

4.1 Brief introduction about Y network

Y network is selected as the case study. Y network has a single inlet, and flow and pressure sensors are installed before and after the inlet valves. The topology and basic information of the water supply network are clear. The schematic of Y network is shown as Figure 2.

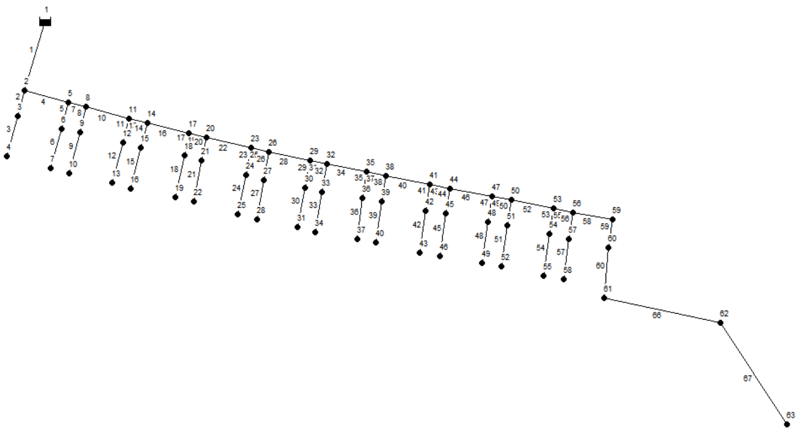


Figure 2. Schematic of Y network

The average daily inlet pressure of the network is 52.5mH_2O. In addition, the minimum night flow in this area are pretty high, which has enough potential for pressure reducing. The basic information of the network is summarized in Table 1.

Table 1. Basic information of Y network

Water supply Sevice area/m^2	Diameter/mm	Length/m	Pipe material
25,000	DN100	433	HDPE
	DN50	418	
Amount of costumers	Highest floor	Number of junctions	Number of pipes
210	5	62	62

Before regulating pressure, the total flow of inlet of Y network within one week was analysed, as shown in Figure 3. There are some differences in water consumption patterns during the week, and the patterns from Monday to Friday are very similar, with the peak of water consumption occurring at 8h and 22h. The pattern of water consumption on Saturday and Saturday is similar, and is significantly different from that on weekdays. The peak of water consumption occurs at 11h and 20h, respectively.

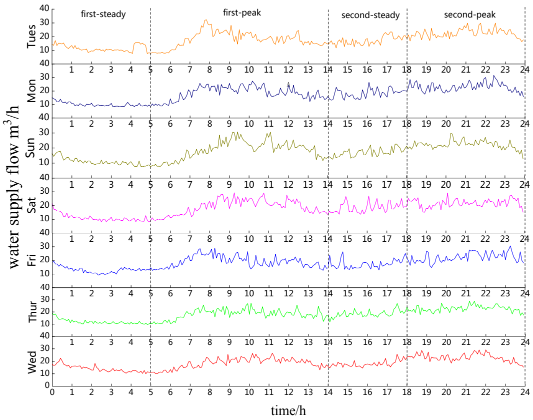


Figure 3. Analysis of weekly water consumption

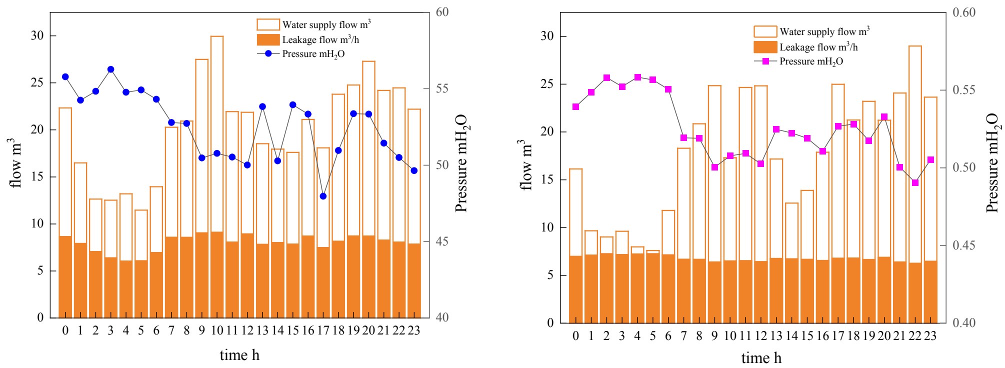
4.2 Minimum night flow analysis

Analysing the flow change of the total meter at the entrance of Y network within a week, the minimum night flow occurs during 2h to 5h at night. Using the minimum night flow during this period to estimate the leakage level. The legal water consumption at night of 1.7L/household/h is adopted, and the difference between the minimum night flow and the legal water consumption at night is used as the leakage flow.

The exponential leakage model (equation (12)) was used to quantify the relationship between inlet pressure and total leakage flow, the leakage index of 1.15 was adopted. According to the change of the inlet pressure of Y network at every hour on Friday and Saturday, the leakage flow of the two days was estimated. The results are shown in Figure 4.

$$Q_l = \alpha H^{\beta} \tag{12}$$

Where, Q_l is leakage flow (m^3/h), α is leakage coefficient, β is leakage exponent, H is the pressure at leaks(mH_2O), α and β could be determined by the minimum night flow and the pressure at that moment.



(a) *Friday* (b) *Saturday*

Figure 4. Variation of leakage flow, total water supply flow, inlet pressure with time on Friday and Saturday

On both Fridays and Saturdays, the leakage rate was nearly 40%. Since the ground elevation of the Y network is relatively flat, considering the service floor height of the most critical node, the working pressure of water appliances and the head loss of the pipes, the water supply pressure at the entrance of the pipe network can meet the demand of water users by reaching 35mH_2O. The actual water supply pressure is as high as 50mH_2O, and the high pressure is the main reason for the high leakage rate.

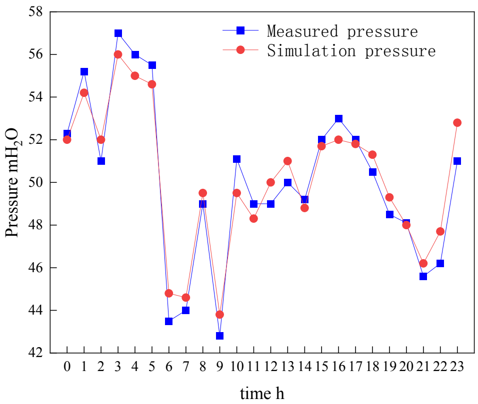
4.3 Construction of leakage model

Collecting and organizing the static information and operation data of the Y network, and build a pressure-driven viscoelastic leakage model based on the water consumption data within a week and 1h as the calculation step. Since all the pipes are PE pipes, the parameter setting are as follows: $J_0 = 8.5\times10^{-3}$ (1/MPa), $\beta = 0.5$, $\lambda = 0.5$.

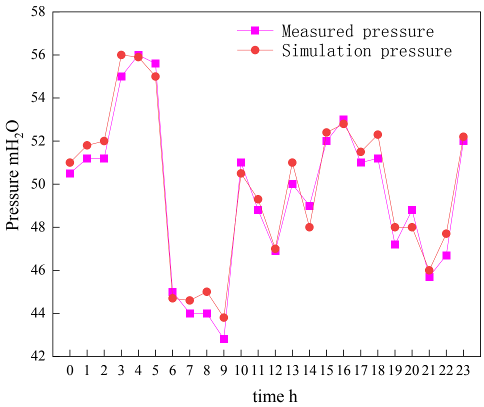
In order to decrease the difference between hydraulic model and actual operation of the Y network, the critical node 63 is selected as the pressure checking point. The pressure gauges was installed at 63 node (shown as Figure 5) to check the accuracy of the hydraulic model by comparing the calculated pressure with the measured pressure.

Figure 5. Pressure gauge installation at critical node

The operating data of Friday and Saturday were selected as the foundation for verification. The accuracy of the model was verified by comparing the calculated with the estimated leakage flow in Figure 4. The variation of measured and simulate calculated pressure value with time at the critical point on Friday and Saturday are shown in Figure 6.



(a) *Comparison of pressure on Friday*



(b) Comparison of pressure on Saturday

Figure 6. Comparison of measured and simulate pressure at the critical node

According to the analysis of Figure 6, the pressure fluctuation on working days is larger than that on weekend. The absolute error between the calculated and the measured pressure is within 5%. The error is very small, and the calculated total leakage volume of the whole day are 155 m^3 and 180 m^3, which are very close to the actual estimated leakage volume. So the accuracy of the established pressure-driven viscoelastic leakage model meets the application requirements and can be used for subsequent analysis.

4.4 Solution of drop-restore pressure leak model

Since the actual water supply in the Y network changes constantly and the pressure also changes hourly, in order to maximize the effect of drop-restore pressure leakage control, it is necessary to optimize the relationship between pressure regulation strategy and hourly water supply scheduling. On the premise of meeting the user's demand, find the best inlet pressure setting value.

In the optimization process, pressure setting of inlet valve every hour were set as the decision variables, the minimum leakage flow was set as the objective function (shown as equation (13)) and the minimum pressure demand at critical node was set as constraint conditions. The particle swarm optimization (PSO) algorithm was used to solve the optimal pressure regulation strategy at the entrance of the Y network and particle is the hourly inlet pressure set value, the particle fitness is the total leakage flow of the network throughout the day.

$$\min\sum_{i=1}^{n}\sum_{j=1}^{m} Q_{ij}=\min\sum_{i=1}^{n}\sum_{j=1}^{m} C\frac{(D_0\text{-}e)}{2e}\cdot J_0\left\{P_j+\sum_{t=1}^{j}(P_t\text{-}P_{t\text{-}1})\left[1+\beta\left(1\text{-}\exp^{-\lambda(t\text{-}\tau_t)}\right)\right]\right\}\sqrt{2gH_j} \qquad (13)$$

Where, n is the number of junction, m is the total period to simulate, Q_{ij} is the leakage flow of j period at i junction (m^3/h), P_j is the pressure at j period (MPa), C is the coefficient, τ_i is time constant at j period, D_0 is the exterior diameter of pipe (mm), e is the thickness of pipe wall, J_o is the instantaneous creep compliance (m^2/N).

Due to the difference in water consumption patterns between weekdays and weekends of the Y network, the field experiment was conducted on Friday and Saturday of the next week in order to verify the leakage control effect of drop-restore pressure regulation. The pressure regulation strategy adopts the fixed outlet pressure control and the time-modulated pressure control, and the operation mode introduces the drop-restore pressure mode.

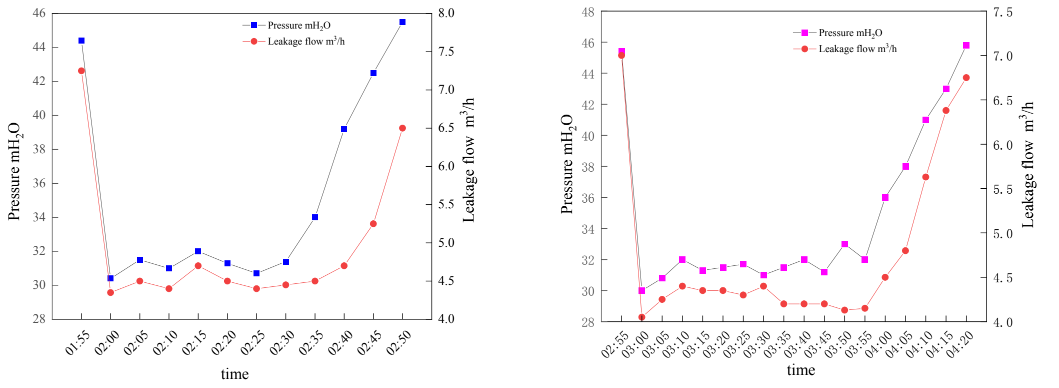
According to the analysis of the water consumption pattern of the Y network, there is still a small amount of water is used at night on weekdays, which is difficult to reflect the actual leakage situation. From 2:00 to 5:00 in the morning on Friday, the drop-restore pressure method is used for pressure regulation, and the outlet pressure is fixed for the rest of the period. For Saturday, the optimal pressure value of each time period is obtained according to the solution of the drop-restore pressure leakage control model. Considering that the inlet valve of Y network is an ordinary valve, which is difficult to be adjusted frequently and accurately, detailed pressure regulation strategy is formulated according to the pressure comfort required by historical records, as shown in Table2.

Table 2 Pressure regulation scheme on Friday and Saturday

Date	time	Pressure setting/mH_2O	time	Pressure setting/mH_2O
Friday	0:00	45.00	4:30-4:59	45.00
	0:00-1:59	45.00	5:00-5:05	35.00
	2:00	30.00	5:05-5:29	35.00
	2:00-2:29	30.00	5:30-5:40	40.00
	2:30	30.00	5:40-14:29	40.00
	2:30-2:49	45.00	14:30-14:40	30.00
	2:50-3:29	45.00	14:40-15:00	30.00
	3:30	45.00	15:00-15:30	40.00
	3:30-3:59	30.00	15:30-17:00	40.00
	4:00	30.00	17:00-17:10	45.00
	4:00-4:30	30.00	17:10-23:59	45.00
Saturday	0:00-1:59	45.00	14:30-17:29	35.00
	2:00-5:29	35.00	17:30-11:59	45.00
	5:30-14:29	45.00		

4.5 Effectiveness verification of leak control scheme

The effect of drop-restore pressure leakage control method is verified according to the filed measured results obtained after the pressure regulation strategy was carried out. During the period of 2:00-5:00 on Friday morning, the user's water consumption is relatively small and could be neglected, and the total water supply flow is approximately regarded as the leakage flow. Figure 7 shows the changes of pressure and leakage flow after the drop-restore pressure strategy is carried out at 2:00-3:00(Figure 7(a)) and 3:00-4:00(Figure 7(b)) respectively.



(a) 2:00-3:00 *(b) 3:00-4:00*

Figure 7. Variation of pressure and leakage flow with time

It can be seen intuitively from Figure 7 that the drop-restore pressure can rapidly and greatly reduce the leakage flow. When the water pressure slowly rises to 38m, the leakage flow still maintains a low value, and then increases rapidly. This verifies the operation mechanism of the drop-restore pressure: due to the lag effect in viscoelastic properties, the change of the leak area occurs behind the change of water pressure. Combined with Figure 7(b), in the process of water pressure rising slowly, the hysteresis effect is not obvious. The reason is that when a certain status is continued for too long after the pressure reduction, the control effect of the drop-restore pressure control strategy will be reduced.

Figure 8 shows the relationship between inlet pressure and leakage flow during the process of pressure reduction from 45mH_2O to 30mH_2O and then quickly returning to 45mH_2O: under the same condition, the relationship curves in the process of pressure-reduction and pressure boost are not coincidence. And the leakage in the pressure reduction stage is always greater than that in the pressure boost stage. The viscoelasticity theory is used to explain the phenomenon: when the operating pressure changes, the change of the leak area always lags behind the pressure, so under the same conditions, the corresponding leak area of pressure reduction is always larger than that of the pressure boost, that is, the leakage flow in the pressure reduction stage is more than that in the pressure boost stage under the same pressure. This abnormal phenomenon is reproduced in the actual network again, and it is verified that in the actual water supply network, the lag effect caused by the viscoelastic properties of the polymer pipe is still obvious.

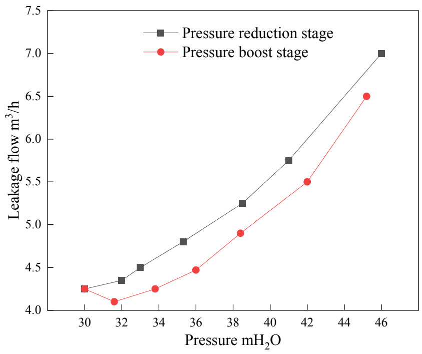
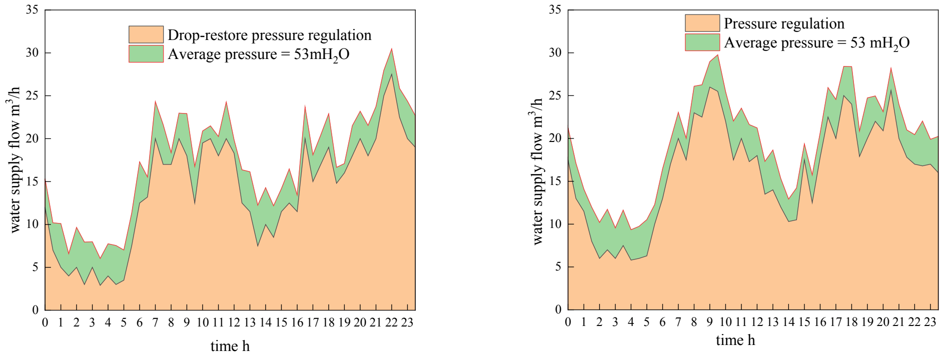


Figure 8. Relationship between pressure and leakage flow

under drop-restore pressure operation

Since the small fluctuation of daily water consumption in the Y network, the operation data of Friday and Saturday and the measured data after the implementation of the pressure control strategy represent the water consumption rule of the pipe network, which are used to evaluate the effect of the pressure regulation strategy. Figure 9 shows the changes of the inlet flowmeter before and after the implementation of the pressure regulation scheme on Friday and Saturday.



(a) Friday *(b) Saturday*

Figure 9. Effect verification of pressure regulation

Comparing the changes in water supply flow before and after the pressure regulation, it can be clearly seen that the total water supply flow has decreased significantly, indicating that the drop-restore pressure regulation has a significant effect on leakage level of Y network. And the most obvious reduction in the water supply flow is between 2:00 and 5:00 in the morning. The benefit evaluation after pressure regulation is shown in Table 3.

Table 3. Benefit evaluation after pressure regulation

Stage	Item	Weekday	Weekend
Before pressure regulation (average pressure = 53.00mH$_2$O)	Daily water consumption (m^3)	431.45	485.09
	Daily leakage volume (m^3)	162.58	191.72
	Daily leakage rate (%)	37.7	39.5
After pressure regulation	Daily water consumption (m^3)	323.45	389.09
	Daily leakage volume (m^3)	54.48	95.72
	Daily leakage rate (%)	16.8	24.6
Decrement of daily leakage rate (%)		20.9	14.9
Estimation of monthly water saving (m^3)		2760	

After the pressure regulation, the leakage flow of the Y network has been significantly reduced. The leakage rate on weekdays is reduced from 37.7% to 16.8%, reduced by 20.9% and the weekend leakage rate reduced from 39.5% to 24.6%, reduced by 14.9% and the leakage rate of weekday is further reduced compared with the weekend. The simulation results of the analysis model and the measured pressure at the critical node show that when the inlet pressure is set to 40.00mH$_2$O, the pressure at the critical node can still meet the user's water demand during the peak water consumption period. After adopting the pressure regulation scheme, it is estimated that the monthly water-saving amount can reach 2,760m^3, and it is conservatively estimated that the annual saving of water supply enterprises is more than 100,000 yuan, and the economic benefits brought by pressure management are considerable.

5 CONCLUSION

In this paper, the relationship between the leakage and pressure of polymer pipes is quantitatively described by the Boltzmann superposition principle and the Voigt-Kelvin model, and a pressure-driven viscoelastic leakage model is constructed. Based on the basic information of the Y network, a hydraulic model based on the pressure-driven viscoelastic leakage model is constructed, and the optimal pressure regulation strategy is solved by the particle swarm algorithm with minimizing the leakage amount as the objective function. After the implementation of the pressure regulation strategy, it is estimated that the annual cost of water supply can be saved by 100,000 yuan, which proves that the proposed method of drop-restore pressure leakage control has widely application prospects.

In this paper, the analysis process of the Y network can be used as a reference for formulating pressure control strategies for other networks containing plastic. Drop-restore pressure leakage control is suitable for water supply areas with high water supply pressure (such as close to the water plant) and high leakage rate; Before carrying out pressure management, it is necessary to analyse the basic information of the field network and the pattern of water use to determine whether it is suitable for pressure management, and then conduct dynamic simulation through the hydraulic model to scientifically guide the field pressure control scientifically.

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