Analysis on Hydraulic Calculation of Pipelines in Automatic Sprinkler Systems

Xun Liu\textsuperscript{a*}, Jing xian Shi\textsuperscript{b*}, Jing Meng\textsuperscript{c}

\textsuperscript{1}Oxford College, Kunming University of Science and Technology, Kunming, Yunnan, 650106, China
\textsuperscript{a*}908576195@qq.com, \textsuperscript{b*}756904468@qq.com, \textsuperscript{c}44898965@qq.com

Abstract—This paper discusses the hydraulic calculation of automatic sprinkler systems in the following aspects: hydraulic calculations respectively in accordance with the GB50084-2001(2005 edition) and the GB50084-2017 and their comparison. Through the comparison, it’s found there is little difference between the results of hydraulic calculations with the flow rate of sprinklers calculated based on their actual pressure or with the flow rate of each sprinkler as a fixed value. To simplify the calculation, it is recommended to use a fixed value for calculation.

1. Introduction
The Code for Design of Sprinkler Systems GB50084-2017 (hereinafter referred to as the new Code) came into force on January 1, 2018, which is inevitable for the progress of the times. The Code for Design of Sprinkler Systems GB50084-2001(2005 edition) (hereinafter referred to as the old Code) was formulated in 2005. With the development for over ten years, China shows a trend of increasing high-rise buildings, massive building complexes and large-space buildings, resulting in higher fire risks. Meanwhile, the sprinkler production technology is developing rapidly towards quick response, specialization, large flow, large water droplets and large diameter. Major adjustments have been made to China's fire protection design codes since 2014. The Code for Fire Protection Design of Buildings GB50016-2014 that combines the Code for Fire Protection Design of Buildings and the Code for Fire Protection Design of Tall Buildings, and the Technical Code for Fire Water Supply and Hydrant System GB50974-2014, etc., were formulated. In this context, the new Code came into being.

The new Code strives to be in line with new technologies and international standards, changing the pattern of the old Code which is in line with the Soviet Union and showing the clue of being in line with western countries in Europe and America.

2. Hydraulic calculation of pipelines in the old Code

2.1 Head loss of pipelines

2.1.1 Calculation formula of head loss
Shievicielev formula is used for the calculation of head loss of each meter of pipelines in the old Code\textsuperscript{(1)}:
\[ i = 0.00107 \frac{V^2}{d_j^{1.3}} \quad \text{or} \quad i = 0.001736 \frac{Q^2}{d_j^{3.3}} \quad (1) \]

Where, \( i \) is the head loss of each meter of pipelines (mH2O/m), \( Q \) is the flow rate (m3/s), \( V \) is the flow velocity (m/s), \( d_j \) is the inner diameter of pipelines (mm).

Table 1 Inner diameters for calculation used during compilation of the hydraulic calculation sheet for steel and cast iron pipes\(^2\)

| Nominal diameter DN (mm) | Inner diameter \( d_j \) for calculation (mm) |
|-------------------------|---------------------------------------------|
| 25                      | 26                                          |
| 32                      | 34.75                                       |
| 40                      | 40                                          |
| 50                      | 52                                          |

In 1953, Shievieliev put forward the empirical formula according to his tests on old cast iron and steel pipes. Therefore, it is mainly applicable to old cast iron and steel pipes. It is also used to keep consistency with the calculation formula of head loss adopted in the original Code for Design of Building Water Supply and Drainage GBJ15-88.

2.1.2 Example of head loss calculation

Head loss is calculated with the arrangement of sprinklers in places at medium risk level I as an example.

![Fig.1 Hydraulic Calculation](image)

According to formula 9.1.1 in the old Code, the sprinkling rate of sprinkler 1 at the most unfavorable point is \( q = K \sqrt{10P} = 80\sqrt{10 \times 0.1} = 80 \text{L/min} = 1.33 \text{L/s} \).

According to Shievieliev formula \( i = 0.001736 \frac{Q^2}{d_j^{3.3}} \), the head loss of section 1–2 in the figure is

\[ i = 0.001736 \frac{(1.33 \times 10^{-3})^2}{(26 \times 10^{-3})^{3.3}} = 1.023 \text{mH2O/m}, \]

The head loss is 1.023\times3.2=3.27mH2O=0.032MPa.

The sprinkling rate of sprinkler 2 is \( q = K \sqrt{10P} = 80\sqrt{10 \times (0.1 + 0.032)} = 1.53 \text{L/s} \).

The head loss of section 2–3 in the figure is

\[ i = 0.001736 \frac{(2.86 \times 10^{-3})^2}{(34.75 \times 10^{-3})^{3.3}} = 0.78 \text{mH2O/m}, \]

The head loss is 0.78\times3.2=2.52mH2O=0.025MPa.
The sprinkling rate of sprinkler 3 is  \( q = K \sqrt{10P} = 80 \sqrt{10 \times (0.132 + 0.025)} = 1.67 \text{L/s} \).

The head loss of section 3~4 in the figure is

\[
i = 0.001736 \left( \frac{4.53 \times 10^{-3}}{34.75 \times 10^{-3}} \right)^{3/2} = 1.98 \text{mH}_2\text{O/m},
\]

The head loss is 1.98 \times 3.2 = 6.33 \text{mH}_2\text{O} = 0.063 \text{MPa}

The sprinkling rate of sprinkler 4 is  \( q = K \sqrt{10P} = 80 \sqrt{10 \times (0.157 + 0.063)} = 1.98 \text{L/s} \).

The head loss of section 4~5 in the figure is

\[
i = 0.001736 \left( \frac{6.51 \times 10^{-3}}{40 \times 10^{-3}} \right)^{3/2} = 1.94 \text{mH}_2\text{O/m},
\]

The head loss is 1.94 \times 3.2 = 6.19 \text{mH}_2\text{O} = 0.062 \text{MPa}

The sprinkling rate of sprinkler 5 is  \( q = K \sqrt{10P} = 80 \sqrt{10 \times (0.22 + 0.062)} = 2.24 \text{L/s} \).

The head loss of section 5~6 in the figure is

\[
i = 0.001736 \left( \frac{8.74 \times 10^{-3}}{52 \times 10^{-3}} \right)^{3/2} = 0.85 \text{mH}_2\text{O/m},
\]

The head loss is 0.85 \times 3.2 = 2.72 \text{mH}_2\text{O} = 0.027 \text{MPa}

Sprinkler 6 is outside the operation area. The head loss of section 6~7 in the figure is

\[
i = 0.001736 \left( \frac{8.74 \times 10^{-3}}{50 \times 10^{-3}} \right)^{3/2} = 0.85 \text{mH}_2\text{O/m},
\]

The head loss is 0.85 \times 1.6 = 1.36 \text{mH}_2\text{O} = 0.013 \text{MPa}

Table 2 shows the hydraulic calculation of sections 1 ~ 7:

| Section | Sprinkler (Nos.) | Flow rate (L/s) | Pipe diameter (mm) | Pipe length (m) | Head loss of section (MPa) | Node pressure (MPa) |
|---------|------------------|-----------------|--------------------|-----------------|---------------------------|---------------------|
| 1~2     | 1                | 1.33            | 25                 | 3.2             | 0.032                     | 0.1                 |
| 2~3     | 2                | 2.86            | 32                 | 3.2             | 0.025                     | 0.132               |
| 3~4     | 3                | 4.53            | 32                 | 3.2             | 0.063                     | 0.157               |
| 4~5     | 4                | 6.51            | 40                 | 3.2             | 0.062                     | 0.22                |
| 5~6     | 5                | 8.74            | 50                 | 3.2             | 0.027                     | 0.282               |
| 6~7     | 6                | 8.74            | 50                 | 1.6             | 0.013                     | 0.31                |
| 7       |                  |                 |                    |                 | \( \Sigma 0.22 \)          | 0.32                |

In the hydraulic calculation herein, the flow rate of sprinklers is calculated based on their actual pressure and the pressure at node 7 is 0.32 MPa. In the Building Water Supply and Drainage Engineering (edited by Wang Zengzhang), the flow rate of each sprinkler is calculated as 1.33 L/s and the pressure at node 7 is 0.29 MPa. There is little difference between the calculation results of the two methods. To simplify the calculation, it is more convenient to use the method specified in the Building Water Supply and Drainage Engineering (edited by Wang Zengzhang), which has little influence on design results.

2.2 Local head loss of pipelines

Local head loss of pipelines should be calculated with the equivalent length method. In the design work, 20% of the frictional head loss is generally used and the head loss of wet alarm valves and water flow indicators is 0.02 MPa.

2.3 Pump head or water supply pressure at system inlet

\[
H = \Sigma h + P_0 + Z \tag{2}
\]
Where, $H$ is the pump head or water supply pressure at the system inlet (MPa); $\Sigma h$ is the cumulative value of frictional and local head loss of pipelines (MPa), which is 0.04 MPa for wet alarm valves, 0.07 MPa for deluge alarm valves and 0.02 MPa for water flow indicators; $P_0$ is the working pressure of the sprinkler at the most unfavorable point (MPa); $Z$ is the difference of elevation between the sprinkler at the most unfavorable point and the lowest water level of the fire pool or the horizontal centerline of the pipe at the system inlet (MPa).

3. Hydraulic calculation of pipelines in the new Code

3.1 Head loss of pipelines

3.1.1 Calculation formula of head loss

Hazen-Williams formula is used for the calculation of head loss of each meter of pipelines in the new Code, i.e.\(^{(2)}\).

\[
 i = 6.05 \left( \frac{d_j^{1.85}}{C_h^{1.85} d_j^{4.87}} \right) \times 10^7 \quad (3)
\]

Where, $i$ is the head loss of pipelines per unit of length (kPa/m); $d_j$ is the inner diameter of pipelines for calculation (mm); $q_g$ is the design flow rate of pipelines (L/min); $C_h$ is the Hazen-Williams coefficient.

Reasons for the use of Hazen-Williams formula in the new Code include:

1) The formula is adopted to keep consistency with the calculation formula of head loss used in the current Chinese national standards - the Code for Design of Building Water Supply and Drainage GB 50015 and the Code for Design of Outdoor Water Supply Engineering GB 50013.

2) Hazen-Williams formula applies to various pipes, while Shieveliev formula is mainly applicable to old cast iron and steel pipes.

3) Hazen-Williams formula is adopted in the code for automatic sprinkler systems in Britain, America, Japan, Germany and other countries. The use of the formula in the new Code manifests the original intention to keep the new Code in line with international standards.

| Pipeline type                                      | $C_h$ |
|---------------------------------------------------|-------|
| Galvanized steel pipes                            | 120   |
| Copper and stainless steel pipes                  | 140   |
| Coated steel pipes and chlorinated polyvinyl chloride pipes | 150   |

3.1.2 Example of head loss calculation

Head loss is also calculated with the arrangement of sprinklers in places at medium risk level I as an example.

Fig.2 Hydraulic Calculation
According to formula 9.1.1 in the new Code, the sprinkling rate of sprinkler 1 at the most unfavorable point is \( q = K \sqrt{10P} = 80 \sqrt{10 \times 0.1} = 80 \text{L/min} \).

The calculation is made based on Hazen-Williams formula \( i = 6.05 \left( \frac{q^{1.85}}{C_h^{1.85} q_j^{1.85}} \right) \times 10^7 \) with galvanized steel pipes as an example. Hazen-Williams coefficient \( C_h \) is valued as 120. The head loss of section 1~2 in the figure is

\[
q = 84.7 \text{L/min}.
\]

The head loss is 3.67×3.2=11.74KPa.

The sprinkling rate of sprinkler 2 is \( q = K \sqrt{10P} = 80 \sqrt{10 \times (0.1 + 0.012)} = 84.7 \text{L/min} \).

The head loss of section 2~3 in the figure is

\[
q = 88.7 \text{L/min}.
\]

The head loss is 7.54×3.2=24.13KPa.

The sprinkling rate of sprinkler 3 is \( q = K \sqrt{10P} = 80 \sqrt{10 \times (0.112 + 0.011)} = 88.7 \text{L/min} \).

The head loss of section 3~4 in the figure is

\[
q = 96.7 \text{L/min}.
\]

The head loss is 6.91×3.2=22.11KPa.

The sprinkling rate of sprinkler 4 is \( q = K \sqrt{10P} = 80 \sqrt{10 \times (0.122 + 0.024)} = 96.7 \text{L/min} \).

The head loss of section 4~5 in the figure is

\[
q = 103.7 \text{L/min}.
\]

The head loss is 3.11×3.2=9.96KPa.

Sprinkler 6 is outside the operation area. The head loss of section 6~7 in the figure is 3.11×1.6=4.98KPa.

Table-4 shows the hydraulic calculation of sections 1 ~ 7:
Table 4 Hydraulic calculation of sections 1 ~ 7

| Section | Sprinkler (Nos.) | Flow rate (L/min) | Pipe diameter (mm) | i (KPa) | Pipe length (m) | Head loss of section (KPa) | Node pressure (MPa) |
|---------|------------------|-------------------|-------------------|---------|----------------|---------------------------|-------------------|
| 1~2     | 1                | 80                | 25                | 3.67    | 3.2            | 11.74                     | 0.1               |
| 2~3     | 2                | 164.7             | 32                | 3.4     | 3.2            | 10.88                     | 0.112             |
| 3~4     | 3                | 253.4             | 32                | 7.54    | 3.2            | 24.13                     | 0.122             |
| 4~5     | 4                | 350.1             | 40                | 6.91    | 3.2            | 22.11                     | 0.144             |
| 5~6     | 5                | 453.8             | 50                | 3.11    | 3.2            | 9.96                      | 0.166             |
| 6~7     | 6                | 453.8             | 50                | 0.85    | 1.6            | 4.98                      | 0.18              |
| 7       |                  |                   |                   |         |                | Σ83.8                     | 0.19              |

3.2 Local head loss of pipelines
The calculation of local head loss of pipelines in the new Code is the same as that in the old Code.

3.3 Pump head or water supply pressure at system inlet

$$H = (1.20 \sim 1.40) \Sigma P_p + P_0 + Z - hc$$  \quad (4)

Where, H is the pump head or water supply pressure at the system inlet (MPa); ΣPp is the cumulative value of frictional and local head loss of pipelines (MPa). The local head loss of alarm valves shall be determined according to product sample or test data. When the data above is not available, the value is set as 0.04 MPa for wet alarm valves, 0.02 MPa for dry alarm valves, 0.08 MPa for pre-action devices, 0.07 MPa for deluge alarm valves and 0.02 MPa for water flow indicators; P0 is the working pressure of the sprinkler at the most unfavorable point (MPa); Z is the difference of elevation between the sprinkler at the most unfavorable point and the lowest water level of the fire pool or the horizontal centerline of the pipe at the system inlet (MPa). Z shall be a negative value (MPa) when the pipe at the system inlet or the lowest water level of the fire pool is higher than the sprinkler at the most unfavorable point; hc is the lowest water pressure of the urban pipe network when pumping water directly from the municipal pipe network (MPa); hc is valued as 0 when water is drawn from the fire pool.

4. Comparison of hydraulic calculations in the new Code and the old Code

4.1 Comparison of head loss calculation of pipelines
To compare the calculation results of Shievieliev and Hazen -Williams formulas, the ratio k1 of calculation results of the two formulas is between 1.1292 and 1.8217 for ordinary steel pipes with diameters of 25 mm ~ 200 mm and flow velocities of 2.5 m/s ~ 10 m/s under the new Code.

The calculated pressure at point "7" in the figure is 0.32 MPa under the old Code and 0.19 MPa under the new Code under the same design conditions. Their ratio is 0.32/0.19=1.68, between 1.1292 and 1.8217. The calculation results herein are conforming.

4.2 Pump head or water supply pressure at system inlet
The following characteristics of the new Code and the old Code are presented in the calculation of pump head or water supply pressure at the system inlet:

1) Consideration is given to the safety factor of 1.2 ~ 1.4 in the calculation of frictional and local head loss of pipelines in the new Code;

2) The new Code fully considers various working conditions of automatic sprinkler systems and supplements that the minimum water pressure of the urban pipe network shall be considered when
water is directly pumped from the municipal pipe network, which is more in line with the requirements of energy-saving design and realizes maximum utilization of resources;

(3) The value of head loss of pre-action devices is supplemented in the new Code.

5. Conclusions
The following conclusions are drawn through the calculation of sprinkler branches under the same design conditions by Shievieliev and Hazen-Williams formulas:

(1) There is little difference between the results of hydraulic calculations with the flow rate of sprinklers calculated based on their actual pressure or with the flow rate of each sprinkler as a fixed value. To simplify the calculation, it is recommended to use a fixed value for calculation.

(2) The ratio of calculated values of head loss of ordinary steel pipes under the old Code and the new Code is between 1.1292 and 1.8217.

(3) Hazen-Williams formula adopted for the calculation of head loss in the new Code is widely applied in western countries such as Europe and America, which also indicates that the fire protection system technology in China will be in line with Europe and America in the future.

(4) The design conditions involved in the pressure calculation of automatic sprinkler systems in the new Code are more comprehensive and considered more carefully.

References
[1] Ministry of Public Security of the People's Republic of China, (2005) Code for Design of Sprinkler Systems GB50084-2001 (2005 edition), Beijing: [S] China Planning Press. 31, 111.
[2] Wang Zhaocai, edit-in-chief, (2011) Common Information [S], China Architecture & Building Press. 42.
[3] Ministry of Public Security of the People's Republic of China, (2017) Code for Design of Sprinkler Systems GB50084-2017 [S], Beijing: China Planning Press. 40, 134.
[4] Wang Zengzhang, editor-in-chief. (2010) Building Water Supply and Drainage Engineering [S], 6th edition, China Architecture & Building Press. 39.