Effectiveness of Friction Loss Calculation Used for Water Mist Fire Extinguishing System on Marine Vessels

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Abstract

Nowadays, Water Mist Fire Extinguishing System is increasingly used in maritime field for various application. The fire extinguishing capability of the system should be verified by hydraulic calculation in the same manner as the conventional water based fire extinguishing system such as sprinkler system, water spray system, etc. Additionally, the review of effectiveness of friction loss calculation method used for hydraulic calculation is needed because the pipe flow characteristic of its piping system has higher Reynolds number than that of the conventional system. In this paper, the review work was carried out based on the NFPA Code 750.

1. Introduction

Traditionally, Halon or Carbon Dioxide (CO_2) fire extinguishing system has been commonly used in ship's machinery spaces. With the phase-out of Halon and the increasing safety concerns regarding the use of CO_2, the need for alternative extinguishing agents has emerged. The developments during the 1990s have shown that "Water Mist Fire Extinguishing System"(hereinafter refer to as "Water Mist System") has the potential to replace, or to provide an alternative to, traditional fire protection systems. Water has many advantages as a fire extinguishing agent; it is inexpensive, non-toxic, and safe for personnel and does not represent a risk to the external environment. [1]

In order to install the water mist system that has passed fire test procedure on board a ship, either administration or recognized organization must give out its assurance of the system's conformity to the design criteria through the fire test. In this regard, the hydraulic calculation is the best way of assuring the verification of the system's fire extinguishing capability as the reproduction of real fire scenario is not practical.

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The design criteria of water mist system are composed of the operating pressure at nozzles which is generally verified by hydraulic calculation and the arrangement of nozzles. Hydraulic calculation calculates the flux and the pressure in each pipe and nozzle, and the pipe network analysis technique is used here to calculate the flow distribution by calculating the energy balance at hydraulic junction points. For accurate calculation of flow distribution, hydraulic calculation standard among many pipe network analysis techniques is required to precisely figure out the flow energy loss.

The two major causes of flow energy loss are the friction loss of straight pipe and the minor loss of pipe fittings and valves. The former loss applies Darcy-Weisbach equation and Hazen-Williams equation, while the latter loss is computed experimentally, based on the fixed values of international standard.

At present, as a hydraulic calculation standard, NFPA CODE 750 “Standard on Water Mist Fire Protection System” is widely used. However, this standard has three problems as follows:

- Friction loss of straight pipe
- Minor loss of pipe fittings and valves
- Convergence condition for iterative calculation

In this paper, therefore, the hydraulic calculation standard for water mist system based on NFPA Code 750 is examined.

2. Introduction of Maritime Application

In maritime field, the water mist system is gradually being used these days. The use of water mist system as total flooding fire extinguishing system for machinery space and accommodation space is permitted in accordance with “International Convention of Safety of Life at Sea(SOLAS)” of International Maritime Organization(IMO).

And, water mist system should be installed in machinery space as local application fire extinguishing system in accordance with the requirements of SOLAS. The local application system is used for primary stage of fire suppression and should be installed on the equipment with high fire risk where ignition source(e.g. hot surface, naked flame, etc.) can be in contact with the flammable material(fuel oil, lubrication oil, etc.). For this purpose, IMO has developed the approval standards and fire test procedure for individual application of water mist system.[2],[3],[4],[5],[6]

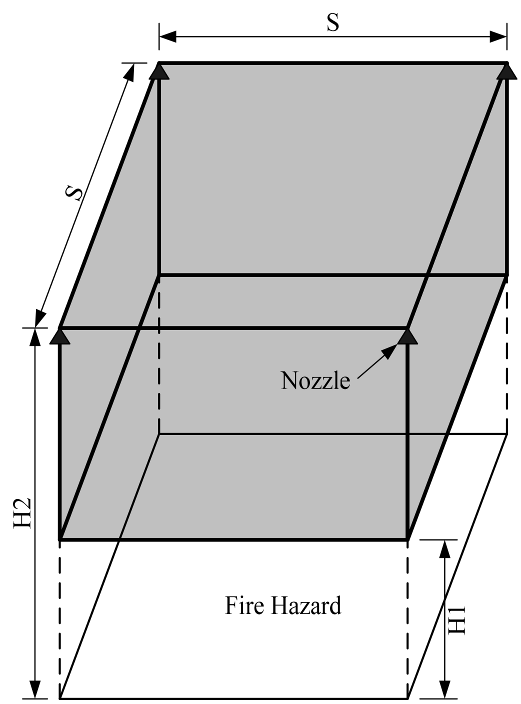

Fig. 1 Concept of design criteria for local application system for ship’s machinery spaces

For reference, the concept of design criteria for local application system is introduced in this paper. The fire test procedure for water mist system which is used as local application system is provided in MSC/Circ.913. According to MSC/Circ.913, the fire test procedure require 1MW and 6MW spray fire test with marine diesel oil. The tested system should be able to extinguish each fire scenario and the re-ignition is not permitted. Through the fire test, three parameters of the tested system was defined as follows:

- Horizontal spacing of nozzles ("S" in Fig. 1)
- Maximum and minimum vertical distance from fire hazard ("H1" & "H2" in Fig. 1)
- Maximum & minimum operating pressure at nozzle.

The parameters which are proven through the fire test should be used as the design criteria of local application system. Additionally, MSC/Circ.668/728 and Res.A.800(19) show the fire test procedure for the water mist system used as total flooding system of ship's machinery spaces and accommodation spaces. These test procedures involve more complex fire scenarios than the procedure for local application system. Referenced IMO circulars should be referred to for more detailed information.

Furthermore, the new fire test procedure is continually under development now because the only parameter used to measure the performance of water mist system is the fire extinguishing time. However, the fire extinguishing time varies greatly even under the same fire test condition. For example, the new fire test procedure suggests that the measurement of three parameters - inerting effect by vaporisation of water mist; mixing of water vapor and combustion products; and gas phase cooling - instead of extinguishing time. [7],[8]

3. Problem of Friction Loss Calculation Method

Generally, Darcy-Weisbach equation and Hazen-Williams equation are used to calculate the friction loss of pipe flow. These equations are defined in NFPA Code 750.

NFPA Code 750, Chapter 6, paragraph 6-2.1 states that "*Exception: Hydraulic calculation can be performed using the Hazen-Williams calculation method for intermediate and high pressure systems having a minimum 3/4in(20mm) pipe size, provided that the maximum flow velocity through the system piping does not exceed 25ft/sec (7.6m/sec).*"

It is general practice to use the Darcy-Weisbach equation for hydraulic calculation because the equation can consider the density and viscosity which affect the flow of fluid according to different types of fluid. In order to use Hazen-Williams equation for hydraulic calculation of water mist system, therefore, the effectiveness of the "*Exception*" paragraph of NFPA Code 750 and Hazen-Williams equation needs to be reviewed.

Darcy-Weisbach equation and Hazen-Williams equation are Eq. (1) and Eq. (2) of below respectively.

$$\Delta P = f \frac{L}{D} \frac{\rho V^2}{2} \tag{1}$$

here,

ΔP : pressure loss, Pa

f : friction loss coefficient

L : length of pipe, m

D : inner diameter of pipe, m

ρ : density of fluid, kg/m^3

V : mean velocity, $m/\sec$

$$\Delta P_H = 6.05L \frac{Q^{1.85}}{C^{1.85} D_H^{\;4.87}} \times 10^5 \qquad (2)$$

here,

ΔP_H : pressure loss, bar

Q : flow rate, $liters/\min$, lpm

C : Hazen-Williams coefficient

D_H : inner diameter of pipe, mm

L : refer to the Eq. (1)

Eq. (3) is used as friction loss coefficient for laminar flow. Eq. (3) derives from velocity distribution formula of “Poiseuille Flow”. And, Eq. (4) is called “Colebrook-White equation” and used as friction loss coefficient for turbulent flow because it is very difficult to read the exact value in Moody Chart.

$$f = \frac{64}{\text{Re}} \qquad (3)$$

$$\frac{1}{\sqrt{f}} = -0.88 \ln\left(\frac{\varepsilon}{3.7D} + \frac{2.5}{\text{Re}\sqrt{f}}\right) \qquad (4)$$

here,

f : friction loss coefficient

ε : roughness of pipe wall, m

Re : Reynolds number

Fig. 2 and Fig. 3 show the original Moody Chart and Moody Chart by Colebrook-White equation respectively. As can be assessed from the figures, they are akin to each other.

Hazen-Williams coefficient varies according to the material of pipe. In general, stainless steel pipe is used for piping system of water mist system. The Hazen-Williams coefficient of stainless steel pipe is 150. More detailed information are outlined in the NFPA Code 750.

The Darcy-Weisbach equation can be used for all pipe flow categories by treating friction loss coefficient as flow variables which are density, viscosity and relative roughness, ε / D. However, the Hazen-Williams coefficient is dimensional value and does not consider flow variables. Due to this reason, Hazen-Williams coefficient should be determined according to each fluid and pipe flow categories.

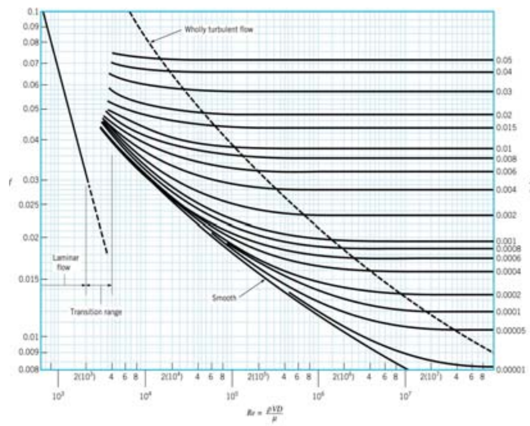

Fig. 2 Moody chart

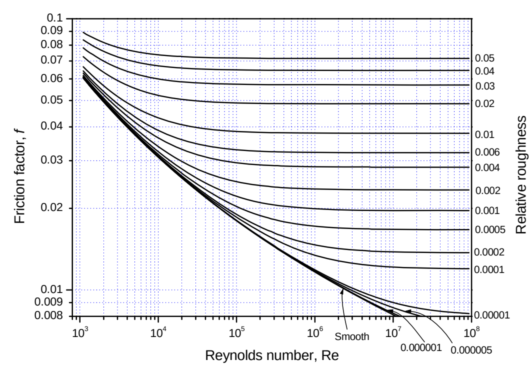

Fig. 3 Moody chart by colebrook-white equation

According to the explanation of T. J. Casey[9], the correlation of friction loss coefficient and Hazen-Williams coefficient can be shown as Eq. (5) to explain the effectiveness of Hazen-Williams equation.

$$\log f = \log C_* - 0.148 \log \text{Re} \qquad (5)$$

here,

f : friction loss coefficient

C_* : modified Hazen-Williams coefficient (constant)
Re : Reynolds number

Additionally, the correlation could be plotted as a straight line of negative slop in log-log scale graph such as Fig. 2 and Fig. 3. So, Hazen-Williams coefficient is valid in the transition turbulent flow zone.

In this paper, the correlation was verified by using Eq. (6) derived from Eq. (1) and Eq. (2).

$$f = 131305.01 \times C^{-1.85}\,\mathrm{Re}^{-0.15}\,D^{-0.02}\rho^{-0.85}\mu^{-0.15} \quad (6)$$

here,
D : inner diameter of pipe, m
ρ : density of fluid, kg/m^3
μ : viscosity, $Pa \cdot \sec$

The Hazen-Williams coefficient is 150 for stainless steel pipe, density and viscosity of fresh water is $995.4 kg/m^3$ and $7.4 \times 10^{-4} Pa \cdot \sec$ respectively. These values are based on fresh water temperature of $32.2^O C$ ($90^O F$) in accordance with Table 6-2.2 of NFPA Code 750.

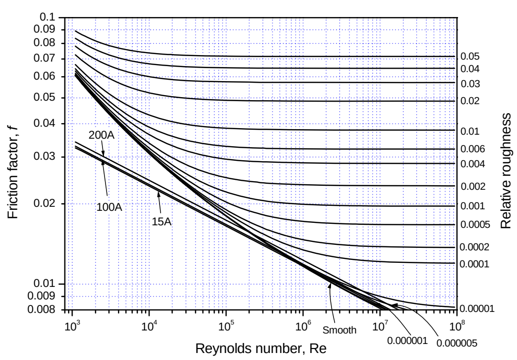

Fig. 4 Correlation of friction loss coefficient and Hazen-Williams coefficient by Eq. (6)

In Fig. 4, there are two problems. First, Hazen-Williams coefficient is underestimated than friction loss coefficient. As a result, the pressure loss by Hazen-Williams equation may be underestimated than the pressure loss of by Darcy-Weisbach equation of the calculation for same piping system. On the other hand, the difference between them can be reduced by adjusting the relative roughness. However, this adjustment has a negative effect of relaxing the design criteria of water mist system.

Secondly, Hazen-Williams coefficient does not satisfy the basic concept of friction loss calculation. If the pipe flow variables such as fluid, Reynolds number, material of pipe, pipe wall roughness, etc. are same, the larger size pipe has lower relative roughness. So, the larger size pipe should have lower friction loss coefficient. However, Hazen-Williams coefficient has opposite tendency.

Therefore, the effectiveness of the 6-2.1, NFPA Code 750 should be verified. According to NFPA Code 750, the maximum allowable condition for Hazen-Williams equation is 20A pipe and mean velocity of 7.6 $m/\sec$. As the "recommended value of absolute roughness or effective height of pipe wall irregularities (NFPA Code 750 Table 6-2.2(a))" of stainless steel pipe for Darcy-Weisbach equation is 0.045 mm , the relative roughness is 0.021. The Hazen-Williams coefficient is 150. Fig. 5 shows the calculation results of Eq. (4) and Eq. (6) with these values. The density and viscosity of fresh water are described in para. 3.5.

In Fig. 5, the results of Hazen-Williams equation is underestimated than the results of Darcy-Weisbach equation. Furthermore, allowed region by NFPA Code 750 has same tendency.

Generally, 15A~32A size stainless steel pipe are generally used for water mist system. Even so, the results of calculation may have a similar tendency of Fig. 5. So,

Table 1 Equivalent length of pipe fittings and valves (NFPA Code 750, unit = m)

Nominal Diameter		Inner Dia. mm	Fittings					Valves			
			Elbow		90 deg. Tee		Coupling	Ball	Gate	Butter fly	Check
			90^o	45^o	branch	straight					
3/8	8A	9.53	0.15	-	0.46	-	-	-	-	-	0.46
1/2	10A	12.7	0.31	0.15	0.61	-	-	-	-	-	0.61
5/8	15 A	15.88	0.46	0.15	0.61	-	-	-	-	-	0.76
3/4	20 A	19.05	0.61	0.15	0.91	-	-	-	-	-	0.91
1	25 A	25.4	0.76	0.31	1.37	-	-	0.15	-	-	1.37
1 1/4	32 A	31.75	0.91	0.31	1.68	0.15	0.15	0.15	-	-	1.68
1 1/2	40 A	38.1	1.22	0.46	2.13	0.15	0.15	0.15	-	-	1.98
2	50 A	50.8	1.68	0.61	2.74	0.15	0.15	0.15	0.15	2.29	2.74
2 1/2	65 A	63.5	2.13	0.76	3.66	0.15	0.15	-	0.31	3.05	3.51
3	80 A	76.2	2.74	1.07	4.57	0.31	0.31	-	0.46	4.72	4.42
3 1/2	90 A	88.9	2.74	1.07	4.27	0.31	0.31	-	0.61	-	3.81
4	100A	101.6	3.81	1.52	6.40	0.31	0.31	-	0.61	4.88	5.64

in the results of hydraulic calculation for same water mist system, the difference between Darcy-Weisbach equation and Hazen-Williams equation cannot be omitted.

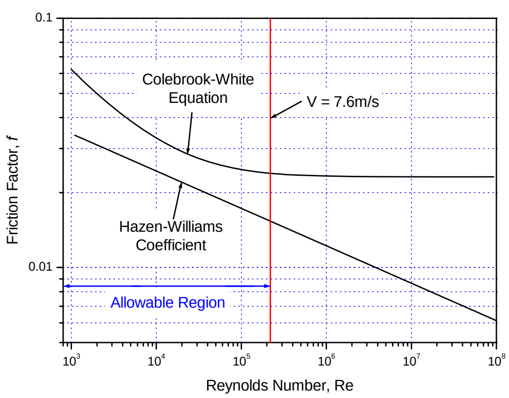

Fig. 5 Correlation of friction loss coefficient and Hazen-Williams coefficient with limitation of NFPA Code 750

4. Problem of Minor Loss

Generally, the flow energy loss of pipe fittings and valves are called “Minor Loss”. This does not mean that the flow energy loss of pipe fittings and valves is small. For example, the flow energy loss of closed valve is infinite. In this document, the flow energy loss of pipe fittings and valves is referred to as “Minor Loss” only for easy description.

There are two methods for applying minor loss to hydraulic calculation. The first method uses loss coefficient and the second method uses equivalent length. The methods can be obtained through experimental approach and consist of complex flow characteristics. However, it is impossible that measuring of the minor loss for all pipe fittings and valves. And, in our opinion, the minor loss which is provided on international standard such as NFPA Code, has a enough safety factor. So, the minor loss which is provided standards should be applied to hydraulic calculation before it is proved that the minor loss of standards has a inadequacy value.

Table 1 is equivalent length of NFPA Code 750. Although there are various standards of equivalent length are presented, NFPA Code 750 is widely used for hydraulic calculation of water mist system. Hence, it is recommended that using equivalent length of NFPA Code 750. Additionally, there are various design standards of loss coefficient, however, the loss coefficient could not consider geometry - diameter - of pipe fittings and valves. Then, loss coefficient should be defined the function of geometry such as the radius of curvature ratio of bend, etc. However, these functions are difficult for use because the functions are generally non-linear function. Furthermore, in actual design work, loss coefficient are generally used as constant, so, it may occur that the minor loss is underestimated or very overestimated.

However, there are three problems which equivalent length of NFPA Code 750 apply to hydraulic calculation.

(1) The value of equivalent length specific nominal diameter is not provided. There are two interpretations can be applied. One is interpolation that linear or nonlinear interpolation of another value. The other is omission which equivalent length applies to hydraulic calculation.
(2) The second problem is unstable tendency. The value of equivalent length is increased with increasing of nominal diameter, however, some values are same or decreased with increasing of nominal diameter.
(3) The inner diameter of pipe is different for inch standard pipe and meter standard pipe. Of course, in our opinion, this problem does not important parameter of minor loss assessment.

To solve these problems, this paper proposes the equivalent length standard for hydraulic calculation based on NFPA Code 750. The proposed equivalent length is made following conditions;

- The value of equivalent length should have 0 when the inner diameter is 0.
- The line should meet the maximum value of NFPA Code 750 with specific gradient.

Fig. 6 shows the sample of the proposed equivalet length standards. The proposed standards are following;

1. 90^o elbow or bend : $L_E = 0.0375D$
2. 45^o elbow or bend : $L_E = 0.015D$
3. Tee – branch : $L_E = 0.063D$
4. Tee – straight : $L_E = 0.0041D$
5. Coupling : $L_E = 0.0041D$
6. Ball Valve : $L_E = 0.006D$
7. Gate Valve : $L_E = 0.0069D$
8. Butterfly Valve : $L_E = 0.062D$
9. Check Valve : $L_E = 0.058D$

here,

L_E : equivalent length, m

D : inner diameter of pipe mm

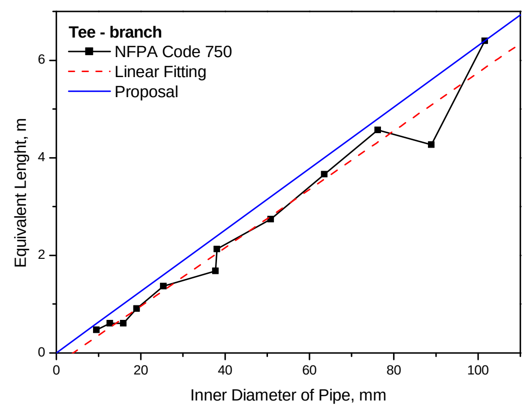

Fig. 6 Concept of propsed equivalent length

5. Problem of Convergence Condition

All of the water based fire extinguishing system has pump and nozzle and the performance and requirement of the system is defined the pressure or flow rate at pump or nozzle. Hence, pressure and flow rate of pump or nozzle will be boundary condition for flow distribution calculation.

In general, the flow distribution is calculated iterative calculation method. Iterative method means that the result is not exact value but approximate value.

Hence, the convergence condition for iterative method should be provided.

The requirement of NFPA Code 750 Ch.6 6-3.5 is "***Hydraulic Junction Points.*** *Pressure at hydraulic junction points shall balance within 0.5psi (0.03bar). The highest pressure at the junction point, and the total flows as adjusted, shall be used in the calculations.*"

In general, the convergence condition of iterative calculation method is not absolute value but relative value. Because, in the great part of engineering calculation, the order of result value can not be predicted.

Furthermore, the operating pressure of almost water mist system is 10bar ~ 100bar. Hence, the convergence condition of NFPA Code 750 of 0.03 bar is 3×10^{-3} ~ 3×10^{-4} . This value is not a few than 1×10^{-5} which is generally used in engineering calculation. Therefore, the relative value as convergence condition for hydraulic calculation is more resonable. And, the recommended relative value is 1×10^{-5} . Additionally, flow rate and pressure can be used for convergence condition.

$$\left|\frac{\sum Q_i^k}{\sum Q_i^{k-1}}\right| \le 10^{-5} \;\&\; \left|\frac{\sum P_i^k}{\sum P_i^{k-1}}\right| \le 10^{-5} \qquad (7)$$

here,

i : node number

k : iteration number

6. Sample Calculation

A sample calculation was carried out with Fig. 7 and Table 2. Fig. 7 shows the piping system which is installed at machinery space of international passenger ship as a local application system. And, Table 3 shows the approved condition and system specification of the water mist system in accordance with MSC/Circ.913.

The calculation was carried out with each friction loss calculation method and the proposed equivalent length is used for minor loss which is indicated in section 4 of this paper. In additional, Eq. (7) was used for convergence condition.

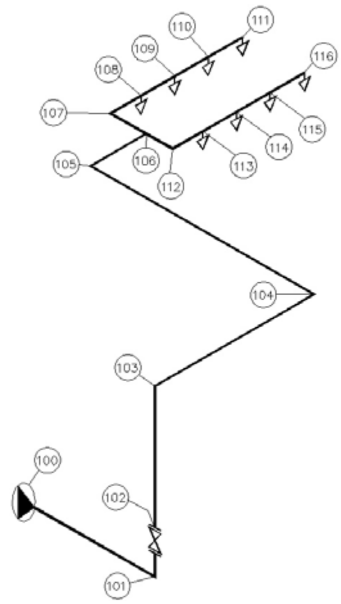

Fig. 7 Isometric diagram of piping system

Table 2 Specification of piping system

Node	Node	ND	L(m)	Elv.(m)
100	101	25A	3.0	0.0
101	102	25A	0.5	0.5
102	103	25A	8.5	8.5
103	104	25A	20.0	0.0
104	105	25A	10.0	0.0
105	106	20A	3.0	0.0
106	107	20A	2.0	0.0
107	108	20A	2.0	0.0
108	109	15A	4.0	0.0
109	110	15A	4.0	0.0
110	111	15A	4.0	0.0
106	112	20A	2.0	0.0
112	113	20A	2.0	0.0
113	114	15A	4.0	0.0
114	115	15A	4.0	0.0
115	116	15A	4.0	0.0

Table 3 Specification of water mist system

Max. horizontal spacing	4m
Min. vertical distance	1m
Max. vertical distance	4m
Min. operating pressure	30bar
Max. operating pressure	90bar
K-factor of Nozzle	1.5 [Q(lpm)=K×P(bar)$^{0.5}$]
Kind of pump	Piston pump
Nominal pump capacity	75bar × 120lpm
Formula of pump	Q(lpm) = -0.4P(bar) + 150

Table 4 Calculation results by Darcy-Weisbach equation

Node	Q(lpm)	P(bar)	V(m/s)	Re
100	120.27	74.32	3.45	126217.5
101		74.17		
101	120.27	74.17	3.45	126217.5
102		74.03		
102	120.27	74.03	3.45	126217.5
103		72.77		
103	120.27	72.77	3.45	126217.5
104		71.71		
104	120.27	71.71	3.45	126217.5
105		71.15		
105	120.27	71.15	5.57	160426.0
106		70.49		
106	60.14	70.49	2.79	80213.0
107		70.34		
107	60.14	70.34	2.79	80213.0
108		70.21		
108	45.05	70.21	3.69	79877.6
109		69.76		
109	30.02	69.76	2.46	53222.2
110		69.56		
110	15.01	69.56	1.23	26605.9
111		69.50		
106	60.14	70.49	2.79	80213.0
112		70.34		
112	60.14	70.34	2.79	80213.0
113		70.21		
113	45.05	70.21	3.69	79877.6
114		69.76		
114	30.02	69.76	2.46	53222.2
115		69.56		
115	15.01	69.56	1.23	26605.9
116		69.50		

Table 5 Calculation results by Hazen-Williams equation

Node	Q(lpm)	P(bar)	V(m/s)	Re
100	120.47	73.84	3.46	126420.4
101		73.71		
101	120.47	73.71	3.46	126420.4
102		73.59		
102	120.47	73.59	3.46	126420.4
103		72.41		
103	120.47	72.41	3.46	126420.4
104		71.53		
104	120.47	71.53	3.46	126420.4
105		71.08		
105	120.47	71.08	5.58	160683.9
106		70.57		
106	60.23	70.57	2.79	80341.9
107		70.44		
107	60.23	70.44	2.79	80341.9
108		70.34		
108	45.14	70.34	3.70	80024.8
109		69.99		
109	30.08	69.99	2.46	53326.1
110		69.83		
110	15.04	69.83	1.23	26658.7
111		69.78		
106	60.23	70.57	2.79	80341.9
112		70.44		
112	60.23	70.44	2.79	80341.9
113		70.34		
113	45.14	70.34	3.70	80024.8
114		69.99		
114	30.08	69.99	2.46	53326.1
115		69.83		
115	15.04	69.83	1.23	26658.7
116		69.78		

Table 4 and Table 5 show the calculation results according to each calculation method. The difference between the pump outlet and the remotest nozzle(Node 116) is 4.82bar and 4.06bar, respectively. The pressure loss according to Hazen-Williams equation is 84.2% of the loss incurred by Darcy-Weisbach equation. In this sample calculation, there was not much difference in the pressure loss.

It is assumed, however, that the cause of such pressure loss difference, is due to the characteristics of the water mist system used for the calculation.

In Table 4 and Table 5, the Reynolds number is 2.66×10^4~1.26×10^5 and almost all of mean velocity of pipe flow is less than 3.5m/s. This two values show that the pipe flow of the system has lower value than the limitation outlined in NFPA Code 750.

And, in general, the pressure loss of pipe flow depends on the flow rate. As only eight nozzles are used for the system, the discharge rate of the pump outlet is small. Furthermore, the adequate size of pipe is used. Therefore, there is not much difference in the pressure loss because the system is designed for the low pressure loss.

Nevertheless, if many nozzles or inadequate size of pipe are used for the system, the difference will be very significant. This tendency can be estimated by Fig. 5.

7. Conclusion

This paper reviewed friction loss calculation method, minor loss evaluation and convergence condition for iterative calculation method. These three items are very important parameters for the hydraulic calculation. Through the study, the following findings were obtained:

(1) The use of Darcy-Weisbach equation was proven to be better for the hydraulic calculation of water mist system for its optimum performance. Additionally, the roughness of pipe wall for designing purpose are recommended as follows:

-Copper, copper nickel, drawn tubing :
$0.0015\,mm$

- Stainless steel pipe:
$0.045\,mm$

- Galvanized steel pipe[10],[11]
$0.15\,mm$

(2) The pressure loss of pipe fittings and valves should be determined by various experimental approaches. However, this approach is not very practical in terms of cost and time. Therefore, it is more prudent to use the minor loss values which are determined with the proper margins as proposed in section 4 of this paper.

(3) Almost all of hydraulic calculation computes the flow distribution at hydraulic junction point by the iterative calculation method. Therefore, relative value should be used for convergence condition. And, the use of lower value of 10^{-5} is recommended for convergence value.

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