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CALCULATION OF WATER DELIVERY TIME IN DRY PIPE SPRINKLER SYSTEMS

Master of Science thesis

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ABSTRACT

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An automatic fire protection can be provided by a sprinkler system. The most common type of a sprinkler system is called a wet type system. A pipe network in the wet type systems is always filled with water and this type of a system can be used in spaces where the temperature remains in range where water occurs in liquid form. Dry pipe sprinkler systems are developed to be used in cold or hot conditions where wet type systems cannot be used. To prevent a sprinkler system from freezing, dry pipe systems are initially filled with pressurized gas and water is lead in after the system is activated. Before water can start to fight against fire, part of the gas has to be removed from the pipe network and water has to replace it. This gas removing and water filling phase weakens the fast response to the ignited fire which is the best advantage of the automatic sprinkler systems.

The scope of this thesis was to develope a calculation program that estimates the time that is consumed when part of the gas is removed from the sprinkler system and is replaced by water. The program was written in Python programming language. The motivation to develope this kind of a calculation program is to improve the designing procedure of the dry pipe sprinkler systems and to ensure that designed systems meet the restrictions of automatic sprinkler systems.

The present practice in building design is to use a Building Infomation Modeling (BIM) programs. In this thesis the written program is developed to work with BIM program. The developed calculation program gets characteristics of the sprinkler pipe network from BIM program where the sprinkler pipe network is designed in three dimensions. From this information, the developed calculation program calculates an estimation of the time that is needed to remove part of the gas and to fill the sprinkler pipe network with water, i.e. the time from system activation to real action of the system.

The results of one example case were compared with the results of a commercial program. The results were satisfactory, which encourages to develope this program more for future use. Due to complex and only slightly limited pipe network configurations, interaction of two fluid phases, and highly transient nature of the water flow in the system, more testing is needed to verify the results and for further development of this calculation program.

TIIVISTELMÄ

HARRI KANGASTIE: Kuivasprinklerjärjestelmien täyttymisajan laskentamenetelmä
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Automaattinen palontorjunta voidaan toteuttaa sprinklerjärjestelmällä. Yleisimmin käytetään märkäjärjestelmiä. Märkäjärjestelmän putkisto on täytetty vedellä, kun järjestelmä on valmiustilassa. Tästä johtuen märkäjärjestelmää voidaan käyttää vain lämpötiloissa, joissa vesi pysyy nestemäisessä muodossa. Erityinen kuivajärjestelmä on kehitetty, jotta automaattinen palontorjunta voidaan toteuttaa myös tiloihin, joissa lämpötila on niin kylmä, että vesi jäätyy, tai niin kuuma, että vesi höyrystyy. Valmiustilassa kuivajärjestelmän putkiverkko on täytetty paineistetulla kaasulla ja vesi johdetaan putkiverkkoon vasta järjestelmän aktivoiduttua. Tulipalosta aiheutuva lämpö aktivoi kuivajärjestelmän ja osa putkistossa olevasta kaasusta täytyy poistaa ja putkisto täytyy täyttää vedellä, ennen kuin varsinainen palonsammutus alkaa. Tämä putkiston täyttymiseen kuluva aika heikentää sprinklerjärjestelmän vahvinta ominaisuutta eli nopeaa reagointia syttyneeseen tulipaloon.

Tämän työn tarkoituksena oli kehittää laskentaohjelma, joka laskee kaasun poistamiseen ja putkiverkon täyttämiseen vedellä kuluvan ajan. Laskentaohjelma kirjoitettiin Python-ohjelmointikielellä. Lähtökohta laskentaohjelman kehitykselle on parantaa kuivajärjestelmän suunnittelutyökaluja, joilla voidaan varmistaa, että suunnitellut järjestelmät täyttävät niille asetetut vaatimukset.

Rakennusten suunnittelussa käytetään yleisesti tietomallinnusohjelmistoja (BIM). Tässä työssä kehitetty laskentaohjelma on suunniteltu toimimaan osana tietomallinnusohjelmaa. Kehitetty laskentaohjelma saa putkiverkoston tiedot syötteenä tietomallinnusohjelmalta, jossa putkistoverkko suunnitellaan kolmidimensioisena. Tässä työssä kehitetty laskentaohjelma laskee annetuista alkuarvoista ja putkiverkon tiedoista täyttymisajan kuivajärjestelmälle.

Laskentaohjelman tuloksia vertailtiin yhdessä testitapauksessa kaupallisen ohjelman

antamiin tuloksiin. Tulokset olivat tyydyttäviä, mikä rohkaisee jatkamaan ohjelman kehitystä. Putkistoverkkojen monimutkaisuuden ja lähes vapaasti valittavien dimensioiden, sekä putkiston täyttymisen aikana voimakkaasti ajasta riippuvan veden virtauksen takia laskentaohjelma tarvitsee lisää testausta. Testitulosten perusteella ohjelmaa voidaan jatkokehittää ja tulosten paikkansapitävyys voidaan varmistaa.

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Harri Kangastie

CONTENTS

LIST OF ABBREVIATIONS AND SYMBOLS

BIM	Building Information Modeling
CEA	European insurance and reinsurance federation
DPV	Dry Pipe Valve

a	Acceleration, Speed of sound
A	Cross-sectional area
d	Inner diameter of pipe
f	Darcy friction factor
g	Gravitational acceleration
h	A step length in numerical integration
h_f	Head of a pressure loss
H	Total head multiplied by the gravitational acceleration
l, L	Water column length
m	Mass
$\dot{m}$	Mass flow rate
p	Pressure
Q	Volume flow
r	Radius of pipe
R	Specific gas constant
Re	Reynolds number
s	Length along a streamline
T	Temperature
v	Velocity
V	Volume
z	Height position

α	Initial value
γ	Ratio of heat capasities
ϵ	Pipe surface roughness
ζ	Pressure loss coefficient
μ	Dynamic viscosity
ρ	Density

1. INTRODUCTION

A sprinkler system is a common way to provide automatic fire protection. The purpose of a sprinkler system is to protect lives and property from fire. The first automatic sprinkler was invented and installed by Henry S. Parmalee in 1874 [11]. The most common installed sprinkler systems are so called wet systems. On the standby mode wet systems are filled with pressurized water, and increasing temperature opens up an automatic sprinkler head and water starts to discharge instantly. The advantage of the sprinkler system is a fast response to the exact area where the fire exists.

In some cases the temperature of the protected space drops below the freezing point of water. These low temperatures prevent the use of a wet type sprinkler system [15]. To apply fire protection to the cold environments, dry pipe sprinkler systems are used. The dry pipe systems can also be used in hot environments, like in industrial ovens, if the temperature of the protected space exceeds the boiling point of water [3].

On the standby mode the pipe network of the dry pipe sprinkler system is filled with pressurised air or nitrogen to prevent the freezing of the system [15]. When the dry pipe system is activated by hot flue gases from the fire, part of the pressurized gas in the pipe network has to be first removed to obtain a certain gas pressure level inside the pipe network. When the certain gas pressure level is reached, water starts to flow in to the dry part of a pipe network. Still part of the pressurized gas is in the pipe network and it has to be removed through the open sprinkler head and simultaneously the pipe network is filled with water. After water has reached the open sprinkler head, water starts to discharge from the system and the fight against fire is started. The advantage of sprinkler systems is a fast response to the ignited fire. The dry pipe sprinkler system suffers of time consuming gas removal and water filling steps, i.e. an air trip time and a water transit time [15]. The sum of the air trip time and the water transit time is called a water delivery time which is the time between the activation and the action of the sprinkler system. The characteristics of a pipe network and used devices in the dry pipe sprinkler system have an effect on the air trip time and on the water transit time. The pipe network should be designed in a way that it maintains a fast response to the ignited fire.

Different standards and limitations are applied to the sprinkler systems. In this work, European insurance and reinsurance federation(CEA) prevention specifications are followed. CEA's Sprinkler Systems Planning and Installation is more detailed and specific compared to European Standard EN 12845 [3]. In CEA's Sprinkler Systems Planning and Installation protected spaces are divided into different hazard classes. There are three base classes: a Light Hazard, an Ordinary Hazard and a High Hazard with several sub classes. The classification depends on the occupancy and fire load of the protected space. An installed sprinkler system has to fulfill the requirements of the hazard class for the protected space. Both the wet and the dry pipe systems have to maintain required flow density to the specified size of area. The flow density depends on the hazard class of the protected space and on the type of installed system. Due to the slower response to the ignited fire, larger flow densities are required for the dry pipe systems. Additionally, the dry pipe system must not exceed a given volumetric size and the water delivery time to the most remote sprinkler head must remain under a certain limit.

The purpose of this thesis is to develope a calculation program to estimate the air trip and the water transit times in the dry pipe sprinkler system. This program is aimed to be used together with BIM program where the actual sprinkler pipe network is designed in three dimensions. In the program development some of the used equations and aspects of system simplification are obtained from a related work [15]. Compared to the related work, a more detailed description of used equations and calculation procedure is provided and the actual pipe network is less simplified to obtain more general coverage. Additionally, in this study, a calculation method for a loop type pipe network configuration is proposed. Time dependent fluid flow is described by one dimensional equations which are discretized in time. One dimensional approach is used to perform fast estimations of the water delivery time. One dimensional approximation leads to a simple and fast calculation procedure that is possible to be developed in the time limit of this kind of thesis work. Several approximations have to be done due to the lack of exact equations considering underlying phenomenas and the limitations of computer programs, and because the aim is to provide fast results. The accuracy of some of these approximations is investigated in this study and some are left to be investigated in further work.

2. DESCRIPTION OF SPRINKLER SYSTEMS

An automatic sprinkler system is an efficient way to provide fire protection. Usually systems are installed inside buildings where temperatures are around normal room temperature. In special cases sprinkler systems are installed in spaces where ambient temperatures are so low or high that water cannot stand in liquid form. As water is used as a fire fighting agent, the pipe network has to be prevented from freezing. The dry pipe sprinkler system is developed to achieve effective fire protection and the ability to operate in low and high temperatures. In this chapter, the details of a pipe network and used equipments are described.

2.1 Sprinkler pipe network and equipments

A sprinkler system consists of at least the following elements: a water source to provide the needed pressure level and water flow rate, a control valve to shut down water flow if needed, a pipe network which covers the protected area, and sprinkler heads to provide the water spray and to take care of the system activation.

The water source can be a municipal water line, a water tank built for this purpose or a natural water source. Requirements for the water sources consider the size of a water source, water quality and a required pressure level. To maintain the required pressure level, additional pumps are often used. Detailed requirements are out of the scope of this study and more information can be found in the literature [3],[16].

The purpose of the pipe network is to distribute water all over the protected area. The pipe networks of sprinkler systems could be divided in three cathegories depending on the network configuration. There are three types of configurations: tree, loop and grid type configuration. All these configurations are used in wet type sprinkler systems, but it is prohibited to use the grid type configuration in a dry pipe sprinkler system [21, p. 6].

Sprinkler heads are distributed equally around the protected area and are connected to the pipe network. Sprinkler heads are responsible for the system activation and in the action, open sprinkler heads provide water spray against fire. Sprinkler heads have two kind of activation routines. Both routines rely on a heat sensitive part which keeps the head closed in temperatures below the activation temperature. In both sprinkler head types the heat sensitive part holds a plug and when the temperature increases, the plug is released to let water discharge from the system. The heat sensitive part is either a glass bulb filled with alcohol mixture or a metal structure where the heat sensitive part is made of metal alloy that has a desired melting point. [26],[7, p. 7]

Additionally, the sprinkler systems include valves, couplings and pipe supports. In a wet pipe system, valves are typically for maintenance purposes to close the system when maintenance is needed. One exception is a control valve which initiates the alarm when the system is activated. In a dry pipe system, a special valve is used to separate the dry part from the water source.

2.2 Dry pipe sprinkler system

Dry pipe systems are more complicated than their wet counterparts. Most commonly the dry pipe systems are used in cold environments to prevent the system from freezing. The dry pipe systems can also be used in hot environments where the temperature exceeds the boiling point of water, like for example in industrial ovens [3, p. 73].

Two kinds of pipe network configurations are accepted to be used in the dry pipe sprinkler systems: a tree and a loop type configuration. A tree type configuration is illustrated in Figure 2.1. Both configurations consist of a main pipe, branch pipes and head pipes. In the tree type configuration a single main pipe forms the body of the pipe network.

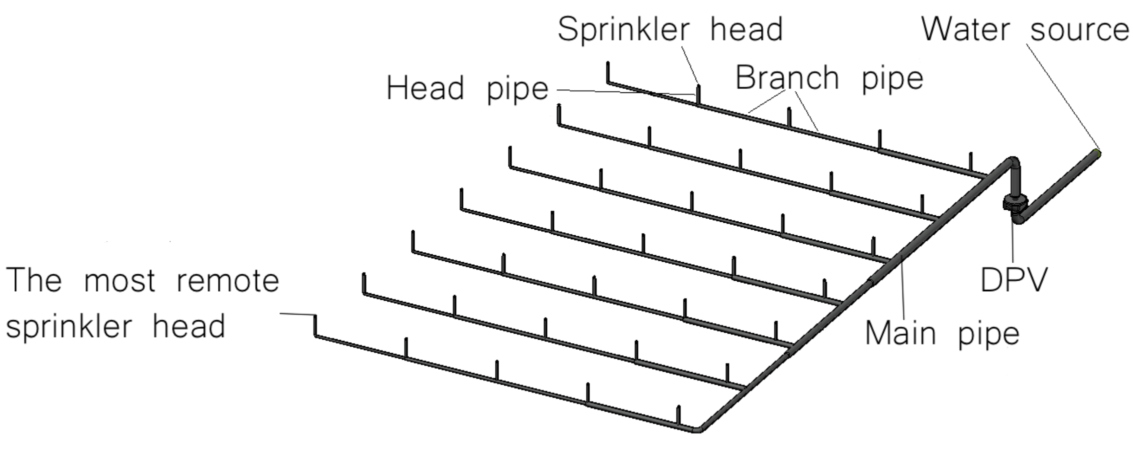

Figure 2.1 *A simple tree type pipe network configuration.*

In the loop type configuration, a loop of the main pipe forms the body of the loop type configuration, like illustrated in Figure 2.2. The dimensions of the protected space, the volume of the dry pipe system and the water delivery time requirements guide the choice between the tree and the loop type pipe network configuration. To explain how the water delivery is calculated, a special term "flow line" is used in this study. The flow line is the path from the water source to the most remote sprinkler head. In the tree type pipe network the flow line is a single path, but in the loop type pipe network there is a loop in the flow line as well.

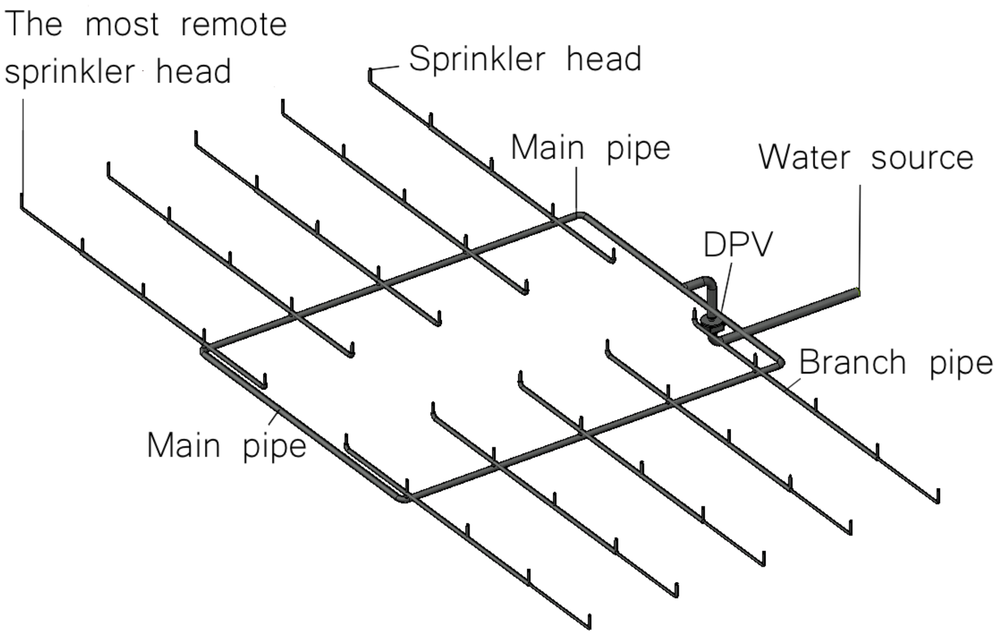

Figure 2.2 *A simple loop type pipe network configuration.*

The branch pipes are connected to the main pipe and the diameter is the same or smaller than the diameter of the main pipe. A head pipe connects the branch pipe and the sprinkler head. The head pipes are usually relatively short and the diameter fits to the sprinkler head connection size.

The sprinkler heads are responsible for system activation in both the wet and the dry pipe systems. Several different kinds of sprinkler heads are available. Sprinkler heads vary in orientation, temperature rating and orifice size. Orientation can be upwards, downwards or sideways. Temperature rating has to be chosen for the existing conditions and the hazard class of the protected space. In the dry pipe systems the orientation of the sprinkler heads should be upwards, except when a dry pendent pattern or sidewall sprinkler heads are used [3, p. 73].

The hazard class of the protected space is the most critical aspect in the sprinkler system designing process. If the flow density of the designed sprinkler system does not meet the requirement of the protected space there is a possibility that fire overpowers the sprinkler system, even if the system is working correctly. The hazard class defines the flow density of water. Hydraulic calculations have to be performed to the designed pipe network, and based on pressure levels from hydraulic calculation the sprinkler heads are chosen. The orifice size of the sprinkler head has to be chosen so that water discharge rate meets the water flow density restrictions. [8]

In the dry pipe system the accumulation of moisture cannot be totally prevented. This accumulated moisture is the reason why upward orientation of the sprinkler heads has to be used. If the orientation is downwards, moisture accumulates to the sprinkler head and this might cause a blockage when accumulated moisture freezes. Downward orientation is only allowed if the dry pendent pattern sprinkler heads are used. The dry pendent pattern sprinkler head is a sprinkler head which is connected directly to the branch pipe and part of the pendent pattern sprinkler head replaces the head pipe. The plug that holds water/pressurized gas on the standby mode is located on one end of the sprinkler head and the discharcing nozzle on the other end. This configuration prevents the moisture accumulation to the sprinkler head which might cause blockage in cold conditions.

A special valve is used to separate the wet and the dry parts of a dry pipe network. This valve is called a dry pipe valve, abbreviated DPV. DPV has to be located in a space where temperature is safely in range where water exists in liquid form. When the system is on the standby mode, DPV holds water in upstream side and pressurized gas in downstream side of the valve. DPV trips automatically when the pressure ratio exceeds a certain value. This value is set by DPV characteristics. DPV is designed in a way that smaller gas pressure holds much greater water pressure. Typically, water/gas pressure ratio of the DPV trip is 5-6 [28]. To prevent an undesirable DPV trip, the gas pressure has to exceed the trip pressure of DPV when the system is on the standby mode. In Table 2.1 the water, the gas and the trip pressures are shown for a commercial DPV [28]. In the table, the difference between the gas pressure on the standby mode and the dry pipe valve trip pressure can be seen. For the gas pressure a certain range is expressed. Gas leaks cannot be totally prevented and equipments providing compresssed gas have to be installed to keep the gas pressure in this range.

The air trip time is the time between the moment when the sprinkler head opens and the moment when DPV trips. For large systems this time can be relatively long and it might prevent a fast response to the ignited fire [10, p. 6]. So called Quick Opening Devices are used to ensure fast response in situations where the dry

Table 2.1 *The standby pressure of the water source, the trip pressure of DPV, and the stand by gas pressure of the pipe network.*

Water pressure [bar]	Gas pressure [bar]	Trip pressure [bar]
1.4	0.7	0.255
4.1	1.0-1.6	0.745
5.5	1.4-1.9	1.0
6.9	1.7 - 2.3	1.25
8.3	2.1-2.6	1.51
10.0	2.4-3.0	1.82
11.4	2.8-3.3	2.07
12.8	3.1-3.7	2.33
14.1	3.4-4.0	2.56
15.5	3.8-4.3	2.82
16.0	4.1-4.6	2.91

part volume of the system is large. Two kinds of Quick Opening Devices are in use, i.e. accelerators and exhausters. After activation, exhausters discharge gas from the dry pipe systems to reduce the gas pressure rapidly to achieve DPV trip pressure faster. Accelerators do not affect the gas pressure inside the system. An accelerator is connected to the pipe network and the accelerator is activated by a relatively small but fast gas pressure change in the system. When the accelerator is activated, it gives a pressure signal to DPV. This signal makes DPV trip immediately, even though the DPV trip pressure is not yet reached. Nowadays exhausters have been replaced by accelerators, and in this study exhausters are not discussed in more detail [10, p. 4].

Accelerators are divided in two cathegories: in mechanical and electrical accelerators. A mechanical accelerator is an older invention. The activation of a mechanical accelerator is based on pressure difference between two chambers. The first chamber is connected directly to the pipe network so that pressure in the chamber equals the pressure of the pipe network at every moment. The second chamber is connected to the first chamber via a small hole. This hole is so small, compared to the chamber size, that only slow changes occur in the second chamber pressure, even if pressure in the first chamber is changing rapidly. The hole between the chambers adjusts the pressure in the second chambers to the gas pressure of the pipe network if the pressure in pipe network changes slowly. These slow changes occur due to temperature changes in the environment or due to small gas leaks from the system. When a sprinkler head opens up, the gas pressure in the pipe network starts to decrease rapidly. The hole between chambers is so small that in the rapid change of the pipe network pressure, the pressure difference between the two chambers is obtained and the accelerator is activated. [10, p.12]

An electrical accelerator is based on a sensor that reacts to the rapid pressure change but disregards the slow pressure changes in the pipe network. Like a mechanical accelerator, also an electrical accelerator sends a pressure signal to DPV which then trips immediately. A mechanical accelerator has a more complex structure and needs more testing and maintenance. An electrical accelerator is faster than the mechanical one and it is said to be more reliable. On the other hand, an electrical accelerator is more expensive, and electricity has to be provided to the installation. [10] If Quick Opening Device is not installed, the DPV trip pressure is expressed in terms of pressure ratio over DPV. If an accelerator is installed, the activation pressure is expressed as pressure change in certain time interval instead.

There are several requirements for the dry pipe sprinkler systems and here some of them are outlined. These requirements are based on CEA Sprinkler Systems: Plannig and Installations [3] and requirements may vary between different standards. The maximum volume of a dry part in the dry pipe sprinkler system is 4 m^3. If the volume of the dry part exceeds 1.5 m^3, a Quick Opening Device has to be installed. [3, p.73] The maximum water pressure in sprinkler heads shall not exceed 12 bars [3, p.44]. Required water delivery time to the most remote sprinkler head varies according to the used standard. The most common requirement is 60 second water delivery time which is required in CEA Sprinkler Systems: Planning and Installations [3]. For example in some other standards, water delivery time is not specified for small systems and 30 second time limit is required for high hazard class systems [15],[20].

A special check valve is installed in the dry pipe systems. The check valve is located near to the most remote sprinkler head from DPV point of view. The check valve orifice size corresponds to the size of the most remote sprinkler head. For existing installations the water delivery time is experimented by this check valve. The water delivery time is experimented by opening this check valve and measuring the time when water starts to discharge from the check valve.

The calculation program developed in this study is not limited to these requirements. Based on these requirements, a useful assumption for the value range of different variables can be done. For example, the difference between made assumptions in calculation can be estimated in certain pressure interval. The aim of the developed calculation program is to estimate the water delivery time to the most remote sprinkler head.

3. GOVERNING EQUATIONS

In this chapter equations governing the water delivery are introduced. In the air trip, a pipe network is modeled as a container from where the gas discharges via open nozzle. This means that pressure losses of gas flow in pipes, and potential and kinetic energies are assumed to be negligible.

Movements of water columns in the sprinkler pipe network are modeled by one dimensional equations. An approximation is made that the water front is sharp and perpendicular to the longitudal axis of the pipe. During the water transit pressurized gas and water are acting on each other. The gas pressures in the pipe network are calculated in the water transit with the one dimensional equations for water. In the literature the water delivery times modeled by this method agree fairly well with the experiments of real installations [15]. As the results were accurate, same kind of approach is used in this study. Compared to the literature, some parts of the method in this study are further developed, and some aspects are introduced in more detail. The pipe network is not simplified as much as it is simplified in the literature, and this leads to more general coverage of the calculation method.

3.1 Air trip time

The air trip time is the time between the most remote sprinkler head opening and the DPV trip event. The aim of the accelerator is to reduce this time. In this study, following factors that depend on the pipe network design and which will impact to the air trip time are:

- Air pressure in the pipe network when the sprinkler head opens
- Orifice size of the open sprinkler head
- Trip pressure of DPV or the activation pressure change of the accelerator
- Volume of the pipe network

From these factors and conditions of the protected space differential equations can be derived to describe the pressure change in the system related to time. Several approximations have to be done. In the literature, for the air trip time calculation, the pipe network is described as a container of which volume corresponds to the volumetric size of the dry part in the actual pipe network [15]. In other words, the pressure losses, and kinetic and potential energy of gas flow in a pipe network is assumed to be negligible. Additionally the gas expansion is assumed to be isothermal. Differential equation for isentropic expansion can also be derived, which is shown later on in this chapter. Both the isothermal and the isentropic solutions are ideal situations and the reality lies between these two solutions. In the isothermal assumption infinite heat transfer from a pipe to gas is assumed and in isentropic assumption this heat transfer is assumed to be zero.

Gas discharge through an open sprinkler head is described by the equations of an isentropic converging nozzle flow. Velocity in the converging nozzle is limited to the speed of sound of flowing media. The speed of sound is achieved if the pressure ratio over a nozzle is less than the critical pressure ratio, shown in Equation (3.1). If this pressure ratio is exceeded i.e. pressure in the upstream side of nozzle decreases, the flow is called sub-sonic.

In the dry pipe sprinkler systems, the pressure ratio between the gas pressure in pipe network and the pressure in the surrounding space is in the range of both sonic and sub-sonic flow conditions. This leads to four differential equations that can be derived to describe the pressure change in system respect to time. These equations are isothermal or isentropic gas expansion in the pipe network with sonic or subsonic nozzle flow trough the sprinkler head. The choice between isothermal or isentropic expansion depends on the made assumption. Sonic or sub-sonic nozzle flow velocity, instead, depends on the pressure ratio between the pipe network and surroundings. This condition often changes from sonic to sub-sonic during the calculation and used equation has to be changed as well.

3.1.1 Mass flow rate in isentropic nozzle flow

The equation for mass flow through nozzle in sonic conditions is derived below, and for sub-sonic conditions later on. Sonic or also called chocked conditions are achieved when pressure ratio across the nozzle is less than the critical pressure ratio. This critical pressure ratio is set by

$$\frac{p^*}{p_0} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \tag{3.1}$$

where p^* is the pressure at nozzle outlet which in here equals the air pressure of the space where the system is located, i.e. athmospheric pressure. p_0 is the stagnation pressure at nozzle inlet and γ is the ratio of heat capasities, i.e. $\frac{c_p}{c_v}$. [22, p. 68] The change of mass of gas in the pipe network equals mass flow rate through the nozzle. It is described by following equation

$$\dot{m} = \rho^* v^* A^* \tag{3.2}$$

where asterix denotes to conditions at the nozzle outlet. $\dot{m}$ is mass flow rate, ρ is density, v is velocity and A is the cross-sectional area of the nozzle. When the equation is applied to the sprinkler head, the cross-sectional area A is the orifice area of the open sprinkler head. Mass conservation is required in the nozzle and so the mass flow rate remains constant along the nozzle. The following relations for isentropic and sonic flow can be found from literature [22, p. 68]. These relations apply to flow that is sonic at the nozzle outlet, i.e. pressure ratio between nozzle inlet and outlet is less than the critical pressure ratio described in Equation (3.1). These two relations are

$$\frac{T^*}{T_0} = \frac{2}{\gamma + 1} \tag{3.3}$$

where T is temperature and super script $*$ denotes to nozzle outlet and subindex 0 denotes to inlet. The other relation is

$$\frac{\rho^*}{\rho_0} = \left(\frac{2}{\gamma + 1}\right)^{\frac{1}{\gamma - 1}} \tag{3.4}$$

By assuming the ideal gas behavior for pressurized gas in the pipe network, which can be done for air and nitrogen [22, p. 43], the following equation for the speed of sound is obtained

$$a = \sqrt{\gamma R T}, \tag{3.5}$$

where a is speed of sound and R is the specific gas constant [22, p. 43]. As the mass flow rate is derived for sonic conditions, the velocity v^* in Equation (3.2) is the speed of sound and Equation (3.5) can be substituted into Equation (3.2). Substituting Equations (3.3) and (3.4) into (3.2) and using the ideal gas law in molar form, i.e. $p = \rho R T$ the following equation for the mass flow rate can be derived:

$$\dot{m} = p_0 A^* \left(\frac{2}{\gamma + 1}\right)^{\frac{1}{\gamma - 1}} \sqrt{\frac{\gamma}{R T_0} \frac{2}{\gamma + 1}} \tag{3.6}$$

In Equation (3.6) mass flow rate is now described in terms of stagnation point which corresponds to conditions in the pipe network when it is modeled as a container. Stagnation conditions exist in a system where kinetic and potential energy of gas are assumed to be negligible, like in a container which is large compared to an open nozzle.

If pressure ratio exceeds the critical pressure ratio, i.e. flow is sub-sonic, the mass flow rate through the isentropic nozzle can be derived starting from following Euler equation

$$v^{*2} - v_0^2 + \left(\frac{2}{\gamma - 1}\right) a_0^2 \left[\left(\frac{p^*}{p_0}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] = 0 \tag{3.7}$$

where sub index 0 denotes to conditions at the nozzle inlet [22, p. 57]. In this case velocity at point 0 can be assumed to be 0 and speed of sound can be obtained from Equation (3.5). Superscript $*$ denotes to the point that is located at nozzle outlet and p^* is then the pressure of the surroundings and v^* is the velocity at the nozzle outlet. Using these and arranging terms, equation for the velocity at nozzle outlet is obtained

$$v^* = \left\{\frac{2}{\gamma - 1}\gamma R T_0 \left[1 - \left(\frac{p^*}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}} \tag{3.8}$$

Using Equation (3.2) and relation

$$\frac{\rho^*}{\rho_0} = \left(\frac{p^*}{p_0}\right)^{\frac{1}{\gamma}} \tag{3.9}$$

[22, p. 31], equation for isentropic mass flow rate in sub-sonic conditions is obtained

$$\dot{m} = \rho_0 \left(\frac{p^*}{p_0}\right)^{\frac{1}{\gamma}} \left\{\frac{2}{\gamma - 1}\gamma R T_0 \left[1 - \left(\frac{p^*}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{\frac{1}{2}} A^* \tag{3.10}$$

Arranging terms and using the ideal gas law, the above equation can be expressed in the following way

$$\dot{m} = A^* p_0 \left\{\frac{2\gamma}{R T_0 (\gamma - 1)} \left[\left(\frac{p^*}{p_0}\right)^{\frac{2}{\gamma}} - \left(\frac{p^*}{p_0}\right)^{\frac{\gamma+1}{\gamma}}\right]\right\}^{\frac{1}{2}} \tag{3.11}$$

3.1.2 Isothermal gas expansion

The change of mass of gas in a pipe network can be derived starting from the ideal gas law. The ideal gas law can be arranged to the following form

$$m = \frac{pV}{RT}, \tag{3.12}$$

where m denotes to the mass of gas and V denotes to the volume of gas. The mass flow rate is derivative of mass respect to time. Applying derivation respect to time for both sides of Equation (3.12) and denoting that positive mass flow direction is out of the pipe network, leads to the following equation

$$\frac{dm}{dt} = -\dot{m} = \frac{d}{dt}\left(\frac{pV}{RT}\right). \tag{3.13}$$

When the expansion of gas in a pipe network is assumed to be isothermal V, R and T are constants on the right hand side of Equation (3.13). These constants can be taken out of the derivative and the following differential equation is obtained

$$\frac{dp}{dt} = -\dot{m}\frac{RT_{initial}}{V_{initial}}. \tag{3.14}$$

subindex *initial* denotes to initial condition which occurs at the moment when the sprinkler head opens up. By substituting Equation (3.6) into (3.14), a differential equation for the gas pressure inside a pipe network is obtained for the pressure ratio that is less than the critical pressure ratio. In the following equation flow through the nozzle is described as isentropic flow and expansion in the pipe network as isothermal expansion

$$\frac{dp}{dt} = -\frac{p}{V_{initial}}\left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}}\sqrt{\gamma RT_{initial}\frac{2}{\gamma+1}}A^* \tag{3.15}$$

In the equation above, p_0 in Equation (3.6) is replaced by p to denote that it is constantly changing during the gas discharge, i.e. p denotes to the changing gas pressure inside a pipe network.

By substituting Equation (3.11) into Equation (3.14), a differential equation is obtained for pressure change in the pipe network when pressure ratio between the pipe network and surroundings exceeds the critical pressure ratio and expansion in the pipe network is described as isothermal

$$\frac{dp}{dt} = -\frac{A^*p}{V_{initial}}\left\{\frac{2\gamma RT_{initial}}{(\gamma-1)}\left[\left(\frac{p^*}{p}\right)^{\frac{2}{\gamma}} - \left(\frac{p^*}{p}\right)^{\frac{\gamma+1}{\gamma}}\right]\right\}^{\frac{1}{2}} \tag{3.16}$$

3.1.3 Isentropic gas expansion

Two of the four differential equations for pressure change in a container are now derived, namely the differential equations for gas pressure with sonic and sub-sonic isentropic nozzle flow assuming isothermal expansion of gas in a pipe network. Two remaining equations are differential equations for gas pressure with sonic and subsonic flow through an isentropic nozzle assuming isentropic expansion of the gas in a pipe network. When deriving equations for isentropic expansion, the equations for mass flow rates through nozzle remain the same, i.e. Equations (3.6) and (3.11). Differential equation for isentropic expansion in a container can be derived starting from Equation (3.13). Unlike in isothermal case, temperature is not constant anymore and cannot be taken out of the derivative. The following isentropic relation for temperature and pressure can be used

$$\frac{T}{T_{initial}} = \left(\frac{p}{p_{initial}}\right)^{\frac{\gamma-1}{\gamma}}. \tag{3.17}$$

[22, p. 56]. Subindex *initial* denots to the starting point of expansion, i.e. in the air trip to the moment when the sprinkler head opens up. The temperature of gas at the end point can be expressed in terms of temperature and pressure at the start point and pressure at the end point. By substituting the above equation into Equation (3.13) following form can be obtained

$$-\dot{m} = \frac{d}{dt}\left(\frac{pV_{initial}}{RT_{initial}\left(\frac{p}{p_{initial}}\right)^{\frac{\gamma-1}{\gamma}}}\right) \tag{3.18}$$

By taking the constants out from the derivative and arranging terms, the equation takes the following form

$$\frac{V_{initial}}{RT_{initial}\left(\frac{1}{p_{initial}}\right)^{\frac{\gamma-1}{\gamma}}}\frac{d}{dt}\left(p^{\frac{1}{\gamma}}\right) = -\dot{m} \tag{3.19}$$

The chain rule can be applied to occuring derivative in the following way

$$\frac{d}{dt}\left(p^{\frac{1}{\gamma}}\right) = \frac{d}{dp}\left(p^{\frac{1}{\gamma}}\right)\frac{dp}{dt} \tag{3.20}$$

By applying derivation to term $\frac{d}{dp}\left(p^{\frac{1}{\gamma}}\right)$ and substituting this into Equation (3.19), the following differential equation for the pressure change in the pipe network is obtained

$$\frac{dp}{dt} = -\dot{m}\frac{RT_{initial}}{V}\gamma\left(\frac{p}{p_{initial}}\right)^{\frac{\gamma-1}{\gamma}} \tag{3.21}$$

This equation is for isentropic expansion of gas and corresponds to Equation (3.14) which is the isothermal counterpart. To obtain the full form of differential equation describing pressure change when isentropic nozzle flow and isentropic expansion are assumed, the mass flow rate equations in sonic and subsonic conditions, i.e. Equations (3.6) and (3.11), have to be substituted into equation (3.21).

3.2 Water transit time

After the DPV trip event water starts to flow in to the dry part of the pipe network. The water transit time is the time from the DPV trip event to the moment when the water starts to discharge from the most remote sprinkler head.

In the air trip the volumetric size of the pipe network was the only character of the pipe network that was taken into account. In the water transit, the pipe network characters are taken into account in more detail. Water flow is modeled in every individual pipe during the water transit. To estimate the water delivery time this water flow has to be described by a set of solvable equations. A part of the pressurized gas is still inside the pipe network and as water and gas share a common interfaces, these phases are acting on each other. And so the equations governing the gas phase during the water transit have to be solved as well.

3.2.1 Gas pressures in a pipe network

To obtain the value for gas pressure at the inlet of the most remote sprinkler head after the DPV trip event, the same kind of equations can be used as were used in the previous section. Equations for the mass flow rates through the nozzle, or the open sprinkler head in this case, remains the same as in the previous section, i.e. Equations (3.6) and (3.11). Equations for the mass change of the gas inside the pipe network were derived starting from Equation (3.13). In isothermal case only the pressure changes and in isentropic case also temperature changes. After the trip event of DPV water is flowing in to the dry part of the pipe network and the volume of the gas is gradually occupied by water. Water in the dry part takes space from the gas and so the volume of gas V is decreasing. To obtain equation for the gas pressure inside the pipe network after the DPV trip event, also the volume V in the Equation (3.13) is changing. By starting from Equation (3.13) and applying product rule to appearing differential $\frac{d}{dt}(pV)$ the following equation is obtained for isothermal case

$$\frac{dp}{dt} = -\left[\dot{m}\frac{RT}{V} + \frac{p}{V}\frac{dV}{dt}\right] \tag{3.22}$$

When Equation (3.6) or (3.11) is substituted into this, the differential equations for the gas pressure after the DPV trip event is obtained for isothermal expansion in a pipe network. Term $\frac{dV}{dt}$ describes the change of the volume of gas that is connected to the most remote sprinkler head, this is calculated by product of the cross-sectional area and the velocity of water front that is occupying the dry part. The sign of this term is negative when the gas volume is decreasing.

Equation for the gas pressure in a pipe network that is under isentropic expansion can be derived starting from Equation (3.13). Applying the product rule and the chain rule to appearing differential $\frac{d}{dt}(p^{\frac{1}{\gamma}}V)$ the following equation is obtained

$$\frac{dp}{dt} = -\frac{\gamma}{V}\left[\dot{m}RT\left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}} + p\frac{dV}{dt}\right] \tag{3.23}$$

The equations above describe the gas pressure in the volume that is connected to the most remote sprinkler head.

While the pipe network is filled up with water, the gas in the closed branch pipes is trapped by water. When water starts to flow into these branch pipes, gas is compressed which increases the pressure of trapped gas. Like earlier for expansion, also for compression solutions for two ideal cases can be derived. These equations are for isothermal and for isentropic compression. It should be noted that the amount of trapped gas remains constant during this compression as branch pipe is closed and water traps the gas inside. The following conditions are valid, pV is constant for isothermal compression and pV^{γ} is constant for isentropic compression [4, p. 361]. Starting from these conditions the following equations can be derived

$$p = p_{initial}\frac{V_{initial}}{V} \tag{3.24}$$

for isothermal compression and

$$p = p_{initial}\left(\frac{V_{initial}}{V}\right)^{\gamma} \tag{3.25}$$

for isentropic compression. Sub index *initial* denotes the conditions at the moment when the gas is trapped by the water into the branch pipe. During the water transit these equations have to be constantly solved for each of the branch pipes where gas is trapped.

3.2.2 Water column motions

After the DPV trip, the pipe network starts to fill up with water. In here approximation of sharp front end of a water column is made, i.e. water is not mixing with gas and front end is perpendicular to the longitudal axis of the pipe. To describe motions of water in the pipe network, water is described as individual columns. At the beginning of the water transit these columns are formed out of water in pipes between the water source and DPV. The number of the water columns increases while the parts of the pipe network are filled with water. The pipe network is divided in parts by node points. The node points are located in the water source, in the t-junctions, in the reductions of diameter in pipes and in points at the end of the pipes. Every water column starts from the node point in the pipe network and ends in the node point or in the gas/water interface.

Governing equation for motions of a single water column can be derived starting from the momentum equation for frictionless flow

$$\frac{D\vec{v}}{Dt} = -\frac{1}{\rho}\nabla p - g\vec{k} \tag{3.26}$$

which is a vector equation and where $\frac{D\vec{v}}{Dt}$ is the material derivative of a velocity $\vec{v}$, i.e. $\frac{D\vec{v}}{Dt} = \frac{\partial\vec{v}}{\partial t} + \vec{v}\cdot\nabla\vec{v}$ and $\vec{k}$ is a unit vector in z-direction i.e. opposite direction to force induced by gravity, ρ is density, g is the gravitational acceleration and p is pressure. As flow in this case is approximated to be one dimeansional, direction of a vector $\vec{v}$ is in streamline direction. The above equation can be converted to a scalar equation by applying the dot product with a distance element $d\vec{s}$ which direction is the direction of a streamline. After applying the dot product with a $d\vec{s}$ and expanding the material derivative the following form is obtained [9]

$$vdv + \frac{\partial v}{\partial t}ds = -\frac{1}{\rho}dp - gdz \tag{3.27}$$

The above equation can be integrated between the points in a single streamline to form equation that is called the unsteady Bernoulli's equation

$$\int_1^2 \frac{\partial v}{\partial t}ds + \int_1^2 \frac{dp}{\rho} + \frac{1}{2}\left(v_2^2 - v_1^2\right) + g(z_2 - z_1) = 0 \tag{3.28}$$

where, in this study, index 1 denotes to the beginning of a water column, index 2 denotes to the end of a water column, v is the velocity, z is the height position and s is the water column length along the streamline. In this study equation describes the movements of incompressible fluid and so ρ is independent from pressure. Second integral term can be evaluated to form $\frac{p_2-p_1}{\rho}$. [29, p. 170-171] As pipe filling process is highly time-dependent, the first integral cannot be evaluated analytically as streamline length is constantly changing. The equation above describes the water column motions without viscous forces. In filling process of a pipe network, the viscous forces are crucial and those have to be added to Equation (3.28).

3.2.3 Pressure loss in pipes

A pressure loss term due to the viscous forces can be added to the Bernoulli's equation [29, p. 355]. The pressure loss term has the same sign as terms describing the end of the water column. The following equation is obtained when the pressure loss term is added to Equation (3.28)

$$\int_1^2 \frac{\partial v}{\partial t} ds + \frac{p_2 - p_1}{\rho} + \frac{1}{2}\left(v_2^2 - v_1^2\right) + g(z_2 - z_1) + gh_f = 0 \tag{3.29}$$

where h_f is the head of pressure loss. The head of pressure loss is expressed in the following form

$$h_f = f\frac{v|v|}{2g}\frac{L}{d} \tag{3.30}$$

where f is the Darcy friction factor, L is the length of the water column and d is the pipe diameter.[29, p. 356] For laminar flow the Darcy friction factor is expressed by the following equation

$$f = \frac{64}{Re} \tag{3.31}$$

where Re is the Reynolds number. The Reynolds number is a dimensionless number that describes the behavior of viscous flows. The Reynolds number is calculated by the following equation

$$Re = \frac{\rho v d}{\mu} \tag{3.32}$$

where μ is the dynamic viscosity of the fluid. [29, p. 27] From the Reynolds number, the nature of flow can be estimated. The flow in a pipe is assumed to be laminar if the Reynolds number remains under 2000. The transition from laminar to turbulent flow starts where a laminar regime ends, and when the Reynolds number increases above 4000, pipe flow can be assumed to be fully turbulent. [29, p. 352] Based on experiments, several correlations have been published to calculate the Darcy friction factor for turbulent flow. In this study, the well known Haaland equation is used

$$\frac{1}{f^{\frac{1}{2}}} \approx -1.8log\left[\frac{6.9}{Re} + \left(\frac{\epsilon/d}{3.7}\right)^{1.11}\right] \tag{3.33}$$

where ϵ is the pipe surface roughness. [29, p. 370]

Between the laminar and the fully turbulent flow regimes, i.e. between Reynolds numbers 2000 and 4000, there exists a transition zone. There is no exact representation when the nature of flow changes from laminar to turbulent. So it is hard to find an equation for the Darcy friction factor in this transition zone in the principle books of fluid dynamics. In this thesis the Darcy friction factor for the transition zone is calculated by Equation (3.33) when the Reynolds number exceeds 3000. In the interval between the Reynolds number 2000 and the Reynolds number 3000 the Darcy friction factor is calculated as a linear change from the value of Equation (3.31) at the Reynolds number 2000 to the value of Equation (3.33) at the Reynolds number 3000. This method overestimates the Darcy friction factor in the transition zone as can be seen in Figure 3.1. In the water transit time calculations this leads to slightly longer air trip times. The pipe flow of water in the sprinkler pipe network is mostly turbulent and the transition from laminar to turbulent does not have a significant role. When the water transit is calculated, the Reynolds number of flow might be in the transition zone and some value for the Darcy friction factor has to be given.

An equation for the Darcy friction factor that covers the flow from the laminar to the fully turbulent is proposed in the literature by N. S. Cheng [5]. This equation takes the following form

$$\frac{1}{f} = \left(\frac{Re}{64}\right)^{\alpha} \left(1.8log\frac{Re}{6.8}\right)^{2(1-\alpha)\beta} \left(2log\frac{3.7d}{\epsilon}\right)^{2(1-\alpha)(1-\beta)} \tag{3.34}$$

where $\alpha = \frac{1}{1+(Re/Re_{LT})^m}$ and $\beta = \frac{1}{1+[Re/(\eta r\epsilon)]^n}$ where r is the pipe radius. In the literature constants η, n, m and Re_{LT} are set in a way that the results satisfy the experimental data of Nikuradse [17]. In figure 3.1 the results of the method that is used in this thesis, the experimental data from Figure 9 in [17] and the results of Equation (3.34) are plotted.

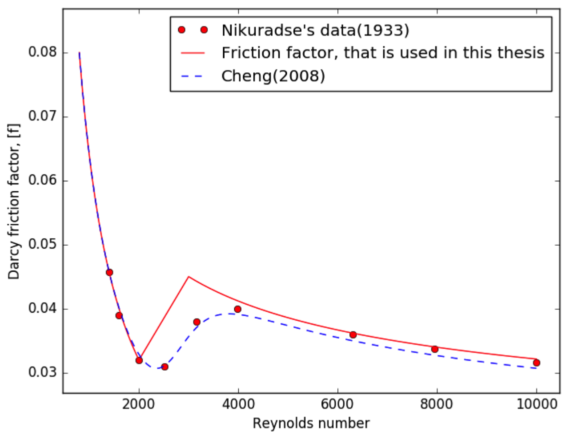

Figure 3.1 *Darcy friction factors from the data of Nikuradse's experiments, from the method used in this study, and from Equation (3.34)*

The experimental data of Nikuradse does not cover every flow situation and the results might only be applicable to limited flow situations. [5] If the test case in Section 7.1 is executed so that the Darcy friction factors are calculated by Equation (3.34), the water transit time is slightly shorter but the difference is only 0.06 seconds. This difference might originate from different values of the Darcy friction factor in the transition zone, but also from slightly different values in the fully turbulent zone. The data points in Figure 3.1 are picked by hand from the figure and the accuracy is poor. The idea of Figure 3.1 is to illustrate the differences between the different methods, but not the exact values of the Darcy friction factor. Equation (3.34) is introduced in this thesis so that the effect of the linear approximation in the transition zone can be somehow estimated.

3.2.4 Local pressure loss

The pressure loss in a pipe consists the pressure loss in a straight pipe, and the local pressure loss in valves, fittings and other additional devices attatched to the pipe. Two commonly used methods exist for the pressure loss calculation of additional devices. The first one is a method where the pressure loss in a device is added to the total pressure loss when fluid flows through the device which is causing the pressure loss. This can be described by equation

$$p_{loss} = \zeta \frac{\rho v^2}{2} \tag{3.35}$$

where ζ is a loss coefficient for a particular device [29, p. 389]. The other method which is used in this study makes use of so called equivalent length. This method is chosen because equivalent lengths are provided from used BIM program where the sprinkler pipe networks are designed.

With the equivalent length method, the pressure loss in a pipe that contains devices causing an additional pressure loss is calculated by Equation (3.27). If pipe contains devices causing an additional pressure loss, length in Equation (3.27) is replaced by equivalent length of the pipe. The equivalent length of the pipe is sum of equivalent lengths of devices and the real length of the pipe. The equivalent length of a device corresponds to a length of a pipe piece with same diameter that causes eqvivalent pressure loss with corresponding flow rate. Both methods provide equal results if the pressure loss coefficients and the equivalent lengths for additional devices are set correctly.

With the used BIM program the equivalent length method had to be chosen. The node points in BIM program are formed only for t-junctions, reductions of diameter and at the end of pipes. This leads to situations where the exact location of the device causing an additional pressure loss is unknown. Forexample there might exist a pipe where there is a horizontal part, a 90° bend, and a vertical part. Data of this pipe from BIM program contains the real length and the equivalent length, etc., but not the exact location of the bend. In this study, an approximation had to be made so that the equivalent length of the additional devices is added linearly while the length of the water column in the pipe is increasing. With pipes full of water this is not an approximation anymore.

A similar linear increase approximation had to be made with the height position of the water front in the pipe. If the feed from BIM program is changed so that nodes are formed also for all additional devices, these approximations does not have to be done anymore. In pipes with moderate dimensions these approximations does not lead to significant errors but for more general coverage of the calculation program this change to the feed is recommended.

3.2.5 Mass conservation

Mass conservation applies to all parts in a pipe network. To meet the requirement of mass conservation, two equations have to be introduced. These two equations are needed in t-junctions and at points where there is a change in the pipe diameter. As water can be treated as incompressible fluid this leads to following form of a mass conservation equation in t-junction

$$A_1 v_1 = A_2 v_2 + A_3 v_3 \tag{3.36}$$

Subscripts 1, 2 and 3 denote pipes connected to the t-junction. For diameter change in a pipe, the mass conservation equation takes the following form

$$A_1 v_1 = A_2 v_2 \tag{3.37}$$

Mass conservation has to be satisfied in all parts of the pipe network during the calculation. The two equations above connects the water column motions together in both sides of a t-junction or a diameter change. When the mass conservation equations are solved simultaneously with equations for the water column motions the mass conservation is satisfied.

Now all the equations governing the air trip and the water transit are introduced. Differential equations describing the gas pressure change in a system are complex, and an analytical solution can easily be obtained only for a case where expansion is isothermal and pressure ratio is less than critical, i.e. for Equation (3.15). The other three differential equations describing gas pressure change in a system have to be integrated numerically. Filling the pipe network with water is a highly time dependent process. An analytical solution for Equation (3.29) cannot be easily found even for one extending water column. A set of equations for a dry pipe network might contain hundreds of equations and to solve this problem numerical methods have to be performed. The solution approach and the solution methods for these equations are described in the following chapters.

4. SOLUTION METHOD OF THE GOVERNING EQUATIONS

To solve the problem described earlier, a computer program is developed in this study. The used programming language is Python 3.5. Python is an object-oriented, interpreted programming language. Compared to system programming languages, Python is relatively easy to learn and fast to write. [23] The interpreted nature with dynamic variable typing makes it ideal for this kind of program development. Additional libraries are written for Python and many of those, like Python itself, are open source. [27] In this study two of the additional libraries are used, called NumPy and matplotlib.

The set of equations for water column motions is converted to a matrix form. In the developed program NumPy library is used to form vectors and matrices and to perform matrix operations to these. NumPy library contains a powerful array object and tools for linear algebra. [18] Matplotlib is a 2-D plotting library for Python. [13] In this study it is used to plot results of the water delivery time calculation. A plotting tool which is fast and easy to use is necessary for this kind of program development. The size of matrices and the number of time steps often come large, and without clear graphical illustration results they are almost impossible to analyse.

4.1 Solution method for the air trip time

In the air trip time calculation, a dry part of a pipe network is modeled as a container from where the gas discharges via an open nozzle. This means that pressure losses of gas flow in pipes, and potential and kinetic energies are assumed to be negligible. Setup of the air trip modeling is illustrated in Figure 4.1.

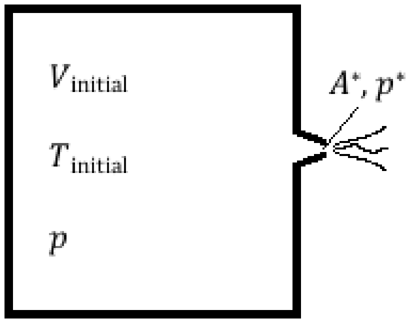

Figure 4.1 *A simple illustration of the air trip modeling.*

In Figure 4.1 volume, pressures, and cross-sectional area are marked like in the governing equations, i.e. Equations (3.6), (3.11), (3.14) and (3.21). $V_{initial}$ is the volume of a container and it corresponds to the volume of dry part in a pipe network. $T_{initial}$ is the gas temperature in the container at the beginning of the air trip, p is the pressure inside the container, A^* is the cross-sectional area of the nozzle which corresponds to the orifice size of the open sprinkler head and p^* is the gas pressure at the nozzle outlet which, in this study, corresponds to the athmospheric pressure.

Equations governing the gas pressure inside the pipe network during the air trip time have to be numerically integrated between the initial gas pressure and the trip pressure of DPV or the activation pressure of the accelerator. This is a so-called initial value problem which can be integrated numerically. The most simple numerical integration method is the Euler's method. The Euler's method takes the following form

$$y_0 = \alpha \tag{4.1}$$

$$y_{n+1} = y_n + hf(x_n, y_n), \qquad n = 0, 1, ..., N-1 \tag{4.2}$$

where α is an initial condition, y_{n+1} is a solution at step $n+1$, h is the length of a step, and $f(x, y)$ is the differential equation. [6, p. 312-313] In the calculation of the air trip time y represents the gas pressure in the pipe network, h is the length of time step, x represents time and $f(x, y)$ is the differential equation for the gas pressure derived in Chapter 3. When performing numerical integration to calculate the air trip time, Equation (5.2) has to be solved repetitively. This is done by a loop in the calculation program with a statement that repeats the loop until the solution reaches the trip pressure of DPV or the activation pressure of the accelerator. The number of time steps equals the repetitions of the loop, and using a loop counter, the air trip time is obtained by multiplying the number of time steps by the length of a single time step.

An analytical solution for a given equation is exact and a numerical solution is an approximation of this. Accuracy depends on the length of a step and the used method. The Euler's method is the most simple to implement, but it is also the least accurate. The Euler's method is first-order accurate, which means that by decreasing the step length by a decade also the error decreases by a decade. From this it can be concluded that the step length should be small when the Euler's method is used. [6, p. 318] More accurate methods are derived as well. In explicite form the methods of Runge-Kutta or alternatively more complex but more accurate implicite methods are available. The computation power of modern personal computers is high and small steps in numerical integration can be used still providing fast solutions. In this study the Euler's and the fourth order Runge-Kutta methods were implemented and compared for the air trip time calculation. The change of gas pressure in a sprinkler pipe network is smooth which favors the Euler's method compared to the Runge-Kutta. In this study, a remarkable difference was not found between these methods in terms of the calculation time that provides an accurate solution.

4.2 Solution method for the water transit time

The water transit is governed by a number of equations for water column motions, a number of mass conservation equations, and by a number of equations for gas pressure. To solve this transient problem, it has to be divided into time steps. The pressure loss term used in Equation (3.29) is only valid for steady flows [29, p. 355]. This leads to the approximation that flow is quasi steady at a single time step. At every time step, the gas pressure ahead of the water front in the flow line is calculated by Equation (3.22) or (3.23) depending on the used approximation for expansion. Pressures of trapped gas in closed branch pipes are calculated by Equation (3.24) or (3.25).

When Equation (3.29) is discretized in time, the transient term $\int_1^2 \frac{\partial v}{\partial t} ds$ can be expressed in terms of the acceleration and the length of the water column in the following way. As water is incompressible and the pipe diameter is constant between node points, the fluid velocity v is independent from point in a stream line. Because of this the partial derivative $\frac{\partial v}{\partial t}$ can be taken out from the integral, and when differentiation is evaluated, the result is the acceleration of the water column. The remaining integral $\int_1^2 ds$ can now be evaluated. Index 1 in the integral term denotes to the beginning of the water column and index 2 to the end of the water column.

When the equation is discretized in time, the integral term $\int_1^2 ds$ then represents the length of the water column l, in a single time step. In the following subsections the calculation method of the water transit is shown by a simple example case.

4.2.1 First stage of the water transit

In this and in the following two subsections a calculation method of the water transit time in a simple tree type pipe network configuration is shown. The pipe network consist of a water source, DPV, two branches, three pipes in the flow line and an open sprinkler head in the end. This example case is illustrated in Figure 4.2.

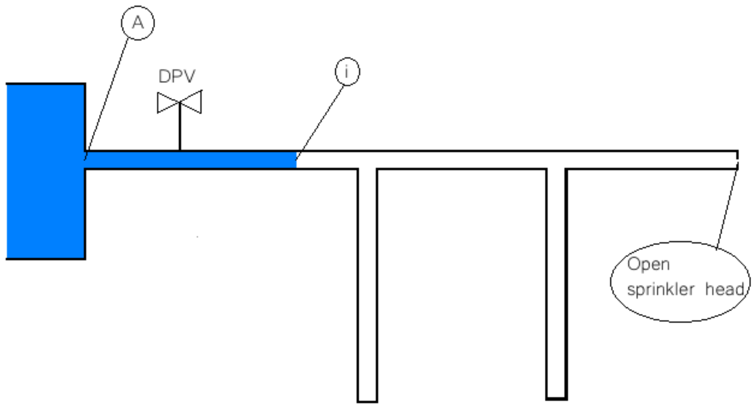

Figure 4.2 *Illustration of a water column in the first stage of the water transit. Only one single water column exists in this stage.*

In this study the opening of DPV is assumed to be instant. In the calculation procedure it means that at the last time step of the air trip, DPV is closed and at the first time step of the water transit it is totally open. At the first time step after the DPV opening the length of the water column is the distance between the water source and DPV, and the velocity of this water column is zero. The water source pressure is the pressure that corresponds to zero volume flow. The gas pressure in the pipe network is the opening pressure of DPV or the activation pressure of an accelerator. These can be used as initial values when Equation (3.29) is discretized in time to obtain an acceleration of the water column at the first time step. Equation (3.29) that describes the water column between the water source and DPV takes the following discretized form

$$a_{A-i,n+1} l_{A-i,n} = H_{A,n} - H_{i,n} \tag{4.3}$$

where a is the acceleration, l is the length of the water column and H is the total head multiplied by the gravitational acceleration. Subindex A denotes to the beginning of the water column. Subindex i denotes to the water/gas intrface in the flow line and subindex $A-i$ to the water column between points A and i. Subindex n denotes to initial values at the present time step and subindex $n+1$ denotes to solution of the time step. $H_{A,n}$ takes the form $\frac{v_{A,n}^2}{2} + \frac{p_{A,n}}{\rho} + gh_{A,n}$, where v_a is the velocity of the water column in water source, p_A is the pressure of the water source, g is the gravitational acceleration and h_A is the height position of the water source. $H_{i,n}$ takes the form $\frac{v_{i,n}^2}{2} + \frac{p_{i,n}}{\rho} + gh_{i,n} + gh_{f,A-i,n}$, where p_i is the pressure in the end of the water column which equals the gas pressure in the pipe network calculated by Equation (3.22) or (3.23), h_i is the height position of the water front and h_f is the head of the pressure loss along the water column calculated by the Equation (3.30).

All the terms in Equation (5.3), except the acceleration, are known from initial values from which the acceleration can be calculated. After the acceleration is calculated, a value for the velocity and the length can be calculated using the Euler's method over a single time step. It has to be taken into account that the time derivative of the water column length is the velocity of the water column and the time derivative of the water column velocity is the acceleration of the water column.

From the velocity and the length of the water column the water source pressure, the gas pressure ahead of the water column, and the pressure loss along the water column can be calculated. After these calculations, the full solution is obtained for the present time step. These values can be used as initial values for the next time step that can then be solved in a same way. In this manner calculation is continued until the water front i reaches the first t-junction.

4.2.2 Second stage of the water transit

The second stage begins when water has reached the first t-junction. The pipe network contains three water columns at this stage. The second stage of the water transit in this example case is illustrated in Figure 4.3. When the water front in the flow line reaches the first t-junction, an initial velocity has to be given for water columns in downstream side of the t-junction. In the developed computer program, an equal initial value is given for the velocity for both of the pipes. The initial values has to be calculated so that the mass conservation is satisfied at every time step.

In this stage, three water columns exist in the pipe network. The water columns are located between points A and B, B and k1, and B and i. Equation (3.29) has to be discretized for all of these water columns. Additionally, there is a flow through

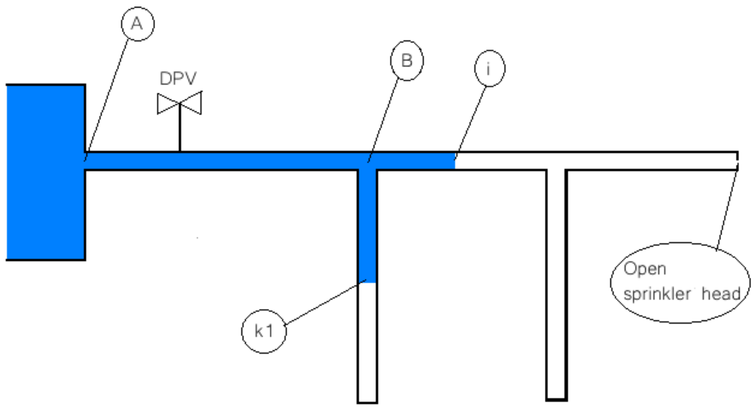

Figure 4.3 *Water columns in the second stage of the water transit. The pipe network contains three water columns in the second stage.*

the t-junction. Mass conservation in the t-junction has to be satisfied at every time step. The mass conservation equation connects the water column motions to each other. In a similar way to the first stage values at the previous time step are used as initial values to calculate the accelerations at the present time step. This leads to a set of linear equations that have to be solved simultaneously at every time step.

In this stage the water column between the water source and the first t-junction ends to an inner node point in the pipe network. Equation (4.3) has to be changed to correspond to the new stage. The discretized equation for the water column between points A and B takes the form

$$a_{A-B,n+1} l_{A-B,n} + H_{B,n+1} = H_{A,n} \tag{4.4}$$

where $H_{B,n+1}$ is the total head multiplied by the gravitational acceleration in the node point B. Except H in the end of the first water column, all the other terms in the above equation remain the same as in Equation (4.3). The discretized equation for the water column between points B and k1 takes the following form

$$a_{B-k1,n+1} l_{B-k1,n} - H_{B,n+1} = -H_{k1,n} \tag{4.5}$$

where $H_{k1,n}$ takes the form $\frac{v_{k1,n}^2}{2} + \frac{p_{k1,n}}{\rho} + gh_{k1,n} + gh_{f,A-i}$ where p_{k1} is the pressure in the end of the water column which equals the gas pressure in the first branch pipe calculated by Equation (3.24) or (3.25). For the water column between points

B and i, the discretized equation takes the form

$$a_{B-i,n+1} l_{B-i,n} - H_{B,n+1} = -H_{i,n} \tag{4.6}$$

In the above equations, the accelerations of all three water columns and the total head in the t-junction are unknown. If Equation (3.36) is derivated with respect to time, also the mass conservation equation can be expressed in terms of accelerations and cross-sectional areas of the corresponding pipes. To satisfy the mass conservation in the t-junction, the following equation has to be solved simultaneously with the three discretized equations above

$$A_{A-B} a_{A-B,n+1} - A_{B-k1} a_{B-k1,n+1} - A_{B-i} a_{B-i,n+1} = 0 \tag{4.7}$$

where A is a cross-sectional area of a pipe. There are four unknown variables in these four equations: the accelerations of the three water columns and the total head multiplied by the gravitational acceleration in the first t-junction. To obtain a solution for this set of equations, the set of equations is expressed in the following matrix form.

$$\mathbf{Ax} = \mathbf{B} \tag{4.8}$$

where

$$\mathbf{A} = \begin{bmatrix} l_{A-B,n} & 0 & 0 & 1 \\ 0 & l_{B-k1,n} & 0 & -1 \\ 0 & 0 & l_{B-i,n} & -1 \\ A_{A-B} & -A_{B-k1} & -A_{B-i} & 0 \end{bmatrix}, \mathbf{x} = \begin{bmatrix} a_{A-B,n+1} \\ a_{B-k1,n+1} \\ a_{B-i,n+1} \\ H_{B,n+1} \end{bmatrix} \quad \textit{and} \quad \mathbf{B} = \begin{bmatrix} H_{A,n} \\ -H_{k1,n} \\ -H_{i,n} \\ 0 \end{bmatrix}$$

The solution of matrix equations is discussed in Section 4.3. Like in the first stage, values at the moment n are obtained from the previous time step. Using the results of the previous time step the accelerations and the total head multiplied by the gravitational acceleration are calculated. From the values of accelerations, like in the first stage, the full solution for the time step can be calculated. At the end of every time step values in the matrix **A** and in the vector **B** have to be updated, using the solution of that step. After the matrix **A** and the vector **B** have been updated, the matrix equation can be solved again to obtain a solution for the next time step. Like in the first stage this calculation procedure is continued until the water front in the flow line reaches the second t-junction.

4.2.3 Final stage of the water transit

The final stage in this particular pipe network begins after the water front has reached the second t-junction. In Figure 4.4 the water columns are illustrated at the final stage. In this stage the pipe network contains five water columns. Discretized

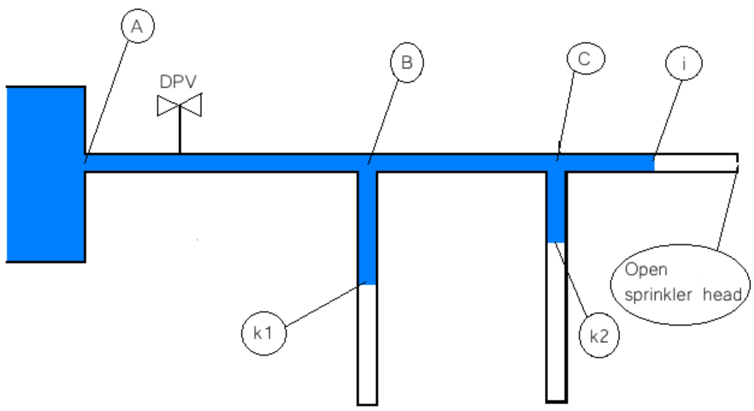

Figure 4.4 *The water columns in the final stage of the water transit. All the pipes contain a water column in the final stage.*

equations for the water columns between points A-B, B-k1, C-i, and C-k2 are formed like in the earlier stages. Also both of the mass conservation equations are similar to one in the second stage. Differing from the water columns in the earlier stages, the water column between points B and C has an inner node point at the both ends. The discretized equation for the water column between points B and C takes the following form

$$a_{B-C,n+1} l_{B-C,n} - H_{B,n+1} + H_{C,n+1} = -g h_{f,B-C,n} \tag{4.9}$$

where h_f is the head of pressure loss along the water column. The matrix and the vectors for the final stage are in the following form

$$\mathbf{A} = \begin{bmatrix} l_{A-B,n} & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & l_{B-k1,n} & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & l_{B-C,n} & 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & l_{C-k2,n} & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & l_{C-i,n} & 0 & -1 \\ A_{A-B} & -A_{B-k1} & -A_{B-C} & 0 & 0 & 0 & 0 \\ 0 & 0 & A_{B-C} & -A_{C-k2} & -A_{C-i} & 0 & 0 \end{bmatrix}$$

Vector **x** which contains the unknown accelerations and the unknown total heads in the t-junctions takes the form

$$\mathbf{x} = \begin{bmatrix} a_{A-B,n+1} \\ a_{B-k1,n+1} \\ a_{B-C,n+1} \\ a_{C-k2,n+1} \\ a_{C-i,n+1} \\ H_{B,n+1} \\ H_{C,n+1} \end{bmatrix}$$

Vector **B** takes the form

$$\mathbf{B} = \begin{bmatrix} H_{A,n} \\ -H_{k1,n} \\ -gh_{f,B-C,n} \\ -H_{k2,n} \\ -H_{i,n} \\ 0 \\ 0 \end{bmatrix}$$

Like in the earlier stages, the accelerations of the five water columns and the total heads multiplied by the gravitational acceleration in both of the t-junctions are obtained as a result when the matrix equation is solved. Using the values of accelerations, the full solution of the time step is obtained in a similar way as in the earlier stages. By using the full solution, the matrix **A** and the vector **B** have to be updated like in the stage two to continue to the next time step. This procedure is continued until the water front i reaches the open sprinkler head. In the developed program, the number of time steps is counted during the water transit time calculation. The result for the water transit time is obtained by multiplying the number of time steps by the length of a single time step.

In a similar way, the discretization, the formation of a set of equations, and the calculation procedure can be performed to a pipe network of any size. Larger number of pipes and t-junctions increases the number of equations and so the size of the matrix and the vectors is increased as well. The developed program is capable to perform this calculation to the pipe network of any size, but of course computer performance starts to limit at some point. This approach is suitable for both the tree and the loop type configurations. When a loop type pipe network is calculated some differencies occurs at the end of the water transit. Differencies are explained in Section 5.3.

4.3 Solution method for the system of linear equations

There are several ways to obtain a solution for a set of linear equations [24]. In this study, a solution is obtained by converting the set of equations to a form of a matrix equation which is then solved by the matrix operations. The set of equations can be converted to the following matrix form

$$\mathbf{A}\mathbf{x} = \mathbf{B} \tag{4.10}$$

where $\mathbf{A}$ is a matrix with known values from the previous time step for the water column lengths, the cross-sectional areas of pipes, and the coefficients for the unknown total heads multiplied by the gravitational acceleration in the inner node points. $\mathbf{x}$ is a vector that contains the unknown accelerations and the total heads multiplied by the gravitational acceleration in the inner node points. $\mathbf{B}$ is a vector that contains the total heads multiplied by the gravitational acceleration in the water source and in the water/gas interfaces, and pressure losses along the water columns from the previous time step. N is the number of the discretized equations of the water column motions and the mass conservation equations in the set of equations that is converted to the matrix form. $\mathbf{A}$ is a square matrix with the size $N * N$ and the length of the vectors $\mathbf{x}$ and $\mathbf{B}$ is N. The value of N changes constantly when the water front passes inner node points in the pipe network and the number of water columns increases. The value of N is the number of water columns in the pipe network added to the number of internal node points that are occupied by water in the pipe network.

In this study an inverse matrix $\mathbf{A}^{-1}$ is formed for the matrix $\mathbf{A}$ to solve the matrix equation above. Both sides of Equation (4.10) are then multiplied by this inverse matrix to obtain the solution for the vector $\mathbf{x}$. [24, p. 163] Linear algebra tools from NumPy library are used to perform these operations [12].

While running the calculation, this matrix equation has to be solved at every time step. As a result, vector $\mathbf{x}$ contains values of the water column accelerations and the total heads multiplied by gravitational acceleration at the inner node points. From accelerations the lengths of the water columns, the velocities of the water columns, the pressure losses, and all the pressures in a pipe network are calculated. After this, the values in the matrix $\mathbf{A}$ and the values in the vector $\mathbf{B}$ are updated and matrix equation is solved to obtain vector $\mathbf{x}$ at the next time step. If the water front reaches an inner node point, the number of the water columns increases and the water columns after this node point have to be taken into the set of equations. This procedure is repeated until the farthest water front in the flow line reaches the most remote sprinkler head.

When a computer is used to perform calculations, several efficient tools are available for solving matrix equations [12]. Mathematically matrix **A** has to be invertible that a solution exist for the matrix equation. [24, p. 170] If there exists a row or a column of zeros in the matrix, the determinant of this matrix is also zero [24, p. 268]. If the determinant of a matrix is zero, it means that the matrix is not invertible [24, p. 271]. A water column length is zero before some water has flown into that particular pipe and this might form a column of zeros to the matrix. To avoid zero values of matrix determinant, small 1 cm initial values are used for the water column lengths in this study.

Theoretically, the value of N has to be changed during the calculation as the number of the equations changes with the changing number of water columns, but by programming techniques it is possible to add equations to the set of equations in an other way. In this study, the value of N i.e. the number of equations, is kept constant and it is initialized by the final value. This can be done if some of the values in the matrix **A** are manipulated during the calculation and the values in the vector **B** are kept as $\frac{p_g}{rho}$ for every empty pipe, p_g being the gas pressure in the volume connected to the open sprinkler head. The manipulated values are the cross-sectional areas in the mass conservation equations. The cross-sectional area of the pipe from where the water front in the flow line will reach the internal node is set to zero in the mass conservation equations of empty internal nodes. When the water front reaches the corresponding node point, the value of this cross-sectional area is changed to the actual value. This manipulation forces the values of the accelerations to zero in the pipes that are still empty. By keeping the size of the matrix and the vectors constant, it was easier to write the program, but in future development this has to be changed to a method where the size of the matrix and the vectors is changed during the calculation. For the results there is no difference between the different methods, but the matrix inversion is a calculation intensive procedure and the size of the matrix should be kept as small as possible to provide results quickly.

The time it takes to solve a matrix equation depends on the matrix size, but also the method how the matrix equation is solved has an influence. Solving the matrix equation by the inverse matrix is not the fastest way [6, p. 223]. In the future development the most suitable way to solve this type of a matrix equation has to be investigated. In the water transit time calculations many of the entries in the matrix **A** are zero, at least when the pipe network contains a large number of pipes. For example in the case in Subsection 4.2.3, around 65% of the matrix entries are zero. If one t-junction and two water columns are added, 75% of the matrix entries are zero. If one more t-junction and two more water columns are added, 80% of the matrix entries are zero. When real installations are calculated, the matrix size is usually much larger, like in Chapter 7.1. A matrix where most of the entries are zero is called a sparse matrix. For the sparse matrices a special data type exists in many of the computational libraries. When a matrix is converted to the sparse form, solution for the matrix equation might be found more efficiently. [6, p. 196, 223] For Python programming language sciPy library provides the sparse matrix data structure and the linear algebra tools for the matrix equations in the sparse form [25].

4.4 Total head at the inner node point

The solution of the previously described matrix equation contains accelerations of water columns and total heads multiplied by the gravitational acceleration in the inner node points. From accelerations water column velocities and lengths can be calculated as described earlier. So far, the total heads multiplied by the gravitational acceleration in the inner node points seem to be useless auxiliary variables. This is the case when a pipe network fills up in order from DPV, pipe after pipe, and pipes do not get empty during the water transit anymore.

A total head in an inner node point comes in use, for example, when there is a large drop in elevation after a t-junction. When the water front in the flow line has reached the inner node point in the t-junction, the branch pipe(connected to this t-juntion) starts to fill up. If there is a drop in the flow line after this t-junction, the gravitational force makes a suction to the t-junction. This suction drops down the total head at the t-junction, which turns the flow direction in the branch pipe to the negative direction. If the height difference is large enough, the branch pipe that is connected to the t-junction might get empty and if the calculation is continued, the water column starts to get unrealistic negative values. In the previously described equations nothing prevents a water column to get negative values. If the flow in a branch pipe is in negative direction it acts like a water source to the system when the branch is empty, which will reduce the calculated water transit time. To avoid this kind of behavior, calculated total heads in the inner node points are used to set a correct gas pressure to the empty branch pipe.

The initial value of the gas pressure in the closed branch pipe is set to the level of the gas pressure ahead of the water front in the flow line at the moment when water traps the gas into the closed branch pipe. This initial value is then used when the gas pressure in a closed branch pipe is calculated by Equation (3.24) or (3.25).

In reality, when a branch pipe gets empty, some of the gas will flow out to adjust the gas pressure to the level of the pressure at the beginning of the pipe. In the developed computer program the total heads at the inner node points are used to set the correct gas pressure to the empty branch pipes. The initial gas pressure is set to a new value at every time step when the value of the water column length in the branch pipe is negative.

A branch pipe might get empty also if the gas pressure ahead of the water front in the flow line is great when gas is trapped into the branch pipe but decreases rapidly after this. This might occur at the very end of the water transit. If the volume of the branch pipe is large compared to the gas volume connected to the open sprinkler head and orifice size of the open sprinkler head, the gas pressure in front of the water front in the flow line decreases rapidly. This behavior of gas pressure can be seen in Figure 7.4, but in that case it does not lead to empty branch pipes. The reason for this behavior can be seen in Equations (3.22) and (3.23). Gas volume V is a denominator in these equations. When the volume of a branch pipe forms the major part of V, the gas pressure starts to decrease rapidly when the volume V is reduced by the volume of the branch pipe.

4.5 Time step length

As stated before, the accuracy of the Euler's method is improved when the time step length is decreased. In the developed computer program the number of performed calculations increases almost linearly when the time step is decreased. This leads to a linear increase in the program execution time. In Table 4.1 the difference of the water delivery time, the execution time of calculation, and the used time step are shown for a test case illustrated in Section 7.1.

Table 4.1 *The calculation result of the water transit time, the execution time of algorithm, and the used time step.*

Water transit time [seconds]	**Execution time [seconds]**	**Used time step [seconds]**
21.411	2972.941	0.0001
21.409	1688.462	0.0002
21.406	512.156	0.0005
21.399	258.002	0.001
21.34	51.854	0.005
21.280	25.880	0.01
20.750	5.276	0.05
20.4	3.323	0.1

In Tabel 4.1 the results of the water transit time can be seen when different time step lengths are used. The difference in the water transit time is fairly small between different lengths of time steps, under 5.5%. When the time step is decreased the result of water transit time slightly increases and sets to 21.41 seconds.

In this test case, 0.1 seconds was the longest time step that gives a result. When the time step was increased to 0.2 seconds the water transit time calculation results an error. At the time step when a pipe starts to fill up, an initial value for the water column velocity has to be given so that mass conservation in a node point is satisfied. With a long time step this initial value might result in a water column length that is longer than the pipe itself after one time step. In the closed branch pipes this is an unrealistic situation and the calculation program is written in a way that it raises an error in these situations.

To prevent this kind of behavior, short, under 1 meter pipes that are connected to the flow line and to a closed sprinkler head are removed from a set of equations. The diameter of these pipes fits to a connection size of sprinkler heads and so the volume of these pipes is small compared to the volume of whole system. As the volume of these pipes is small and so the amount of water that accumulates in them is small, they can be removed. Still, some short pipes might exist in the pipe networks and the time step has to be individually adjusted for every case. It is safe to use a small time step but the execution time might then become too large. The length of a time step is a compromise between accurate results and a short execution time.

5. SOLUTION APPROACH FOR REAL SYSTEMS

To obtain a set of equations that describe a real system but is easier to solve than the whole configuration, it is useful to simplify the actual pipe network. In the water delivery time calculation, the length of time when the front end of water reaches the most remote sprinkler head is under the scope. In this study, a flow line that is the path between the water source and the most remote sprinkler head is calculated precisely without simplifications. Instead, the branch pipes where every sprinkler head is closed can be simplified in a way that is shown in the literature [15]. The simplification of closed branch pipes is explained in Section 5.1.

The method shown in the literature simplifies the whole dry pipe network into five pipes, each containing a water column at the end of the water transit [15]. If a system simplified in this way is calculated like the example case in Section 4.2, this leads to a matrix and vectors whose sizes are known beforehand. In this method the size is always the same, no matter of the number of branch pipes in the actual system.

Differing from the literature, in this study the number of branch pipes connected to the flow line remains the same as in the actual system, and the number of branch pipes is not limited. The individual forks from flow line are simplified as shown in the next section. This approach leads to a matrix and vectors whose sizes are not known beforehand, and the sizes vary between different systems. In Figure 5.1, an example of one actual configuration is shown, and in the next section simplifications are described in more detail.

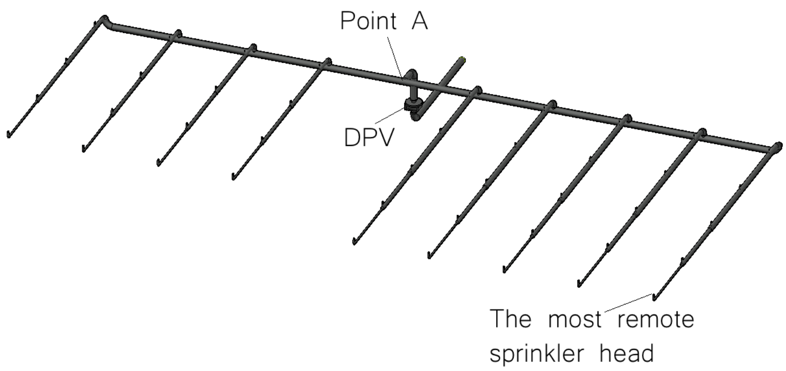

Figure 5.1 *A tree type sprinkler pipe network. This pipe network is simplified as an example to form feed data for the water delivery time calculation algorithm.*

5.1 Formation of equivalent system

From BIM program, two sets of data that describe the designed pipe network are obtained. The first data set contains information of the node points in the pipe network. For every node point the data includes:

- the node number
- the height position of the node
- the index which indicates if the node is a sprinkler head or not
- the index which indicates if the node is in the flow line or not
- the K-factor of a sprinkler head if a sprinkler head is connected to this node point

The other data set contains information on the pipes between the node points. The data set of pipes contains:

- the node number at the beginning of the pipe
- the node number at the end of the pipe
- the equivalent length of the pipe
- the actual length of the pipe
- the inner diameter of the pipe

- the Hazen-Williams coefficient of the pipe
- the surface roughness of the pipe
- the flow index which indicates if the pipe is in the flow line or not

This data is supplied in form of two text files which are read in the developed program. From this data, the feed for the developed calculation algorithm is formed. This data is simplified, as shown later to make calculation easier. In the developed program, the simplified data is saved in a suitable form for the calculation.

In some configurations only part of the main pipe is in the flow line, like in the one illustrated in Figure 5.1. Part of the main pipe which is out of the flow line is still connected to a number of branch pipes and those branch pipes are connected to a number of head pipes. This part is on the left hand side of the point A in Figure 5.1. This part is connected to the flow line only from one point. This dead end part is simplified in this study by replacing it with a single pipe that has the same diameter as the one which is the actual connection diameter to the flow line. The length of this pipe is calculated in the way that it has the corresponding volume to all pipes connected to this simplified part. The same kind of simplification is done to all branch pipes and head pipes out of the flow line i.e. the flow line contains as many forks as there are in the actual pipe network. Each one of these forks is a single pipe with volume corresponding to the actual volume and the diameter the same as the diameter of the actual connection to the flow line.

As there is no flow through these simplified pipes and water is more like accumulating in than flowing through these pipes during the water transit, this simplification can be done. The flow line where water is flowing from the water source to the most remote sprinkler head is not simplified in any way. In Figure 5.2 the simplified system is shown. This system originates from the system shown in Figure 5.1.

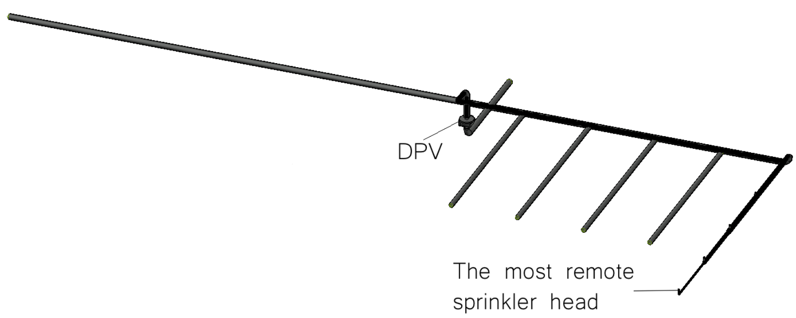

Figure 5.2 *A simplified configuration for the calculation algorithm. The flow line is the path between DPV and the most remote sprinkler head.*

5.2 Form of feed to the calculation

In the simplifications introduced in the previous section, data from BIM program is modified to describe the simplified system. To form the feed for the calculation algorithm and to perform calculations, a class is defined to form an object for every pipe in the simplified pipe network. To these objects values are stored which describe the characters of pipes and water columns between the node points in the simplified pipe network. Additionally, a number of methods is defined in the class for these objects. [27, Ch. 9] For the calculation all the objects describing the pipes and the water columns in the simplified pipe network are stored into a list type data structure in the computer program so that every element in the list contains the data of a single pipe and the data of the water column in it.

The needed values of the pressure levels for calculation are the initial gas pressure, the pressure of the water source, and the trip pressure of DPV or the activation pressure drop of the accelerator. The water source pressure can be given as a single constant value or as data pairs connecting the pressure of the water source to the certain volume flow.

In the developed computer program numpy.polyfit function is used to obtain the polynomial function for the water source pressure. The polyfit function in the numpy library uses the least squares method to obtain the coefficients to the polynomial function from discrete data points [19]. Data pairs could be obtained from a pump curve if a pump is selected, or the same kind of curve or data could be received for municipal water line. In the calculation algorithm developed in this study, five data pairs are used and a third order polynomial function is formed from these data pairs, this is illustrated in Figure 7.2. The polynomial function provides a water source pressure at every volume flow occuring during the water transit. When the calculation is executed care should be taken that the interval of the data points covers the occuring volume flows in the water source.

The accuracy of the polynomial function depends on the shape of an actual curve and on the degree of the polynomial function. To increase the degree of the polynomial function, the number of data pairs has to be increased as well. By the least squares method the best fit for the given data can be obtained. Usually pump curves and water line curves are fairly smooth and a third order polynomial correlates well with the actual curves. [14, p. 23-32]

Additionally, the diameter of the open sprinkler head orifice, the initial temperature of gas, the gravitational acceleration, and the following material properties have to be given: the ratio of heat capacities of gas, the specific gas constant, the dynamic viscosity of water, and the density of water.

5.3 Solution approach for a loop type pipe network configuration

For the loop type pipe networks, the solution approach differs from the tree type configurations. A similar simplification can be done for the parts of the pipe network where every sprinkler head is closed. The flow line is different from what it is in the tree type configuration. In the tree type configurations the flow line is a single path from DPV to the most remote sprinkler head. In the loop type configurations the flow line is a loop as well, so there are two routes from DPV to the most remote sprinkler head. This makes the calculation procedure of the water transit in the loop type pipe network different from the calculation procedure of the tree type pipe network. Equations describing the water transit in the loop type networks remain the same as for the tree type pipe networks for every water column, internal node point, and for every gas volume.

In a tree type pipe network the calculation of the water transit is straight forward as shown in Chapter 4.2. The calculation of a loop type pipe network follows the same routine until the farthest water front reaches the t-junction where the most remote branch pipe begins, i.e. the farthest water front reaches Node A in Figure 5.3. After this moment a gas volume appears between two of the water fronts. This gas volume can be seen in Figure 5.3 and it appears between Node A and the water front B. After this moment, in the developed program, the calculation is stopped and the list of pipes and the set of equations are modified. This has to be done because it is not known in prior which one of the water fronts in the loop part will reach this internal node point first. This moment is illustrated in Figure 5.3.

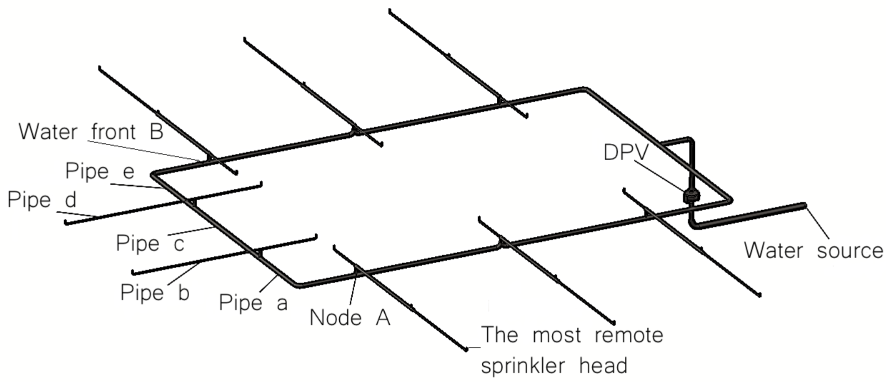

Figure 5.3 *A loop type configuration at the moment when a gas volume appears between two water fronts.*

In the case of Figure 5.3 the farthest water front in the flow line has just reached the internal node point A and the other water front(water front B) in the flow line is at the beginning of pipe e. Node A in Figure 5.3 is the internal node point where the branch pipe to the most remote sprinkler head begins. Of course all the pipes from DPV to the farthest water fronts have water columns in them at this moment.

The calculation is stopped at the moment when one of the water fronts reaches the node point A. After the calculation has been stopped, pipes a, b, c, d, and e are replaced by two pipes in the list of pipes and the set of equations is updated to correspond this new situation. The two replacement pipes have the diameter of pipe a and pipe e and the length of these pipes is calculated so that the sum of the volumes of these two pipes correspond to the sum of the volumes of pipes a, b, c, d, and e. In a similar way the gas volume between the farthest water fronts is modeled in any loop type pipe network, no matter of the number of actual pipes between these water fronts.

The water columns in these two replacement pipes are modeled like the water columns in the branch pipes where all the sprinkler heads are closed. One exception occurs: when the gas pressure in these pipes is calculated by Equation (3.24) or (3.25), the initial volume is the volume of both of these pipes and the gas volume is the initial volume minus the volume of water columns in these pipes. This leads to an equal gas pressure in both pipes which models the gas pressure between the farthest water fronts in the actual system. After these modifications the calculation is started again and continued until the water front reaches the most remote sprinkler head.

6. DIFFERENCE BETWEEN THE USED ASSUMPTIONS

A number of assumptions and approximations have to be made when a fast calculation method is developed. When assumptions and approximations are made those have to be validated, if possible or at least errors have to be estimated. In this chapter some of the errors are estimated for different assumptions.

6.1 Expansion of gas in the pipe network

Expansion can be said to be a cooling process. It means that the temperature of the expanding media will decrease if heat is not provided. As stated before the expansion is isothermal if the heat transfer is infinite. In the case of the pipe network, isothermal expansions mean that on standby mode the pipes and the gas in the pipes are adapted to the temperature of surroundings and during the expansion the gas temperature remains at this constant value. In actual systems the heat transfer is never infinite but the amount of heat transferred is a product of the heat transfer rate and the length of heat transfer process. This means that if the expansion is relatively slow and some heat transfer occur expansion can be close to isothermal.

An isentropic process is also adiabatic which means that no heat is transferred during the process. In reality, processes can be assumed to be isentropic if the amount of heat transferred is small. This means that the heat transfer rate is small or the process is fast.

By taking the existing pressure levels in the dry pipe sprinklers from Table 2.1 and the volume restrictions of the dry pipe sprinklers into account, differences between the isothermal and the isentropic expansion assumptions in a pipe network can be compared [3]. The errors of the air trip time will be largest when the air trip time is longest. These long air trip times occur when the dry part of the system is large and the orifice size of the open sprinkler head is small. The restriction that a Quick Opening Device has to be used when the volume of dry part in the pipe network exceeds 750 litres means that the longest air trip times occur in systems with the size of 750 litres. As the water delivery time is usually longest with systems of 4000 litres and difficulties to meet the water delivery time restrictions are hardest with these systems, also the results of the system with the accelerator installed are compared.

As can be seen from the differential equations governing the air trip time i.e. Equations (3.14) and (3.21), temperature affects the air trip time. By increasing the gas temperature, the pressure change respect to time increases which leads to a shorter air trip time. Vice versa, with a low initial temperature a longer air trip time is obtained. For this validation temperature is chosen to be - 30°C which is assumed to present the coldest environments where the dry pipe sprinkler systems are used.

Air is used as discharging gas with the ratio of specific heat capasities as 1.4 and the specific gas constant as 287 $\frac{J}{kgK}$. In these calculations the open sprinkler head orifice diameter is 1.27 cm which represents the smallest normally allowed sprinkler head size [10, p.15]. Initial air pressures obtained from the Table 2.1 are 0.7 bar, 1.6 bar, 3.0 bar, 4.0 bar and 4.6 bar. For calculation of a 750 litre system, the gas pressures of the DPV trip are respectively 0.255 bar, 0.745 bar, 1.82 bar, 2.56 bar, 2.91 bar. For a larger 4000 litre system differences are calculated assuming that the accelerator is installed. The pressure drop of 0.14 bar is used as an activation pressure drop of the accelerator [10, p. 10]. In Table 6.1 the results of the calculation are shown.

Table 6.1 *Calculation results for the air trip time in the extreme cases.*

System volume [liters]	**Initial pressure/ Final pressure [bar]**	**Air trip time, isothermal [Seconds]**	**Air trip time, isentropic [Seconds]**	**Difference [Seconds]**
750	0.7 / 0.26	11.04	9.17	1.87
750	1.6 / 0.75	13.23	12.38	0.85
750	3 / 1.82	11.56	12.23	-0.67
750	4 / 2.56	11.21	12.65	-1.44
750	4.6 / 2.91	11.82	13.77	-1.95
4000	0.7 / 0.56	15.17	12.59	2.58
4000	1.6 / 1.46	9.62	9.01	0.61
4000	3 / 2.86	6.2	6.57	-0.37
4000	4 / 3.86	4.95	5.58	-0.63
4000	4.6 / 4.46	4.41	5.14	-0.73

The calculations are made for the extrem cases taking the CEA Sprinkler Systems: Planning and Installations into account [3]. The requirements in different parts of the world vary and larger systems are allowed in some places [16]. As can be seen from the results, if the expansion is calculated as isothermal, longer air trip times are obtained at the low initial pressures and shorter times at the higher initial pressures when compared to the isentropic expansion results. The largest differences that are obtained between these two methods are around 17% which is a somewhat large difference. The absolute difference between these two methods is well under 3 seconds in every case which is 5% of the total 60 second time restriction. The air trip times are fairly fast processes, which favors the isentropic expansion approximation, but to justify this assumption or to derive more accurate one, a heat transfer study between the gas and the pipes has to be made.

6.2 Compression of trapped gas in the branch pipes

Among the other things the water delivery time depends on the amount of water that has to be pumped into the pipe network before water starts to discharge from the open sprinkler head. In a pipe network this amount consists of the volume of the flow line and the volume change of the trapped gas in the closed branch pipes, i.e. the volume of the water that is accumulated into the branch pipes. The compression of the trapped gas in the branch pipes is governed either by Equation (3.24) or by Equation (3.25) i.e. the isothermal or the isentropic compression respectively. To estimate the differences between these two assumptions, the maximum pressure is obtained from sprinkler system restrictions [3, p. 44] and the minimum initial pressure is the atmospheric pressure. The change of unit volume from the minimum pressure to the maximum pressure was calculated. Results are shown in Figure 6.1.

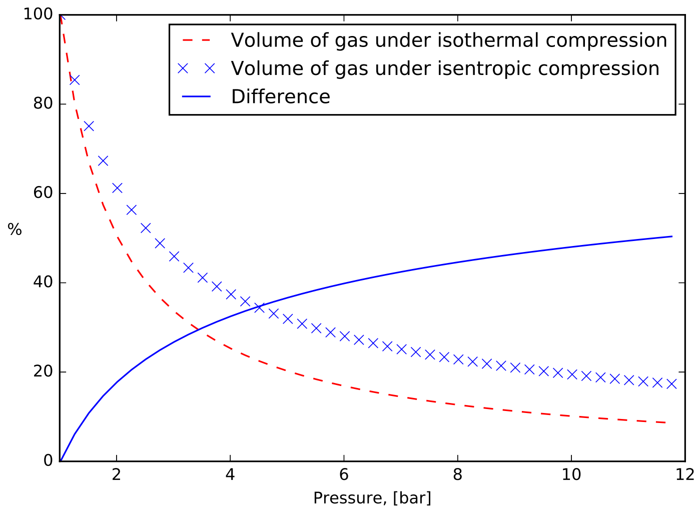

Figure 6.1 *Volume of the gas compressed isothermally and isentropically from 1 bar to 12 bars.*

To estimate the difference in the water delivery time between these two assumptions, calculations for the existing dry pipe system is performed with both assumptions. This system is introduced in more detail in Section 7.1. The pipe network in this test is somewhat large with the dry part volumetric size of $4.8m^3$. The tree type pipe network consist of 22 branch pipes. With the isothermal assumption, the water transit time is 21.4 seconds and the amount of water accumulated to the closed branch pipes is $0.56m^3$. With the isentropic assumption for the gas compression, the water transit time is 21.0 seconds and the amount of water accumulated to the closed branch pipes is $0.47m^3$. The difference in the water transit time is not large in this test. In this particular pipe network the main pipe diameter and the volume were large compared to the volume of branch pipes.

A test with another pipe network with a smaller main pipe and extremely long branch pipes gives the following results. The volume of dry part in this system is $3.9m^3$, the calculated water transit time is 48.7 seconds and the amount of accumulated water is $1.49m^3$ if the compression is assumed to be isothermal. With the isentropic assumption for compression the calculated rersults are 44.1 seconds for the water transit time and $1.23m^3$ for the accumulated water. The absolute difference is 4.6 seconds which is around 7.7% of the 60 second water delivery time restriction.

As can be assumed from Equations (3.24) and (3.25), more water is accumulated to the branch pipes if the isothermal compression is assumed. In both cases the isothermal assumption leads to a longer water transit time, which is intuitive because more water has to be pumped into the system before water starts to discharge from the most remote sprinkler head.

7. RESULTS, ANALYSIS AND FUTURE WORK

In this chapter one test case is introduced where the results from the developed program are compared to the results of a commercial program. Due to the lack of water delivery time results from experiments or from other calculations only the results of this one test case can be compared. In Section 7.2 the results of a loop type pipe network calculation are shown to illustrate how the developed program works with the loop type pipe network configuration. In the last section of this chapter suggestions for the further development are given.

7.1 Tree type pipe network configuration

In the first example case, the water delivery time calculation is performed to the tree type pipe network configuration. The pipe network configuration of the test case is shown in Figure 7.1. The first test case includes a long feed pipe between the water source and DPV. The whole feed pipe is not shown in Figure 7.1.

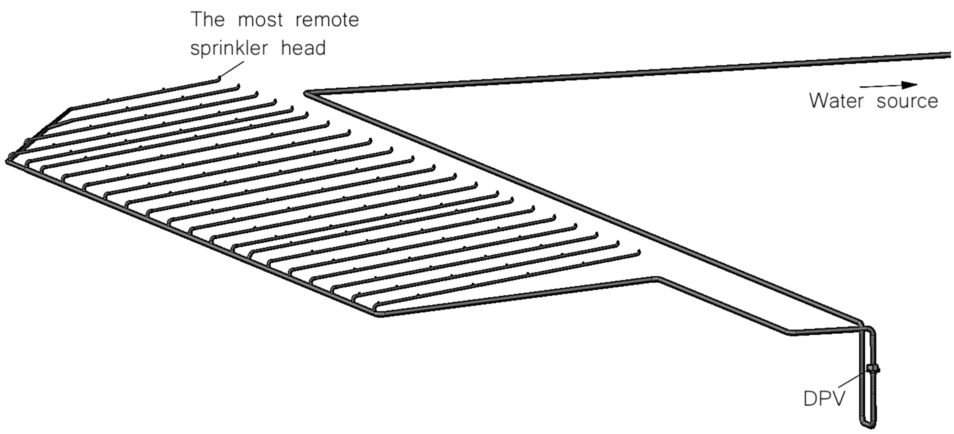

Figure 7.1 *Pipe network configuration in the first test case.*

The feed pipe consists of a 180-meter-long pipe with the inner diameter of 280 mm, and a 246-meter-long pipe with the inner diameter of 200 mm. The height position of the water source is minus 10 cm and the height position of DPV is 5.5 meters. The sprinkler system consists of 120 sprinkler heads. The height position of the most remote sprinkler head is 8.9 meters. The diameter of the most remote sprinkler head orifice is 23.6 mm. The volume of the dry part in the system is 4793 litres. The water source pressure is given in a form of five data pairs. This data is shown in Table 7.1

Table 7.1 *Data set of the water source pressure.*

Flow $[m^3/s]$	**Pressure [bar]**
0	10.7
0.126	9.8
0.189	8.5
0.221	7.4
0.252	6

From this data set a third order polynomial is formed to obtain the water source pressure at every volume flow. The polynomial takes the following form

$$p = -29605713 * Q^3 + 2063780 * Q^2 - 499512 * Q + 1069975 \tag{7.1}$$

where p is the pressure in Pascal units and Q is the volume flow in m^3/s. When the calculation of is executed maximum volume flow is 0.255 m^3/s. This is slightly more than the interval of the data points, but still acceptable. In Figure 7.2 the points of this data set and the plot of the polynomial function are illustrated.

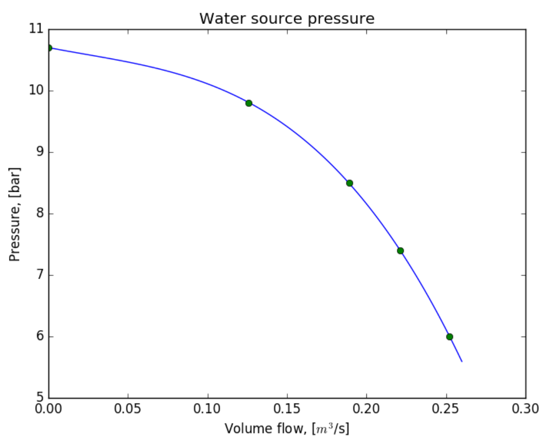

Figure 7.2 *The plot of the polynomial function and the data points of the water source pressure.*

In Appendix A the initial values and the material properties that are used in this example case are listed in more detail. Also the text files obtained as a feed from BIM program are shown in Appendix A. The whole pipe network configuration is described by these text files. The only addition is the location of DPV that is given by hand in the developed program.

An accelerator was installed in the system but, in this case, DPV is opened by the pressure difference over DPV. As the pressure of water source is 10.7 bars on standby mode and as the pressure ratio for DPV opening was given as 5.5(water/gas), the gas pressure is 1.945 bars at the moment when DPV opens. The standby gas pressure of the system is given as 2 bars, which is lower than it should be in reality reffering to Table 2.1. As the pressure change during the air trip time is only 0.05 bars, the difference between the isothermal and the isentropic expansion is negligible 0.025 seconds. When calculated by the program developed in this study, the results of the air trip time are 1.014 seconds and 1.039 seconds for the isothermal and the isentropic expansion respectively. This is somewhat larger than the result of the commercial computer program which gives the result of 0.61 seconds.

Figure 8 on page page 15 of [10] gives an alternative reference for the air trip time calculation. The values of gas pressures are converted to the Pascal units and the air trip time between the pressure levels of 172093 Pa and 170852 Pa is calculated assuming the isentropic expansion. The developed program gives a result of 4.82 seconds while the value in the literature is 5 seconds. This result is in sufficient range. Again the pressure difference is small and 0.01 psi difference in the initial values results an error of 0.27 seconds. From this it can be concluded that the 0.18 second difference is so small that it might originate from rounding errors or other small errors in the initial values.

After the air trip time, the water transit time is calculated. For this tree type configuration the result of the water transit time is 22.23 seconds when calculated by the commercial program. The values that are used in the commercial program for the surface roughness of pipes, the temperature of gas, and the material properties of fluids are unknown. The values that are used when the calculations are performed by the developed program are given in Appendix A. Two different values are used for the surface roughness of pipes to show the effect of the surface roughness to the water transit time. If the surface roughness is set to 0.045 mm, which could be the roughness of a new steel pipe, the developed program gives a result of 21.4 seconds for the water transit time. If the surface roughness is set to 0.15 mm, which could be the roughness of galvanized iron, the result for the water transit time is 22.5 seconds. In these calculations the isothermal assumption is used for the gas expansion and compression in the pipe network.

Several graphs can be plotted from the results of this calculation. As the problem is time depedent, x-axis describes the time in seconds from DPV opening in every graph. In Figure 7.3 the volume of gas that is connected to the most remote sprinkler head is plotted.

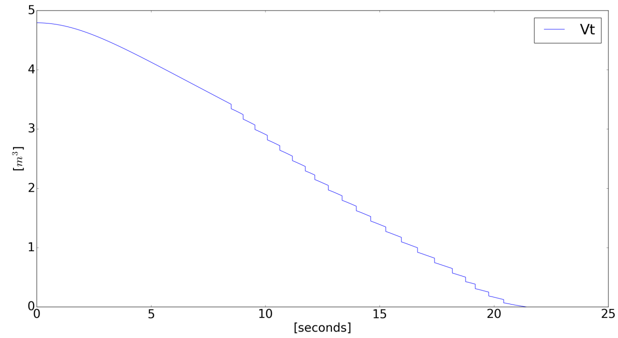

Figure 7.3 *The volume of gas that is connected to the most remote sprinkler head during the water transit.*

In Figure 7.3 the plot starts from 4.8 m^3 as it is the total volume of the dry part in this pipe network. Around 8.5 seconds after the DPV trip event, the water front reaches the first t-junction which is the beginning of the first branch pipe. This can be seen from the plot as there is a step change in the gas volume. The gas volume is decreased by the volume of the branch pipe as gas in the branch pipe is separated instantly when water traps the gas. A similar step change occurs in the gas volume every moment when the water front passes the t-junction where a branch pipe begins. Eventually the gas volume decreases to zero when the water front reaches the most remote sprinkler head.

In Figure 7.4 the gas pressure in the volume that is connected to the most remote sprinkler head is plotted.

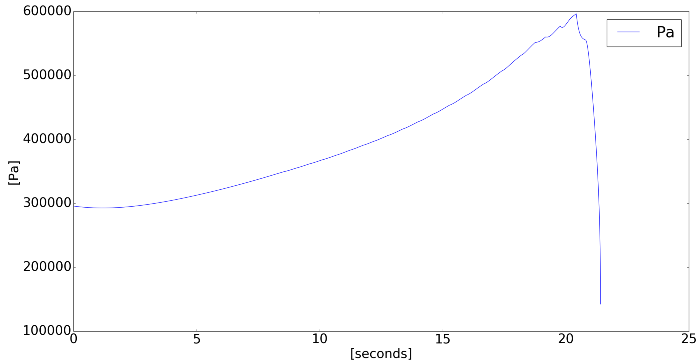

Figure 7.4 *The gas pressure that is connected to the most remote sprinkler head during the water transit.*

In this test case, the volume flow of water in the flow line is most of the time greater than the volume flow of gas through the most remote sprinkler head, which leads to an increase in the gas pressure. At the end of the calculation the gas volume is so small that pressure starts to decrease rapidly. This behavior can be seen in Equation (3.22) where the gas volume is a denominator. Also the small diameter of the last pipes increases the pressure loss along the water columns, which leads to a smaller volume flow in these pipes.

During the water transit, the pipes in the flow line are filled one after another until the last pipe in the flow line is full. In Figure 7.5 the water column lengths in the pipes in the flow line are plotted.

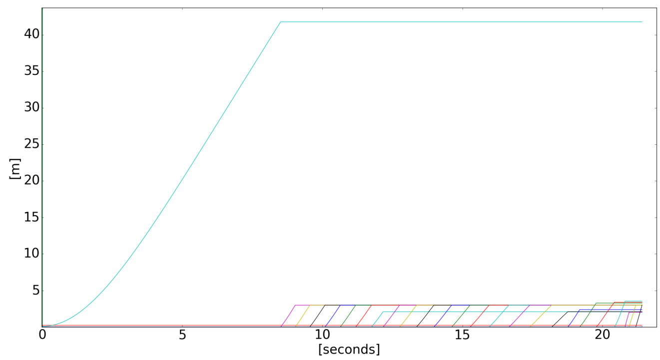

Figure 7.5 *The water column lengths in the pipes in the flow line during the water transit.*

In figure 7.5 the pipes in upstream side of DPV are not shown, because these pipes are already full at the beginning. As it can be seen, the length of the first pipe on the downstream side of DPV is around 42 meters. When the water front reaches a t-junction, the pipe on the upstream side of the t-junction is filled and the next pipe in the flow line starts to fill up. Most of the pipes in the flow line are short as the distance between the branch pipes is between 2 to 3 meters.

In Figure 7.6 the water column lengths in the branch pipes are plotted. There are 22 branch pipes in this pipe network configuration and one of them is the branch pipe to which the most remote sprinkler head is connected. The water column lengths in the 21 closed branch pipes are shown in Figure 7.6. From these plots the dynamic behavior of the water transit in the sprinkler pipe network can be seen. When the water front reaches a t-junction, water starts to flow at the same velocity to both of the empty pipes on the downstream side of this t-junction. As can be seen, the water column lengths in the branch pipes increase quickly at the beginning, but when the pressure of trapped gas in the branch pipe increases, the velocity of the water column in the branch pipe decreases and some backward flow is also obtained.

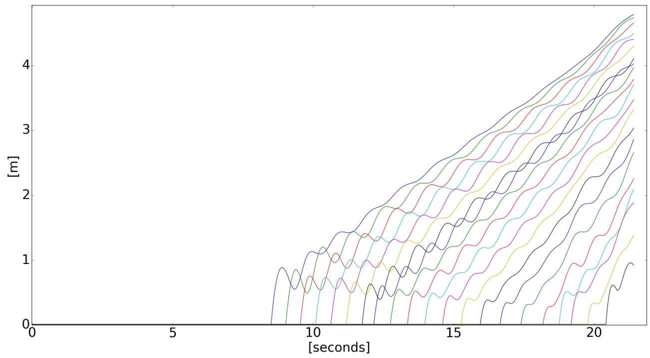

Figure 7.6 *The water column lengths in the branch pipes during the water transit.*

At the moment when the branch pipe starts to fill up, a total head at the beginning node corresponds to the gas pressure ahead of this node point. When the water front moves farther away in the flow line, also the pressure loss along this water column increases which leads to increase in the total head in the inner node point. This increasing trend of total heads at the inner node points leads to the increasing water column lengths in the branch pipes.

7.2 Loop type pipe network configuration

In this second example, the water delivery time calculation is performed on the loop type pipe network configuration. The pipe network in the second example case is illustrated in Figure 7.7. The results of this test are not compared to any other results and they are only shown to illustrate how the developed program works with the loop type pipe network configuration.

The loop type pipe network is modified from the tree type pipe network shown in Section 7.1. The area that is covered by the sprinkler pipe network is approximately the same, around 900 m^2, in both cases. The distance between the sprinkler heads is 2-3 meters in both cases. The feed pipes on the upstream side of DPV, the polynomial function of water source pressure, and the orifice size of the most remote sprinkler head are the same as well. Also the other initial values and material properties are the same. The diameter of pipes between DPV and the first t-junction is the same 200 mm as in the first example case and the diameter of pipes in the loop part is 150 mm. The diameters of the branch pipes follow the diameters in the first example case: the first pipe that is connected to the flow line is 100 mm in diameter, the following pipes are 80 mm in diameter, and the short head pipes that are connected to the sprinkler heads are 25 mm in diameter. The volume of the dry part in the loop type configuration is 4588 liters which is 234 liters smaller than the

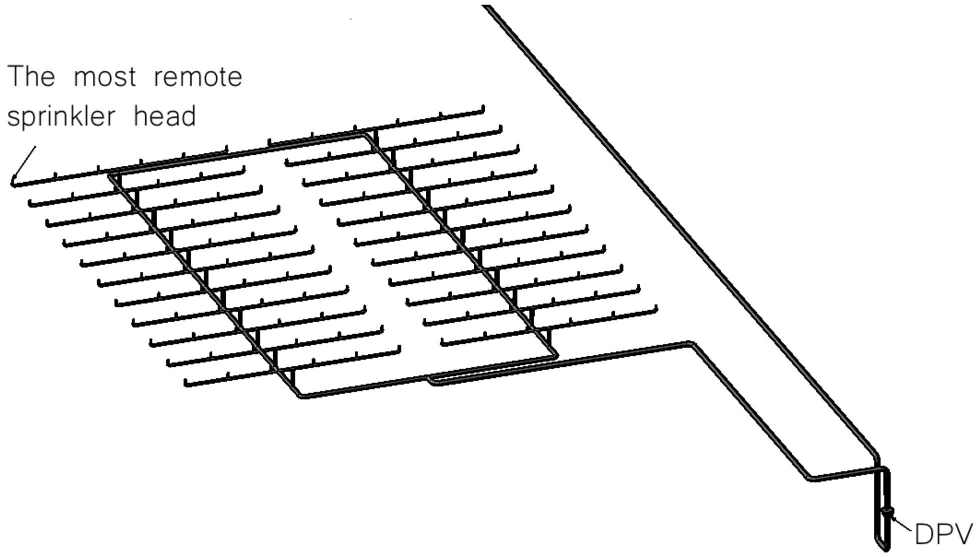

Figure 7.7 *The loop type pipe network configuration of the second test case.*

dry part volume in the first example case.

The air trip time in this case is 0.98 seconds when the initial gas pressure in the pipe network is 2 bars and the gas pressure is 1.945 bars when DPV opens. The result of the water transit time in this case is 17.4 seconds. In calculation the isothermal equations are used for compression and expansion. As there are no other results to compare to, it is difficult to analyze the length of the water transit time. The system is a little bit smaller and the distance between DPV and the most remote sprinkler head is shorter than in the tree type pipe network in Section 7.1. From this it can be assumed that the water transit time should be shorter than in the first example case. Because the size of the dry part is in the same range, around the same amount of water has to be pumped to fill up the flow line in this case. Based on this it can be expected that the water transit time is shorter but still in the same range as in the first example case.

Similar graphs than in Section 7.1 are plotted from the results of this calculation. In Figure 7.8 the volume of gas that is connected to the most remote sprinkler head is plotted. Similar behavior of the gas volume can be seen as in Figure 7.3. The loop part of the pipe network is almost symmetrical and the gas volume is decreased by the two branch pipe volumes at each step change. In the second last step change, part of the loop is separated by water from the gas volume that is connected to the most remote sprinkler head and this is the reason why this step change is the largest one. This moment is illustrated earlier in Figure 5.3. In the last step change, that

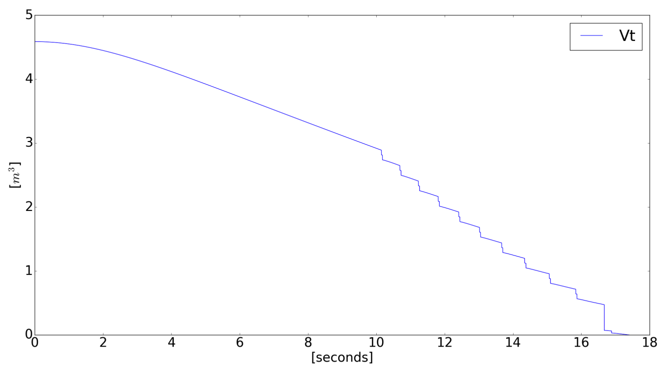

Figure 7.8 *The volume of gas that is connected to the open sprinkler head.*

is so small that it is even hard to see in the plot, half of the last branch pipe is separated from the gas volume. This occurs around 17 seconds after DPV opening.

In Figure 7.9 the gas pressure in the volume that is connected to the most remote sprinkler head is plotted.

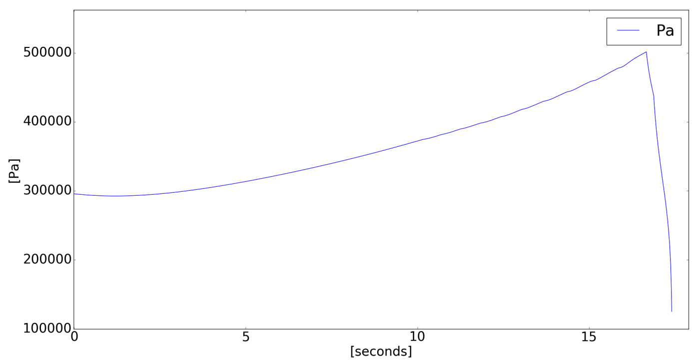

Figure 7.9 *The gas pressure that is connected to the most remote sprinkler head during the water transit.*

Again similar behaviour of the gas pressure is seen as with the tree type configuration in Section 7.1. The gas pressure increases as the volume flow into the flow line is greater than the volume flow of gas through the most remote sprinkler head. When water front reaches the last branch pipe the gas volume is so small and the pressure loss of the water columns in the last pipes is so great that the gas pressure decreases rapidly.

In the following two graphs the water column lengths in the flow line are plotted. In Figure 7.10 the lengths of all the water columns on the downstream side of DPV are plotted. The first pipe on the downstream side of DPV is around 42 meters long. At 8.5 seconds the water front reaches the loop part of the pipe network. Pipes between t-junctions in the loop part of pipe network are filling up one after another.

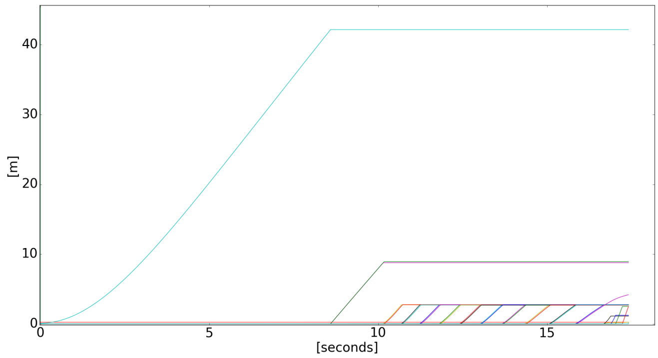

Figure 7.10 *The water column lengths in pipes at the flow line during the water transit.*

The farthest water front reaches the branch pipe where the most remote sprinkler head is connected at around 16.7 seconds after DPV opening. The close-up of the water column lengths after this moment is plotted in Figure 7.11.

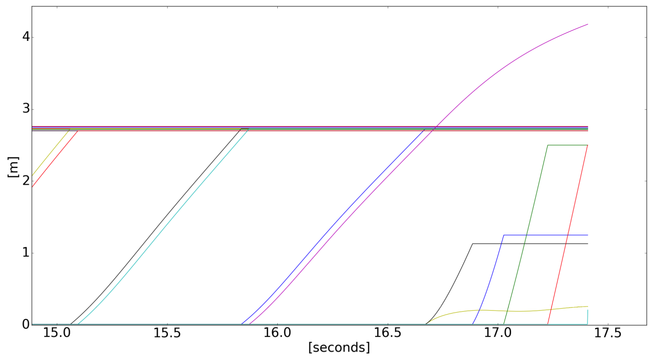

Figure 7.11 *The close-up of the water column lengths in pipes in the flow line near the end of the water transit.*

As described in Section 5.3, the list of pipes and the set of equations are manipulated to correspond to the new situation when the farthest water front reaches the beginning of the branch pipe where the most remote sprinkler head is connected. In this test case it happens around 16.7 seconds after DPV opening. This can be seen in Figure 7.11 as two plots with curvy shape originate at that moment. One starts from zero meters and the other from around 2.7 meters. These curvy plots illustrate the water column lengths in the pipes that are formed when the farthest water front reaches the branch pipe where the most remote sprinkler head is connected. These two pipes model the water columns on both sides of the gas volume in the loop part. Other plots appearing after 16.7 seconds describe the progression of water columns in branch pipe where the most remote sprinkler head is connected.

In Figure 7.12 the water column lengths in 21 branch pipes are plotted.

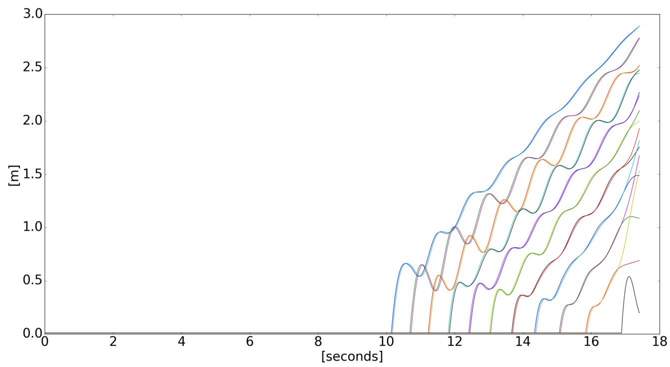

Figure 7.12 *The water column lengths in the branch pipes during the water transit.*

The loop part of the pipe network is almost symmetrical and therefore the branch pipes on each side of the loop start to fill up almost at the same time. As all the pipes are similar, also the water column lengths behave in a similar way. For these reasons two lines overlap each other in many of the plots in Figure 7.12. 16.7 seconds after DPV opening the farthest water front reaches the last branch pipe and gas pressure ahead of the farthest water front decreases rapidly. This can be seen in Figure 7.12. After 16.7 seconds the velocity of water columns decreases in the nearest branch pipes on the loop side where the most remote sprinkler head exists and the over lapping plots starts to diverge.

7.3 Future work

The complex structure of the developed computer program, only slightly limited pipe network configurations, and transient nature of fluid flow during the water transit lead to program behavior that is hard to predict in some cases. Program testing is needed in future and the program has to be developed based on these test results. Some aspects that have to be taken under scope in the future development are discussed in this section.

In Section 4.6 calculations are executed with different time step lengths. Table 4.1 shows that execution times of the calculation are getting quite long when the length of a time step is decreased. This kind of a program has to be fast enough so that it is convenient to use it simultaneously when a pipe network is designed. The scope of this thesis was to develope an algorithm to calculate the water delivery time from the feed provided by the used BIM program and from the given initial values. In future work, the developed program has to be optimized to provide accurate results in shorter times. The interpreted nature of Python programming language makes it slower compared to the compiled languages when a lot of calculations have to be done and the built-in functions cannot be used for this. If in future this program remains written in Python, some functions will perform faster if those are converted to extensions which are written in compiled language. One option is to use Cython C-extension for Python package [1]. Alternatively the whole program can be written in some compiled language, which should be straight forward because the program exists in Python already. [2] Of course some parts of the developed program might work faster if more clever programming techniques are used.

The solution for the matrix equation was discussed in Section 4.3. Solving the matrix equation requires a lot of computing power when the matrix size becomes large. To enhance the calculation performance, the size of matrix has to be kept as small as possible. Applying the method where the matrix size is variable should be possible with small changes in the code. This should lead to a remarkable improvement in the calculation power of the developed program. Also a proper method to solve the matrix equation and the possibility to use the sparse matrix data structure might result in better performance.

In Section 4.6, the length of a time step was discussed briefly. In the developed program, a single constant value for a time step is used. In future work the possibility to use a varying length for time step has to be investigated. The length of the time step should be decreased if the change of the water column length in one time step is large compared to the length of that particular pipe where the water column exists. These factors have to be calculated during the execution of the program and a proper time step length has to be set when needed.

In general the developed program needs more testing to verify the results of the air trip time and the water transit time. Results can be expected to be sufficiently good because the same kind of equations are used to govern the air trip and the water transit with the least amount of simplifications in this program as in a fairly accurate method shown in the literature [15]. During the program testing, different kinds of pipe networks with different kinds of initial values have to be used, and preferably the results should be compared to experimental results of real installations. Further development of the program should be based on the test results.

8. CONCLUSIONS

The scope of this thesis was to investigate methods how the water delivery time can be estimated in the dry pipe sprinkler systems. A fairly general coverage of the developed method was expected. The building where the automatic fire protection is installed defines the characteristics and performance that is demanded from the fire protection system. This often leads to a complex structure of the pipe network configuration. At the beginning of the water delivery the pipe network is full of pressurized gas and at the end it is partly filled with flowing water and partly with gas. The modeling of this change from initial state to the state at the end is a highly transient problem where fluids in two phases are flowing and acting on each other. Due to the complexity of sprinkler pipe network gonfigurations and transient nature of the water delivery in the dry pipe systems, a computer based numerical algorithm was developed to ensure that the water delivery time is modeled accurately in different kinds of pipe network configurations.

A computer program was written to calculate the water delivery time from initial values and characteristics of the pipe network. As characteristics of the pipe networks are complex and the nature of water flow during the water delivery is transient, an analytical solution cannot be found for the water delivery time. This leads to the use of a numerical method to model the water delivery time. The developed program is aimed to be able to estimate the water delivery time quickly to ensure the convenient use of program during the designing process of the automatic fire protection systems. The required computing power of the developed program should be low to ensure that results can be provided in moderate time. To make the need of computing power as low as possible, simple one dimensional equations are used to describe the dynamic motions of water columns inside the pipe network, even though significant simplifications have to be made.

The computer program was written in Python 3.5 programming language. In this kind of program development Python benefits from dynamic variable typing, easy-to-use plotting and linear algebra tools, and fairly easy-to-read code. In future development the performance of the program has to be under scope and the decision of used language has to be based on calculation performance. At least some parts of the written program might perform better if some other language is used.

This kind of modeling tool has to be verified somehow to ensure that it can be used in the designing process of automatic fire protection systems. The developed program was tested for different pipe network configurations to be sure that the program executes the calculation as it should. Robustness of the developed program is good when the time step is in the right range. Due to the lack of measured or calculated results of the water delivery time in existing systems, the results of the developed program were only compared with one test case. The compared results were well in the same range, which encourages the further development of this calculation program.

In this thesis, suggestions for future development are also given. Automatic time step adjusting during the calculation will improve the robustness of the calculation program. The use of variable matrix and vector size, the proper solution method for the matrix equations, improved programming techniques, and compiled programming language will increase the calculation power of the program. The most important work in the future will be the comparison of the results provided by the developed calculation program to the results of experiments in existing systems.

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APPENDIX A. FEED TO CALCULATION IN THE FIRST EXAMPLE CASE

In this appendix the initial values, the material properties and the information of pipe network configuration in the first test case in section 7.1 are shown.

The initial values and the material properties that are used in the first example case:
Density of water: 1000 kg/m^3
Gravitational acceleration: 9.8 m/s^2
Ratio of specific heats: 1.4
Specific gas constant: 287 $J/kg * K$
Gas temperature: 277 K
Dynamic viscosity of water: 0.001 kg/ms
Surface roughness of pipes: 0.045 mm
Diameter of the open sprinkler orifice: 2.36 cm
Time step: 0.0005 s
Pressure of surroundings: 101325 Pa
Opening pressure of DPV: 194500 Pa
Initial pressure of water source: 200000 Pa

In this pipe network there exist two pipes between the water source and DPV, and the third pipe models DPV. At the beginnig of the calculation all of these pipes are full of water. In the performed calculations 0.1 meter initial length for the water column in the fourth pipe is given.

The text file obtained from BIM program that describes the node points at the original pipe network is shown next. The data of a single node point is written in a single line in the text file. Data is written in a single line in the following order: the node number, the virtual node (true for inner node points, false for sprinkler heads), the height position of node point, the K-factor of sprinkler head (-1 if virtual node), the flow index (0 if node is not in the flow line, else 1). To save some space the data set is composed in two columns in this appendix.

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259,false,8.9172,115.0, 0
257,false,8.5432,115.0, 0
255,false,8.1693,115.0, 0
263,false,9.7500,115.0, 0

The text file obtained from BIM program that describes the pipes between the node points at the original pipe network is shown next. Information of a single pipe is writtten in a single line. One line consist the following information of a single pipe: the number of the beginning node, the number of the end node, the eqvivalent length of pipe, the real length of pipe, the inner diameter, the Hazen-Williams coefficient, the surface roughness (not used in this thesis, same value for surface roughness is set to every pipe by an initial value), the flow index (0 for pipes that are not in the flow line, 1 for pipes that are in the flow line). To save some space the data set is composed in two columns in this appendix.

6,15,3.00,3.00,205.0,120, 1.00000, 1
183,16,0.49,0.49,100.0,120, 1.00000, 0
4,10,52.32,41.76,205.0,120, 1.00000, 1
3,4,0.25,0.25,150.0,120, 1.00000, 1
7,29,3.65,2.04,80.0,120, 1.00000, 1
6,7,3.55,3.55,100.0,120, 1.00000, 1
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