# TSNet Documentation

*Release 0.2.2*

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CHAPTER 1

# Introduction to TSNet

TSNet performs transient simulation in water networks using Method of Characteristics (MOC).

- Free software: MIT license
- Github: https://github.com/glorialulu/TSNet.git
- Documentation: https://tsnet.readthedocs.io.

## 1.1 Overview

Hydraulic transients in water distribution networks (WDNs), typically induced by pipe bursts, valve operations, and pump operations, can disturb the steady-state flow conditions by introducing extreme pressure variability and imposing abrupt internal pressure force onto the pipeline systems [WOLB05]. These disturbances have been identified as one of the major contributing factors in the many pipe deterioration and catastrophic failure in WDNs [RERS15], thereby wasting a significant amount of treated water and creating unexpected possibilities of contamination intrusion [ASCE17]. Consequently, transient simulation, as a prominent approach to understand and predict the behavior of hydraulic transients, has become an essential requirement for ensuring the distribution safety and improving the efficiency in the process of design and operation of WDNs. In addition to improving design and operation of WDNs, various other transient-based applications, such as network calibration, leak detection, sensor placement, and condition assessment, has also enhanced the popularity and necessity of transient simulation

Acknowledgedly, a number of commercial software for transient simulation in water distribution systems is available in the market; however, the use of these software for research purposes is limited. The major restriction is due to the fact that the programs are packed as black boxes, and the source codes are not visible, thus prohibiting any changes, including modification of existing and implementation of new elements, in the source codes. Additionally, the commercial software is designed to perform only single transient simulations and do not have the capabilities to automate or run multiple transient simulations. Users are required to modify the boundary conditions using the GUI, perform the simulation, and manually record the hydraulic responses in the various conditions, which significantly complicated the research process.

There is a clear gap that currently available simulation software are not suitable for many research applications beyond the conventional design purposes. Hence, the motivation of this work is two-fold:

1. Provide users with open source and freely available python code and package for simulating transients in water distribution systems that can be integrated with other case specific applications, e.g. sensor placement and event detection; and

2. Encourage users and developers to further develop and extend the transient model.

## 1.2 Features

TSNet is a Python package designed to perform transient simulation in water distribution networks. The software includes capability to:

- Create transient models based on EPANET INP files
- Operating valves and pumps
- Add disruptive events including pipe bursts and leakages
- Choose between steady,quasi-steady, and unsteady friction models
- Perform transient simulation using Method of characteristics (MOC) techniques
- Visualize results

For more information, go to https://tsnet.readthedocs.io.

## 1.3 Version

TSNet is a ongoing research project in the University of Texas at Austin. The current version is 0.2.2, which is still a pre-release.

## 1.4 Contact

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## 1.5 Disclaimer

No warranty, expressed or implied, is made as to the correctness of the results or the suitability of the application.

## 1.6 Cite TSNet

To cite TSNet, use one of the following references:

Xing, Lu, and Lina Sela. "Transient simulations in water distribution networks: TSNet python package." Advances in Engineering Software 149 (2020): 102884.

## 1.7 License

TSNet is released under the MIT license. See the LICENSE.txt file.

CHAPTER 2

# Installation

## 2.1 Setup Python Environment

TSNet is tested against Python versions 3.5, 3.6, and 3.7. It can be installed on Windows, Linux, and Mac OS X operating systems. Python distributions, such as Anaconda, are recommended to manage the Python environment as they already contain (or easily support installation of) many Python packages (e.g. SciPy, NumPy, pandas, pip, matplotlib, etc.) that are used in the TSNet package. For more information on Python package dependencies, see *Dependencies*.

## 2.2 Stable Release (for users)

To install TSNet, run this command in your terminal:

```
$ pip install tsnet
```

This is the preferred method to install tsnet, as it will always install the most recent stable release.

If you don't have pip installed, this Python installation guide can guide you through the process.

## 2.3 From Sources (for developers)

The sources for TSNet can be downloaded from the Github repo.

You can either clone the public repository:

```
$ git clone git://github.com/glorialulu/tsnet
```

Or download the tarball:

```
$ curl  -OL https://github.com/glorialulu/tsnet/tarball/master
```

Once you have a copy of the source, you can install it with:

```
$ python setup.py install
```

## 2.4 Dependencies

Requirements for TSNet include Python (3.5, 3.6, or 3.7) along with several Python packages. The following Python packages are required:

1. Numpy [VaCV11]: the fundamental package needed for scientific computing with Python included in Anaconda distribution http://www.numpy.org/
2. Matplotlib [Hunt07]: Python 2D plotting library included in Anaconda distribution http://matplotlib.org/
3. NetworkX [HaSS08]: Network creation and manipulation engine, install on a python-enabled command line with *pip install wntr* https://networkx.github.io/
4. WNTR [WNTRSi]: Water Network Tool for Resilience install on a python-enabled command line with *pip install wntr* http://wntr.readthedocs.io
5. pytest: Unit Tests engine install on a python-enabled command line with *pip install -U pytest* https://docs.pytest.org/en/latest/

# CHAPTER 3

# Software Conventions and Limitations

## 3.1 Units

All data in TSNet is stored in the following International System (SI) units:

- Length = $m$
- Diameter = $m$
- Water pressure = $m$ (this assumes a fluid density of 1000 $kg/m^3$)
- Elevation = $m$
- Mass = $kg$
- Time = $s$
- Demand = $m^3/s$
- Velocity = $m/s$
- Acceleration = $g$ (1 $g$ = 9.8 $m/s^2$)
- Volume = $m^3$

If the unit system specified in .inp file is US units, it will be converted to SI unit in the simulation process. When setting up analysis in TSNet, all input values should be specified in SI units. All simulation results are also stored in SI units.

## 3.2 Modelling Assumptions and Limitations

TSNet is constantly under development. Current software limitations are as follows:

- Demands on the start and end nodes of pumps and valves are not supported. If demands are defined on these nodes in the .inp file, they will be ignored in transient simulation, and the simulation results may not be accurate due to discrepancies between the initial conditions and the first step in transient simulation. Warnings will be printed.

- Multi-branch junctions on the start and end nodes of pumps and valves are not supported. It is assumed that valves and pumps are connected by pipes in series.
- During transient simulation, demands are pressure dependent .
- Pipe Friction coefficients are converted to Darcy-Weisbach coefficients based on initial conditions.
- Pipe bursts and leaks occur only on the nodes.
- Transient simulation relies on a feasible steady state solution; hence, it is essential to verify that the steady state simulation succeeds without errors.

# CHAPTER 4

# Getting Started

To use tsnet in a project, open a Python console and import the package:

```
import tsnet
```

## 4.1 Simple example

A simple example, Tnet1_valve_closure.py is included in the examples folder. This example demonstrates how to:

- Import tsnet
- Generate a transient model
- Set wave speed
- Set time step and simulation period
- Perform initial condition calculation
- Define valve closure rule
- Run transient simulation and save results to .obj file
- Plot simulation results

```
# Open an example network and create a transient model
tm = tsnet.network.TransientModel('/Users/luxing/Code/TSNet/examples/networks/Tnet1.
↪inp')

# Set wavespeed
tm.set_wavespeed(1200.) # m/s

# Set time options
tf = 20   # simulation period [s]
tm.set_time(tf)
```

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```
# Set valve closure
ts = 5 # valve closure start time [s]
tc = 1 # valve closure period [s]
se = 0 # end open percentage [s]
m = 2 # closure constant [dimensionless]
tm.valve_closure('VALVE',[tc,ts,se,m])

# Initialize steady state simulation
t0=0
tm = tsnet.simulation.Initializer(tm,t0)

# Transient simulation
tm = tsnet.simulation.MOCSimulator(tm)

# report results
node = ['N2','N3']
tm.plot_node_head(node)
```

Three additional EPANET INP files and example files are also included in the TSNet examples repository in the examples folder. Example networks range from a simple 8-node network to a 126-node network.

CHAPTER 5

# Transient Modeling Framework

The framework of performing transient simulation using TSNet is shown in Figure 5.1 The main steps of transient modelling and simulation in TSNet are described in subsequent sections.

## 5.1 Transient Model

The transient model inherits the WNTR water network model [WNTRSi], which includes junctions, tanks, reservoirs, pipes, pumps, valves, patterns, curves, controls, sources, simulation options, and node coordinates. It can be built directly from an EPANet INP file. Sections of EPANet INP file that are not compatible with WNTR are described in [WNTRSi].

Compared with WNTR water network model, TSNet transient model adds the features designed specifically for transient simulation, such as spatial discretization, temporal discretization, valve operation rules, pump operation rules, burst opening rules, surge tanks, and storage of time history results. For more information on the water network model, see *TransientModel* in the API documentation.

A transient model can be created directly from an EPANET INP file. The following example build a transient model.

```
inp_file = 'examples/networks/Tnet1.inp'
tm = tsnet.network.TransientModel(inp_file)
```

## 5.2 Initial Conditions

TSNet employed WNTR [WNTRSi] for simulating the steady state in the network to establish the initial conditions for the upcoming transient simulations.

**WNTRSimulators** can be used to run demand-driven (DD) or pressure-dependent demand (PDD) hydraulics simulations, with the capacity of simulating leaks. The default simulation engine is DD. An initial condition simulation can be run using the following code:

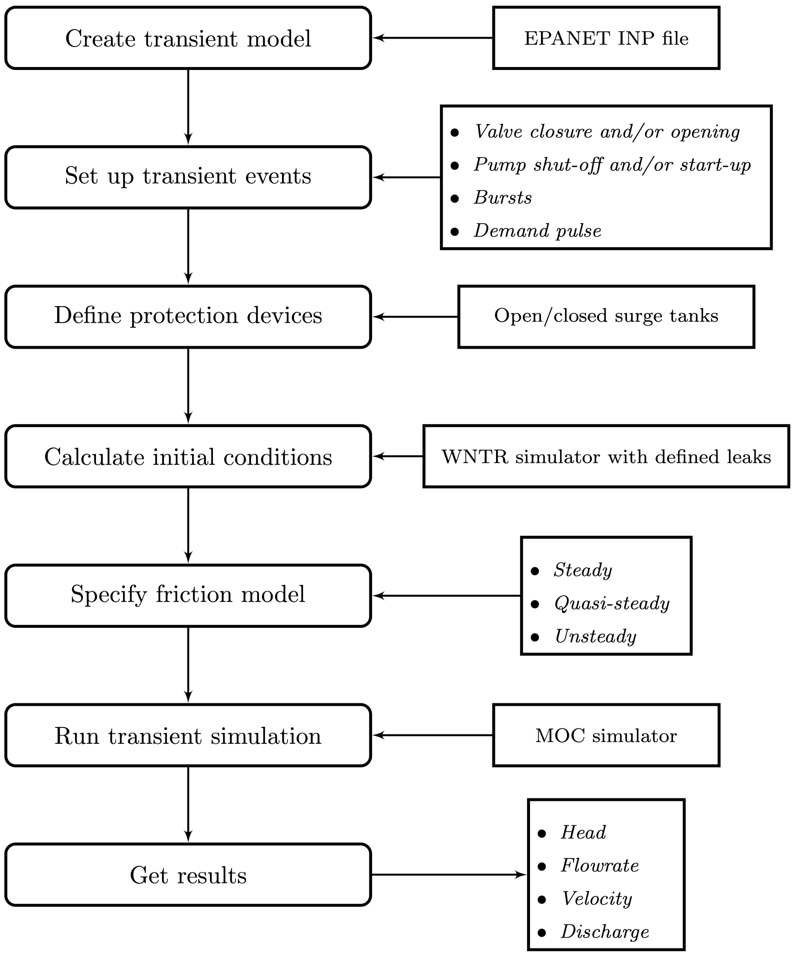


Figure 5.1: Flowchart of transient simulation in TSNet

```
t0 = 0. # initialize the simulation at 0 [s]
engine = 'DD' # demand driven simulator
tm = tsnet.simulation.Initializer(tm, t0, engine)
```

$t_0$ stands for the time when the initial condition will be calculated. More information on the initializer can be found in the API documentation, under `Initializer`.

## 5.3 Transient Simulation

After the initial conditions are obtained, TSNet adopts the Method of Characteristics (MOC) for solving governing transient flow equations. A transient simulation can be run using the following code:

```
results_obj = 'Tnet1' # name of the object for saving simulation results
tm = tsnet.simulation.MOCSimulator(tm, results_obj)
```

The results will be returned to the transient model (tm) object, and then stored in the 'Tnet1.obj' file for the easiness of retrieval.

In the following sections, an overview of the solution approaches and boundary conditions is presented, based on the following literature [LAJW99] , [MISI08], [WYSS93].

### 5.3.1 Governing Equations

#### Mass and Momentum Conservation

The transient flow is governed by the mass and momentum conservation equation [WYSS93]:

$$\begin{aligned}\frac{\partial H}{\partial t} + \frac{a^2}{g}\frac{\partial V}{\partial x} - gV\sin\alpha = 0 \\ \frac{1}{g}\frac{\partial V}{\partial t} + \frac{\partial H}{\partial x} + h_f = 0\end{aligned}$$

where $H$ is the head, $V$ is the flow velocity in the pipe, $t$ is time, $a$ is the wave speed, $g$ is the gravity acceleration, $\alpha$ is the pipe slope, and $h_f$ represents the head loss per unit length due to friction.

#### Method of Characteristics (MOC)

The Method of Characteristics (MOC) method is used to solve the system of governing equations above. The essence of MOC is to transform the set of partial differential equations to an equivalent set of ordinary differential equations that apply along specific lines, i.e., characteristics lines (C+ and C-), as shown below [LAJW99]:

$$\begin{aligned}C+: \quad \frac{dV}{dt} + \frac{g}{a}\frac{dH}{dt} + gh_f - \frac{g}{a}V\sin\alpha = 0 \quad \text{along } \frac{dx}{dt} = a \\ C-: \quad \frac{dV}{dt} - \frac{g}{a}\frac{dH}{dt} + gh_f - \frac{g}{a}V\sin\alpha = 0 \quad \text{along } \frac{dx}{dt} = -a\end{aligned}$$

#### Headloss in Pipes

### Steady/ quasi-steady friction model

TSNet adopts Darcy-Weisbach equation to compute head loss, regardless of the friction method defined in the EPANET .inp file. This package computes Darcy-Weisbach coefficients ($f$) based on the head loss per unit length ($h_{f0}$) and flow velocity ($V_0$) in initial condition, using the following equation:

$$f = \frac{h_{f0}}{V_0^2/2gD}$$

where $D$ is the pipe diameter, and $g$ is gravity acceleration.

Subsequently, in transient simulation the headloss ($h_f$) is calculated based on the following equation:

$$h_f = f\frac{V^2}{2gD}$$

### Unsteady friction model

In addition to the steady friction model, TSNet includes the quasi-steady and the unsteady friction models. The head loss term ($h_f$) can be expressed as a sum of steady/quasi-steady part ($h_{fs}$) and unsteady part ($h_{fu}$), i.e., $h_f = h_{fs} + h_{fu}$. TSNet incorporates the instantaneous acceleration-based model [VIBS06] to calcualte the unsteady friction:

$$h_{fu} = \frac{k_u}{2g}\left(\frac{\partial V}{\partial t} + a\cdot \text{sign}(V)\left|\frac{\partial V}{\partial x}\right|\right)$$

where $h_{fu}$ is the head loss per unit length due to unsteady friction, $\frac{\partial V}{\partial t}$ is the local instantaneous acceleration, $\frac{\partial V}{\partial x}$ is the convective instantaneous acceleration, and $k_u$ is Brunone's friction coefficient, which can be analytically determined using Vardy's sheer decay coefficient ($C^*$) [VABR95]:

$$k_u = \frac{C^*}{2}$$

$$C^* = \begin{cases} 0.00476 & \text{laminar flow } (Re \leq 2000) \\ \frac{7.41}{Re^{\log(14.3/Re^{0.05})}} & \text{turbulent flow } (Re > 2000) \end{cases}$$

TSNet allows the user to choose the friction model using TSNet API simply by specifying the friction model to be used in `MOCSimulator`. The friction argument can take three values: 'steady', 'quasi-steady', and 'unsteady':

```
results_obj = 'Tnet3' # name of the object for saving simulation results
friction = 'unsteady' # or "steady" or "quasi-steady", by default "steady"
tm = tsnet.simulation.MOCSimulator(tm, results_obj, friction)
```

### Pressure-driven Demand

During the transient simulation in TSNet, the demands are treated as pressure-dependent discharge; thus, the actual demands will vary from the demands defined in the INP file. The actual demands ($d_{actual}$) are modeled based on the instantaneous pressure head at the node and the demand discharge coefficients, using the following equation:

$$d_{actual} = k\sqrt{H_p}$$

where $H_p$ is the pressure head and $k$ is the demand discharge coefficient, which is calculated from the initial demand ($d_0$) and pressure head ($H_{p0}$):

$$k = \frac{d_0}{\sqrt{H_{p0}}}$$

It should be noted that if the pressure head is negative, the demand flow will be treated zero, assuming that a backflow preventer is installed on each node.

### 5.3.2 Choice of Time Step

The determination of time step in MOC is not a trivial task. There are two constraints that have to be satisfied simultaneously:

1. The Courant's criterion has to be satisfied for each pipe, indicating the maximum time step allowed in the network transient analysis will be:

$$\Delta t \leqslant \min\left(\frac{L_i}{N_i a_i}\right), i = 1, 2, ..., n_p$$

2. The time step has to be the same for all the pipes in the network, therefore restricting the wave travel time $\frac{L_i}{N_i a_i}$ to be the same for any computational unit in the network. Nevertheless, this is not realistic in a real network, because different pipe lengths and wave speeds usually cause different wave travel times. Moreover, the number of sections in the $i^{th}$ pipe ($N_i$) has to be an integer due to the grid configuration in MOC; however, the combination of time step and pipe length is likely to produce non-integer value of $N_i$, which then requires further adjustment.

This package adopted the wave speed adjustment scheme [WYSS93] to make sure the two criterion stated above are satisfied.

To begin with, the maximum allowed time step ($\Delta t_{max}$) is calculated, assuming that there are two computational units on the critical pipe (i.e., the pipe that results in the smallest travel time, which depends on the length and the wave speed for that pipe):

$$\Delta t_{max} = \min\left(\frac{L_i}{2a_i}\right), i = 1, 2, ..., n_p$$

After setting the initial time step, the following adjustments will be performed. Firstly, the $i^{th}$ pipes ($p_i$) with length ($L_i$) and wave speed ($a_i$) will be discretized into ($N_i$) segments:

$$N_i = \text{round}\left(\frac{L_i}{a_i \Delta t_{max}}\right), i = 1, 2, \ldots, n_p$$

Furthermore, the discrepancies introduced by the rounding of $N_i$ can be compensated by correcting the wave speed ($a_i$).

$$\Delta t = \text{argmin}_{\phi,\Delta t}\left\{\sum_{i=1}^{n_p} {\phi_i}^2 \mid \Delta t = \frac{L_i}{a_i(1 \pm \phi_i)N_i} \quad i = 1, 2, \ldots, n_p\right\}$$

Least squares approximation is then used to determine $\Delta t$ such that the sum of squares of the wave speed adjustments ($\sum {\phi_i}^2$) is minimized [MISI08]. Ultimately, an adjusted $\Delta t$ can be determined and then used in the transient simulation.

It should be noted that even if the user defined time step satisfied the Courant's criterion, it will still be adjusted.

If the user defined time step is greater than $\Delta t_{max}$, a fatal error will be raised and the program will be killed; if not, the user defined value will be used as the initial guess for the upcoming adjustment.

```
dt = 0.1   # time step [s], if not given, use the maximum allowed dt
tf = 60    # simulation period [s]
tm.set_time(tf,dt)
```

The determination of time step is not straightforward, especially in large networks. Thus, we allow the user to ignore the time step setting, in which case $\Delta t_{max}$ will be used as the initial guess for the upcoming adjustment.

Alternatively, the user can also specify the number of segments on the critical pipe:

```
N = 3  # number of computational units on the critical pipe, default 2.
tf = 60   # simulation period [s]
tm.set_time_N(tf,N)
```

## Example

We use a small network, shown in Figure 5.2, to illustrate how time step is determined as well as the benefits and drawbacks of combining or removing small pipes. Figure 5.2 (a) shows a network of three pipes with length of 940m, 60m, and 2000m, respectively. The wave speed for all the pipes is equal to 1000m/s. The procedure for determine the time step is as follows:

- Calculate the maximum time step ($\Delta t_{max}$) allowed by Courant's criterion, assuming that there are two computational units on the critical pipe (i.e., the pipe that results in the smallest travel time, which depends on the length and the wave speed for that pipe), i.e., for pipe 2 $N_2 = 2.$}

$$\Delta t_{max} = \min\left(\frac{L_i}{2a_i}\right) = \left(\frac{L_2}{N_2 a_2}\right) = \frac{60}{2 \times 1000} = 0.03s$$

- Compute the required number of computational units for all other pipes, i.e, $N_1$ for pipe 1 and $N_3$ for pipe 3, using $\Delta t_{max}$ as the time step. Since the number of computational units on each pipe has to be integer, the numbers are rounded to the closest integer, thus introducing discrepancies in the time step of different pipes.

$$N_1 = \text{round}\left(\frac{L_1}{a_1 \Delta t_{max}}\right) = \frac{940}{1000 \times 0.03} = 31$$
$$N_3 = \text{round}\left(\frac{L_3}{a_3 \Delta t_{max}}\right) = \frac{2000}{1000 \times 0.03} = 67$$

  With these number of computational units, the time steps for each pipe become:

$$\Delta t_1 = \frac{L_1}{N_1 a_1} = 0.03032s$$
$$\Delta t_3 = \frac{L_3}{N_3 a_3} = 0.02985s$$

  However, all the pipes have to have the same time step for marching forward; hence, we need to adjust the wave speed to match the time step for all pipes.

$$\Delta t = \frac{L_i}{a_i^{adj} N_i}$$

- Compensate the discrepancies introduced by rounding number of computation units through adjusting wave speed from $a_i$ to $a_i^{adj} = a_i(1 + \phi_i)$. The sum of squared adjustments ($\sum {\phi_i}^2$) is minimized to obtain the minimal overall adjustment. In this example, the wave speeds of the three pipes are adjusted by $\phi_1 = 0.877\, \phi_2 = -0.196\%, \phi_3 = 0.693\%$, respectively.
- Finally, the time step can be calculated based on the number of computational units and the adjusted wave speed of each one of three pipes that now share the same time step:

$$\Delta t = \frac{L_i}{a_i(1 \pm \phi_i) N_i} = 0.03006s$$

Noticeably, the maximum allowed time step for this network is fairly small. Meanwhile, the total number of segments ($31 + 2 + 67 = 100$) is relatively large; thus, in order to conduct a transient simulation of $10s$, the overall number of computation nodes in x-t plane will be $10/0.03006 \times 100 = 33267$. The computation efforts can be significantly

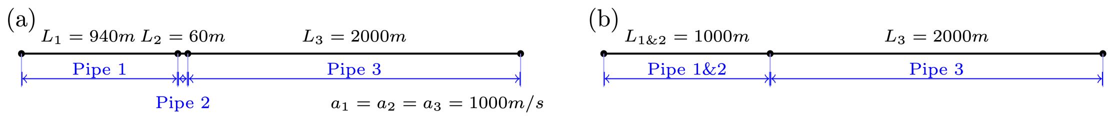


Figure 5.2: Example network for determining the time step: (a) before combing pipes; (b): after combing pipes.

reduced by, for example, combing/removing the shorted pipe, i.e., pipe 2. Figure 5.2 (b) illustrates the network after combing pipe 1 and pipe 2. Following the same steps shown above, it can be determined that the maximum time step is $0.5s$, and the number of computation units for pipes 1 and 2 are 2 and 4, respectively, thus significantly reducing the total number of computation nodes in x-t plane required for $10s$ simulation to $10/0.5 \times (2 + 4) = 26$.

In this example, we implicitly assumed that pipe properties were the same (e.g., diameter, material), however these properties affect wave propagation, reflection, and damping. Hence, despite the benefits in reducing computation costs, merging or removing pipes to improve computational efficiency is not straightforward and requires careful considerations of how these changes will affect modeling accuracy. In other words, any discontinuity or change in pipe properties will create changes in wave propagation, and hence, if removed will change the model. For example, suppose pipe 1 and 3 in Figure 5.2 have the same diameter, while pipe 2 has smaller diameter, then a certain portion of wave speed will be reflected at junctions connecting the pipes. However, if pipe 2 is to be removed, and pipe 1 is then connected to pipe 3, which exhibit the same diameter, there will be no reflection observed in the new junction, thus altering the wave propagation in the network. Therefore, precautions are required before removing or combing the short pipes, or modifying network topology in general.

Moreover, the simulation time step can be controlled by specifying large number of segments in the critical pipe, which will also control the wave speed adjustments ($\phi$), as shown in Figure 5.3 calculated for network Tnet1. The black curve shows the reduction in the simulation time step as the number of segments in the critical pipe increases. Subsequently, the decreased time step results in a reduction in wave speed adjustment ($a^{adj} = a \times (1 + \phi)$), as illustrated by the red curve. The red line represents the average wave speed adjustment and the shaded area represents the maximum and minimum wave speed adjustments for all pipes in the network. For example, when the critical pipe is divided into 40 segments, the time step is reduced to less than 0.001s, and the adjustment of wave speed is reduced to about 0.005, which is negligibly small. However, there is obviously a computational trade-off between numerical accuracy and computational efficiency.

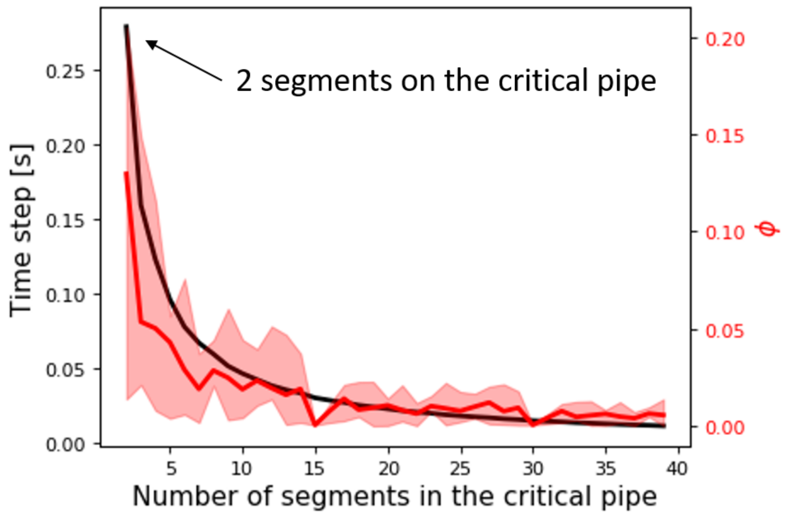


Figure 5.3: Time step (black, left y-axis) versus the number of computational units on the critical pipe and the wave speed adjustments (red, right y-axis) showing the mean (red line) and the max-min range (shaded area).

### 5.3.3 Numerical Scheme

The explicit MOC technique adopted to solve the compatibility equations is explained in a simple network. Figure 5.4 illustrates a simple piped network and the corresponding MOC characteristic grid on the x-t plane. Boundary nodes (represented by the void circles), are defined by the physical elements in the network (or any discontinuity), such as tanks, junctions, valves, pumps, leaks and bursts. Inner nodes (represented by solid circles) are numerically specified to divide a single pipe into several segments, i.e., *computational units*, so that the propagation of pressure waves can be properly modeled. The heads, $H$, and flow velocities, $V$, are computed for each computational node, either boundary or inner node, and at each time based on the information at a previous time. Depending on the type of the computational node (i.e. inner or boundary) and the specific boundary condition, the flows and heads may be allocated and computed differently. Figure 5.5 shows a general example of two computational units for computing flow velocities and heads. Note that for inner nodes, where there is no change in pipe or flow conditions, $H_2^t = H_3^t$ and $V_2^t = V_3^t$. Otherwise, additional head/flow boundary conditions will be introduced between points 2 and 3 in addition to the two compatibility equations. Detailed descriptions about different boundary conditions are discussed in the next section.

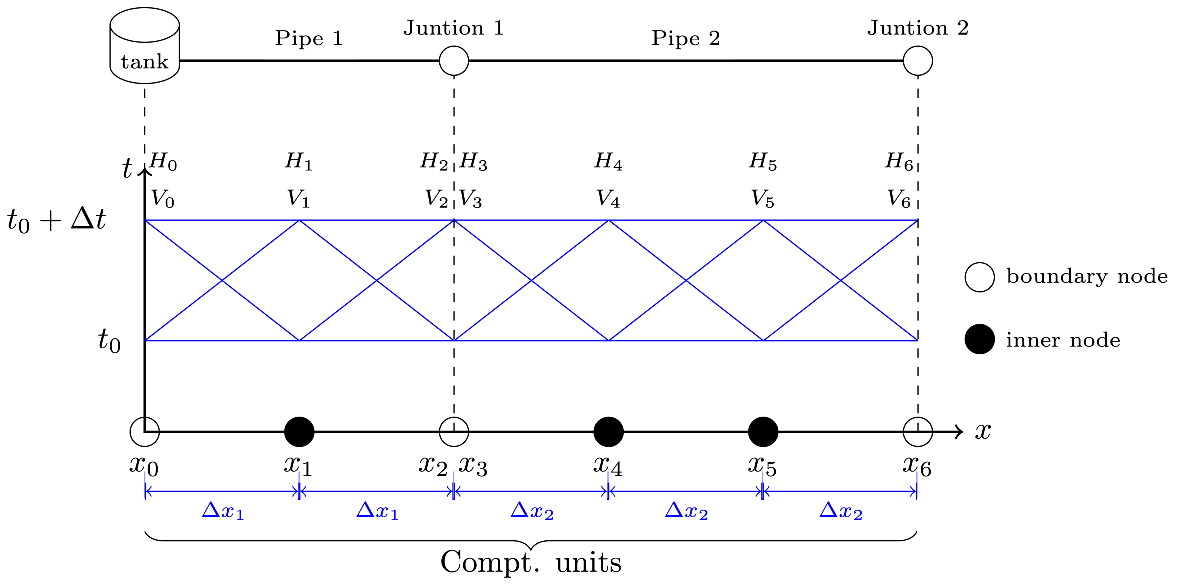

tank
Pipe 1
Juntion 1
Pipe 2
Juntion 2
$t$
$H_0$ $H_1$ $H_2$ $H_3$ $H_4$ $H_5$ $H_6$
$V_0$ $V_1$ $V_2$ $V_3$ $V_4$ $V_5$ $V_6$
$t_0 + \Delta t$
$t_0$
boundary node
inner node
$x$
$x_0$ $x_1$ $x_2$ $x_3$ $x_4$ $x_5$ $x_6$
$\Delta x_1$ $\Delta x_1$ $\Delta x_2$ $\Delta x_2$ $\Delta x_2$
Compt. units

Figure 5.4: Topology of a simple network

#### Steady/quasi-steady Friction Model

The solution of the compatibility equations is achieved by integrating the above equations along specific characteristic lines of the numerical grid, which are solved to compute the head and flow velocity, $H_i^t, V_i^t$, at new point in time and space given that the conditions at the previous time step are known. The two characteristic equations describing the hydraulic transients with steady friction model ($h_f = h_{f_s} = f\frac{V^2}{2gD}$) are discretized and formulated as:

$$\begin{aligned} C+: \quad & (V_i^t - V_{i-1}^{t-1}) + \frac{g}{a}(H_i^t - H_{i-1}^{t-1}) + \frac{f\Delta t}{2D}V_{i-1}^{t-1}|V_{i-1}^{t-1}| + \frac{g\Delta t}{a}V_{i-1}^{t-1}\sin\alpha = 0 \\ C-: \quad & (V_i^t - V_{i+1}^{t-1}) - \frac{g}{a}(H_i^t - H_{i+1}^{t-1}) - \frac{f\Delta t}{2D}V_{i+1}^{t-1}|V_{i+1}^{t-1}| - \frac{g\Delta t}{a}V_{i+1}^{t-1}\sin\alpha = 0 \end{aligned} \tag{5.1}$$

Once the MOC characteristic grid and numerical scheme are established, the explicit time marching MOC scheme can be conducted in the computational units shown in Figure 5.5 as follows:

- First, given initial conditions, the heads and flow velocities at all computational nodes are known, and are updated for the next time step, i.e. $H_2^t, V_2^t, H_3^t$, and $V_3^t$ will be updated based on $H_1^{t-1}, V_1^{t-1}, H_4^{t-1}$, and $V_4^{t-1}$.

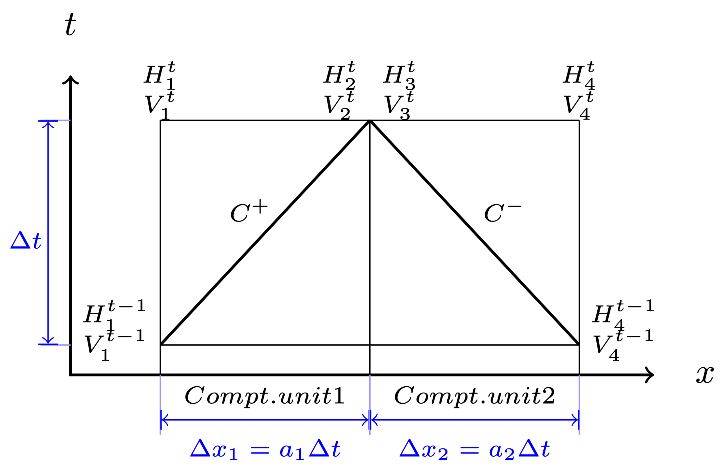


Figure 5.5: MOC characteristic grids in x-t plane for two adjacent computational units

- Then, the relation between $H_2^t$ and $V_2^t$ with known $H_1^{t-1}, V_1^{t-1}$, and properties of the computation unit 1, such as wave speed $(a_1)$ and friction factor$(f_1)$ are established along the positive characteristic line $(C^+)$:

$$V_2^t + \frac{g}{a_1} H_2^t = V_1^{t-1} + \frac{g}{a_1} H_1^{t-1} - \frac{f_1 \Delta t}{2D_1} V_1^{t-1} |V_1^{t-1}| + \frac{g\Delta t}{a_1} V_1^{t-1} \sin \alpha_1$$

- Similarly, $H_3^t$ and $V_3^t$ is updated using the compatibility equations along the negative characteristic line $(C^-)$ and conditions at previous time step, $H_4^{t-1}, V_4^{t-1}$ :

$$V_3^t - \frac{g}{a_2} H_3^t = -V_4^{t-1} + \frac{g}{a_2} H_4^{t-1} + \frac{f_2 \Delta t}{2D_2} V_4^{t-1} |V_4^{t-1}| - \frac{g\Delta t}{a_2} V4^{t-1} \sin \alpha_2$$

- Subsequently, the system of equations is supplemented using the boundary conditions at the node connecting the two computation units, such as energy equations that specify the relation between $H_2^t$ and $H_3^t$ and continuity equations for $V_2^t$ and $V_3^t$. Different boundary conditions can be defined to characterize different connections, including valves, pumps, surge tanks, and pipe-to-pipe junctions with/or without leak, burst, and demand. For example, if the connection is a pipe-to-pipe junction with a leak, the boundary conditions can be defined as:

$$H_2^t = H_3^t; V_2^t A_1 = V_3^t A_2 + k_l \sqrt{H_2^t}$$

  where, $k_l$ is the leakage coefficient and $A_1, A_2$ are the cross-sectional area of computation units 1 and 2, respectively. More boundary conditions are discussed in the next section.

- Ultimately, the system of equations containing compatibility equations, and the two boundary conditions can be solved for the four unknowns, i.e.,:math:*H_2^t, V_2^t, H_3^t*, and $V_3^t$, thus completing the time marching from $t-1$ to $t$.

## Unsteady Friction Model

The local $(\frac{\partial V}{\partial x})$ and convective instantaneous $(\frac{\partial V}{\partial t})$acceleration terms are approximated using finite-difference schemes on the characteristic grid, as shown in Figure 5.6. The explicit fist-order finite difference scheme is implemented such that the computation of the acceleration terms does not interact with adjacent computational sections, thus preserving the original structure of the MOC scheme. Mathematically, the acceleration terms along positive and negative characteristic lines can be represented as:

$$
\begin{aligned}
C^{+} : \frac{\partial V^{+}}{\partial t} &= \frac{V_1^{t-1} - V_1^{t-2}}{\Delta t} \\
\frac{\partial V^{+}}{\partial x} &= \frac{V_2^{t-1} - V_1^{t-1}}{\Delta x} \\
C^{-} : \frac{\partial V^{-}}{\partial t} &= \frac{V_4^{t-1} - V_4^{t-2}}{\Delta t} \\
\frac{\partial V^{-}}{\partial x} &= \frac{V_4^{t-1} - V_3^{t-1}}{\Delta x}
\end{aligned}
$$

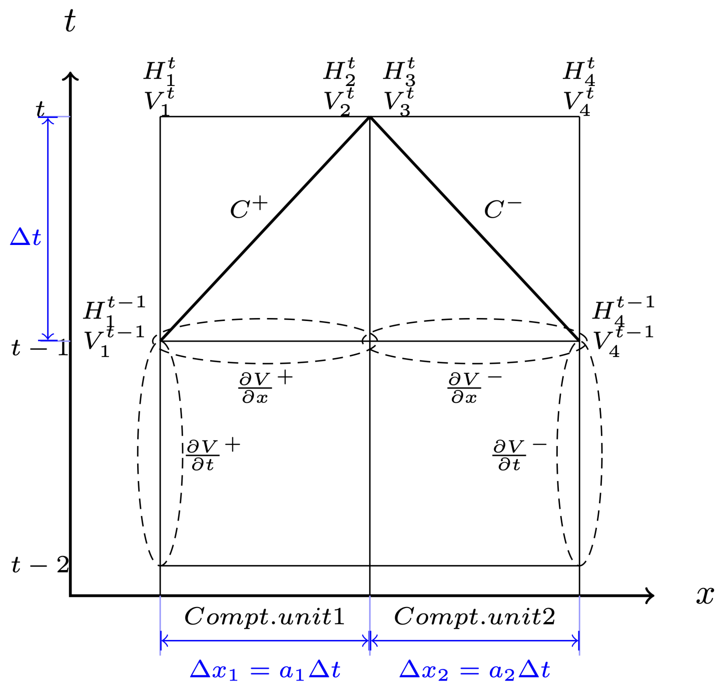

$t$
$x$
$H_1^t$ $V_1^t$
$H_2^t$ $V_2^t$
$H_3^t$ $V_3^t$
$H_4^t$ $V_4^t$
$t$
$\Delta t$
$t-1$
$t-2$
$C^{+}$
$C^{-}$
$H_1^{t-1}$ $V_1^{t-1}$
$H_4^{t-1}$ $V_4^{t-1}$
$\frac{\partial V}{\partial x}^{+}$
$\frac{\partial V}{\partial x}^{-}$
$\frac{\partial V}{\partial t}^{+}$
$\frac{\partial V}{\partial t}^{-}$
$Compt.unit1$
$Compt.unit2$
$\Delta x_1 = a_1 \Delta t$
$\Delta x_2 = a_2 \Delta t$

Figure 5.6: MOC characteristic grid with finite difference unsteady friction

Subsequently, the formulation of unsteady friction can be incorporated into the compatibility equations with additional terms describing the instantaneous acceleration-based unsteady friction model, as below:

$$
\begin{aligned}
C+: \quad & (V_i^t - V_{i-1}^{t-1}) + \frac{g}{a}(H_i^t - H_{i-1}^{t-1}) + \frac{g}{a}\Delta t V_{i-1}^{t-1}\sin\alpha + \frac{f\Delta x}{2D}V_{i-1}^{t-1}|V_{i-1}^{t-1}| \\
& + \frac{k_u}{2g}\left[(V_{i-1}^{t-1} - V_{i-1}^{t-2}) + \operatorname{sign}(V_{i-1}^{t-1})\left|V_i^{t-1} - V_{i-1}^{t-1}\right|\right] = 0 \\
C-: \quad & (V_i^t - V_{i+1}^{t-1}) - \frac{g}{a}(H_i^t - H_{i+1}^{t-1}) + \frac{g}{a}\Delta t V_{i+1}^{t-1}\sin\alpha - \frac{f\Delta x}{2D}V_{i+1}^{t-1}|V_{i+1}^{t-1}| \\
& - \frac{k_u}{2g}\left[(V_{i+1}^{t-1} - V_{i+1}^{t-2}) + \operatorname{sign}(V_{i+1}^{t-1})\left|V_{i+1}^{t-1} - V_i^{t-1}\right|\right] = 0
\end{aligned}
\tag{5.2}
$$

### 5.3.4 Boundary Conditions

Boundary conditions are required to characterize the devices or discontinuities, such as such as tanks, junctions, valves, pumps, leaks and bursts, between two computational units. Supplemented by the boundary conditions specifying the relations between $H_2^t, H_3^t, V_2^t, V_3^t$ as in Figure 5.5 or Figure 5.6, the compatibility equations (Eq.5.1 or Eq.5.2) can then be solved to obtain $H_2^t, H_3^t, V_2^t$, and $V_3^t$. The following sections discuss the boundary conditions for devices and discontinuities in detail.

#### Surge tanks

The modeling of water hammer protection devices, including the open and closed surge tanks, are also incorporated in TSNet. An open surge tank is modeled as an open chamber connected directly to a pipeline and is open to the atmosphere [WYSS93]. Initially, the water head $(z)$ in the tank equals to the hydraulic head in the upstream pipeline. During transient simulation, the open surge tank moderates pressure transients by storing the excess water when a pressure jump occurs in the pipeline connection, or supplying water in the event of a pressure drop. Then, the boundary conditions at the open surge tank can be formulated as:

$$\begin{aligned} &V_2^t A_1 - V_3^t A_2 = Q_T^t && \text{continuity} \\ &H_2^t = H_3^t && \text{energy conservation} \\ &H_2^t = z^t && \text{energy conservation} \\ &z^t = z^{t-1} + \frac{\Delta t}{a A_T}\left(Q_T^t + Q_T^{t-1}\right) && \text{tank water level} \end{aligned} \tag{5.3}$$

where $Q_T$ is the flow rate into the surge tank, $z$ is the water level in the surge tank, and $A_T$ is the cross-sectional area of the surge tank. With six equations (two compatity equations and four boundary conditions) and six unknowns $(V_2^t, V_3^t, H_2^t, H_3^t, z^t, Q_T^t)$, the above system of equations can be solved at each time step. Other devices can be modeled as well by defining the corresponding boundary conditions to replace Eq.5.3.

In TSNet, an open surge tank is assumed to exhibit infinite height so that the tank never overflows. The user can add an open surge tank to an existing network in the TSNet model by defining the desired location and the cross-sectional area of the surge tank, as shown:

```
tank_node = 'JUNCTION-90'
tank_area = 10   # tank cross sectional area [m^2]
tm.add_surge_tank(tank_node, [tank_area], 'open')
```

Although the infinite height assumption is not realistic, due to the modeling simplicity, open surge tanks can serve an good initial approach for investigating the placement of surge protection devices. In fact, the major disadvantages of open surge tanks is that it typically cannot accommodate large pressure transients unless the tank is excessively tall and large, which limits its usefulness.

Hence, we also included closed surge tank, i.e., air chamber, in TSNet as more realistic water hammer protection devices. An air chamber is a relatively small sealed vessel with compressed air at its top and water in the bottom [WYSS93]. During transient simulation, the closed surge tank also moderates pressure transients by slowing down the deceleration or the acceleration of water flow. For example, when pressure in the upstream connection increases, water flows into the tank, water level in the tank increases, air volume compresses, and air pressure increases, thus slowing down the acceleration of the water inflow into the tank and the increase in pressure. Similarly, when pressure in the upstream connection drops, water flows from the tank, then water level in the chamber decreases, air volume increases, and air pressure decreases, thus slowing the deceleration of the water flow and the decrease of pressure head. The boundary conditions characterizing close surge tank in the computational units shown in Figure 5.5 are formulated as:

$$
\begin{aligned}
&V_2^t A_1 - V_3^t A_2 = Q_T^t && \text{continuity}\\
&H_2^t = H_t^3 && \text{energy conservation}\\
&H_A^t = H2^t + H_b - z_t && \text{energy conservation}\\
&z^t = z^{t-1} + \frac{\Delta t}{aA_T}\left(Q_T^t + Q_T^{t-1}\right) && \text{tank water level}\\
&H_A^t \mathcal{V}_A^t = \text{constant} && \text{perfect gas law}\\
&\mathcal{V}_A^t = \mathcal{V}_A^{t-1} - A_T\left(z^t - z^{t-1}\right) && \text{tank air volume}
\end{aligned}
$$

where $Q_T$ is the flow rate into the surge tank, $z$ is the water level in the surge tank, $H_A, \mathcal{V}_A$ are the total head, and the volume of the air in the surge tank, $H_b$ is the barometric pressure, and $A_T$ is the cross-sectional area of the surge tank.

The user can add a closed surge tank by specifying the location, cross-sectional area, total height of the surge tank, and initial water height in the tank:

```
tank_node = 'JUNCTION-90'
tank_area = 10   # tank cross sectional area [m^2]
tank_height = 10  # tank height [m]
water_height = 5  # initial water level [m]
tm.add_surge_tank(tank_node, [tank_area,tank_height,water_height], 'closed')
```

### Valve Operations

Valve operations, including closure and opening, are supported in TSNet. The default valve shape is gate valve, the valve characteristics curve of which is defined according to [STWV96]. The following examples illustrate how to perform valve operations.

Valve closure can be simulated by defining the valve closure start time ($ts$), the operating duration ($t_c$), the valve open percentage when the closure is completed ($se$), and the closure constant ($m$), which characterizes the shape of the closure curve. These parameters essentially define the valve closure curve. For example, the code below will yield the blue curve shown in Figure 5.7. If the closure constant ($m$) is instead set to 2, the valve curve will then correspond to the orange curve in Figure 5.7.

```
tc = 1 # valve closure period [s]
ts = 0 # valve closure start time [s]
se = 0.5 # end open ratio
m = 1 # closure constant [dimensionless]
valve_op = [tc,ts,se,m]
tm.valve_closure('VALVE',valve_op)
```

Furthermore, valve opening can be simulated by defining a similar set of parameters related to the valve opening curve. The valve opening curves with $m = 1$ and $m = 2$ are illustrated in Figure 5.8.

```
tc = 1 # valve opening period [s]
ts = 0 # valve opening start time [s]
se = 0.5 # end open ratio
m = 1 # opening constant [dimensionless]
valve_op = [tc,ts,se,m]
tm.valve_opening('VALVE',valve_op)
```

### Pump Operations

The TSNet also includes the capability to perform controlled pump operations by specifying how the pump rotation speed changes over time. Explicitly, during pump start-up, the rotational speed of the pump is increased based on the

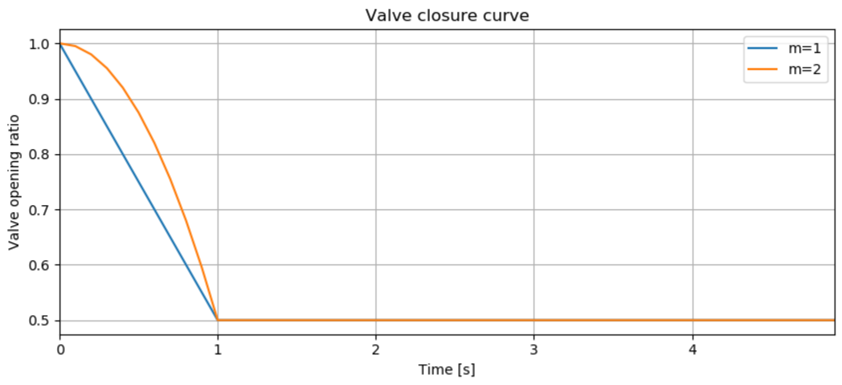


Figure 5.7: Valve closure operating rule

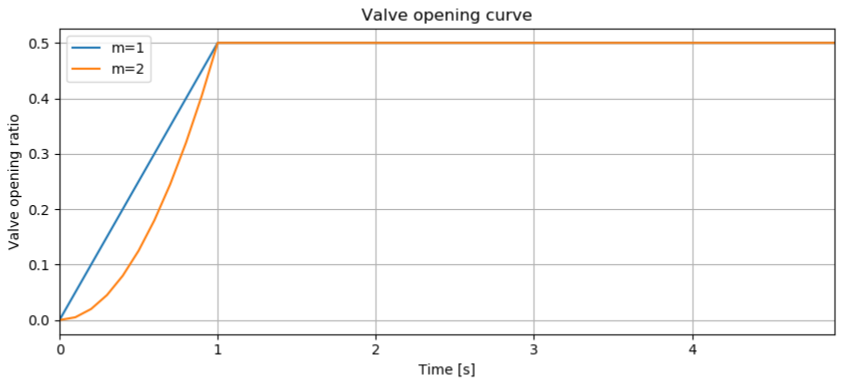


Figure 5.8: Valve opening operating rule

user defined operating rule. The pump is then modeled using the two compatibility equations, a continuity equation, the pump characteristic curve at given rotation speed, and the affinity laws [LAJW99], thus resulting in the rise of pump flowrate and the addition of mechanical energy. Conversely, during pump shut-off, as the rotational speed of the pump decreased according to the user defined operating rule, the pump flowrate and the addition of mechanical energy decline. However, pump shut-off due to power failure, when the reduction of pump rotation speed depends on the characteristics of the pump (such as the rotate moment of inertia), has not been included yet.

The following example shows how to add pump shut-off event to the network, where the parameters are defined in the same manner as in valve closure:

```
tc = 1 # pump closure period
ts = 0 # pump closure start time
se = 0 # end open percentage
m = 1 # closure constant
pump_op = [tc,ts,se,m]
tm.pump_shut_off('PUMP2', pump_op)
```

Correspondingly, the controlled pump opening can be simulated using:

```
tc = 1 # pump opening period [s]
ts = 0 # pump opening start time [s]
se = 1 # end open percentage [s]
m = 1 # opening constant [dimensionless]
pump_op = [tc,ts,se,m]
tm.pump_start_up('PUMP2',pump_op)
```

It should be noted that a check valve is assumed in each pump, indicating that the reverse flow will be prevented immediately.

### Leaks

In TSNet, leaks and bursts are assigned to the network nodes. A leak is defined by specifying the leaking node name and the emitter coefficient ($k_l$):

```
emitter_coeff = 0.01 # [ m^3/s/(m H20)^(1/2)]
tm.add_leak('JUNCTION-22', emitter_coeff)
```

Existing leaks should be included in the initial condition solver (WNTR simulator); thus, it is necessary to define the leaks before calculating the initial conditions. For more information about the inclusion of leaks in steady state calculation, please refer to WNTR documentation [WNTRSi]. During the transient simulation, the leaking node is modeled using the two compatibility equations, a continuity equation, and an orifice equation which quantifies the leak discharge ($Q_l$):

$$Q_l = k_l \sqrt{H_{p_l}}$$

where $H_{p_l}$ is the pressure head at the leaking node. Moreover, if the pressure head is negative, the leak discharge will be set to zero, assuming a backflow preventer is installed on the leaking node.

### Bursts

The simulation of burst and leaks is very similar. They share similar set of governing equations. The only difference is that the burst opening is simulated only during the transient calculation and not included in the initial condition calculation. In other words, using burst, the user can model new and evolving condition, while the leak model simulates an existing leak in the system. In TSNet, the burst is assumed to be developed linearly, indicating that the burst area increases linearly from zero to a size specified by the user during the specified time period. Thus, a burst event can be modeled by defining the start and end time of the burst, and the final emitter coefficient when the burst is fully developed:

```
ts = 1 # burst start time
tc = 1 # time for burst to fully develop
final_burst_coeff = 0.01 # final burst coeff [ m^3/s/(m H20)^(1/2)]
tm.add_burst('JUNCTION-20', ts, tc, final_burst_coeff)
```

### Demand Pulse

TSNet simulates transients generated by instantaneous demand pulse by allowing the demand coefficient to change with time We assume that the amplitude of a demand pulse ($pa(t)$) follows a symmetrical trapezoidal time-domain function, as illustrated in Figure 5.9; thus, the demand pulse can be modeled by defining the start time ($ts$), the total duration ($tc$), the transmission time ($tp$), and the peak of the amplitude ($dp$). Moreover, it should be noted that the assumed trapezoidal pulse shape is defined by method *demandpulse()* in `model` module. It can be easily modified to take any shape with moderate coding efforts. Subsequently, the time-varying demand coefficient is defined as $k(t) = k_0 + k_0 \times pa(t)$.

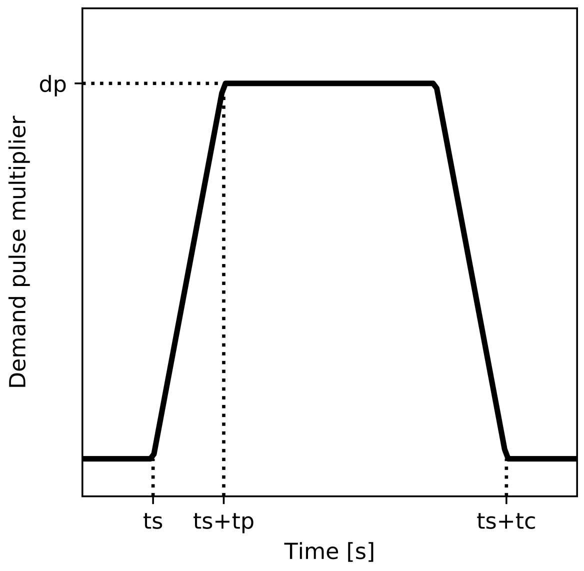


Figure 5.9: Demand pulse curve

A demand pulse shape is defined and assigned to a specified junction:

```
tc = 1 # total demand period [s]
ts = 1 # demand pulse start time [s]
tp = 0.2 # demand pulse transmission time [s]
dp = 1 # demand peak amplitude [unitless]
demand_pulse = [tc,ts,tp,dpa]
tm.add_demand_pulse('N2',demand_pulse)
```

CHAPTER 6

# Simulation Results

## 6.1 Results Structure

Simulation results are returned and saved in the *tsnet.network.model.TransientModel* object for each node and link in the networks.

Node results include the following attributes:

- Head [m]
- Emitter discharge (including leaks and bursts) [$m^3/s$]
- Actual demand discharge [$m^3/s$]

Link results include the following attributes:

- Head at start node [m]
- Flow velocity at start node [$m^3/s$]
- Flow rate at start node [$m^3/s$]
- Head at end node [m]
- Flow velocity at end node [$m^3/s$]
- Flow rate at end node [$m^3/s$]

The result for each attribute is a Numpy array, representing the time history of the simulation results, the length of which equals the total number of simulation time steps ($tn$).

For example, the results of head, emitter discharge and demand discharge at node 'JUNCTION-105' can be accessed by:

```
node = tm.get_node['JUNCTION-105']
head = node.head
emitter_discharge = node.emitter_discharge
demand_discharge = node.demand_discharge
```

To obtain the results on pipe 'LINK-40':

```
pipe = tm.get_link('LINK-40')
start_head = pipe.start_node_head
end_head = pipe.end_node_head
start_velocity = pipe.start_node_velocity
end_velocity = pipe.end_node_velocity
start_flowrate = pipe.start_node_flowrate
end_flowrate = pipe.end_node_flowrate
```

## 6.2 Time Step and Time Stamps

Additionally, the time step (in seconds) and the time stamps (in seconds from the start of the simulation) are also stored in the `tsnet.network.model.TransientModel` object. They can be retrieved by:

```
dt = tm.time_step
tt = tm.simulation_timestamps
```

The results can then be plotted with respect to the time stamps using **matplotlib** or any other preferred package, as shown in Figure 6.1:

```
import matplotlib.pyplot as plt
plt.plot(tt ,head)
```

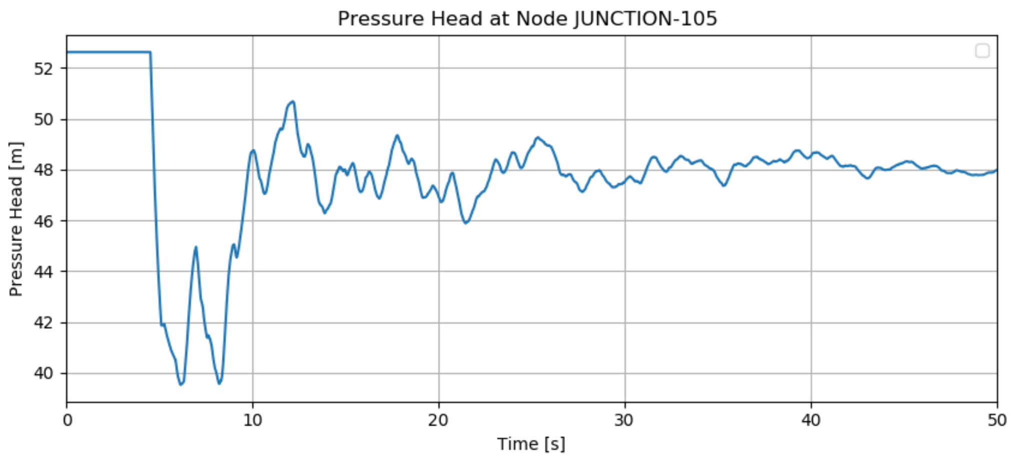


Figure 6.1: Head results at JUNCTION-105

## 6.3 Results Retrieval

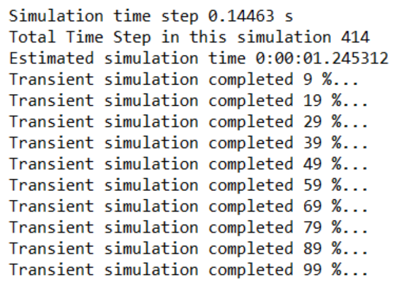
The `tsnet.network.model.TransientModel` object, including the information of the network, operation rules, and the simulated results, is saved in the file **results_obj.obj**, located in the current folder. The name of the results file is defined by the input parameter *result_obj*. If *result_obj* is not given, the default results file is *results.obj*.

To retrieve the results from a previously completed simulation, one can read the `tsnet.network.model.TransientModel` object from the **results_obj.obj** file and access results from the objet by:

```
import pickle
file = open('results.obj', 'rb')
tm = pickle.load(file)
```

## 6.4 Runtime and Progress

At the beginning of transient simulation, TSNet will report the approximation simulation time based on the calculation time of first few time steps and the total number of time steps. Additionally, the computation progress will also printed on the screen as the simulation proceeds, as shown in Figure 6.2.



```
Simulation time step 0.14463 s
Total Time Step in this simulation 414
Estimated simulation time 0:00:01.245312
Transient simulation completed 9 %...
Transient simulation completed 19 %...
Transient simulation completed 29 %...
Transient simulation completed 39 %...
Transient simulation completed 49 %...
Transient simulation completed 59 %...
Transient simulation completed 69 %...
Transient simulation completed 79 %...
Transient simulation completed 89 %...
Transient simulation completed 99 %...
```

Figure 6.2: Runtime output about calculation time and process.

CHAPTER 7

# Example Applications

## 7.1 Example 1 - End-valve closure

This example shows how to simulate the closure of a valve located at the boundary of a network. The first example network is shown below in Figure 7.1, adopted from [[STWY67],WOLB05]_. It comprises 9 pipes, 8 junctions, one reservoir, 3 closed loops, and one valve located at the downstream end of the system. There are five steps that the user needs to take to run the transient simulation using the TSNet package:

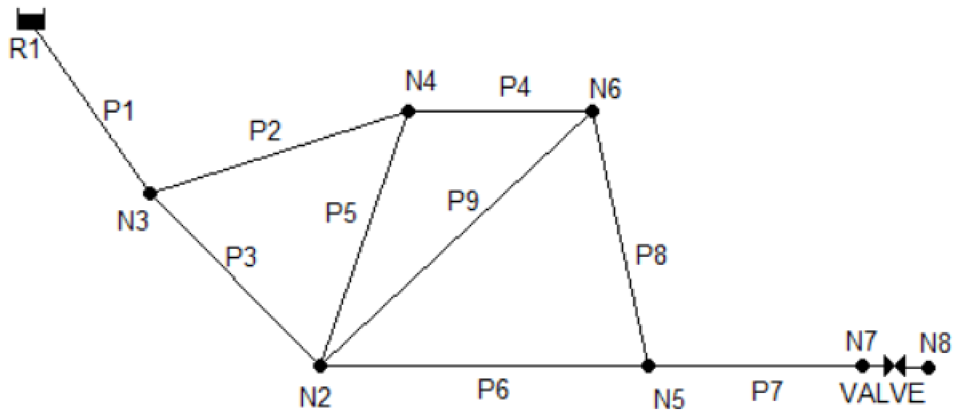


Figure 7.1: Tnet1 network graphics

1. Import TSNet package, read the EPANET INP file, and create transient model object.

```
import tsnet
# Open an example network and create a transient model
tm = tsnet.network.TransientModel('/Users/luxing/Code/TSNet/examples/networks/Tnet1.
↪inp')
```

2. Set the wave speed for all pipes to $1200m/s$, time step to $0.1s$, and simulation period to $60s$.

```
tm.set_wavespeed(1200.) # m/s

# Set time options
tf = 20    # simulation period [s]
tm.set_time(tf)
```

3. Set valve operating rules, including how long it takes to close the valve ($tc$), when to start close the valve ($ts$), the opening percentage when the closure is completed ($se$), and the shape of the closure operating curve ($m$, 1 stands for linear closure, 2 stands for quadratic closure).

```
ts = 5 # valve closure start time [s]
tc = 1 # valve closure period [s]
se = 0 # end open percentage [s]
m = 2 # closure constant [dimensionless]
tm.valve_closure('VALVE',[tc,ts,se,m])

# Initialize steady state simulation
```

4. Compute steady state results to establish the initial condition for transient simulation.

```
tm = tsnet.simulation.Initializer(tm,t0)

# Transient simulation
tm = tsnet.simulation.MOCSimulator(tm)
```

5. Run transient simulation and specify the name of the results file.

```
# report results
node = ['N2','N3']
tm.plot_node_head(node)
```

After the transient simulation, the results at nodes and links will be returned and stored in the transient model (tm) instance. The time history of flow rate on the start node of pipe P2 throughout the simulation can be retrieved by:

```
>>> print(tm.links['P2'].start_node_flowrate)
```

To plot the head results at N3:

yields Figure 7.2:

Similarly, to plot the flow rate results in pipe P2:

yields Figure 7.3:

## 7.2 Example 2 - Pump operations

This example illustrates how the package models a transient event resulting from a controlled pump shut-off , i.e., the pump speed is ramped down. This example network, Tnet2, is shown below in Figure 7.4. Tnet2 comprises 113 pipes,

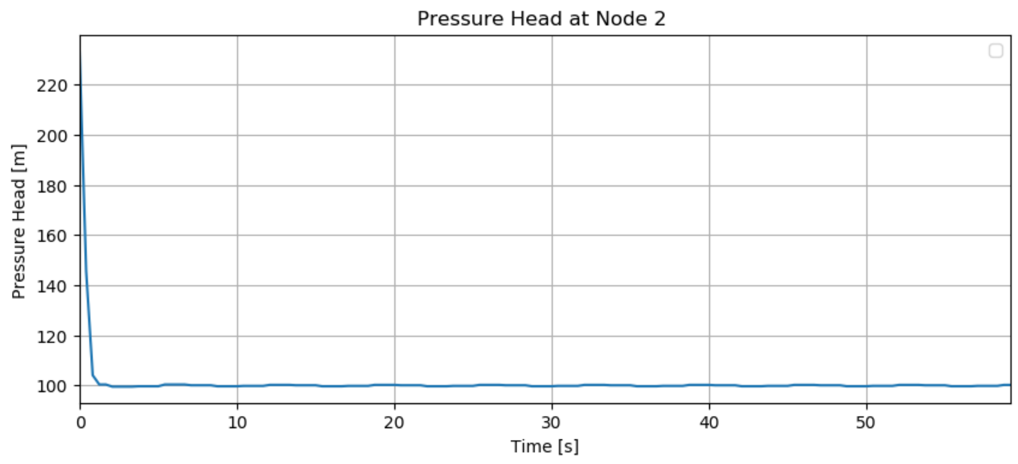


Figure 7.2: Tnet1 - Head at node N3.

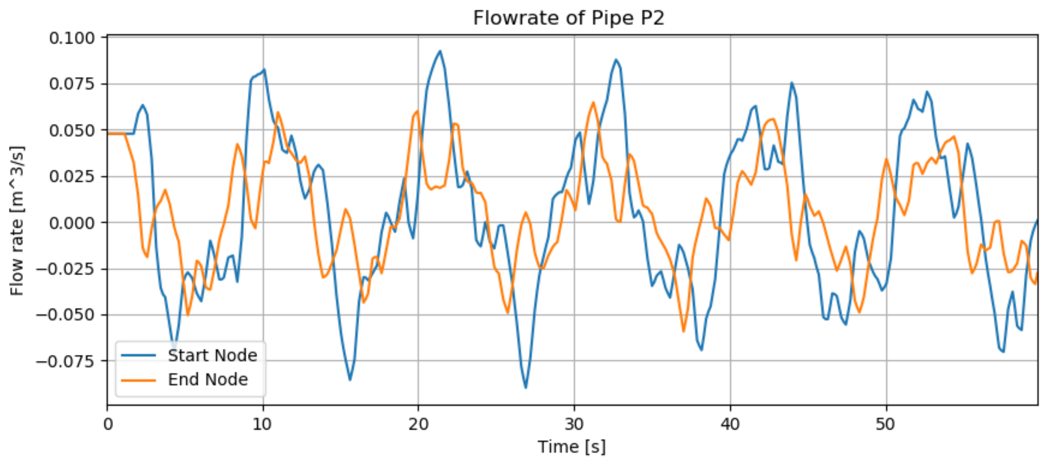


Figure 7.3: Tnet1 - Flow rate at the start and end node of pipe P2.

91 junctions, 2 pumps, 2 reservoir, 3 tanks, and one valve located in the middle of the network. A transient simulation of 50 seconds is generated by shutting off PUMP2. There are five steps user needs to take:

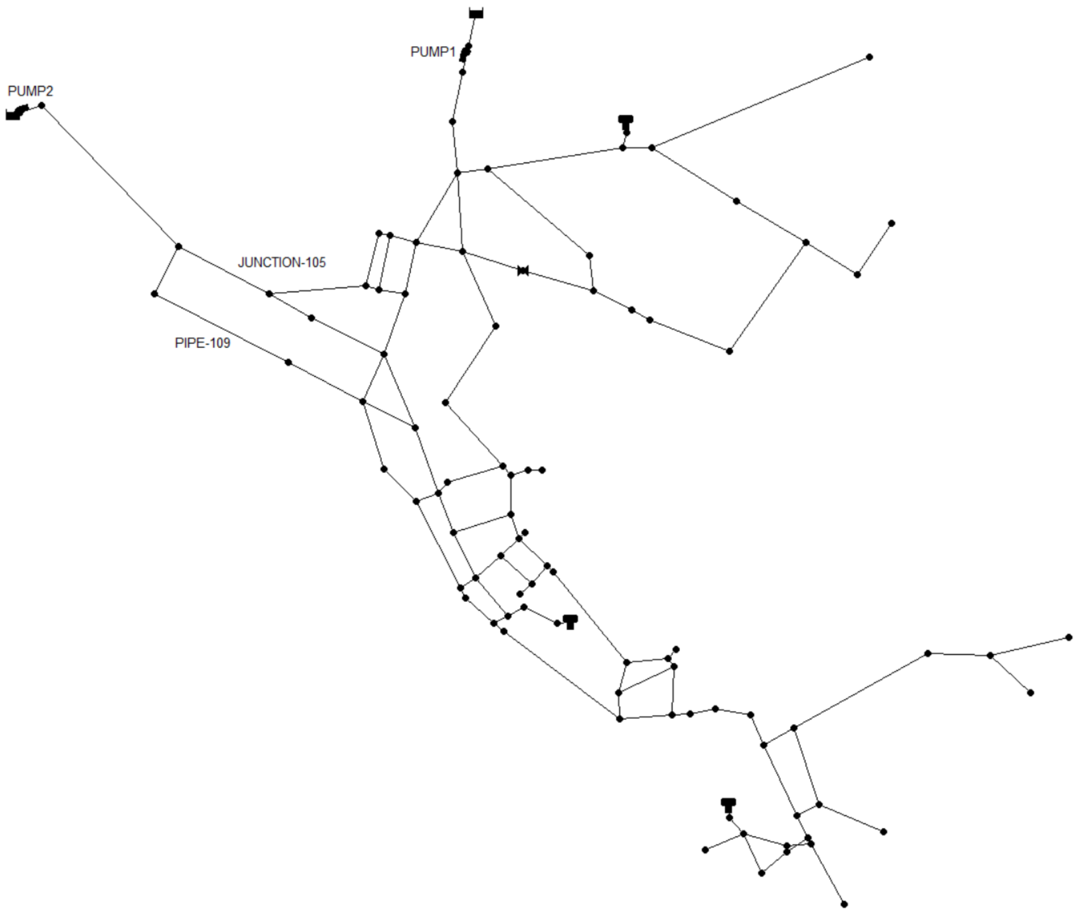


Figure 7.4: Tnet2 network graphics

1. Import TSNet package, read the EPANET INP file, and create transient model object.

```
import tsnet
# open an example network and create a transient model
inp_file = '/Users/luxing/Code/TSNet/examples/networks/Tnet2.inp'
tm = tsnet.network.TransientModel(inp_file)
```

2. Set the wave speed for all pipes to be $1200m/s$ and simulation period to be $50s$. Use suggested time step.

```
# Set wavespeed
tm.set_wavespeed(1200.)
# Set time step
tf = 20 # simulation period [s]
tm.set_time(tf)
```

3. Set pump operating rules, including how long it takes to shutdown the pump ($tc$), when to the shut-off starts ($ts$), the pump speed multiplier value when the shut-off is completed ($se$), and the shape of the shut-off operation curve ($m$, 1 stands for linear closure, 2 stands for quadratic closure).

```
# Set pump shut off
tc = 1 # pump closure period
ts = 1 # pump closure start time
se = 0 # end open percentage
m = 1 # closure constant
pump_op = [tc,ts,se,m]
tm.pump_shut_off('PUMP2', pump_op)
```

4. Compute steady state results to establish the initial condition for transient simulation.

```
# Initialize steady state simulation
t0 = 0. # initialize the simulation at 0s
engine = 'DD' # or PPD
tm = tsnet.simulation.Initializer(tm, t0, engine)
```

5. Run transient simulation and specify the name of the results file.

```
# Transient simulation
results_obj = 'Tnet2' # name of the object for saving simulation results.head
tm = tsnet.simulation.MOCSimulator(tm,results_obj)
```

After the transient simulation, the results at nodes and links will be returned to the transient model (tm) instance, which is then stored in **Tnet2.obj**. The actual demand discharge at JUNCTION-105 throughout the simulation can be retrieved by:

```
>>> print(tm.nodes['JUNCTION-105'].demand_discharge)
```

To plot the head results at JUNCTION-105:

```
import matplotlib.pyplot as plt
node = 'JUNCTION-105'
node = tm.get_node(node)
fig = plt.figure(figsize=(10,4), dpi=80, facecolor='w', edgecolor='w')
plt.plot(tm.simulation_timestamps, node._head, 'k', lw=3)
plt.xlim([tm.simulation_timestamps[0],tm.simulation_timestamps[-1]])
# plt.title('Pressure Head at Node %s '%node)
plt.xlabel("Time [s]", fontsize=14)
plt.ylabel("Pressure Head [m]", fontsize=14)


# plt.legend(loc='best')
```

yields Figure 6.1:

Similarly, to plot the velocity results in PIPE-109:

```
# fig.savefig('./docs/figures/tnet2_node.png', format='png',dpi=100)

pipe = 'PIPE-109'
pipe = tm.get_link(pipe)
fig = plt.figure(figsize=(10,4), dpi=80, facecolor='w', edgecolor='w')
plt.plot(tm.simulation_timestamps,pipe.start_node_velocity,label='Start Node')
plt.plot(tm.simulation_timestamps,pipe.end_node_velocity,label='End Node')
plt.xlim([tm.simulation_timestamps[0],tm.simulation_timestamps[-1]])
plt.title('Velocity of Pipe %s '%pipe)
plt.xlabel("Time [s]")
plt.ylabel("Velocity [m/s]")
plt.legend(loc='best')
```

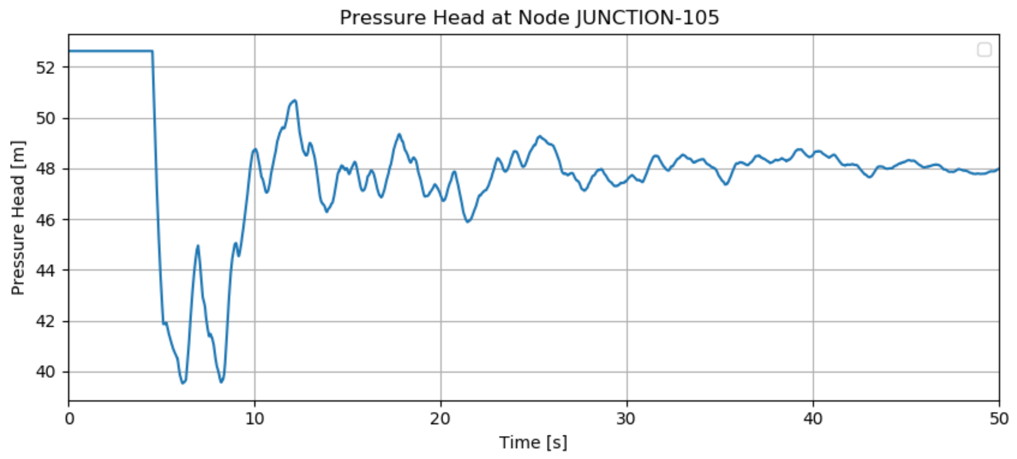


Figure 7.5: Tnet2 - Head at node JUNCTION-105.

yields Figure 7.6:

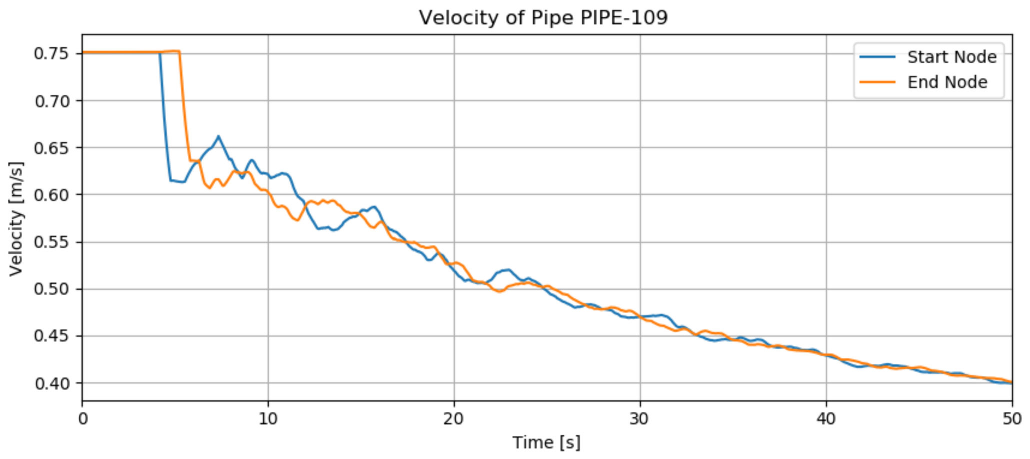


Figure 7.6: Tnet2 - Velocity at the start and end node of PIPE-109.

## 7.3 Example 3 - Burst and leak

This example reveals how TSNet simulates pipe bursts and leaks. This example network, adapted from [OSBH08], is shown below in Figure 7.7. Tnet3 comprises 168 pipes, 126 junctions, 8 valve, 2 pumps, one reservoir, and two tanks. The transient event is generated by a burst and a background leak. There are five steps that the user would need to take:

1. Import TSNet package, read the EPANET INP file, and create transient model object.

```
import tsnet
# open an example network and create a transient model
inp_file = '/Users/luxing/Code/TSNet/examples/networks/Tnet3.inp'
tm = tsnet.network.TransientModel(inp_file)
```

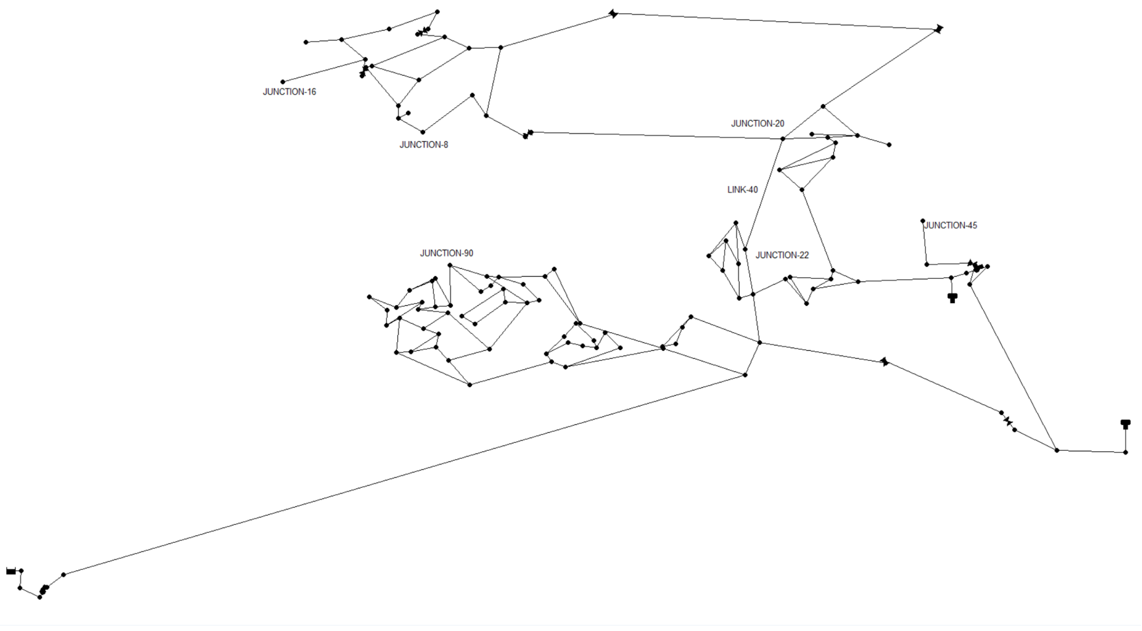


Figure 7.7: Tnet3 network graphics

2. The user can import custom wave speeds for each pipe. To demonstrate how to assign different wave speed, we assume that the wave speed for the pipes is normally distributed with mean of $1200m/s$ and standard deviation of :math: *100m/s*. Then, assign the randomly generated wave speed to each pipe in the network according to the order the pipes defined in the INP file. Subsequently, set the simulation period as $20s$, and use suggested time step.

```
# Set wavespeed
import numpy as np
wavespeed = np.random.normal(1200., 100., size=tm.num_pipes)
tm.set_wavespeed(wavespeed)
# Set time step
tf = 20 # simulation period [s]
tm.set_time(tf)
```

3. Define background leak location, JUNCTION-22, and specify the emitter coefficient. The leak will be included in the initial condition calculation. See WNTR documentation [WNTRSi] for more info about leak simulation.

```
# Add leak
# emitter_coeff = 0.01 # [ m^3/s/(m H20)^(1/2)]
# tm.add_leak('JUNCTION-22', emitter_coeff)
```

4. Compute steady state results to establish the initial condition for transient simulation.

```
# Initialize steady state simulation
t0 = 0. # initialize the simulation at 0s
engine = 'PDD' # or Epanet
tm = tsnet.simulation.Initializer(tm, t0, engine)
```

5. Set up burst event, including burst location, JUNCTION-20, burst start time ($ts$), time for burst to fully develop ($tc$), and the final emitter coefficient (final_burst_coeff).

```
# Add burst
ts = 1 # burst start time
tc = 1 # time for burst to fully develop
final_burst_coeff = 0.01 # final burst coeff [ m^3/s/(m H20)^(1/2)]
tm.add_burst('JUNCTION-20', ts, tc, final_burst_coeff)
```

6. Run transient simulation and specify the name of the results file.

```
# Transient simulation
result_obj = 'Tnet3' # name of the object for saving simulation results
tm = tsnet.simulation.MOCSimulator(tm,result_obj)
```

After the transient simulation, the results at nodes and links will be returned to the transient model (tm) instance, which is subsequently stored in **Tnet3.obj**.

To understand how much water has been lost through the leakage at JUNCTION-22, we can plot the leak discharge results at JUNCTION-22:

```
import matplotlib.pyplot as plt
node = 'JUNCTION-22'
node = tm.get_node(node)
fig = plt.figure(figsize=(10,4), dpi=80, facecolor='w', edgecolor='k')
plt.plot(tm.simulation_timestamps,node.emitter_discharge)
plt.xlim([tm.simulation_timestamps[0],tm.simulation_timestamps[-1]])
plt.title('Leak discharge at Node %s '%node)
plt.xlabel("Time [s]")
plt.ylabel("Leak discharge [m^3/s]")
plt.legend(loc='best')
plt.grid(True)
plt.show()
```

yields Figure 7.8:

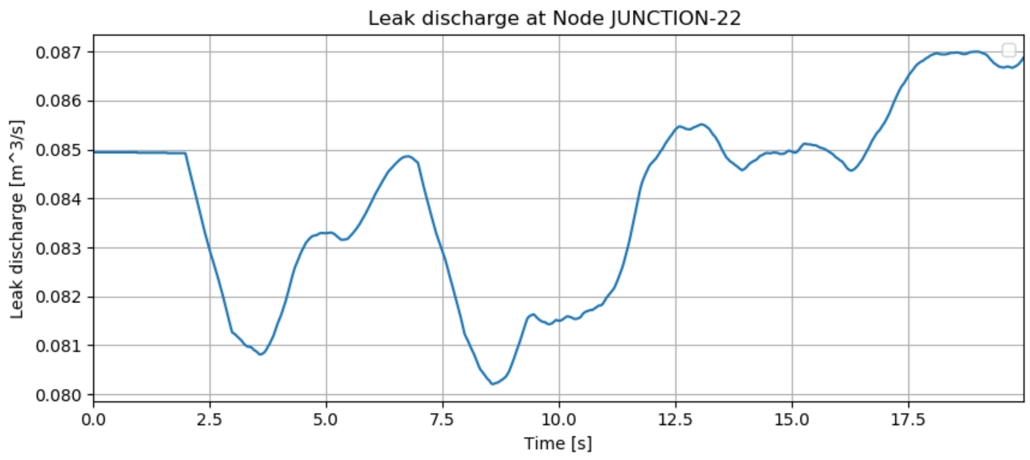


Figure 7.8: Tnet3 - Leak discharge at node JUNCTION-22.

Similarly, to reveal how much water has been wasted through the burst event at JUNCTION-20, we can plot the burst discharge results at JUNCTION-20:

```
node = 'JUNCTION-20'
node = tm.get_node(node)
```

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```
fig = plt.figure(figsize=(10,4), dpi=80, facecolor='w', edgecolor='k')
plt.plot(tm.simulation_timestamps,node.emitter_discharge)
plt.xlim([tm.simulation_timestamps[0],tm.simulation_timestamps[-1]])
plt.title('Burst discharge at Node %s '%node)
plt.xlabel("Time [s]")
plt.ylabel("Burst discharge [m^3/s]")
plt.legend(loc='best')
plt.grid(True)
plt.show()
```

yields Figure 7.9:

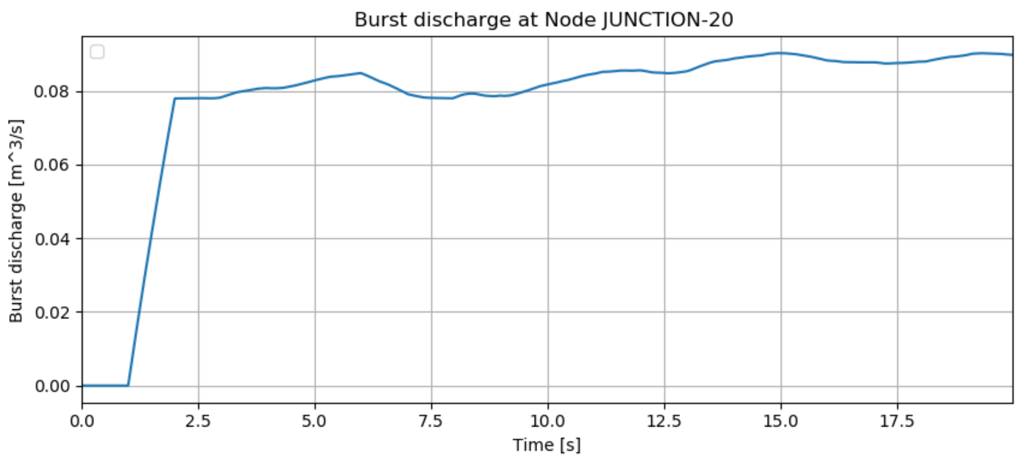

Figure 7.9: Tnet3 - Burst discharge at node JUNCTION-20.

Additionally, to plot the velocity results in LINK-40:

```
pipe = 'LINK-40'
pipe = tm.get_link(pipe)
fig = plt.figure(figsize=(10,4), dpi=80, facecolor='w', edgecolor='k')
plt.plot(tm.simulation_timestamps,pipe.start_node_velocity,label='Start Node')
plt.plot(tm.simulation_timestamps,pipe.end_node_velocity,label='End Node')
plt.xlim([tm.simulation_timestamps[0],tm.simulation_timestamps[-1]])
plt.title('Velocity of Pipe %s '%pipe)
plt.xlabel("Time [s]")
plt.ylabel("Velocity [m/s]")
plt.legend(loc='best')
plt.grid(True)
plt.show()
```

yields Figure 7.10:

Moreover, we can plot head results at some further nodes, such as JUNCTION-8, JUNCTION-16, JUNCTION-45, JUNCTION-90, by:

```
node1 = tm.get_node('JUNCTION-8')
node2 = tm.get_node('JUNCTION-16')
node3 = tm.get_node('JUNCTION-45')
node4 = tm.get_node('JUNCTION-90')
fig = plt.figure(figsize=(10,4), dpi=80, facecolor='w', edgecolor='k')
```

(continues on next page)

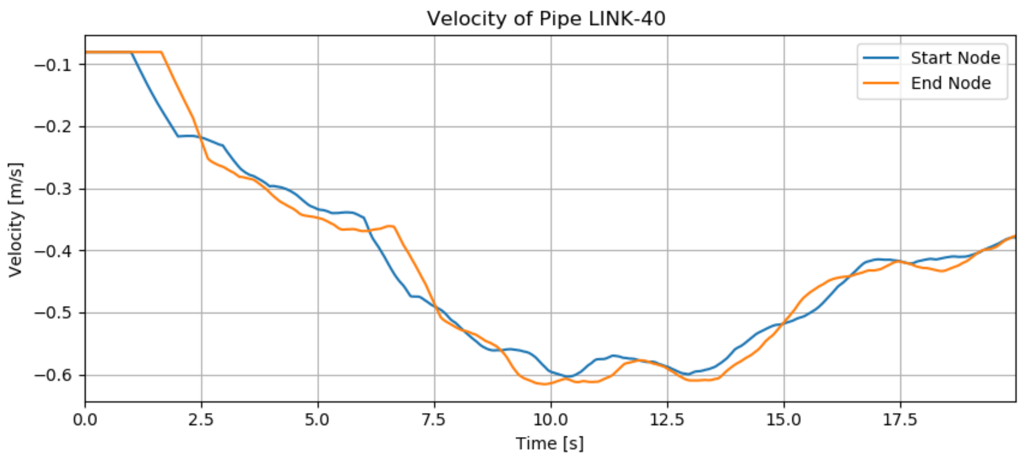

Figure 7.10: Tnet3 - Velocity at the start and end node of LINK-40.

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```
plt.plot(tm.simulation_timestamps, node1._head, label='JUNCTION-8')
plt.plot(tm.simulation_timestamps, node2._head, label='JUNCTION-16')
plt.plot(tm.simulation_timestamps, node3._head, label='JUNCTION-45')
plt.plot(tm.simulation_timestamps, node4._head, label='JUNCTION-90')
plt.xlim([tm.simulation_timestamps[0],tm.simulation_timestamps[-1]])
plt.title('Head on Junctions')
plt.xlabel("Time [s]")
plt.ylabel("Head [m]")
plt.legend(loc='best')
plt.grid(True)
plt.show()
```

The results are demonstrated in Figure 7.11. It can be noticed that the amplitude of the pressure transient at JUNCTION-8 and JUNCTION-16 is greater than that at other two junctions which are further away from JUNCTION-20, where the burst occurred.

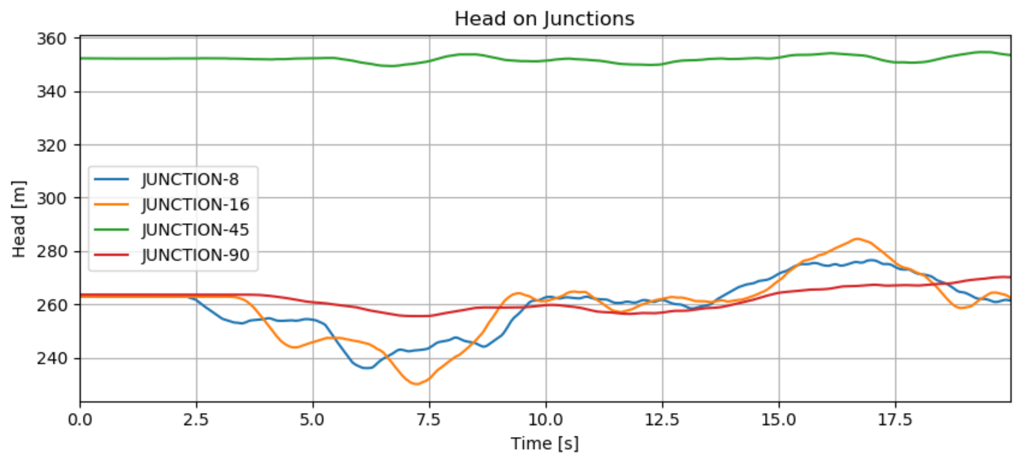

Figure 7.11: Tnet3 - Head at multiple junctions.

More examples are includeded in https://github.com/glorialulu/TSNet/tree/master/examples.

CHAPTER 8

# Comparison with Hammer

During the development process, we have consistently compared TSNet results with Bentley Hammer [HAMMER] using different networks and many different transient events. In this section, we present the comparison between TSNet and Hammer results. The Hammer models used to generate the events is also included in the GitHub example directory (https://github.com/glorialulu/TSNet/tree/master/examples/networks) for the user's reference.

## 8.1 Tnet 0

We first show the comparison for a simple network, consisting of one reservoir, two pipes, and one valve, as illustrated in Figure 8.1. The wave speed for both pipes is $1200m/s$, and lengths and diameters are given in the figure. The transient event is generated by closing the end-valve at the beginning of the simulation during 2s; thus, the flow rate at the end valve decreases linearly from $0.05m^3/s$ at $t = 0s$ to $0m^3/s$ at $t = 2s$ and remains zero thereafter. Figure 8.2 (a) shows the flow rate through the valve, and Figure 8.2 (b) presents the pressure transients generated at node N-1 during 60s simulation period. The solid line represents TSNet results and the dashed-dotted line shows Hammer results. These results indicate a perfect match between TSNet and Hammer simulation results for this simple network.

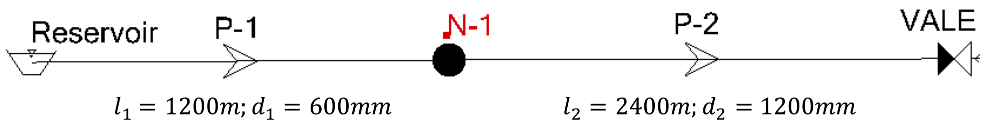

Figure 8.1: Topology of a simple network.

## 8.2 Tnet 3

We then show the comparison between TSNet and Hammer results for a more complicated network, Tnet3, for three different transient events:

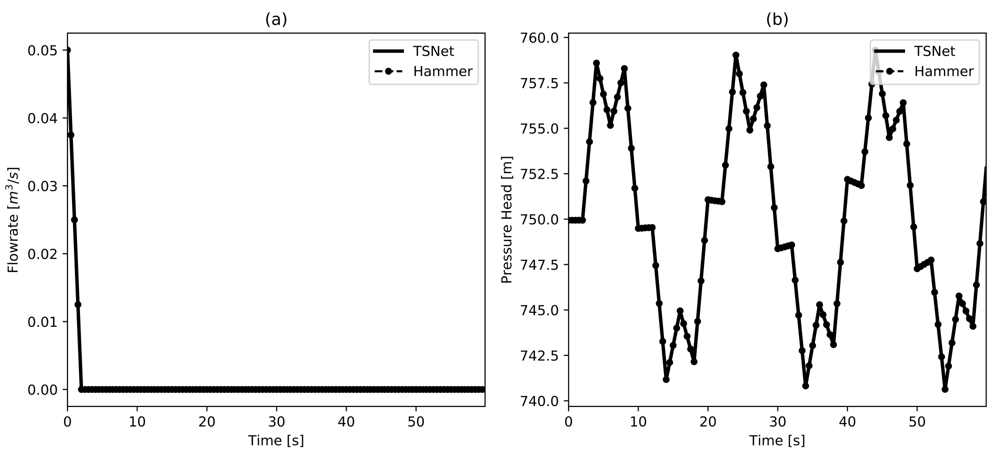

Figure 8.2: Comparison of TSNet and Hammer results: (a) flow at the valve; (b) pressure head at N-1.

1. Shut down of PUMP-1,
2. Burst at JUNCTION-73, and
3. Closure of VALVE-1.

The results for the three transient-generating events are shown in Figure 8.3, Figure 8.4, and Figure 8.5, respectively.

- We would like to note beforehand that we do not expect to obtain the exact same results from TSNet as Hammer since different numerical schemes were implemented, such as wave speed adjustment, pressure dependent demand, and boundary conditions.

## 8.2.1 Pump shut-down

Both TSNet and Hammer are utilized to simulate the shut down of PUMP-1. The time step is specified as 0.002s in both software. Figure 8.3 reports the pressure change with respect to the nominal pressure at multiple junctions, where the solid lines represent TSNet results and the dashed lines show Hammer results. TSNet and Hammer results are very similar to each other in terms of attenuation and phase shift throughout the 20s simulation period, despite slight discrepancies, which can be explained by the different wave speed adjustment schemes and boundary condition configurations adopted by the two software.

## 8.2.2 Burst event

Aburst event was simulated at Junction-73 using both TSNet and Hammer. Figure 8.4 reports the pressure change with respect to the nominal pressure at multiple junctions, where the solid lines represent TSNet results, and the dashed lines show Hammer results. It can be observed that during the first transient cycle, i.e., around 0-8s, TSNet and Hammer results exhibit very good agreement with each other. Although the discrepancies increase a bit in terms of attenuation and phase shift during the latter period, the overall match is satisfactory considering that different time step and wave speed adjustment schemes are adopted in the two software.

## 8.2.3 Valve closure

Both TSNet and Hammer are utilized to simulate the closure of VALVE-1. The comparison of the results is presented in Figure 8.5. Again, adequate resemblance can be observed between the TSNet (a) and Hammer results (b). Considering that pressure transients are of smaller amplitude and more chaotic, the results are presented in two separate plots with same scale for clarity.

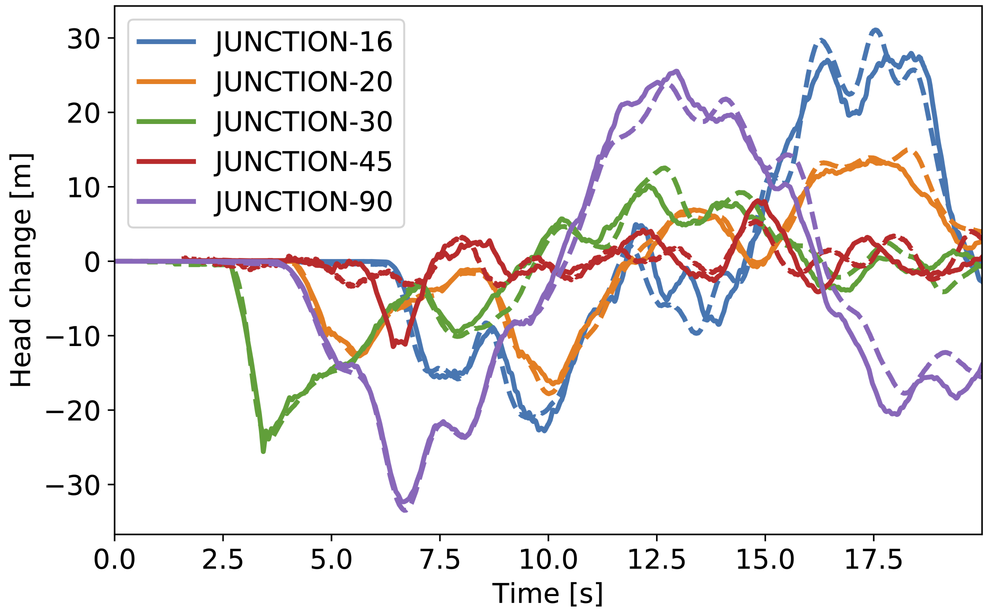

Figure 8.3: Comparison of pressure transients at multiple junctions generated by shutting down PUMP-1 in TNet3: TSNet (solid lines) Hammer (dashed lines) results.

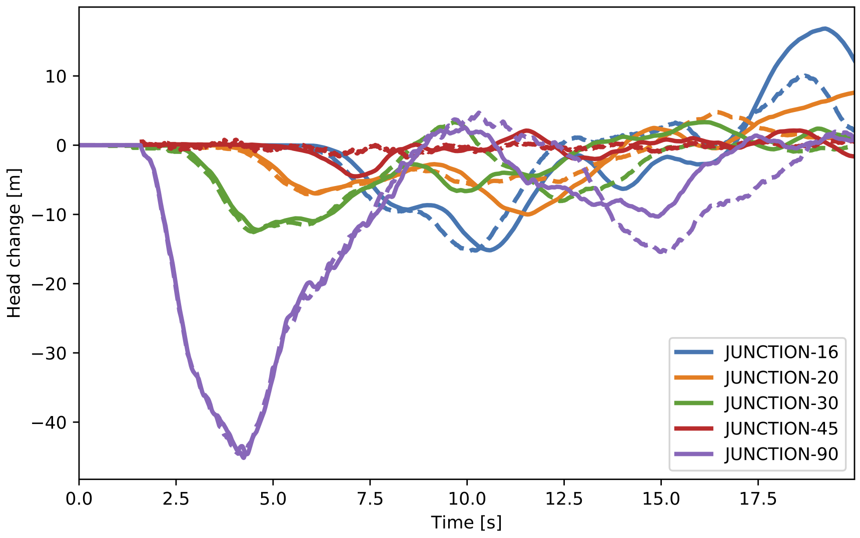

Figure 8.4: Comparison of pressure transients at multiple junctions generated by the burst at JUNCTION-73 in Tnet3: TSNet (solid lines) Hammer (dashed lines) results.

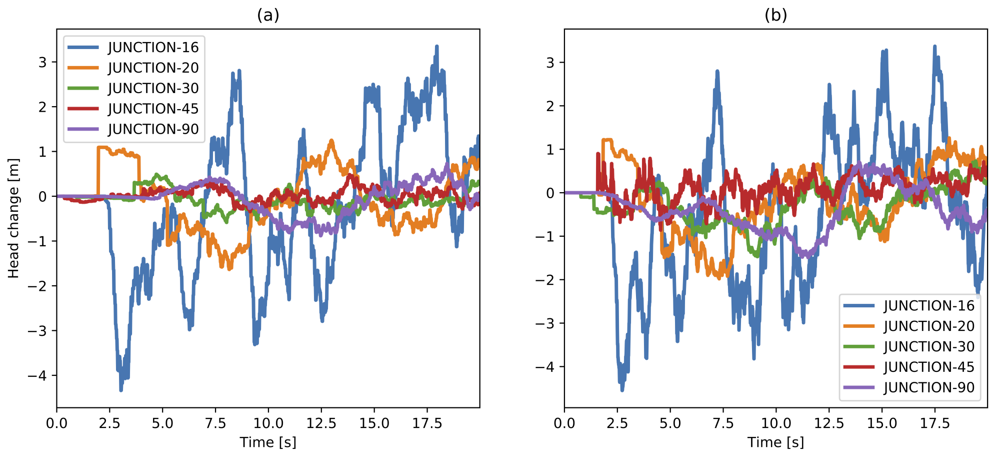

Figure 8.5: Comparison of pressure transients at multiple junctions generated by closing VALVE-1 in Tnet3: (a): TSNet results, (b): Hammer results.

# CHAPTER 9

# Contributing

Contributions are welcome, and they are greatly appreciated! Every little bit helps, and credit will always be given.

You can contribute in many ways:

## 9.1 Types of Contributions

### 9.1.1 Report Bugs

Report bugs at https://github.com/glorialulu/TSNet/issues.

If you are reporting a bug, please include:

- Your operating system name and version.
- Any details about your local setup that might be helpful in troubleshooting.
- Detailed steps to reproduce the bug.

### 9.1.2 Fix Bugs

Look through the GitHub issues for bugs. Anything tagged with “bug” and “help wanted” is open to whoever wants to implement it.

### 9.1.3 Implement Features

Look through the GitHub issues for features. Anything tagged with “enhancement” and “help wanted” is open to whoever wants to implement it.

### 9.1.4 Write Documentation

TSNet could always use more documentation, whether as part of the official TSNet docs, in docstrings, or even on the web in blog posts, articles, and such.

### 9.1.5 Submit Feedback

The best way to send feedback is to file an issue at https://github.com/glorialulu/TSNet/issues.

If you are proposing a feature:

- Explain in detail how it would work.
- Keep the scope as narrow as possible, to make it easier to implement.
- Remember that this is a volunteer-driven project, and that contributions are welcome :)

## 9.2 Get Started!

Ready to contribute? Here's how to set up *TSNet* for local development.

1. Fork the *TSNet* repo on GitHub.
2. Clone your fork locally:

```
$ git clone git@github.com:your_name_here/TSNet.git
```

3. Install your local copy into a virtualenv. Assuming you have virtualenvwrapper installed, this is how you set up your fork for local development:

```
$ mkvirtualenv TSNet
$ cd TSNet/
$ python setup.py develop
```

4. Create a branch for local development:

```
$ git checkout -b name-of-your-bugfix-or-feature
```

   Now you can make your changes locally.

5. When you're done making changes, check that your changes pass flake8 and the tests, including testing other Python versions with tox:

```
$ flake8 TSNet tests
$ python setup.py test or py.test
$ tox
```

   To get flake8 and tox, just pip install them into your virtualenv.

6. Commit your changes and push your branch to GitHub:

```
$ git add .
$ git commit -m "Your detailed description of your changes."
$ git push origin name-of-your-bugfix-or-feature
```

7. Submit a pull request through the GitHub website.

## 9.3 Pull Request Guidelines

Before you submit a pull request, check that it meets these guidelines:

1. The pull request should include tests.
2. If the pull request adds functionality, the docs should be updated. Put your new functionality into a function with a docstring, and add the feature to the list in README.rst.
3. The pull request should work for Python 3.5, 3.6 and 3.7, and for PyPy. Check https://travis-ci.org/glorialulu/TSNet/pull_requests and make sure that the tests pass for all supported Python versions.

## 9.4 Tips

To run a subset of tests:

```
$ py.test .\tests\test_tsnet.py
```

## 9.5 Deploying

A reminder for the maintainers on how to deploy. Make sure all your changes are committed (including an entry in HISTORY.rst). Then run:

```
$ bumpversion patch # possible: major / minor / patch
$ git push
$ git push --tags
```

Travis will then deploy to PyPI if tests pass.

# CHAPTER 10

# Credits

## 10.1 Development Lead

- Lu Xing <xinglu@utexas.edu>
- Lina Sela <linasela@utexas.edu>

## 10.2 Contributors

This package is being developed and supported by the WATSUP group at UT Austin. Contributing group members

- Gerardo Andres Riano Briceno <griano@utexas.edu>
- Ahmed A. Abokifa <ahmed.abokifa@utexas.edu>

# CHAPTER 11

# History

## 11.1 0.1.0 (2019-08-15)

- First release on PyPI.

## 11.2 0.1.1 (2019-09-21)

## 11.3 0.1.2 (2020-01-20)

1. Fixed bugs about dead end and single pipe.
2. Added plot and change detection methods.

## 11.4 0.2.0 (2020-4-23)

1. Added quasi-steady and unsteady friction model.
2. Added open and closed surge tanks.
3. Added demand-pulse simulation.
4. Updated docs.

## 11.5 0.2.1 (2020-09-09)

1. Fixed minor bugs about valve default settings.
2. Updated documentation.

3. Updated WNTR compatibility.

## 11.6 0.2.2 (2020-09-24)

1. Updated WNTR compatibility.

## 11.7 0.2.3 (2021-11-12)

1. Only support WNTR version up until 0.3.0

## 11.8 0.2.4 (2022-06-17)

1. fix minor issues regarding reporting messages
2. Only support WNTR version up until 0.2.3.

## 11.9 0.3.0 (2023-02-22)

1. Support WNTR version 1.0.0
2. Test on python 3.10 and 3.11.
3. Drop supports for Python 3.6 and 3.7

# CHAPTER 12

# tsnet package

## 12.1 Subpackages

### 12.1.1 tsnet.network package

#### Submodules

#### tsnet.network.control module

The tsnet.network.control module includes method to define network controls of the pump and valve.These control modify parameters in the network during transient simulation.

`tsnet.network.control.`**`valveclosing`**(*dt*, *tf*, *valve_op*)
Define valve operation curve (percentage open v.s. time)

**Parameters**

- **`dt`** (*`float`*) – Time step
- **`tf`** (*`float`*) – Simulation Time
- **`valve_op`** (*`list`*) – Contains parameters to define valve operation rule valve_op = [tc,ts,se,m] tc : the duration takes to close the valve [s] ts : closure start time [s] se : final open percentage [s] m : closure constant [unitless]

**Returns** **s** – valve operation curve

**Return type** list

`tsnet.network.control.`**`valveopening`**(*dt*, *tf*, *valve_op*)
Define valve operation curve (percentage open v.s. time)

**Parameters**

- **`dt`** (*`float`*) – Time step
- **`tf`** (*`float`*) – Simulation Time

- **valve_op** (*list*) – Contains parameters to define valve operation rule valve_op = [tc,ts,se,m] tc : the duration takes to close the valve [s] ts : closure start time [s] se : final open percentage [s] m : closure constant [unitless]

**Returns** **s** – valve operation curve

**Return type** list

`tsnet.network.control.`**`pumpclosing`**(*dt*, *tf*, *pump_op*)
Define pump operation curve (percentage open v.s. time)

**Parameters**

- **dt** (*float*) – Time step
- **tf** (*float*) – Simulation Time
- **valve_op** (*list*) – Contains parameters to define valve operation rule valve_op = [tc,ts,se,m] tc : the duration takes to close the valve [s] ts : closure start time [s] se : final open percentage [s] m : closure constant [unitless]

**Returns** **s** – valve operation curve

**Return type** list

`tsnet.network.control.`**`pumpopening`**(*dt*, *tf*, *pump_op*)
Define pump operation curve (percentage open v.s. time)

**Parameters**

- **dt** (*float*) – Time step
- **tf** (*float*) – Simulation Time
- **pump_op** (*list*) – Contains parameters to define pump operation rule pump_op = [tc,ts,se,m] tc : the duration takes to start up the pump [s] ts : open start time [s] se : final open percentage [s] m : closure constant [unitless]

**Returns** **s** – valve operation curve

**Return type** list

`tsnet.network.control.`**`burstsetting`**(*dt*, *tf*, *ts*, *tc*, *final_burst_coeff*)
Calculate the burst area as a function of simulation time

**Parameters**

- **dt** (*float*) – Time step
- **tf** (*float*) – Simulation Time
- **ts** (*float*) – Burst start time
- **tc** (*float*) – Time for burst to fully develop
- **final_burst_coeff** (*list or float*) – Final emitter coefficient at the burst nodes

`tsnet.network.control.`**`demandpulse`**(*dt*, *tf*, *tc*, *ts*, *tp*, *dp*)
Calculate demand pulse multiplier

Parameters dt : float

Time step

**tf** [float] Simulation Time

**tc** [float] Total pulse duration

**ts** [float] Pulse start time

**tp** [float] Pulse increase time

**dp** [float] Pulse multiplier

### tsnet.network.discretize module

The tsnet.network.discretize contains methods to perform spatial and temporal discretization by adjusting wave speed and time step to solve compatibility equations in case of uneven wave travel time.

`tsnet.network.discretize.`**`discretization`**(*tm*, *dt*)

Discretize in temporal and spatial space using wave speed adjustment scheme.

**Parameters**

- **`tm`** (*`tsnet.network.geometry.TransientModel`*) – Network
- **`dt`** (*`float`*) – User defined time step

**Returns** **tm** – Network with updated parameters

**Return type** tsnet.network.geometry.TransientModel

`tsnet.network.discretize.`**`max_time_step`**(*tm*)

Determine the maximum time step based on Courant's criteria.

**Parameters** **`tm`** (*`tsnet.network.geometry.TransientModel`*) – Network

**Returns** **max_dt** – Maximum time step allowed for this network

**Return type** float

`tsnet.network.discretize.`**`discretization_N`**(*tm*, *dt*)

Discretize in temporal and spatial space using wave speed adjustment scheme.

**Parameters**

- **`tm`** (*`tsnet.network.geometry.TransientModel`*) – Network
- **`dt`** (*`float`*) – User defined time step

**Returns** **tm** – Network with updated parameters

**Return type** tsnet.network.geometry.TransientModel

`tsnet.network.discretize.`**`max_time_step_N`**(*tm*, *N*)

Determine the maximum time step based on Courant's criteria.

**Parameters** **`tm`** (*`tsnet.network.geometry.TransientModel`*) – Network

**Returns** **max_dt** – Maximum time step allowed for this network

**Return type** float

`tsnet.network.discretize.`**`cal_N`**(*tm*, *dt*)

Determine the number of computation unites ($N_i$) for each pipes.

**Parameters**

- **`tm`** (*`tsnet.network.geometry.TransientModel`*) – Network
- **`dt`** (*`float`*) – Time step for transient simulation

`tsnet.network.discretize.`**`adjust_wavev`**(*tm*)

Adjust wave speed and time step to solve compatibility equations.

**Parameters** **`tm`** (*`tsnet.network.geometry.TransientModel`*) – Network

**Returns**

- **tm** (*tsnet.network.geometry.TransientModel*) – Network with adjusted wave speed.
- **dt** (*float*) – Adjusted time step

### tsnet.network.model module

The tsnet.network.geometry read in the geometry defined by EPANet .inp file, and assign additional parameters needed in transient simulation later in tsnet.

**class** `tsnet.network.model.`**`TransientModel`**(*inp_file*)

Bases: `wntr.network.model.WaterNetworkModel`

Transient model class. :param inp_file_name: Directory and filename of EPANET inp file to load into the

WaterNetworkModel object.

**`set_wavespeed`**(*wavespeed=1200*, *pipes=None*)

Set wave speed for pipes in the network

**Parameters**

- **`wavespeed`** (*`float or int or list, optional`*) – If given as float or int, set the value as wavespeed for all pipe; If given as list set the corresponding value to each pipe, by default 1200.
- **`pipes`** (*`str or list, optional`*) – The list of pipe to define wavespeed, by default all pipe in the network.

**`set_roughness`**(*roughness*, *pipes=None*)

Set roughness coefficient for pipes in the network

**Parameters**

- **`roughness`** (*`float or int or list`*) – If given as float or int, set the value as roughness for all pipe; If given as list set the corresponding value to each pipe. Make sure to define it using the same method (H-W or D-W) as defined in .inp file.
- **`pipes`** (*`str or list, optional`*) – The list of pipe to define roughness coefficient, by default all pipe in the network.

**`set_time`**(*tf*, *dt=None*)

Set time step and duration for the simulation.

**Parameters**

- **`tf`** (*`float`*) – Simulation period
- **`dt`** (*`float, optional`*) – time step, by default maximum allowed dt

**`set_time_N`**(*tf*, *N=2*)

Set time step and duration for the simulation.

**Parameters**

- **`tf`** (*`float`*) – Simulation period
- **`N`** (*`integer`*) – Number of segments in the critical pipe

**add_leak**(*name*, *coeff*)
Add leak to the transient model

**Parameters**

- **name** (*str, optional*) – The name of the leak nodes, by default None
- **coeff** (*list or float, optional*) – Emitter coefficient at the leak nodes, by default None

**add_burst**(*name*, *ts*, *tc*, *final_burst_coeff*)
Add leak to the transient model

**Parameters**

- **name** (*str*) – The name of the leak nodes, by default None
- **ts** (*float*) – Burst start time
- **tc** (*float*) – Time for burst to fully develop
- **final_burst_coeff** (*list or float*) – Final emitter coefficient at the burst nodes

**add_blockage**(*name*, *percentage*)
Add blockage to the transient model

**Parameters**

- **name** (*str*) – The name of the blockage nodes, by default None
- **percentage** (*list or float*) – The percentage of the blockage flow discharge

**valve_closure**(*name*, *rule*, *curve=None*)
Set valve closure rule

**Parameters**

- **name** (*str*) – The name of the valve to close
- **rule** (*list*) – Contains paramters to define valve operation rule rule = [tc,ts,se,m] tc : the duration takes to close the valve [s] ts : closure start time [s] se : final open percentage [s] m : closure constant [unitless]
- **curve** (*list*) – [(open_percentage[i], 1/kl[i]) for i ] List of open percentage and the corresponding inverse of valve coefficient

**valve_opening**(*name*, *rule*, *curve=None*)
Set valve opening rule

**Parameters**

- **name** (*str*) – The name of the valve to close
- **rule** (*list*) – Contains paramters to define valve operation rule rule = [tc,ts,se,m] tc : the duration takes to open the valve [s] ts : opening start time [s] se : final open percentage [s] m : closure constant [unitless]
- **curve** (*list*) – [(open_percentage[i], kl[i]) for i ] List of open percentage and the corresponding valve coefficient

**pump_shut_off**(*name*, *rule*)
Set pump shut off rule

**Parameters**

- **name** (*str*) – The name of the pump to shut off

- **rule** (*list*) – Contains paramaters to define valve operation rule rule = [tc,ts,se,m] tc : the duration takes to close the pump [s] ts : closure start time [s] se : final open percentage [s] m : closure constant [unitless]

**pump_start_up** (*name*, *rule*)
Set pump start up rule

**Parameters**

- **name** (*str*) – The name of the pump to shut off
- **rule** (*list*) – Contains paramaters to define valve operation rule rule = [tc,ts,se,m] tc : the duration takes to close the valve [s] ts : closure start time [s] se : final open percentage [s] m : closure constant [unitless]

**add_demand_pulse** (*name*, *rule*)
Add demand pulse to junction

**Parameters**

- **name** (*str or list*) –

  **The name of junctions to add demand pulse** rule : list

  Contains paramters to define valve operation rule
- **= [tc,ts,stay,dp,m]** (*rule*) – tc : total duration of the pulse [s] [s] ts : start time of demand [s] stay: duration of the demand to stay at peak level [s] dp : demand pulse multiplier [uniteless]

**add_surge_tank** (*name*, *shape*, *tank_type='open'*)
Add surge tank

**Parameters**

- **name** (*str*) – the name of the node to add a surge tank
- **shape** (*list*) –

  **if closed: [As, Ht, Hs]** As : cross-sectional area of the surge tank Ht : tank height Hs : initial water height in the surge tank

  if open: [As]
- **tank_type** (*int*) – type of the surge tank, "closed" or "open", by default 'open'

**detect_pressure_change** (*name*, *threshold*, *drift*, *show=False*, *ax=None*)
Detect pressure change in simulation results

**Parameters**

- **name** (*str*) – The name of the node
- **threshold** (*positive number, optional (default = 1)*) – amplitude threshold for the change in the data.
- **drift** (*positive number, optional (default = 0)*) – drift term that prevents any change in the absence of change.
- **show** (*bool, optional (default = True)*) – True (1) plots data in matplotlib figure, False (0) don't plot.
- **ax** (*a matplotlib.axes.Axes instance, optional (default = None)*) –

**plot_node_head**(*name*, *ax=None*)

Detect pressure change in simulation results

**Parameters**

- **name** (*str or list*) – The name of node
- **ax** (*a matplotlib.axes.Axes instance, optional (default = None)*) –

### tsnet.network.topology module

The tsnet.network.topology figure out the topology, i.e., upstream and downstream adjacent links for each pipe, and store the information in lists.

tsnet.network.topology.**topology**(*wn*)

Figure out the topology of the network

**Parameters**

- **wn** (*wntr.network.model.WaterNetworkModel*) – .inp file used for EPAnet simulation
- **npipe** (*integer*) – Number of pipes

**Returns**

- **links1** (*list*) – The id of adjacent pipe on the start node. The sign represents the direction of the pipe. + : flowing into the junction - : flowing out from the junction
- **links2** (*list*) – The id of adjacent pipe on the end node. The sign represents the direction of the pipe. + : flowing into the junction - : flowing out from the junction
- **utype** (*list*) – The type of the upstream adjacent links. If the link is not pipe, the name of that link will also be included. If there is no upstream link, the type of the start node will be recorded.
- **dtype** (*list*) – The type of the downstream adjacent links. If the link is not pipe, the name of that link will also be included. If there is no downstream link, the type of the end node will be recorded.

### Module contents

The tsnet.network package contains methods to define 1. a water network geometry, 2. network topology, 3. network control, and 4 .spatial and temporal discretization.

## 12.1.2 tsnet.postprocessing package

### Submodules

### tsnet.postprocessing.time_history module

The tsnet.postprocessing.time_history module contains functions to plot the time history of head and velocity at the start and end point of a pipe

tsnet.postprocessing.time_history.**plot_head_history**(*pipe*, *H*, *wn*, *tt*)

Plot Head history on the start and end node of a pipe

**Parameters**

- **pipe** (*str*) – Name of the pipe where you want to report the head
- **H** (*list*) – Head results
- **wn** (*wntr.network.model.WaterNetworkModel*) – Network
- **tt** (*list*) – Simulation timestamps

`tsnet.postprocessing.time_history.`**`plot_velocity_history`**(*pipe*, *V*, *wn*, *tt*)

Plot Velocity history on the start and end node of a pipe

**Parameters**

- **pipe** (*str*) – Name of the pipe where you want to report the head
- **V** (*list*) – velocity results
- **wn** (*wntr.network.model.WaterNetworkModel*) – Network
- **tt** (*list*) – Simulation timestamps

#### Module contents

The tsnet.postprocessing package contains functions to postprocess the simulation results.

## 12.1.3 tsnet.simulation package

### Submodules

#### tsnet.simulation.initialize module

The tsnet.simulation.initialize contains functions to 1. Initialize the list containing numpy arrays for velocity and head. 2. Calculate initial conditions using Epanet engine. 3. Calculate D-W coefficients based on initial conditions. 4. Calculate demand coefficients based on initial conditions.

`tsnet.simulation.initialize.`**`Initializer`**(*tm*, *t0*, *engine='DD'*)

Initial Condition Calculation.

Initialize the list containing numpy arrays for velocity and head. Calculate initial conditions using Epanet engine. Calculate D-W coefficients based on initial conditions. Calculate demand coefficients based on initial conditions.

**Parameters**

- **tm** (*tsnet.network.geometry.TransientModel*) – Simulated network
- **t0** (*float*) – time to calculate initial condition
- **engine** (*string*) – steady state calculation engine: DD: demand driven; PDD: pressure dependent demand, by default DD

**Returns** **tm** – Network with updated parameters

**Return type** tsnet.network.geometry.TransientModel

`tsnet.simulation.initialize.`**`cal_demand_coef`**(*demand*, *pipe*, *Hs*, *He*, *t0=0.0*)

Calculate the demand coefficient for the start and end node of the pipe.

**Parameters**

- **demand** (*list*) – Demand at the start (demand[0]) and end demand[1] node

- **pipe** (*object*) – Pipe object
- **Hs** (*float*) – Head at the start node
- **He** (*float*) – Head at the end node
- **t0** (*float, optional*) – Time to start initial condition calculation, by default 0

**Returns** **pipe** – Pipe object with calculated demand coefficient

**Return type** object

`tsnet.simulation.initialize.`**`cal_roughness_coef`**(*pipe*, *V*, *hl*)

Calculate the D-W roughness coefficient based on initial conditions.

**Parameters**

- **pipe** (*object*) – Pipe object
- **V** (*float*) – Initial flow velocity in the pipe
- **hl** (*float*) – Initial head loss in the pipe

**Returns** **pipe** – Pipe object with calculated D-W roughness coefficient.

**Return type** object

`tsnet.simulation.initialize.`**`pump_operation_points`**(*tm*)

### tsnet.simulation.main module

The tsnet.simulation.main module contains function to perform the workflow of read, discretize, initial, and transient simulation for the given .inp file.

`tsnet.simulation.main.`**`MOCSimulator`**(*tm*, *results_obj='results'*, *friction='steady'*)

MOC Main Function

**Parameters**

- **tm** (`tsnet.network.model.TransientModel`) – Network
- **results_obj** (*string, optional*) – the name of the results file, by default 'results'
- **friction** (*string, optional*) – friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'

**Returns** **tm** – Simulated network

**Return type** *tsnet.network.model.TransientModel*

### tsnet.simulation.single module

The tsnet.simulation.single contains methods to perform MOC transient simulation on a single pipe, including 1. inner pipe 2. left boundary pipe (without C- charateristic grid) 3. right boundary pipe (without C+ characteristic grid)

`tsnet.simulation.single.`**`inner_pipe`**(*linkp*, *pn*, *dt*, *links1*, *links2*, *utype*, *dtype*, *p*, *H0*, *V0*, *H*, *V*, *H10*, *V10*, *H20*, *V20*, *pump*, *valve*, *friction*, *dVdt*, *dVdx*, *dVdt10*, *dVdx10*, *dVdt20*, *dVdx20*)

MOC solution for an individual inner pipe.

**Parameters**

- **linkp** (*object*) – Current pipe object
- **pn** (*int*) – Current pipe ID

- **dt** (*float*) – Time step
- **H** (*numpy.ndarray*) – Head of current pipe at current time step [m]
- **V** (*numpy.ndarray*) – Velocity of current pipe at current time step [m/s]
- **links1** (*list*) – Upstream adjacent pipes
- **links2** (*list*) – Downstream adjacent pipes
- **utype** (*list*) – Upstream adjacent link type, and if not pipe, their name
- **dtype** (*list*) – Downstream adjacent link type, and if not pipe, their name
- **p** (*list*) – pipe list
- **H0** (*numpy.ndarray*) – Head of current pipe at previous time step [m]
- **V0** (*numpy.ndarray*) – Velocity of current pipe at previous time step [m/s]
- **H10** (*list*) – Head of left adjacent nodes at previous time step [m]
- **V10** (*list*) – Velocity of left adjacent nodes at previous time step [m/s]
- **H20** (*list*) – Head of right adjacent nodes at previous time step [m]
- **V20** (*list*) – Velocity of right adjacent nodes at previous time step [m/s]
- **pump** (*list*) – Characteristics of the pump
- **valve** (*list*) – Characteristics of the valve
- **friction** (*str*) – friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'
- **dVdt** (*numpy.ndarray*) – local instantaneous acceleration approximation to be used for unsteady friction calculation, 0 if not in unsteady friction mode [m/s^2]
- **dVdx** (*numpy.ndarray*) – convective instantaneous acceleration approximation to be used for unsteady friction calculation, 0 if not in unsteady friction mode [m/s^2]
- **dVdt10** (*list*) – local instantaneous acceleration of left adjacent nodes at previous time step [m]
- **dVdx10** (*list*) – convective instantaneous acceleration of left adjacent nodes at previous time step [m/s]
- **dVdt20** (*list*) – local instantaneous acceleration of right adjacent nodes at previous time step [m]
- **dVdx20** (*list*) – convective instantaneous acceleration of right adjacent nodes at previous time step [m/s]

**Returns**

- **H** (*numpy.ndarray*) – Head results of the current pipe at current time step. [m]
- **V** (*numpy.ndarray*) – Velocity results of the current pipe at current time step. [m/s]

`tsnet.simulation.single.`**`left_boundary`**(*linkp*, *pn*, *H*, *V*, *H0*, *V0*, *links2*, *p*, *pump*, *valve*, *dt*, *H20*, *V20*, *utype*, *dtype*, *friction*, *dVdt*, *dVdx*, *dVdt20*, *dVdx20*)

MOC solution for an individual left boundary pipe.

**Parameters**

- **linkp** (*object*) – Current pipe object
- **pn** (*int*) – Current pipe ID

- **H** (*numpy.ndarray*) – Head of current pipe at current time step [m]
- **V** (*numpy.ndarray*) – Velocity of current pipe at current time step [m/s]
- **links2** (*list*) – Downstream adjacent pipes
- **p** (*list*) – pipe list
- **pump** (*list*) – Characteristics of the pump
- **valve** (*list*) – Characteristics of the valve
- **n** (*int*) – Number of discretization of current pipe
- **dt** (*float*) – Time step
- **H0** (*numpy.ndarray*) – Head of current pipe at previous time step [m]
- **V0** (*numpy.ndarray*) – Velocity of current pipe at previous time step [m/s]
- **H20** (*list*) – Head of right adjacent nodes at previous time step [m]
- **V20** (*list*) – Velocity of right adjacent nodes at previous time step [m/s]
- **utype** (*list*) – Upstream adjacent link type, and if not pipe, their name
- **dtype** (*list*) – Downstream adjacent link type, and if not pipe, their name
- **friction** (*str*) – friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'
- **dVdt** (*numpy.ndarray*) – local instantaneous velocity approximation to be used for unsteady friction calculation, 0 if not in unsteady friction mode [m/s^2]
- **dVdx** (*numpy.ndarray*) – convective instantaneous velocity approximation to be used for unsteady friction calculation, 0 if not in unsteady friction mode [m/s^2]
- **dVdt20** (*list*) – local instantaneous acceleration of right adjacent nodes at previous time step [m]
- **dVdx20** (*list*) – convective instantaneous acceleration of right adjacent nodes at previous time step [m/s]

**Returns**

- **H** (*numpy.ndarray*) – Head results of the current pipe at current time step. [m]
- **V** (*numpy.ndarray*) – Velocity results of the current pipe at current time step. [m/s]

tsnet.simulation.single.**right_boundary**(*linkp*, *pn*, *H0*, *V0*, *H*, *V*, *links1*, *p*, *pump*, *valve*, *dt*, *H10*, *V10*, *utype*, *dtype*, *friction*, *dVdt*, *dVdx*, *dVdt10*, *dVdx10*)

MOC solution for an individual right boundary pipe.

**linkp** [object] Current pipe object

**pn** [int] Current pipe ID

**H** [numpy.ndarray] Head of current pipe at current time step [m]

**V** [numpy.ndarray] Velocity of current pipe at current time step [m/s]

**links1** [list] Upstream adjacent pipes

**p** [list] pipe list

**pump** [list] Characteristics of the pump

**valve** [list] Characteristics of the valve

**n** [int] Number of discretization of current pipe

**dt** [float] Time step

**H0** [numpy.ndarray] Head of current pipe at previous time step [m]

**V0** [numpy.ndarray] Velocity of current pipe at previous time step [m/s]

**H10** [list] Head of left adjacent nodes at previous time step [m]

**V10** [list] Velocity of left adjacent nodes at previous time step [m/s]

**utype** [list] Upstream adjacent link type, and if not pipe, their name

**dtype** [list] Downstream adjacent link type, and if not pipe, their name

**friction: str** friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'

**dVdt: numpy.ndarray** local instantaneous velocity approximation to be used for unsteady friction calculation, 0 if not in unsteady friction mode [m/s^2]

**dVdx: numpy.ndarray** convective instantaneous velocity approximation to be used for unsteady friction calculation, 0 if not in unsteady friction mode [m/s^2]

**dVdt10** [list] local instantaneous acceleration of left adjacent nodes at previous time step [m]

**dVdx10** [list] convective instantaneous acceleration of left adjacent nodes at previous time step [m/s]

**Returns**

**H** [numpy.ndarray] Head results of the current pipe at current time step. [m]

**V** [numpy.ndarray] Velocity results of the current pipe at current time step. [m/s]

## tsnet.simulation.solver module

The tsnet.simulation.solver module contains methods to solver MOC for different grid configurations, including: 1. inner_node 2. valve_node 3. pump_node 4. source_pump 5. valve_end 6. dead_end 7. rev_end 8. add_leakage

`tsnet.simulation.solver.`**`Reynold`**`(`*V*, *D*`)`
Calculate Reynold number

**Parameters**

- **`V`** (*`float`*) – velocity
- **`D`** (*`float`*) – diameter

**Returns** **Re** – Reynold number

**Return type** float

`tsnet.simulation.solver.`**`quasi_steady_friction_factor`**`(`*Re*, *KD*`)`
Update friction factor based on Reynold number

**Parameters**

- **`Re`** (*`float`*) – velocity
- **`KD`** (*`float`*) – relative roughness height (K/D)

**Returns** **f** – quasi-steady friction factor

**Return type** float

`tsnet.simulation.solver.`**`unsteady_friction`**`(`*Re*, *dVdt*, *dVdx*, *V*, *a*, *g*`)`
Calculate unsteady friction

**Parameters**

- **Re** (*float*) – velocity
- **dVdt** (*float*) – local instantaneous acceleration
- **dVdx** (*float*) – instantaneous convective acceleration
- **V** (*float*) – velocity
- **a** (*float*) – wave speed
- **g** (*float*) – gravitational acceleration

**Returns** **Ju** – unsteady friction factor

**Return type** float

`tsnet.simulation.solver.`**`cal_friction`**(*friction*, *f*, *D*, *V*, *KD*, *dt*, *dVdt*, *dVdx*, *a*, *g*)
Calculate friction term

**Parameters**

- **friction** (*str*) – friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'
- **f** (*float*) – steady friction factor
- **D** (*float*) – pipe diameter
- **V** (*float*) – pipe flow velocity
- **KD** (*float*) – relative roughness height
- **dt** (*float*) – time step
- **dVdt** (*float*) – local instantaneous acceleration
- **dVdx** (*float*) – convective instantaneous acceleration
- **a** (*float*) – wave speed
- **g** (*float*) – gravitational accelerations

**Returns** total friction, including steady and unsteady

**Return type** float

`tsnet.simulation.solver.`**`cal_Cs`**(*link1*, *link2*, *H1*, *V1*, *H2*, *V2*, *s1*, *s2*, *g*, *dt*, *friction*, *dVdx1*, *dVdx2*, *dVdt1*, *dVdt2*)
Calculate coefficients for MOC characteristic lines

**Parameters**

- **link1** (*object*) – Pipe object of C+ charateristics curve
- **link2** (*object*) – Pipe object of C- charateristics curve
- **H1** (*list*) – List of the head of C+ charateristics curve
- **V1** (*list*) – List of the velocity of C+ charateristics curve
- **H2** (*list*) – List of the head of C- charateristics curve
- **V2** (*list*) – List of the velocity of C- charateristics curve
- **s1** (*list*) – List of signs that represent the direction of the flow in C+ charateristics curve
- **s2** (*list*) – List of signs that represent the direction of the flow in C- charateristics curve
- **dt** (*float*) – Time step

- **g** (*float*) – Gravity acceleration
- **friction** (*str*) – friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'
- **dVdx1** (*list*) – List of convective instantaneous acceleration on the C+ characteristic curve
- **dVdx2** (*list*) – List of convective instantaneous acceleration on the C- characteristic curve
- **dVdt1** (*list*) – List of local instantaneous acceleration on the C+ characteristic curve
- **dVdt2** (*list*) – List of local instantaneous acceleration on the C- characteristic curve

**Returns**

- **A1** (*list*) – list of left adjacent pipe cross-section area
- **A2** (*list*) – list of right adjacent pipe cross-section area
- **C1** (*list*) – list of left adjacent pipe MOC coefficients
- **C2** (*list*) – list of right adjacent pipe MOC coefficients

`tsnet.simulation.solver.`**`inner_node_unsteady`**(*link*, *H0*, *V0*, *dt*, *g*, *dVdx*, *dVdt*)
Inner boundary MOC using C+ and C- characteristic curve with unsteady friction

**Parameters**

- **link** (*object*) – current pipe
- **H0** (*list*) – head at previous time step
- **V0** (*list*) – velocity at previous time step
- **dt** (*float*) – Time step
- **g** (*float*) – Gravity acceleration
- **dVdx** (*list*) – List of convective instantaneous acceleration
- **dVdt** (*list*) – List of local instantaneous acceleration

**Returns**

- **HP** (*float*) – Head at current pipe inner nodes at current time
- **VP** (*float*) – Velocity at current pipe inner nodes at current time

`tsnet.simulation.solver.`**`inner_node_quasisteady`**(*link*, *H0*, *V0*, *dt*, *g*)
Inner boundary MOC using C+ and C- characteristic curve with unsteady friction

**Parameters**

- **link** (*object*) – current pipe
- **H0** (*list*) – head at previous time step
- **V0** (*list*) – velocity at previous time step
- **dt** (*float*) – Time step
- **g** (*float*) – Gravity acceleration
- **dVdx** (*list*) – List of convective instantaneous acceleration
- **dVdt** (*list*) – List of local instantaneous acceleration

**Returns**

- **HP** (*float*) – Head at current pipe inner nodes at current time
- **VP** (*float*) – Velocity at current pipe inner nodes at current time

`tsnet.simulation.solver.`**`inner_node_steady`**(*link*, *H0*, *V0*, *dt*, *g*)

Inner boundary MOC using C+ and C- characteristic curve with unsteady friction

**Parameters**

- **`link`** (*`object`*) – current pipe
- **`H0`** (*`list`*) – head at previous time step
- **`V0`** (*`list`*) – velocity at previous time step
- **`dt`** (*`float`*) – Time step
- **`g`** (*`float`*) – Gravity acceleration

**Returns**

- **HP** (*float*) – Head at current pipe inner nodes at current time
- **VP** (*float*) – Velocity at current pipe inner nodes at current time

`tsnet.simulation.solver.`**`valve_node`**(*KL_inv*, *link1*, *link2*, *H1*, *V1*, *H2*, *V2*, *dt*, *g*, *nn*, *s1*, *s2*, *friction*, *dVdx1*, *dVdx2*, *dVdt1*, *dVdt2*)

Inline valve node MOC calculation

**Parameters**

- **`KL_inv`** (*`int`*) – Inverse of the valve loss coefficient at current time
- **`link1`** (*`object`*) – Pipe object of C+ charateristics curve
- **`link2`** (*`object`*) – Pipe object of C- charateristics curve
- **`H1`** (*`list`*) – List of the head of C+ charateristics curve
- **`V1`** (*`list`*) – List of the velocity of C+ charateristics curve
- **`H2`** (*`list`*) – List of the head of C- charateristics curve
- **`V2`** (*`list`*) – List of the velocity of C- charateristics curve
- **`dt`** (*`float`*) – Time step
- **`g`** (*`float`*) – Gravity acceleration
- **`nn`** (*`int`*) – The index of the calculation node
- **`s1`** (*`list`*) – List of signs that represent the direction of the flow in C+ charateristics curve
- **`s2`** (*`list`*) – List of signs that represent the direction of the flow in C- charateristics curve
- **`friction`** (*`str`*) – friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'
- **`dVdx1`** (*`list`*) – List of convective instantaneous acceleration on the C+ characteristic curve
- **`dVdx2`** (*`list`*) – List of convective instantaneous acceleration on the C- characteristic curve
- **`dVdt1`** (*`list`*) – List of local instantaneous acceleration on the C+ characteristic curve
- **`dVdt2`** (*`list`*) – List of local instantaneous acceleration on the C- characteristic curve

`tsnet.simulation.solver.`**`pump_node`**(*pumpc*, *link1*, *link2*, *H1*, *V1*, *H2*, *V2*, *dt*, *g*, *nn*, *s1*, *s2*, *friction*, *dVdx1*, *dVdx2*, *dVdt1*, *dVdt2*)

Inline pump node MOC calculation

**Parameters**

- **pumpc** (*list*) – Parameters (a, b,c) to define pump characteristic cure, so that .. math:: h_p = a*Q**2 + b*Q + c
- **link1** (*object*) – Pipe object of C+ charateristics curve
- **link2** (*object*) – Pipe object of C- charateristics curve
- **H1** (*list*) – List of the head of C+ charateristics curve
- **V1** (*list*) – List of the velocity of C+ charateristics curve
- **H2** (*list*) – List of the head of C- charateristics curve
- **V2** (*list*) – List of the velocity of C- charateristics curve
- **dt** (*float*) – Time step
- **g** (*float*) – Gravity acceleration
- **nn** (*int*) – The index of the calculation node
- **s1** (*list*) – List of signs that represent the direction of the flow in C+ charateristics curve
- **s2** (*list*) – List of signs that represent the direction of the flow in C- charateristics curve
- **friction** (*str*) – friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'
- **dVdx1** (*list*) – List of convective instantaneous acceleration on the C+ characteristic curve
- **dVdx2** (*list*) – List of convective instantaneous acceleration on the C- characteristic curve
- **dVdt1** (*list*) – List of local instantaneous acceleration on the C+ characteristic curve
- **dVdt2** (*list*) – List of local instantaneous acceleration on the C- characteristic curve

`tsnet.simulation.solver.`**`source_pump`**(*pump*, *link2*, *H2*, *V2*, *dt*, *g*, *s2*, *friction*, *dVdx2*, *dVdt2*)

Source Pump boundary MOC calculation

**Parameters**

- **pump** (*list*) – pump[0]: elevation of the reservoir/tank pump[1]: Parameters (a, b,c) to define pump characteristic cure, so that .. math:: h_p = a*Q**2 + b*Q + c
- **link2** (*object*) – Pipe object of C- charateristics curve
- **H2** (*list*) – List of the head of C- charateristics curve
- **V2** (*list*) – List of the velocity of C- charateristics curve
- **dt** (*float*) – Time step
- **g** (*float*) – Gravity acceleration
- **s2** (*list*) – List of signs that represent the direction of the flow in C- charateristics curve
- **friction** (*str*) – friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'
- **dVdx2** (*list*) – List of convective instantaneous acceleration on the C- characteristic curve

- **dVdt2** (*list*) – List of local instantaneous acceleration on the C- characteristic curve

`tsnet.simulation.solver.`**`valve_end`**(*H1*, *V1*, *V*, *nn*, *a*, *g*, *f*, *D*, *dt*, *KD*, *friction*, *dVdx2*, *dVdt2*)

End Valve boundary MOC calculation

**Parameters**

- **H1** (*float*) – Head of the C+ charateristics curve
- **V1** (*float*) – Velocity of the C+ charateristics curve
- **V** (*float*) – Velocity at the valve end at current time
- **nn** (*int*) – The index of the calculation node
- **a** (*float*) – Wave speed at the valve end
- **g** (*float*) – Gravity acceleration
- **f** (*float*) – friction factor of the current pipe
- **D** (*float*) – diameter of the current pipe
- **dt** (*float*) – Time step
- **KD** (*float*) – relative roughness height
- **friction** (*str*) – friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'
- **dVdx2** (*list*) – List of convective instantaneous acceleration on the C- characteristic curve
- **dVdt2** (*list*) – List of local instantaneous acceleration on the C- characteristic curve

`tsnet.simulation.solver.`**`dead_end`**(*linkp*, *H1*, *V1*, *elev*, *nn*, *a*, *g*, *f*, *D*, *dt*, *KD*, *friction*, *dVdx1*, *dVdt1*)

Dead end boundary MOC calculation with pressure dependant demand

**Parameters**

- **linkp** (*object*) – Current pipe
- **H1** (*float*) – Head of the C+ charateristics curve
- **V1** (*float*) – Velocity of the C+ charateristics curve
- **elev** (*float*) – Elevation at the dead end node
- **nn** (*int*) – The index of the calculation node
- **a** (*float*) – Wave speed at the valve end
- **g** (*float*) – Gravity acceleration
- **f** (*float*) – friction factor of the current pipe
- **D** (*float*) – diameter of the current pipe
- **dt** (*float*) – Time step
- **KD** (*float*) – relative roughness height
- **friction** (*str*) – friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'
- **dVdx1** (*list*) – List of convective instantaneous acceleration on the C+ characteristic curve
- **dVdt1** (*list*) – List of local instantaneous acceleration on the C+ characteristic curve

`tsnet.simulation.solver.`**`rev_end`**(*H2*, *V2*, *H*, *nn*, *a*, *g*, *f*, *D*, *dt*, *KD*, *friction*, *dVdx2*, *dVdt2*)

Reservoir/ Tank boundary MOC calculation

**Parameters**

- **H2** (*list*) – List of the head of C- charateristics curve
- **V2** (*list*) – List of the velocity of C- charateristics curve
- **H** (*float*) – Head of the reservoir/tank
- **nn** (*int*) – The index of the calculation node
- **a** (*float*) – Wave speed at the valve end
- **g** (*float*) – Gravity acceleration
- **f** (*float*) – friction factor of the current pipe
- **D** (*float*) – diameter of the current pipe
- **dt** (*float*) – Time step
- **KD** (*float*) – relative roughness height
- **friction** (*str*) – friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'
- **dVdx2** (*list*) – List of convective instantaneous acceleration on the C- characteristic curve
- **dVdt2** (*list*) – List of local instantaneous acceleration on the C- characteristic curve

`tsnet.simulation.solver.`**`add_leakage`**(*emitter_coef*, *block_per*, *link1*, *link2*, *elev*, *H1*, *V1*, *H2*, *V2*, *dt*, *g*, *nn*, *s1*, *s2*, *friction*, *dVdx1=0*, *dVdx2=0*, *dVdt1=0*, *dVdt2=0*)

Leakage Node MOC calculation

**Parameters**

- **emitter_coef** (*float*) – float, optional Required if leak_loc is defined The leakage coefficient of the leakage .. math:: Q_leak = leak_A [ m^3/s/(m H20)^(1/2)] * sqrt(H)
- **link1** (*object*) – Pipe object of C+ charateristics curve
- **link2** (*object*) – Pipe object of C- charateristics curve
- **H1** (*list*) – List of the head of C+ charateristics curve
- **V1** (*list*) – List of the velocity of C+ charateristics curve
- **H2** (*list*) – List of the head of C- charateristics curve
- **V2** (*list*) – List of the velocity of C- charateristics curve
- **dt** (*float*) – Time step
- **g** (*float*) – Gravity acceleration
- **nn** (*int*) – The index of the calculation node
- **s1** (*list*) – List of signs that represent the direction of the flow in C+ charateristics curve
- **s2** (*list*) – List of signs that represent the direction of the flow in C- charateristics curve
- **friction** (*str*) – friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'

- **dVdx1** (*list*) – List of convective instantaneous acceleration on the C+ characteristic curve
- **dVdx2** (*list*) – List of convective instantaneous acceleration on the C- characteristic curve
- **dVdt1** (*list*) – List of local instantaneous acceleration on the C+ characteristic curve
- **dVdt2** (*list*) – List of local instantaneous acceleration on the C- characteristic curve

`tsnet.simulation.solver.`**`surge_tank`**(*tank*, *link1*, *link2*, *H1*, *V1*, *H2*, *V2*, *dt*, *g*, *nn*, *s1*, *s2*, *friction*, *dVdx1*, *dVdx2*, *dVdt1*, *dVdt2*)

Surge tank node MOC calculation

**Parameters**

- **tank** (*int*) – tank shape parameters [As, z, Qs]

  As : cross-sectional area of the surge tank z : water level in the surge tank at previous time step Qs : water flow into the tank at last time step
- **link1** (*object*) – Pipe object of C+ charateristics curve
- **link2** (*object*) – Pipe object of C- charateristics curve
- **H1** (*list*) – List of the head of C+ charateristics curve
- **V1** (*list*) – List of the velocity of C+ charateristics curve
- **H2** (*list*) – List of the head of C- charateristics curve
- **V2** (*list*) – List of the velocity of C- charateristics curve
- **dt** (*float*) – Time step
- **g** (*float*) – Gravity acceleration
- **nn** (*int*) – The index of the calculation node
- **s1** (*list*) – List of signs that represent the direction of the flow in C+ charateristics curve
- **s2** (*list*) – List of signs that represent the direction of the flow in C- charateristics curve
- **friction** (*str*) – friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'
- **dVdx1** (*list*) – List of convective instantaneous acceleration on the C+ characteristic curve
- **dVdx2** (*list*) – List of convective instantaneous acceleration on the C- characteristic curve
- **dVdt1** (*list*) – List of local instantaneous acceleration on the C+ characteristic curve
- **dVdt2** (*list*) – List of local instantaneous acceleration on the C- characteristic curve

`tsnet.simulation.solver.`**`air_chamber`**(*tank*, *link1*, *link2*, *H1*, *V1*, *H2*, *V2*, *dt*, *g*, *nn*, *s1*, *s2*, *friction*, *dVdx1*, *dVdx2*, *dVdt1*, *dVdt2*)

Surge tank node MOC calculation

**Parameters**

- **tank** (*int*) – tank shape parameters [As, ht, C, z, Qs]

  As : cross-sectional area of the surge tank ht : tank height C : air constant z : water level in the surge tank at previous time step Qs : water flow into the tank at last time step

- **link1** (*object*) – Pipe object of C+ charateristics curve
- **link2** (*object*) – Pipe object of C- charateristics curve
- **H1** (*list*) – List of the head of C+ charateristics curve
- **V1** (*list*) – List of the velocity of C+ charateristics curve
- **H2** (*list*) – List of the head of C- charateristics curve
- **V2** (*list*) – List of the velocity of C- charateristics curve
- **dt** (*float*) – Time step
- **g** (*float*) – Gravity acceleration
- **nn** (*int*) – The index of the calculation node
- **s1** (*list*) – List of signs that represent the direction of the flow in C+ charateristics curve
- **s2** (*list*) – List of signs that represent the direction of the flow in C- charateristics curve
- **friction** (*str*) – friction model, e.g., 'steady', 'quasi-steady', 'unsteady', by default 'steady'
- **dVdx1** (*list*) – List of convective instantaneous acceleration on the C+ characteristic curve
- **dVdx2** (*list*) – List of convective instantaneous acceleration on the C- characteristic curve
- **dVdt1** (*list*) – List of local instantaneous acceleration on the C+ characteristic curve
- **dVdt2** (*list*) – List of local instantaneous acceleration on the C- characteristic curve

#### Module contents

The tsnet.simulation package contains methods to run transient simulation using MOC method

### 12.1.4 tsnet.utils package

#### Submodules

#### tsnet.utils.calc_parabola_vertex module

The tsnet.utils.calc_parabola_vertex contains function to calculate the parameters of a parabola based on the coordinated of three points on the curve.

`tsnet.utils.calc_parabola_vertex.`**`calc_parabola_vertex`**(*points*)

Adapted and modifed to get the unknowns for defining a parabola

**Parameters** **points** (*list*) – Three points on the pump characteristics curve.

#### tsnet.utils.memo module

`tsnet.utils.memo.`**`decorator`**(*d*)

Make function d a decorator: d wraps a function fn.

`tsnet.utils.memo.`**`memo`**(*f*)

Decorator that caches the return value for each call to f(args). Then when called again with same args, we can just look it up.

### tsnet.utils.print_time_delta module

`tsnet.utils.print_time_delta.`**`print_time_delta`**`(`*seconds*`)`

### tsnet.utils.valve_curve module

The tsnet.utils.valve_curve contains function to define valve characteristics curve, gate valve by default.

`tsnet.utils.valve_curve.`**`valve_curve`**`(`*s*, *coeff=None*`)`

Define valve curve

**Parameters**

- **s** (*float*) – open percentage
- **valve** (*str, optional*) – [description], by default 'Gate'

**Returns** **k** – Friction coefficient with given open percentage

**Return type** float

### Module contents

The tsnet.utils package contains helper functions.

## 12.2 Module contents

Top-level package for tsnet.

# CHAPTER 13

# Abbreviations

| | |
|---|---|
| **API** | : Application programming interface |
| **EPA** | : Environmental Protection Agency |
| **IDE** | : Integrated development environment |
| **SI** | : International System of Units |
| **US** | : United States |
| **MOC** | : Method of Characteristics |
| **TSNET** | : Transient Simulation in water Networks |

# CHAPTER 14

# Reference

CHAPTER 15

# Indices and tables

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# Python Module Index

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