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Project Report

Auditory Representation of Transient Hydraulic Phenomena: A Novel Approach to Sonification of Pressure Waves in Hydraulic Systems

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Abstract

This study explores the novel integration of data sonification into hydraulic engineering by translating transient pressure fluctuations in a hydraulic system into sound. Using a simple hydraulic model built in KYPipe, a pump connected to a reservoir and a tank was simulated to trip, causing transient pressure changes. These pressure variations were mapped onto the C-major scale using Microsoft Excel, creating an auditory representation. The methodology included generating a sound library using recorded piano samples and applying VBA code to link pressure values with musical notes. The results demonstrated that sonification provides an innovative means of presenting transient hydraulic phenomena, enabling users to identify critical events such as pressure spikes audibly. While the study highlights challenges, such as computational limitations and resolution trade-offs in mapping, it opens pathways for employing auditory data representation in engineering contexts. Future work could focus on expanding audio sample libraries and optimizing computational methods to improve resolution and usability.

Keywords: hydraulic transients; water hammer; transient pressure; data sonification; data auralization; pressure wave analysis; hydraulic networks

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1. Introduction

Data sonification is the production, study, and application of non-speech auditory representation of data for informational purposes. Data sonification is a new, interdisciplinary, and developing area of modern inquiry and practice that coexists with data visualization. Sonification and auralization are used interchangeably; the latter specifically refers to presenting data in audio format. There are several reasons why sound might, in some situations, be the ideal means of information representation and communication.

For instance, most of us can easily attest from personal experience that performing a purely visual side-by-side comparison of two sets of textual data demands a high level of focus and is prone to error, especially over longer periods of time. In contrast, it is relatively simpler to listen to an audio form of such representations.

For thousands of years, sound has also been a crucial component of both theoretical and empirical research. The idea of the harmony of the spheres, which integrates the philosophical theory that mathematical relationships represent qualities or "tones" of energy ratios, played a unifying role in the development of the arts and sciences at least as far back as Pythagoras (born around 569 BCE). The use of ratios and sound has been fundamental to the conceptualization and realization of Western music throughout all eras [1].

The philosophical idea known as the "harmony of the spheres" views the proportions in the motions of the Sun, Moon, and planets as a form of music. The idea of the "harmony of the spheres" incorporates the metaphysical idea that mathematical relationships communicate qualities or "tones" of energy that appear in numbers, visual angles, shapes, and sounds, all of which are interconnected within a system of ratios. Pythagoras was the first person to discover that intervals between harmonious sound frequencies form simple numerical ratios and that the pitch of a musical note is inversely proportional to the length of the string that produces it. The Pythagorean theory, which had its roots in ancient Greece, was later developed by astronomer Johannes Kepler in the 16th century. Kepler thought that even though this "music" was not audible, the soul could still hear it. Up until the end of the Renaissance, the concept was still appealing to academics and had an impact on many schools of thought [1].

This study combines the fields of sonification and hydraulic engineering. The engineering discipline that explains and predicts the behavior of liquids and gases at rest or in motion is known as fluid mechanics. Many commonplace occurrences, such as why a ship floats, why pumps are required to convey water, why an inflated balloon shrinks in cold air, etc., may be explained using the principles covered in fluid mechanics [2]. This study implements data sonification of transient pressure in a hydraulic system.

Purpose of Study

The objective of this study is to present a novel method of presenting transient pressure in a hydraulic model. The objective of this study is accomplished by creating a simple hydraulic model in KYPipe where a pump is connected to a reservoir and a tank. The pump is simulated to trip which creates transient pressure in the pipe downstream of the pump. The transient pressure data are sonified by mapping the pressure values to frequencies of the C-major scale using Microsoft Excel by referencing a sound sample library created for this study. This study presents the unique methodology used for the sound-mapping process of transient pressure of a hydraulic network, as well as its limitations and future recommendations. After conducting a rigorous literature review, no methodology of sonification of transient pressure in a hydraulic network was found.

2. Literature Review

2.1. Transient Pressure and the Wave Plan Method

Hydraulic transients, often referred to as water hammer, are rapid changes in pressure and flow conditions within pressurized conduit systems [3,4]. These transients arise primarily from abrupt velocity changes in the working fluid, such as those caused by sudden valve closures or openings, pump starts or stops, rapid variations in flow demand, or equipment malfunctions. Mass oscillation can further contribute to transient events when liquid columns move at different velocities within the pipeline [5].

Below are some of the common causes of transient events in hydraulic networks:

Vale operations (closure/opening): Rapid closure of valves can reduce flow velocity to zero almost instantly, creating a pressure wave that travels at high speed through the pipeline. Conversely, quickly opened valves also initiate shock waves due to the sudden acceleration of fluid [6].

Pump starts and stops: Pump trips (loss of power) alter flow velocity abruptly. Pump start-ups also induce pressure surges when flow is accelerated from a stationary to an operating condition [2,6].

Sudden changes in flow demand: Rapid changes in system demand (e.g., large industrial consumers opening/closing flow) can generate transients that propagate through the entire pipeline network.

Water hammer: This term is often used interchangeably with hydraulic transients and is characterized by a distinctive pressure wave or "hammer blow" effect.

Mass oscillations: In systems with large storage tanks, surge vessels, or extended pipe segments, fluid columns can oscillate back and forth, creating cyclical pressure fluctuations [5,7].

When closed conduits were first used to convey water, the search for pressure protection for water conduits may have begun. Beginning in the early 20th century, significant scientific research was conducted to determine what causes abrupt increases in pressure in closed conduits [6]. Abrupt pressure increases in pipelines could damage pipes and other equipment such as pumps and valves.

Joukowski's equation is commonly used to estimate the pressure increase associated with a change in pipeline velocity. Joukowski's equation, shown below, can be derived by applying momentum concepts.

$$\Delta P = \frac{(C)(\Delta V)\gamma}{g} \quad (1)$$

where ΔP—pressure increase due to velocity change; ΔV—velocity change; C—wave speed.

Notice from Joukowski's equation that the magnitude of the pressure increase is directly proportional to the magnitude of the velocity change. For example, when a valve is suddenly closed, the velocity in a pipeline may go from 0.91 to 1.22 m/s to zero almost instantly. Depending upon the wave speed, the resulting pressure increase could several times higher than the initial pressure in the pipeline, which could potentially cause damage to the pipeline or connected equipment. It is important for engineers to consider the potential pressure increase when designing and operating pipelines to ensure its safety and reliability.

In a pipeline system, pressure waves travel at very high speeds—as much as 1220 m/s—through all hydraulically linked locations. The speed at which a pressure wave travels through a pipeline is dependent upon the pipeline material and the pipe wall thickness. When pressure waves reach pipe junctions, that is, locations where two or more pipes come together, they are both reflected and transmitted. Additionally, they completely reflect off reservoirs, dead ends, tanks, and totally closed valves. Pumps, turbines, and other loss components, such as completely or partially open valves, modify pressure waves [6].

A quick change in flowrate will be accompanied by a rapid change in pressure. The sudden shift in pressure that results is thought of as a pressure wave that travels through the pipeline system. As the pressure wave moves through the pipe segment, frictional loss occurs in the pipe which helps to dampen the magnitude of the pressure wave. At junction nodes, particularly basic junction nodes made of merely two pipes with differing elastic properties, pressure waves are also reflected and transmitted.

Equation (2) below can be used to calculate the pressure head at a discontinuity following the arrival of a pressure wave. This is depicted visually in Figure 1.

$$HJ(t') = HJ(t) + \Delta H(Ti) \quad (2)$$

where HJ(t′)—pressure head at discontinuity j after the pressure wave arrives; HJ(t)—pressure head at discontinuity j the instant before the pressure wave arrives; ΔH—magnitude of the arriving pressure wave; T_i—transmission coefficient for the pipe containing the pressure wave ΔH.

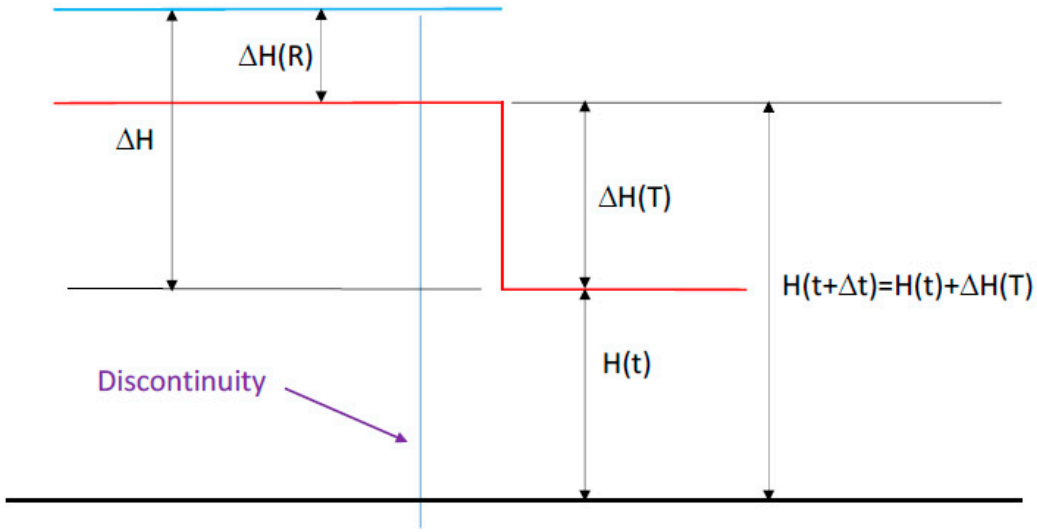

Figure 1. Head change at a discontinuity due to pressure wave [2].

An abrupt change or disturbance in the pressure or flow characteristics of a fluid within a system is referred to as a discontinuity. Flow path obstructions, sudden valve closures, and changes in pipe diameter, etc. can all result in discontinuities. When a discontinuity occurs, it can give rise to pressure waves, also known as water hammer or hydraulic transients, which can propagate through the fluid system, causing fluctuations in pressure and velocity.

The head at a discontinuity following the arrival of a pressure wave is equal to the head before the arrival of the pressure wave plus the portion of head contributed by transmission as illustrated in the figure below [2].

Wood et al. give a thorough explanation and the derivation of a full set of equations for modeling surge protection devices, such as pressure relief valves, surge tanks, and air valves. This technique is known as the wave plan method [7].

2.2. Effects and Consequences

Hydraulic transients can exert significant impacts on pipeline systems, often leading to pipe failures, leakage, equipment damage, system instability, and operational disruptions. Excessive pressures or vacuum conditions may result in pipe bursts, joint failures, or structural deterioration [3]. Pumps, turbines, valves, and other mechanical components are particularly vulnerable to fatigue or catastrophic failure when subjected to repeated high-pressure surges. Furthermore, persistent oscillations or resonance caused by transient events can undermine normal operations, making it difficult to maintain stable flow or pressure at critical points in the system [5]. In many cases, frequent or severe transients require shutdowns for inspection and repairs, reducing overall system availability and increasing maintenance costs [6].

2.3. Mitigation Strategies

Various surge control and protective devices are employed to minimize the magnitude and duration of transient pressures in pipeline systems. Strategically placed surge tanks can absorb excessive pressure rises and provide additional fluid when pressure drops occur, thereby smoothing out rapid fluctuations [4]. Air chambers, which store compressed air, and air valves, such as air release/vacuum breaker valves, help counteract sudden positive or negative pressure waves while preventing sub-atmospheric conditions that could lead to column separation [3]. Control valves, including surge anticipation valves and pressure relief valves, automatically release pressure spikes to a safe discharge path, therefore

limiting peak overpressure. Surge suppressors and accumulators, such as bladder-type or piston-type accumulators, temporarily store hydraulic energy to reduce the amplitude of pressure transients. Additionally, following operational best practices such as gradual valve operations and careful pump ramp-up or ramp-down procedures can further mitigate transients by minimizing abrupt changes in flow [8].

2.4. Literature Review on Sonification

In 1981, Sara Bly conducted research to present information using sound. The study examined the possibility of using sound to share information, especially when it was difficult or impossible to use visuals. The author examined various sonification approaches, including parameter mapping such as pitch, volume, timbre, and event-based triggers, highlighting the importance of clear, intuitive mappings and the need to account for human auditory perception limits. Through examples such as monitoring complex systems and aiding individuals with visual impairments, the author demonstrated the practical potential of auditory displays. Overall, this study laid critical groundwork for modern sonification techniques and emphasized the value of further research in this emerging field [9].

In 2008, Zhao et al. looked into the possibility of data sonification as a way to make information easier for people with visual impairments. The authors examined several auditory display methods most notably parameter mapping, earcons, and auditory icons. Earcons are short, distinctive sounds (for instance, a beep to indicate an error) commonly used in computer operating systems to convey specific information. The authors highlighted the importance of balancing aesthetics with functionality, avoiding information overload, and tailoring displays to user needs. The author found parameter mapping particularly effective for complex data, while simpler cues like earcons worked best for basic events. Proper training and customization further enhanced user comprehension. The study concluded that sonification holds significant promise for improving data accessibility, calling for more research to refine and expand these techniques [10].

In 2009, Forssén et al. investigated sonification techniques for traffic noise within the LISTEN project, aiming to develop tools for urban planning and noise control. The authors highlighted the challenges of realistically simulating environmental noise and described a methodology for capturing, processing, and rendering passenger car pass-by sound data. The study also examined how factors such as vehicle speed, road surface, and microphone placement affect perceived sonification quality by comparing simulated outputs with real-world recordings. Overall, the authors demonstrated that sonification can be a powerful tool for analyzing and mitigating traffic noise problems. The authors concluded by advocating further research to refine these methods and enhance their applicability in addressing environmental noise challenges [11].

In 2019, Lenzi et al. made a sonification system that would help operators at water distribution plants find cyber threats and anomalies in water distribution systems. The authors suggested trying out a method that combined sonification techniques with cybersecurity measures to make it easier to monitor and protect important infrastructure. Recognizing that such infrastructure is highly vulnerable to cyberattacks, the authors emphasized the importance of robust monitoring methods capable of detecting threats in real time. Their solution involved transforming operational data into sound using different mapping techniques to help operators quickly identify anomalous events and cyber intrusions. To evaluate their method, they simulated a series of cyberattacks on a water distribution system and examined how effectively operators could detect these attacks when guided by auditory cues. Results showed that with thoughtfully designed mappings, sonification substantially improved the operator's ability to recognize irregularities and potential breaches. Consequently, the study highlighted that merging data sonification with

strategic cybersecurity measures can provide an additional layer of real-time protection for critical water infrastructure. This research offers a valuable contribution by demonstrating how auditory displays can enhance situational awareness and safeguard vital resources in the water sector [12].

In 2020, Axon et al. investigated how transforming computer network traffic data into auditory signals could help operators detect cyber threats more quickly and accurately than with traditional visual methods. The authors noted sonification's potential to provide an additional data dimension, enable real-time monitoring, and reduce cognitive load, yet also recognized key challenges like selecting appropriate sound mappings and avoiding information overload. Experimental results showed participants identifying anomalies more efficiently when guided by sonified data. In the end, the researchers urged further interdisciplinary work to refine sonification approaches and enhance cybersecurity strategies across complex networked systems [13].

In 2021, Muralidharan et al. introduced "Sonify", a tool that leverages machine learning and computer vision to convert visual graphs into audio cues, thereby enhancing data accessibility for visually impaired (VIP) individuals. By mapping elements like axes and data points to distinct sounds, the system allows users to interpret complex information using auditory cues. User studies showed that both VIP and sighted participants benefited from this approach, demonstrating how sonification can broaden data accessibility and engagement [14].

In summary, sonification is the process of representing data or information through sound. It serves as an alternative to visual representation, particularly for visually impaired individuals who face challenges interpreting complex visual data. Sonification has various applications, such as detecting cyber threats in water distribution systems, monitoring computer networks, and enhancing accessibility for visually impaired users. Despite its benefits, sonification has some limitations. One of the main challenges is the need for an appropriate mapping strategy to make sure that sonified data accurately convey the intended information. Finding a balance between auditory aesthetics with functionality and managing information overload are some additional challenges. Sonification techniques must consider human auditory perception limitations when designing sound displays to be considered effective. Research has shown that sonification techniques can effectively help visually impaired individuals perceive and understand data.

Sonification has the potential to transform the way data are represented and interpreted especially for visually impaired people. It offers new possibilities for enhancing accessibility, detecting anomalies, and improving cybersecurity as well. However, to fully realize its potential researchers must discuss the limitations and challenges associated with sonification techniques and continue to develop innovative solutions that can be applied across different fields.

3. Methodology

3.1. Hydraulic Model

A hydraulic model was built in KYPipe's Surge software, part of Pipe2022, a computer simulation model that has the ability to examine pressure changes associated with rapid changes in flow. KYPipe was originally developed by Dr. Don J. Wood and colleagues at the University of Kentucky in the 1970s [15]. Over time, the software evolved through further research and collaboration, eventually being commercialized by KYPipe LLC, Lexington, KY, USA. Today, KYPipe offers both steady-state and transient (surge) analysis capabilities, making it particularly well suited for designing and optimizing water distribution networks, wastewater systems, and various industrial pipeline applications. The robust transient module, based in part on the wave plan method pioneered by Wood and coauthors,

enables comprehensive modeling of rapid flow changes and pressure surges. The hydraulic model developed for this study included a pump connected to a reservoir and a tank as shown in Figure 2 below. The pump was simulated to trip (suddenly lose power) after 5 s of operation to create transient pressure (or water hammer) in the pipe downstream of the pump.

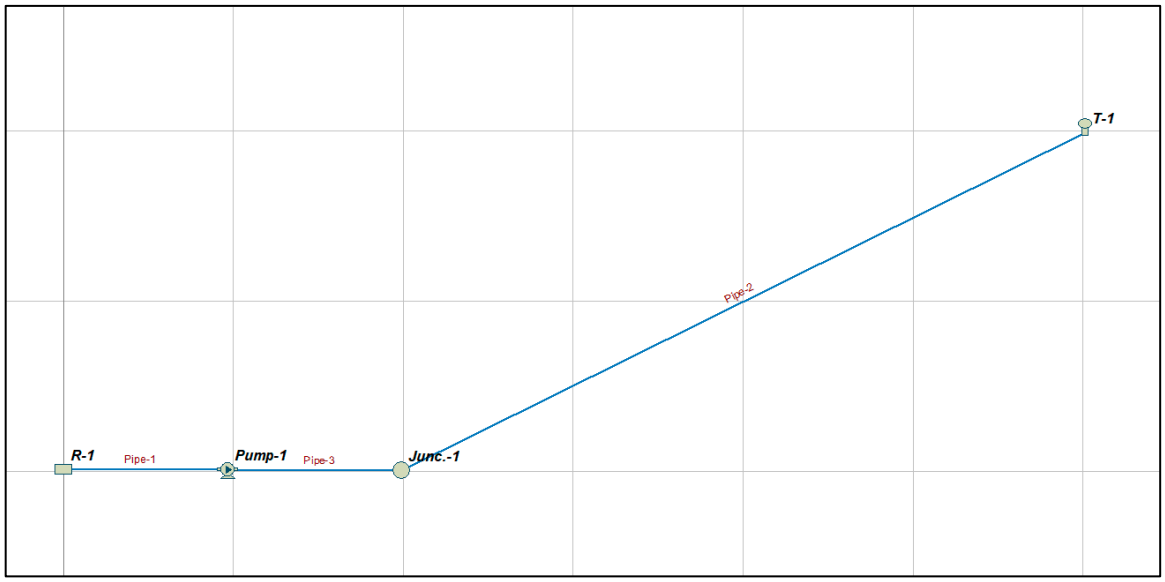

Figure 2. KYPipe model schematic.

The following are elevations and other relevant parameters of the model.
Reservoir elevation: 433.6 m
Reservoir grade: 468.6 m
Pump type: Grundfos SP 9–29 pump
Pipe length from reservoir to pump: 5 m
Pipe length from pump to junction: 5 m
Pipe length from junction to tank: 900 m
Tank elevation: 580.5 m
Tank volume: 500 m^3
Pipe type: 150 mm HDPE
Dimension ratio: 11
Hydrostatic design stress, σ_s: 6890 kPa
Fluid density: 1000 kg/m^3
Bulk modulus of water: 2,200,000 kPa [15]

3.2. Pump File Number and Inertia

When a pump suddenly loses power, called a pump trip, the pump speed begins to decrease. The duration and manner over which the pump speed goes from full operational speed to zero speed is dependent upon the mass of the rotating components of the pump (pump inertia). KYPipe has the functionality to model the full rotational dynamics of a pump trip using what are called pump files.

In KYPipe, the selection of pump file number depends upon the specific speed of the pump. The inertia and specific speed calculator were utilized to select the corresponding pump file number. Figure 3 shows the input parameters and results obtained for the Grundfos SP 9–29 pump. The pump inertia was found to be 0.19 Nm^2, specific speed equaled 3.33, and the suggested pump file number was 1.

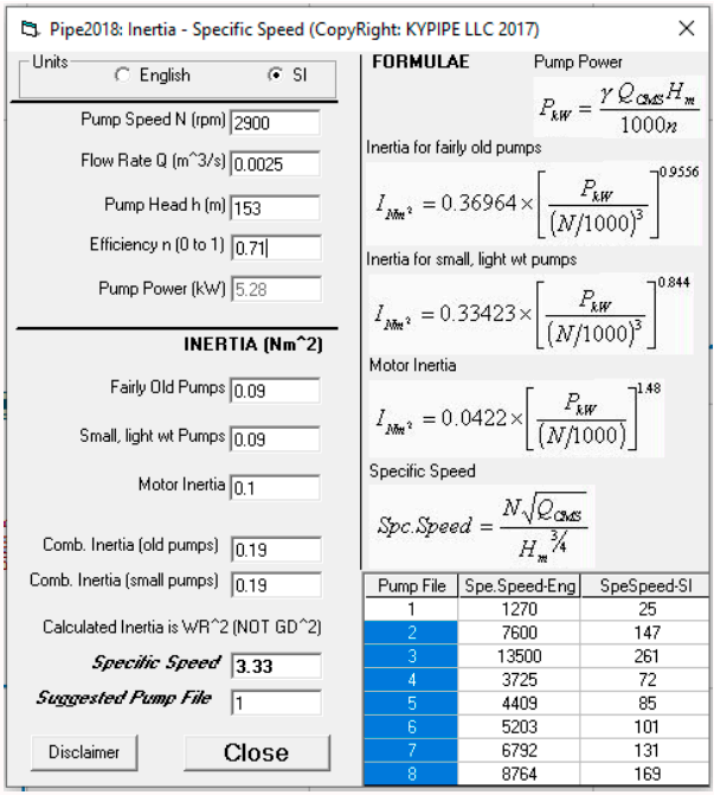

Figure 3. Inertia and specific speed calculator.

Figure 4 shows pressure history of the pump from time t = 4.8 s to t = 6.4 s where the pump trip occurs at t = 5 s. The *x*-axis (time step) of the chart was truncated for visual clarity and to make the pump trip waveform from steady-state to transient easier to see.

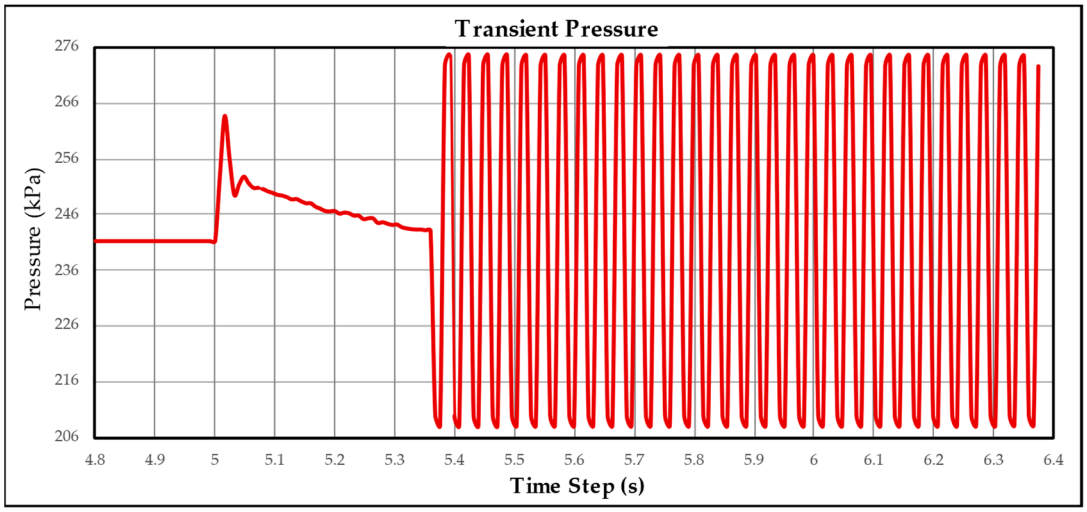

Figure 4. Pressure history of KYPipe hydraulic model from 4.8 s to 6.4 s.

3.3. The Major Scale

In music theory, one of the most common scales in Western music is the major scale [16]. A scale is a set of notes within an octave. An octave is the interval between two notes (or frequencies) where the higher note is twice that of the lower note. An interval is the distance in frequency between two notes in music theory. For example, the frequency 440 Hz, which is the "A" note in music, will have an octave at 880 Hz.

Western music divides the octave into twelve equal intervals represented by 12 notes. This is known as the 12-tone equal temperament (12-TET) system. The 12-TET system occurred sometime in the 16th century [17]. It divides the octave into 12 equal parts that are all evenly spaced on a logarithmic scale with a ratio equal to the 12th root of 2 ($\sqrt[12]{2}$ = 1.05946). Prior to the 12-TET system, Pythagorean tuning was used throughout the world. Music composed before the 16th century would sound different or even sometimes, be perceived as "out of tune" because our ears have been trained to get accustomed to the 12-TET system. The set of 12 notes from its starting frequency to an octave higher is known as the chromatic scale.

Scales in music theory are made from the chromatic scale in Western music. Different scales contain different number of notes. The major scale contains seven notes and is derived by a specific set of ratios. Figure 5 below shows piano keys with the C-major scale labeled. Looking at a piano, to play the C-major scale, one would play all the white keys starting at C note and ending at the B note. The notes would be C, D, E, F, G, and A.

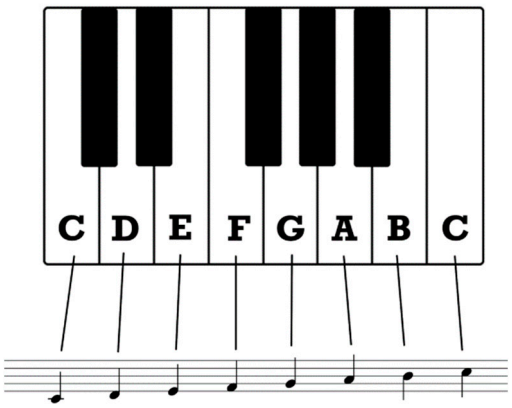

Figure 5. The C-major scale on a piano and staff (source: Google images).

3.4. Sound Mapping and Sound Library

In this study, the first step was to simulate the hydraulic model to obtain pressure values in a pipe caused by a pump trip. The maximum and minimum pressure values were found, and an octave range was selected to be mapped onto the pressure ranging from 208.29 kPa to 274.34 kPa onto notes spanning from C0 to B7. The note C0 was assigned to a pressure of 206.84 kPa and the note B7 was assigned to a pressure of 282.67 kPa. Each successive note was mapped to a pressure increase of 1.39 kPa. Table 1 shows the musical note assigned to pressure ranging from 206.84 kPa to 282.67 kPa.

Table 1. Pressure values and the corresponding musical note.

Pressure (kPa)	Musical Note	Pressure (kPa)	Musical Note
206.84	C0	245.51	C4
208.35	D0	246.89	D4
209.79	E0	248.21	E4
211.22	F0	249.59	F4
212.36	G0	250.97	G4
213.74	A0	252.35	A4
215.12	B0	253.73	B4
216.50	C1	255.11	C5

Table 1. *Cont.*

Pressure (kPa)	Musical Note	Pressure (kPa)	Musical Note
217.87	D1	256.47	D5
219.25	E1	257.86	E5
220.63	F1	259.24	F5
222.01	G1	260.62	G5
223.39	A1	261.99	A5
224.77	B1	263.37	B5
226.15	C2	264.75	C6
227.53	D2	266.13	D6
228.91	E2	267.51	E6
230.28	F2	268.91	F6
231.66	G2	270.28	G6
233.04	A2	271.66	A6
234.42	B2	273.04	B6
235.80	C3	274.42	C7
237.18	D3	275.79	D7
238.56	E3	277.17	E7
239.94	F3	278.55	F7
241.32	G3	279.93	G7
242.70	A3	281.31	A7
244.07	B3	282.69	B7

A sound library was created by using sound samples recorded in Logic Pro X which is a music production software by Apple Inc., Cupertino, CA, USA. Figure 6 below shows samples recorded using the sound of a Steinway grand piano. The sounds were exported as wave files.

A VBA code (Appendix A) was written in Microsoft Excel where the time step and pressure values were read in two columns, and a musical note was assigned to each pressure. The macro would then play the corresponding frequency by referencing the note from the sound library.

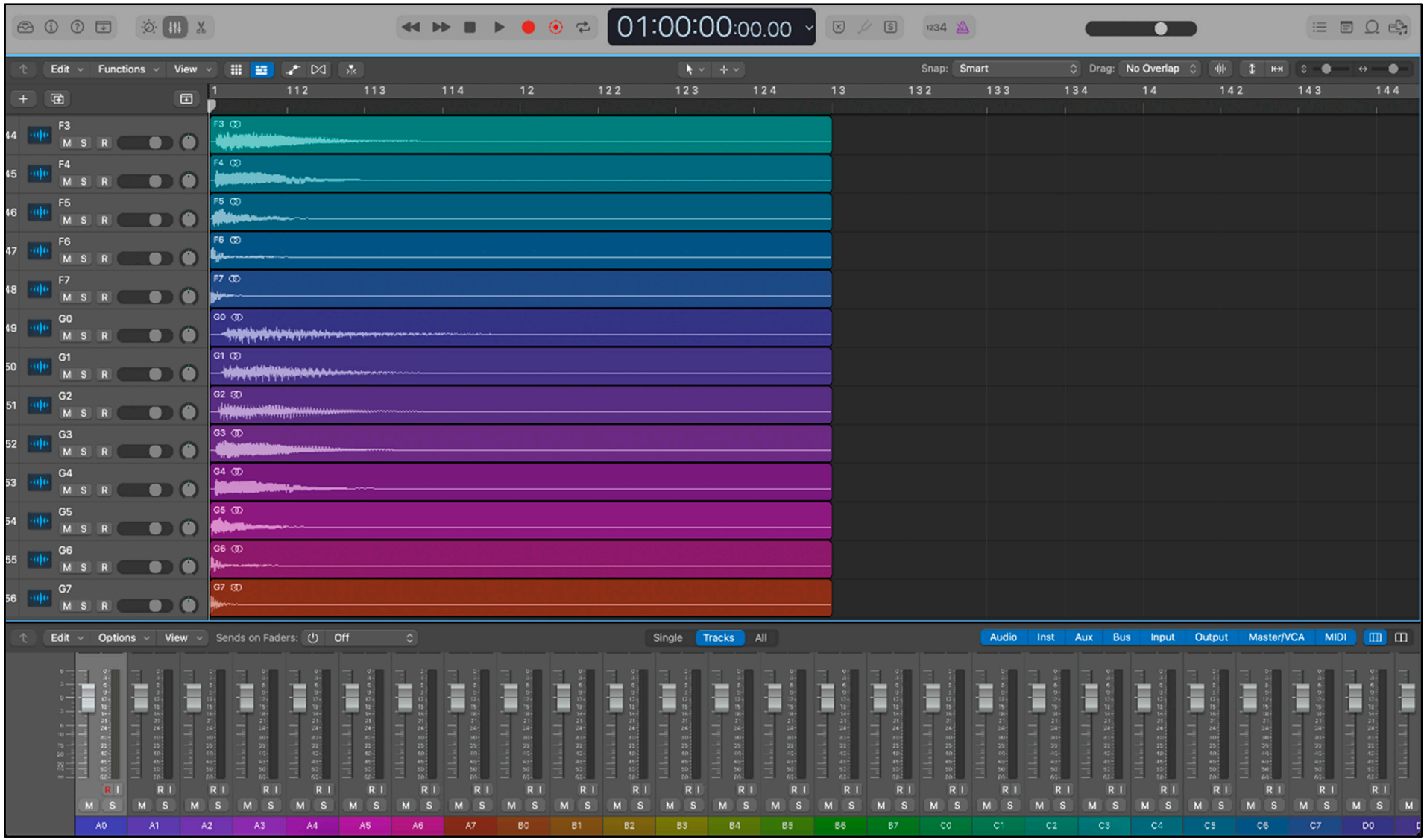

Figure 6. Sound samples recorded in Logic Pro X Digital Audtio Workstation.

4. Results

The following video file is the output of the Microsoft Excel macro where, at each time step, the pressure value is sonified by assigning a frequency and a musical note from the C-major scale. The macro then plays the wave file that corresponds to the referenced note in the sound library. Microsoft Excel executed the macro at a slow speed without allowing the user to change the speed at which audio files were played; therefore, Logic Pro software was used to record and speed up the audio produced by Microsoft Excel. Furthermore, the audio output of Excel macro was routed through a virtual synthesizer in Logic Pro to produce a continuous sound. The video is available on YouTube and can be viewed at the following link "https://www.youtube.com/watch?v=HYqgvy5XawI (accessed on 26 April 2023)" [18].

The start of the video clip corresponds to time t = 4.8 s of the simulation. The pump trip occurs at t = 5 s. The simulation runs at a steady-state until t = 5 s where a pump trip occurs and the pressure goes into transient state. At time t = 5.36 s, the pressure fluctuates. Table A1 in Appendix A provides pressure values at each time step for the 10 s simulation. When playing the sound clip, one notices the steady-state conditions before the pump trip as a series of sounds having the same pitch. When the pump trip is initiated, the sound is very high pitched, thus indicating the pressure spike. Specifically, the results of the transient analysis indicate a pressure spike of 274.34 kPa. Immediately the pitch lowers, thus indicating a pressure drop to 208.29 kPa. The pressures and sounds then fluctuate as friction dampen out the pressure wave with an eventual return to steady-state conditions.

Figure 7 is a screenshot of the Microsoft Excel file where the VBA code was written to sonify pressures. As the macro runs, it prints the pitch associated with the pressure in the third column and plays the sound simultaneously.

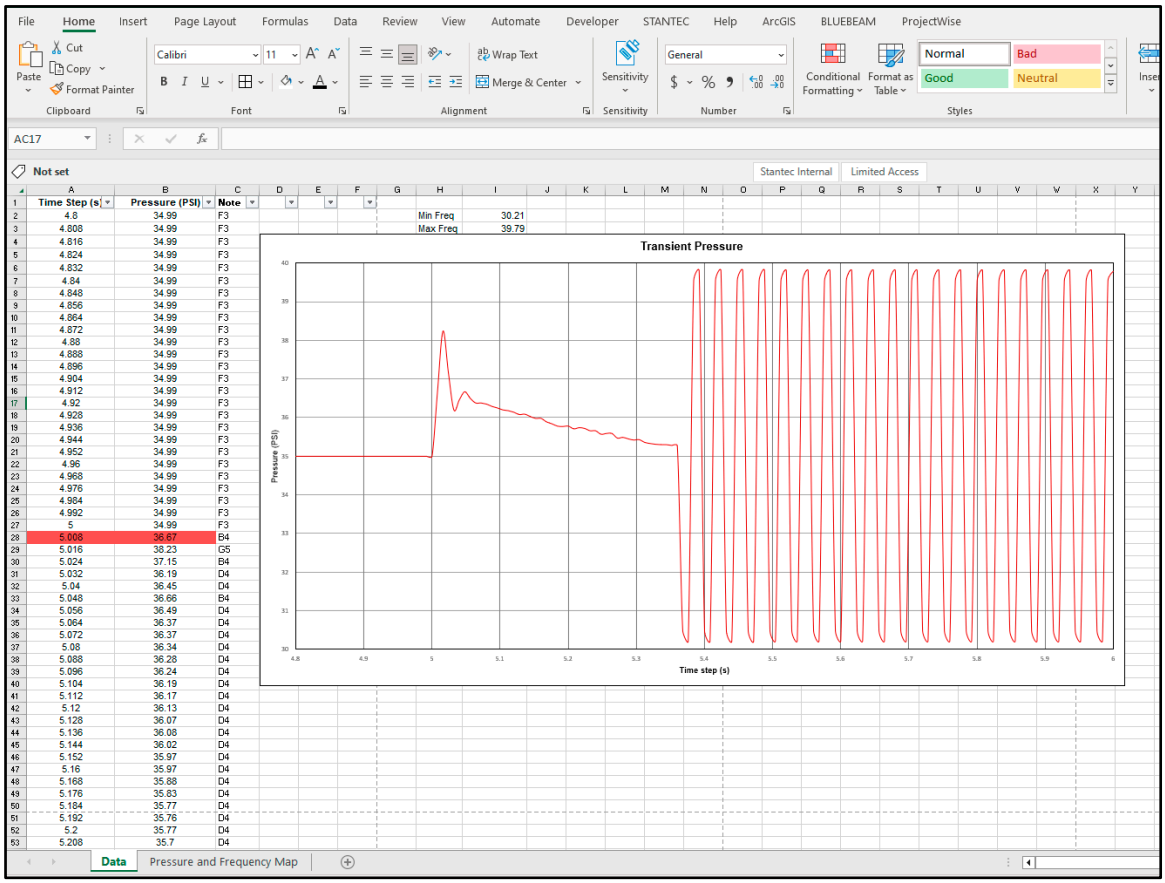

Figure 7. Microsoft Excel spreadsheet.

5. Limitation and Practical Considerations

A key consideration in applying sonification to hydraulic transients is specifying which transient phenomena are being targeted. In the present study, the focus is on water hammer events and rapid flow changes associated with pump trip scenarios. However, other important transient phenomena, such as cavitation and column separation, may arise in pipelines lacking surge suppression devices [3]. These events can cause significant pressure drops or vapor pocket formation, potentially leading to pipe collapse, implosion, or severe oscillations once the vapor pocket collapses [5]. Although such effects were not directly modeled in this study, the principles of mapping pressure data to acoustic signals can be extended to identify unique acoustic signatures corresponding to both cavitation and column separation.

Moreover, practical implementation of acoustic monitoring is inherently challenging when pipelines and distribution networks are buried or otherwise inaccessible. Direct placement of acoustic sensors on the pipe may be infeasible in such scenarios. One potential workaround is indirect acoustic sensing, where sensors are installed on the ground surface or within accessible chambers (e.g., valve vaults, pump houses) to detect vibrations or pressure waves transmitted through the ground or pipe supports [19]. Advanced data-driven analysis involving machine learning or signal-processing techniques can further isolate characteristic acoustic patterns from background noise, allowing researchers and operators to identify transient events more accurately [20]. Such methods often rely on extracting features (e.g., amplitude, frequency shifts) that correlate with specific transient phenomena and comparing these features against known baseline conditions or training datasets.

Another key recommendation is integration with other monitoring systems, including real-time pressure transducers and flow meters [21]. Correlating acoustic signals with direct measurements of pressure or flow changes can enhance both the accuracy and reliability of transient detection. By combining acoustic data with conventional sensor data, operators can develop a more robust diagnostic system. This multi-sensor approach can be programmed to raise alarms whenever transient-driven anomalies arise, thus forming a holistic pipeline monitoring framework.

Overall, while the proposed sonification method demonstrates the feasibility of translating transient pressure data into audible cues, field deployments must account for the practical challenges of buried pipelines, the complexity of various transient modes (including cavitation and column separation), and the importance of coupling acoustic sensing with other monitoring strategies for comprehensive pipeline management.

6. Conclusions and Recommendations

A hydraulic network model was created in KYPipe with a pump connected to a reservoir and a tank. The pump was simulated to be tripped at 5 s of operation to create water hammer effects in the pipeline. The pressure values were sonified by utilizing music theory. The maximum and minimum pressures were identified, and a range of octaves were selected to map the pressure to notes of the C-major scale. The range of octaves was from C0 to B7. A sound library was created in Apple Logic Pro using sound samples of the Steinway grand piano and each sample was exported as a wave file into a folder. VBA code was written where pressure values were assigned a musical pitch and as the macro was executed, the corresponding musical note was referenced from the sound library and played simultaneously. This innovative integration of hydraulic simulation with auditory display not only provides an intuitive means of visualizing transient events but also opens new avenues for real-time monitoring and analysis of hydraulic phenomena. Furthermore, the sonification approach can serve as an effective training tool for engineers and operators,

facilitating rapid recognition of abnormal pressure transients without constant reliance on visual data. This method has the potential to enhance operational safety in water distribution and industrial systems by providing immediate auditory feedback during critical events.

One of the limitations of the study was the computation power. A large dataset was produced by running the surge analysis simulation in KYPipe because the time step of simulation was a very small value (t = 0.008 s). Running the macro on the entire dataset would freeze the computer. Therefore, for the sonified output, pressure history from time t = 4.8 s to t = 6 s was used. Another limitation was controlling the speed at which the Microsoft Excel macro runs. For example, if the audio file of the sample was 3 s, then Microsoft Excel would play the next sample after 3 s which resulted in some silence or a pause in audio. To overcome this, the sample sizes were trimmed to 1 s and the audio output was sped up in Logic Pro; however, this resulted in producing sonification that sounded highly discretized instead of a smooth transitioning sound. Furthermore, using the notes of music scales omits many frequencies that fall in between two consecutive notes of a scale. For example, the note C1 in the C-major scale has a frequency of 32.7 Hz and the next note in the scale, D1, has a frequency of 36.71 Hz. The frequencies that lie between 32.7 Hz and 36.71 Hz get omitted in the sound-mapping process. The pressure values were assigned the closest matching frequencies of the C-major scale in the sound-mapping process. This resulted in losing resolution in terms of translating pressure into sound. However, mapping smaller increments of pressure change would require creating a large number of sound samples. This may result in a sound mapping method that is not perceived well by the human ear and information overload, which are issues discussed in several research studies conducted in other fields of sonification. Furthermore, this may require a lot of processing power of a computer, especially, if a Microsoft Excel macro is used for sonification. This compromise reduced the resolution of the sonification, potentially overlooking subtle transient fluctuations. However, these approximations resulted in a more musical output, which was a deliberate design choice.

A future recommendation for this study would be the creation of a larger collection of audio samples, where pressure can be discretized into smaller values in order to map pressure to sound more accurately, if computation power is not an issue. Additionally, exploring adaptive mapping algorithms that dynamically adjust the pitch-to-pressure relationship could capture subtle variations more effectively while minimizing auditory overload. Integrating alternative sonification techniques may also enhance the overall user experience and broaden the application of this methodology in both engineering and monitoring contexts. Overall, the unique methodology used in this study to sonify transient pressure of a hydraulic network was successful using a sound mapping technique that is easy to understand and perceive by the human ear.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to file size limitations and format considerations.

Conflicts of Interest: The author declares no conflict of interest.

Appendix A

Appendix A.1. VBA CODE

```
Sub Play_Data_Freq()
    Dim rng_Data As Range
    Dim i As Integer, iRow As Integer, iFreq As Integer
    Dim sFolderPath As String, sAudioFile As String
    Set rng_Data = Sh_Data.Range("B2", Range("B2").End(xlDown).Address)
    'Change the path below for the music library
    sFolderPath = "C:\Users\Khizer\Documents\UdaytonNew\Independent Study\SoundLibrary"
    'Traverse rows in the data sheet
    For i = 1 To rng_Data.Rows.Count
        iFreq = rng_Data.Cells(i, 1)
        On Error Resume Next
        'Lookup the filename in Frequency sheet for the data and get the closest (same or next biggest) match
        iRow = WorksheetFunction.Match(Round(iFreq, 0), Sh_Freq.Range("A:A"), 2)
        If iRow > 0 Then
            rng_Data.Cells(i, 1).Offset(0, 1) = Sh_Freq.Range("B" & iRow)
            'Play the file in Syncronous mode
            'The filename is derived based on frequency vs Filename data in the Frequency sheet
            SoundMe (sFolderPath & "\" & Sh_Freq.Range("B" & iRow) & ".wav")
        End If
    Next i
End Sub
```

Appendix A.2. KYPipe Simulation Results

Table A1. KYPipe model results.

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
0	241.25	4.992	241.25
0.008	241.25	5	241.25
0.016	241.25	5.008	252.83
0.024	241.25	5.016	263.59
0.032	241.25	5.024	256.14
0.04	241.25	5.032	249.52
0.048	241.25	5.04	251.31
0.056	241.25	5.048	252.76
0.064	241.25	5.056	251.59
0.072	241.25	5.064	250.76
0.08	241.25	5.072	250.76
0.088	241.25	5.08	250.56
0.096	241.25	5.088	250.14
0.104	241.25	5.096	249.87
0.112	241.25	5.104	249.52

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
0.12	241.25	5.112	249.38
0.128	241.25	5.12	249.11
0.136	241.25	5.128	248.69
0.144	241.25	5.136	248.76
0.152	241.25	5.144	248.35
0.16	241.25	5.152	248
0.168	241.25	5.16	248
0.176	241.25	5.168	247.38
0.184	241.25	5.176	247.04
0.192	241.25	5.184	246.63
0.2	241.25	5.192	246.56
0.208	241.25	5.2	246.63
0.216	241.25	5.208	246.14
0.224	241.25	5.216	246.35
0.232	241.25	5.224	246.21
0.24	241.25	5.232	245.8
0.248	241.25	5.24	245.8
0.256	241.25	5.248	245.18
0.264	241.25	5.256	245.32
0.272	241.25	5.264	245.32
0.28	241.25	5.272	244.49
0.288	241.25	5.28	244.63
0.296	241.25	5.288	244.35
0.304	241.25	5.296	244.14
0.312	241.25	5.304	244.21
0.32	241.25	5.312	243.73
0.328	241.25	5.32	243.52
0.336	241.25	5.328	243.39
0.344	241.25	5.336	243.32
0.352	241.25	5.344	243.32
0.36	241.25	5.352	243.18
0.368	241.25	5.36	243.11
0.376	241.25	5.368	210.01
0.384	241.25	5.376	208.29
0.392	241.25	5.384	272.62
0.4	241.25	5.392	274.34
0.408	241.25	5.4	210.01
0.416	241.25	5.408	208.29
0.424	241.25	5.416	272.62

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
0.432	241.25	5.424	274.34
0.44	241.25	5.432	210.01
0.448	241.25	5.44	208.29
0.456	241.25	5.448	272.62
0.464	241.25	5.456	274.34
0.472	241.25	5.464	210.08
0.48	241.25	5.472	208.29
0.488	241.25	5.48	272.55
0.496	241.25	5.488	274.34
0.504	241.25	5.496	210.08
0.512	241.25	5.504	208.36
0.52	241.25	5.512	272.55
0.528	241.25	5.52	274.27
0.536	241.25	5.528	210.08
0.544	241.25	5.536	208.36
0.552	241.25	5.544	272.55
0.56	241.25	5.552	274.27
0.568	241.25	5.56	210.08
0.576	241.25	5.568	208.36
0.584	241.25	5.576	272.55
0.592	241.25	5.584	274.27
0.6	241.25	5.592	210.08
0.608	241.25	5.6	208.36
0.616	241.25	5.608	272.55
0.624	241.25	5.616	274.27
0.632	241.25	5.624	210.08
0.64	241.25	5.632	208.36
0.648	241.25	5.64	272.55
0.656	241.25	5.648	274.27
0.664	241.25	5.656	210.08
0.672	241.25	5.664	208.36
0.68	241.25	5.672	272.55
0.688	241.25	5.68	274.27
0.696	241.25	5.688	210.08
0.704	241.25	5.696	208.36
0.712	241.25	5.704	272.55
0.72	241.25	5.712	274.27
0.728	241.25	5.72	210.08
0.736	241.25	5.728	208.36

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
0.744	241.25	5.736	272.55
0.752	241.25	5.744	274.27
0.76	241.25	5.752	210.08
0.768	241.25	5.76	208.36
0.776	241.25	5.768	272.55
0.784	241.25	5.776	274.27
0.792	241.25	5.784	210.08
0.8	241.25	5.792	208.36
0.808	241.25	5.8	272.55
0.816	241.25	5.808	274.27
0.824	241.25	5.816	210.08
0.832	241.25	5.824	208.36
0.84	241.25	5.832	272.55
0.848	241.25	5.84	274.27
0.856	241.25	5.848	210.08
0.864	241.25	5.856	208.36
0.872	241.25	5.864	272.55
0.88	241.25	5.872	274.27
0.888	241.25	5.88	210.08
0.896	241.25	5.888	208.36
0.904	241.25	5.896	272.55
0.912	241.25	5.904	274.27
0.92	241.25	5.912	210.08
0.928	241.25	5.92	208.36
0.936	241.25	5.928	272.55
0.944	241.25	5.936	274.27
0.952	241.25	5.944	210.08
0.96	241.25	5.952	208.36
0.968	241.25	5.96	272.55
0.976	241.25	5.968	274.27
0.984	241.25	5.976	210.08
0.992	241.25	5.984	208.36
1	241.25	5.992	272.55
1.008	241.25	6	274.27
1.016	241.25	6.008	210.08
1.024	241.25	6.016	208.36
1.032	241.25	6.024	272.55
1.04	241.25	6.032	274.27
1.048	241.25	6.04	210.08

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
1.056	241.25	6.048	208.36
1.064	241.25	6.056	272.55
1.072	241.25	6.064	274.27
1.08	241.25	6.072	210.08
1.088	241.25	6.08	208.36
1.096	241.25	6.088	272.55
1.104	241.25	6.096	274.27
1.112	241.25	6.104	210.08
1.12	241.25	6.112	208.36
1.128	241.25	6.12	272.55
1.136	241.25	6.128	274.27
1.144	241.25	6.136	210.08
1.152	241.25	6.144	208.36
1.16	241.25	6.152	272.55
1.168	241.25	6.16	274.27
1.176	241.25	6.168	210.08
1.184	241.25	6.176	208.36
1.192	241.25	6.184	272.55
1.2	241.25	6.192	274.27
1.208	241.25	6.2	210.08
1.216	241.25	6.208	208.36
1.224	241.25	6.216	272.55
1.232	241.25	6.224	274.27
1.24	241.25	6.232	210.08
1.248	241.25	6.24	208.36
1.256	241.25	6.248	272.55
1.264	241.25	6.256	274.27
1.272	241.25	6.264	210.08
1.28	241.25	6.272	208.36
1.288	241.25	6.28	272.55
1.296	241.25	6.288	274.27
1.304	241.25	6.296	210.15
1.312	241.25	6.304	208.36
1.32	241.25	6.312	272.48
1.328	241.25	6.32	274.27
1.336	241.25	6.328	210.15
1.344	241.25	6.336	208.43
1.352	241.25	6.344	272.48
1.36	241.25	6.352	274.2

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
1.368	241.25	6.36	210.15
1.376	241.25	6.368	208.43
1.384	241.25	6.376	272.48
1.392	241.25	6.384	274.2
1.4	241.25	6.392	210.15
1.408	241.25	6.4	208.43
1.416	241.25	6.408	272.48
1.424	241.25	6.416	274.2
1.432	241.25	6.424	210.15
1.44	241.25	6.432	208.43
1.448	241.25	6.44	272.48
1.456	241.25	6.448	274.2
1.464	241.25	6.456	210.15
1.472	241.25	6.464	208.43
1.48	241.25	6.472	272.48
1.488	241.25	6.48	274.2
1.496	241.25	6.488	210.15
1.504	241.25	6.496	208.43
1.512	241.25	6.504	272.48
1.52	241.25	6.512	274.2
1.528	241.25	6.52	210.15
1.536	241.25	6.528	208.43
1.544	241.25	6.536	272.48
1.552	241.25	6.544	274.2
1.56	241.25	6.552	210.15
1.568	241.25	6.56	208.43
1.576	241.25	6.568	272.48
1.584	241.25	6.576	274.2
1.592	241.25	6.584	210.15
1.6	241.25	6.592	208.43
1.608	241.25	6.6	272.48
1.616	241.25	6.608	274.2
1.624	241.18	6.616	210.15
1.632	241.25	6.624	208.43
1.64	241.25	6.632	272.48
1.648	241.25	6.64	274.2
1.656	241.25	6.648	210.15
1.664	241.25	6.656	208.43
1.672	241.25	6.664	272.48

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
1.68	241.25	6.672	274.2
1.688	241.25	6.68	210.15
1.696	241.25	6.688	208.43
1.704	241.25	6.696	272.48
1.712	241.25	6.704	274.2
1.72	241.25	6.712	210.15
1.728	241.25	6.72	208.43
1.736	241.25	6.728	272.48
1.744	241.25	6.736	274.2
1.752	241.25	6.744	210.15
1.76	241.25	6.752	208.43
1.768	241.25	6.76	272.48
1.776	241.25	6.768	274.2
1.784	241.25	6.776	210.15
1.792	241.25	6.784	208.43
1.8	241.25	6.792	272.48
1.808	241.25	6.8	274.2
1.816	241.25	6.808	210.15
1.824	241.25	6.816	208.43
1.832	241.25	6.824	272.48
1.84	241.25	6.832	274.2
1.848	241.25	6.84	210.15
1.856	241.25	6.848	208.43
1.864	241.25	6.856	272.48
1.872	241.25	6.864	274.2
1.88	241.25	6.872	210.15
1.888	241.25	6.88	208.43
1.896	241.25	6.888	272.48
1.904	241.25	6.896	274.2
1.912	241.25	6.904	210.15
1.92	241.25	6.912	208.43
1.928	241.25	6.92	272.48
1.936	241.25	6.928	274.2
1.944	241.25	6.936	210.15
1.952	241.25	6.944	208.43
1.96	241.25	6.952	272.48
1.968	241.25	6.96	274.2
1.976	241.25	6.968	210.15
1.984	241.25	6.976	208.43

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
1.992	241.25	6.984	272.48
2	241.25	6.992	274.2
2.008	241.25	7	210.15
2.016	241.25	7.008	208.43
2.024	241.25	7.016	272.48
2.032	241.25	7.024	274.2
2.04	241.25	7.032	210.15
2.048	241.25	7.04	208.43
2.056	241.25	7.048	272.48
2.064	241.25	7.056	274.2
2.072	241.25	7.064	210.15
2.08	241.25	7.072	208.43
2.088	241.25	7.08	272.48
2.096	241.25	7.088	274.2
2.104	241.25	7.096	210.15
2.112	241.25	7.104	208.43
2.12	241.25	7.112	272.48
2.128	241.25	7.12	274.2
2.136	241.25	7.128	210.22
2.144	241.25	7.136	208.43
2.152	241.25	7.144	272.41
2.16	241.25	7.152	274.14
2.168	241.25	7.16	210.22
2.176	241.25	7.168	208.5
2.184	241.25	7.176	272.41
2.192	241.25	7.184	274.14
2.2	241.25	7.192	210.22
2.208	241.25	7.2	208.5
2.216	241.25	7.208	272.41
2.224	241.25	7.216	274.14
2.232	241.25	7.224	210.22
2.24	241.25	7.232	208.5
2.248	241.25	7.24	272.41
2.256	241.25	7.248	274.14
2.264	241.25	7.256	210.22
2.272	241.25	7.264	208.5
2.28	241.25	7.272	272.41
2.288	241.25	7.28	274.14
2.296	241.25	7.288	210.22

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
2.304	241.25	7.296	208.5
2.312	241.25	7.304	272.41
2.32	241.25	7.312	274.14
2.328	241.25	7.32	210.22
2.336	241.25	7.328	208.5
2.344	241.25	7.336	272.41
2.352	241.25	7.344	274.14
2.36	241.25	7.352	210.22
2.368	241.25	7.36	208.5
2.376	241.25	7.368	272.41
2.384	241.25	7.376	274.14
2.392	241.25	7.384	210.22
2.4	241.25	7.392	208.5
2.408	241.25	7.4	272.41
2.416	241.25	7.408	274.14
2.424	241.25	7.416	210.22
2.432	241.25	7.424	208.5
2.44	241.25	7.432	272.41
2.448	241.25	7.44	274.14
2.456	241.25	7.448	210.22
2.464	241.25	7.456	208.5
2.472	241.25	7.464	272.41
2.48	241.25	7.472	274.14
2.488	241.25	7.48	210.22
2.496	241.25	7.488	208.5
2.504	241.25	7.496	272.41
2.512	241.25	7.504	274.14
2.52	241.25	7.512	210.22
2.528	241.25	7.52	208.5
2.536	241.25	7.528	272.41
2.544	241.25	7.536	274.14
2.552	241.25	7.544	210.22
2.56	241.25	7.552	208.5
2.568	241.25	7.56	272.41
2.576	241.25	7.568	274.14
2.584	241.25	7.576	210.22
2.592	241.25	7.584	208.5
2.6	241.25	7.592	272.41
2.608	241.25	7.6	274.14

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
2.616	241.25	7.608	210.22
2.624	241.25	7.616	208.5
2.632	241.25	7.624	272.41
2.64	241.25	7.632	274.14
2.648	241.25	7.64	210.22
2.656	241.25	7.648	208.5
2.664	241.25	7.656	272.41
2.672	241.25	7.664	274.14
2.68	241.25	7.672	210.22
2.688	241.25	7.68	208.5
2.696	241.25	7.688	272.41
2.704	241.25	7.696	274.14
2.712	241.25	7.704	210.22
2.72	241.25	7.712	208.5
2.728	241.25	7.72	272.41
2.736	241.25	7.728	274.14
2.744	241.25	7.736	210.22
2.752	241.25	7.744	208.5
2.76	241.25	7.752	272.41
2.768	241.25	7.76	274.14
2.776	241.25	7.768	210.22
2.784	241.25	7.776	208.5
2.792	241.25	7.784	272.41
2.8	241.25	7.792	274.14
2.808	241.25	7.8	210.22
2.816	241.25	7.808	208.5
2.824	241.25	7.816	272.41
2.832	241.25	7.824	274.14
2.84	241.25	7.832	210.22
2.848	241.25	7.84	208.5
2.856	241.25	7.848	272.41
2.864	241.25	7.856	274.14
2.872	241.25	7.864	210.22
2.88	241.25	7.872	208.5
2.888	241.25	7.88	272.41
2.896	241.25	7.888	274.14
2.904	241.25	7.896	210.22
2.912	241.25	7.904	208.5
2.92	241.25	7.912	272.41

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
2.928	241.25	7.92	274.14
2.936	241.25	7.928	210.22
2.944	241.25	7.936	208.5
2.952	241.25	7.944	272.41
2.96	241.25	7.952	274.14
2.968	241.25	7.96	210.22
2.976	241.25	7.968	208.57
2.984	241.25	7.976	272.41
2.992	241.25	7.984	274.07
3	241.25	7.992	210.29
3.008	241.25	8	208.57
3.016	241.25	8.008	272.34
3.024	241.25	8.016	274.07
3.032	241.25	8.024	210.29
3.04	241.25	8.032	208.57
3.048	241.25	8.04	272.34
3.056	241.25	8.048	274.07
3.064	241.25	8.056	210.29
3.072	241.25	8.064	208.57
3.08	241.25	8.072	272.34
3.088	241.25	8.08	274.07
3.096	241.25	8.088	210.29
3.104	241.25	8.096	208.57
3.112	241.25	8.104	272.34
3.12	241.25	8.112	274.07
3.128	241.25	8.12	210.29
3.136	241.25	8.128	208.57
3.144	241.25	8.136	272.34
3.152	241.25	8.144	274.07
3.16	241.25	8.152	210.29
3.168	241.25	8.16	208.57
3.176	241.25	8.168	272.34
3.184	241.25	8.176	274.07
3.192	241.25	8.184	210.29
3.2	241.25	8.192	208.57
3.208	241.25	8.2	272.34
3.216	241.25	8.208	274.07
3.224	241.25	8.216	210.29
3.232	241.25	8.224	208.57

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
3.24	241.25	8.232	272.34
3.248	241.25	8.24	274.07
3.256	241.25	8.248	210.29
3.264	241.25	8.256	208.57
3.272	241.25	8.264	272.34
3.28	241.25	8.272	274.07
3.288	241.25	8.28	210.29
3.296	241.25	8.288	208.57
3.304	241.25	8.296	272.34
3.312	241.25	8.304	274.07
3.32	241.25	8.312	210.29
3.328	241.25	8.32	208.57
3.336	241.25	8.328	272.34
3.344	241.25	8.336	274.07
3.352	241.25	8.344	210.29
3.36	241.25	8.352	208.57
3.368	241.25	8.36	272.34
3.376	241.25	8.368	274.07
3.384	241.25	8.376	210.29
3.392	241.25	8.384	208.57
3.4	241.25	8.392	272.34
3.408	241.25	8.4	274.07
3.416	241.25	8.408	210.29
3.424	241.25	8.416	208.57
3.432	241.25	8.424	272.34
3.44	241.25	8.432	274.07
3.448	241.25	8.44	210.29
3.456	241.25	8.448	208.57
3.464	241.25	8.456	272.34
3.472	241.25	8.464	274.07
3.48	241.25	8.472	210.29
3.488	241.25	8.48	208.57
3.496	241.25	8.488	272.34
3.504	241.25	8.496	274.07
3.512	241.25	8.504	210.29
3.52	241.25	8.512	208.57
3.528	241.25	8.52	272.34
3.536	241.25	8.528	274.07
3.544	241.25	8.536	210.29

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
3.552	241.25	8.544	208.57
3.56	241.25	8.552	272.34
3.568	241.25	8.56	274.07
3.576	241.25	8.568	210.29
3.584	241.25	8.576	208.57
3.592	241.25	8.584	272.34
3.6	241.25	8.592	274.07
3.608	241.25	8.6	210.29
3.616	241.25	8.608	208.57
3.624	241.25	8.616	272.34
3.632	241.25	8.624	274.07
3.64	241.25	8.632	210.29
3.648	241.25	8.64	208.57
3.656	241.25	8.648	272.34
3.664	241.25	8.656	274.07
3.672	241.25	8.664	210.29
3.68	241.25	8.672	208.57
3.688	241.25	8.68	272.34
3.696	241.25	8.688	274.07
3.704	241.25	8.696	210.29
3.712	241.25	8.704	208.57
3.72	241.25	8.712	272.34
3.728	241.25	8.72	274.07
3.736	241.25	8.728	210.29
3.744	241.25	8.736	208.57
3.752	241.25	8.744	272.34
3.76	241.25	8.752	274.07
3.768	241.25	8.76	210.29
3.776	241.25	8.768	208.57
3.784	241.25	8.776	272.34
3.792	241.25	8.784	274.07
3.8	241.25	8.792	210.29
3.808	241.25	8.8	208.64
3.816	241.25	8.808	272.34
3.824	241.25	8.816	274
3.832	241.25	8.824	210.29
3.84	241.25	8.832	208.64
3.848	241.25	8.84	272.27
3.856	241.25	8.848	274

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
3.864	241.25	8.856	210.36
3.872	241.25	8.864	208.64
3.88	241.25	8.872	272.27
3.888	241.25	8.88	274
3.896	241.25	8.888	210.36
3.904	241.25	8.896	208.64
3.912	241.25	8.904	272.27
3.92	241.25	8.912	274
3.928	241.25	8.92	210.36
3.936	241.25	8.928	208.64
3.944	241.25	8.936	272.27
3.952	241.25	8.944	274
3.96	241.25	8.952	210.36
3.968	241.25	8.96	208.64
3.976	241.25	8.968	272.27
3.984	241.25	8.976	274
3.992	241.25	8.984	210.36
4	241.25	8.992	208.64
4.008	241.25	9	272.27
4.016	241.25	9.008	274
4.024	241.25	9.016	210.36
4.032	241.25	9.024	208.64
4.04	241.25	9.032	272.27
4.048	241.25	9.04	274
4.056	241.25	9.048	210.36
4.064	241.25	9.056	208.64
4.072	241.25	9.064	272.27
4.08	241.25	9.072	274
4.088	241.25	9.08	210.36
4.096	241.25	9.088	208.64
4.104	241.25	9.096	272.27
4.112	241.25	9.104	274
4.12	241.25	9.112	210.36
4.128	241.25	9.12	208.64
4.136	241.25	9.128	272.27
4.144	241.25	9.136	274
4.152	241.25	9.144	210.36
4.16	241.25	9.152	208.64
4.168	241.25	9.16	272.27

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
4.176	241.25	9.168	274
4.184	241.25	9.176	210.36
4.192	241.25	9.184	208.64
4.2	241.25	9.192	272.27
4.208	241.25	9.2	274
4.216	241.25	9.208	210.36
4.224	241.25	9.216	208.64
4.232	241.25	9.224	272.27
4.24	241.25	9.232	274
4.248	241.25	9.24	210.36
4.256	241.25	9.248	208.64
4.264	241.25	9.256	272.27
4.272	241.25	9.264	274
4.28	241.25	9.272	210.36
4.288	241.25	9.28	208.64
4.296	241.25	9.288	272.27
4.304	241.25	9.296	274
4.312	241.25	9.304	210.36
4.32	241.25	9.312	208.64
4.328	241.25	9.32	272.27
4.336	241.25	9.328	274
4.344	241.25	9.336	210.36
4.352	241.25	9.344	208.64
4.36	241.25	9.352	272.27
4.368	241.25	9.36	274
4.376	241.25	9.368	210.36
4.384	241.25	9.376	208.64
4.392	241.25	9.384	272.27
4.4	241.25	9.392	274
4.408	241.25	9.4	210.36
4.416	241.25	9.408	208.64
4.424	241.25	9.416	272.27
4.432	241.25	9.424	274
4.44	241.25	9.432	210.36
4.448	241.25	9.44	208.64
4.456	241.25	9.448	272.27
4.464	241.25	9.456	274
4.472	241.25	9.464	210.36
4.48	241.25	9.472	208.64

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
4.488	241.25	9.48	272.27
4.496	241.25	9.488	274
4.504	241.25	9.496	210.36
4.512	241.25	9.504	208.64
4.52	241.25	9.512	272.27
4.528	241.25	9.52	274
4.536	241.25	9.528	210.36
4.544	241.25	9.536	208.64
4.552	241.25	9.544	272.27
4.56	241.25	9.552	274
4.568	241.25	9.56	210.36
4.576	241.25	9.568	208.64
4.584	241.25	9.576	272.27
4.592	241.25	9.584	274
4.6	241.25	9.592	210.36
4.608	241.25	9.6	208.64
4.616	241.25	9.608	272.27
4.624	241.25	9.616	274
4.632	241.25	9.624	210.36
4.64	241.25	9.632	208.64
4.648	241.25	9.64	272.27
4.656	241.25	9.648	273.93
4.664	241.25	9.656	210.36
4.672	241.25	9.664	208.7
4.68	241.25	9.672	272.27
4.688	241.25	9.68	273.93
4.696	241.25	9.688	210.43
4.704	241.25	9.696	208.7
4.712	241.25	9.704	272.21
4.72	241.25	9.712	273.93
4.728	241.25	9.72	210.43
4.736	241.25	9.728	208.7
4.744	241.25	9.736	272.21
4.752	241.25	9.744	273.93
4.76	241.25	9.752	210.43
4.768	241.25	9.76	208.7
4.776	241.25	9.768	272.21
4.784	241.25	9.776	273.93
4.792	241.25	9.784	210.43

Table A1. *Cont.*

Time Step (s)	Pressure (kPa)	Time Step (s)	Pressure (kPa)
4.8	241.25	9.792	208.7
4.808	241.25	9.8	272.21
4.816	241.25	9.808	273.93
4.824	241.25	9.816	210.43
4.832	241.25	9.824	208.7
4.84	241.25	9.832	272.21
4.848	241.25	9.84	273.93
4.856	241.25	9.848	210.43
4.864	241.25	9.856	208.7
4.872	241.25	9.864	272.21
4.88	241.25	9.872	273.93
4.888	241.25	9.88	210.43
4.896	241.25	9.888	208.7
4.904	241.25	9.896	272.21
4.912	241.25	9.904	273.93
4.92	241.25	9.912	210.43
4.928	241.25	9.92	208.7
4.936	241.25	9.928	272.21
4.944	241.25	9.936	273.93
4.952	241.25	9.944	210.43
4.96	241.25	9.952	208.7
4.968	241.25	9.96	272.21
4.976	241.25	9.968	273.93
4.984	241.25	9.976	210.43
		9.984	208.7
		9.992	272.21
		10	273.93

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