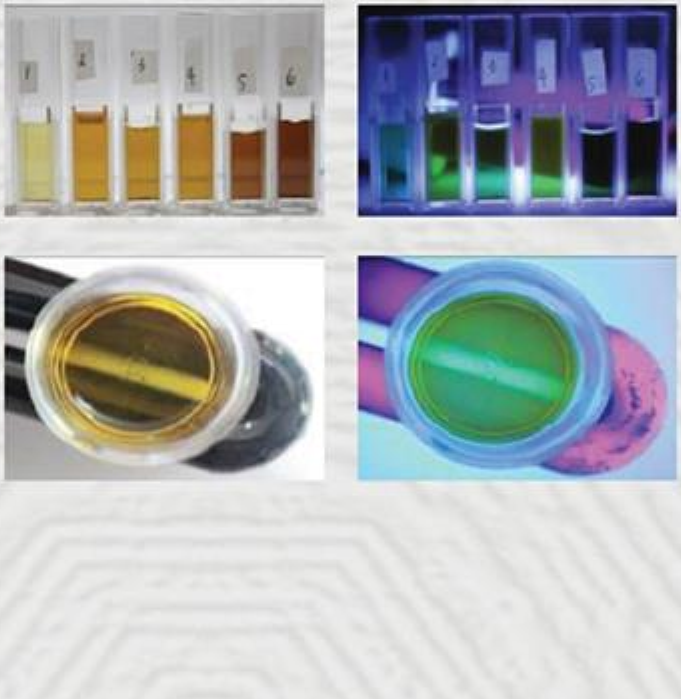
Advanced Materials Science and Technology II



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Preface

The present volume contains selected papers of the 2014 International Conference of Advanced Materials Science and Technology (ICAMST 2014) held on September 16-17, 2014 in Solo, Indonesia. The conference, which has been jointly organized by Sebelas Maret University, Universitas Gadjah Mada, Institut Teknologi Bandung, Semarang State University, Diponegoro University, Indonesia, has received 151 abstracts. After having reviewed the abstracts, 108 papers were presented in the conference. Finally, under a tight peer-review process, 86 papers were accepted in Advanced Materials Research.

The papers are categorized into several groups that cover new developments and research results related to theoretical and experimental studies of advanced materials as well as their various processing and wide variety of applications. They include nanofibers, electronic materials, magnetic materials, composites, ceramics, and alloys as well as measurement and characterization techniques of materials.

Finally, we are grateful to PT. Mitra Intimarga, PT. Era Mitra Perdana, and Abadi Nusa as sponsors; Indonesian Physical Society (HFI) Central Java and Yogyakarta Chapter, Materials Research Society of Indonesia (MRS-ID), and Physics and Applied Physics Society of Indonesia (PAPSI) for their technical supports. Last but not least, we also wish to thank reviewers for invaluable comments and suggestions.

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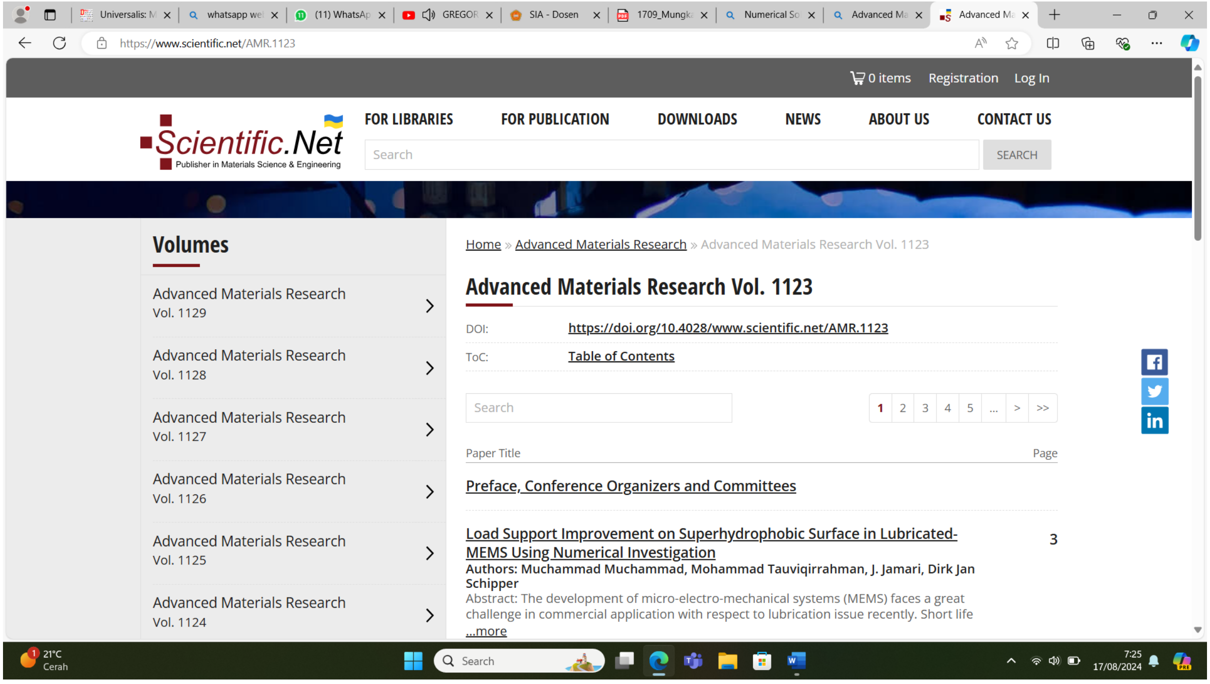
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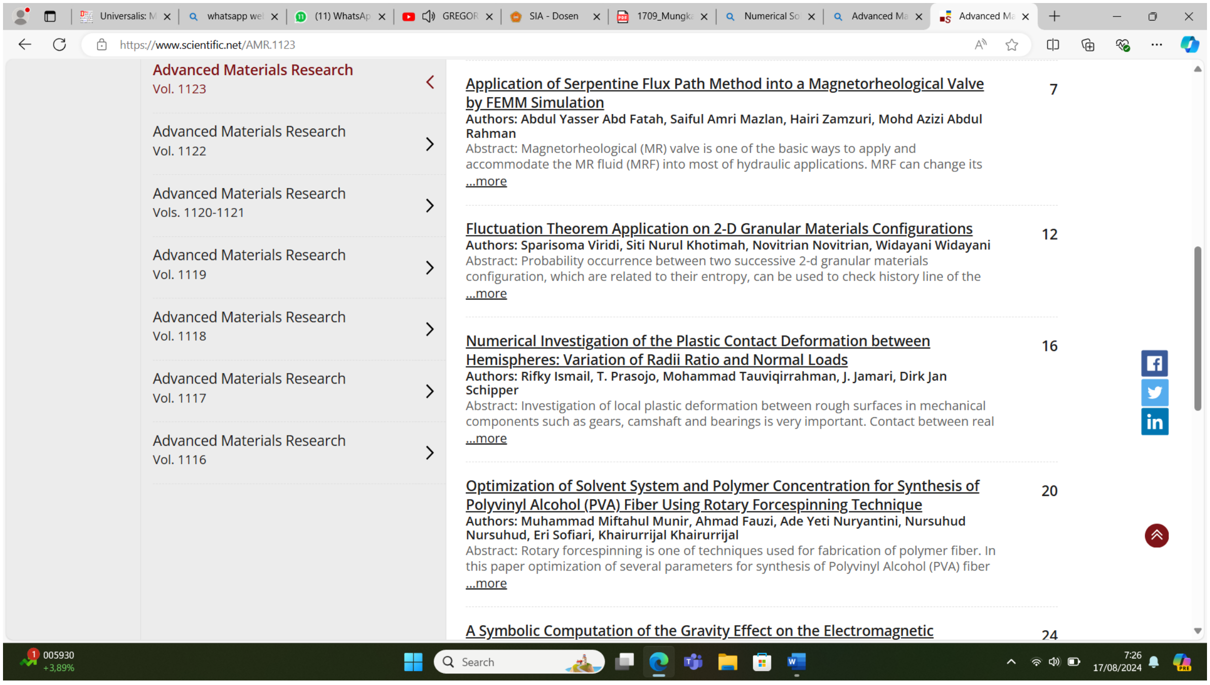
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Numerical Solutions to Fast Transient Pipe Flow Problems

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Keywords: fast transient flow, finite volume method, pipe flow, water hammer

Abstract. We promote a finite volume method to solve a water hammer problem numerically. This problem is of the type of fast transient pipe flow. The mathematical model governing the problem is a system of two simultaneous partial differential equations. As the system is hyperbolic, our choice of numerical method is appropriate. In particular, we consider water flows through a pipe from a pressurized water tank at one end to a valve at the other end. We want to know the pressure and velocity profile in the pipe when the valve closes as a function of time. We find that the finite volume method is very robust to solve the problem.

Introduction

Fast transient flow often occurs in pipe systems. This is usually caused by a valve closing a pipe containing a steady flow initially. The problem of flow affected by the valve is also known as the water hammer problem.

Markendahl [1] used finite volume methods to solve the water hammer problem. Various closing times were tested. Markendahl [1] obtained that the duration of the closing time of the valve does not affect the maximum pressure hitting the valve. Instead of affecting the maximum pressure, the closing time does affect the pressure distribution in the whole one-dimensional pipe.

Some other works on water hammer flows have been available in the literature. One of them was conducted by Zhao and Ghidaoui [2], who proposed Godunov-type solutions for solving the problem. LeVeque [3] offered a Roe scheme to solve the same problem. Different models were solved by other researchers, such as, Tian *et al.* [4] and Kaliatka *et al.* [5]. Markendahl [1] incorporated the theory presented by Zhao and Ghidaoui [2], Nilsson [6] as well as Moody [7]. Among the literature, we find that the work of Markendahl [1] is simpler but provides enough knowledge to solve the problem.

The present paper is very much in line with and extends the work of Markendahl [1]. However, instead of varying the closing time, we vary the initial velocity of water in the pipe. The closing time is fixed. In this work we show that different initial velocities of water lead to different values of maximum pressure hitting the pipe. Furthermore we research the relationship between the varying initial velocities and the values of maximum pressure, exactly at the instant time when the valve is completely closed. A finite volume method with the standard Lax-Friedrichs formulation is applied in this paper.

This paper is organized as follows. First we recall the governing equations for the water hammer problem. Then the numerical method is explained. After that we present numerical results to answer our research questions. At the end this paper is concluded with a summary.

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Governing Equations

The model governing one-dimensional water hammer flows is the system of two equations

$$\frac{\partial p(x,t)}{\partial t}+\rho c^2\frac{\partial u(x,t)}{\partial x}=0, \tag{1}$$

$$\frac{\partial u(x,t)}{\partial t}+\frac{1}{\rho}\frac{\partial p(x,t)}{\partial x}=0. \tag{2}$$

The independent variables are the one-dimensional space x and time t. The notation p represents the pressure, u the velocity, ρ the density, and c the propagation speed of pressure wave.

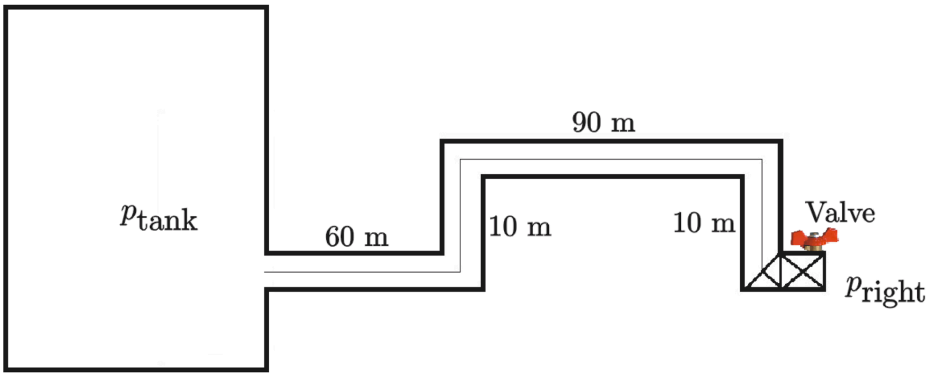

Figure 1: The pipe system (see Markendahl [1]) that we solve using the finite volume method.

Following Markendahl [1], we consider a one-dimensional space $[0,L]$. Water flows from a tank to a valve, as shown in Fig. 1. The position $x=0$ is the interface between the tank and the pipe. The position $x=L$ is the location of the valve. The boundary condition at $x=0$ is $p(0,t)=p_{\text{tank}}$, where p_{tank} is the tank pressure on the left end. The boundary condition at $x=L$ satisfies

$$\frac{1}{2}\rho u(L,t)^2=\alpha(t)^2[p(L,t)-p_{\text{right}}], \tag{3}$$

where p_{right} is the environment pressure on the right end. The variable α is the opening coefficient of the valve and is defined as

$$\alpha(t)=1-\frac{t-t_{\text{start}}}{t_{\text{stop}}}. \tag{4}$$

The constant $K=1/\alpha^2$ is called the loss coefficient. It satisfies $p-p_{\text{right}}=\frac{1}{2}K\rho u^2$. The initial condition is a steady fluid flow with a constant pipe pressure and a constant velocity.

Some notes should be taken into account. In the mathematical model, the effect of pipe bending is assumed to be negligible, so that the model is one-dimensional. Frictions to the pipe wall is neglected, so the pipe is assumed to be ideal. Turbulent flow is out of the scope of this paper.

Numerical Method

A finite volume method is used to solve the water hammer flow equations (Eq. 1 and Eq. 2). We consider the following vectors

$$\mathbf{q}(x,t)=\begin{pmatrix}p\\u\end{pmatrix},\quad \mathbf{f}(\mathbf{q}(x,t))=\begin{pmatrix}\rho c^2 u\\ \frac{1}{\rho}p\end{pmatrix}. \tag{5}$$

The water hammer flow equations form

$$\frac{\partial \mathbf{q}(x,t)}{\partial t}+\frac{\partial \mathbf{f}(\mathbf{q}(x,t))}{\partial x}=0, \tag{6}$$

which is a system of hyperbolic conservation laws [3].

We discretize Eq. 6 using the standard finite volume method with uniform space step Δx and uniform time step Δt. The space $[0, L]$ is discretized into a finite number of cells, $C_i = [x_{i-1/2}, x_{i+1/2}]$, $i = 1, 2, 3, \ldots, N$. The total number of cells is denoted by N. The time is discretized as $t^n = n\Delta t.$ The fully discrete finite volume scheme for Eq. 6 is given by

$$\mathbf{Q}_i^{n+1} = \mathbf{Q}_i^n - \frac{\Delta t}{\Delta x}(\mathbf{F}_{i+1/2}^n - \mathbf{F}_{i-1/2}^n). \tag{7}$$

Here the numerical quantity $\mathbf{Q}_i^n$ is the averaged quantity over the ith cell at time t^n. The numerical flux $\mathbf{F}_{i-1/2}^n$ is the averaged flux flowing through the interface $x_{i-1/2}$ during one time step. In this paper, we use the Lax-Friedrichs formulation to compute the flux $\mathbf{F}_{i-1/2}^n$. We refer to the work of LeVeque [3] for the Lax-Friedrichs flux formulation.

The boundary condition is numerically treated as follows. At the left end ($x_{1/2} = 0$),

$$\mathbf{F}_{1/2} = \begin{pmatrix} \rho c^2[u_1 + \frac{1}{\rho c}(p_{\text{tank}} - p_1)] \\ \frac{1}{\rho} p_{\text{tank}} \end{pmatrix}. \tag{8}$$

for every time step. At the right end ($x_{N+1/2} = L$),

$$\mathbf{F}_{N+1/2} = \begin{pmatrix} \rho c^2 u_{N+1/2} \\ \frac{1}{\rho} p_{N+1/2} \end{pmatrix}. \tag{9}$$

The velocity at the right end of the space is

$$u_{N+1/2} = -\frac{c}{K} + \frac{c}{K}\sqrt{1 + \frac{2K}{\rho c^2}(p_N - p_{\text{right}} + \rho c u_N)} \,. \tag{10}$$

The pressure at the right end of the space is

$$p_{N+1/2} = p_{\text{right}} + \frac{1}{2}K\rho u_{N+1/2}^2 \,. \tag{11}$$

Note that after the valve is completely closed, the velocity at the right end is zero. This means that for $t \geq t_{\text{stop}}$, we need to enforce $u_{N+1/2} = 0$. Therefore for $t \geq t_{\text{stop}}$, we take

$$\mathbf{F}_{N+1/2} = \begin{pmatrix} 0 \\ \frac{1}{\rho} p_N + c u_N \end{pmatrix}. \tag{12}$$

More explanation about numerical settings and boundary conditions can be found in the work of Markendahl [1], Zhao and Ghidaoui [2], Nilsson [6] and Moody [7].

Numerical Results

We want to solve the fast transient pipe flow problem with the model shown in Fig. 1. If units of quantities are omitted, they should be understood to have SI units. The dimensional space is $[0, 170]$, where the value 170 is the total of three segments 60, 10, 90 and 10 m.

For our numerical test, we take $p_{\text{tank}} = 100{,}000$ Pa and $p_{\text{right}} = 0$. The propagation speed of pressure wave is $c = 1{,}500$ m/s. The standard water density is taken as $\rho = 1{,}000$ kg/m^3. The initial pressure in the pipe is considered to be the same as the pressure in the tank, that is, $p(x,0) = p_{\text{tank}}$. The initial velocity of water flowing in the pipe is varied and we investigate the effect of such variation to the system.

We present the results for various values of initial velocity in Table 1. In this table we have four scenarios, where the initial velocity is varied by four times a previous value. The first scenario takes the initial velocity $u(x,0) = 0.5$ m/s. The second, third and fourth take $u(x,0) = 1, 8, 32$ m/s respectively. As written in Table 1, the p order is approximately 1. This means that the varying initial velocity is in linear relationship with the maximum pressure hitting the closing valve. In addition, the u order is about 0.5. This means that the varying initial velocity is in square-root relationship with the velocity hitting the closing valve. We infer that the initial velocity influences the pressure hitting the closing valve significantly.

Table 1: The pressure and velocity hitting the valve. Here $t_{\text{stop}} = 0.1$ and $N = 10{,}000$.

Initial velocity	Results for the pressure		Results for the velocity	
	p_N	p order	u_N	u order
0.5	8.2488×10^5	-	0.0167	-
2	3.0508×10^6	0.9435	0.0328	0.4869
8	1.2001×10^7	0.9879	0.0657	0.5011
32	4.7902×10^7	0.9985	0.1319	0.5027

Another result to note is about the numerical method itself. Our numerical experiments show that the finite volume method described in this paper is simple and easy to implement. In addition the method is stable and very robust in solving the water hammer problem.

Summary

Investigation of fast transient flows has been done. We obtain that the higher the initial velocity of the pipe flow leads to the higher the pressure hitting the closing valve. Based on the considered mathematical model, the relationship between the initial velocity and the pressure hitting the closing valve is linear. If we increase the initial velocity to be four times a benchmark initial velocity, then the maximum pressure hitting the closing valve will be four times the pressure of the benchmark problem. These research results may be used to prepare valves for pipe systems, so that valves have enough strength to stop pipe flows periodically. The preparation may correspond to the material used in the valve, the structure of the valve and the installation of the valve into the pipe.

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