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The hydraulic hammer effect in solar tower fluid circuit temperature controller ⋆

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Abstract: This article addresses the possible occurrence of hydraulic hammer effects in solar power towers and the limitations they impose on the response bandwidth of the control loop that governs the valve actuating on heating fluid flow. The partial differential equations that model the traveling waves associated to the hammer effect are solved with different methods. A finite dimensional approximation of the exact solution, by a transfer function with a finite number of poles is obtained. It is concluded that, for the speed of response of the temperature controller associated to the valve, there is no danger of inducing hydraulic hammer effects that can damage the equipment.

Keywords: Power plants, constraint and security monitoring and Control, solar plants, hammer effect, modelling of infinite dimensional systems.

1. INTRODUCTION

The hydraulic hammer (HH) is a phenomena that develops in closed pipes and consists of multiply reflected traveling pressure waves when the fluid flow is suddenly interrupted by an obstacle, such as a closing control valve. This work addresses the possible occurrence of hydraulic hammer effects in solar power towers and the limitations they impose on the response bandwidth of the control loop that governs the valve actuating on heating fluid flow.

1.1 Literature Review

Due to its practical importance for different kinds of plants, the hydraulic hammer (HH) effect has been the subject of a wide literature. Although there are no published references that specifically concern solar thermal plants, much of the available results may however be applied to this case.

In Ghidaoui *et al.* (2005) a comprehensive overview of both historical developments and present day research and practice in the field of hydraulic transients is presented. The classic analysis of the pressure wave propagation after sudden valve closure (hydraulic hammer), using the Newton Law, is treated in Fluid Mechanics introductory books like Jović (2013) and Nakayama (1998). Recent fluid mechanics advances in unsteady pipe flow friction modeling and hydraulic-hammer wave attenuation, shape and timing are treated for instance in Bergant *et al.* (2001), Bergant *et al.* (2008) and Bergant *et al.* (2008b). A recent Ph. D. thesis Kim (2012) solves hydraulic hammer hyperbolic partial differential equations by the method of characteristics and compares these solutions with the results obtained in an experimental apparatus, in studies on dynamics of unsteady pipe flow involving backflow prevention assemblies.

Rigorous physical model solutions obtained from coupled hyperbolic partial differential equations using transfer functions for infinite dimensional systems and complex analysis theory can be found in Litrico *et al.* (2009) and Curtain *et al.* (2009).

In the same line of research of the present paper, Provenzano (2015) reports the use of an analytical algorithm for solving the unsteady, one dimensional, hydraulic hammer model, claiming that it allows to estimate the instantaneous head at any point of a single pipeline. The so called general expression for the pressure (in time along the pipe) is included, without proofs or references.

1.2 Fluid control valve in solar towers

Figure 1 shows a simplified schema of the solar power plant considered, with emphasis on the molten salt circuit. The objective of the plant is to capture solar energy in a heat transfer fluid (such as molten salt) and to store it in thermal form in a tank from where it can be extracted to feed a steam generator that is connected to a conventional turbo-generator to produce electrical power. For that sake, the molten salt fluid is taken from a cold storage tank and pumped through a flow control valve and the tower receiver, where its temperature is increased due to the concentrated sun radiation, after which it is stored in a hot tank. The molten salt fluid is extracted from the hot tank, passes through the steam generator and goes to the cold tank. The salt valve is driven by a flow controller that

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adjusts the salt flow such as to keep the salt temperature at the receiver outlet close to the desired level. In the plant considered, the fluid flow is forced by a constant velocity pump and the flow is changed by a control valve. If the rate of change of the valve is too high, the phenomena known as hydraulic hammer (HH) may be induced.

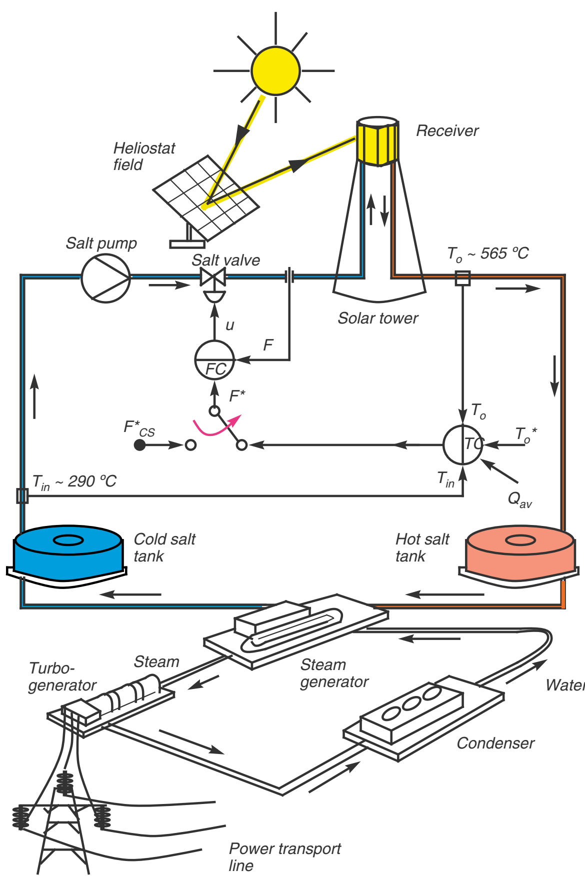

Fig. 1. Simplified $P\&I$ diagram of the molten salt circuit in a solar tower plant.

2. THE HYDRAULIC HAMMER EQUATIONS

The hydraulic hammer effect is a pressure traveling wave caused when a fluid (usually a liquid but sometimes also a gas) in motion is forced to stop or change direction suddenly (momentum change). A hydraulic hammer occurs when a valve closes suddenly at an end of a pipeline system, causing a pressure rising wave that propagates in the upstream current fluid and along the pipe. This paper is devoted to a quantitative analysis of the hydraulic hammer effect, in particular for the molten salt circuit used on solar power towers.

Let t (s) denote time and x (m) denote the position along the pipe. The hydraulic hammer effect can be simulated by solving the following partial differential equations Ghidaoui *et al.* (2005)

$$\frac{\partial p}{\partial t} + \rho c^2 \frac{\partial v}{\partial x} = 0, \quad \frac{\partial v}{\partial t} + \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{f}{2D} v|v| = 0, \tag{1}$$

where p is the pressure inside pipe, v is the fluid velocity, ρ is the fluid density, assumed to be constant, D is the pipe internal diameter $B = \rho c^2$ is the equivalent bulk modulus and f is the friction factor. The steady-state is given by

Table 1. Model parameters.

Parameter	Value	Units
L	20	m
D	0.1	m
ρ	1000	Kg/m^3
f	0.03	-
c	1200	m^3/s
P_0	0.2	MPa
V_L	2.0	m^3/s

$$\frac{\partial v}{\partial x} = 0, \quad \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{f}{2D} v|v| = 0. \tag{2}$$

Choosing $v(L,t) = V_L$ and $p(0,t) = P_0$ as boundary conditions it yields

$$v_{ee}(x) = V_L p_{ee}(x) = P_0 - \rho \frac{f}{2D} V_L^2 x. \tag{3}$$

In conclusion, solving equations (1) for a sudden change in the fluid velocity at the pipe end, $v(L,t)$ boundary condition, it is possible to predict the pressure wave in the fluid. In general, approximate solutions are found numerically, although in some particular cases an exact analytical solution can be derived.

3. NUMERICAL SOLUTION

Equations (1) can be solved numerically Jović (2013) using a space semi-discretization approach that leads to the following set of ODEs when the pipe is divided in N identical sections, with $\Delta x = \frac{L}{N}$,

$$\begin{bmatrix} \dot{p} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} 0 & A_{12} \\ A_{21} & 0 \end{bmatrix} \begin{bmatrix} p \\ v \end{bmatrix} + B \begin{bmatrix} P_0 \\ V_L \end{bmatrix} + \begin{bmatrix} 0 \\ F(v) \end{bmatrix}, \tag{4}$$

with

$$p = \begin{bmatrix} p_1 \\ p_2 \\ \vdots \\ p_N \end{bmatrix}, \quad v = \begin{bmatrix} v_0 \\ v_1 \\ \vdots \\ v_{N-1} \end{bmatrix} \text{ and } F_i = -\frac{f}{2D} v_i|v_i|. \tag{5}$$

Matrices $A = \begin{bmatrix} 0 & A_{12} \\ A_{21} & 0 \end{bmatrix}$ and B are written from the following finite approximation for space derivatives

$$\dot{p}_i = -\rho c^2 \frac{(v_i - v_{i-1})}{\Delta x} \quad (i = 1, \ldots, N), \tag{6}$$

and

$$\dot{v}_i = -\frac{1}{\rho}\frac{(p_{i+1} - p_i)}{\Delta x} - \frac{f}{2D} v_i|v_i| \quad (i = 0, \ldots, N-1), \tag{7}$$

yielding $2N$ ODEs that can be solved numerically.

Consider the example given by table 1. In alternative, a Non-oscillatory Central Differencing schemes like MUSCL may be utilized to avoid spurious oscillations in the solution when discontinuities are present Shampine (2005). Figure 2 shows a normalized pressure wave that is useful to compare with different computational methods.

The main point to remark here is the occurrence of a fast oscillation that occurs at each transition of the pressure