Two-phase flow model for energetic proton beam induced pressure waves in mercury target systems in the planned European Spallation Source

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Abstract. Two-phase flow calculations are presented to investigate the thermo-hydraulical effects of the interaction between 2 ms long 1.3 GeV proton pulses with a closed mercury loop which can be considered as a model system of the target of the planned European Spallation Source (ESS) facility. The two-fluid model consists of six first-order partial differential equations that present one dimensional mass, momentum and energy balances for mercury vapor and liquid phases are capable to describe quick transients like cavitation effects or shock waves. The absorption of the proton beam is represented as instantaneous heat source in the energy balance equations. Densities and internal energies of the mercury liquid-vapor system is calculated from the van der Waals equation, but general method how to obtain such properties using arbitrary equation of state is also presented. A second order accurate high-resolution shock-capturing numerical scheme is applied with different kind of limiters in the numerical calculations. Our analysis show that even 75 degree temperature heat shocks cannot cause considerable cavitation effects in mercury.

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1 Introduction

A well-known non-destructive material research method is neutron scattering. Free neutrons for neutron beams for research purposes need to be extracted from their bound states of atomic nuclei. Energetic neutron beams can be produced in fission of heavy elements (e.g. \textsuperscript{235}U) or by spallation. In fission of \textsuperscript{235}U 190 MeV heat is released for each extracted fast neutron while in the spallation process only about 30 MeV heat is deposited per fast neutron. The deposited heat has to be removed by cooling and it ultimately becomes a limiting thermodynamic factor for the amount of neutrons produced. As a second distinct advantage of pulsed spallation sources over continuous ones is that a larger part of the neutrons produced can be delivered to the sample in monochromatic beams. These two advantages of spallation sources make it possible to construct more powerful neutron sources with larger neutron flux than ever before. The simple goal of the planned European Spallation Source (ESS) is to provide Europe with the most powerful neutron facility. A choice of a 5 MW proton beam power at 1.3 GeV proton energy with 111 mA proton beam current and with 16.66 Hz repetition rate of 2 ms long neutron pulses will produce an average thermal neutron flux density of \(3 \times 10^{14}\) n/cm\(^2\)s in the ESS mercury target. A detailed analysis of the planned ESS can be found elsewhere \cite{1}. This sudden proton pulse causes a thermal and a pressure shock in the target which may cause cavitation or tensile stress.

The question of cavitation erosion \cite{2} has crucial importance in the constructional planning of any spallation neutron source target facility. Research groups in Japan and in the United States performed various experimental (both in-beam and off-beam) and theoretical investigations \cite{3,4} to overcome this difficulty.

In the following study we present and analyze a one dimensional six-equation two-fluid model which is capable to describe transients like pressure waves, quick evaporation or condensation which is proportional to cavitation caused by energetic proton interaction in mercury target.

Our model has a delicate numerical scheme and capable to capture shock waves and describe transient waves...

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which may propagate quicker than the local speed of sound [5]. Most of the two-phase models have numerical methods which describes usual flow velocities much below the sonic conditions.

Our model can successfully reproduce the experimental data of different one- or two-phase flow problems such as ideal gas Riemann problem, critical flow of ideal gas in convergent-divergent nozzle, column separation or cavitation induced water hammer, rapid depressurization of hot liquid from horizontal pipes or even steam condensation induced water hammer [6].

According to our knowledge there is no real two-phase flow calculation for mercury flow system. Some timorous attempts were presented with the help of some commercial three dimensional industrial codes like Fluent or ANSYS [7,8] but the results are questionable. Some commercial three dimensional industrial codes like Fluent or ANSYS [7,8] but the results are questionable. Some results show complete and immediate vaporization during external magnetic fields into account [9] but consider sinuson collider mercury target. These studies takes strong cal simulation of magnetohydrodynamic processes in the for sudden heat shocks.

There are study for three dimensional numerical simulation of magnetohydrodynamic processes in the muon collider mercury target. These studies takes strong external magnetic fields into account [9] but consider single phase only neglecting evaporation or condensations. The liquid phase of mercury was modeled using the stiffened poltropic equation of state and the vapor phase was considered to be ideal gas. There is a literature survey on various fluid flow data for mercury from the politropic equation state [10] which can be directly applied in calculations. There are also different equation of states (EOS) available for mercury from microscopic molecular simulation [11,12] of from macroscopic theories like virial expansion [13] or from generalized van der Waals equation like the Redlich-Kwong equation [14] or the like [15]. Thermodynamical and flow properties of other liquid metals are also in the focus of recent scientific interest [14,16].

In the next sections we introduce our applied model, give a detailed analysis about phase transitions and present our pressure wave results with comparison to other studies [3,4].

2 Theory

2.1 Theory of two-phase flow

There is a large number of different two-phase flow models with different levels of complexity [17,18] which are all based on gas dynamics and shock-wave theory. In the following we present our one dimensional six-equation equal-pressure two-fluid model. The density, momentum and energy balance equations for both phases are the following:

\[
\frac{\partial A(1-\alpha)\rho_l v_l}{\partial t} + \frac{\partial A(1-\alpha)\rho_l v_l(v_l - w_l)}{\partial x} = -A\Gamma_g, \tag{1}
\]

\[
\frac{\partial A\alpha p_l}{\partial t} + \frac{\partial A\alpha p_l v_l(v_l - w_l)}{\partial x} = A\Gamma_g, \tag{2}
\]

\[
\frac{\partial A(1-\alpha)\rho_l v_l}{\partial t} + \frac{\partial A(1-\alpha)\rho_l v_l(v_l - w_l)}{\partial x} = -A\Gamma_g, \tag{3}
\]

\[
\frac{\partial A\alpha p_l}{\partial t} + \frac{\partial A\alpha p_l v_l(v_l - w_l)}{\partial x} = A\Gamma_g, \tag{4}
\]

\[
\frac{\partial A(1-\alpha)\rho_l v_l}{\partial t} + \frac{\partial A(1-\alpha)\rho_l v_l(v_l - w_l)}{\partial x} + \frac{\partial A(1-\alpha)\rho_l v_l v_l}{\partial t} + A\Gamma_g = A\alpha p_l \cos \theta - A\Gamma_{g,wall}, \tag{5}
\]

\[
\frac{\partial A\alpha p_l}{\partial t} + \frac{\partial A\alpha p_l v_l(v_l - w_l)}{\partial x} + \frac{\partial A\alpha p_l v_l v_l}{\partial t} + A\alpha p_l \cos \theta + E_{I,wall}(x,t) = A\alpha p_l \cos \theta - A\Gamma_{g,wall}, \tag{6}
\]

Index l refers to the liquid phase and index g to the gas phase. Nomenclature and variables are described in Table 1. Left hand side of the equations contain the terms with temporal and spatial derivatives. Hyperbolicity of the equation system is ensured with the virtual mass term $CVM$ and with the inter-facial term (terms with $\Gamma$) known for mercury.

\[
Nu = \max\{4, (1/8)(Re - 1000)Pr)/(1 + 12.7\sqrt{f_k/8}
\times(P_r^{0.67} - 1))\} \tag{7}
\]

to the Subbotin [19] correlation

\[
Nu = 7 + 0.025Pe^{0.8}, \tag{8}
\]

which is well established for liquid metals. Where Nu is the Nusselt, Pr is the Prandt, Re is the Reynolds and Pe is the Péclet number, $f_k$ is the heat diffusivity. Unfortunately, there are no more correlations (like bubble drag coefficients) known for mercury.