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Characteristics of laminar MHD fluid hammer in pipe

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ABSTRACT

As gradually wide applications of MHD fluid, transportation as well as control with pumps and valves is unavoidable, which induces MHD fluid hammer. The paper attempts to combine MHD effect and fluid hammer effect and to investigate the characteristics of laminar MHD fluid hammer. A non-dimensional fluid hammer model, based on Navier–Stocks equations, coupling with Lorentz force is numerically solved in a reservoir–pipe–valve system with uniform external magnetic field. The MHD effect is represented by the interaction number which associates with the conductivity of the MHD fluid as well as the external magnetic field and can be interpreted as the ratio of Lorentz force to Joukowsky force. The transient numerical results of pressure head, average velocity, wall shear stress, velocity profiles and shear stress profiles are provided. The additional MHD effect hinders fluid motion, weakens wave front and homogenizes velocity profiles, contributing to obvious attenuation of oscillation, strengthened line packing and weakened Richardson annular effect. Studying the characteristics of MHD laminar fluid hammer theoretically supplements the gap of knowledge of rapid-transient MHD flow and technically provides beneficial information for MHD pipeline system designers to better devise MHD systems.

1. Introduction

Magnetohydrodynamic (MHD) flows, whose fluid is conductive and controllable by external magnetic field, have abundant applications such as MHD generator [1–3], fluid journal bearings [4], and MHD motor [5] so they have attracted wide ranges of researches all over the world for technological and theoretical interests. The fluid motion and electromagnetic field interact with each other and depend on each other in the flow region, which is a complex process. The motion of MHD fluid interacts with the external magnetic field and generates Lorentz force which affects the fluid motion in reverse. Consequently different characteristics appear compared with that of traditional flow. Ramos et al. simulate laminar MHD pipe flows in Ref. [6], in which velocity profiles and friction factor influenced by different magnetic parameter as well as flow respond under an oscillating magnetic field are discussed. Hussam et al. simulate a MHD flow pass a circular cylinder positioned offset from the duct centerline with high Hartmann number in Ref. [7]. How the vortex structure and heat transfer are influenced by the positon of the circular cylinder and by Reynolds number is elaborately discussed. In Ref. [8], three-dimensional simulations are conducted to figure out the influences of magnetic obstacle on fluid flow and heat transfer with various constrainment factors, Reynolds numbers and interaction parameters. In Refs. [9,10], characteristics of MHD turbulent flows are cautiously discussed by large-eddy simulation and direct numerical simulation respectively. Rheological characteristics [4,11], free surface [12,13] and linear stability [14,15] of MHD flow are discussed as well. Ref. [16] considers a special MHD pipe flows where the fluids both inside and outside the pipe are electrically conductive. The characteristics of fluid and electromagnetic fields of MHD flow with power extraction are recently three-dimensionally simulated and discussed in detailed [17]. Steady energy structure of MHD flow is also provided and discussed in Ref. [18]. Unsteady MHD free convection flows coupling with heat and mass transfer in a porous medium are analytically studied with the help of Laplace transform technique in Refs. [19–23] where an easily-access simplified Lorentz force is provided. As stated above, details of fluid field and electromagnetic field of MHD flow under various conditions have been considered in previous literatures. However, most considerations are under steady state or relatively tardy transient state. Rapid-transient fluid motions such as MHD fluid hammer are seldom reported. Although Walker [24,25] provides the concept of MHD fluid hammer and analytically solves the MHD equations for rectangular duct, viscosity of the fluid is absent and discussions of the characteristics of MHD fluid hammer are not adequate.

Fluid hammer is another topic with both technological and scientific values. It is usually caused by sudden closure of valve, pump start up or shut down, or any other rapid change of flow conditions and it propagates rapidly at the acoustic speed of fluid, which as a result usually induces large pressure gradient and

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Nomenclature

Variables

H	pressure head in MHD flow
$\bar{H}$	non-dimensional pressure head in MHD flow
u	axial velocity
$\bar{u}$	non-dimensional axial velocity
V	average velocity on cross section
V_0	initial average velocity on cross section
$\bar{V}$	non-dimensional average velocity on cross section
B_0	strength of external magnetic field
a	acoustic velocity
L	length of the pipe
D	diameter of the pipe
R	radius of the channel
ρ	mass density of MHD fluid
μ	dynamic viscosity of MHD fluid
σ	conductivity of MHD fluid

Parameters

ξ	length/diameter ratio
Ma	Mach number
Re	Reynolds number
M	interaction number

invalidates the pipeline system. As gradually wide ranges of applications of MHD fluid, MHD fluid hammer is unavoidable and understanding its characteristics is desired. Traditionally, fluid hammer is called water hammer because the fluid considered is Newtonian without any momentum sources except gravitation. Various researches on water hammer have been done. Quasi-one-dimensional model [26] is a historical and popular model to describe water hammer. Lots of numerical methods designed for it are kept proposing [27–29] and some recent water hammer researches are still based on it [30–32]. The quasi-one-dimensional model is capable of predicting the first pressure jump while it is unable to predict the attenuation because the steady state friction law is inappropriate. Zielke [33] put forward a corrective friction law which is greatly effective. More detailed improvements of friction laws for quasi-one-dimensional model are introduced in review paper [34]. Another weakness of quasi-one-dimensional model is that it provides limited information of fluid field. So quasi-two-dimensional models and related numerical schemes are proposed [35–38], which have achieved great successes in both laminar and turbulent regimes. More information such as velocity profile and shear stress profile are able to be indicated. Instead of using algebraic turbulent model, $k - \varepsilon$ and $k - \omega$ turbulent models are coupled with quasi-two-dimensional model to investigate more details about turbulent water hammer [39–41]. Wahba proposes an accessible numerical scheme for quasi-two-dimensional model [42] and conducts a series investigation about fluid hammer including attenuation, comparisons of turbulent models, viscous dissipation and non-Newtonian fluid hammer [43–46]. These literatures provide inspirations for modeling MHD fluid hammer and numerical schemes for rapid-transient flow.

In order to theoretically supplement the gap of knowledge of rapid-transient MHD flow and to technically provide beneficial information for MHD pipeline system designers to better devise MHD systems, MHD laminar fluid hammer is numerically studied in this article in a reservoir–pipe–valve system with homogeneous external magnetic field. It should be noted that the flows considered are laminar and Newtonian. In addition, the interaction number M, which is defined and interpreted in Section 2, is the key parameter in discussions, representing the strength of Lorentz force as well as MHD effect. The arrangement of the article is provided. In Section 2, the definition of the flow is illustrated and the problem as well as the governing equations is stated in detailed with some reasonable assumptions. In Section 3, the implemented numerical schemes and numerical settings are introduced and validated. In Section 4, the numerical results of laminar MHD fluid hammer such as pressure head, average velocity, wall shear stress, velocity profiles and shear stress profiles are provided. The cases discussed are divided into three categories and some characteristics of MHD laminar fluid hammer are discovered. Possible explanations of such phenomena are also provided by comparing different cases and analyzing fluid fields.

2. Problem statement and governing equations

A classical reservoir–pipe–valve system with external magnetic field, shown in Fig. 1, is considered. The coordinate system is cylindrical, installed at the pipe axis and located at the entrance of the pipe. A reservoir is located at the inlet of the pipe, which provides a time-invariant pressure head H_{re}. A valve is placed at the outlet of the pipe and its sudden closure induces MHD Fluid Hammer. The pipe is horizontal with homogeneous circular cross section, whose length and diameter are L and D respectively. The pipe wall is assumed to be tough enough and the pipe is well-fixed so that the variances of its cross section and length are negligible. An external magnetic field is applied along the pipe with a constant strength B_0 and a direction perpendicular to the pipe axis. The interaction between MHD fluid motion and external magnetic field induces magnetic force or equivalently Lorentz force which, in reverse, affects the fluid motion.

In cases of laminar pipe flow, a quasi-two dimensional model, which is provided in Ref. [37], is appropriate to describe the fluid transient motion in pipe. Some common approximations have been made, which are (a) that the fluid flow is axisymmetric, (b) that the lateral or radial velocity component is negligible and (c) that boundary layer approximation is applied, resulting in zero gradient of pressure head in radial direction. The lateral velocity component has been calculated by Vardy et al. [36] and the results indicate that lateral velocity component is approximately four orders of magnitude smaller than axial velocity component. The validation of this quasi-two dimensional model has been done in Ref. [45] by comparing its numerical results with the experimental data of Holmboe and Rouleau [47] and of Brunone et al. [48] and with the numerical results of Vardy et al. [36]. In addition, the fluid considered in this article is Newtonian. In order to compute the interaction between fluid motion and external magnetic field, Lorentz force is added in the axial momentum equation as a momentum source. Consistent with the boundary layer approximation in the quasi-two dimensional fluid hammer model, the

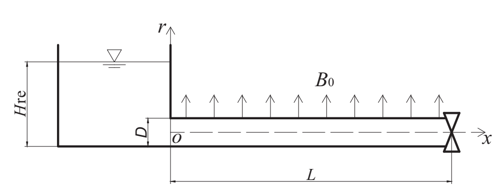

Fig. 1. The physical model of MHD fluid hammer.