MHD supersonic flow control: OpenFOAM simulation

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Abstract. MHD flow control is a relevant topic in today's aerospace engineering. An OpenFOAM density-based solver that is capable of handling MHD supersonic flow problems with constant magnetic field is developed. The proposed solver is based on Balbas-Tadmor central difference schemes. This solver can be applied to studying the potential of MHD flow control systems for atmospheric entry vehicles. A supersonic flow around a spherically blunt cone both with and without MHD interaction is studied. Gases with thermodynamic parameters characteristic for Earth's and Martian atmospheres are considered. The results show visible effect of magnetic field on surface temperature of the body. The differences between shock standoff distances and general shockwave configurations of MHD and non-MHD flow are also apparent. The solution is stable for Stuart number below 0.2. Conditional instability of the solver can be attributed to the MHD term's contribution to the local speed of sound and can be avoided by taking it into account. The developed application has proven the suitability of the used schemes for resolving steep gradients in MHD supersonic flow problems. The study itself has shown theoretical possibility of studying the MHD flow control using OpenFOAM. Further research may include an effort to stabilize the solver and to enhance the mathematical model of the flow.

Keywords: magnetohydrodynamics, finite volume method in fluid dynamics, supersonic flows, numerical simulations, shock waves in fluid dynamics

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1. Introduction

Non-mechanical ways to control the bow shock is a relevant problem in today's aerospace engineering. Heavy dynamic and thermal loads that affect the aircrafts and space vessels during atmospheric reentry or traveling with a supersonic velocity can cause severe damage and even destruction. Aerodynamic form of probes and vessels can help minimize the damaging effects, but mere mechanical means are not

always sufficient. Different approaches to solve these problems were proposed over the years, one of the most promising of which is magnetohydrodynamic (MHD) flow control. The idea behind it is using a generated magnetic field that would interact with ionized gas in front of the vehicle and alter the flow around it in such a way that the aerodynamic heating and stress effects are diminished. This concept has many applications, such as MHD heat shield [1] or non-mechanical flight trajectory control systems [2]. A sufficient degree of ionization can be achieved both naturally by heating of the gas, or artificially, using electron beam [3] or similar system. Since experiments, involving this kind of apparatus is extremely expensive, mathematical modeling becomes an important research tool. Commercial CFD packages often lack proper instruments, extensibility and flexibility required to model such a phenomenon. That's why we opted to use OpenFOAM numerical simulation platform. We set to numerically investigate the supersonic around the body with magnetic interaction, for which a new solver needs to be developed. If developed successfully, such a solver can prove useful for any research related to MHD supersonic flow.

2. Physical formulation

We investigate the flow around a spherically blunted cone. This shape is characteristic for various reentry vehicles as it provides flight stability with relatively low aerodynamic heating. We do not include an afterbody of any kind into our geometry, since the region of interest for us is in the front, where magnetic interaction takes place. Cone base has a radius of 1m, and its vertex is spherically blunted with a curvature radius of 10 cm. The field generating coil is located in the frontal part of the body and is set to generate a magnetic field of 1 Tesla directly in front of the body. The opening angle of the cone is 120 degrees.

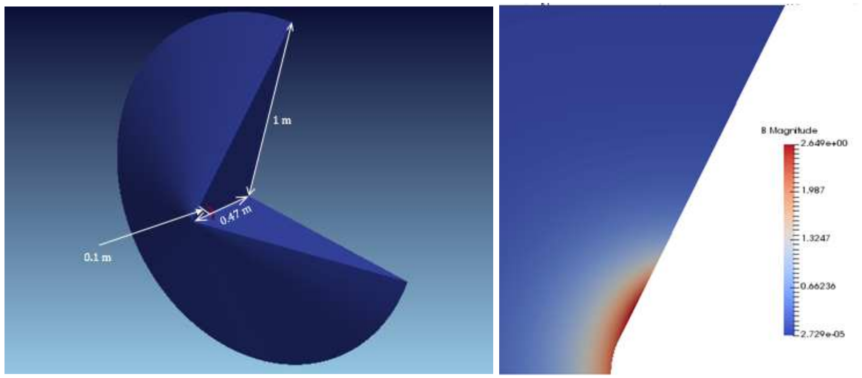

Fig. 1. The geometry of the body with a section removed (left) and the distribution of the magnetic field (right).

Thermophysical properties of the surrounding gas correspond to those of upper and mid layers of Earth and Mars atmosphere. The table below (tab. 1) shows those properties as well as Mach number corresponding to the velocity of 1000 m/s in each case. Values for Martian atmosphere were taken from [4]. Atmospheric properties of the 2 planets differ dramatically, so the pressure on the same altitude can be a hundred times higher on the Earth than it is on the Mars. The velocity of incoming flow is ranging between 1000 and 2000 m/s, so that the Mach number is between 3 and 5. The electrical conductivity of the gas is set to be constant, it's value - 80 $Ohm \cdot m$. This value can be realistically obtained by heating, further increase may require an auxiliary ionizing system, such as electron beam. Constant conductivity can be justified by the fact that magnetic field magnitude fades as a square of the distance from the coil, so the conductivity effect far from the body can be neglected.

Tab. 1. Thermophysical parameters

	Earth	***Mars***
Gas	Air	CO_2
Molar weight (g/mol)	28.97	44.01
$\boldsymbol{p_\infty}$**(Pa)**	3000	30
$\boldsymbol{t_\infty}$**(K)**	216.5	190
$\boldsymbol{Mach\|_{u=1000\frac{m}{s}}}$	3.37	4.46

3. Mathematical model

To model the flow we use magnetohydrodynamic (MHD) approximation. The set of governing equations in our case consists of conservation laws for mass, momentum and energy. The equations of electromagnetic field are omitted, since we consider the field to be constant. Low magnetic Reynolds number ($Re_{mag} \ll 1$) allows us to disregard velocity's effect on magnetic field. In our case it is of order 10^{-1}. Knudsen number for the studied flows ranges from 10^{-5} to 10^{-3}, which is well within the area of continuous model applicability. MHD terms values are determined by the generalized Ohm's law and the respective formulas.

$$\boldsymbol{j} = \sigma(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}), \qquad \boldsymbol{F} = \boldsymbol{j} \times \boldsymbol{B}, \qquad \boldsymbol{Q} = \boldsymbol{j} \cdot E.$$

Thus, the MHD system for our case can be written as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla \cdot \left[\rho \mathbf{vv} + \left(p + \frac{1}{2}B^2\right) I_{3\times3} - \mathbf{BB}\right] = 0,$$

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho v^2 + \rho e + \frac{1}{2}B^2\right) + \nabla \cdot \left[\left(\frac{1}{2}\rho v^2 + \rho e + p + B^2\right)\mathbf{v} - \mathbf{v} \cdot \mathbf{BB}\right] = 0.$$

3.1 Case geometry and boundary conditions

We take the advantage of the cylindrical symmetry of our problem and pose it in 2 dimensions. In OpenFOAM this can be achieved by making the computational domain a sector of a cylinder and setting "wedge" boundary conditions on its' sides. The remaining boundary conditions are "outlet" and "inlet" for the respective surfaces, "zeroGradient" condition for upper boundary and a specific set for the surfaces representing the body. Velocity condition on the body surface is "slip". Temperature condition on this boundary may vary, since we try to estimate the heat flux towards the body without knowing in thermophysical properties. We opted to set flux conditions rather than temperature. This way we can estimate the flux between the body and surrounding gas by the resulting temperature.

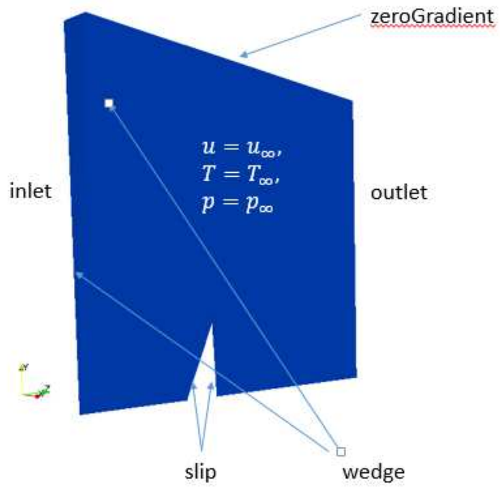

Fig. 2. Computational domain shape and boundary conditions

4. Solver development

OpenFOAM has a considerable range of capabilities in modeling the hypersonic flow, however not all of them are viable for our case, even without the imposed magnetic field. Pressure-based solvers like sonicFOAM tend to have so called overshoots in the solution they provide for pressure profile between the body and bow shock. The best performing density-based solver is rhoCentralFOAM, however it also has its issues, since it requires computational grid to fit no less than about 30 cells into the aforementioned layer between the bow shock and the body to properly calculate its parameters.

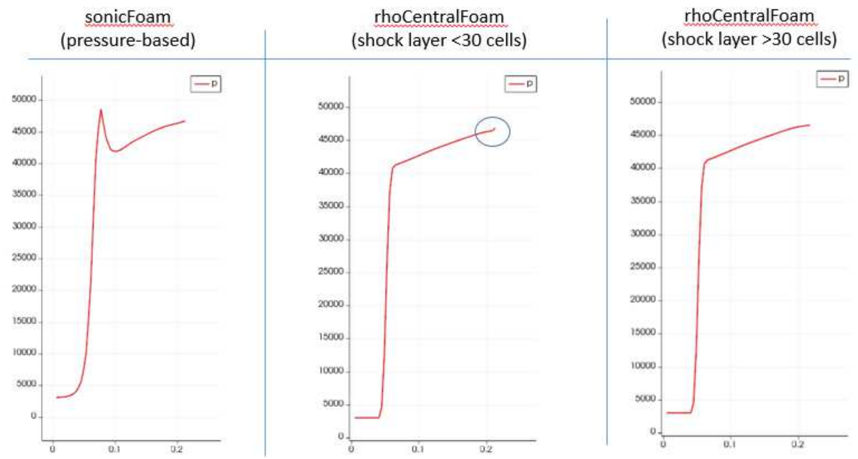

Fig. 3. Standard OpenFOAM solvers capabilities in resolving bow shock

Attempts have been made in the past to develop an MHD solver for OpenFOAM, some of which were relatively successful [5]. The proposed solvers, however, are based on outdated now methods and have stability problems.

We developed a solver that can resolve bow shock problems in presence of constant magnetic field by modifying *rhoCentralFoam*. *rhoCentralFoam* uses central difference schemes of Kurganov and Tadmor [6]. Our modification is based on the MHD extension of those schemes, proposed by Balbas and Tadmor [7]. Since there is no need at the moment to add magnetic field equations, we can simply include the MHD terms to the equations that already are in *rhoCentralFoam*, along with the procedures to interpolate and reconstruct the additional fluxes. Balbas and Tadmor schemes are expected to perform well on resolving the steep gradient fields that are characteristic for problems with bow shock.

5. Results

Our developed solver was tested on the problem of MHD controlled flow over the spherically blunted cone. The performance varied depending on the Stuart number: the solver is stable when the Stuart number is below 0.2, instabilities start to occur when it exceeds this value. Distributions of thermodynamical parameters were obtained as a result.

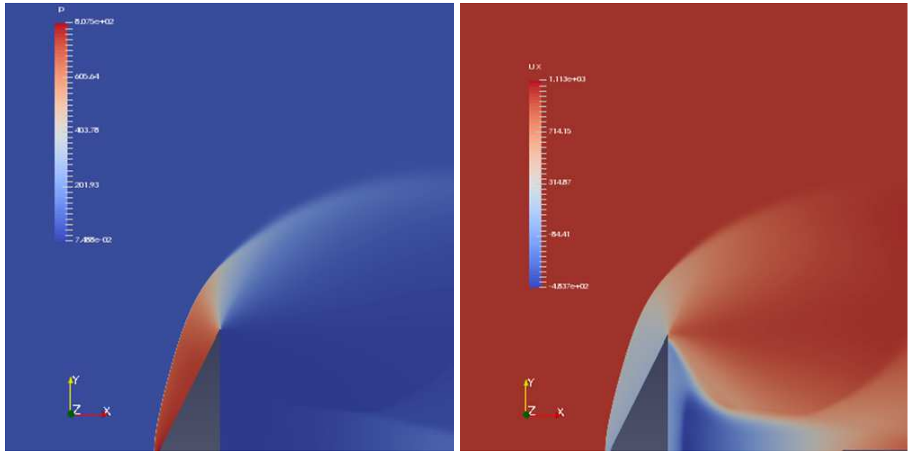

Fig. 4. Pressure (left) and longitudinal velocity (right) calculated for MHD case.

One of the main goals of this research is the development of an OpenFOAM solver that is capable of resolving bow shock with magnetic interaction. Our solver's stability is restricted to the low Stuart number flows, when the Stuart number exceeds 0.2-0.25 in the large region of the domain, the solution tends to diverge.

To illustrate the solvers capabilities and the difference between the MHD and non-MHD flow we considered the temperature and pressure profiles on the front surface of the body. Figures below show the discrepancy between the two cases: the temperature is lowered overall and especially in the regions where the magnetic field magnitude is greatest.

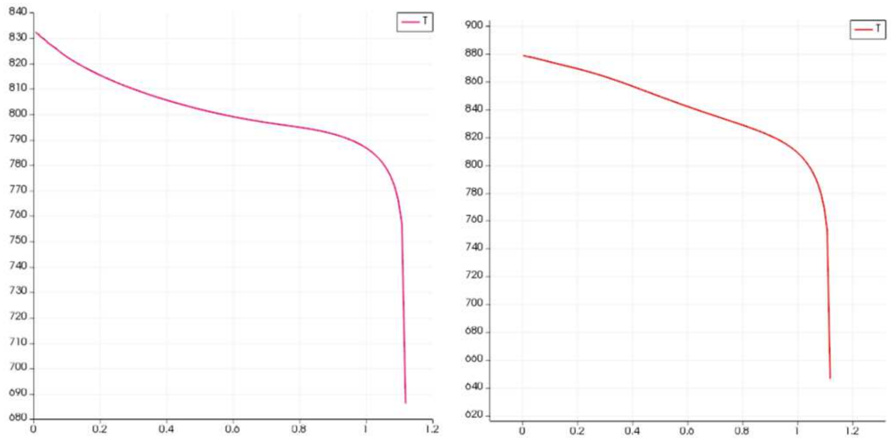

Fig.5. Front surface temperature for MHD (left) and non-MHD (right) flows

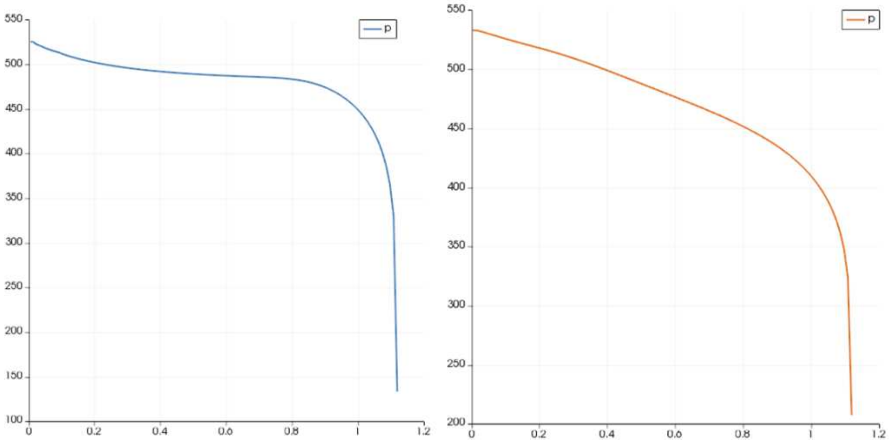

Fig.6. Front surface pressure for MHD (left) and non-MHD (right) flows

Another observed result is an increase of the shockwave standoff distance in presence of the magnetic field. Overall results can be said to be fitting the qualitative theoretical expectations. To compare them quantitatively additional experimental data is required.

Conclusion

We have developed a solver that is capable of resolving the MHD supersonic flow problems with constant magnetic field, such as MHD flow control around a blunted body, within the limited range of Stuart numbers. The results can be considered as a proof of suitability of Balbas-Tadmor schemes for simulation of the MHD supersonic flow. Further research should include the enhancement of the solver: widening the range of problems it can be applied to and improvement of its stability. Other approaches to the solution of MHD problems (mainly Godunov-type schemes) should also be considered. Finally, further investigation into the phenomenon will require developing an OpenFOAM thermophysical model that includes the relevant properties, such as conductivity and ionization.

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Численное моделирование МГД управления сверхзвуковым потоком в среде OpenFOAM

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Аннотация. МГД управление сверхзвуковым потоком является важной проблемой в современных аэрокосмических исследованиях. На основе центральных разностных схем Балбаса и Тадмора был разработан OpenFOAM-солвер, способный решать задачи моделирования сверхзвукового МГД потока. С его помощью была решена задача обтекания твердого тела в форме сферически затупленного конуса. Получаемое решения оказывается устойчивым для потоков с числом Стюарта не более 0.2. В дальнейшем планируется улучшение устойчивости солвера и совершенствование математической модели.

Ключевые слова: магнитная гидродинамика, сверхзвуковые течения, численное моделирование, метод конечных элементов в гидрогазодинамике, численное моделирование, ударные волны в газодинамике.

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