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Research Article

On the Effects of Viscosity on the Shock Waves for a Hydrodynamical Case—Part I: Basic Mechanism

Huseyin Cavus

Physics Department, Arts & Science Faculty, Canakkale Onsekiz Mart University, 17100 Canakkale, Turkey

Correspondence should be addressed to Huseyin Cavus; h_cavus@comu.edu.tr

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The interaction of shock waves with viscosity is one of the central problems in the supersonic regime of compressible fluid flow. In this work, numerical solutions of unmagnetised fluid equations, with the viscous stress tensor, are investigated for a one-dimensional shock wave. In the algorithm developed the viscous stress terms are expressed in terms of the relevant Reynolds number. The algorithm concentrated on the compression rate, the entropy change, pressures, and Mach number ratios across the shock wave. The behaviour of solutions is obtained for the Reynolds and Mach numbers defining the medium and shock wave in the supersonic limits.

1. Introduction

Shock waves are rather common phenomena in the supersonic flows of any fluid. They arise in many areas that are related with hydrodynamics such as fluid mechanics, aerodynamics, astrophysics, solar physics, and space physics. If a medium is shocked, particles behind the shock front experience both compressive and shear forces. They push the particles away from their original equilibrium positions.

Shock waves are studied by many authors. Somow and Spector [1] studied the basic mechanisms of the hydrodynamic shocks in the solar atmosphere during flares. Effects of inhomogeneities in solar wind plasma on the interplanetary shock waves are also studied by Heinemann [2]. Their observational studies are given in the work of De Lucas et al. [3]. Magara and Shibata [4] worked on the formation of shock waves due to plasma ejections in the solar atmosphere. Khidr and Mahmoud [5] obtained results for the case of an arbitrary Prandtl number in strong shock waves, using a modified power law for viscosity in terms of temperature and Mach number. Kuznetsov [6] studied the stabilities of shock waves in hydrodynamic discontinuities and flows in the relaxation zone. On the other hand, Hamad and El-Fayes [7] studied the entropy change for the structure of inviscid plasma by neglecting viscosity in the gas phase. Compression rate in bow shocks was studied by Kabin [8], and the Euler equations for a one-dimensional hydrodynamic model were considered [9]. In a more recent study, Swift et al. [10] derived expressions for shock formation, based on the local curvature of the flow characteristics during dynamic compression.

Motion occurs in a continuous medium because of some external causes like pressure gradients and body forces; this way, the fluid velocity distribution becomes inhomogeneous in general. In consequence, resistance to variations in the distribution of cohesive forces in fluids may such come into play to remove inhomogeneities in velocities. Such resistive effects produce the phenomenon of viscosity in fluid motions [11]. Therefore, viscosity, which measures the resistance of a fluid system as a function of velocity, should also be taken into account as one of the most important effects in the equations of motion. For the shock heating of solar corona, Orta et al. [12] obtained that the shock thickness and profile depend on the viscosity and resistivity, and heating ultimately occurs because of them. Dispersive shock waves were studied by Ballai et al. [13]. They showed that dispersion will alter the amplitude and propagation speed of a shock wave.

For supersonic flows the coexistence of shock waves with viscous effects produces interesting features. The interaction of viscous effects with a shock wave is a key feature in many fluid dynamics systems [14]. Considerable theoretical and numerical interest should be expressed in the strengthening of a shock wave propagating through a viscous medium. The viscous interactions of a solar wind stream were studied by Korzhov et al. [15] and it was found that the Kelvin-Helmholtz instability is excited due to the presence of shear flows. Coronal mass ejections (CMEs) and solar wind are the main results of the solar activity. These events can drive interplanetary shock waves and produce geomagnetic storms. Study of these events is very important for space weather purposes. The shock waves occur where the solar wind changes from being supersonic (with respect to the surrounding interplanetary medium) to being subsonic. In the supersonic regime of compressible gas flow, the interaction of shock waves with viscosity is one of the central problems. To define such type of shock process, the Navier-Stokes equations should be solved. Mathematically this process can be approximated to a hydrodynamical case.

The Reynolds number is another defining feature of fluid motion. Reynolds, a British scientist, showed that the transition from laminar to turbulent flow is directly related to a dimensionless number defined as the Reynolds number [16]. This dimensionless number gives the relation between inertial and viscous forces in a fluid flow. If the inertial forces are large (the flow rate is high), then the flow will rather occur turbulently. When the viscous forces are large enough compared to the inertial ones, then a laminar fluid flow character will be observed.

The main purpose of this paper is to describe the basic mechanism of the shock wave problem, in which the viscous terms cannot be neglected in deriving the jump relations. To define this type of shock process, the Navier-Stokes equations defining the momentum conservation should be solved. The viscous behaviour of a fluid can be described by using the Reynolds number. The formalism used for a one-dimensional study is explained in more detail in the following section. Solutions are presented in terms of physical parameters such as compression rate, Mach number and pressure ratios, and entropy change across the shock waves. Results will be given in Section 3. Our results are compared with other similar works in Section 4, together with a discussion and conclusion.

2. Physical Formulation of the Problem

2.1. Basic Equations. The basic formulation for unmagnetised plasma is also known as the system of hydrodynamical equations in conservative form. For a compressible viscous shock wave for steady flow, the equations, are [17–19]

$$\int_A \rho u_j n_j dA = 0, \tag{1}$$

$$\int_A \left(\rho u_i u_j + p\delta_{ij} - \tau_{ij}\right) n_j dA = 0, \tag{2}$$

$$\int_A \left(\rho H - \tau_{ij}\right) u_j n_j dA = 0, \tag{3}$$

$$p = \rho \mathrm{RT}. \tag{4}$$

These basic equations to be solved consist of the conservation of the mass (1), the momentum (2), and the energy for adiabatic flow (3) together with the ideal gas law (4). Here ρ, u, dA, n_i, δ_{ij}, τ_{ij}, p, and H denote the density, velocity, infinitesimal surface area, unit normal ($i = 1, 2, 3$), the Kronecker delta, viscous stress tensor, pressure, and the total enthalpy, respectively.

2.2. One-Dimensional Problem. Using these steady viscous flow relations with letting subscript 1 and 2 as the upstream and downstream shock front, respectively, fluid equations can be written for a one-dimensional case (say along x-axes). The Rankine-Hugoniot jump relations [20] can be obtained through (1)–(3). We use the viscous tensor in one dimension as

$$\tau = \tau_{xx} = \frac{4}{3}\mu\frac{du}{dx}, \tag{5}$$

where μ is the dynamic viscosity coefficient. We define the compression ratio, κ, in terms of the upstream and downstream velocities:

$$\frac{u_2}{u_1} = \kappa^{-1}. \tag{6}$$

We can define the Reynolds number, Re, through

$$\mu\left(\frac{du}{dx}\right) \approx \frac{\left(\rho u^2\right)}{\mathrm{Re}}. \tag{7}$$

With the use of (5)–(7) in (1)–(4), we can obtain the equation as follows (after a little algebra):

$$\begin{aligned}&\left[\left(\frac{1}{2} - \frac{4}{3}\frac{1}{\mathrm{Re}_1}\right)(\gamma - 1) M_1^2 + 1\right]\kappa^2 \\ &\quad - \left[\left(1 - \frac{4}{3}\frac{1}{\mathrm{Re}_1}\right)\gamma M_1^2 + 1\right]\kappa + \left(\frac{\gamma + 1}{2} - \frac{4}{3}\frac{1}{\mathrm{Re}_2}\right) M_1^2 = 0.\end{aligned} \tag{8}$$

Here Re_1 and Re_2 are the upstream and downstream Reynolds number, respectively, and M_1 is the value of the upstream Mach number. The last equation is also called the general equation and it can be solved numerically by imposing the appropriate conditions. Since $1 < \gamma < 2$, this equation has just one positive root. Moreover the solution reduces to the inviscid hydrodynamic value for the vanishing values of dynamic viscosity.

2.3. Value of the Downstream Reynolds Number. In order to simplify the problem, the downstream Reynolds number, Re_2, can be expressed as a function of the adiabatic index, Re_1, and M_1 is similar to Bruhn et al. [21]. Figure 1 shows the change of Re_2 with respect to Re_1 for different values of M_1 for the monatomic with gas $\gamma = 5/3$. There is a limitation on the upstream Mach number (M_1) in order to have a shock wave. Shock waves are common phenomena in supersonic upstream flows ($M_1 > 1$) of any fluid. From the quadratic structure of (8) and the limitation on the value

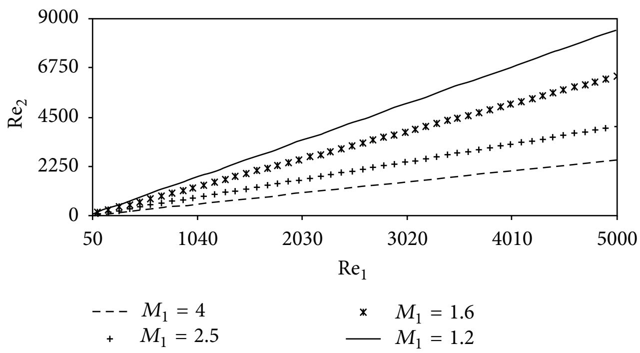

Figure 1: Behaviour of the Re_2 as a function of Re_1 for different values of M_1.

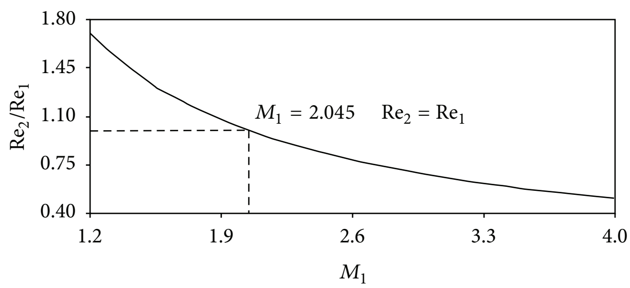

Figure 2: Upstream Mach number, M_1, dependence of Re_2/Re_1. Note that, at $M_1 \approx 2$, $Re_2 = Re_1$.

of M_1, Re_1 must be greater than or equal to 50 as shown in the horizontal axis of Figure 1. Re_2 increases with respect to increasing values of Re_1. On the other hand, Re_2 has larger values for smaller values of M_1. In Figure 2, the ratio Re_2/Re_1 is given as a function of M_1. It is decreasing as the upstream Mach number increases and the ratio of the Reynolds number is equal to unity (i.e., $Re_1 = Re_2$) at the value of $M_1 \approx 2$ as shown in this figure. This value is considered as the transition point from weak to strong shocks.

3. Model Results

We have attempted to find some special solutions of (8) and the Rankine-Hugoniot jump relations using the method given in the previous section with an algorithm developed and adapted to Maple 9.5. Table 1 represents the variation of the parameters describing the physical structure for the inviscid shock waves. These parameters are compression rate (i.e., densities ratio), the Mach numbers ratio (M_2/M_1), pressures ratio (p_2/p_1), and the entropy difference ($S_2 - S_1$) provided by the solutions of inviscid forms of the hydrodynamic equations. These values will be used as a reference model. Finally, one can easily conclude that vanishing values of the viscosity means higher values of Reynolds number from its definition.

Table 1: Change of physical parameters for inviscid shock waves ($\mu = 0$, i.e., higher Re).

M_1	κ	M_2/M_1	p_2/p_1	$S_2 - S_1$
1.200	1.297	0.705	1.550	0.055
1.900	2.185	0.328	4.263	1.839
2.600	2.770	0.210	8.200	5.061
3.300	3.136	0.154	13.363	8.574
4.000	3.368	0.123	19.750	11.961

Table 2: Representation of pressures ratio (p_2/p_1) with respect to M_1 for $Re_1 = 50$ and $Re_1 = 4500$.

M_1	$Re_1 = 50$	$Re_1 = 4500$
1.2	1.446	1.549
1.9	4.192	4.262
2.6	8.117	8.199
3.3	13.281	13.362
4.0	19.700	19.750

3.1. Variations of Parameters with respect to Mach Numbers. As explained in the previous section, distributions of physical parameters can be obtained from the solutions of (8) and the Rankine-Hugoniot relations. The related quantities, Mach numbers and pressures ratios, compression rate, and entropy change are presented in Figures 3–7 and Table 2 for a monatomic gas with $\gamma = 5/3$.

Figures 3 and 4 show the changes in the compression rate (κ) with respect to the upstream Mach number, M_1, and Re_2/Re_1, respectively. Figure 3 was drawn for two different values of Re_1. It shows that, for weak shocks ($M_1 < 2$), there is no variation with respect to upstream Mach number in accordance with Khidr and Mahmoud [5]. However, for strong shocks ($M_1 > 2$), there are considerable differences between the values of compression rate for different values of Re_1. Another important result of strong shocks is the fact that the value of κ approaches its inviscid value (3.368) as given in Table 1 for the higher values of Re_1 (e.g., 4500) shown as the upper dashed line in Figure 3.

Figure 4 represents the Re_2/Re_1 dependence of κ. It tends to decrease with increasing values of ratio. It also exhibits an interesting feature. For the small values of the Reynolds numbers ratio, it gives a larger compression rate at the smaller value of Re_1 (i.e., 50). It has comparable values in the vicinity of the $Re_2/Re_1 = 1$ for both high and low values of Re_1. However, for the larger values of ratio, the shape is visibly changed, and it gives larger compression rates at the larger value of $Re_1 = 4500$.

Table 2 summarizes the results obtained for pressures ratio (p_2/p_1) with the values of the upstream Mach number in the supersonic region for two different values of Re_1. p_2/p_1 approaches its inviscid value ($p_2/p_1 = 19.750$) given in Table 1 for the higher values of Re_1 in the strong shock regime.

In Figure 5, variation of M_2/M_1 is presented as a function Re_2/Re_1 for two different values of the upstream Reynolds number. It has the tendency of growing with the

Table 3: Reynolds number, Re_1, dependence of M_2/M_1 and p_2/p_1 for different values of M_1 and Re_2/Re_1 values.

Re_1	$M_1 = 1.2$ ($Re_2/Re_1 = 1.704$)		$M_1 = 1.6$ ($Re_2/Re_1 = 1.278$)		$M_1 = 2.5$ ($Re_2/Re_1 = 0.818$)		$M_1 = 4$ ($Re_2/Re_1 = 0.511$)	
	M_2/M_1	p_2/p_1	M_2/M_1	p_2/p_1	M_2/M_1	p_2/p_1	M_2/M_1	p_2/p_1
100	0.7224	1.5017	0.4315	2.9166	0.2207	7.5220	0.1217	19.7281
1000	0.7068	1.5454	0.4293	2.9467	0.2211	7.5585	0.1225	19.7481
2000	0.7060	1.5477	0.4291	2.9483	0.2212	7.5605	0.1226	19.7491
3000	0.7057	1.5485	0.4291	2.9489	0.2212	7.5612	0.1226	19.7494
4000	0.7056	1.5489	0.4291	2.9492	0.2212	7.5615	0.1226	19.7495
5000	0.7055	1.5491	0.4291	2.9493	0.2212	7.5617	0.1226	19.7496

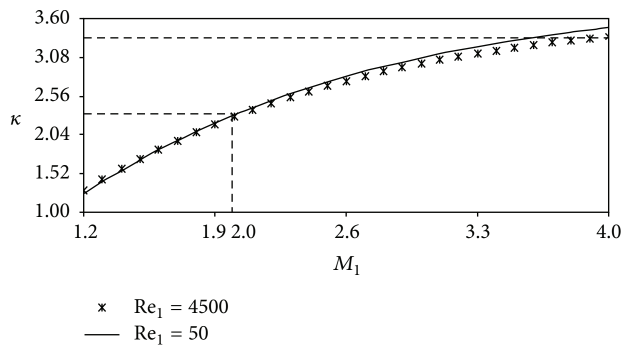

Figure 3: Variations of compression rate with respect to M_1 for different values of upstream Re.

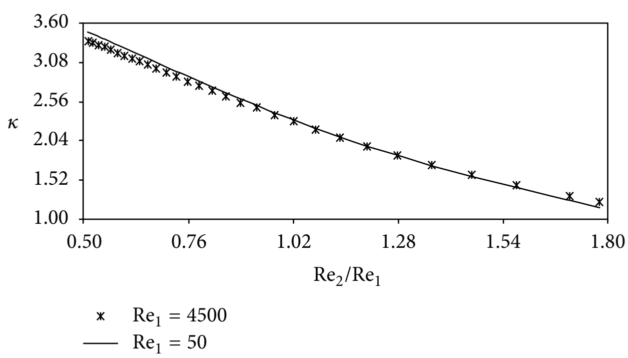

Figure 4: Variations of compression rate with respect to Re_2/Re_1.

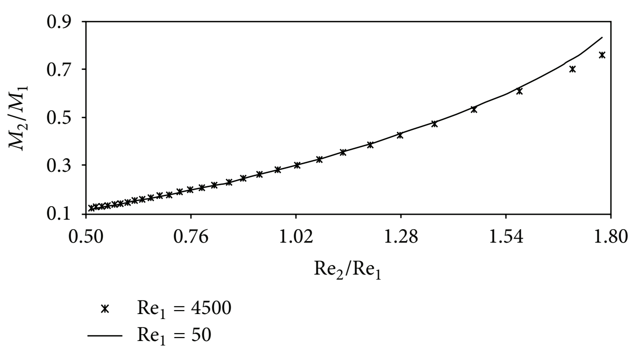

Figure 5: Change of Mach numbers ratio (M_2/M_1) as a function of Re_2/Re_1 for two different Re_1 values.

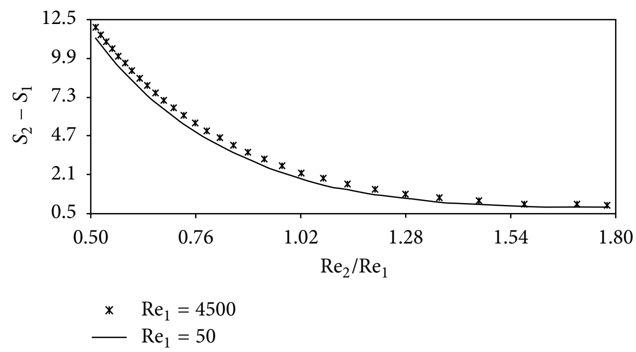

Figure 6: Distributions of entropy difference $S_2 - S_1$ as a function of Re_2/Re_1 for two different values of Re_1.

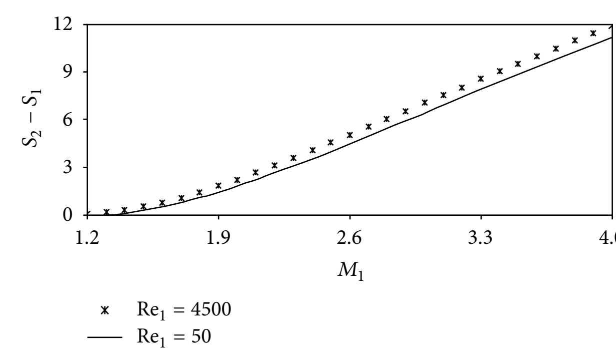

Figure 7: Same as Figure 6, but as a function of M_1.

values of Re_2/Re_1. This parameter shows another important consequence. The shock wave becomes a Prandtl-Meyer expansion wave (i.e., $M_2 > M_1$) for very high values of Re_2/Re_1.

The entropy change depicted in Figures 6 and 7 can be expressed in terms of pressures ratio and compression rate as follows [22]:

$$S_2 - S_1 = \frac{R}{\gamma - 1} \ln \left[\frac{p_2}{p_1} \kappa^{-\gamma} \right]. \quad (9)$$

In Figure 6, variation of $S_2 - S_1$ with respect to Re_2/Re_1 ratio has the tendency to decrease with increasing ratio. For higher values of Re_1, $S_2 - S_1$ has larger values as expected since higher values of the Reynolds number close the case of inviscid flow value given in Table 1.

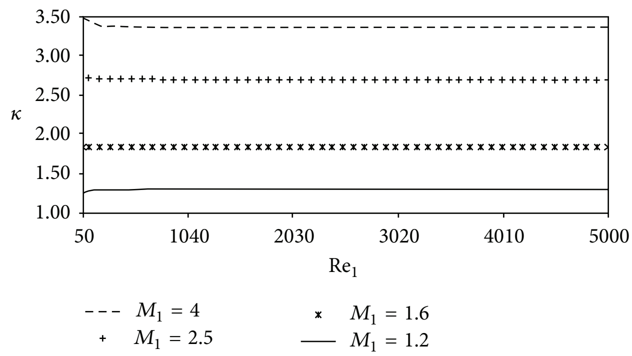

FIGURE 8: Variations of compression rate as a function of Re_1 at four different upstream Mach number values.

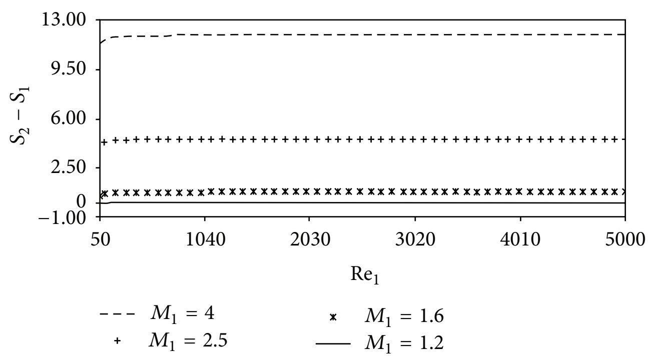

FIGURE 9: Variations of entropy difference $S_2 - S_1$ with Re_1 for four different values of M_1.

In Figure 7, dependence of entropy change, $S_2 - S_1$, with respect to M_1 is given. It has the tendency to increase with increasing M_1. For the higher values of Re_1 (i.e., vanishing values of viscosity), $S_2 - S_1$ has larger values as expected.

3.2. Variations with Respect to Reynolds Number. In this subsection, the distributions of physical parameters are given as a function of the upstream Reynolds number, Re_1, in Figures 8 and 9 and Table 3 again for a monatomic gas.

In Figure 8, the values of compression rate (κ) are given as a function of Re_1 for different values of M_1. It is increasing with the values of the upstream Mach number and also reaches very high values for strong shock cases of $M_1 = 2.5$ and 4.

From Figure 9, it is seen that the entropy change is negative for smaller values of $M_1 \leq 1.2$ in the region of very small Re_1 (i.e., <50) across the shock. This case violates the second law of thermodynamics (i.e., $S_2 - S_1 < 0$). Thus the weak shock waves (i.e., $M_1 = 1.2$) are nearly isentropic.

In Table 3, Re_1 dependencies of the Mach numbers and pressures ratios are given for different values of M_1. One of the most important features of these results is that the values of M_2/M_1 have a decreasing tendency with the increasing values of Re_1 for $\mathrm{Re}_2/\mathrm{Re}_1 > 1$ and a decreasing tendency for $\mathrm{Re}_2/\mathrm{Re}_1 < 1$. The critical value of the Mach number for this turning point was found to be 2.045 which equates the Reynolds numbers ratio to unity as in Figure 2. This point is important not only for the Reynolds numbers ratio but also for the strength of shock waves. The pressures ratio (p_2/p_1) has the increasing tendency and reaches a value close to the inviscid flow value given in Table 1 for the higher values of the Reynolds number with increasing values of Mach number (i.e., strong shocks).

4. Discussion and Conclusion

When a fluid is shocked, particles after the shock front experience both compressive and stress forces. In such a movement viscous forces largely depend on plasma particles motions. In the present work, the detailed analysis of the structure of steady hydrodynamical equations including the viscous stress tensor in conservative forms was attempted in order to investigate the effects of the Reynolds number on the shock waves.

Since the Reynolds number gives the relation between inertial and viscous forces of the fluid flow, the character of flow can be determined from the Reynolds number. If inertial forces are dominant and the Reynolds number $\mathrm{Re} > 2000$, flow is turbulent. If viscous forces surpass, then the value of the Reynolds number $\mathrm{Re} < 2000$ and flow becomes laminar. Using fluid-velocity dependence, viscosity can change the character of flow. As expected, a high Reynolds number can be a result of vanishing viscosity and its lower values are the result of higher viscosity. Since the viscous stress is written as a function of fluid velocity, the viscosity can be determined by the change in the fluid velocity. Such a dissipative mechanism controls the values of flow variables. The viscous terms in the Rankine-Hugoniot jump relations can be expressed in terms of the Reynolds number using its definition. In this present paper, the basic mechanism of the problem is given in order to investigate the effects of viscosity and the Reynolds number. The behaviour of shock waves in supersonic flows with varying Reynolds and Mach numbers was examined using analytical and numerical methods.

We obtained that, in strong shocks, physical parameters have the increasing tendency to reach a value close to the inviscid flow values obtained for the higher values of the upstream Reynolds number making the flow turbulent. Depending on increasing values of viscosity, the values parameters decrease across the shock.

As in Mace and Adamson Jr. [23], for the shock waves in a transonic region, compression rate is independent of the Reynolds number. The results in this regime agree well with the inviscid values. These results are in good concordance with the results obtained in the work of Kabin [8] for weak shocks. Viscosity makes the profiles of compression ratio smooth for very high values of the Mach number. The compression rate is increasing with the values of the upstream Mach number. However, there are considerable differences between the compression rates for different values of Re_1 for strong shocks. That is, compression rate is higher for laminar upstream flow and is lower for turbulent upstream flow.

The Mach numbers ratio has a decreasing tendency for the larger values of Re_1 in the region of $\mathrm{Re}_2/\mathrm{Re}_1 > 1$.

In other words, a shock wave becomes a Prandtl-Meyer expansion wave for very high values of $\mathrm{Re}_2/\mathrm{Re}_1$ for the transonic values of the upstream Mach number (<2) as it is seen from Figure 1. M_2/M_1 decreases for $\mathrm{Re}_2/\mathrm{Re}_1 < 1$ in the region of $M_1 > 2$. When the upstream Reynolds number is dominant, the shock waves become very strong (see Figure 2). Viscosity makes the problem smooth, and the downstream shock waves become more turbulent if Re_1 is turbulent in the transonic limits of M_1 in accordance with the results of Jamme et al. [24]

As given in the work of Gamba [25], for the turbulent case of Re_1 (i.e., >2000), we obtained that the entropy change increases with increasing values of upstream shock speed. It is also clear that the entropy change decreases with the increasing values of the Reynolds numbers ratio $\mathrm{Re}_2/\mathrm{Re}_1$ and it has close results for both extreme values of the Re_1. It is also found that the weak shocks are nearly isentropic for smaller values of upstream Re similar to the results of De Sterck et al. [26].

In summary, the present study provides results useful for future studies including dissipative shocks. These types of shock waves arise frequently in the cases where the velocity of fluid is greater than the local sound speed; they find an application in gas dynamics, fluid mechanics, aerodynamics, astrophysics, solar physics, and space physics, for both magnetised and unmagnetised fluid motions.

It is planned to use the present algorithm and its results to be applied to solar coronal shock waves. The effects of viscous flows on the shock wave happened after 13/12/2006—CME is under study in order to apply the present results. The simulations of the effects of the Reynolds number on the shock waves for magnetized plasma in both one and multidimensions are also under study.

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References

[1] B. V. Somow and A. R. Spector, "Hydrodynamic shock wave formation in the solar chromosphere and corona during flares," *Space Science Reviews*, vol. 32, no. 1-2, pp. 27–41, 1982.

[2] M. Heinemann, "Effects of solar wind inhomogeneities on transit times of interplanetary shock waves," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 64, no. 3, pp. 315–325, 2002.

[3] A. de Lucas, R. Schwenn, A. Dal Lago, E. Marsch, and A. L. Clúa de Gonzalez, "Interplanetary shock wave extent in the inner heliosphere as observed by multiple spacecraft," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 73, no. 10, pp. 1281–1292, 2011.

[4] T. Magara and K. Shibata, "Plasma ejections and shock waves in the solar atmosphere," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 70, no. 2–4, pp. 546–554, 2008.

[5] M. A. Khidr and M. A. A. Mahmoud, "The shock-wave structure for arbitrary Prandtl numbers and high mach numbers," *Astrophysics and Space Science*, vol. 113, no. 2, pp. 289–301, 1985.

[6] N. M. Kuznetsov, "Stability of shock waves," *Soviet Physics Uspekhi*, vol. 32, no. 11, article 993, 1989.

[7] H. Hamad and F. El-Fayes, "Analytical solution for shock waves in dusty gases," *Acta Mechanica*, vol. 119, pp. 53–63, 1996.

[8] K. Kabin, "A note on the compression ratio in MHD shocks," *Journal of Plasma Physics*, vol. 66, no. 4, pp. 259–274, 2001.

[9] C. Escudero, "On one-dimensional models for hydrodynamics," *Physica D*, vol. 217, no. 1, pp. 58–63, 2006.

[10] D. C. Swift, R. G. Kraus, E. N. Loomis, D. G. Hicks, J. M. McNaney, and R. P. Johnson, "Shock formation and the ideal shape of ramp compression waves," *Physical Review E*, vol. 78, no. 6, Article ID 066115, 2008.

[11] Z. U. A. Warsi, *Fluid Dynamics: Theoretical and Computational Approaches*, CRC Press, Boca Raton, Fla, USA, 1999.

[12] J. A. Orta, M. A. Huerta, and G. C. Boynton, "Magnetohydrodynamic shock heating of the solar corona," *The Astrophysical Journal Letters*, vol. 596, no. 1, pp. 646–655, 2003.

[13] I. Ballai, E. Forgacs-Dajka, and A. Marcu, "Dispersive shock waves in the solar wind," *Astronomische Nachrichten*, vol. 328, no. 8, pp. 734–737, 2007.

[14] J. Blazek, *Computational Fluid Dynamics: Principles and Applications*, Elsevier, Amsterdam, The Netherlands, 2001.

[15] N. P. Korzhov, V. V. Mishin, and V. M. Tomozov, "On the viscous interaction of solar wind streams," *Soviet Astronomy*, vol. 29, pp. 215–218, 1985.

[16] O. Reynolds, "An experimental investigation of the circumstances which determine whether the motion of water shall be direct or sinuous, and of the law of resistance in parallel channels," *Philosophical Transactions of the Royal Society*, vol. 174, pp. 935–982, 1883.

[17] L. D. Landau and E. M. Lifshitz, *Fluid Mechanics*, Pergamon Press, New York, NY, USA, 1959.

[18] D. D. Knight, *The Handbook of Fluid Dynamics*, CRC Press, Boca Raton, Fla, USA, 1998.

[19] A. R. Choudhuri, *The Physics of Fluids and Plasmas*, Cambridge University Press, Cambridge, Mass, USA, 1998.

[20] Y. B. Zel'dovich and Y. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, Dover, New York, NY, USA, 2002.

[21] F. C. Bruhn, K. Pauly, and V. Kaznov, "Extremely low mass spherical rovers for extreme environments and planetary exploration enabled with MEMS," in *Proceedings of the 8th International Symposium on Artificial Intelligence, Robotics and Automation in Space (i-SAIRAS '05)*, Munich, Germany, 2005.

[22] F. M. White, *Fluid Mechanics*, McGraw-Hill, New York, NY, USA, 1994.

[23] J. L. Mace and T. C. Adamson Jr., "Shock waves in transonic channel flows at moderate Reynolds number," *AIAA Journal*, vol. 24, no. 4, pp. 591–598, 1986.

[24] S. Jamme, J.-B. Cazalbou, F. Torres, and P. Chassaing, "Direct numerical simulation of the interaction between a shock wave and various types of isotropic turbulence," *Flow, Turbulence and Combustion*, vol. 68, no. 3, pp. 227–268, 2002.

[25] I. M. Gamba, "Boundary-layer formation for viscosity approximations in transonic flow," *Physics of Fluids A*, vol. 4, no. 3, pp. 486–490, 1992.

[26] H. de Sterck, H. Deconinck, S. Poedts, and D. Roose, " A bow shock flow containing (almost) all types of ("exotic") MHD discontinu," in *Proceedings of the 7th International Conference on Hyperbolic Problems Theory, Numerics, Applications*, M. Fey and R. Jeltsch, Eds., Birkhäuser, Basel, Switzerland, 1998.


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