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Research Article

Numerical Study of Magnetohydrodynamic Flow of Dusty Fluid Through Different Channels

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Abstract. In this paper, Magnetohydrodynamic (MHD) flow through various channels such as rectangular, hexagonal, octagonal, decagonal, dodecagonal, and tetradecagonal channels of dusty gas and dust particles has been analyzed under the influence of magnetic field parameters and time. Numerical values of the velocity of dust particles and gas were calculated using Laplace transform for a non-dimensional equation. It is observed that for a given value of the magnetic parameter, the velocity of gas and dust particles decreases increases alternately as we move from one channel to another channel and found that for a particular channel, the velocity of gas and dust particles decreases as the value of magnetic field parameter increases. It is also observed that for a given value of the magnetic parameter, the velocity of gas and the velocity of dust particles increase with time. The velocity of dust particles is less than the velocity of the gas.

Keywords. Channel; Magnetic parameter; Laplace transform; Dusty gas; Dust particles

Mathematics Subject Classification (2020). 76W10

1. Introduction

The study of dusty gas in a hexagonal channel was first considered by Sharma and Gupta [11]. With the same phenomenology, the thermal dispersion effect on the MHD flow of gas was examined by Sharma and Varshney [10]. They obtained the velocity of gas and the velocity of dust particles under the observation of thermal dispersion effect and volume fraction. Sharma et al. [12] expressed the variations of velocity profile and temperature for distinct values of Prandtl and Hartmann numbers by using the finite difference method. Chutia and Deka [1] investigated velocity, magnetic field, and current density for different values of Hartmann number under

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moving walls in rectangular ducts by using the central difference method. Madhura and Swetha [7] have employed Laplace and Fourier transforms and the Crank Nicolson method to obtain the velocities of fluid and dust particles in a porous medium for different values of volume fraction. They also found graphically that the nature of flow is parabolic. Madhura et al. [8] determined that the velocity of dust particles and fluid decreases in Beltrami flow. They also confirmed that vortex lines and streamlines are parallel. Kalpana and Madhura [4] deduced that for non-conservative flow velocity of dust particles is lesser than the velocity of the fluid, and the temperature is minimum near the wavy wall and maximum near a flat wall. They also concluded that heat flux and shearing stress are higher for non-convective flow than convective flow. Hamdan et al. [3] analyzed the dust-phase velocity and found that it is the product of the phase velocity and a position function. Manuilovich [9] studied the motion of dusty gas in a plane channel. Gupta et al. [2] expressed the velocity of the gas in a rectangular channel with a constant pressure gradient. Madhura and Swetha [6] examined the motion of dusty gas in a hexagonal channel with a time-dependent pressure gradient. Recently, Lal and Agarwal [5] discussed dusty gas flow in a horizontal pipe with a pressure gradient. In this paper, we obtained the velocity of gas and dust particles through different channels, namely rectangular channel, hexagonal channel, octagonal channel, decagonal channel, dodecagonal channel, and tetradecagonal channel.

2. Mathematical Formulation and Solution of the Problem

The governing equations of motion for dusty fluid are written as

$$\frac{\partial \boldsymbol{u}}{\partial t} = -\frac{1}{\rho}\frac{\partial P}{\partial z} + \frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \frac{KN_0}{\rho}(\boldsymbol{v}-\boldsymbol{u}) - \frac{\sigma\beta_0^2 u}{\rho}, \tag{2.1}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} = \frac{K}{m'}(\boldsymbol{u}-\boldsymbol{v}), \tag{2.2}$$

where u be the velocity of gas and v be the velocity of dust particles, ρ be the density, and m' be the mass. K be the Stoke's resistance coefficient, N_0 be the number density, σ be the electrical conductivity, P_0 be the pressure, v be the kinematic viscosity, and M is the magnetic parameter.

Assuming the following dimensionless variables as

$$x^* = \frac{x}{L},\ \ y^* = \frac{y}{L},\ \ z^* = \frac{z}{L},\ \ P^* = \frac{PL^2}{\rho v},\ \ t^* = \frac{t}{L^2},\ \ u^* = \frac{Lu}{v},\ \ v^* = \frac{Lv}{v},\ \ M = \frac{\sigma L^2\beta_0^2}{\rho}.$$

Dropping the star notation, the equations (2.1) and (2.2) reduce to

$$\frac{\partial \boldsymbol{u}}{\partial t} = -\frac{\partial P}{\partial z} + \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \varepsilon(\boldsymbol{v}-\boldsymbol{u}) - M\boldsymbol{u}, \tag{2.3}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} = \tau'(\boldsymbol{u}-\boldsymbol{v}), \tag{2.4}$$

where $\phi = \frac{m'N_0}{\rho}$, $\varepsilon = \phi\tau$, $\tau_0 = \frac{m'}{K}$, $\tau' = \frac{1}{\tau_0}$ and $-\frac{\partial P}{\partial z} = \phi(t)$.

2.1 Evolution of Velocity of Gas and Dust Particles Through a Rectangular Channel

Consider a rectangular channel under the effect of magnetic field parameter by using the following transformations

$$X = y,\ \ Y = y + x,\ \ Z = y - x.$$

Equations (2.1) and (2.2) become

$$\frac{\partial \boldsymbol{u}}{\partial t} = \phi(t) + \left(\frac{\partial^2}{\partial X^2} + 2\frac{\partial^2}{\partial Y^2} + 2\frac{\partial^2}{\partial Z^2} + \frac{\partial^2}{\partial XY} - 2\frac{\partial^2}{\partial YZ} + \frac{\partial^2}{\partial XZ}\right) u + \varepsilon(v-u) - Mu, \tag{2.5}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} = \tau'(u-v). \tag{2.6}$$

Associated with initial and boundary conditions

$$\text{(i)}\quad u = v = 0 \quad \text{for } t = 0, \tag{2.7}$$

$$\text{at } X = \frac{1}{2},\ Y = 1,\ Z = 1$$

$$\text{(ii)}\quad \frac{\partial \boldsymbol{u}}{\partial X} = 0 = \frac{\partial \boldsymbol{v}}{\partial X},\ \frac{\partial \boldsymbol{u}}{\partial Y} = 0 = \frac{\partial \boldsymbol{v}}{\partial Y},\ \frac{\partial \boldsymbol{u}}{\partial Z} = 0 = \frac{\partial \boldsymbol{v}}{\partial Z}. \tag{2.8}$$

Here u and v are even functions so multiplying equations (2.5) and (2.6) by $\cos(lx)\cos(mY)\cos(nZ)$ then integrate it with the limits 0 to $\frac{1}{2}$, 0 to 1 and 0 to 1 and using conditions (2.7) and (2.8).

Equations (2.5) and (2.6) become

$$\frac{\partial U}{\partial t} = \frac{(-1)^{l+m+n}}{lmn}\phi(t) + BU + \varepsilon(V-U) - MU, \tag{2.9}$$

$$\frac{\partial V}{\partial t} = \tau'(U-V), \tag{2.10}$$

where $B = l^2 + 2m^2 + 2n^2$,

$$U = \int_0^{\frac{1}{2}}\int_0^1\int_0^1 u(X,Y,Z)\cos(lX)\cos(mY)\cos(nZ)\,dX\,dY\,dZ \tag{2.11}$$

and

$$V = \int_0^{\frac{1}{2}}\int_0^1\int_0^1 v(X,Y,Z)\cos(lX)\cos(mY)\cos(nZ)\,dX\,dY\,dZ. \tag{2.12}$$

Using Laplace transform, equations (2.9) and (2.10) become

$$P\overline{U} = \frac{(-1)^{l+m+n}}{lmn}\overline{\phi(P)} - B\overline{U} + \varepsilon(\overline{V} - \overline{U}) - M\overline{U}, \tag{2.13}$$

$$P\overline{V} = \tau'(\overline{U} - \overline{V}), \tag{2.14}$$

where $\overline{U}$, $\overline{V}$ and $\overline{\phi(P)}$ represents the Laplace transform of U, V and $\phi(t)$, respectively.

$$\overline{U} = \frac{(-1)^{l+m+n}\overline{\phi(P)}}{lmn(P_1-P_2)}\left[\frac{P_1+\varepsilon}{P-P_1} - \frac{P_2+\varepsilon}{P-P_2}\right], \tag{2.15}$$

$$\overline{V} = \frac{(-1)^{l+m+n}\overline{\phi(P)}}{lmn(P_1-P_2)}\left[\frac{1}{P-P_1} - \frac{1}{P-P_2}\right], \tag{2.16}$$

where P_1 and P_2 are two roots of the quadratic equation

$$P^2 + (B+\varepsilon+\tau+M)P + \varepsilon B = 0, \tag{2.17}$$

$$P_1 = -\frac{1}{2}[(B+\varepsilon+\tau+M) + \{(B+\varepsilon+\tau+M)^2 - 4\varepsilon B\}^{\frac{1}{2}}], \tag{2.18}$$

and

$$P_2 = -\frac{1}{2}[(B+\varepsilon+\tau+M) - \{(B+\varepsilon+\tau+M)^2 - 4\varepsilon B\}^{\frac{1}{2}}]. \tag{2.19}$$

On using the Convolution theorem and substitute $\phi(t)=c$, equations (2.15) and (2.16) become

$$u=\frac{16c}{3\sqrt{3}}\sum_{l=m=n=1}^{\infty}\frac{(-1)^{l+m+n}}{lmnB}\left[1-\frac{1}{(P_1-P_2)}\{(P_1+B)e^{P_2t}-(P_2+B)e^{P_1t}\}\right]\cos(lX)\cos(mY)\cos(nZ), \tag{2.20}$$

$$v=\frac{16c}{3\sqrt{3}}\sum_{l=m=n=1}^{\infty}\frac{(-1)^{l+m+n}}{lmnB}\left[1+\frac{1}{(P_1-P_2)}\{P_2e^{P_1t}-P_1e^{P_2t}\}\right]\cos(lX)\cos(mY)\cos(nZ). \tag{2.21}$$

2.2 Evolution of Velocity of Gas and Dust Particles Through a Hexagonal Channel

Consider a hexagonal channel under the effect of magnetic field parameter by using the following transformations

$$X=y,\ \ Y=y+1.732x,\ \ Z=y-1.732x.$$

Equations (2.1) and (2.2) become

$$\frac{\partial \boldsymbol{u}}{\partial t}=\phi(t)+\left(\frac{\partial^2}{\partial X^2}+4\frac{\partial^2}{\partial Y^2}+4\frac{\partial^2}{\partial Z^2}+\frac{\partial^2}{\partial XY}-2\frac{\partial^2}{\partial YZ}+\frac{\partial^2}{\partial XZ}\right)u+\varepsilon(v-u)-Mu, \tag{2.22}$$

$$\frac{\partial \boldsymbol{v}}{\partial t}=\tau'(u-v). \tag{2.23}$$

Associated with initial and boundary conditions

$$\text{(i)}\quad u=v=0 \quad \text{for } t=0, \tag{2.24}$$

$$\text{at } X=0.866,\ Y=1.732,\ Z=1.732$$

$$\text{(ii)}\quad \frac{\partial \boldsymbol{u}}{\partial X}=\frac{\partial \boldsymbol{v}}{\partial X}=0,\ \ \frac{\partial \boldsymbol{u}}{\partial Y}=\frac{\partial \boldsymbol{v}}{\partial Y}=0,\ \ \frac{\partial \boldsymbol{u}}{\partial Z}=\frac{\partial \boldsymbol{v}}{\partial Z}=0. \tag{2.25}$$

Further, the velocity of gas and the velocity of dust particles are solved in the same manner as in a rectangular channel.

2.3 Evolution of Velocity of Gas and Dust Particles Through an Octagonal Channel

Consider an octagonal channel under the effect of magnetic field parameter by using the following transformations

$$X=y,\ \ Y=y+2.414x,\ \ Z=y-2.414x.$$

Equation (2.1) and (2.2) become

$$\frac{\partial \boldsymbol{u}}{\partial t}=\phi(t)+\left(\frac{\partial^2}{\partial X^2}+6.827\frac{\partial^2}{\partial Y^2}+6.827\frac{\partial^2}{\partial Z^2}+\frac{\partial^2}{\partial XY}-2\frac{\partial^2}{\partial YZ}+\frac{\partial^2}{\partial XZ}\right)u+\varepsilon(v-u)-Mu, \tag{2.26}$$

$$\frac{\partial \boldsymbol{v}}{\partial t}=\tau'(u-v). \tag{2.27}$$

Associated with initial and boundary conditions

$$\text{(i)}\quad u=v=0 \quad \text{for } t=0, \tag{2.28}$$

$$\text{at } X=1.207,\ Y=2.414,\ Z=2.414$$

$$\text{(ii)}\quad \frac{\partial \boldsymbol{u}}{\partial X}=\frac{\partial \boldsymbol{v}}{\partial X}=0,\ \ \frac{\partial \boldsymbol{u}}{\partial Y}=\frac{\partial \boldsymbol{v}}{\partial Y}=0,\ \ \frac{\partial \boldsymbol{u}}{\partial Z}=\frac{\partial \boldsymbol{v}}{\partial Z}=0. \tag{2.29}$$

Further, the velocity of gas and the velocity of dust particles are solved in the same manner as in a rectangular channel.

2.4 Evolution of Velocity of Gas and Dust Particles Through a Decagonal Channel

Consider a decagonal channel under the effect of magnetic field parameter by using the following transformations

$$X = y,\ \ Y = y + 3.077x,\ \ Z = y - 3.077x.$$

Equation (2.1) and (2.2) become

$$\frac{\partial \boldsymbol{u}}{\partial t} = \phi(t) + \left(\frac{\partial^2}{\partial X^2} + 10.468\frac{\partial^2}{\partial Y^2} + 10.468\frac{\partial^2}{\partial Z^2} + \frac{\partial^2}{\partial XY} - 2\frac{\partial^2}{\partial YZ} + \frac{\partial^2}{\partial XZ}\right)u + \varepsilon(v - u) - Mu, \tag{2.30}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} = \tau'(u - v). \tag{2.31}$$

Associated with initial and boundary conditions

$$\text{(i)}\quad u = v = 0 \quad \text{for } t = 0, \tag{2.32}$$

$$\text{at } X = 1.539,\ Y = 3.077,\ Z = 3.077$$

$$\text{(ii)}\quad \frac{\partial \boldsymbol{u}}{\partial X} = \frac{\partial \boldsymbol{v}}{\partial X} = 0,\ \ \frac{\partial \boldsymbol{u}}{\partial Y} = \frac{\partial \boldsymbol{v}}{\partial Y} = 0,\ \ \frac{\partial \boldsymbol{u}}{\partial Z} = \frac{\partial \boldsymbol{v}}{\partial Z} = 0. \tag{2.33}$$

Further, the velocity of gas and the velocity of dust particles are solved in the same manner as in a rectangular channel.

2.5 Evolution of Velocity of Gas and Dust Particles Through a Dodecagonal Channel

Consider a dodecagonal channel under the effect of magnetic field parameter by using the following transformations

$$X = y,\ \ Y = y + 3.732x,\ \ Z = y - 3.732x.$$

Equations (2.1) and (2.2) become

$$\frac{\partial \boldsymbol{u}}{\partial t} = \phi(t) + \left(\frac{\partial^2}{\partial X^2} + 14.928\frac{\partial^2}{\partial Y^2} + 14.928\frac{\partial^2}{\partial Z^2} + \frac{\partial^2}{\partial XY} - 2\frac{\partial^2}{\partial YZ} + \frac{\partial^2}{\partial XZ}\right)u + \varepsilon(v - u) - Mu, \tag{2.34}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} = \tau'(u - v). \tag{2.35}$$

Associated with initial and boundary conditions

$$\text{(i)}\quad u = v = 0 \quad \text{for } t = 0, \tag{2.36}$$

$$\text{at } X = 1.866,\ Y = 3.732,\ Z = 3.732$$

$$\text{(ii)}\quad \frac{\partial \boldsymbol{u}}{\partial X} = \frac{\partial \boldsymbol{v}}{\partial X} = 0,\ \ \frac{\partial \boldsymbol{u}}{\partial Y} = \frac{\partial \boldsymbol{v}}{\partial Y} = 0,\ \ \frac{\partial \boldsymbol{u}}{\partial Z} = \frac{\partial \boldsymbol{v}}{\partial Z} = 0. \tag{2.37}$$

Further, the velocity of gas and the velocity of dust particles are solved in the same manner as in a rectangular channel.

2.6 Evolution of Velocity of Gas and Dust Particles Through a Tetradecagonal Channel

Consider a tetradecagonal channel under the effect of magnetic field parameter by using the following transformations

$$X = y,\ \ Y = y + 4.381x,\ \ Z = y - 4.381x.$$

Equations (2.1) and (2.2) become

$$\frac{\partial \boldsymbol{u}}{\partial t} = \phi(t) + \left(\frac{\partial^2}{\partial X^2} + 20.196\frac{\partial^2}{\partial Y^2} + 20.196\frac{\partial^2}{\partial Z^2} + \frac{\partial^2}{\partial XY} - 2\frac{\partial^2}{\partial YZ} + \frac{\partial^2}{\partial XZ}\right)u + \varepsilon(v - u) - Mu, \tag{2.38}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} = \tau'(u - v). \tag{2.39}$$

Associated with initial and boundary conditions

(i) $u = v = 0 \quad \text{for } t = 0,$ (2.40)

at $X = 2.19,\ Y = 4.381,\ Z = 4.381$

(ii) $\frac{\partial \boldsymbol{u}}{\partial X} = \frac{\partial \boldsymbol{v}}{\partial X} = 0,\quad \frac{\partial \boldsymbol{u}}{\partial Y} = \frac{\partial \boldsymbol{v}}{\partial Y} = 0,\quad \frac{\partial \boldsymbol{u}}{\partial Z} = \frac{\partial \boldsymbol{v}}{\partial Z} = 0.$ (2.41)

Further, the velocity of gas and the dust particles are solved in the same manner as in a rectangular channel.

3. Results and Discussion

The velocity of dusty gas and dust particles is investigated for distinct channels with number of sides N. Variation of velocity for distinct values of magnetic parameter M with respect to time t are tabulated and shown in graphs. It is evident from the graphs that for a given value of M, the velocity decreases increases alternately as we increase the sides of channels and also found that as time increases, the velocity of gas and dust particles increases. The velocity of the gas is more than the dust particles (Tables 1-3 and Figures 1-6).

Table 1. Velocities for distinct N and M at $t = 0.1$

N	For $t = 0.1$					
	u/c			v/c		
	For $M = 1$	For $M = 6$	For $M = 11$	For $M = 1$	For $M = 6$	For $M = 11$
4	.05882	.04756	.03921	.000710	.000620	.000540
6	.00323	.00265	.00222	.000041	.000036	.000032
8	.03066	.02571	.02193	.000420	.000370	.000340
10	.00382	.00326	.00286	.000057	.000051	.000046
12	.01851	.01630	.01453	.000300	.000280	.000250
14	.00438	.00394	.00359	.000075	.000069	.000064

Table 2. Velocities for distinct N and M at $t = 0.2$

N	For $t = 0.2$					
	u/c			v/c		
	For $M = 1$	For $M = 6$	For $M = 11$	For $M = 1$	For $M = 6$	For $M = 11$
4	.09057	.06346	.04745	.00238	.00186	.001510
6	.00439	.00325	.00253	.00013	.00010	.000085
8	.03698	.02905	.02378	.00118	.00098	.000840
10	.00420	.00350	.00298	.00015	.00013	.000110
12	.01928	.01676	.01483	.00071	.00063	.000570
14	.00444	.00399	.00362	.00017	.00016	.000140

Table 3. Velocities for distinct N and M at $t = 0.3$

N	For $t = 0.3$					
	u/c			v/c		
	For $M = 1$	For $M = 6$	For $M = 11$	For $M = 1$	For $M = 6$	For $M = 11$
4	.10783	.06916	.04964	.00453	.00328	.00254
6	.00482	.00340	.00260	.00023	.00017	.00014
8	.03832	.02963	.02412	.00198	.00160	.00135
10	.00424	.00352	.00300	.00023	.00020	.00017
12	.01932	.01683	.01491	.00112	.00099	.00088
14	.00444	.00400	.00364	.00026	.00024	.00022

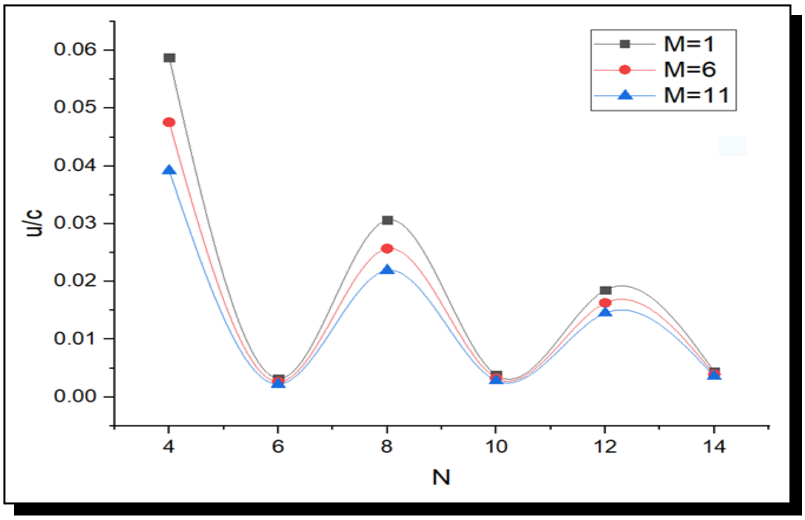

Figure 1. Velocity profiles of gas for distinct channels under magnetic parameter M at time $t = 0.1$

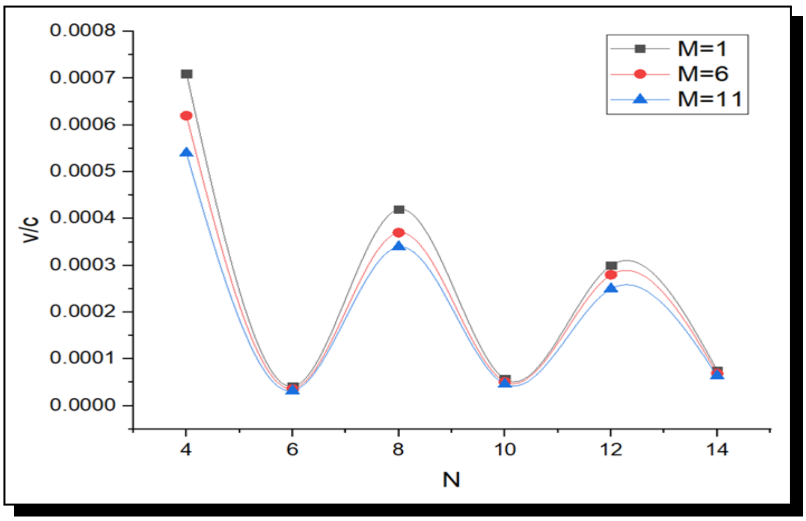

Figure 2. Velocity profiles of dust particles for distinct channels under magnetic parameter M at time $t = 0.1$

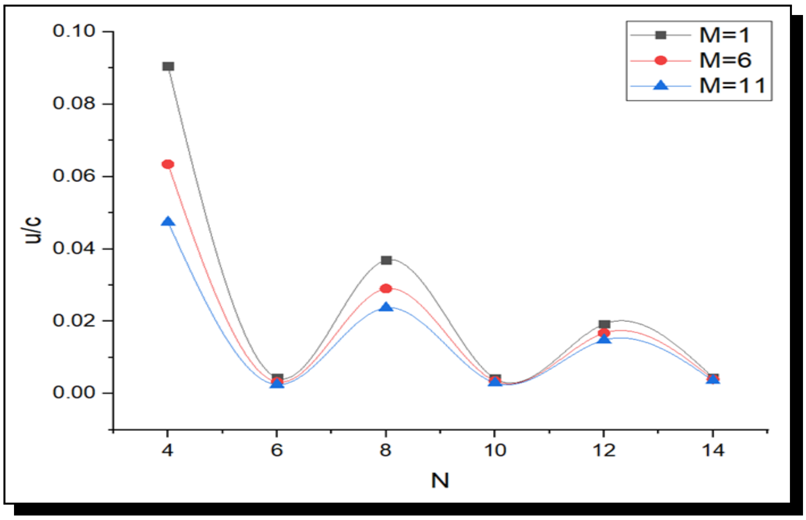

Figure 3. Velocity profiles of gas for distinct channels under magnetic parameter M at time $t = 0.2$

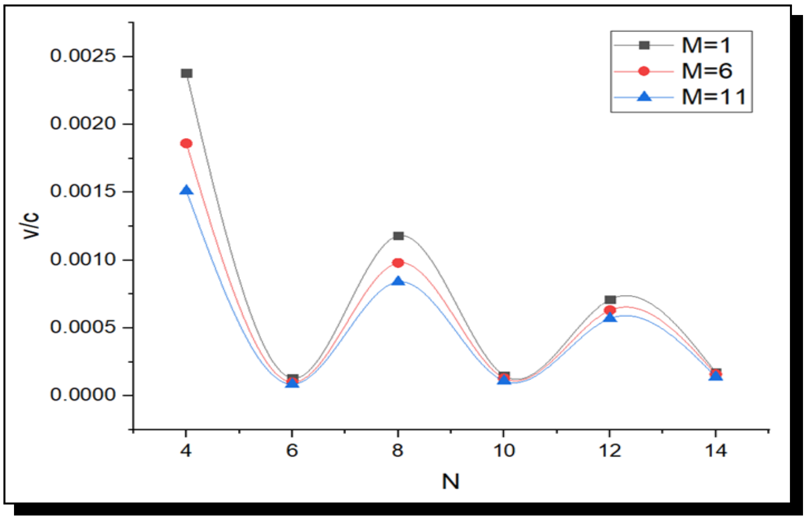

Figure 4. Velocity profiles of dust particles for distinct channels under magnetic parameter M at time $t = 0.2$

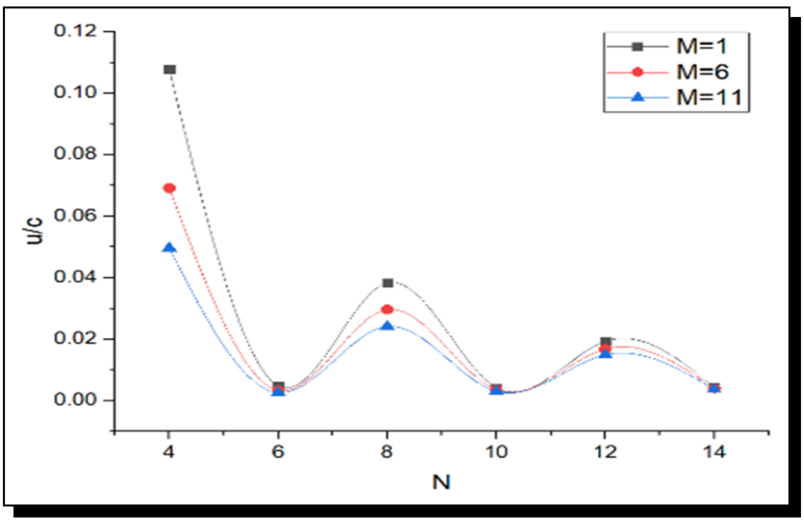

Figure 5. Velocity profiles of gas for distinct channels under magnetic parameter M at time $t = 0.3$

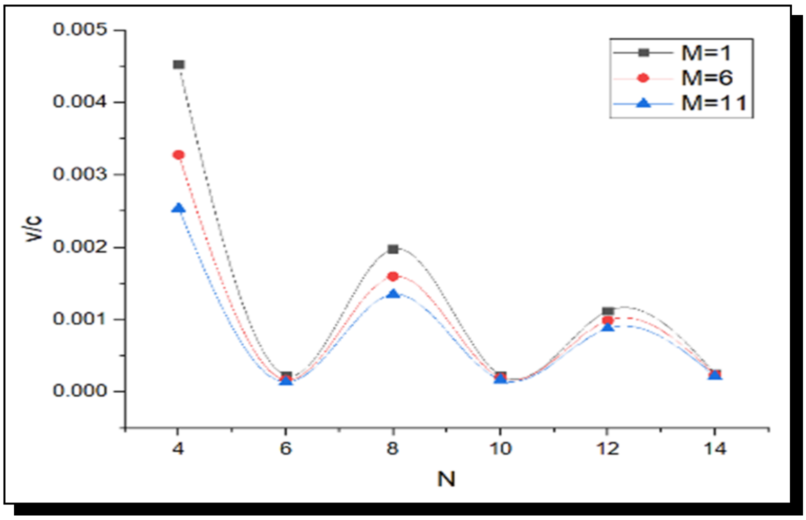

Figure 6. Velocity profiles of dust particles for distinct channels under magnetic parameter M at time $t = 0.3$

4. Conclusions

A numerical study of the velocity of dusty gas and dust particles has been developed under the effects of magnetic field parameters through different channels with time. Tables 1-3 and Figures 1-6 depicted the variation of velocities for different channels and concluded that as we move from one channel to another, velocity decreases increases alternately for a given value of M. As time increases, the velocity of gas and dust particles increases for a given value of M. For a particular channel, the velocity of gas and dust particles decreases for a given value of M and velocity of dust particles is lesser than the velocity of the gas.

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Competing Interests

The authors declare that they have no competing interests.

Authors' Contributions

All the authors contributed significantly in writing this article. The authors read and approved the final manuscript.

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