ONE-DIMENSIONAL STUDY OF SHOCK WAVE PROPAGATION IN A ROTATING DUSTY NON-IDEAL GAS

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Abstract- Strength of overtaking waves on the freely propagating strong spherical converging shock waves in the dusty gaseous non-uniform medium has been investigated. The non-uniformity of the medium arises due to solid body rotation of the mixture and the flow behind the shock. It is assumed that the medium in which shock propagates, is a suspension of inert dust particles and non-ideal gas. The particles are of small spherical uniform size and uniformly distributed in the medium. It is also assumed that the condition of equilibrium flow is maintained. Neglecting the Coriolis forces, the analytical expressions for the shock velocity and shock strength for freely propagation as well as under the influence of flow behind the shock front have been derived using CCW method. The non-dimensional expressions for pressure and particle velocity are also obtained. The variations of all flow variables with propagation distance(r), angular velocity (Ω), and mass concentration of dust particles in the medium (k_p) are shown through figures. The results reported here are compared with those for dusty perfect gas[26]. It is observed that the presence of non-idealness in the gaseous medium has significant effects on flow variables of shock propagation.

Keywords- Dusty shock, strong, non-ideal gas, effect of overtaking disturbances.

I INTRODUCTION


In most of the problems associated with the explosion waves, the assumption of the gas to be an ideal gas is not practically true. Anisimov and Spiner[7] simplified the equation of state for non-ideal(real) gas and studied the problem of shock explosion. Rnga Rao and Purohit[8], Ojha[9], Vishwakarma and Nath[10] and Singh et. al[11] have also considered the problem of shock wave explosion for non-ideal gases. Assuming constant initial density distribution Vishwakarma and Patel[12] have used similarity method to explore the problem of diverging cylindrical shock wave in a low conducting non-ideal gas under the influence of angular and azimuthal components of magnetic induction.

The propagation of shock wave in dusty atmosphere has many applications in engineering and geophysical science. The problem of dusty shock dynamics has been tackled by severe scientist like Carrier[13], Kriebel[14], Rudinger[15], Taylor[16], Sedov[17], Marble[18], Pai [19], Miura and Glass[20] and Igra and Ben-Dor[21]. Using Chester[22]- Chisnell[23]- Whitham[24] (CCW) theory Singh and Pandey[25], have investigated the motion of magnetogasdynamics shock waves in a self-gravitating and rotating gas. Neglecting the EOD, Yadav et. al. [26] have investigated the effect of magnetic fields on the behaviour of weak shock waves in the suspension of a perfect gas and dust particles. Singh and Gogoi [27] have used the similarity method to study isothermal and adiabatic motion of strong shock wave in the mixture of non-ideal gas and small solid dust particles. They discussed the effects of variation of the parameter of non-idealness of the gas in the mixture.
Recently, Gangwar [28] has considered the problem of strong shock wave propagation in dusty real gaseous non-uniform medium, for freely under EOD and found that shock is strengthened as the EOD is taken into account. The effect of self-gravitational forces on the motion of strong imploding shock waves in dusty real gas has also been reported by Gangwar[29] by using CCW theory.

In the present study, we have estimated the strength of overtaking disturbances on the freely propagating strong spherical converging shock in the dusty gaseous non-uniform medium by using Yadav technique[3]. The non-uniformity of the medium arises due to solid body rotation of the mixture and the flow behind the shock. It is assumed that the medium in which shock propagates, is a suspension of dust particles and non-ideals gas. The particles are small spherical uniform size and uniformly distributed in the medium. It is also assumed that the condition of equilibrium flow is maintained. Neglecting the Coriolis forces, the analytical expressions for the modified shock velocity and shock strength under the EOD have been derived using CCW method. The non-dimensional expressions for pressure and particle velocity are also obtained. The variation of all flow variables with propagation distance(r), angular velocity (Ω), and mass concentration of dust particles in the medium (k_p) have been shown through figures. The results reported here are compared with those for dusty perfect gas[26]. It is observed that the presence of non-idealsness in the gaseous medium has significant effects on flow variables of shock propagation.

II GOVERNING EQUATION, BOUNDARY CONDITIONS AND ANALYTICAL EXPRESSIONS.

The basic equations for the spherical symmetrical flow of dusty gas can be written as [3],[19]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} + \frac{1}{r} \frac{\partial p}{\partial r} - \frac{v^2}{r} = 0
\] (1)

\[
\frac{\partial p}{\partial t} + u \frac{\partial p}{\partial r} + \frac{1}{r} \left( \frac{\partial}{\partial r} \right) p + 2pu + \frac{2}{r} = 0
\] (2)

\[
\frac{\partial \varepsilon}{\partial t} + u \frac{\partial \varepsilon}{\partial r} + \frac{1}{r} \left( \frac{\partial}{\partial r} \right) \varepsilon + \frac{2p}{r^2} = 0
\] (3)

where u, p, and ρ are the particle velocity, the pressure and density at a distance ‘r’ from the center of explosion at time ‘t’. ϵ is the internal energy and v is the angular velocity of mixture.

The equation of state of the mixture of non-ideal gas and small dust particles is given by [7],[8],[19] and [27]

\[
p = \frac{(1-k_p)}{1-Z} \left[ 1 + b \rho \left( 1-k_p \right) \right] p R' T
\] (4)

where R’ is the gas constant, T the temperature, Z and k_p are the volume fraction of solid particles in the mixture and mass concentration of solid particles in the mixture, respectively.

The mass concentration of the dust particles in the mixture (k_p) is as follows [19]

\[ k_p = \sigma Z \] (5)

where \( \sigma = \frac{\rho_p}{\rho} \) is the ratio of density to solid particle to the specific density of a non-ideal gas(dust loading parameter) \( \rho_p \) is the species density of dust particles. The range of σ is form σ=1 to ∞. The fundamental parameters of Pai model[19] are k_p and σ. The internal energy is given by[19]

\[
\varepsilon = p \left( 1-Z \right) \left[ \rho \left( \Gamma-1 \right) \left( 1+b \rho \left( 1-k_p \right) \right) \right]
\] (6)

Initial volume fraction is given by[19],[30]

\[
Z_o = k_p \left[ \sigma \left( 1-k_p \right) + k_p \right]
\] (7)

At equilibrium two phase flows for an isentropic change of state of the mixture, the speed of sound is given by [13]

\[
a^2 = \frac{p \left[ \Gamma + \left( 1-Z \right) b \rho \left( 1-k_p \right) \right]}{\rho \left( 1-Z \right)}
\] (8)

At the equilibrium, state of the gas is assumed to be specified by the condition

\[
\frac{1}{\rho_o} \frac{dp_o}{dr} - r \Omega_o^2 = 0
\] (9)

On solving the above equation becomes

\[
p_o = \frac{1}{2} \rho_o r^2 \Omega_o^2
\] (10)

Hence from equation (8) speed of sound in undisturbed medium \( a_o \) is given by

\[
a_o^2 = \left[ \frac{\Gamma + \left( 1-Z_o \right) b \rho \left( 1-k_p \right)}{2 \left( 1-Z_o \right)} \right] r^2 \Omega_o^2
\] (11)

The jump conditions across the strong shock are given by[12],[14] and [23]

\[
u = (1-\beta)U
\] (12)

\[
\rho = \rho_o / \beta
\] (13)

\[
p = (1-\beta) \rho_o U^2
\] (14)

\[
Z = Z_o / \beta
\] (15)

The quantity \( \beta (0 < \beta < 1) \) is obtained by the relation

\[
\frac{2(\beta-Z)\beta}{\rho \left( \Gamma-1 \right) \left( \beta + b \left( 1-k_p \right) \right) p U} + \beta = \left[ 1 + \frac{2(F_2-F_1)}{p U} \right] = 0
\] (16)
where the suffix “o” represents the values at front of shock and $b_0 = b \rho_0$ is the parameter of non-idealness of the mixture.

For strong shock, it is assumed that $F_1 F_2$ is negligible in the comparison to the product of $U$ and $p[14]$, therefore equation (17) may be written as

$$\beta^2 (\Gamma +1) + \beta [b(1-k_r) - 1] (\Gamma -1) - 2Z_o = 0$$

(17)

where $\beta$ is shock density ratio.

Using jump conditions the speed of sound behind the spherical strong shock is given by

$$a^2 = U^2 \left[ \frac{1}{\beta - Z_o} \right]$$

(18)

(a) Freely propagation

For spherical converging shocks, the characteristic form of the system of basic equations (1)-(3) is

$$dp - \rho a du + \frac{2 \rho a^2 u dr}{(u-a) r} + \frac{2 \rho a v dr}{(u-a) r} = 0$$

(19)

Substituting the values of respective quantities from boundary conditions (12)-(18). At constant initial density distribution ($\rho_0 = \text{constant}$ and $v_0 = \Omega_0$), after simplifying, we have

$$\frac{dU^2}{dr} + M \frac{U^2}{r} = N \Omega_0^2$$

(20)

where

$$M = \frac{4}{\eta - \mu +1} = M \left[ \Gamma, \beta, Z_o, b, k_p \right]$$

$$N = \frac{2(\beta - Z_o)(\beta +1)}{(1- \beta)^2 \mu (\mu - \eta -1)} = N \left[ \Gamma, \beta, Z_o, b, k_p \right]$$

$$\eta = \frac{4 \beta (\beta - Z_o)}{[\Gamma \beta^2 + (\Gamma \beta - Z_o) b(1-k_p)]}$$

$$\mu^2 = \frac{(1+ \beta) \beta - Z_o}{(1- \beta) [\Gamma \beta^2 + (\Gamma \beta - Z_o) b(1-k_p)]}$$

On integrating equation (20), we have

$$U = \left[ \frac{r^2 \Omega_0^2}{M + 2} + Kr^{-M} \right]^\frac{1}{2}$$

(21)

This equation represents the expression for the shock velocity just behind the shock for freely propagation. Using equation (11), (14) and (12), the analytical expressions for shock strength($U/a_o$), non-dimensional pressure($p/p_0$) and particle velocity($u/a_o$) for freely propagation of spherical converging shock in dusty non-ideal gas may be written as, respectively

$$U/a_o = \left[ \frac{2(1-Z_o)}{(1+ \beta) [\Gamma + (\Gamma - Z_o) b(1-k_p)]} \right]$$

(22)

$$p/p_o = \left[ \frac{2(1-Z_o) (1- \beta)}{(1+ \beta) (1+ \beta) [\Gamma + (\Gamma - Z_o) b(1-k_p)]} \right]$$

(23)

(b) Effect of overtaking disturbances

It is assumed that shock propagates along C, characteristic and produces velocity increment $du$, whereas overtaking wave propagate along $C_*$ characteristic create velocity increment $du_*$. For $C_*$ disturbance, the fluid velocity increments form the equation (12) [3]

$$du_* = (1- \beta) du$$

(25)

Now substituting the value of $dU$ from equation (20), we get

$$du_* = \left[ \frac{(1- \beta)}{2U} \left( N \Omega_0^2 - M \frac{U^2}{r} \right) \right]^*$$

(26)

To estimate the strength of overtaking disturbance an independent $C_*$ disturbances is considered. The characteristics equation for the $C_*$ disturbances is given by

$$dp + \rho a du + \frac{2 \rho a^2 u dr}{(u+a) r} - \frac{2 \rho a v^2 dr}{(u+a) r} = 0$$

(27)

Substituting the values from equations (11)-(21) in equation (27), and after simplifying equation we get the velocity increment for $C_*$ disturbance

$$du_* = \left[ \frac{(1- \beta)}{2U} \left( N \Omega_0^2 - M \frac{U^2}{r} \right) \right]$$

(28)

where

$$M_* = \frac{4}{\eta + \mu +1} = M \left[ \Gamma, \beta, Z_o, b, k_p \right]$$

$$N_* = \frac{2(\beta - Z_o)(1+ \beta)}{(1- \beta)^2 \mu (\mu - \eta -1)} = N \left[ \Gamma, \beta, Z_o, b, k_p \right]$$

Therefore, the net velocity increment [3]

$$du_* - du = (1- \beta) du'$$

(29)

Here $U'$ has been used in place of $U$ to differentiate the shock velocity with overtaking disturbances.

On putting the values from (26) and (28) into above equation, we have
\[
\frac{dU^*}{dr} = N' r \Omega^2 - M^* \frac{U^2}{r}
\]

where \( N' = N - N_s \) and \( M^* = M - M_s \).

On solving the equation (30), we get the modified expression for the shock velocity \( U^* \) for spherical converging strong shock under the influence of overtaking disturbances.

\[
U^* = \left( r^2 \Omega^2 - \frac{N'}{M' + 2} + K r^{M^* - 2} \right)^{1/2}
\]  

(31)

Using equation (11) and equation (31), modified shock strength \( U/\text{a}_0 \) just behind the shock under the effect of overtaking disturbances may be written as

\[
\frac{U^*}{\text{a}_0} = \left[ \frac{2(1-Z_b)}{(\Gamma+\Gamma-Z_b)\lambda(1-k_p)} \left( \frac{N'}{M' + 2} + K r^{M^* - 2} \right) \right]^{1/2}
\]

(32)

The expression for non-dimensional pressure \( p/p_0 \) and flow velocity in the region behind the shock modified by overtaking disturbances is given by, respectively

\[
\frac{p^*}{p_0} = \frac{2(1-\beta)}{(1-Z_b)} \left( \frac{N'}{M' + 2} + K r^{M^* - 2} \right)
\]

(33)

The expression for non-dimensional particle velocity \( U/\text{a}_0 \) in the region behind the shock is given by

\[
\frac{u^*}{\text{a}_0} = \left[ \frac{2(1-Z_b)(1-\beta)}{(\Gamma+\Gamma-Z_b)\lambda(1-k_p)} \left( \frac{N'}{M' + 2} + K r^{M^* - 2} \right) \right]^{1/2}
\]

(34)

III RESULTS AND DISCUSSION

Analytical expressions (21)-(24) and (31)-(34) represent the shock velocity, shock strength, pressure and particle velocity just behind the spherical converging strong shock in a dusty non-ideal gaseous medium having solid body rotating initial density distribution both for freely propagation and under effect of overtaking disturbances.

Initial volume fraction of solid particles in medium \( Z_0 \) depends on mass concentration of solid particles in the mixture \( k_p \) and ratio of the density of solid particle to the density of gas. Values of initial volume fraction \( Z_0 \) for some values of \( k_p \) and \( \sigma \) are calculated from the equation (13). Initially taking \( U/a_0=15 \) for strong shock at \( r=1.1 \) for \( k_p=0.1, \sigma=20, b=0.02, Z_b=0.00222, \beta=0.16, \gamma=1.4 \) and \( \Gamma=1.36 \) the variation of shock velocity, shock strength, non-dimensional pressure and non-dimensional particle velocity with propagation distance \( r \) have been calculated and displayed through figures (1-4). It is found from figure (1-4) that all the flow variables increase as strong shock converges dusty non-ideal gas. The dotted line(…) shows the increment in the values of all flow variables, when effect of overtaking taken is into account. The similar variation of all flow variables with propagation distance have been reported by [28] for the case of uniform density distribution. It is also observed from figures (1-4) that strength of the strong spherical converging shock increases as the realness of the gaseous phase of the mixture increase \( \beta=0, 0.01 \) and \( 0.02 \). The variation of all flow variables with concentration of dust particles in the mixture \( k_p \) are shown in the figures (5-9) and it is found that as \( K_p \) increases, the values of all flow variables increase. The similar results have also been obtained by [29] in case of self-gravitating dusty gas. It may be concluded from the general observation of these figures that the consideration of non-idealness of the gas has significant role on the variation of all flow variables [cf Fig (1-8)].

![Figure 1 Variation of Shock velocity with propagation distance (r)](image-url)
Figure 2 Variation of shock strength with propagation distance (r)

Figure 3 Variation of pressure with propagation distance (r)
Figure 4: Variation of particle velocity with $r$ ($\cdot$ for EOD and $O$ for $\bar{b}=0$, * for EOD at $\bar{b}=0.02$)

Figure 5: Variation of shock velocity with $k_p$ at $\bar{b}=0.01$ (* for EOD and + for FP)
Figure 6: Variation of shock strength with $k_p$ at $\bar{\eta}=0.01$ (O for EOD and + for FP).

Figure 7: Variation of pressure ($p/p_0$) with $k_p$ at $\bar{\eta}=0.01$ (O for EOD and + for FP)
REFERENCE


