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Analysis of Cylindrical Imploding Shock Wave in Dusty Real Gas with Exponential Varying Density

P. K. Gangwar[1], Deepak Kumar[2]
[1]*Department of Physics, Bareilly College, Bareilly-243001, U.P.*
[2]*Department of Physics, Shari Venkateshwara University, Gajraula, Amroha,-244236, U.P. INDIA*

Abstract: In this paper, the effect of overtaking disturbances has been estimated on the propagation of cylindrical imploding strong shock wave in a real dusty gas. It is assumed that the dusty gas is the mixture of a real gas and a large number of small spherical solid particles of uniform size. Considering the exponential varying initial density distribution, analytical expressions for shock strength and shock velocity immediately behind the shock have been derived for freely as well as under the influence of overtaking waves. The modified expressions for the non-dimensional pressure and flow velocity have also been obtained. The variations of all the flow variables have been computed and discussed through graphs. It is observed that the presence of dust particles has a significant role in the shock wave propagation and the shock is strengthened, as the non-idealness (realness) of the gases mixture increases. Finally the results obtained here are compared with earlier results as well as those for ideal dusty gas having uniform initial density distribution.
Keywords: Effect of overtaking disturbances, CCW, dusty, imploding, real gas, shock.

I. INTRODUCTION

Propagation of shock wave in a dusty gas has received considerable attention due to its application to space science, bomb blast, lunar ash flow, coal mine explosions, nozzle flow, missiles and other engineering problems. Severalauthors (Carrier[1], Taylor[2], Seddon[3], Marble[4], Pai et al[5], Miura and Glass[6], Ingra et. al.[7], Greeter and Regenfelder[8] have considered and discussed the problem of shock wave propagation, experimentally and theoretically. Vishwakarma[9] generalized Ray and Bromwich[10] solution in dusty ideal gashaving exponentially varying initial density distribution, using a non-similarity method and obtained that the presence of small spherical dust particles in the gaseous medium has significant effects on the variation of shock strength and other flow variables. Vishwakarma and Nath [11] have found the self-similar solution of the problem of exponential shock in a dusty gas. Propagation of shock wave in a mixture of ideal gas and small dust particles with radiation heat flux and exponentially varying density has been investigated by Vishwakarmaet. al.[12] using similarity method. Using CCW method, Yadav et al.[13] have explored the problem of propagation of weak cylindrical shock in the mixture of ideal gas and dust particle in presence of constant axial magnetic field. Singh and Gogoi [14] have use the equation of state for non-ideal gases simplified by Anisimov and Spiner[15], to study the propagation of spherical shock wave in the mixture of non-ideal gas and dust particles by similarity solutions. Recently, the effect of self-gravitation on the propagation of cylindrical imploding strong shock wave in dusty ideal gas is analysed by using CCW method by Deepak et. al.[16]. Neglecting the effect of overtaking disturbances, Prakashet. al. [17] have investigated the problem of shock wave propagation in a real gas having uniform initial density distribution.

Very recently, Gangwar [18] has studied theoretically the effect of overtaking disturbances on adiabatic propagation of cylindrical strong shock waves in mixture of small spherical inert dust particles and a real gas having power varying initial density distribution. He found that the consideration of flow behind the shock has a significant effect on the flow variables of shock propagation.

The aim of the present study is to investigate the motion of cylindrical imploding shock in a real dusty gas having uniform initial density distribution by using CCW (Chester[19]-Chisnell[20]-Whitham[21]) method, The effect of overtaking disturbances (EOD) on the freely propagation of shock is included using a technique developed by Yadav[22]. The strength of overtaking waves is estimated under the assumption that both C_+ and C_- disturbances propagate in the medium of same density distribution. It is assumed that the real (non-ideal) dusty gas is the mixture of real gas and a large number of small spherical solid particles of uniform size. The particles are inert and uniformly distributed in the gas. Initial volume fraction of the solid particles is also assumed constant in this particular study. The particles do not interact with each other therefore their thermal motion is negligible. Initial density of the medium is taken to be constant and medium ahead of the shock front is at rest with small counter pressure. We also assumed that the particles behave like a pseudo-fluid. Maintaining the equilibrium flow condition in the flow field, the analytical expressions for the shock velocity, shock strength, pressure, and flow velocity have been derived. The variation of flow variables with propagation distance (r), mass concentration of solid particles in the mixture (k_p) and the ratio of the density of solid particles to the initial density of gas (σ) are obtained and discussed through figures. The results accomplished are compared with those for dusty ideal gas [13] and earlier results for real dusty gas[18].

II. BASIC EQUATIONS

The governing equations for one dimensional, unsteady, adiabatic and cylindrical symmetrical flow of a mixture of real (non-ideal) gas and small spherical solid particles can be written as[12]-[14]

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}+\frac{1}{\rho}\frac{\partial p}{\partial r}=0 \tag{1}$$

$$\frac{\partial \rho}{\partial t}+u\frac{\partial \rho}{\partial r}+\rho\frac{\partial u}{\partial r}+\frac{\rho u}{r}=0 \tag{2}$$

$$\frac{\partial \varepsilon}{\partial t}+u\frac{\partial \varepsilon}{\partial r}+\frac{p}{\rho^2}\left(\frac{\partial \rho}{\partial t}+u\frac{\partial \rho}{\partial r}\right)=0 \tag{3}$$

where, u, p, ρ andεdenote respectively, the flow velocity, the pressure and density at a distance r from the origin at time 't'.

It is assumed that dusty real gas to be a mixture of a real (non-ideal) gas and small spherical solid particles. The equation of state of the pseudo-fluid of solid particles in the medium is simply [14], [15]

$$\rho_{sp}=\text{constant} \tag{4}$$

Whereρ_{sp} is the species density of solid particles. The equation of state of the mixture of real gas and small solid particles is given by[14]

$$p=\frac{\left(1-k_p\right)}{1-Z}\left[1+b\bar{\rho}\left(1-k_p\right)\right]\rho R^{*}T \tag{5}$$

Where Z is the volume fraction of solid particles in the mixture, R^* is the gas constant for medium, T the temperature, $K_p$is the mass concentration of solid particles in the mixture.

The relation between k_p and Z is as follows [23]

$$k_p=Z\rho_{sp}/\rho \tag{6}$$

Where$\rho_{sp}$is the species density of solid particles. In equilibrium flow, $K_p$is a constant in the whole flow-field. Therefore from the equations (4) and (6) we have

$$k_p=Z/\rho=\text{constant} \tag{7}$$

We have the relation for Z is[23,24]

$$Z=K_p\Big/\left\{\sigma\left(1-k_p\right)+k_p\right\} \tag{8}$$

Where $\sigma=\rho_{sp}/\rho$ the ratio of density to solid particle to the specific density of a realgas(specific density), Hence the fundamental parameters of the Pai model are K_p and σ which describe the effects of the dust-loading. For the dust loading parameterσ, we have range of σ=1 to $\sigma\to\infty$.

The internal energy of the mixture can be written as follows [23]

$$\varepsilon=\left[K_pC_{sp}+\left(1-K_p\right)C_v\right]T=C_{vm}T \tag{9}$$

Where C_{sp} is the specific heat of solid particles, C_v the specific heat of the gas at constant volume process and C_{ame} the specific heat of the mixture at constant volume process.

The specific heat of the mixture at constant pressure process is given by

$$C_{pm}=K_pC_{sp}+\left(1-K_p\right)C_p \tag{10}$$

Where C_p is the specific heat of the gas at constant pressure process.

The ratio of specific heat of the mixture is[23]

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$$\Gamma = \frac{C_{pm}}{C_{vm}} = \frac{\gamma + \delta\Phi}{1 + \delta\Phi} \tag{11}$$

where $\gamma = \frac{C_p}{C_v}, \delta = \frac{K_p}{1 - K_p}$ and $\Phi = \frac{C_{sp}}{C_v}$

Therefore, internal energy is given by

$$\varepsilon = \frac{p(1-Z)}{\rho(\Gamma - 1)\left[1 + b\rho(1-k_p)\right]} \tag{12}$$

The initial volume fraction of the solid particles Z_o is, in general not a constant, but the volume occupied by the solid particles is very small because the density of the solid particles is much larger than that of the gas [14], hence Z_o may be assumed a small constant and is given by[24]

$$Z_o = K_p / G(1-k_p) + k_p \tag{13}$$

The speed of sound *'a'* in the equilibrium two phase flow for an isentropic change of state of the mixture of the real gas and small spherical solid particles may be calculated as [14] on neglecting $b^2\rho^2$ and higher order terms.

$$a^2 = \frac{p}{\rho(1-Z)}\left[\Gamma + (\Gamma - Z)b\rho(1-k_p)\right] \tag{14}$$

The speed of sound in unperturbed medium a_o is given by the relation

$$a_0^2 = \frac{p_o\left\{\Gamma + (\Gamma - Z_o)\bar{b}(1-k_p)\right\}}{\rho_o(1-Z_o)} \tag{15}$$

To represent the quantities u, p, ρ and Z in terms of their undisturbed values, the jump conditions across the strong shock are given by[12],[14] and [23]

$$u = (1-\beta)U, \quad \rho = \rho_o/\beta, \quad p = (1-\beta)\rho_o^2 U^2, \quad Z = Z_o/\beta \tag{16}$$

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

$$2(\beta - Z)\beta \Big/ \left[\rho(\Gamma - 1)\left\{\beta + \bar{b}(1-k_p)\right\}\right] + \beta - \left[1 + 2(F_2 - F_1)/pU\right] = 0 \tag{17}$$

where $\bar{b} = b\rho_o$ (say) and U=dR/dt denotes the shock velocity, R is the shock radius, $U/a_o = M$ is the Mach number, the suffix "$_o$" refers to the values in front of the shock.

As the shock is strong, we assume F_1-F_2 to be negligible in the comparison with the product of p and U [14], therefore above equation may be written as

$$\beta^2(\Gamma + 1) + \beta\left[\left\{\bar{b}(1-k_p) - 1\right\}(\Gamma - 1) - 2Z_o\right] - (\Gamma - 1)\bar{b}(1-k_p) = 0 \tag{18}$$

where the quantity β is the shock density ratio which is an unknown parameter to be determined. Using the boundary conditions the speed of sound is given by

$$a = \sqrt{(1-\beta)\left\{\Gamma\beta^2 + (\Gamma\beta - Z_o)\bar{b}(1-k_p)\right\} / (\beta - Z_o)}\,U \tag{19}$$

We consider that a strong shock wave is proposed into a medium, at rest, with negligibly small counter pressure. Also the initial density of the medium (mixture of a non-ideal gas and small spherical solid particles) is assumed to obey the exponential law

$$\rho_o = \alpha e^{\lambda r} \tag{20}$$

whereα is the density at the centre and λ is the density parameter which is a positive constants.

A. For freely propagation(FP)

For cylindrical imploding shock, the characteristic form of the system of equations (1)-(3), is given by

$$dp - \rho a du + \frac{\rho a^2 u}{(u-a)}\frac{dr}{r} = 0 \tag{21}$$

Substituting the values from equations (16)-(19) and (20) in above equation, we have

$$\frac{dU}{U} + L\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)\frac{dr}{r} + M\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)dr = 0 \tag{22}$$

where $L\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right) = \dfrac{1}{\left[\dfrac{2\beta(\beta-Z_o)}{\left\{\Gamma\beta^2+(\Gamma\beta-Z_o)\bar{b}(1-k_p)\right\}} - \sqrt{\dfrac{(1+\beta)^2(\beta-Z_o)}{(1-\beta)\left\{\Gamma\beta^2+(\Gamma\beta-Z_o)\bar{b}(1-k_p)\right\}}}+1\right]}$

$$M\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right) = \frac{\lambda}{\left[2-\dfrac{1}{\beta}\sqrt{\dfrac{(1-\beta)\left\{\Gamma\beta^2+(\Gamma\beta-Z_o)\bar{b}(1-k_p)\right\}}{(\beta-Z_o)}}\right]}$$

On solving, we get

$$U = K\exp\left\{-M\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)r\right\}r^{-L\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)} \tag{23}$$

where K is the constant of integration.
This is the expression for the shock velocity for the freely propagation(FP) in the dusty real gas.
At the equilibrium state $u = 0 = \partial/\partial t$, and $\rho_o = \alpha e^{\lambda r}$ the equation (1) gives

$$p_o = \alpha e^{\lambda r}/\lambda \tag{24}$$

On putting the value of P_o and ρ_o, we have

$$a_o^2 = \frac{\Gamma+(2\Gamma-Z_o)\bar{b}(1-k_p)}{(1-Z_o)\left\{1+b(1-k_p)\right\}\lambda} \tag{25}$$

Using equation (23) and (25)the expression for the shock strength(U/a_o) is given by

$$\frac{U}{a_o} = K\sqrt{\frac{\lambda(1-Z_o)}{\left\{\Gamma+(\Gamma-Z_o)\bar{b}(1-k_p)\right\}}}\exp\left\{-M\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)r\right\}r^{-L\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)} \tag{26}$$

B. Effect of overtaking disturbances(EOD)

The fluid velocity increment due to overtaking disturbances, using boundary conditions and equation (22), we have

$$du_- = (1-\beta)dU \tag{27}$$

Using equation (22), after simplifying the equation (27), becomes

$$du_- = (1-\beta)\left[L\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)\frac{dr}{r} + M\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)dr\right]U \tag{28}$$

To estimate the strength of overtaking disturbance (i.e. effect of flow behind the shock) an independent C_+ disturbances is considered. The characteristics equation for C_+ disturbances is given by

$$dp + \rho a du + \frac{2\rho a^2 u}{(u+a)}\frac{dr}{r} = 0 \tag{29}$$

Substituting the values from equations (16)-(19) and (20) in equation(29), we have

$$\frac{dU}{U} + L_1\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)\frac{dr}{r} + M_1\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)dr = 0 \tag{30}$$

where $L_1\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)=\dfrac{1}{\left[\dfrac{2\beta(\beta-Z_o)}{\left\{\Gamma\beta^2+(\Gamma\beta-Z_o)\bar{b}(1-k_p)\right\}}+\sqrt{\dfrac{(1+\beta)^2(\beta-Z_o)}{(1-\beta)\left\{\Gamma\beta^2+(\Gamma\beta-Z_o)\bar{b}(1-k_p)\right\}}}+1\right]}$

$$M_1\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)=\frac{\lambda}{\left[2+\dfrac{1}{\beta}\sqrt{\dfrac{(1-\beta)\left\{\Gamma\beta^2+(\Gamma\beta-Z_o)\bar{b}(1-k_p)\right\}}{(\beta-Z_o)}}\right]}$$

The fluid velocity increment due to overtaking disturbances, using equation

$$du_+=(1-\beta)\left[L_1\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)\frac{dr}{r}+M_1\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)dr\right]U \tag{31}$$

The resultant fluid velocity increment will be due to both C_- and C_+ disturbances. Therefore the net increase in fluid velocity[22]

$$du_- - du_+ = (1-\beta)dU^* \tag{32}$$

On putting the values from (28) and (31), the equation (32) gives

$$\frac{dU^*}{U^*}+\left[L^*\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)\right]\frac{dr}{r}+\left[M^*\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)\right]dr=0 \tag{33}$$

where $L^*\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)=L\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)-L_1\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)$

$$M^*\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)=M\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)-M_1\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)$$

On integrating the expression for shock velocity(U^*) and shock strength(U^*/a_o) under the influence of overtaking disturbances (modified shock velocity) may be given as

$$U^*=K\exp\left\{-M^*\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)r\right\}r^{-L^*\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)} \tag{34}$$

$$\frac{U^*}{a_o}=K\sqrt{\frac{\lambda(1-Z_o)}{\left\{\Gamma+(\Gamma-Z_o)\bar{b}(1-k_p)\right\}}}\exp\left\{-M^*\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)r\right\}r^{-L^*\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)} \tag{35}$$

III. RESULTS AND DISCUSSIONS

The expressions for pressure (p/p_o), flow velocity(u/a_o) for freely propagating shock and modified pressure (p^*/p_o) and flow velocity(u^*/a_o) under the influence of overtaking waves are given by, respectively

$$\frac{p}{p_o}=(1-\beta)\lambda K^2\exp 2\left\{-M\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)r\right\}r^{-2L\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)} \tag{36}$$

$$\frac{u}{a_o}=(1-\beta)K\sqrt{\frac{\lambda(1-Z_o)}{\left\{\Gamma+(\Gamma-Z_o)\bar{b}(1-k_p)\right\}}}\exp\left\{-M\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)r\right\}r^{-L\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)} \tag{37}$$

$$\frac{p^*}{p_o}=(1-\beta)\lambda K^2\exp 2\left\{-M^*\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)r\right\}r^{-2L^*\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)} \tag{38}$$

$$\frac{u^*}{a_o}=(1-\beta)K\sqrt{\frac{\lambda(1-Z_o)}{\left\{\Gamma+(\Gamma-Z_o)\bar{b}(1-k_p)\right\}}}\exp\left\{-M^*\left(\beta,\Gamma,Z_o,k_p,\bar{b},\lambda\right)r\right\}r^{-L^*\left(\beta,\Gamma,Z_o,k_p,\bar{b}\right)} \tag{39}$$

Initial volume fraction of solid particles in medium (Z_o) 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_o for some values of k_p and σ are calculated from the equation (13).Initially taking shock strength U/a_o=12 at r=1.1 for k_p=0.1, σ=50, $\bar{b}$=0.02, Z_o=0.00222, β=0.16, γ=1.4α=1, λ=1.1 and Γ=1.36 the variation of shock velocity, shock strength, non-dimensional pressure and non-dimensional flow velocity with propagation distance(r) have been calculated and displayed through figures(1-8,11-14). It is observed that shock strength increases asymptotically as cylindrical shock implodes in the medium. It is clear from the graphs that under the effect of

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overtaking disturbances increase are more prominent and when non-ideal gas taken into account, the increase is slightly sharper. Figures (5-14) represents the variation of all flow variables with respect to propagation distance (r) for different values of concentration of dust particles in the mixture(k_p)*viz*k_p=0.1and 0.4[cf Fig. (5-8)] and σ= 50,100,200, 300 and 500[cf. Fig. (9-10)] and also with different values of density parameter (λ)*viz*λ= 0.1 and 0.2[cf. Fig. (11-14)]. Analysis of the graphs shows that all flow variable increases with propagation distance and increase is more prominent for effect of overtaking disturbances. The trends of figures (1-4) shows that all flow variables increase gradually with $\bar{b}$ for freely propagation in respect of their modified values under the influence of the flow behind the shock (EOD). It is also observed that the increase in all flow variables vary slowly with k_p. This Increasing pattern is almost same for EOD with slightly larger values. It is clear from figures(9-10) the shock velocity and shock strength both decreases with dust loading ratio(σ) for both freely as well as EOD. Figure(11-14) represents that shock is strengthened as the density parameter (λ) increases. The similar variation of all flow variables with propagation distance have been reported by [18] for power varying initial density distribution. It may be concluded from the general observation of these figures that the consideration of non-idealness (realness) of the gas have significant role on the variation of all flow variables. The consideration of the effect of the flow behind the shock front (EOD) is also important for the accuracy of the results obtained by the CCW theory.

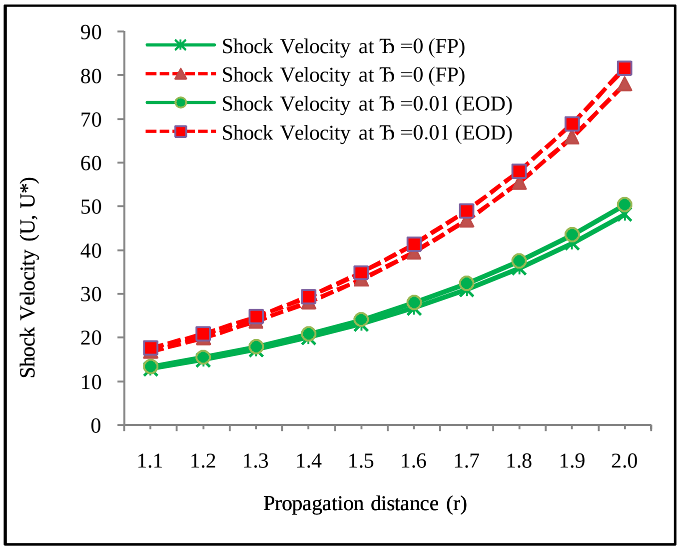

Figure 1: Variation of shock velocity with propagation distance (r) for $\bar{b}$=0,0.01 at K_p =0.1, λ=1.1, σ=50.

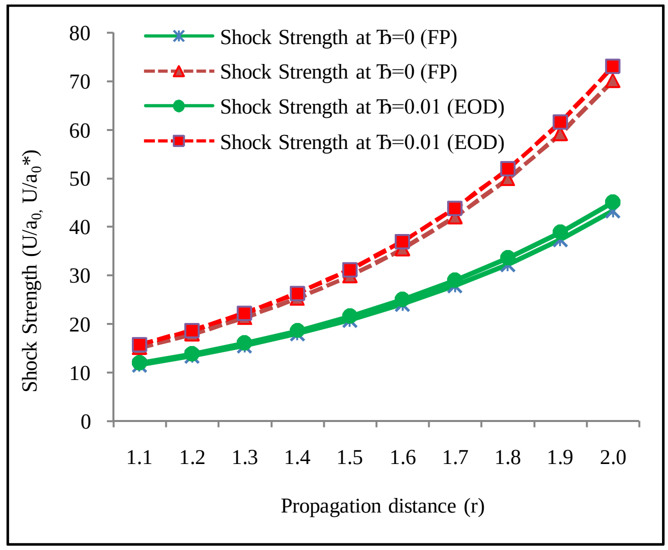

Figure 2: Variation of shock strength with propagation distance (r) for $\bar{b}$=0,0.01 at K_p =0.1, λ=1.1, σ=50.

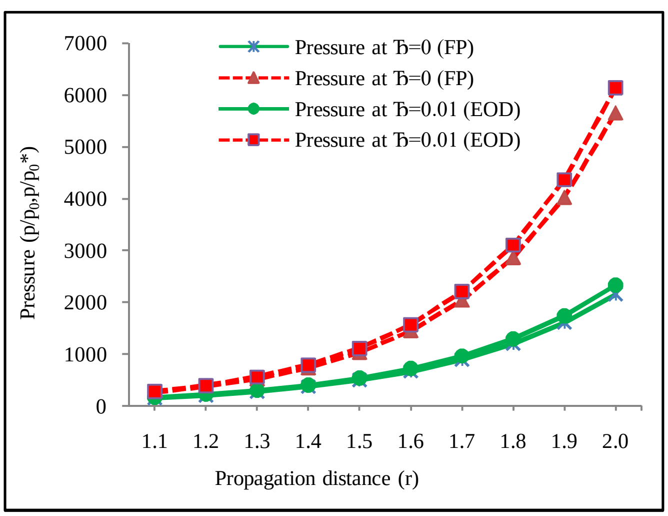

Figure 3: Variation of pressure with propagation distance (r) for $\bar{b}$=0,0.01 at K_p =0.1, λ=1.1, σ=50.

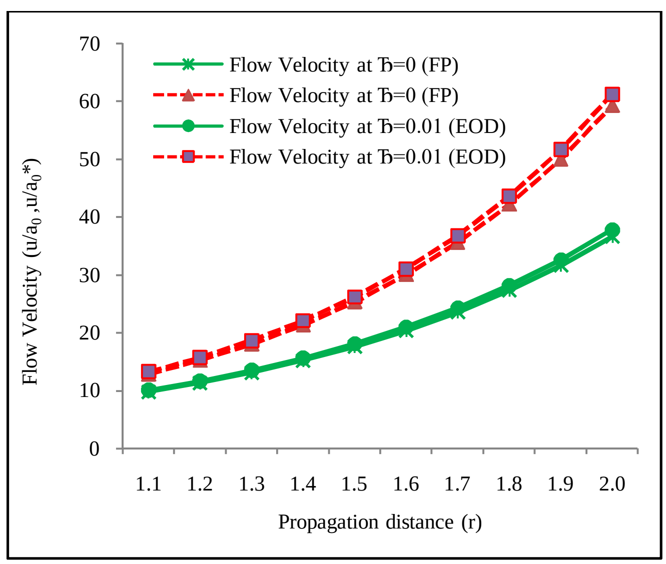

Figure 4: Variation of flow velocity with propagation distance (r) for $\bar{b}$=0,0.01 at K_p =0.1, λ=1.1, σ=50.

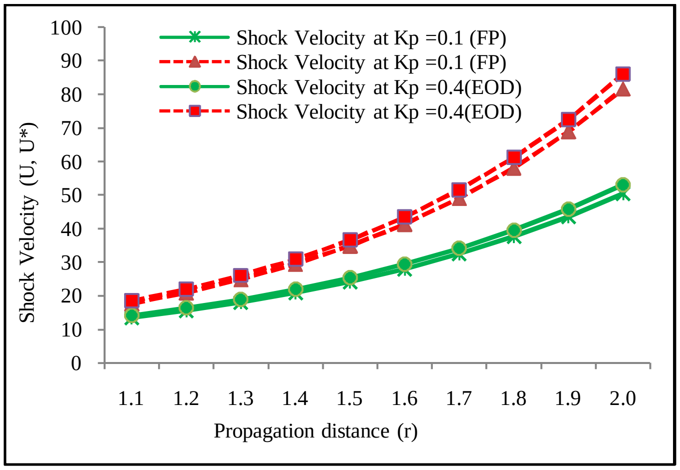

Figure 5: Variation of shock velocity with propagation distance (r) for at K_p =0.1,0.4 for $\bar{b}$=0.01, λ=1.1, σ=50.

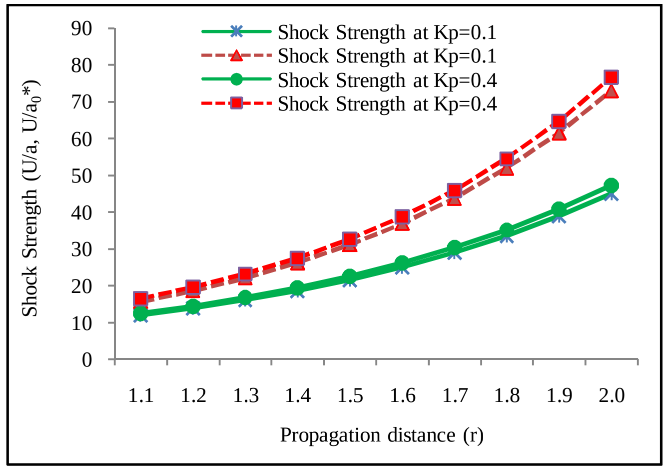

Figure 6: Variation of shock strength with propagation distance (r) for at K_p =0.1,0.4 for $\bar{b}$=0.01, λ=1.1, σ=50.

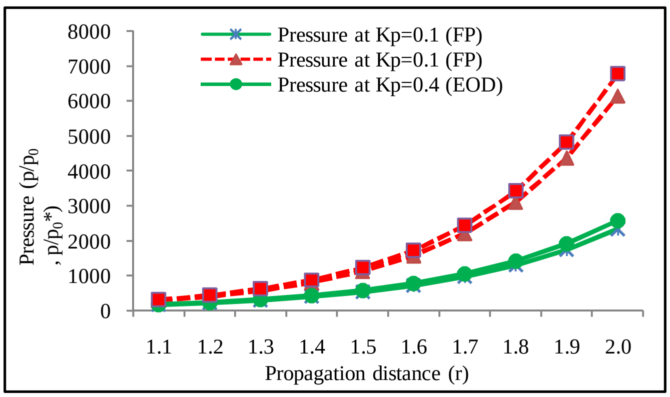

Figure 7: Variation of pressure with propagation distance (r) for at K_p =0.1,0.4 for $\bar{b}$=0.01, λ=1.1, σ=50.

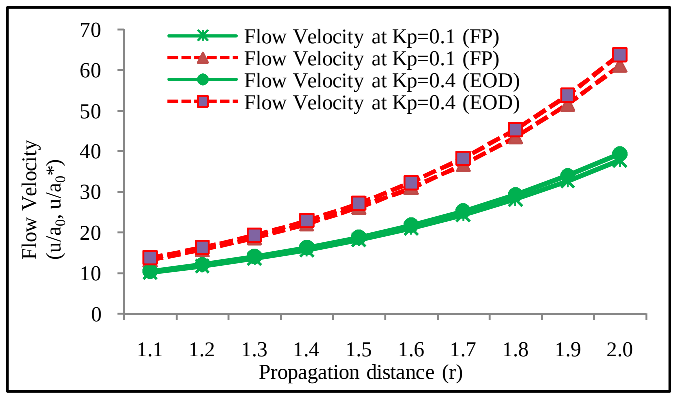

Figure 8: Variation of flow velocity with propagation distance (r) for at K_p =0.1,0.4 for $\bar{b}$=0.01, λ=1.1, σ=50.

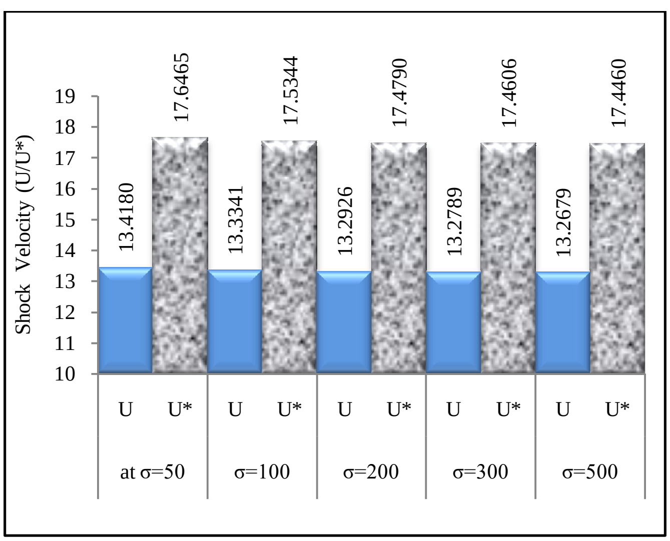

Figure9: Variation of shock velocity with σ.

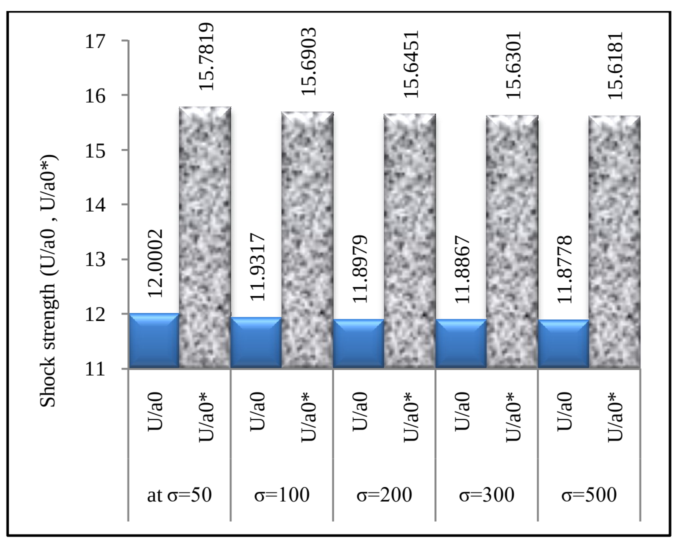

Figure 10: Variation of shock strength with σ.

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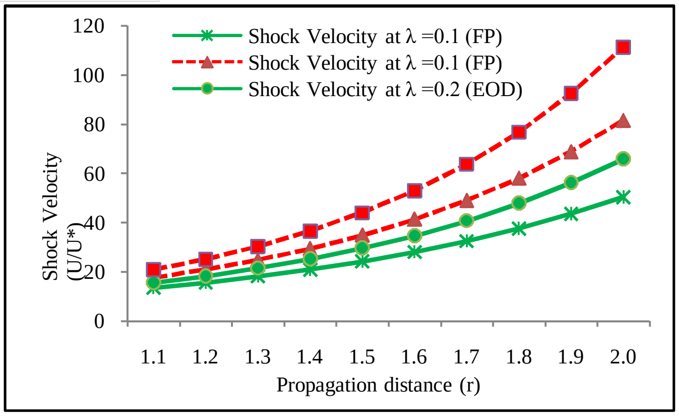

Figure 11: Variation of shock velocity with propagation distance (r) for λ=0.1, 0.2 at $\bar{b}$=0.01 at K_p =0.1, , σ=50.

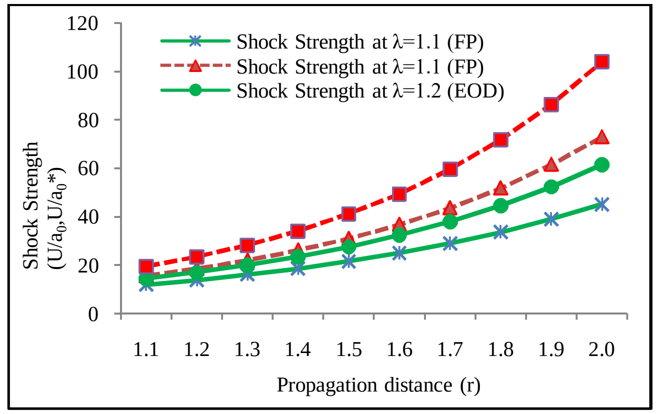

Figure 12: Variation of shock strength with propagation distance (r) for λ=1.1,1.2 at $\bar{b}$=0.01 at K_p =0.1, , σ=50.

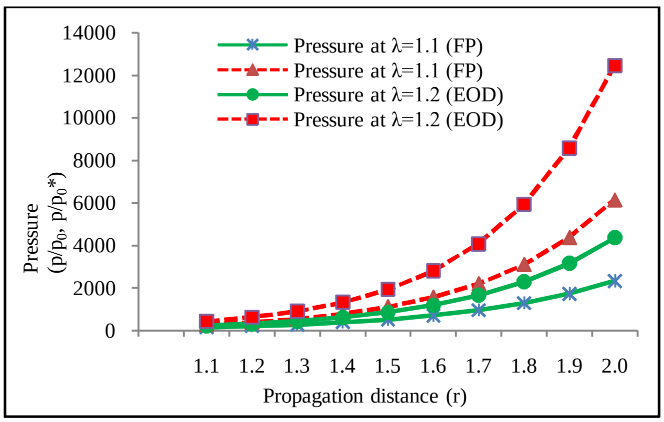

Figure 13: Variation of pressure with propagation distance (r) for λ=1.1,1.2 at $\bar{b}$=0.01 at K_p =0.1, , σ=50.

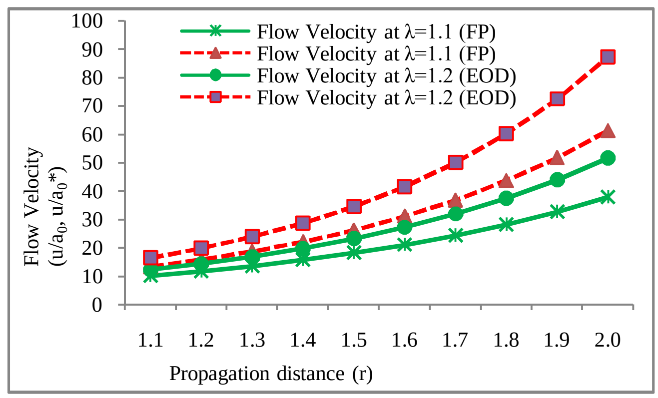

Figure 14: Variation of flow velocity with propagation distance (r) for λ=1.1,1.2 at $\bar{b}$=0.01 at K_p =0.1, , σ=50.

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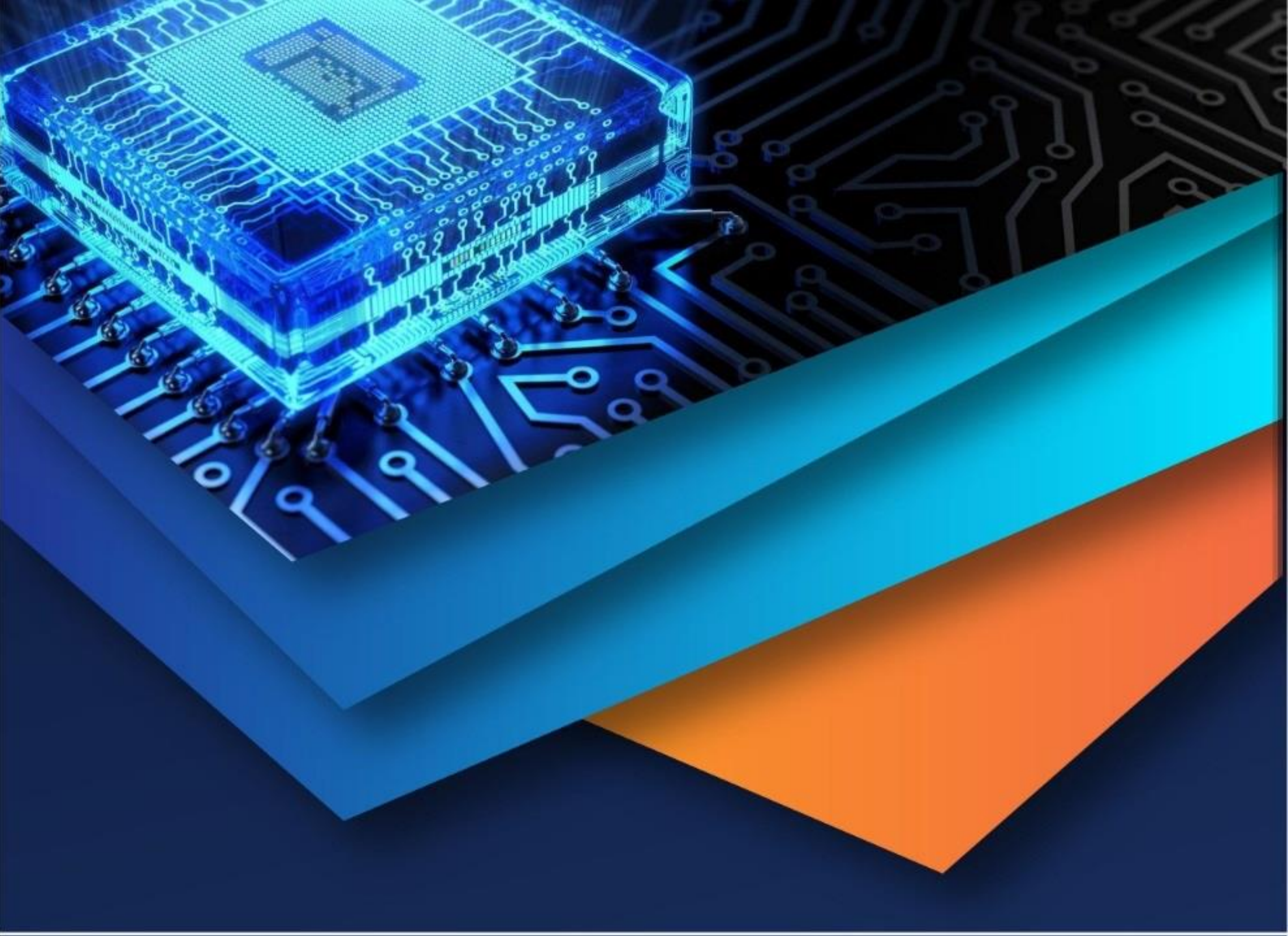

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