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Propagation of Shock Waves in a Non-Ideal Dusty Gas with Heat Radiation

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Abstract: In present problem a similarity solution for the propagation of spherical shock wave in a mixture of non-ideal gas and small solid particles with heat radiation flux is obtained. In course of derivation solid particles are considered as pseudo-fluid and the equilibrium flow condition is assumed to be maintained. The total energy of the shocked gas (between shock front and the inner expanding surface) is assumed to be increasing with time. The effects due to presence of non-idealness parameter, the mass concentration of the solid particles and volumetric extension of the solid particles are investigated in presence of heat radiation.

Keywords: shock waves, non-ideal gas, dusty gas, pseudo-fluid.

Mathematics Subject Classification: 2010-76L05.

1. Introduction

The problem of propagation of shock waves in dusty gases has attracted many research workers because of its wide range of applications in nozzle flow, lunar ash flow, coal-dust-gas explosions, supersonic flight in polluted air, collision of coma with a planet and many other engineering problems (Pai[1], Higashino and Suzuki[2], Miura and Glass[3]). The propagation of self-similar shocks in gases has been studied by many authors such as Taylor[4], Carruset al[5], Rogers[6], Sedov[7], Elliot[8], Sakurai[9], Korobeinikov[10] and many others, under different physical situations. By using the same method of similarity solution the propagation of shock waves in dusty gases has been studied and the effects due to presence of solid particles are investigated by Suzuki et al[11], Pai et al[12], Steiner and Hirschler[13], Vishwakarma and Pandey[14]. Taking into account the effects due to radiation heat transfer, Gretler and Regenfelder[15, 16] have obtained similarity solutions for strong shock waves in a dust-laden gas. This problem of propagation of shock waves in dusty gases has also been studied by Ojha and Srivastava[17] by using energy hypothesis of Thomas[18]. In all the above studies dusty gas is assumed to be a mixture of small particles and a perfect as.

In most of the problems associated with explosion waves the assumption of the gas to be an ideal gas is not true. Taking into account the non-idealness of the gas, the problem of propagation of explosion waves has been studied by Anisimov and Spiner[19], Ranga Rao and Purohit[20], Singh[21], Ojha[22], Vishwakarma and Nath[23] and Ojha& Srivastava[24]. Considering the dusty medium as the mixture of non-ideal gas and small solid particles Vishwakarma and Nath[25] have generalised the solutions given by Steiner and Hirschler[13] for the propagation of strong shock wave in a mixture of a perfect gas and small solid particles driven out by a piston moving according to power law.

At high temperature, intense radiation heat transfer takes place behind a strong shock and therefore an assumption of zero temperature gradient throughout the flow may be taken Korobeinikov[10], Gretler and Regenfelder[16]. Also at high temperature gas being ideal is not correct. Therefore, in present problem, our aim is to present a similarity solution for the propagation of strong shock wave in a mixture of non-ideal gas and small solid particles, taking into account the effect of radiation flux (Gretler and Regenfelder[16]).

Following above studies, the solid particles are considered as a pseudo-fluid and it is assumed that the equilibrium flow condition is maintained. The total energy of the flow between the shock front and the inner expanding surface (a contact surface or a piston) is supposed to be increasing with time. It is investigated that in absence of viscosity how the parameter of non idealness of the gas in the mixture $\bar{b}$, the mass concentration of the solid particles k_p and the ratio of the density of the solid particles to the initial density of the gas G in presence of radiation heat flux affect the flow field behind the shock.

2. Fundamental Equations and Boundary Conditions

The non-steady, one-dimensional flow field is a function of two independent variables: the time t and the space co-ordinate r. The basic conservation equations of mass, momentum and energy for one-dimensional unsteady spherically symmetric flow of a mixture of non-ideal gas and small solid particles with radiation heat-flux in Eulerian co-ordinates are expressed as (Gretler and Regenfelder[16], Ojha and Srivastava[24]).

(2.1) $$\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial r} + \rho\frac{\partial u}{\partial r} + \frac{2\rho u}{r} = 0\,.$$

(2.2) $$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial r}+\frac{1}{\rho}\frac{\partial p}{\partial r}=0.$$

(2.3) $$\frac{\partial e}{\partial t}+u\frac{\partial e}{\partial r}-\frac{p}{\rho^2}\left(\frac{\partial \rho}{\partial t}+u\frac{\partial \rho}{\partial r}\right)+\frac{1}{\rho r^2}\frac{\partial}{\partial r}(r^2F)=0.$$

where ρ is the density, u is the velocity, p is the pressure, e is the internal energy per unit mass and F is the radiation heat flux.

The thermal radiation may be expressed by the one-dimensional radiation-transport equation (Vincenti and Kruger[26]). Considering the radiation diffusion model for an optical thick medium and assuming local thermodynamic equilibrium, the radiation transport equation may be written as

(2.4) $$F=-\frac{16}{3}\frac{\sigma}{\alpha_R}T^3\frac{\partial T}{\partial r}$$

where σ is the Stefan-Boltzmann constant and α_R is the Rosseland mean absorption coefficient.

The equation of state for a mixture of non-ideal gas and small solid particles may be written as (Pai et al[12], Vishwakarma and Nath[25]),

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

where k_p and Z are the mass concentration and volume fraction of solid particles in the mixture, b is the internal volume of the molecules of the gas, R′ is the gas constant and T is the temperature.

The relation between Z and the mass concentration k_p of the solid particles in the mixture taken as a constant in the whole flow field, is given by (Pai et al[12]),

(2.6) $$k_p=\frac{Z\rho_{sp}}{\rho}$$

where $Z=\frac{Z_1}{\rho_1}\rho$, while ρ_{sp} is the species density of the solid particles and Z_1 and ρ_1 are the initial values of Z and ρ respectively. Also, we have the relation

(2.7) $$Z_1=\frac{k_p}{(1-k_p)G+k_p}=\frac{\delta}{G+\delta}$$

where $\delta = \dfrac{k_p}{1-k_p}$ and $G = \dfrac{p_{sp}}{\rho_g}$ is the ratio of the density of solid particles to the species density of the gas. G represents volumetric extension of dust in the mixture.

The internal energy per unit mass of the mixture may be written as (Vishwakarma & Nath[25])

(2.8) $$e = \frac{p(1-Z)}{(\Gamma-1)\rho\{1+b\rho(1-k_p)\}}$$

where Γ is the ratio of the specific heats of the mixture and is given by

(2.9) $$\Gamma = \frac{\gamma+\delta\beta'}{1+\delta\beta'}$$

In (2.9) $Z_\gamma = \dfrac{c_p}{c_v}$ and $\beta' = \dfrac{c_{sp}}{c_v}$ are constant parameters; c_{sp} being the specific heat of solid particles while c_p and c_v are the specific heats of gas at constant pressure and constant volume respectively.

For an isentropic change of state of the mixture, we may write the speed of sound in the mixture of non-ideal gas and small solid particles as (Vishwakarma et al[23])

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

The absorption coefficient α_R is assumed to vary with temperature only and therefore it can be written in the form of power law (Gretler and Regenfelder (2002))

(2.11) $$\alpha_R = \alpha_{R_0}\left(\frac{T}{T_o}\right)^{\beta_R}$$

where the subscript 0 refers to a reference state. In order to obtain a self-similar solution, the exponent β_R must satisfy the similarity requirements.

At the shock front, we have the usual equations for conservation of mass, momentum and energy (Zeldovich and Raizer[27], Ojha and Srivastava [24])

(2.12) $$\rho_1 U = \rho_2 (U - u_2)$$

(2.13) $$p_1 + \rho_1 U^2 = P_2 + \rho_2 (U - u_2)^2$$

(2.14) $$e_1 + \frac{p_1}{\rho_1} + \frac{1}{2}U^2 + \frac{F_2}{\rho_1 U} = e_2 + \frac{p_2}{\rho_2} + \frac{1}{2}(U - u_2)^2$$

(2.15) $$T_1 = T_2$$

where the subscripts 2 and 1 denote conditions just behind and ahead of the shock respectively and U denotes the shock velocity. From (2.12) - (2.15), we may write

(2.16) $$\frac{\rho_2}{\rho_1} = \frac{1}{\beta} = \frac{Z_2}{Z_1}$$

(2.17) $$u_2 = (1 - \beta)U$$

(2.18) $$p_2 = p_1 + (1 - \beta)\rho_1 U^2$$

(2.19) $$F_2 = \left\{ \Gamma\beta^2 - Z_1\beta + (\Gamma - 1)\beta(1 - k_p)\bar{b} + \frac{\Gamma(1+\beta)\bar{b}(1-k_p)}{\{1+\bar{b}(1-k_p)\}\gamma M^2} - \frac{(\Gamma - 1)\bar{b}^2(1-k_p)^2 - \Gamma\beta}{\{1+\bar{b}(1-k_p)\}\gamma M^2} + \frac{Z_1\bar{b}(1-k_p)}{\{1+\bar{b}(1-k_p)\}\gamma M} \right\} \times \frac{(1-\beta)\rho_1 U^3}{(\Gamma - 1)\{\beta + \bar{b}(1-k_p)\}} - \frac{1+\beta}{2}(1-\beta)\rho_1 U^3$$

where $M = \left(\frac{\rho_1 U^2}{\gamma p_1}\right)^{\frac{1}{2}}$ is the shock - Mach number referred to the frozen speed of sound $\left(\frac{\gamma p_1}{\rho_1}\right)^{\frac{1}{2}}$ and $\bar{b} = \rho_1 b$. The quantity $\beta (0 < \beta < 1)$ is given by the relation

(2.20) $$\gamma M^2\{1+\bar{b}(1-k_p)\}\beta^2 - \{1+\bar{b}(1-k_p)\}\{1+\gamma M^2 Z_1\}\beta - (1-Z_1)\bar{b}(1-k_p) = 0.$$

Suppose that the total energy of the flow field behind the shock is time dependent and varying as (Rogers[6])

(2.21) $$E = E_0 R^q(t)\ ,\ q \geq 0$$

where E_0 and q are constants. Equation (2.21) includes blast waves when $q = 0$. The positive values of q correspond to the class in which the total energy increases with time. This increase can be achieved by the pressure exerted on the fluid by an expanding surface (a contact surface or a piston). Thus the flow is headed by a shock front and has an expanding surface as an inner boundary.

3. Similarity Solutions

The basic equations can be made dimensionless by transforming the independent variables for space r and time t into the similarity variable (Rogers[6])

(3.1) $$\eta = r e^{-kt}$$

where k is an arbitrary constant. If the flow is headed by a shock front given by $\eta = \eta_0$, a constant, then the shock radius is given by

(3.2) $$R = \eta_0 e^{kt}$$

and shock velocity is given by

(3.3) $$U = \frac{dR}{dt} = kR$$

Let the solution of the problem exist in similarity form as

(3.4) $$u = Uf(x)$$

(3.5) $$\rho = \rho_1 g(x)$$

(3.6) $$p = \rho_1 U^2 h(x)$$

(3.7) $$F = \rho_1 U^3 Q(x)$$

where $x = \frac{\eta}{\eta_0} = \frac{r}{R}$ and ρ_1 is density of the undisturbed mixture just ahead of the shock front. The total energy carried by the shock is given by

(3.8) $$E = 4\pi \int_{r_p}^{R} \rho \left(e + \frac{1}{2} u^2 \right) r^2 dr$$

where r_p is the radius of the inner expanding surface. Using similarity transformations (3.4) – (3.7) and equation (2.8) in equation (3.8) we get

$$E = 4\pi \rho_1 R^3 U^2 \int_{x_0}^{1} \left(\frac{1}{2} g f^2 + \frac{(1 - Z_1 g)h}{(\Gamma - 1)\{1 + \bar{b} g (1 - k_p)\}} \right) x^2 dx \tag{3.9}$$

where x_0 is the co-ordinate of the expanding surface. From equations (2.21) and (3.9), it follows that the motion of the shock front is given by the equation

$$R^{\frac{3}{2}} \frac{dR}{dt} = \left(\frac{E_0}{4\pi \rho_1 J} \right)^{\frac{1}{2}} R^{\frac{q}{2}} \tag{3.10}$$

where

$$J = \int_{x_0}^{1} \left(\frac{1}{2} g f^2 + \frac{(1 - Z_1 g)h}{(\Gamma - 1)\{1 + \bar{b}\, g(1 - k_p)\}} \right) x^2 dx \tag{3.11}$$

Using equation (3.3) in equation (3.10) we have

$$R^{\frac{5}{2}} = \frac{1}{k} \left(\frac{E_0}{4\pi \rho_1 J} \right)^{\frac{1}{2}} R^{\frac{q}{2}} \tag{3.12}$$

Initially taking $R \geq 0$ it is clear from equation (3.12) that value of $q = 5$ corresponds to the uniform expansion of a surface. Therefore, the solution of physical significance appears for the values of q which are between 0 and 5. Using the similarity transformations (3.4) – (3.7), the fundamental equations (2.1) – (2.3) take the forms

$$(x - f)\frac{dg}{dx} = g\left(\frac{df}{dx} + \frac{2f}{x} \right) \tag{3.13}$$

$$(x - f)\frac{df}{dx} = \frac{1}{g}\frac{dh}{dx} + \left(\frac{q - 3}{2} \right) f \tag{3.14}$$

$$(x - f)\frac{dh}{dx} = (x - f)\left[\frac{h - h(Z_1 g - 2)\bar{b}\,(1 - k_p)\, g}{g\,(1 - Z_1\, g)\{1 + \bar{b}\, g\,(1 - k_p)\}} \right. \tag{3.15}$$

$$+\frac{(\Gamma-1)h\{1+\bar{b}\,g(1-k_p)\}^2}{g(1-Z_1 g)\{1+\bar{b}\,g(1-k_p)\}}\Bigg]\frac{dg}{dx}+(q-3)\,h$$

$$+\frac{(\Gamma-1)\{1+\bar{b}\,g(1-k_p)\}}{1-Z_1 g}\left(\frac{2Q}{x}+\frac{dQ}{dx}\right)$$

From equation (2.11) and (2.4), we get

(3.16) $$F=-\frac{16}{3}\frac{\sigma T_0^{\beta_r}}{\alpha_{R_0}}T^{3-\beta_R}\frac{\partial T}{\partial r}$$

with the help of equation of state (2.5) and similarity transformations (3.4) – (3.7) equation (3.16) gives

(3.17) $$Q=-\left\{\frac{16}{3}\frac{k\sigma T_0^{\beta_R}\left(1-Z_1 g\right)^{3-\beta_R}U^{4-2\beta_R}h^{3-\beta_R}}{\alpha_{R_0}\rho_1\left(1-k_p\right)^{4-\beta_R}R'^{4-\beta_R}g^{3-\beta_R}\left\{1+\bar{b}g\left(1-k_p\right)\right\}^{3-\beta_R}}\right\}$$

$$\times\left\{\frac{1-Z_1 g}{g\left\{1+\bar{b}g\left(1-k_p\right)\right\}}\frac{dh}{dx}-\frac{h-h\left(Z_1 g-2\right)\bar{b}g\left(1-k_p\right)}{g^2\left\{1+\bar{b}g\left(1-k_p\right)\right\}^2}\frac{dg}{dx}\right\}$$

From equation (3.17) we observe that the similarity solution of the problem exist only when

(3.18) $$\beta_R=2$$

and therefore (3.17) reduces to

(3.19) $$Q=-X\left[\frac{1-Z_1 g}{g\left\{1+\bar{b}g\left(1-k_p\right)\right\}}\frac{dh}{dx}-\frac{h-h\left(Z_1 g-2\right)\bar{b}g\left(1-k_p\right)}{g^2\left\{1+\bar{b}g\left(1-k_p\right)\right\}^2}\frac{dg}{dx}\right]$$

where

(3.20) $$X=\frac{h\left(1-Z_1 g\right)}{\left(1-k_p\right)^2\left\{1+\bar{b}g\left(1-k_p\right)\right\}}\frac{\Gamma_R}{g}$$

and

(3.21) $$\Gamma_R=\frac{16}{3}\frac{T_0^2 k\sigma}{\alpha_{R_0}R'^2\rho_1}$$

Γ_R is the radiative non-dimensional heat transfer parameter which depends on the mean free path of radiation $\frac{1}{\alpha_R}$

By solving equations (3.13), (3.14), (3.15) and (3.19) for $\frac{df}{dx}, \frac{dg}{dx}, \frac{dh}{dx}$ and $\frac{dQ}{dx}$ we get

(3.22) $$\frac{df}{dx}=\left[\frac{2fh-2fh(Z_1g-2)\bar{b}g(1-k_p)}{gx\{1+\bar{b}g(1-k_p)\}^2(x-f)}+\frac{(1-Z_1g)}{1+\bar{b}g(1-k_p)}\left(\frac{q-3}{2}\right)f-\frac{Q}{X}\right]$$
$$\left[\frac{g\{1+\bar{b}g(1-k_p)\}^2(x-f)}{(1-Z_1g)g\{1+\bar{b}g(1-k_p)\}(x-f)^2-h+h(Z_1g-2)\bar{b}g(1-k_p)}\right]$$

(3.23) $$\frac{dg}{dx}=\frac{g}{x-f}\left(\frac{df}{dx}+\frac{2f}{x}\right)$$

(3.24) $$\frac{dh}{dx}=g(x-f)\frac{df}{dx}-\left(\frac{q-3}{2}\right)gf$$

(3.25) $$\frac{dQ}{dx}=\frac{(1-Z_1g)}{(\Gamma-1)\{1+\bar{b}g(1-k_p)\}}\left[g(x-f)^2\frac{df}{dx}-\left(\frac{q-3}{2}\right)f(x-f)g\right.$$
$$-\left\{\frac{h-h(Z_1g-2)\bar{b}(1-k_p)g(\Gamma-1)h\{1+\bar{b}g(1-k_p)\}}{(1-Z_1g)\{1+\bar{b}g(1-k_p)\}}\right\}\left(\frac{df}{dx}+\frac{2f}{x}\right)$$
$$\left.-(q-3)h-\frac{2(\Gamma-1)\{1+\bar{b}g(1-k_p)\}}{1-Z_1g}\frac{Q}{X}\right]$$

Substituting (3.3) – (3.7) in the boundary conditions (2.16) – (2.19) we have

(3.26) $$f[1]=1-\beta$$

(3.27) $$g[1]=Z[1]=\frac{1}{\beta}$$

(3.28) $$h[1]=1-\beta+\frac{1}{\gamma M^2}$$

(3.29) $$Q[1]=(1-\beta)\left\{\frac{\Gamma\beta^2-Z_1\beta+(\Gamma-1)\beta\bar{b}\left(1-k_p\right)}{(\Gamma-1)\left\{\beta+\bar{b}\left(1-k_p\right)\right\}}-\frac{1+\beta}{2}\right.$$
$$\left.-\left(\frac{\Gamma\beta+\Gamma(1+\beta)\bar{b}\left(1-k_p\right)+Z_1\bar{b}\left(1-k_p\right)-(\Gamma-1)\bar{b}^2\left(1-k_p\right)^2}{(\Gamma-1)\left\{1+\bar{b}\left(1-k_p\right)\right\}\left\{\beta+\bar{b}\left(1-k_p\right)\right\}\gamma M^2}\right)\right\}$$

Table.1: Variation of density ratio β for different values of k_p, Γ and $\bar{b}$ with β´ =1, γ=1.4, M= √10 and G=1,10,100.

Sr. No.	k_p	Γ	G	Z_1	$\bar{b}$	β
1	0	1.4	-	0	0	0.0714286
					0.04	0.0991395
					0.08	0.1167480
2	0.1	1.36	1	0.1	0	0.1714290
					0.08	0.1937170
			10	0.0109890	0	0.0824176
					0.08	0.1214760
			100	0.0011099	0	0.0725385
					0.08	0.1144200
3	0.3	1.2799	1	0.3	0	0.3714290
					0.08	0.3784350
			10	0.0410900	0	0.1125190
					0.08	0.1387050
			100	0.0042670	0	0.0756956
					0.08	0.1099880

5. Results and Discussion

Table 1 shows the variation of density ratio β, for different values of k_p , Γ, Z_1 and $\bar{b}$ with $\beta' = 1$, $\gamma = 1.4$ and G=1, 10, 100. It is clear from the table that as k_p increases, β increases for G = 1, but decreases for higher values of G. It is also clear from the table that an increase in the value of non-ideal parameter $\bar{b}$ also increases the value of β i.e. decreases shock strength.

Equations (3.22) – (3.25) are integrated numerically with boundary conditions (3.26) – (3.29) for the values of $k_p, \Gamma, Z_1, \bar{b}$ and β given in table 1 along with $q=2.5, M=\sqrt{10}$ and $\Gamma_R=10$ and the results obtained are plotted in figs. 1–4

Fig. 1 gives variation of reduced velocity behind the shock wave Cases 1, 2 & 3 of the fig. 1 represent the variation of velocity in ideal and non-ideal gases in absence of solid particles which shows that the presence of non-ideal parameter increases velocity behind the shock within the range x = 1 to x = 0.95. Cases 4 – 5, 6 – 7, 8 – 9 give variation of velocity behind the shock in ideal and non-ideal dusty gases when volumetric extension G of the solid particles are 1, 10 and 100 with $k_p = 0.1$ respectively. It is clear that in all these cases velocity increases in presence of non-ideal gas with a slight increase in range. It is also clear that increase in G decreases velocity. Cases 10 – 15 give variation in velocity behind the shock in ideal and non-ideal gases when $k_p = 0.3$ with volumetric extension G = 1, 10 and 100 respectively. We observe that the nature of variation in velocity is the same as in previous cases but range of variation increases with increasing k_p.

Cases 1, 2 and 3 of Fig. 2 are the variation of reduced density behind the shock wave in absence of solid particles in ideal and non-ideal gases. Cases 4 – 5, 6 – 7, 8 – 9 give the variation of density in ideal and non-ideal dusty gases when $k_p = 0.1$ and volumetric extension G of the solid particles are 1, 10 and 100 respectively. In all these cases density increases faster in non-ideal gases in comparison to ideal gases. Range of variation in these cases is x=1 to x=0.95. Cases 10-11, 12-13, 14-15 represent variation in density when $k_p = 0.3$ with volumetric extension G=1, 10 and 100 respectively. Clearly the nature of variation is the same as in above cases with increasing range from x=1 to x=0.91. It is clear from the figure that in all the cases increase in density becomes faster with the increase in G.

Cases 1, 2 and 3 of Fig. 3 are the variation of reduced pressure behind the shock wave in absence of solid particles in ideal and non-ideal gases which shows that decrease in pressure becomes slow with the increase of non-ideal parameter $\bar{b}$. Cases 4-5 of the fig. 3 shows that pressure slightly increases and then decreases behind the shock when G=1 and $k_p = 0.1$ while in cases 6-7 and 8-9 pressure decreases continuously within the range x=1 to x=0.94. The decrease in pressure becomes faster with the increase of G. The presence of non-ideal parameter always slows down the decrease in pressure. Cases 10-11 show that pressure increases continuously behind the shock when G=1 and $k_p = 0.3$ while in cases 12-13 and 14-15 we observe that pressure decreases with the range x=1 to x= 0.92 and then increases abruptly when $k_p = 0.3$ and G=10 and 100 respectively.

Fig. 4 gives the variation of radiation heat flux behind the shock wave. It is clear from the figure that in all the cases the variation in flux first increases slightly and then decreases behind the shock within the range x=1 to x=0.91 except in the cases 4-5 and 10-11 where G=1 and k_p = 0.1 and 0.3 respectively. In all the above cases the variation of the flux becomes faster in presence of non-ideal parameter.

Thus, it is clear that the presence of small solid particles and non-idealness of the gas affect greatly the variation in flow variables behind the shock.

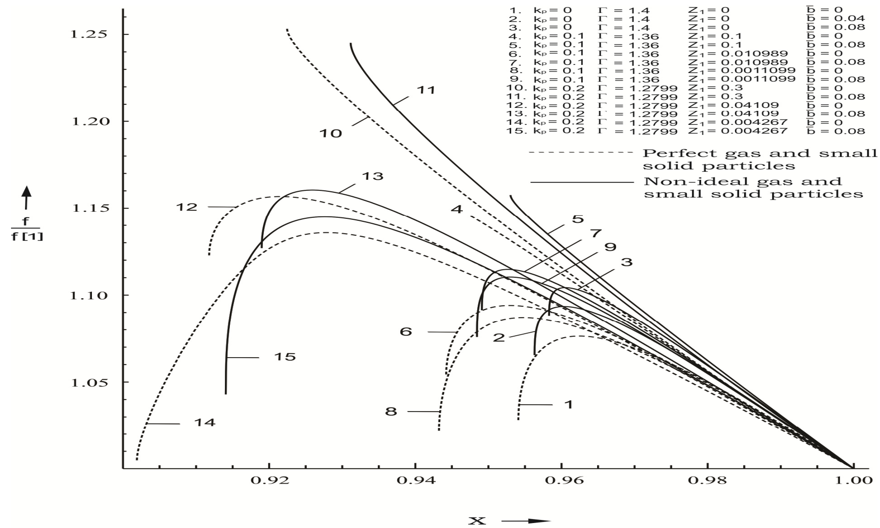

Figure 1: variation of $f/f\,[1]$ w. r. t. x

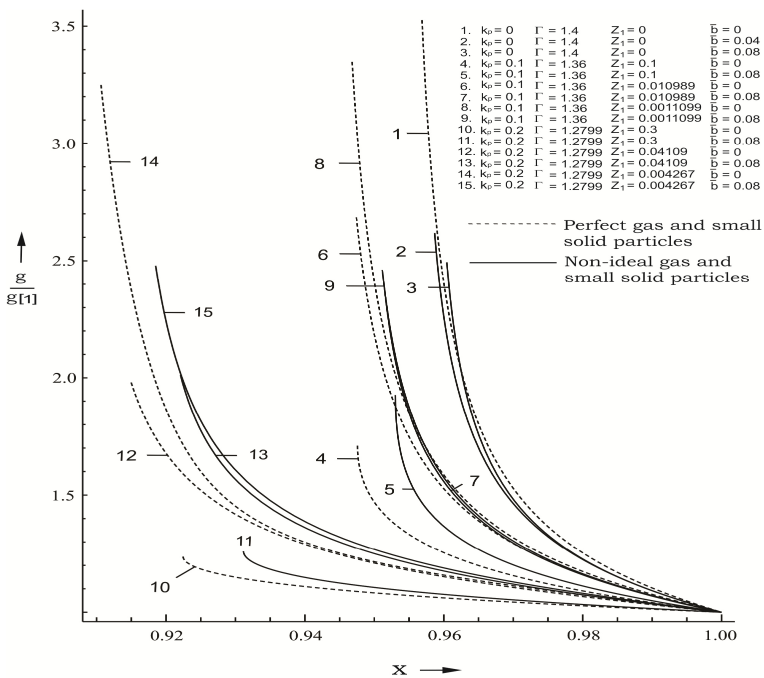

Figure 2: Variation of $g/g\,[1]$ w.r.t. x

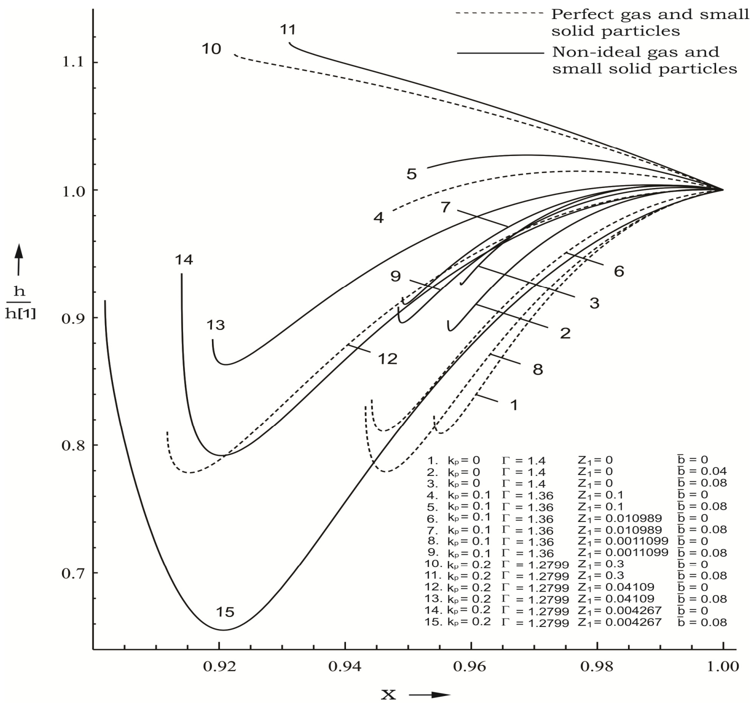

Figure 3: Variation of $h/h\,[1]$ w.r.t. x

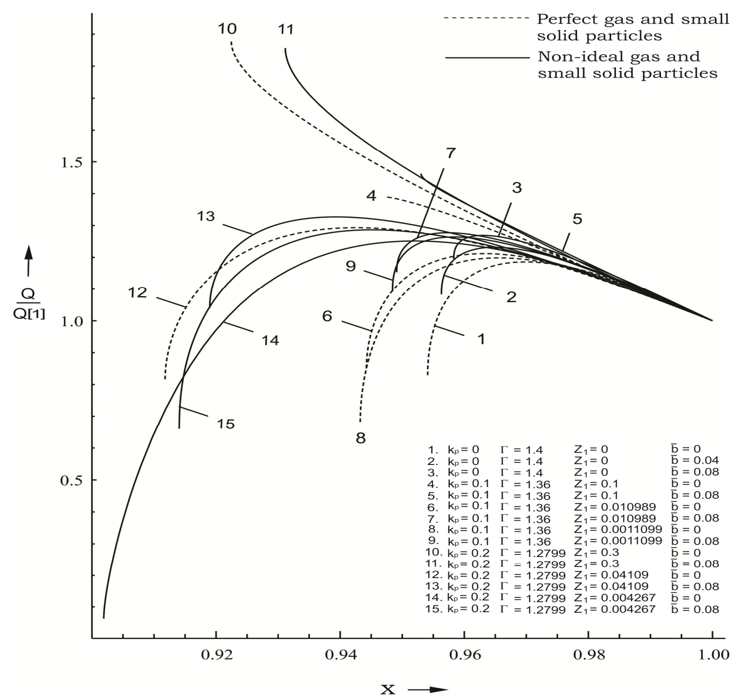

Figure 4: Variation of $Q/Q\,[1]$ w.r.t. x

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