JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
45, 4, pp. 801-817, Warsaw 2007

PROPAGATION OF SPHERICAL SHOCK WAVES IN A DUSTY GAS WITH RADIATION HEAT-FLUX

K. K. Singh

North Eastern Hill University, Department of Mathematics, Shillong, India

J. P. Vishwakarma

D.D.U. Gorakhpur University, Department of Mathematics and Statistics, Gorakhpur, India
e-mail : jpv_univgkp@yahoo.com

The propagation of spherical shock waves in a dusty gas with radiation heat-flux and exponentially varying density is investigated in the paper. The equilibrium flow conditions are assumed to be maintained, and the radiation is considered to be of a diffusion type for an optically thick grey gas model. The shock wave moves with variable velocity and the total energy of the wave is non-constant. Non-similar solutions are obtained, and the effects of variation of the radiation parameter and time are investigated. The effects of an increase in (i) the mass concentration of solid particles in the mixture and (ii) of the ratio of the density of solid particles to the initial density of gas on the flow variables in the region behind the shock are also investigated.

Key words: shock waves, dusty gas, radiation heat-flux

1. Introduction

Grover and Hardy (1966), Hayes (1968), Ray and Bhowmick (1974), Laumbach and Probstein (1969), Verma and Vishwakarma (1980) and many others have discussed the propagation of shock waves in a medium where density varies exponentially. These authors have not taken radiation effects into account. Laumbach and Probstein (1970a,b), Bhowmick (1981) and Singh and Srivastava (1982) obtained similarity or non-similarity solutions for the shock propagation in an exponential medium with radiation heat transfer effects. Pai *et al.* (1980) obtained similarity solutions for a strong shock wave propagation in a dusty gas with constant density. Vishwakarma and Nath (2006) found similarity solutions for an unsteady flow behind a strong exponential shock driven out by a piston in a dusty gas in both cases, when the flow between the shock and the piston was isothermal or adiabatic. Vishwakarma (2000) studied the propagation of shock waves in a dusty gas with exponentially varying density, using a non-similarity method.

In the present work, we generalize the solution given by Vishwakarma (2000) for a strong explosion in a dusty gas (mixture of a perfect gas and small solid particles) taking radiation flux into account. It is assumed that the dusty gas is grey and opaque, and the shock is isothermal. The assumption that the shock is isothermal is a result of the mathematical approximation in which the radiation flux is taken to be proportional to the temperature gradient, which excludes the possibility of a temperature jump (see, e.g. Zel'dovich and Raizer (1967), Bhowmick (1981), Singh and Srivastava (1982)). Radiation pressure and radiation energy are considered to be very small in comparision to material pressure and energy, respectively, and therefore only the radiation flux is taken into account. In order to get some essential features of shock propagation, small solid particles are considered as a pseudo-fluid, and it is assumed that the equilibrium flow condition is maintained in the flow field, and that the viscous stress and heat conduction of the mixture are negligible (Suzuki *et al.* (1976), Pai *et al.* (1980)). Although density of the mixture is assumed to be increasing exponentially, the volume occupied by the solid particles may be very small under ordinary conditions owing to large density of the particle material. Hence, for simplicity, the initial volume fraction of solid particles Z_1 is assumed to be a small constant (Vishwakarma (2000)).

The effects of variation of the radiation parameter at different times on the flow variables behind the shock are obtained. The effects of an increase in (i) the mass concentration of solid particles in the mixture and (ii) the ratio of the density of solid particles to the initial density of gas on the flow variables behind the shock are also investigated.

2. Fundamental equations and boundary conditions

The fundamental equations for one dimensional, spherically symmetric and unsteady flow of a mixture of gas and small solid particles taking radiation flux into account, can be written as (c.f. Vishwakarma, 2000; Singh and Srivastava, 1982)

$$
\begin{aligned}
&\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + \frac{1}{\rho}\frac{\partial p}{\partial r} = 0\\
&\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial r} + \rho\frac{\partial u}{\partial r} + \frac{2\rho u}{r} = 0\\
&\frac{\partial U_m}{\partial t} + u\frac{\partial U_m}{\partial r} - \frac{p}{\rho^2}\Big(\frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial r}\Big) + \frac{1}{\rho r^2}\frac{\partial}{\partial r}(Fr^2) = 0
\end{aligned}
\tag{2.1}
$$

where ρ is density of the mixture, u – flow velocity in the radial direction, p – pressure of the mixture, U_m – internal energy per unit mass of the mixture, F – radiation heat flux, r – distance, and t – time.

Assuming local thermodynamic equilibrium, and taking Rosseland's diffusion approximation, we have

$$
F = -\frac{c\mu}{3}\frac{\partial}{\partial r}(aT^4) \tag{2.2}
$$

where $ac/4$ is the Stefan-Boltzmann constant; c – velocity of light; and μ – mean free path of radiation, which is a function of density ρ and absolute temperature T.

Following Wang (1966), we have

$$
\mu = \mu_0\rho^{\alpha^*}T^{\beta^*} \tag{2.3}
$$

where α^* and β^* are constants.

The equation of state of a mixture of gas and small solid particles can be written as (Pai, 1977)

$$
p = \frac{(1-K_p)}{1-Z}\rho R^* T \tag{2.4}
$$

where R^* is the gas constant, Z – volume fraction of solid particles in the mixture and K_p – mass concentration of solid particles.

The relation between K_p and Z is given by

$$
K_p = \frac{Z\rho_{sp}}{\rho} \tag{2.5}
$$

where ρ_{sp} is the species density of solid particles. In the equilibrium flow, K_p is a constant in the whole flow field.

The internal energy of the mixture may be written as follows

$$
U_m = [K_pC_{sp} + (1-K_p)C_v]T = C_{vm}T \tag{2.6}
$$

where C_{sp} is the specific heat of the solid particles, C_v – specific heat of the gas at constant volume, and C_{vm} – specific heat of the mixture at constant volume. The specific heat of the mixture at constant pressure process is

$$C_{pm} = K_p C_{sp} + (1 - K_p)C_p \tag{2.7}$$

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

The ratio of the specific heats of the mixture is given by (Marble, 1970; Pai, 1977)

$$\mathit{\Gamma} = \frac{C_{pm}}{C_{vm}} = \frac{\gamma\Big(1 + \frac{\delta\beta'}{\gamma}\Big)}{1 + \delta\beta'} \tag{2.8}$$

where

$$\gamma = \frac{C_p}{C_v} \qquad\qquad \delta = \frac{K_p}{1 - K_p} \qquad\qquad \beta' = \frac{C_{sp}}{C_v}$$

The internal energy U_m is therefore, given by

$$U_m = \frac{p(1 - Z)}{\rho(\mathit{\Gamma} - 1)} \tag{2.9}$$

We consider that a spherical shock wave is propagated into the medium, at rest, with small constant counter pressure. Also, the initial density of the medium is assumed to obey the exponential law

$$\rho = K\mathrm{e}^{\alpha r} \tag{2.10}$$

where α and K are suitable constants.

The shock is assumed to be isothermal (formation of the isothermal shock is a result of the mathematical approximation in which the flux is taken to be proportional to the temperature gradient. This excludes the possibility of a temperature jump, see for example Zel'dovich and Raizer (1967), Bhowmick (1981), Singh and Srivastava (1982)) and, hence, the conditions across it are

$$\begin{aligned}
&\rho_2(V - u_2) = \rho_1 V = m_s(say)\\
&p_2 + \rho_2(V - u_2)^2 = p_1 + \rho_1 V^2\\
&U_{m_2} + \frac{p_2}{\rho_2} + \frac{1}{2}(V - u_2)^2 - \frac{F_2}{m_s} = U_{m_1} + \frac{p_1}{\rho_1} + \frac{1}{2}V^2\\
&\frac{Z_2}{\rho_2} = \frac{Z_1}{\rho_1} \qquad\qquad T_2 = T_1
\end{aligned} \tag{2.11}$$

where $V = dR/dt$ denotes the velocity of the shock at $r = R(t)$, indices 1 and 2 refer to the values just ahead and just behind the shock surface, and $F_1 = 0$ (Laumbach and Probstein, 1970). From equations (2.11), we get

$$\begin{aligned} u_2 &= (1-\beta)V & \rho_2 &= \frac{\rho_1}{\beta} \\ p_2 &= (1-Z_1)\rho_1 V^2 & Z_2 &= \frac{Z_1}{\beta} \\ F_2 &= (1-\beta)\Big[\frac{(1+\Gamma)\beta + (1-\Gamma) - 2Z_1}{2(\Gamma-1)} - \frac{1-Z_1}{(\Gamma-1)M_e^2}\Big]\rho_1 V^3 \end{aligned} \tag{2.12}$$

where β is given by

$$\beta = Z_1 + \frac{1-Z_1}{\Gamma M_e^2} \tag{2.13}$$

and

$$M_e^2 = \frac{V^2}{a_1^2} \qquad a_1^2 = \frac{\Gamma p_1}{\rho_1(1-Z_1)}$$

M_e being the shock-Mach number referred to the speed of sound a_1 in the dusty gas.

The initial volume fraction of the solid particles Z_1 is, in general, not constant. But the volume occupied by the solid particles is very small because density of the solid particles is much larger than that of the gas (Miura and Glass, 1985), hence Z_1 may be assumed as a small constant. The expression for Z_1 is (Pai, 1977; Naidu *et al.*, 1985)

$$Z_1 = \frac{K_p}{G(1-K_p) + K_p} \tag{2.14}$$

where $G = \rho_{sp}/\rho_g$ is the ratio of the density of solid particles to the initial density of the gas. Values of Z_1 for some typical values of K_p and G are given in Table 1.

Table 1. Values of Z_1 for some typical values of K_p and G

K_p	G	Z_1
0.2	10	0.02439
	50	0.00498
	100	0.00249
0.4	10	0.06250
	50	0.01316
	100	0.00662

Let the solution to equations (2.1) and (2.2) be of the form (Ray and Bhowmick, 1974; Verma and Vishwakarma, 1976; Singh and Srivastava, 1982; Vishwakarma, 2000)

$$\begin{aligned} u &= t^{-1}U(\eta) & \rho &= t^{\Omega}D(\eta) \\ p &= t^{\Omega-2}P(\eta) & F &= t^{\Omega-3}Q(\eta) \end{aligned} \tag{2.15}$$

where

$$\eta = te^{\lambda r} \qquad \lambda \neq 0 \tag{2.16}$$

and the constants Ω and λ are to be determined subsequently. We choose the shock surface to be given by

$$\eta_0 = \text{const} \tag{2.17}$$

so that its velocity is given by

$$V = -\frac{1}{\lambda t} \tag{2.18}$$

which represents the outgoing shock surface, if $\lambda < 0$.

The solution toe equations (2.1) and (2.2) in form (2.15) are compatible with the shock conditions if

$$\Omega = 2 \qquad \lambda = -\frac{\alpha}{2} \qquad \alpha^* = 1 \qquad \beta^* = -\frac{5}{2} \tag{2.19}$$

Since necessarily $\lambda < 0$, relation (2.19) shows that $\alpha > 0$, meaning thereby that the shock expands outwardly in an exponentially increasing medium (Hayes, 1968; Vishwakarma, 2000; Yousaf, 1987).

The strength of the shock, under these conditions, remains constant, for

$$M_e^2 = \frac{V^2}{a_1^2} = \frac{V^2}{\frac{\Gamma p_1}{\rho_1(1-Z_1)}} = \frac{4(1-Z_1)K}{\Gamma p_1 \alpha^2 \eta_0^2} = \text{const}$$

From equations (2.18) and (2.19), we obtain

$$R = \frac{2}{\alpha}\log\frac{t}{\tau} \tag{2.20}$$

where τ is the duration of the initial impulse.

3. Solution to the equations

The flow variables in the flow-field behind the shock front will be obtained by solving equations (2.1) and (2.2). From equations (2.15), (2.18) and (2.19), we obtain

$$\frac{\partial u}{\partial t} = u\lambda V - V\frac{\partial u}{\partial r} \qquad \frac{\partial \rho}{\partial t} = V\rho\alpha - V\frac{\partial \rho}{\partial r}$$
$$\frac{\partial p}{\partial t} = -V\frac{\partial p}{\partial r} \tag{3.1}$$

Using equations (3.1)-(3.3) and the transformations

$$r' = \frac{r}{R} \qquad u' = \frac{u}{V} \qquad p' = \frac{p}{p_2}$$
$$\rho' = \frac{\rho}{\rho_2} \qquad F' = \frac{F}{F_2} \tag{3.2}$$

in fundamental equations (2.1) and (2.2), we obtain

$$\begin{aligned}
\frac{d\rho'}{dr'} &= \frac{\rho'}{1-u'}\Big[2\log\frac{t}{\tau} + \frac{du'}{dr'} + \frac{2u'}{r'}\Big]\\
\frac{dp'}{dr'} &= \frac{\rho'}{(1-Z_1)\beta}\Big[(1-u')\frac{du'}{dr'} + u'\log\frac{t}{\tau}\Big]\\
\frac{dF'}{dr'} &= \frac{(1-Z_1)}{(1-\beta)\Big[\frac{(1+\Gamma)\beta+(1-\Gamma)-2Z_1}{2} - \frac{1-Z_1}{M_e^2}\Big]}\cdot\\
&\cdot\Big\{\Big[\frac{(\beta-Z_1\rho')(1-u')^2\rho'}{(1-Z_1)\beta^2} - \Gamma p'\Big]\frac{du'}{dr'} +\\
&+\frac{(1-u')(\beta-Z_1\rho')\rho'u'\log\frac{t}{\tau}}{(1-Z_1)\beta^2} - \frac{2\Gamma p'u'}{r'}\Big\} - \frac{2F'}{r'}\\
\frac{du'}{dr'} &= \frac{1}{p'\beta^2(1-Z_1)-(\beta-Z_1\rho')\rho'(1-u')^2}\cdot\\
&\cdot\Big[\frac{F'(1-Z_1)\beta(1-u')\sqrt{\rho'}\log\frac{t}{\tau}}{NL\sqrt{p'}\sqrt{\beta-Z_1\rho'}} + (1-u')(\beta-Z_1\rho')\rho'u'\log\frac{t}{\tau} +\\
&-2p'\beta^2(1-Z_1)\log\frac{t}{\tau} - \frac{2p'u'\beta^2(1-Z_1)}{r'}\Big]
\end{aligned} \tag{3.3}$$

where

$$N = \frac{4ac\mu_0\alpha}{3\sqrt{R^{*3}}} \tag{3.4}$$

is a non-dimensional radiation parameter and

$$L = \frac{(\Gamma - 1)\sqrt{(1-Z_1)^3}}{2(1-\beta)\Big[\frac{(1+\Gamma)\beta+(1-\Gamma)-2Z_1}{2} - \frac{1-Z_1}{M_e^2}\Big]\beta\sqrt{(1-K_p)^3}} \tag{3.5}$$

Also, the total energy of the flow field behind the shock front is given by

$$E = \frac{16\pi K R^3}{\beta\alpha^2\tau^2}\int_0^1 \Big[\frac{p'(1-Z_1)(\beta - Z_1\rho')}{\Gamma - 1} + \frac{1}{2}\rho' u'^2\Big] r'^2\, dr' \tag{3.6}$$

Hence, the total energy of the shock wave is non-constant and varies with R^3.

In terms of the dimensionless variables r', p', ρ', u' and F', the shock conditions take the form

$$\begin{aligned} &r' = 1 \qquad &p' = 1 \qquad &\rho' = 1 \\ &u' = 1 - \beta \qquad &F' = 1 & \end{aligned} \tag{3.7}$$

Equations (3.3) alongwith the boundary conditions (3.7) give the solution to our problem. The solution so obtained is a non-similar one, since motion behind the shock can be determined only when a definite value for time is prescribed.

4. Results and discussion

The distribution of the flow variables behind the shock front is obtained by numerical integration of equations (3.3) with boundary conditions (3.7). For the purpose of numerical integration, the values of the parameters are taken to be (Pai *et al.*, 1980; Miura and Glass, 1985; Vishwakarma, 2000; Singh and Srivastava, 1982), $\gamma = 1.4$; $K_p = 0$, 0.2, 0.4; $G = 10$, 50; $\beta' = 1$; $M_e^2 = 20$; $N = 0.6$, 0.8, 10; and $t/\tau = 2$, 4. Starting from the shock front, the numerical integration is carried out until the singularity of the solution

$$p'\beta^2(1-Z_1) - (\beta - Z_1\rho')\rho'(1-u')^2 = 0$$

is reached. This marks the inner boundary of the disturbance, and at this surface the value of r' remains constant. The inner boundary is the position in the flow-field behind the shock front at which the Chapman-Jouget condition

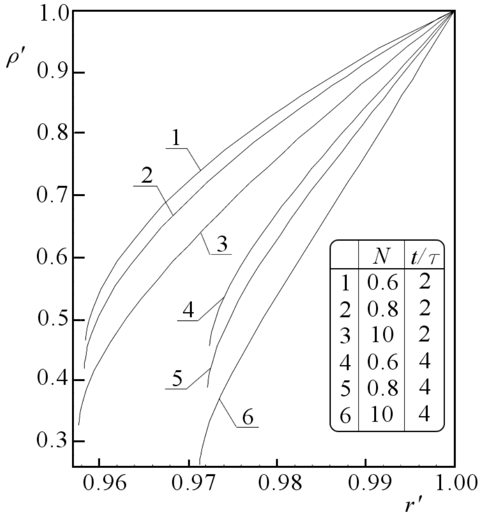

Fig. 1. Variation of reduced density ρ' in the region behind the shock front for $K_p = 0.2$ and $G = 50$

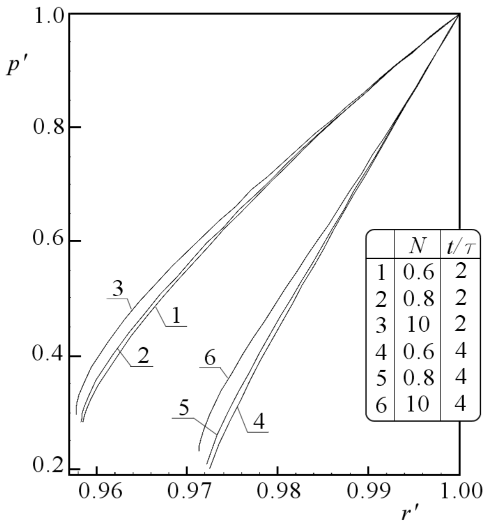

Fig. 2. Variation of reduced pressure p' in the region behind the shock front for $K_p = 0.2$ and $G = 50$

is satisfied, i.e., the position at which the line $r/R(t) =$ const coincides with an isothermal characteristic.

Figures 1 and 5, 2 and 6, 3 and 7, and 4 and 8 show variation of the reduced flow variables ρ', p', F' and u', respectively, with reduced distance r'.

Figures 1, 2, 5 and 6 show that, as we move inwards from the shock front, reduced density and pressure decrease, while Figures 3, 4, 7 and 8 show that the reduced radiation heat flux and fluid velocity increase.

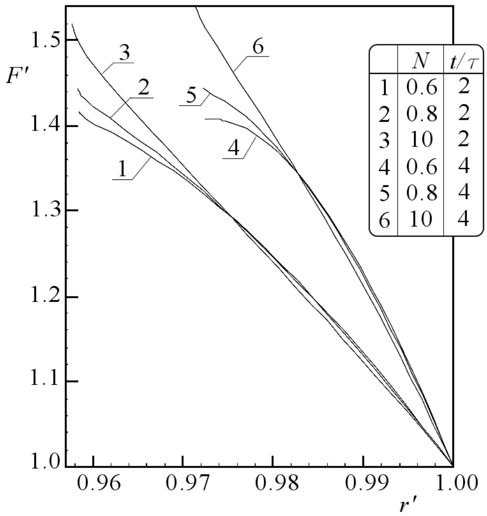

Fig. 3. Variation of reduced radiation heat flux F' in the region behind the shock front for $K_p = 0.2$ and $G = 50$

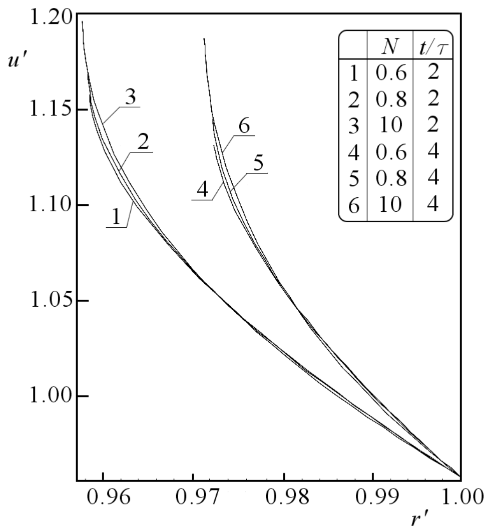

Fig. 4. Variation of reduced flow velocity u' in the region behind the shock front for $K_p = 0.2$ and $G = 50$

Tables 2, 3 and 4 display the density ratio $1/\beta$ across the shock and the position of the inner boundary surface r'_p (say) for various values of constant parameters.

Table 2. Density ratio $\rho_2/\rho_1 = 1/\beta$ across the shock front for different values of K_p and G

K_p	G	$\frac{\rho_2}{\rho_1} = \frac{1}{\beta}$
0		27.99998
0.2	10	16.30122
	50	23.43556
	100	24.82961
0.4	10	9.96989
	50	18.88506
	100	21.42447

Table 3. Position of the inner boundary surface for different values of the radiation parameter N and time t/τ with $K_p = 0.2$ and $G = 50$

$\frac{t}{\tau}$	N	Position of the inner boundary surface (r'_p)
2	0.6	0.95844
	0.8	0.95828
	10	0.95769
4	0.6	0.97232
	0.8	0.97212
	10	0.97127

It is found, from Fig. 1 to Fig. 4 and Table 3 that the effects of an increase in the value of the radiation parameter N, which depends on the mean free path of radiation, are:

- to decrease the density ρ', and to increase the pressure p' at any point in the flow-field behind the shock. The decrease of density and the increase of pressure become significant near the inner boundary surface,
- to increase the radiation heat flux F' and the velocity u' near the inner boundary surface, and
- to increase, slightly, the distance of the inner boundary surface from the shock surface.

The effects of an increase in the time (t/τ) are (see Figs 1-4):

- to decrease the density ρ' and the pressure p',
- to increase the radiation heat flux F' and the velocity u', and
- to decrease the distance of the inner surface from the shock front (see Table 3).

Figures 5 to 8 show that for given values of N and G, the effects of an increase in the mass concentration of the solid particles K_p at a given instant are

- to increase the density ρ', the pressure p', the radiation heat flux F' and to decrease the flow velocity u',
- to decrease the slopes of the density, pressure, flow velocity profiles and to increase the slope of the radiation heat flux profile in the region behind the shock front, and
- to increase the distance between the inner contact surface and the shock front (see Table 4). This means that an increase in the mass concentration of the solid particles has an effect to decrease the shock strength.

Table 4. Position of the inner boundary surface for different values of K_p and G with $N = 10$ and $t/\tau = 2$

K_p	G	Position of the inner boundary surface (r'_p)
0		0.96241
0.2	10	0.94595
	50	0.95769
	100	0.95923
0.4	10	0.92257
	50	0.95101
	100	0.95494

Also Figs 5 to 8 show that for given values of N and K_p, the effects of an increase in the ratio of the density of the solid particles to the initial density of the gas G at a given instant are

- to decrease the density ρ', the pressure p', the radiation heat flux F' and to increase the flow velocity u',
- to increase the slopes of the density, pressure, flow velocity profiles and to decrease the slope of the radiation heat flux profile in the region behind the shock front, and

- to decrease the distance between the inner contact surface and the shock front (see Table 4). This means that an increase in the ratio of the density of the solid particles to the initial density of gas has an effect to increase the shock strength.

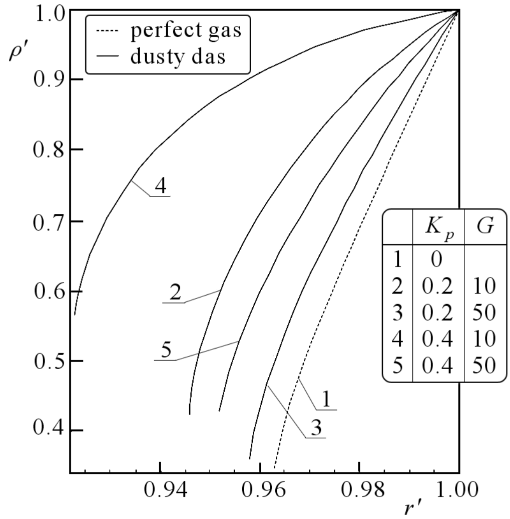

Fig. 5. Variation of reduced density ρ' in the region behind the shock front for $N = 10$ and $t/\tau = 2$

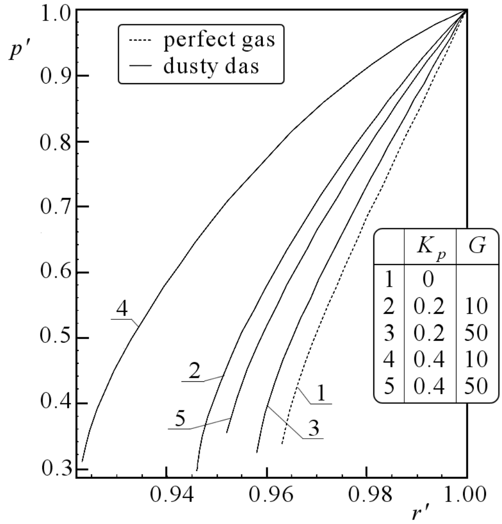

Fig. 6. Variation of reduced pressure p' in the region behind the shock front for $N = 10$ and $t/\tau = 2$

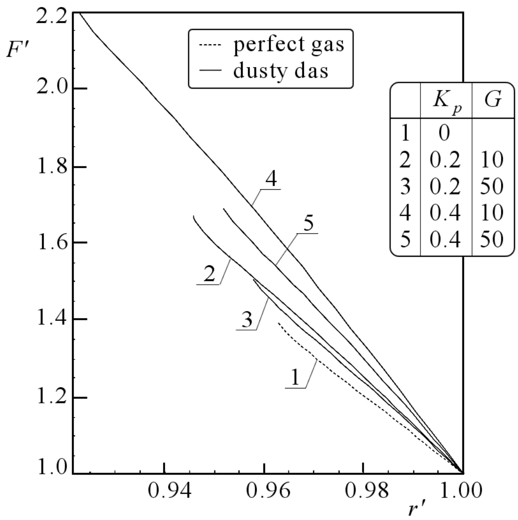

Fig. 7. Variation of reduced radiation heat flux F' in the region behind the shock front for $N = 10$ and $t/\tau = 2$

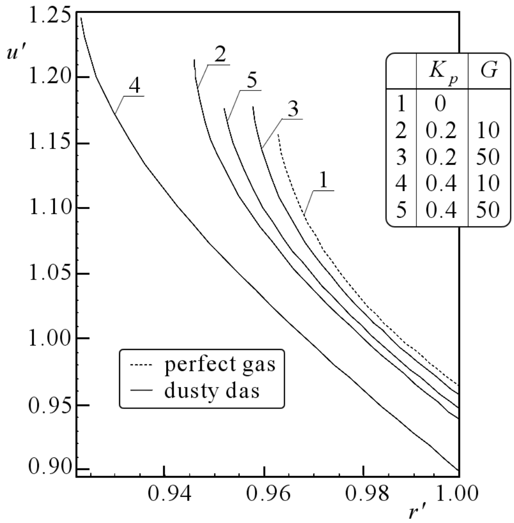

Fig. 8. Variation of reduced flow velocity u' in the region behind the shock front for $N = 10$ and $t/\tau = 2$

The effects of an increase in K_p or G on the shock strength may be explained with the help of the compressibility of the medium as follows.

The adiabatic compressibility of the mixture of the gas and small solid particles may be calculated as (c.f. Moelwyn-Hughes, 1961)

$$C = \frac{1}{\rho}\Big(\frac{\partial\rho}{\partial p}\Big)_S = \frac{1-Z}{\Gamma p}$$

where $(\partial\rho/\partial p)_S$ denotes the derivative of ρ with respect to p at a constant entropy. The non-dimensional compressibility $C' = C/C_2$ can be expressed as

$$C' = \frac{\Big(1 - \frac{Z_1}{\beta}\rho'\Big)}{p'\Big(1 - \frac{Z_1}{\beta}\Big)}$$

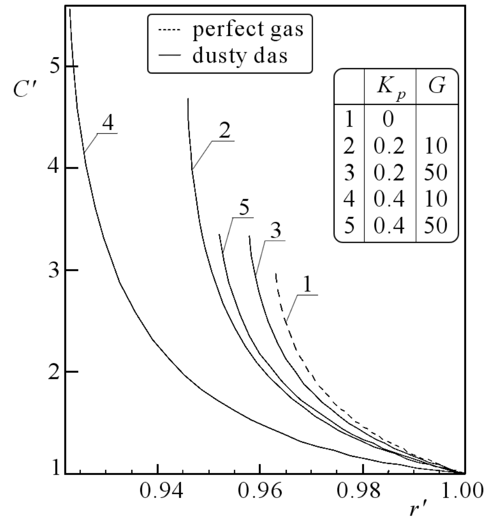

Fig. 9. Variation of non-dimensional compressibility C' in the region behind the shock front for $N = 10$ and $t/\tau = 2$

It is plotted against r' in Fig. 9. This figure shows that the compressibility decreases as the value of K_p increases, whereas it increases as the value of G increases. The decrease in the compressibility causes weaker compression of the gas behind the shock and, hence, a decrease in the shock strength. The increase in the compressibility causes stronger compression of the gas behind the shock and, hence, an increase in the shock strength.

References

1. BHOWMICK J.B., 1981, An exact analytical solution in radiation gas dynamics, *Astrophys. Space Sci.*, **74**, 2, 481-485

2. Grover R., Hardy J.W., 1966, The propagation of shocks in exponentially decreasing atmospheres, *Astrophys. J.*, **143**, 48-60

3. Hayes W.D., 1968, A self-similar strong shocks in an exponential medium, *J. Fluid Mech.*, **32**, 305-315

4. Laumbach D.D., Probstein R.F., 1969, A point explosion in a cold exponential atmosphere Part I, *J. Fluid Mech.*, **35**, 53-75

5. Laumbach D.D., Probstein R.F., 1970a, A point explosion in a cold exponential atmosphere Part II, Radiating flow, *J. Fluid Mech.*, **40**, 833-858

6. Laumbach D.D., Probstein R.F., 1970b, Self-similar strong shocks with radiation in a decreasing exponential atmosphere, *Phys. Fluids*, **13**, 1178-1183

7. Marble F.E., 1970, Dynamics of dusty gases, *A. Rev. Fluid Mech.*, **2**, 397-446

8. Miura H., Glass I.I., 1985, Development of the flow induced by a piston moving impulsively in a dusty gas, *Proc. Roy. Soc., London A*, **397**, 295-309

9. Moelwyn-Hughes E.A., 1961, *Physical Chemistry*, Pergamon Press, London

10. Naidu G.N., Venkatanandam K., Ranga Rao M.P., 1985, Approximate analytical solutions for self-similar flows of a dusty gas with variable energy, *Int. J. Eng. Sci.*, **23**, 39-49

11. Pai S.I., 1977, *Two phase flows, Chap. V*, Vieweg Tracts in Pure Appl. Phys., **3**, Vieweg Verlag, Braunschweig, Germany

12. Pai S.I., Menon S., Fan Z.Q., 1980, Similarity solution of a strong shock wave propagation in a mixture of a gas and dusty particles, *Int. J. Eng. Sci.*, **18**, 1365-1373

13. Ray G.D., Bhowmick J.B., 1974, Propagation of cylindrical and spherical explosion waves in an exponential medium, *Def. Sci. J.*, **24**, 9-14

14. Singh J.B., Srivastava S.K., 1982, Propagation of spherical shock waves in an exponential medium with radiation heat flux, *Astrophys. Space Sci.*, **88**, 2, 277-282

15. Suzuki T., Ohyagi S., Higashino F., Takano A., 1976, The propagation of reacting blast waves through inert particle clouds, *Acta Astronautica*, **3**, 517-529

16. Verma B.G., Vishwakarma J.P., 1976, Propagation of magnetogasdynamic plane shock waves in an exponential medium, *Nuovo Cimento*, **32** B, 2, 267-272

17. Verma B.G., Vishwakarma J.P., 1980, Axially symmetric explosion in magnetogasdynamics, *Astrophys. Space Sci.*, **69**, 177-188

18. Vishwakarma J.P., 2000, Propagation of shock waves in a dusty gas with exponentially varying density, *Eur. Phys. J. B*, **16**, 369-372

19. Vishwakarma J.P., Nath G., 2006, Similarity solutions for unsteady flow behind an exponential shock in a dusty gas, *Phys. Scr.*, **74**, 493-498

20. Wang K.C., 1966, Approximate solution of a plane radiating "piston problem", *Phys. Fluids*, **9**, 10, 1922-1928

21. Yousaf M., 1987, Strong shocks in an exponential atmosphere, *Phys. Fluids*, **30**, 12, 3669-3672

22. Zel'dovich Ya.B., Raizer Yu.P., 1967, *Physics of Shock Waves and High Temperature Hydrodynamics Phenomena*, Vol. II, Academic Press, New York

Propagacja sferycznych fal uderzeniowych w zanieczyszczonym gazie z uwzględnieniem radiacyjnej wymiany ciepła

Streszczenie

W pracy zajęto się problemem propagacji sferycznych fal uderzeniowych o wykładniczym rozkładzie gęstości w zanieczyszczonym gazie z uwzględnieniem radiacyjnej wymiany ciepła. Założono równowagowe warunki przepływu czynnika, a samą radiację przyjęto typu dyfuzyjnego w modelu optycznie nieprzezroczystego gazu. Fala uderzeniowa przemieszcza się ze zmienną prędkością, a całkowita energia fali również się zmienia. W analizie otrzymano rozwiązania niepodobne przy rozważaniu wpływ czasu i zmienności strumienia radiacji. Zbadano ponadto efekt wzrostu koncentracji masy cząstek stałych zanieczyszczenia oraz stosunku gęstości tych cząstek do początkowej gęstości gazu na parametry przepływu w obszarze bezpośrednio za czołem fali.

Manuscript received March 9, 2007; accepted for print May 23, 2007