

Decay of a saw tooth –profile in Two-Phase-Flows of gas-particle mixture.

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Abstract

In this paper, progressive - wave approach is used to obtain asymptotic solution of the non - linear system of partial - differential equations governing two- phase flows of gas –particle - mixture in case of reacting gases. For wave amplitude a Burger type equation is obtained from which Bernoulli type evolution equation is derived. This evolution equation governs the growth and decay of acceleration front and its analytical solution is obtained. Next for saw –tooth profile length and decay behavior is investigated. These results are compared numerically with help of Runge-Kutta method of fourth order. Numerical results shows that the applied numerical method is in good agreement for length of Saw – Tooth profile for cylindrical case. In case of decay behavior it is in good agreement with analytical one for plane and cylindrical case. In preparation of graphs origin 7.5 is applied.

Key – Words –saw- tooth, two-phase, reacting mixture

Classification 76T

Introduction

Studies of non - linear waves by using the progressive wave theory have been carried out by several authors. Germain⁴ reviewed the theory of progressive wave for wide applications in several fields. By using asymptotic expansion method Varley and Cumberbatch²⁸ have studied the finite-amplitude, radically symmetric and isentropic waves in fluids. Seymour and Varley²⁴ have studied high frequency periodic disturbances in dissipative systems and their results were applied to non - linear transmission lines, non - linear dielectrics and non - linear waves in a

reacting gas mixture. Through asymptotic analysis approach, Fusco² concluded that for a wave motion described by non homogeneous quasi - linear-hyperbolic system, coupling between non - linearity and dissipative effects can be established. Fusco and Engelbrecht³ have presented asymptotic analysis of non linear waves in rate-dependent media to study the high and low frequency wave processes and have obtained an evolution equation for a visco-elastic media. Sharma et al²⁵ and Shukla et al²⁶ have applied the progressive wave approach to study the decay behavior of a saw - tooth profile in magneto fluid and chemically reacting gases respectively .

Studies of non - linear effects on the wave propagation have been extensively carried out by Jeffery and Taniuti⁵,Whitham²⁹,Courant and Friedrichs¹. In recent technological advancement in different branches of engineering and science, compressible flows of dusty gas has attracted the attention of many investigators^{6,10,12,13-18,23,27}. The study of wave propagation in a mixture of gas and dust particle has many engineering applications such as flow in rocket, nuclear-reactors, fuel-spray , air pollution and numerous application in underground applications^{7,9}.

It is not always possible to exactly solve non –linear differential equation, hence numerical solution plays an important role to deal with such problems . Numerical calculations leads to approximate results , thus there is a difference between the exact and computed values , known as rounding error . If this error is manageable method is suitable for the problem . References¹⁹⁻²² shows some numerical solutions of non – linear waves .

Having such important applications of two – phase flows of gas particle mixture , in present paper using asymptotic analysis , analytical and numerical solution of decay of saw-tooth profile in two-phase flow of reacting gas is investigated . Throughout this article we have considered the two – phase flows model considered by Rudinger²³ , when particle volume fraction is negligible.

Basic Equations

The basic equations governing the one dimensional motion of mixture of a reacting gas and a large number of small dust particles of uniform spherical shape , when viscosity and heat conductivity of gas are neglected are given by Rudinger²³

$$\frac{D \rho}{Dt} + \rho u_{,x} + \frac{(\rho u m)}{x} = 0 \quad , \quad (1)$$

$$\frac{D u}{Dt} + \frac{1}{\rho(\eta + 1)} p_{,x} = 0 \quad , \quad (2)$$

$$\frac{Dh}{Dt} - \frac{1}{\rho} \frac{Dp}{Dt} = 0, \quad (3)$$

where p , u , ρ and h denote pressure, velocity, density and enthalpy of the mixture respectively. $\frac{D}{Dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial x}$ and a comma followed by an index denote partial derivative with respect to that index, $m = 0, 1, 2$ for planar, cylindrical, spherical symmetry. Considering moderate particle loading case considered by Rudinger²³ η (mass flow ratio for equilibrium case) and density ρ of mixture are defined as

$\rho = \rho_p + \rho_g$, ρ_p , ρ_g being density of particle material and gas respectively.

$\eta = \frac{\phi}{(1-\phi)}$, when gas and particle velocity are equal, ϕ being mass fraction of particle.

We assume that the time characterizing a macroscopic change under study is long compared to the time of establishing Boltzmann's distribution among translational degrees of freedom of the molecules in the mixture, thus rate equation is given by

$$\frac{Dq}{Dt} = \dot{q}, \quad (4)$$

where according to Vincenti and Kruger²⁹ q is assumed to be a known function of p , ρ and q . Thus canonical equation of state is given by

$$h = h(p, S, q), \quad (5)$$

S being entropy of medium.

Using Gibbs relation

$$T dS = dh - \frac{1}{\rho} dp + A dq \quad (6)$$

and canonical equation of state, we have following equivalent system of governing equations

$$\cdot p_{,t} + u p_{,x} + \rho a_f^2 \left\{ u_{,x} + \frac{(mu)}{x} \right\} + a_f^2 \left[\frac{(A \rho_{,s})}{T} + \rho_{,q} \right] \dot{q} = 0. \quad (7)$$

$$u_{,t} + uu_{,x} + p_{,x} \frac{1}{\rho(\eta+1)} = 0, \quad (8)$$

$$S_{,t} + u S_{,x} - \frac{A \dot{q}}{T} = 0, \quad (9)$$

$$q_{,t} + u q_{,x} - \dot{q} = 0 \quad , \quad (10)$$

where T is temperature , A the affinity of the internal transformation characterized by variable q and $a_f^2 = \frac{-h_{,p}}{\rho(\eta+1) \left(h_{,p} - \frac{1}{\rho} \right)}$ being resulting

sound speed.

Equations (7- 10) in dimensionless form can be written as

$$U^i_{,t} + C^{ij} U^i_{,x} + D^i = 0 \quad , \quad (11)$$

U^i being Column vector with four components p , u , S , q , C^{ij} is 4X4 matrix, D^i is a column vector with four components which can be obtained from equations(7-10) by inspection. System (11) is hyperbolic in nature and matrix C^{ij} of equation (11) has four real eigenvalues $(u \pm a_f)$ and u twice .Left and right eigenvectors corresponding to eigenvalues $(u \pm a_f)$ are given by

$$L^1 = [1, \rho a_f, 0, 0] ,$$

$$R^1 = \left[1, \frac{1}{\rho a_f}, 0, 0 \right]^T ,$$

where superscript T denotes transposition .

Progressive wave solution

To find an asymptotic solution of system (11), let us consider asymptotic expansion for U^i in the following form

$$U^i(x, t) = U^i_0 + \epsilon U^i_1(x, t, \xi) + \epsilon^2 U^i_2(x, t, \xi) + O(\epsilon^n) \quad , \quad (12)$$

where U^i_0 , is a known constant state solution of equation (11) such that

$$D^i(U_0) = 0 \quad \text{and} \quad \epsilon = \frac{\tau_{ch}}{\tau_\alpha} \ll 1 \quad \text{is a small parameter} ,$$

τ_{ch} -characterizes time scale for medium and τ_α is attenuation time characterizing dissipative mechanism .

Introducing Taylor's expansion of C^{ij} and D^i in neighborhood of the known constant solution U^i_0 and using asymptotic expansion given by equation (12) in equation (11) and collecting coefficients of constant term and ϵ , we have following set of equations

$$(C^{ij}_0 - \lambda \delta^i_j) U^j_{1,\xi} = 0 \quad (13)$$

$$(C^{ij}_0 - \lambda \delta^i_j) U^{j, \xi}_2 + f^{-1}_{,x} \{ (U^i_{1,t} + C^{ij}_0 (U^j_{i,x})) \} + U^k_1 (C^{ij}_{,Uk})_0 (U^j_{1,\xi}) + f_{,x}^{-1} U^k_1 (D^i_{,Uk})_0 = 0, \quad (14)$$

where $\xi = \frac{f(x,t)}{\epsilon}$ is fast variable, $f(x,t)$ being Phase Function

characterizing wave front, $\lambda = -\frac{f_{,t}}{f_{,x}}$ and δ^i_j being kronecker delta.

Equation (13) shows that $U^i_{1,\xi}$ is collinear to a right eigenvector R^i_{10} thus U^i_1 can be written as

$$U^i_1(x, \xi, t) = g(x, t, \xi) R^i_{10} + S^i(x, t), \quad (15)$$

$g(x, t, \xi)$ being wave amplitude which we have to determine and S^i are constant of integration, which are not of a progressive wave nature and can be taken as zero.

The phase equation and evolution function g are given by

$$f(x, t) = x - x_0 - a_{f0} t \quad (16)$$

and

$$\frac{\partial g}{\partial \tau} + E_0 g \frac{\partial g}{\partial \xi} + Q_0 g = 0, \quad (17)$$

where

$$E_0 = \left[\frac{(\Gamma + 1)}{2\rho a_f} \right]_0,$$

$$Q_0 = \left(\frac{1}{2\tau_0} \right) \left[\left\{ \left(\frac{a_{f0}^2}{a_{e0}^2} \right) - 1 \right\} + \left\{ \frac{(m a_{f0})}{2(x_0 + a_{f0} t)} \right\} \right],$$

a_f is frozen speed of sound, $\frac{\partial}{\partial \tau} = \frac{\partial}{\partial t} + a_{f0} \frac{\partial}{\partial x}$ is Ray derivative,

$$\Gamma = 1 + \rho \frac{\partial a_f^2}{\partial p} = \gamma_M \frac{(1 + \zeta \eta)}{(1 + \gamma_M \zeta \eta)}, \text{ratio of specific heats of mixture},$$

$$\gamma_M = \Omega \frac{(1 + \zeta \eta)}{(1 + \Omega \zeta \eta)}, \Omega = \frac{(4+q)}{3}, \text{for ideal case } \Omega = \gamma, \eta \text{ being mass}$$

loading ratio, ζ is relative specific heat (c/c_p), c being specific heat of particle material, c_p is specific heat of gas at constant pressure and subscript zero implies that quantity is evaluated at equilibrium which means

$$\Gamma_0 = \Gamma(p_0, S_0, q_0)$$

Acceleration wave front

In order to consider an acceleration wave front described by the curve

$f(x, t) = 0$, u may be represented by

$$u = \epsilon u_1(x, t, \xi) + O(\epsilon^2),$$

where

$$\text{and } \begin{cases} u_1 = 0, & \text{for } \xi < 0 \\ u_1 = O(\xi) & \text{for } \xi > 0. \end{cases}$$

Thus in view of equation (15), $g(x, t, \xi)$ is given by

$$g(x, t, \xi) = \begin{cases} 0 & \text{for } \xi < 0 \\ \xi f(x, t) + O(\epsilon^2) & \text{for } \xi > 0, \end{cases} \quad (18)$$

$$\text{where, } f(x, t) = \frac{\sigma}{a_{f0}}$$

$$\text{and } \sigma = [u, x]$$

denotes the jump in the velocity gradient across the acceleration front

and may be described as the wave amplitude of acceleration front.

Substituting $g(x, \xi, t)$ from equation (18) into equation (17), we have

following Bernoulli type equation

$$\frac{d\sigma}{dt} + \sigma \left[B + \frac{m a_f}{2(x + a_f t)} \right] + \Lambda_0 \sigma^2 = 0, \quad (19)$$

$$\text{where, } \Lambda_0 = \frac{(\Gamma + 1)}{2}, \text{ and}$$

$$B_0 = \frac{1}{2\tau_0} \left\{ \frac{a_{f0}^2}{a_{e0}^2} - 1 \right\}.$$

Equation (19) governs growth and decay of acceleration front and its solutions are

$$\sigma = \frac{\sigma^* \exp(-B_0 t)}{1 + \frac{\Lambda_0 \sigma^*}{B_0} \{1 - \exp(-B_0 t)\}}$$

$$\text{for } m = 0, \quad (20)$$

$$\sigma = \frac{\sigma^* \exp(-B_0 t) (x_0 + a_{f0} t)^{(-\frac{1}{2})}}{(x_0)^{(-\frac{1}{2})} + \Lambda_0 \sigma^* \sqrt{\frac{\pi}{B_0 a_{f0}}} \exp\left(\frac{B_0 x_0}{a_{f0}}\right) \left(\operatorname{erf} \sqrt{\frac{B_0 x}{a_{f0}}} - \operatorname{erf} \sqrt{\frac{B_0 x_0}{a_{f0}}} \right)}$$

$$\text{for } m = 1 \quad (21)$$

$$\sigma = \frac{\sigma^* \exp(-B_0 t) (x_0 + a_{f0} t)^{(-1)}}{(x_0)^{(-1)} + \frac{\Lambda_0 \sigma^*}{a_{f0}} \exp\left(\frac{B_0 x_0}{a_{f0}}\right) \left(Ei \sqrt{\frac{B_0 x_0}{a_{f0}}} - Ei \sqrt{\frac{B_0 x}{a_{f0}}} \right)}$$

$$\text{for } m = 2, \quad (22)$$

where,

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2) dt$$

and

$$Ei(x) = \int_0^x \frac{(1 - e^{(-t)})}{t} dt - \ln x - r,$$

are error and exponential functions respectively . In deriving these results help of reference 8 is taken . $\sigma^* \neq 0$ is the initial value of σ . As B_0 and Λ_0 are positive constant solution of equations (20) to (21) shows that all

expansion waves ($\sigma^* > 0$) decreases exponentially and will be damped out ultimately. On the other hand compressive waves

($\sigma^* < 0$) will decay out and terminate into a shock –wave and in case

$\sigma^* = B_0 / \Lambda_0$, velocity at wave- front will remain constant. **A results similar to reference 11 .**

Decay of saw – tooth profile

Now we consider a physical situation when a compressive wave terminates into a weak shock front propagating in to the medium at rest , followed by an expansion wave front .Such physical situation may be described in the form of a saw – tooth profile . As time passes, the compressive part of the initial wave steepness into a weak –shock due to non- linear effects ,but the expansion part propagates in the form of an expansion wave following the shock with a speed of propagation a_{f0} . The associated shock part propagates at a faster speed $G > a_{f0}$ and location of the shock at any time t is given by

$$x_s(t) = x_0 + a_{f0} t + L(t) , \quad (23)$$

$L(t)$ being the length of the saw – tooth profile at any time t .

The velocity G in this case is given by

$$G = \frac{d x_s(t)}{dt} = a_{f0} + \frac{dL}{dt} . \quad (24)$$

From weak – shock conditions , we have

$$G = a_{f0} + \frac{u_1(\Gamma + 1)}{4} = a_{f0} + \frac{u_1 \Lambda_0}{2} , \quad (25)$$

where $u_1 = a_{f0} \delta$, $\delta = \frac{[\rho]}{\rho_0}$ denotes shock–strength parameter.

The particle velocity u at the rear of the weak–shock heading the saw – tooth profile can be expressed as

$$u_1 = \sigma L(t) . \quad (26)$$

From equations (23) to (25) we have

$$\frac{dL}{dt} = \frac{\{\sigma L(t) \Lambda_0\}}{2} . \quad (27)$$

Integrating equation (27) , we have

$$\frac{L}{L^*} = \left[1 + \frac{(\Lambda_0 \sigma^*) \{1 - \exp(-B_0 t)\}}{B_0} \right]^{1/2}$$

$$\text{for } m = 0 , \quad (28)$$

$$\frac{L}{L^*} = \left(1 + \Lambda_0 \sigma^* (x_0)^{(1/2)} \sqrt{\frac{\pi}{B_0 a_{f0}}} \exp \frac{B_0 x_0}{a_{f0}} \left(\operatorname{erf} \sqrt{\frac{B_0 x}{a_{f0}}} - \operatorname{erf} \sqrt{\frac{B_0 x_0}{a_{f0}}} \right) \right)^{\frac{1}{2}}$$

$$\text{for } m = 1 \quad (29)$$

$$\frac{L}{L^*} = \left(1 + \frac{(\Lambda_0 \sigma^* x_0)}{a_{f0}} \exp \frac{B_0 x_0}{a_{f0}} \left(Ei \sqrt{\frac{B_0 x_0}{a_{f0}}} - Ei \sqrt{\frac{B_0 x}{a_{f0}}} \right) \right)^{\frac{1}{2}} \quad \text{for } m = 2 . \quad (30)$$

Applying equations (20 – 22) and (28 – 30) in equation (26) we have

$$u = \frac{L^* \sigma^* \exp (-B_0 t)}{\left(1 + \frac{(\Lambda_0 \sigma^*) \{1 - \exp (-B_0 t)\}}{B_0} \right)^{\frac{1}{2}}} \quad \text{for } m = 0 , \quad (31)$$

$$u = \frac{\sigma^* L^* \exp (-B_0 t) \{x_0 (x_0 + a_{f0} t)\}^{(-1/2)}}{\left(1 + \left\{ \Lambda_0 \sigma^* (x_0)^{(1/2)} \right\} \sqrt{\frac{\pi}{B_0 a_{f0}}} \exp \left(\frac{B_0 x_0}{a_{f0}} \right) \left[\operatorname{erf} \sqrt{\frac{B_0 x}{a_{f0}}} - \operatorname{erf} \sqrt{\frac{B_0 x_0}{a_{f0}}} \right] \right)^{\frac{1}{2}}}$$

$$\text{for } m = 1 \quad (32)$$

$$u = \frac{\sigma * L * \exp(-B_0 t) \{x_0 (x_0 + a_{f0} t)\}^{-1}}{\left(1 + \frac{(\Lambda_0 \sigma * x_0)}{a_{f0}} \exp \frac{B_0 x_0}{a_{f0}} \left[Ei \sqrt{\frac{B_0 x_0}{a_{f0}}} - Ei \sqrt{\frac{B_0 x}{a_{f0}}} \right] \right)^{\frac{1}{2}}}$$

for $m = 2$, (33)

Result

Using progressive - wave approach solution of the non - linear system of partial - differential equations governing two- phase flows of gas –particle - mixture in case of reacting gases is obtained .Analytical and numerical solution of evolution equation and saw –tooth profile is derived . For numerical solution Runge-Kutta method of fourth order is applied . Results are compared through graphs . In preparation of graphs origin 7.5 is used. a It is concluded that applied numerical result is in good agreement for cylindrical case , but for decay behavior of Saw – Tooth profile it is in good agreement with analytical one for plane case also .

Conclusion

Fig.1-3 , shows the non-equilibrium effects on the length of saw-tooth profile for planer, cylindrical and spherical waves and is concluded that for cylindrical waves numerical results are in good agreement with analytical result where for planer and spherical cases ,there is a large variation in analytical and numerical result ,hence it requires to apply some other method which provide more accurate result and less error. Fig.4-6 shows decay of saw-tooth profile under non-equilibrium effects and results shows that for planer and cylindrical case numerical method has a good agreement with analytical one, but for spherical case it require some modification to get more accurate result.

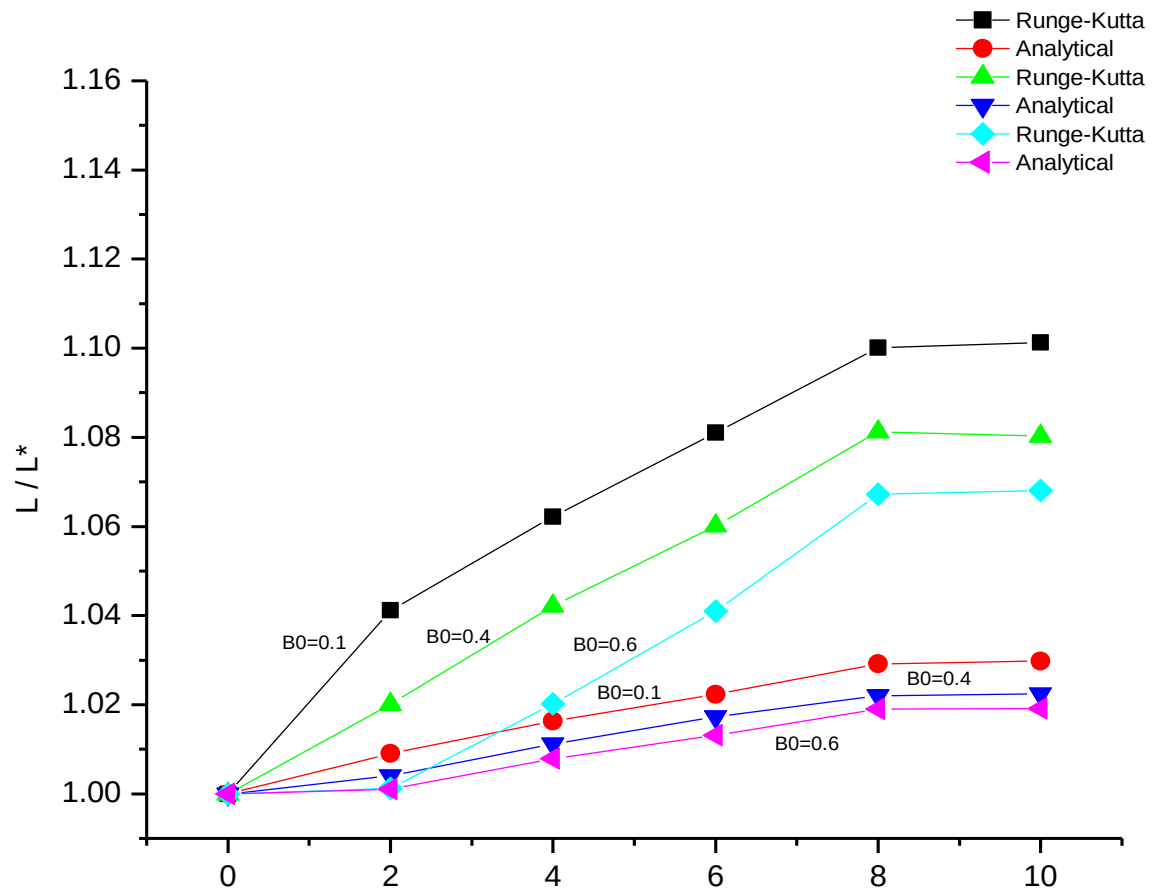


Figure 1: Non-equilibrium effect on the length of a saw-tooth profile for plane wave

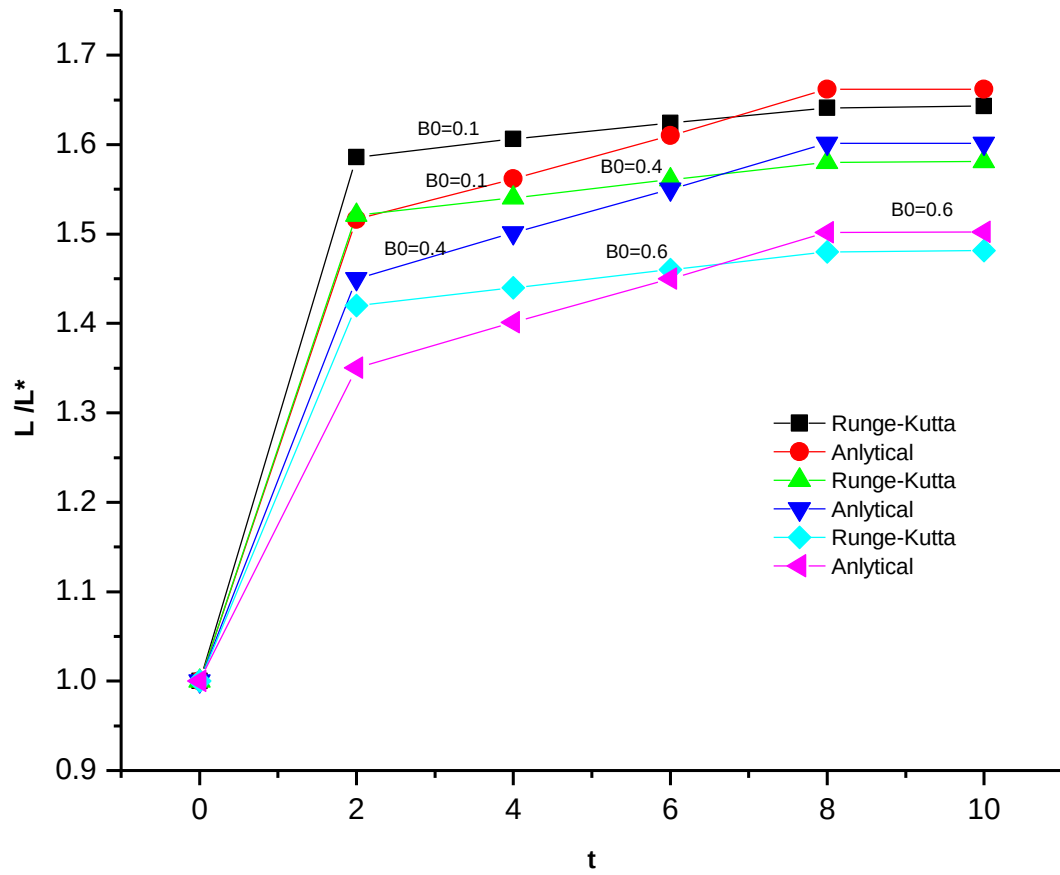


Figure 2 : Non-equilibrium effects on the length of a saw- tooth profile for cylindrical wave

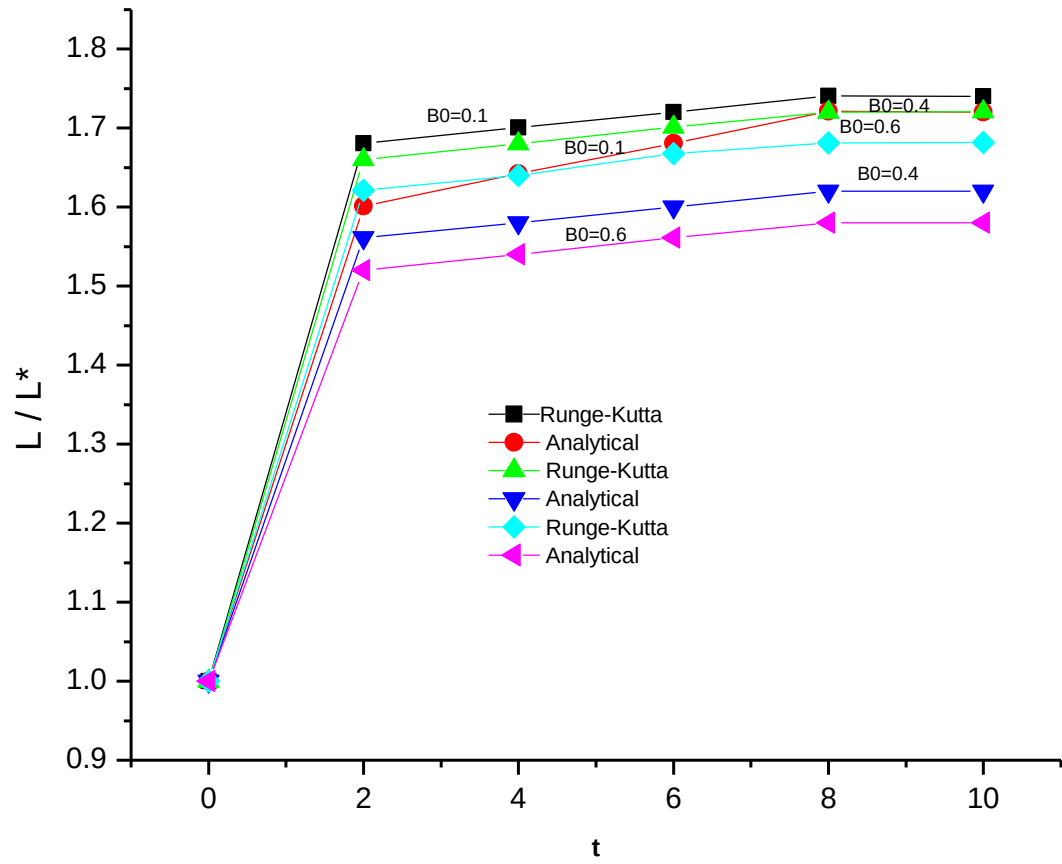


Figure 3: Non-equilibrium effects on the length of a saw- tooth profile for spherical wave

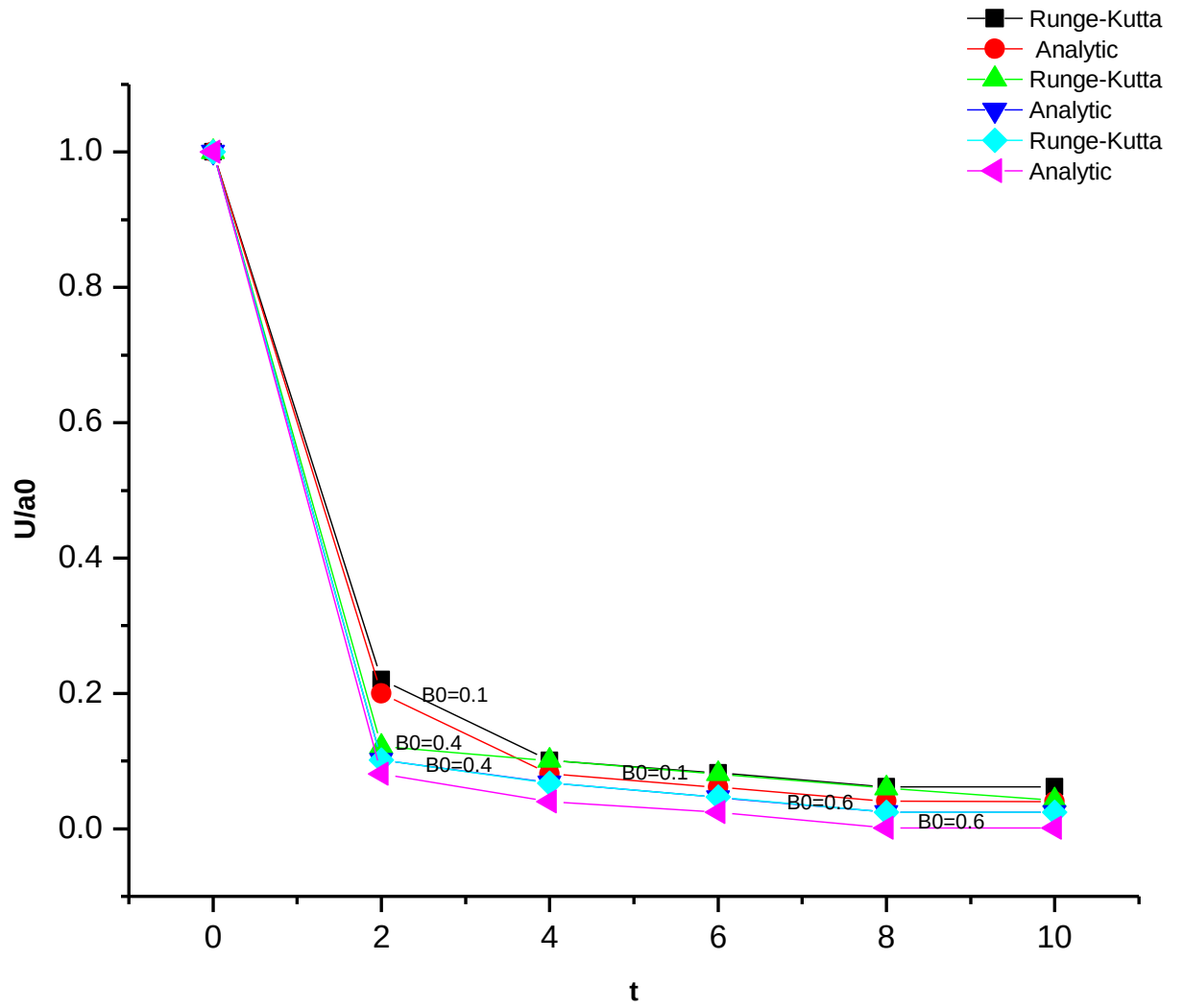


Figure4: Decay of saw-tooth profile for plane wave under non-equilibrium effect

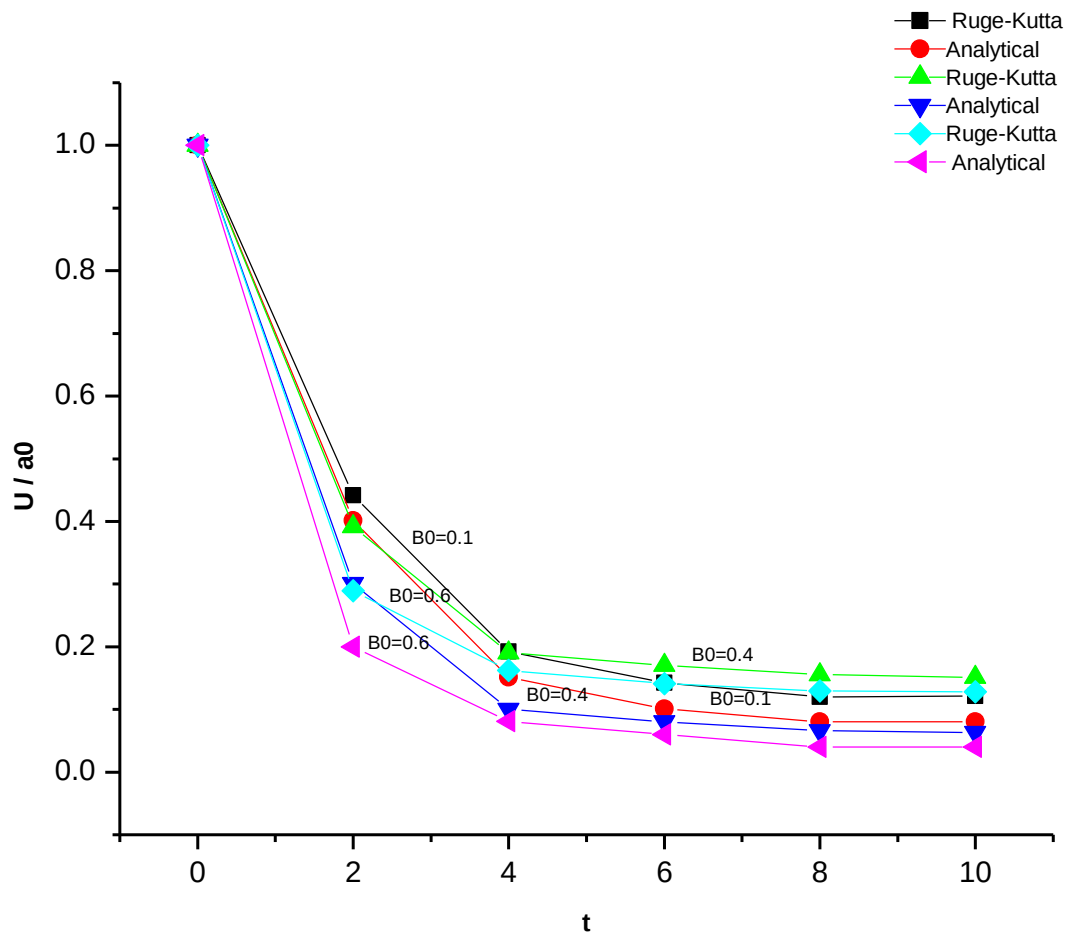


Figure 5: Decay of saw tooth profile for cylindrical wave for non equilibrium effect

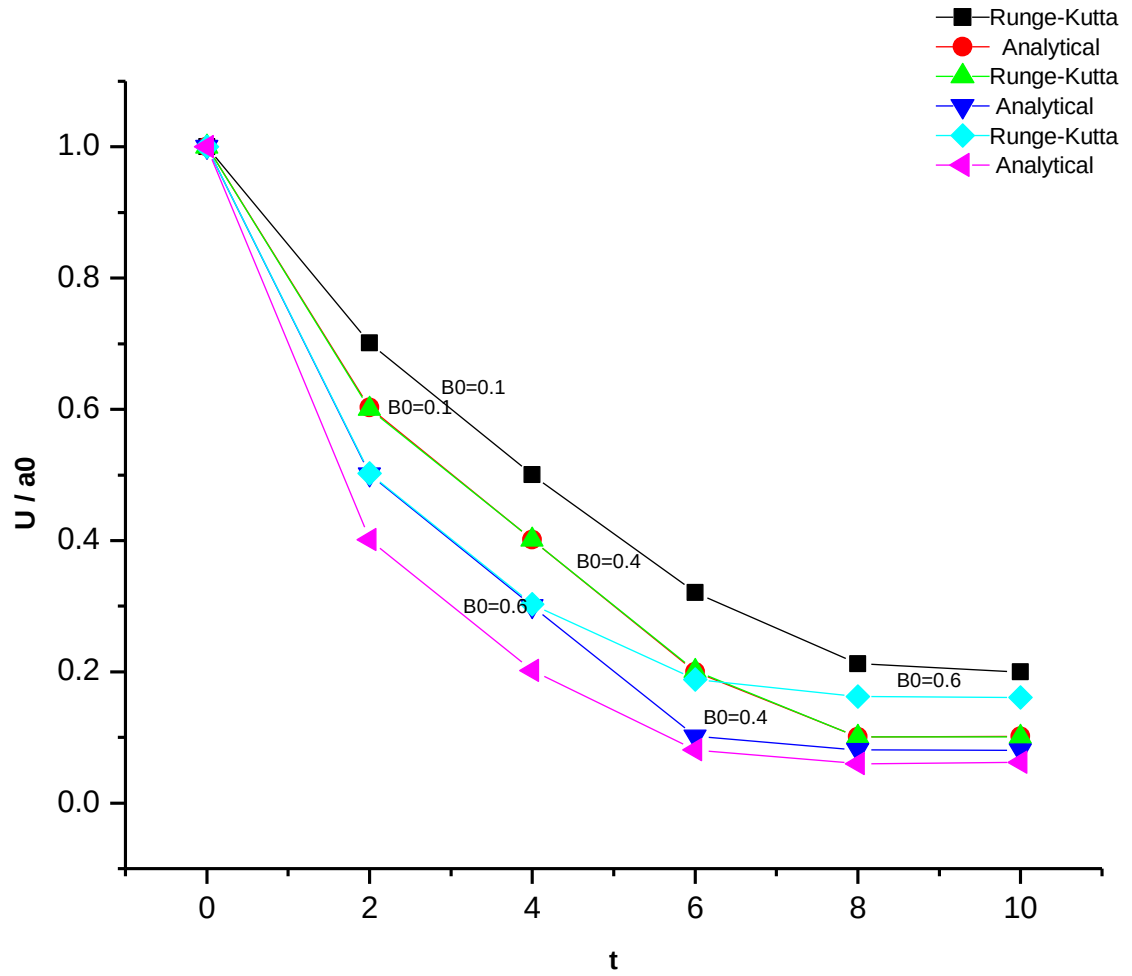


Figure 6: Decay of saw-tooth profile of spherical wave under effect of non- equilibrium effect

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