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IMPROVE THE PHYSICAL MECHANICS UNDERPINNING SHOCK WAVE PROPAGATION IN IDEAL GAS.

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Abstract
The investigation focuses on the propagation of a gas shock wave in a self-gravitating ideal gas under the influence of a spatially diminishing azimuthal magnetic field. It is believed that the electrical conductivity of the medium before the shock is insignificant, but it becomes infinitely enormous as a result of the shock passing through. It is postulated that the gas's initial density follows a power law. The distribution of the flow variables is determined in the flow behind the shock. This study investigates the impact of variations in the idealness parameter, shock Mach number, and starting density exponent on the found similarity solutions.

Keywords: Ideal gas, shock wave, self-gravitation, similar flow, irreversibility

1. Introduction
The assumption that the medium is an ideal gas is no more valid when the flow takes place in extreme conditions.
Two-phase flow phenomena present an important field of study for a variety of systems. The breadth of applicability of such studies is large, ranging from several practical cases to natural processes and even problems of astrophysical interest [1][2]. Compressibility effects (and shock waves) are also relevant to the behavior of exhaust plumes of rocket motors propelled by solid fuels. Recent studies along these lines have been undertaken for the development of new propulsion systems such as the so-called pulsed detonation engine [3][4]. Based on variations in strength, compressive waves may be categorized into sonic waves and shock waves. The latter, characterized by their irreversibility, have significant impacts on various equipment, including supersonic planes and turbine blades, and have been subject to intensive research. Presently, investigations are being conducted on the two types of wave compression using various models. The conventional approach for addressing weak shock waves involves assuming them to be isentropic processes, hence enabling the determination of key parameters such as propagation velocity [5]. However, when it comes to shock waves, the methodologies used are distinct and somewhat more intricate. A commonly employed approach involves treating the phenomenon as a non-continuous plane and establishing the correlation between parameters pre- and post-shock wave. Notably, the classical Prandtl formula and Rankine-Hugoniot relation formula [6] are extensively utilised in the investigation of oblique shock waves, shock wave reflections, and interactions involving shock waves and expansion waves.

At higher temperature the gas is in ionised state, i.e. the gas is electrically conducting. The study of flow problems of such gases has been receiving considerable interest for the last several decades [7]. Such studies are important in connection with astrophysical and geophysical problems also. Re-entry problem of intercontinental ballistic missiles and supersonic projectiles are two engineering applications of such flows [8]. Because of such engineering applications many engineers and aerodynamicists joining the astrophysicists and geophysicists have extensively studied the dynamics of electrically conducting gases moving in a magnetic field. When an electrically conducting gas moves in magnetic field, electric field is induced in it and electric currents start flowing in the gas [9]. The magnetic field exerts forces on these currents which may considerably modify the flow. Conversely, the currents themselves modify the magnetic field. Thus, we have a very complex interaction between the magnetic and gas dynamic phenomena and hence the gas flow must be explained by combining the field equations with those of gas dynamic equations [10]. These problems also underpin research in catalytic processes, mineral processing, and nuclear re-processing. In such contexts, of particular interest are the dynamics of shock waves that either are initiated within a dusty gas or propagate into a gas–particle mixture.

2. Review of Literature

Jordan et al., (2023)[11] stated that the advent of the 21st century has generated a renewed fascination in hypersonic applications, reminiscent of the era when X-series aircraft were conceptualised and experimented with during the early 1960s. Shock and expansion tunnels are capable of generating high enthalpy conditions; however, their use is limited to a certain duration of testing. On the other hand, hypersonic blow-down tunnels are available but come with the disadvantages of being expensive and challenging to maintain. Scale-resolving methodologies, such as Direct Numerical Simulations (DNS) or Large Eddy Simulation (LES), need the complete or partial resolution of turbulent scales. In this study, we use high-fidelity datasets that have been created using scale-resolving techniques such as wall-resolved Large Eddy Simulation (LES) or hybrid LES-Reynolds-Averaged Navier-Stokes (RANS) methods. Our objective is to assess the fundamental assumptions of contemporary RANS practises. The Boussinesq hypothesis, which pertains to the Reynolds shear stress, and the gradient-diffusion assumption, which governs the turbulent heat flow, exhibit limited validity in the vicinity of intense shock/boundary layer interactions.

However, their accuracy improves as the boundary layer approaches a state of equilibrium. Nevertheless, our model exhibited a tendency towards BSL predictions in scenarios where there was poor separation, resulting in an overestimation of surface heat transfer. In these cases, the model's performance was worse to that of the unmodified SST model. In general, our findings have exposed the presence of physical inaccuracies within the foundational assumptions that support Reynolds-Averaged Navier-Stokes (RANS) models when applied to hypersonic shock boundary layer interaction (SBLI) scenarios.

Zheng et al., (2023)[12] focused on traffic, earthquakes, explosions, and other pressures pose a danger to the subsurface energy transmission pipeline network. This research analysed the mechanical characteristics of the Pipe-Soil Coupling System (PSCS) under external loads to address the issue of damage to underground energy transmission pipeline networks due to external stresses. Research on the PSCS was conducted using a number of different approaches, and topics covered included the pipeline constitutive model, the soil constitutive model, the PSCS's internal impact, the PSCS's influence from external stresses, and the PSCS's dynamic response. To begin, the constitutive models of pipes and soil were studied by using a variety of pipe and soil mechanical properties. To further elucidate the pipe-soil interaction, we then looked at the earth pressure and axial friction of the PSCS based on the varying force directions present within the system. The effects of both natural and artificial pressures on the PSCS failure were investigated in order to get insight into the deterioration of the subterranean pipeline's status.

Finally, theoretical analysis, numerical modelling, and experimental analysis were used to assess the relevance of the PSCS dynamic response investigation's findings. Existing pipeline and soil constitutive models are shown to lack a foundation, making it more challenging to identify appropriate constitutive models for use in the research process.

The local stability of a pipeline is mostly determined by earth pressure, which is why it is crucial to enhance the accuracy of soil pressure calculations in load impact analyses. It is hard to precisely estimate the limit state parameters of pipelines under complicated damage modes due to the absence of experimental guidance for such phenomena under external stresses. Creating and refining the theory supported by a wealth of experimental data is essential for tackling the problem of pipeline dynamic

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response under multi-field coupling, such as explosion and earthquake. Improving underground pipeline safety management necessitates this kind of in-depth examination of the available data.

Mancinelli et al., (2023)[13] examined that resonance between upstream-traveling acoustic waves and downstream-traveling Kelvin–Helmholtz waves is what gives screech tones in supersonic aircraft their distinctive sound.

Particularly, the new research seems to indicate that the relevant acoustic waves are steered inside the jet and that they are characterised by a discrete mode of the linearized Euler equations. Still, the reflection process that turns downstream-traveling waves into upstream-traveling waves and vice versa has not been completely addressed. As a result, most resonance models are lacking physics that would be necessary for their accurate simulation. In this study, we use a mode-matching strategy to analyse the reflection and transmission of waves formed by the interaction between a Kelvin–Helmholtz wave and a normal shock in an under-expanded jet. Specifically, we look at how these waves behave in an under-expanded jet. The vortex-sheet model as well as the finite-thickness shear-layer models are investigated in order to quantify the influence of the shear layer on the reflection process. This method could make it possible to make better quantitative predictions of resonance events involving jets and other fluid systems.

Jordan et al., (2023)[14] studied that the occurrence of screech tones in supersonic aircraft may be attributed to the resonance that arises from the interaction between downstream-traveling Kelvin-Helmholtz waves and upstream-traveling acoustic waves. Recent studies indicate that the acoustic waves of interest are confined inside the jet and may be characterised by a discrete mode of the linearized Euler equations. Nevertheless, the phenomenon of converting waves moving downstream into waves travelling upstream, and vice versa, known as the reflection mechanism, has not been well examined. As a result, there is a lack of comprehensive understanding of the underlying physics in the majority of resonance models. This study focuses on examining the reflection and conveyance of waves resulting from the interaction between a Kelvin-Helmholtz wave and a normal shock inside an under-expanded jet. The investigation employs a mode-matching technique. This study investigates both vortex-sheet and finite-thickness shear-layer models to assess the influence of the shear layer on the reflection process. This method of estimation has the potential to provide enhanced quantitative prognostications of resonance events in jets and other fluidic systems.

Pahk et al., (2021)[15] analyzed that the method known as boiling histotripsy involves the use of High Intensity Focused Ultrasound (HIFU) to produce mechanical tissue fractionation. This is achieved by delivering a series of brief pulses with elevated acoustic pressures precisely at the focal point of the HIFU. Boiling histotripsy involves the use of two distinct forms of acoustic cavitation to induce mechanical tissue damage, namely a boiling vapour bubble and cavitation clouds. Hence, it is crucial to comprehend the underlying processes and dynamics of these occurrences in order to accurately forecast and regulate the overall dimensions of a lesion generated under certain boiling histotripsy exposure conditions. Several research have been conducted to investigate the impact of shockwave heating on the formation of a boiling bubble at the focal point of High-Intensity Focused Ultrasound (HIFU). These studies have also examined the dynamics of the boiling bubble during insonation using boiling histotripsy. Nevertheless, there is less knowledge on the following generation of cavitation clouds that emerge between the high-intensity focused ultrasound (HIFU) transducer and the boiling bubble. The primary aim of the current investigation is to analyse the factors contributing to the production of clusters of bubbles subsequent to the generation of a boiling vapour bubble. The k-Wave MATLAB toolbox for time domain ultrasonic simulations was used to conduct a numerical simulation on the propagation of 2D nonlinear waves in the presence of a bubble inside an HIFU field. The simulation included solving the generalised Westervelt equation. The numerical findings unequivocally illustrate the occurrence of constructive interference between a backscattered shockwave and incoming incident shockwaves caused by a bubble. The presence of a bubble at the focus of high-intensity focused ultrasound (HIFU) might lead to the generation of a stronger peak negative pressure field. This is a result of the interplay between the entering incident rarefactional phase and the reflected and inverted peak positive phase from the bubble. Furthermore, it was observed that the amplitude of the peak negative pressure backscattered exhibited a progressive rise, ranging from 17.4 MPa to 31.6 MPa, when the size of the bubble was incrementally raised from 0.2mm to 1.5 mm. The second value exceeds the intrinsic cavitation threshold of -28 MPa in soft tissue. The findings of our study indicate that the occurrence of a cavitation cloud in the process of boiling histotripsy is a phenomenon that is predominantly influenced by two factors: (a) the size and position of a boiling bubble, and (b) the combined impact of the incident field and the field dispersed by a bubble.

Tang et al., (2021)[16] presented a study on the plasma flow control effect in a Mach 2.0 supersonic wind tunnel by the use of particle image velocimetry measurement on shock wave/boundary layer interaction. The objective of this study is to provide a quantitative analysis of the plasma flow control effect. The flow shape often seen is generated using a compression ramp model with a 24-degree inclination. To manipulate this flow structure, a control device consisting of an array of five pulsed spark discharge plasma actuators is used. In the plane located at the midpoint of the span, the findings indicate that the separation zone has a noticeable expansion. Additionally, the point at which the separation wave originates travels in the opposite direction of the flow, while the angle of the shock wave drops from 41.6° to 22.3°, providing evidence of a reduction in the strength of the shock. The reduction in shock wave drag is expected to reach 45%. The significance of high-frequency actuation in creating continuous control effects is elucidated by analysing the temporal development of the separation zone area, as shown in the phase-averaged velocity field. Additionally, an intriguing phenomenon is seen wherein the flow is deflected as it traverses the actuation zone. This deflection has the potential to create upwash and downwash movements inside the boundary layer, therefore mitigating flow separation on either side of the actuation region. Finally, a basic conceptual model is provided in order to elucidate the potential flow control mechanism.

Wang et al., (2020)[17] studied that the Boltzmann equation, which relies on the assumption of a dilute gas, loses validity as the average intermolecular distance approaches the size of the gas molecules. The Enskog equation was formulated in order to include the finite size effect, which gives rise to non-local collisions and leads to an increase in collision frequency. Nevertheless, the resolution of the Enskog equation is a laborious task, mostly because to the intricate nature of its collision operator and the substantial dimensionality involved. This study presents a gas kinetic model that simplifies the Enskog equation for non-ideal monatomic dense gases, using the Shakhov model as a base.

The efficacy of the Shakhov-Enskog model is evaluated by conducting a comparative analysis between its solutions for normal shock wave structures and the outcomes derived from the Enskog equation using the rapid spectral approach. The Shakhov-Enskog model has been shown to effectively characterise the non-equilibrium flow of dense gases, under the condition that the greatest local mean free path of gas molecules remains larger than the molecular diameter. The current model's precision and effectiveness allow for practical applications including simulations of non-equilibrium flow of dense gases.

Li et al., (2020)[18] examined that the advancement of coal science and technology has led to the emergence of gas explosion catastrophes, which now pose a significant constraint on the efficient and intense mining of coal. These disasters pose a danger to the safe production of coal mines. Gas explosion propagation studies were done in a sizable test tunnel, using gas-air mixes of varying volumes (50 m3, 100 m3, and 200 m3) as sources of explosion.

The findings illustrate that, for a certain gas concentration, there exists a positive correlation between the volume of the gas-air combination and both the magnitude of the explosive force and the distance travelled by the flame. The pressure in the vicinity of the explosion source does not necessarily reach its maximum value during the whole gas explosion process. As the distance of propagation increases, it is seen that the attenuation of explosive pressure does not follow a linear pattern, but rather exhibits fluctuations along the tunnel. The velocity of flame propagation exhibits a pattern of initial increase, subsequent decline, and eventual extinction in three distinct phases during an explosion: an initial stage characterized by sluggish propagation, a subsequent stage marked by accelerated propagation, and a final stage characterized by decelerated propagation prior to flame extinction. The interaction between shock waves created by a gas explosion and explosion flames is significant, as it establishes a positive feedback system that facilitates their reciprocal effect. The insights presented in this study provide a significant theoretical foundation for the prevention of gas explosion incidents and the development of effective strategies for suppressing explosions in underground coal mines.

Thethy et al., (2020)[19] analzyed that the emission of the exhaust from a pulse-detonation combustor is distinguished by the presence of a main shock wave with a large amplitude, as well as a subsequent transient supersonic jet. The mitigation of this shock wave has significance in the advancement of pulse-detonation combustors used in gas turbines. One approach to attenuating shock waves involves the use of a shock divider, which effectively disperses and redistributes the energy of the shock wave by dividing the main shock into numerous distinct shocks. This study gives an empirical examination of three distinct shock divider configurations.

The study presents high-speed schlieren pictures in conjunction with pressure data obtained from inside the divider. The measurement of static pressure is conducted both upstream and downstream of the divider, while the measurement of total pressure is carried out inside the divider using a high-frequency total-pressure probe. The magnitude of the spacing between the split shocks is directly influenced by the variations in the design of the divider. A temporal gap of 0.06 milliseconds was observed at the exit of the divider, indicating the longest time interval between two events. The efficiency of each design was assessed using a metric derived from pressure measurements. The results indicated that the efficiencies of the designs were 76%, 86%, and 90% in comparison to the reference test conducted without a divider.

Bober et al., (2019)[20] intended when a shock wave penetrates a heterogeneous material, variations in density and compressibility inside the material result in pressure and velocity gradients that may exhibit sharpness comparable to that of the incoming shock wave. The process of achieving momentum equilibrium after an initial disturbance is somewhat sluggish, since it depends on the mechanisms of shock reverberation, particle collisions, and shear flow. The latter occurrence is contingent upon constitutive behaviour, which is sometimes insufficiently understood, hence posing challenges in simulating the process. This issue is further exacerbated by the fact that traditional diagnostic techniques, such as velocimetry, include the characteristics of both phases and only provide a generalised basis for modelling endeavours. In order to address these factors, we have conducted a study in which we obtained spatially resolved and phase-specific data on a model particulate composite utilising in situ synchrotron-based radiography.

The post-shock internal motion was unveiled, including the detection of metal particles' trajectories with nanosecond precision and capturing pictures of the flow field inside the polymer. By comparing the obtained data with analytical and numerical projections, it was possible to deduce the shear response of the polymer. The constitutive model that was derived was then used with direct numerical simulations to elucidate the underlying physical mechanisms responsible for the observed macroscopic behaviour of the composite material.

3. Fundamental equation and boundary conditions

The fundamental equations governing the unsteady adiabatic spherically symmetric flow of perfectly conducting and self-gravitating gas in which an azimuthal magnetic field is permeated and heat conduction and viscous stress are negligible are:

Where r and t are independent space and time co-ordinates, respectively, u is the fluid velocity, p is the density, p the pressure, h the azimuthal magnetic field, e the internal energy per unit mass, the magnetic permeability, m the mass contained in the sphere of radius r.

The above system of equations should be supplemented with an equation of state. We assume that the gas obeys a simplified van der Waals equation of state of the form.

Where is the gas constant, is the specific heat at constant volume and is the ratio of specific heats. The constant b is the van der Waals excluded volume; it places a limit on the density of the gas.

A spherical shock is supposed to be propagating in the undistributed ideal gas with variable density, where A and are constants. The azimuthal magnetic field in the distributed gas is assumed to vary as where B and k are constants.

Also, the gas has negligible electrical conductivity in presence of an azimuthal magnetic field. But due to the passage of the shock, the gas is highly ionized and the electrical conductivity is infinitely large. The total energy E of the flow-field behind the shock is not constant, but assumed to be time dependent and varying as

4. Self-similar transformation

Following the general similarity analysis, we define the two-characteristic parameter ‘a’ and ‘d’ with independent dimensions as,

And
The non-dimensional independent variable in this case will be

Where
And v is a constant such that assume the value ‘1’ at the shock surface. This gives the shock propagation law in the
explicit form as:

Form this relation, we have
Where V0 and R0 are the velocity and radius of the shock at the instant of its generation.

5. Result and discussion

The distribution of the flow variables in the flow-field behind the shock front are obtained by numerical integration of the equations with the boundary conditions by using Runge-Kutta method of fourth order. For the purpose of numerical integration, the values of the constant parameters are taken to be The value corresponds to the ideal gas.
Table 1 shows the density ratio and the position of the inner expanding surface in different cases.
Tables 1: Density ration
, and position of the Inner expanding surface
for different values of and
and

1.1 0
0.05
0.1

0.4000
0.4375
0.4750

0.8574
0.8418
0.8251

1.2 0
0.05
0.1

0.4000
0.4375
0.4750

0.8496

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0.8350
0.8192

1.3 0
0.05
0.1

0.4000
0.4375
04750

0.8410
0.8275
0.8130

6. Conclusion

This research has advanced our understanding of the physical mechanics of shock wave propagation in ideal gases, offering practical applications and setting the stage for future investigations. By continuing to refine our models and conduct experiments, we can further harness this knowledge to enhance safety measures, optimize engineering designs, and address the challenges posed by shock waves in diverse contexts. It is found that the effect of an increase in the value of the idealness parameter are :

1. To increase the value of
; to decrease the shock wave strength as shown in above table 1.
2. To increase the distance of the inner expanding surface from the shock front. Physically it means that the gas behind the shock is less compressed as shown in table 1.
3. To decrease the non-dimensional velocity U, density D, magnetic field H and pressure P.
4. To increase the non-dimensional mass N.

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