

FACTORS THAT INFLUENCE THE OPERATION OF THE ROCKET SYSTEM

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ABSTRACT

Compressibility is unavoidable in high-velocity gas flows, and it is accompanied by appreciable physical changes coupled with complex interaction with performance factors. When designing a high velocity flow system, it is necessary to recognize that compressibility produces a separate set of physical results which may involve significant variations in density, pressure and temperature. Interest in this study is therefore to identify the relevant features and where possible, how they interact with system performance. The equations of continuity, momentum, and energy may be required in the study of fluid flows. For compressible flows, a number of numerical models are available and these include the One-Equation Model (Spalart-Allmaras) and Two-Equation standard $k-\epsilon$ models in its various forms. The Spalart Allmaras model is considered a viable model option for the study of the characteristics of compressible high-velocity rocket system. Various forms of drag losses occur in supersonic fluid flow systems. For the re-entry vehicle a blunt nosed leading-edge design is adopted for temperature reduction in this region.

Keywords: Compressible, propellant, re-entry, nozzle, rocket motor, blunt body

1 INTRODUCTION

The study of gas dynamics may involve such factors as gas effects, wall catalysis and ablation, radiation cooling effects, shock-wave boundary-layer interaction and transition, sneak flows; nozzle flows, turbulence base flows and propulsion [1]. In general, liquids and gases are the states of matter that come under a similar class as “fluids”. The incompressible fluid flows refer principally to cases with constant density. On the other hand, the compressible flows are generally considered as “variable density flows” [2]. As the fluid velocity approaches that of sound, variation in fluid properties become significant. At this stage therefore, compressibility becomes important and its role needs be given adequate attention. Compressibility of a fluid may be seen as a measure of variation in fluid pressure and hence density. In high-speed fluid flows, noticeable changes in fluid properties may not be limited to pressure and density. These changes may involve temperature and even dissociation of gases [3, 4]. Propulsion system generally produce thrust that may be deployed to relocate a body from one place to another. There are many applications in which propulsion systems are employed and these include the jet engine, missiles, assisted takeoff vehicles, space vehicles and much more. These applications can be separated into two main categories: jet and rocket propulsion. The difference between the two is that in jet propulsion the oxygen within earth’s atmosphere is utilized as an oxidant whereas in rocket propulsion the oxidant is carried onboard since there is no oxygen in outer space. Despite these two major differences between jet and rocket propulsion, all propulsion systems operate on the same fundamental principles. They all produce thrust which is responsible for changing the motion of the body [5]. Modeling and simulation software packages (such as Solid Works and ANSYS) are engineering tools that assist in the study and analysis of

engineering systems. The scope is not limited to fluid dynamics they could be applied to any process which involves transport phenomena. To solve an engineering problem, one can make use of various methods such as analytical or the experimental study. The analytical method may, at times, prove very difficult and complicated to implement whereas the experimental may result to cost escalation and therefore uneconomical. If any error in the design was detected during prototype testing, another prototype has to be produced in which the error has been rectified and again tested. In all, this is a time-consuming and costly process. The introduction of simulation using engineering software has overcome a lot of these difficulties and revolutionized this sector in engineering application [6, 7]. Modeling in engineering practice is employed as a tool for studying and checking the feasibility, functionality, trade-offs, features of design and construction pitfalls [7]. All these features, factors and parameters combine in one way or the other to affect the performance of propulsion system. The purpose of this study is to look at the essential features that functionally contribute to the working of the rocket system.

2 RELEVANT FEATURES

2.1 Rocket Propulsion System

The rocket motor must be adequately designed for propulsion to take place. for the system to Propulsion, in a broad sense is the act of adjusting the motion of a body. Propulsion mechanisms provides a force that moves bodies that are initially at rest, changes the velocity or overcomes retarding forces when a body is propelled through a medium. Rocket propulsion is a class of jet propulsion that produce thrust by ejecting high temperature and high pressure combusted propellant gases through the exit nozzle. Rocket propulsion system can be classified according to the energy source, propellant type and basic function. According to the energy source-propulsion are often classified as chemical, nuclear, and solar rockets. Under the propellant type are the solid and liquid propellant rockets. The final group embraces functionality including the booster, sustainer, attitude control, orbit station rockets etc. [8]. In rocketry, burnt propellant gases ejected through the nozzle produce the thrust. The gas ejected has mass and velocity, hence a corresponding momentum. Through the conservation of momentum, a reaction force that changes the motion of a body is produced. Focusing specifically on model rockets, thrust is produced by a motor that ejects burnt propellant at high velocities which correspondingly leads to rocket velocities [5, 8].

2.2 Propellants

Thrust can only be produced when fuel and oxidant are stoichiometrically available. There are two types of propellant two – liquid and solid propellants. In application, the later propellant is used for short range and as booster rockets whereas the former is for long range missiles. Solid propellants contain all the elements required for combustion. Two solid propellant types are available. The propellant is homogeneous when the fuel and oxidant are contained within the same molecule and these double base propellants include a combination of nitroglycerin-nitrocellulose [$C_3H_5(NO_2)_3-C_6H_7O_2(NO_2)_3$] with small quantities of additives. On the other hand, it is composite propellant when a heterogeneous mixture of oxidizing crystals in an organic plastic-like fuel binder is involved. The oxidizer for the later includes crystals of ammonium perchlorate, ammonium nitrate, potassium perchlorate and potassium nitrate. For the solid propellant, burning rate is proportional to chamber pressure. Combustion rate can be controlled pressure variation, choice of propellant grain and stoichiometry. The common grain shapes and sizes include tubular, rod and tube, star, double-anchor and multi-fin. The main drawback of the solid propellant rocket is difficulty in cooling. Liquid propellant can either be monopropellant (single substance capable of exothermic breakdown upon igniting) or bipropellant (fuel and oxidant, separately stored, pressurized and then injected into the combustion chamber). Hydrazine (N_2H_4) is an example of a monopropellant whereas liquid oxygen and liquid hydrogen are bipropellant. There are other less common types of propellants and these include: electrostatic, electromagnetic forces, nuclear, ion, plasma and photon propulsion.

2.3 Nozzle

The resulting combustion gases have to be expanded and this is achieved through the de Laval, convergent-divergent nozzle to produce thrust. The velocity of the combustion gases exit of the

combustor is subsonic to attain sonic velocity, choked condition at the throat and thereafter continues supersonically downstream to nozzle exit. The pressure of combustion gases at nozzle exit compared with ambient pressure can either be under-expanded or over-expanded. However, because the rocket will be operating in an environment of varying altitude hence reducing pressure, it may be advisable to design based either the mean ambient pressure or the altitude pressure where the rocket will spend the most time [8, 9, 10].

2.4 High Speed Flow Regime

The Mach number (M) is an important flow parameter defined as the ratio of the speed of an object (or of a flow) to the speed of sound and can range from zero to infinity, but this broad range falls naturally into several flow regimes including subsonic, transonic, supersonic, hypersonic and hyper velocity flows as indicated in Figure 1.

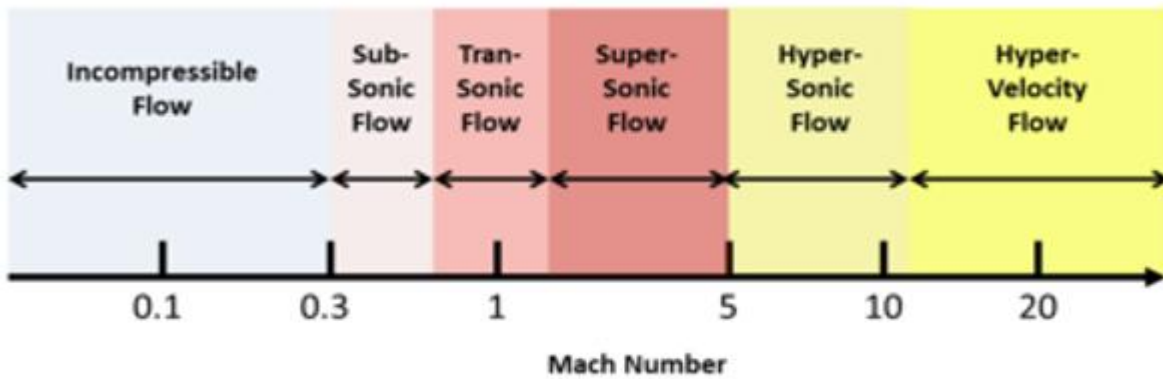


Figure 1. Spectrum of Mach number flow regimes [11]

At very low flow speeds Mach number is irrelevant but once the speed of the flow approaches the speed of sound, however, this parameter becomes important, and shock waves begin to appear. The transonic regime is described by a special (and far more complex) mathematical treatment. In the supersonic regime the flow is dominated by wave motion at oblique angles. Above about 5 Mach number, these wave angles grow so small that a special mathematical approach is required to define the hypersonic speed regime [17]. A high-speed flow over an object with a particular length develops a laminar boundary layer at the leading edge of the object and remains laminar for the case of relatively low Reynolds number. The oncoming freestream because of the presence of the viscous boundary layer no longer sees the object but rather a fictitious curvature. Consequently, a curved induced shock wave is generated at the leading edge. A region between the object surface and the shock known as shock layer depends on the Mach number, Reynolds number and the surface temperature. The shock layer can be characterized by a region of viscous flow and inviscid flow or the entire layer can be fully viscous referred to as merged shock layer. Furthermore, dissipation of kinetic energy within the boundary layer (viscous dissipation) with associated high temperature fields resulting in high heat transfer rates and losses [12].

3 MODELING AND EXPERIMENTATION (WIND TUNNEL STUDIES)

One other route to understanding the functional characteristics of the rocket technology and hence improve the performance is by modeling and experimentation. The compressible flow fields over a rocket propulsion system are governed by Reynolds-Average Navier-Stokes (RANS) Equation, a modified version of Navier-Stokes (NS) Equation specifically for turbulent flow [13]. The basis of the RANS Equation in the conservative and invariant form can be traced to the NS equation whose various variants are listed below for viscous compressible flow.

$$\text{Continuity; } \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0 \tag{1}$$

$$\text{Momentum; } \frac{\partial}{\partial t} (\rho V) + \nabla \cdot (\rho VV) = -\nabla p + \nabla \cdot \tau + F \tag{2}$$

$$\text{Energy: } \frac{\partial}{\partial t} \left[\rho \left(e + \frac{V^2}{2} \right) \right] + \nabla \cdot \left[\rho \left(e + \frac{V^2}{2} \right) \mathbf{V} \right] = \rho \mathbf{q} + \rho (\mathbf{F} \cdot \mathbf{V}) - \nabla \cdot (p\mathbf{V}) + \nabla \cdot (k\nabla T) + \dot{\omega}_{\text{viscous}} \quad (3)$$

where ρ is the air density, \mathbf{V} is the air velocity, p is pressure, τ is the deviatoric shear stress tensor, \mathbf{F} is the body forces acting on a control volume, e is internal energy, k is the thermal conductivity, T is temperature and $\dot{\omega}_{\text{viscous}}$ is the rate of work done by frictional viscous forces [13, 14, 15]. The complete derivation of the NS Equations is found in [15]. In high velocity compressible fluid flow turbulence modeling, Reynolds' decomposition is introduced, where the instantaneous quantities are function of a time-average quantities and fluctuating quantities. Equation (4) shows the Reynolds decomposition in terms of velocity. The concept here is to express the instantaneous velocity, u_i as a combination of time average velocity \bar{u}_i and fluctuating velocity u'_i .

$$u_i = \bar{u}_i + u'_i. \quad (4)$$

By applying the Reynolds decomposition into the continuity and momentum equations, the derivations give the RANS Equations, as shown in Equation (5). In the equation, the derivative of $(-\rho \bar{u}_i \bar{u}_j)$ is the Reynolds Stress [15].

$$\frac{\partial \rho \bar{u}_i}{\partial t} + \frac{\partial \rho \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_j} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial \bar{u}_m}{\partial x_m} \right) \right] + \frac{\partial}{\partial x_j} (-\rho \bar{u}_i \bar{u}_j) \quad (5)$$

The Spalart-Allmaras turbulence model follows closely the Reynolds Averaged equation set. The Spalart-Allmaras turbulence model has been developed for aerospace applications that are wall-bounded and subject to adverse pressure and density gradients. This model is given below as;

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \quad (6)$$

$$\frac{\partial \rho \bar{u}_i}{\partial t} + \frac{\partial \rho \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_j} + \frac{\partial}{\partial x_j} (2\mu S_{ij} - \rho \bar{u}_i \bar{u}_j) \quad (7)$$

$$\frac{\partial (\rho e_o)}{\partial t} + \frac{\partial}{\partial x_j} [\rho u_j e_o + u_j p + q_j - u_i \tau_{ij}] = 0 \quad (8)$$

$$-\overline{u'_i u'_j} = 2\nu_T S_{ij} \quad (9)$$

The Spalart-Allmaras model is a relatively simple one-equation model that solves a modeled transport equation for the kinematic eddy (turbulent) viscosity. This embodies a relatively new class of one-equation models in which it is not necessary to calculate a length scale related to the local shear layer thickness. The model has been shown to give good results for boundary layers subjected to adverse pressure gradients.

4 FLUID AND FLOWS

4.1 Compressibility

Fluid flows are usually treated as being compressible when the Mach number is higher than 0.3 [16]. The issue of compressibility of flow is very relevant when considering the performance of high-speed systems such as aircrafts, jet engines, rockets, missiles and a host of others. Compressible flow is inevitable. for high-velocity projectiles and combat aircraft that move at velocities higher the speed of sound, while spacecraft and meteorites generally move at velocities approach that of sound [17]. Investigations into the behaviour of fired bullets led to improvement in the accuracy and capabilities of guns and artilleries and the work of Gustaf de Laval advanced the theoretical aspects of the field, while researchers such as Mach sought to know the physical phenomena involved through experimentation [18].

4.2 Drag

In fluid dynamics, drag is a force acting opposite to the relative motion of an object immersed in the fluid. Unlike other resistive forces, such as dry friction which is nearly independent of velocity, drag forces depend on velocity. For laminar flow, the drag force is proportional to the velocity and the squared of velocity for a turbulent flow [19]. Drag is generally caused by two factors.

4.2.1 Skin Friction

In general, when a fluid flows over a stationary surface, e.g., the flat plate, the bed of a river, or the pipe wall, the fluid touching the surface is brought to rest by the shear stress at the wall. In the boundary layer the flow adjusts from zero velocity at the wall to a maximum in the freestream. Therefore, a moving fluid layer exerts tangential shear forces on the surface layer below because of the no-slip condition caused by viscous effects. This type of drag force depends mainly on the geometry, the roughness of the solid surface, and the type of fluid flow [19].

4.2.2 Form Drag

Form drags, also known as pressure drag, arises because of the shape and size of the object. This type of drag force is an interesting consequence of the Bernoulli's effect. According to Bernoulli's principle, faster-moving air exerts less pressure, and this causes a pressure difference between surfaces of the object. The general size and shape of the body are the most important factors in form drag. Generally, bodies with a larger presented geometric cross-section will have higher drag than thinner bodies. In the particular case of re-entry vehicles, the worst-case scenario is at re-entry where the normal supersonic slender nosed leading-edge body cannot be used because of higher losses. For the re-entry vehicles, a blunt nosed leading edge, "non- aerodynamic-shape" design is adopted as this has been found to reduce re-entry heating losses [20, 21, 22], see Figure 2. The inter ballistic missiles and the shuttle service are examples.

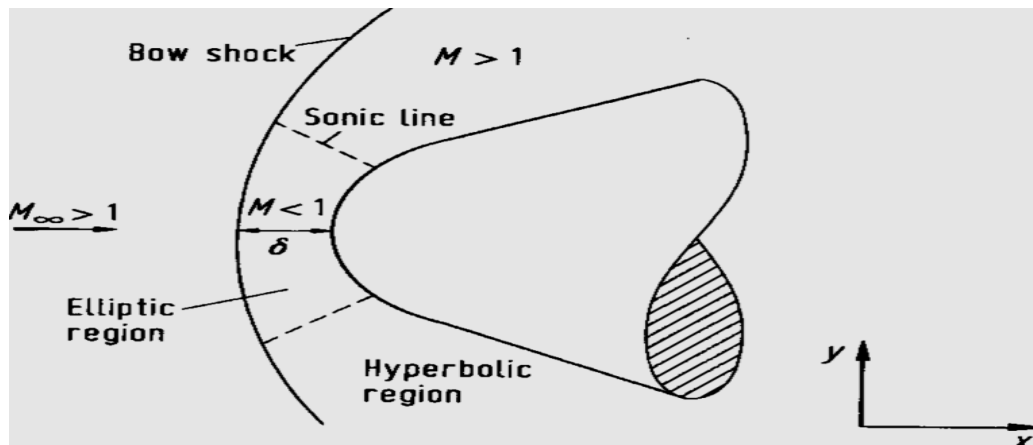


Figure 2. Re-entry Nose Cone for High-Speed Rocket and Missiles [20]

The blunt leading edge is adopted so as to losses in the form of heat. Both of these forces, in general, have components in the direction of flow, and thus the resulting drag force is due to the combined effects of pressure and skin friction forces in the flow direction. When the friction and pressure drag coefficients are present, the total drag coefficient is determined by simply adding two [19].

5 CONCLUSIONS

The parameters and features that affect the performance of high velocity rocket system have been identified and discussed. Compressibility at supersonic speeds is accompanied by variation in associated parameters. Other factors involved the nozzle, propulsion, propellants, drag force etc.

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