Convergent- divergent nozzle pdf

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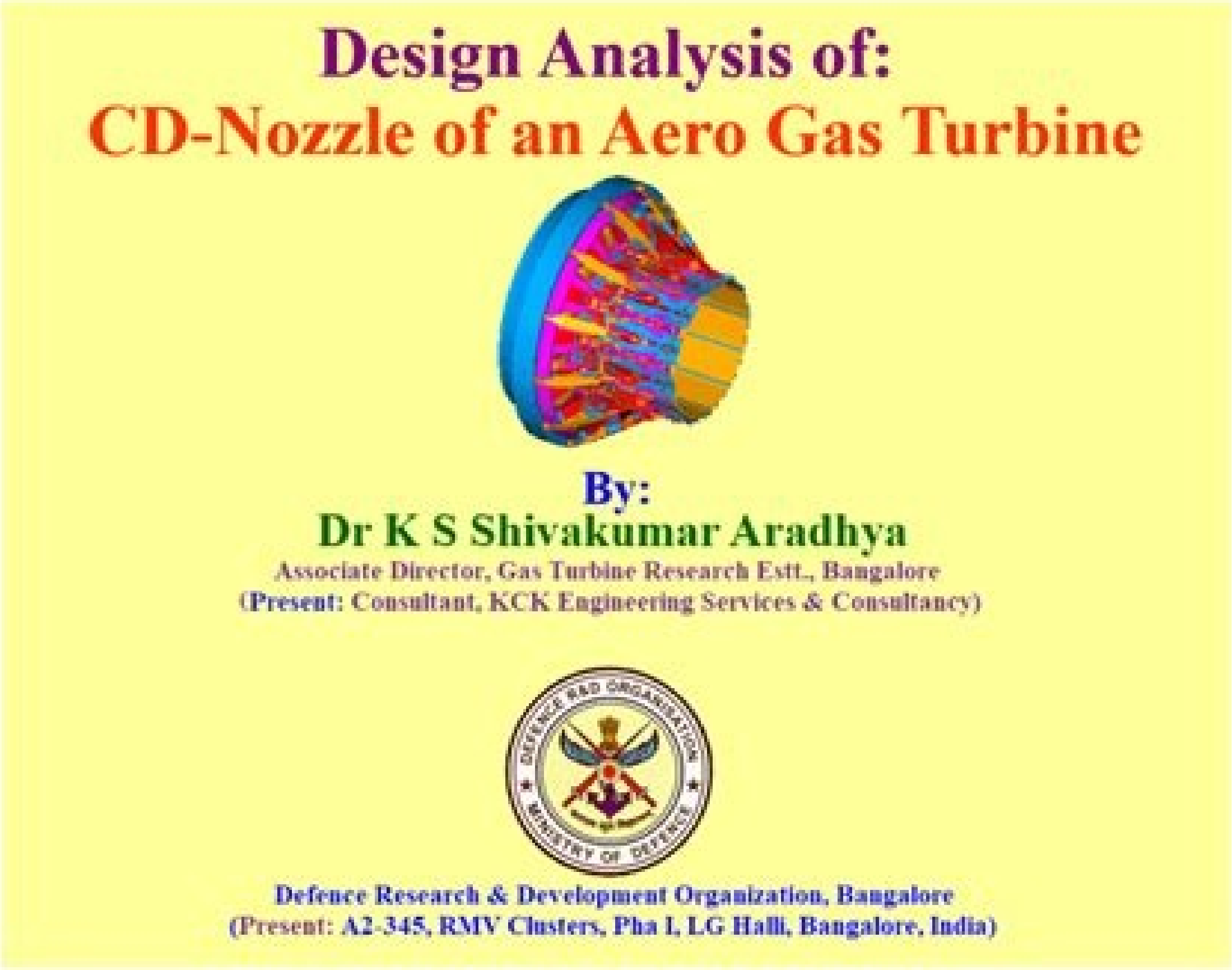
Technical Lecture 1:

(Delivered at School of Engineering, The University of Vermont, Burlington VT 05405, USA on 21st September, 2007.)



Design Analysis of:
CD-Nozzle of an Aero Gas Turbine

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SLIDE 1: Lecture Topic

This lecture presents the details of design analysis, validation and the optimization of a Convergent-Divergent nozzle (CD-Nozzle) of an aero engine used to propel a fighter aircraft.

The lecture is presented under the following headings (Slide 2):

- **I Introduction**
- **II Design Analysis**
- **III Conclusions**

Further, the second section "Design Analysis" is presented under the following subheadings:

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EDITORIAL

Nozzle flow separation

Abdellah Hadjadj · Marcello Onofri

1 Introduction

Flow separation in supersonic convergent–divergent nozzles has been the subject of several experimental and numerical studies in the past. Today, with the renewed interest in supersonic flights and space vehicles, the subject has become increasingly important, especially for aerospace applications (rockets, missiles, supersonic aircrafts, etc.). Flow separation in supersonic nozzles is a basic fluid-dynamics phenomenon that occurs at a certain pressure ratio of chamber to ambient pressure, resulting in shock formation and shock/turbulent-boundary layer interaction inside the nozzle. From purely gas-dynamics point of view, this problem involves basic structure of shock interactions with separation shock, which consists of incident shock, Mach reflections, reflected shock, triple point and sliplines (see Figs. 1, 2). Several viscous phenomena, such as boundary layers with adverse pressure gradients, induced separation, recirculation bubbles, shear layers may additionally occur and can strongly affect the flow-field inside the nozzle (see Figs. 3, 4).

Previous studies on supersonic nozzles [1, 2] have shown that shock-wave/boundary layer interaction (SWBLI) occurring in highly overexpanded nozzles may exhibit strong unsteadiness that cause symmetrical or unsymmetrical flow separation. In rocket design community, shock-induced separation is considered undesirable because an asymmetry in the flow can yield dangerous lateral forces, the so-called side-loads, which may damage the nozzle [3]. This phenomenon has received significant attention in the past and it is still an active subject of research, whose primarily motivation is to improve nozzle performance under overexpanded flow conditions and to mitigate against nozzle side-loads produced by shock unsteadiness as well as asymmetric boundary-layer separation.

2 Flow separation in nozzles: a brief literature survey

Several experimental studies, performed on either subscale [3–6] or full-scale [3] optimized nozzles, corroborated by different numerical simulations [7–11], demonstrated the existence of two distinct separation processes, namely the Free Shock Separation (FSS), in which the boundary layer separates from the nozzle wall and never reattaches (see Fig. 3), and the restricted shock separation (RSS) characterized by a closed recirculation bubble, downstream of the separation point, with reattachment on the wall (see Fig. 4). In fact, the earliest studies attributed the cause of the measured side-loads to asymmetric FSS, that yields a tilted separation surface as reported by [3, 12]. Subsequently, in the early 70s, during cold-flow subscale tests for the J-2S engine development, Nave and Coffey [3], in a study that can be considered the pioneer milestone for the field, observed that the highest value of side loads takes place during the transition from FSS structure to different kind of separated nozzle flow structures, which had not been noticed before. In particular, the pressure downstream of the separation point showed an unsteady behavior with strong oscillations, and finally jumped to values quite above the ambient pressure.

They attributed this behavior to the reattachment of the separated flow to the nozzle wall, and because of the limited extension of this separated region, they called it restricted

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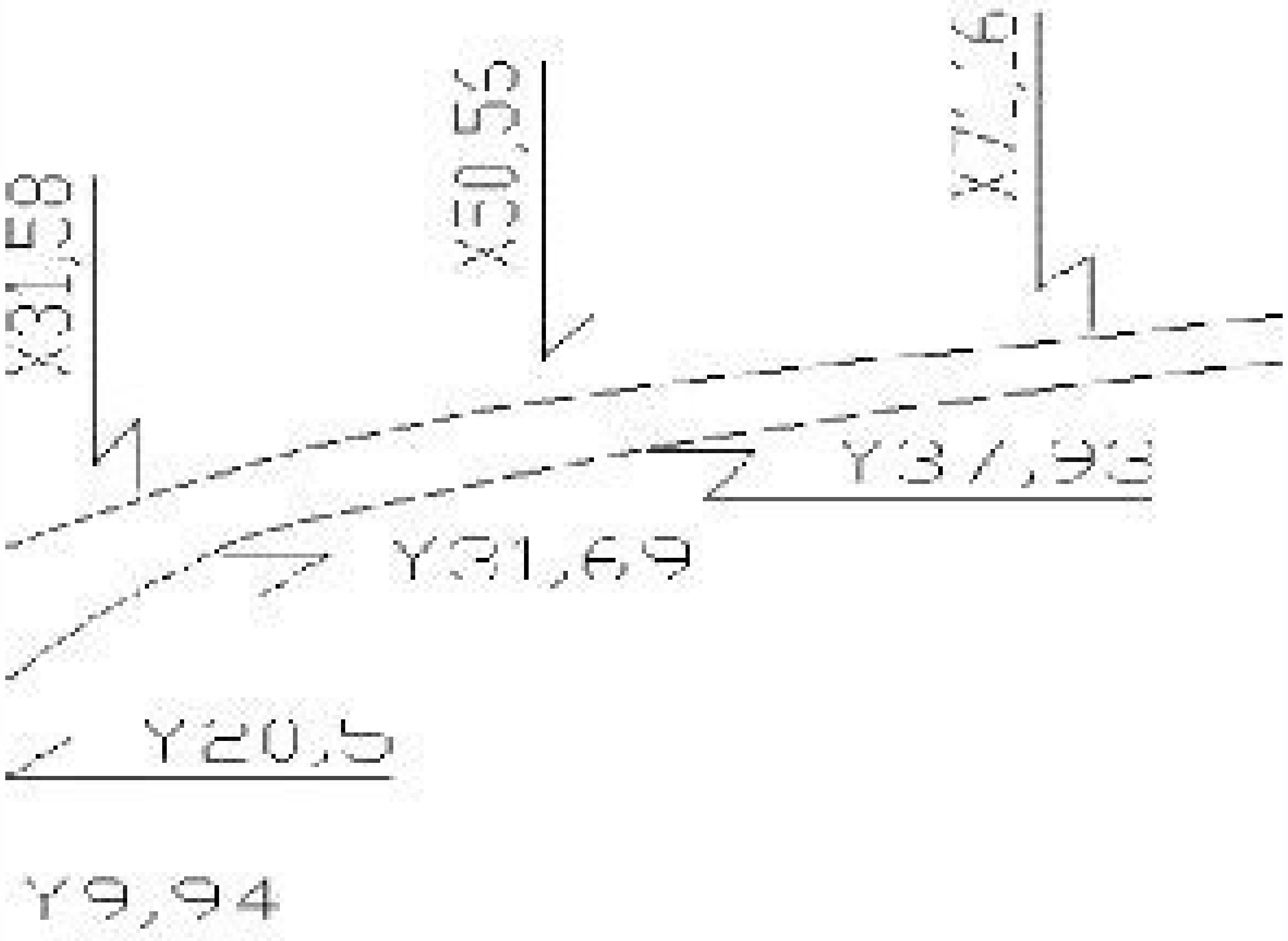

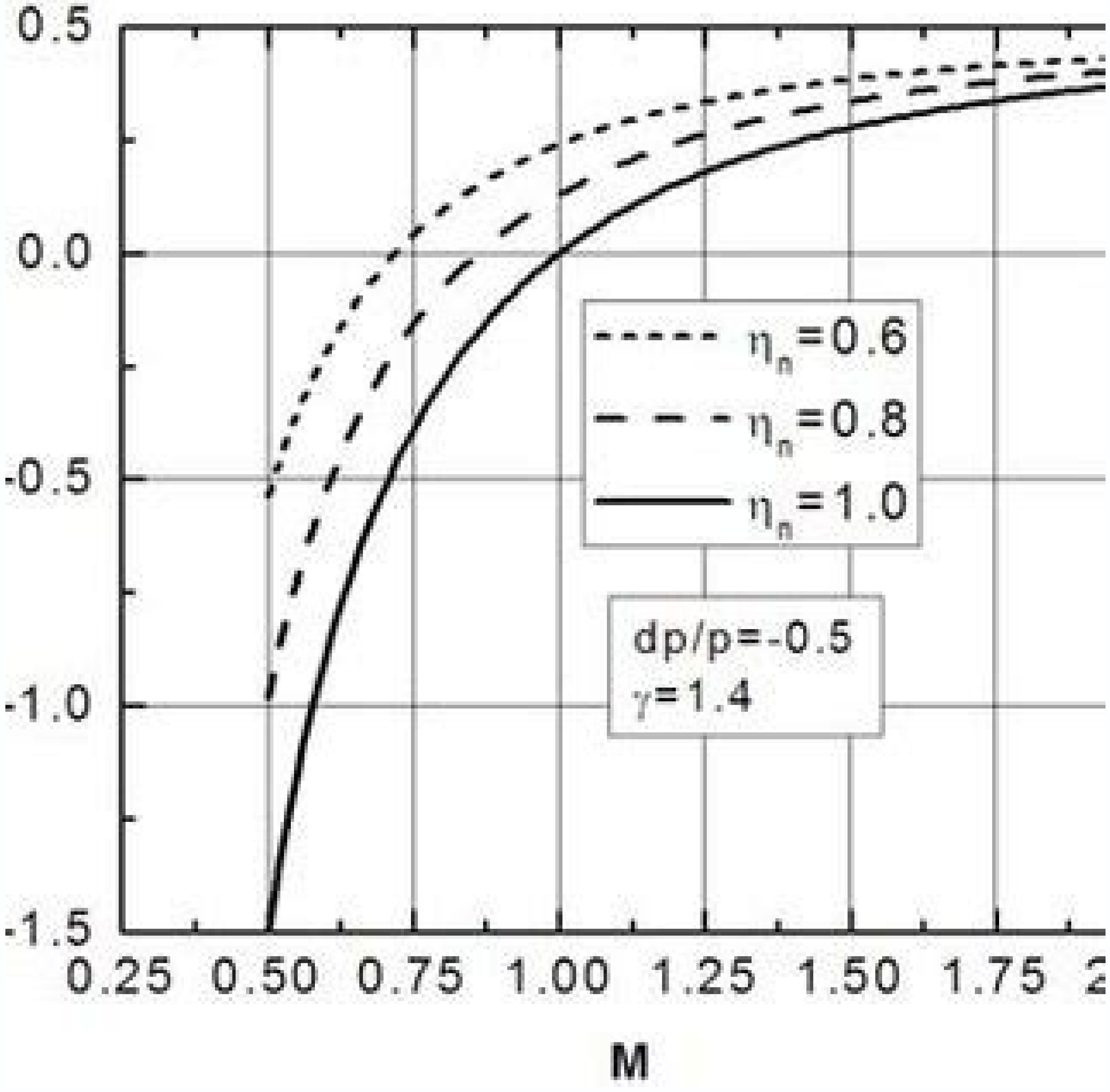

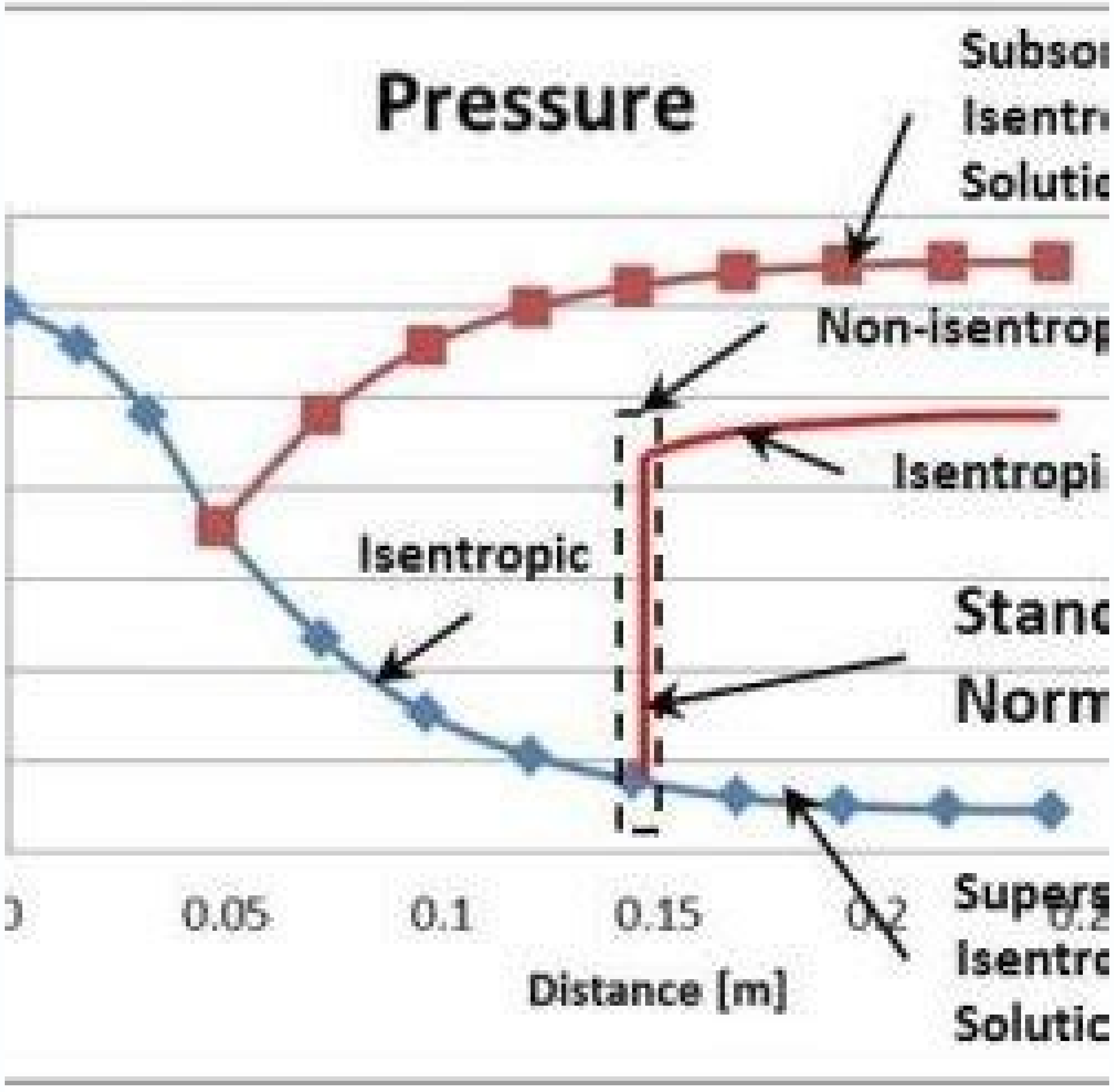

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Cd nozzle rendered in solidworks Nozzles are actually used to modify the flow of a fluid (i.e. by increasing kinetic energy of the flow in expense of its pressure). Convergent-divergent type of nozzles are mostly used for supersonic flows because it is impossible to create supersonic flows (mach number more than one) in convergent type of nozzle and therefore it restricts us to a limited amount of mass flow through a particular nozzle. In convergent-divergent type of nozzles we can increase the flow velocity much higher than sonic velocity that is why these type of nozzles have a wide applications such as propelling nozzles in jet engines or in air intake for engines working at high rotations per minute (rpm). Principal Of Operation[edit | edit source] For understanding the working principle of convergent-divergent type of nozzles, first we need to look the working principle of only convergent type of nozzles.In these type of nozzles the area of the nozzle reduces gradually in the direction of flow.The pressure at intake is called stagnation pressure and the pressure at exit is called back pressure.The value of back pressure can never be more than 1 in case of a nozzle. As we start reducing the back pressure we observe that flow velocity and mass flow rate also starts increasing, but this will happen up to a certain limit, after which no increase in velocity or mass flow rate takes place. This situation is known as choked i.e. no further increase in mass flow rate takes place whatever be the back pressure now. This situation takes place at a particular mach number i.e. at mach number '1'. But the case is not the same when we use a divergent nozzle just after the convergent. Actually the principle reverses i.e. when we attach a divergent nozzle just after the convergent nozzle our flow speed starts increasing with the decrease in back pressure and also the mass flow rate. And therefore in this type of nozzles we can reach to the speeds above sonic i.e. supersonic. Mach number:: It is the ratio of speed of flow in a medium to the speed of sound in that medium. For mach numbers ≤ 0.3 we consider the flow to be incompressible because the density variation is below 5% and for flows having mach number ≥ 0.3 we consider the flow to be compressible because the density variation can not be neglected now. For supersonic flows increase in velocity causes flow velocity to increase . And therefore for our case i.e. supersonic flows we will be doing all he calculations considering compressible flow only. Normal Shock: It is a completely irreversible process takes place in the Convergent divergent type of nozzles (or in venturi) at the divergent section. A sudden change in pressure, temperature, and flow velocity takes place while supersonic flow was taking place. After shock flow becomes subsonic and stays subsonic till end. Width of this shock is very less i.e. about 4 times the mean free path of the gas molecules. Formulas Used[edit | edit source] m= mass flow rate V= velocity ρ {\displaystyle \rho } = density γ {\displaystyle \gamma } = specific heat ratio A= area M= mach number a= speed of sound p {\displaystyle p} -difference in pressures on body V {\displaystyle V} -velocity of fluid surrounding the body g {\displaystyle g} -acceleration due to gravity z {\displaystyle z} -height of body p 0 {\displaystyle {p_{0}}} - stagnation pressure p e {\displaystyle {p_{e}}} - back pressure A {\displaystyle {A}} - Area at exit of nozzle A ∗ {\displaystyle {A^{*}}} - Area at throat Conservation of mass:: m= ρ {\displaystyle \rho } *V*A Conservation of momentum:: ρ {\displaystyle \rho } *V*dV = -d p {\displaystyle p} Isentropic steady flow:: d P P = γ ∗ d ρ ρ {\displaystyle {\frac {dP}{P}}=\gamma *{\frac {d\rho }{\rho }}} Bernoulli's principle:: P ρ + V 2 2 + g z = c o n s t a n t {\displaystyle {\frac {P}{\rho }}+{\frac {V^{2}}{2}}+gz=constant} p 0 p e = (1 + γ − 1 2 . M 2) γ γ − 1 {\displaystyle {\frac {p_{0}}{p_{e}}}=(1+{\frac {\gamma -1}{2}}.M^{2})^{\frac {\gamma }{\gamma -1}}} A A ∗ = 1 M (2 + (k − 1) . M 2 K + 1) k + 1 2 (1 − k) {\displaystyle {\frac {A}{A^{*}}}={\frac {1}{M}}\left({\frac {2+(k-1).M^{2}}{K+1}}\right)^{\frac {k+1}{2(1-k)}}} [edit | edit source] Consider a converging-diverging nozzles having throat area of 0.002 m 2 {\displaystyle 0.002m^{2}} Advantages and Applications Of Convergent-Divergent Types Of Nozzles[edit | edit source] convergent-divergent(C-D) type of nozzles have a lot of application as a propelling nozzle in automobile and jets. Few examples of the application of convergent divergent type of nozzles in engineering are: *Steam turbines : In power plants . *Rockets : for providing sufficient thrust to move upwards. *The supersonic gas turbine engine : for the air intake when air requirement of engine is high. C-D nozzles can be seen in water supply pumps or in formula car intake system or in jet engines for providing sufficient thrust to propel at high speeds mostly in supersonic jets. Ramjets, scramjets, and rockets all use nozzles to accelerate hot exhaust to produce thrust as described by Newton's third law of motion. The amount of thrust produced by the engine depends on the mass flow rate through the engine, the exit velocity of the flow, and the pressure at the exit of the engine. The value of these three flow variables are all determined by the nozzle design. A nozzle is a relatively simple device, just a specially shaped tube through which hot gases flow. Ramjets and rockets typically use a fixed convergent section followed by a fixed divergent section for the design of the nozzle. This nozzle configuration is called a convergent-divergent, or CD, nozzle. In a CD nozzle, the hot exhaust leaves the combustion chamber and converges down to the minimum area, or throat, of the nozzle. The throat size is chosen to choke the flow and set the mass flow rate through the system. The flow in the throat is sonic which means the Mach number is equal to one in the throat. Downstream of the throat, the geometry diverges and the flow is isentropically expanded to a supersonic Mach number that depends on the area ratio of the exit to the throat. The expansion of a supersonic flow causes the static pressure and temperature to decrease from the throat to the exit, so the amount of the expansion also determines the exit pressure and temperature. The exit temperature determines the exit speed of sound, which determines the exit velocity. The exit velocity, pressure, and mass flow through the nozzle determines the amount of thrust produced by the nozzle. On this slide we derive the equations which explain and describe why a supersonic flow accelerates in the divergent section of the nozzle while a subsonic flow decelerates in a divergent duct. We begin with the conservation of mass equation: mdot = r * V * A = constant where mdot is the mass flow rate, r is the gas density, V is the gas velocity, and A is the cross-sectional flow area. If we differentiate this equation, we obtain: V * A * dr + r * A * dV + r * V * dA = 0 divide by (r * V * A) to get: dr / r + dV / V + dA / A = 0 Now we use the conservation of momentum equation: r * V * dV = - dp and an isentropic flow relation: dp / p = gam * dr / r where gam is the ratio of specific heats. This is Equation #10 on the page which contains the derivation of the isentropic flow relations We can use algebra on this equation to obtain: dp = gam * p / r * dr and use the equation of state p / r = R * T where R is the gas constant and T is temperature, to get: dp = gam * R * T * dr gam * R * T is the square of the speed of sound a: dp = (a^2) * dr Combining this equation for the change in pressure with the momentum equation we obtain: r * V * dV = - (a^2) * dr V / (a^2) * dV = - dr / r - (M^2) * dV / V = dr / r using the definition of the Mach number M = V / a. Now we substitute this value of (dr /r) into the mass flow equation to get: - (M^2) * dV / V + dV / V + dA / A = 0 (1 - M^2) * dV / V = - dA / A This equation tells us how the velocity V changes when the area A changes, and the results depend on the Mach number M of the flow. If the flow is subsonic then (M < 1) and the term multiplying the velocity change is positive (1 - M^2 > 0). An increase in the area (dA > 0) produces a negative increase (decrease) in the velocity (dV < 0). For our CD nozzle, if the flow in the throat is subsonic, the flow downstream of the throat will decelerate and stay subsonic. So if the converging section is too large and does not choke the flow in the throat, the exit velocity is very slow and doesn't produce much thrust. On the other hand, if the converging section is small enough so that the flow chokes in the throat, then a slight increase in area causes the flow to go supersonic. For a supersonic flow (M > 1) the term multiplying velocity change is negative (1 - M^2 < 0). Then an increase in the area (dA > 0) produces an increase in the velocity (dV > 0). This effect is exactly the opposite of what happens subsonically. Why the big difference? Because, to conserve mass in a supersonic (compressible) flow, both the density and the velocity are changing as we change the area. For subsonic (incompressible) flows, the density remains fairly constant, so the increase in area produces only a change in velocity. But in supersonic flows, there are two changes; the velocity and the density. The equation: - (M^2) * dV / V = dr / r tells us that for M > 1, the change in density is much greater than the change in velocity. To conserve both mass and momentum in a supersonic flow, the velocity increases and the density decreases as the area is increased. Activities: Guided Tours Navigation .. Beginner's Guide Home Page

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