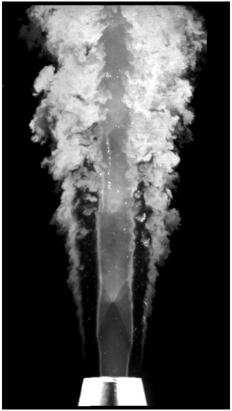
Turbulent Mixing in Supersonic Flows and Volcanic Eruptions



by

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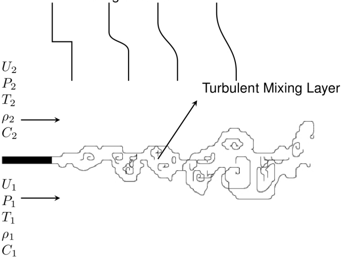
Introduction

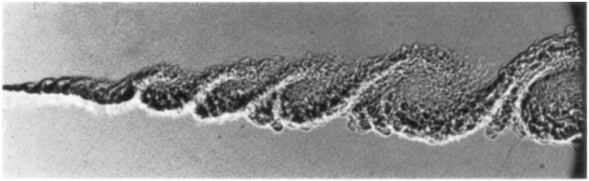
The highlights of this presentation are:

- Turbulent Mixing and its Relevance to Volcanic Eruptions.
- Explosive Volcanic Eruption as a Supersonic Free Jet.
- Problems of Turbulent Mixing in Supersonic Flow.
- Investigations on Turbulent Mixing in Supersonic Flow.
- Novel supersonic nozzles – method to enhance mixing in supersonic flow by altering supersonic nozzle shape.
- Implications of these studies to volcanic eruptions.

Turbulent Mixing



Schematic of Turbulent Mixing Layer



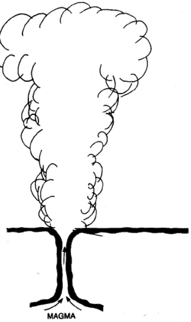
Length scales, entrainment and mixing in a Turbulent Mixing Layer (Brown and Roshko, JFM, 1974)

- A mixing layer separates two fluid streams of different momentum, energy and composition.
- Diffusive effects of the shear layer responsible for gradual transfer of flow quantities and mixing between the two streams.
- A turbulent mixing layer consists of a large variety of scales that bring about large increase in entrainment and mixing between the two flows.
- Entrainment process - an engulfment of one fluid by the other happening mostly at large scales, while mixing is a small scale phenomenon.

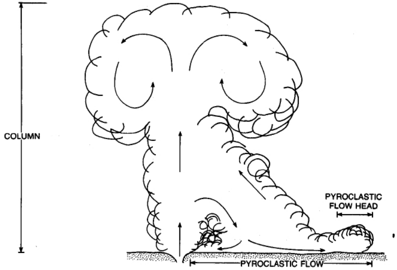
Turbulent Mixing in Volcanic Plumes

Huge Range of Turbulent Mixing scales in a Volcanic Plume. (http://www.geo.mtu.edu/volcanoes/hazards/primer/images/volc-images/sthelenserup.jpg)

- Turbulent Entrainment and Mixing between the ejected material (volcanic gas and hot ash (solid)) from a volcanic eruption and the ambient air, is crucial in the dynamics and development of the plume and hence the kind of disaster it can cause (Suzuki and Koyaguchi, Earth Planets Space, 2013, Journal of Earth Simulator, 2007).
- The kind of volcanic plume completely dependent on :
  - Rate of density change with height.
  - Entrainment and Mixing with the ambient air



Schematic of a Plinian Eruption

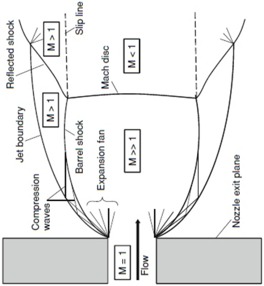


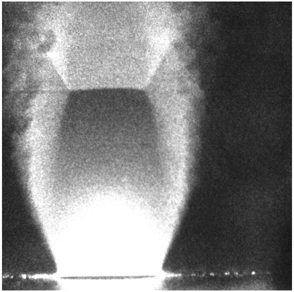
Schematic of a Fountain type of Eruption with Pyroclatic flow. (Greg & Kenneth, J. Geophysical Research, 1989)

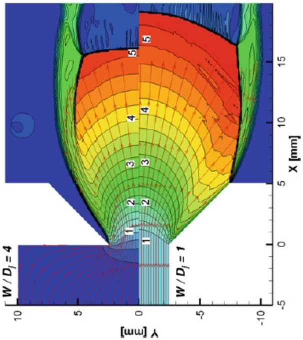
- Large entrainment and mixing between hot pyroclast and air causes global density of the plume to fall, buoyancy gives rise to very high plinian eruption.

- Low entrainment does not decrease the global density and hence the eruption column collapses under gravity causing pyroclastic flow along the ground.

Explosive Volcanic Eruption as A Supersonic Free Jet





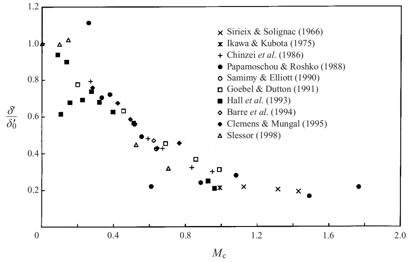


Study on the effect of geometry and flow condition on jet features (Hatanaka & Saito, Shock Waves, 2012)

- High overpressures within the volcano causes a supersonic jet to develop.(Greg & Kenneth, 1989; Ogden et.al. J. Geophysical Research, 2008)

- The local fluid velocity is greater than the speed of sound in the medium when the flow is supersonic ($\approx$ 340 m/s, 1200 kmph).
- Compressibility is important and cannot be neglected. Behavior of supersonic flows is often counter intuitive.
- Supersonic flows contain shock waves and expansion waves to respond to local conditions of pressure and geometry.
- Supersonic Jets have been studied extensively for various applications and the physics involved are used to explain features in volcanic eruptions also (Greg & Kenneth, 1989; Ogden et.al. J. Geophysical Research, 2008).
- The effect of a Mach disk to the Volcanic Plume has been detailed – causes a annular flow with low speed and high speed regions (Ogden et.al. J. Geophysical Research, 2008).
- The effects of geometry and overpressures on the flow have been studied numerically and experimentally (Ogden et.al. J. Geophysical Research, 2008; Hatanaka & Saito, Shock Waves, 2012)
- Compressibility drastically affects mixing and entrainment, which is the crux for the development of volcaninc plumes.

Effect of Compressibility on Turbulent Mixing

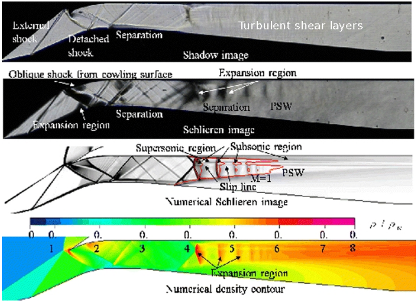


A summary of various results on effects of compressibility on mixing layers. (Slessor, Zhuang, Dimotakis, JFM 2000)

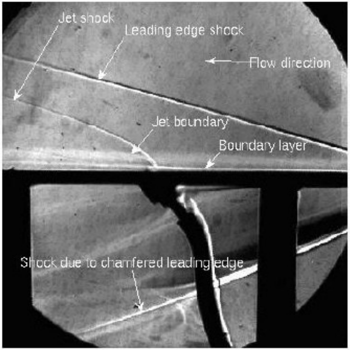
$$M_c = \frac{(U_1 - U_2)}{a_1 + a_2}$$

- Compressibility experssed in terms of the convective Mach number.
- Compressibility greatly affects the growth rate of turbulent mixing layers at high Mach numbers.
- The Figure, expressed in terms of the ratio of growth rate of compressible to incompressible mixing layers clearly shows that mixing asymptotically tends to 0.2 times that of the incompressible growth rate at high Mach numbers.
- This has enormous significance to many gasdynamic devices such as supersonic inlets, SCRAMJET engines, supersonic ejector to name a few; and of course to entrainment and mixing in volcanic jets.

Flows involving Supersonic Mixing Layers



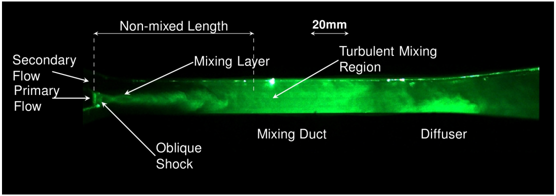
Compressible turbulent shear layer in a supersonic inlet (Lee. et.al., Jl. of Visualization, Feb 2010).



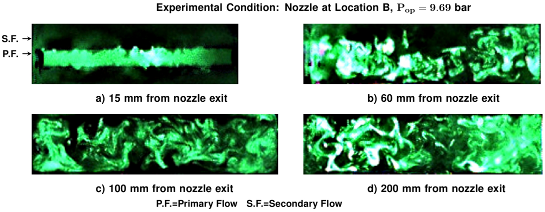
Compressible mixing of sonic jet in supersonic crossflow (Thesis,Ratan J.,2009).

- Mixing of fluids at high Mach numbers is important in many engineering applications.
- Supersonic inlets contain complex flow features like interaction of shocks and shear layers.
- Specifically, scramjet combustors require rapid mixing between the fuel and air at supersonic speed.
- The rate of mixing is also important in aeroacoustics of rocket and jet engine exhausts.

Supersonic Ejector



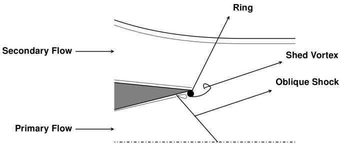
Mie scattering of mixing in a supersonic ejector(Srisha M V Rao et.al., Physics of Fluids, 2014).



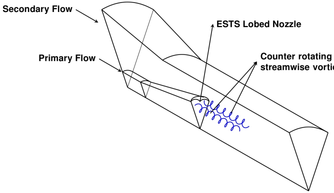
Cross sectional images of mixing in a supersonic ejector.

- Compressible turbulent mixing is the driving factor in the operation of a supersonic ejector.
- Supersonic ejector has many applications.
- Key to improving performance of the ejector and to design short ejectors is in enhancement of mixing.
- However, the stagnation pressure losses should be minimal.

Novel Nozzles for Mixing Enhancement



a) Schematic showing the application of Tip Ring Nozzle to mixing enhancement in a supersonic ejector

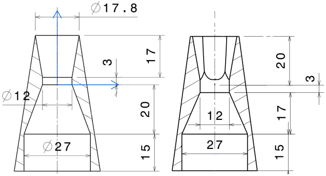


b) Schematic showing the application of ESTS lobed nozzle to mixing enhancement in the ejector

Novel techniques to enhance mixing. (Srisha M V Rao et.al., Applied Thermal Engineering, 2014).

- Innovative changes to nozzle shape increases mixing.
- Many methods like - use of tabs, non-circular nozzles, chevron nozzles, lobed nozzles.
- Disturb the mixing layer by some means - Tip Ring nozzle (shock-B.L interaction leading to shedding of vortices)
- Generate streamwise vortices – ESTS lobed nozzle.

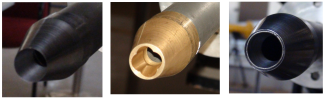
Experiments on Free Jets from Novel Nozzles



a) Details of the conical supersonic nozzle

b) Details of the ESTS supersonic nozzle

Nozzles used in the study – drawings.

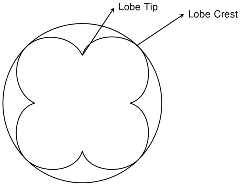


a) Conical Nozzle

b) Elliptic Sharp Tipped Shallow (ESTS) Lobed Nozzle

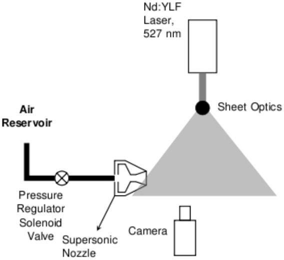
c) Ring at the Tip of Nozzle

Photographs of nozzles in the setup.



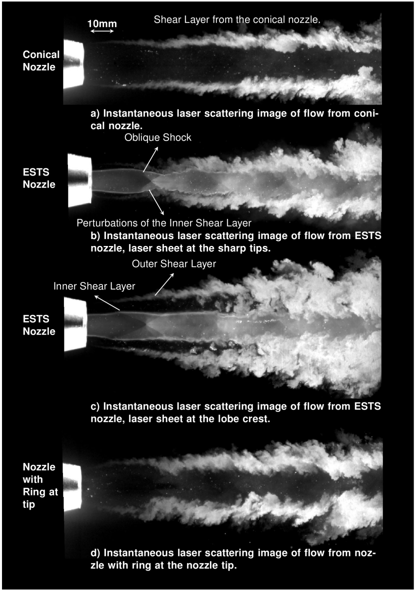
Schematic of the exit section of the ESTS nozzle.

- ESTS - Elliptic Sharp Tipped Shallow lobed supersonic nozzle.

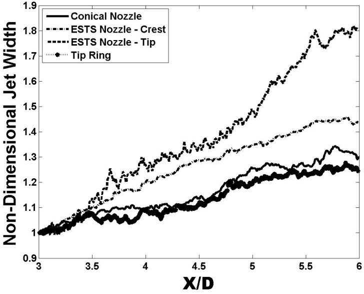


Setup for Mie scattering flow visualization.

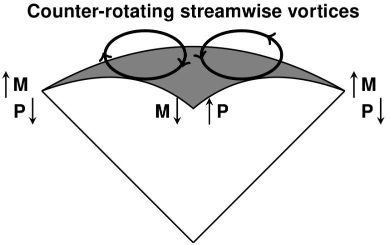
Streamwise Flow Visualization



- Mach number 2.3, Primary stagnation pressure 9.6 bars.
- The supersonic flow from conical nozzle mixes slowly. Long potential core can be seen.
- The flow from ESTS lobed nozzle shows much greater entrainment and mixing – shorter potential core.
- Asymmetric shock structure and presence of double shear layers in the near field of nozzle ($<$3D)
- Perturbations to the mixing layer clearly visible.
- Tip ring causes disturbance to the mixing layer and increases thickness, implying enhanced mixing and entrainment.



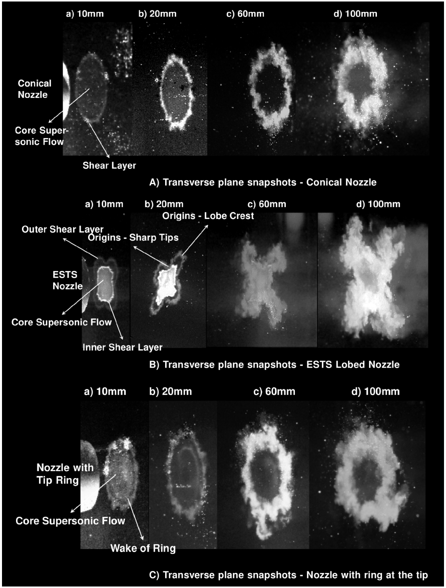
Comparison of growth rate of jet width.



Schematic of mechanism for production of streamwise vortices.

- The average growth rate of the jet width can be evaluated from the images (non-dimensionalized by the jet width at the start of analysis).
- ESTS nozzle shows more than double the rate (0.28 at the tip and 0.15 at the crest) compared to conical nozzle (0.11) and tip ring nozzle (0.10).
- Variation of Mach number at the periphery of the ESTS lobed nozzle causes pressure differences that can cause a secondary flow to roll up as streamwise vortex pairs at the tips.

Cross sectional Flow Visualization



- Conical nozzle – shape of the mixing layer is a circular ring . Azimuthal perturbations are naturally present. They grow along streamwise direction.
- ESTS lobed nozzle – X shaped mixing layer. Pinching at lobe tips brings ambient fluid close to jet core. Jet core fluid is pushed outwards at lobe crests. Increase in shear perimeter.
- Twin shear layers visible at near field, far field that merge to form large vortex pairs.
- Wake of Tip Ring clearly visible in the near field. Disturbance caused leads to an increased thickess of mixing layer.

Observations on Mixing Enhancement

- Complex nozzle geometry - Lobed nozzles, use of vortex generating tabs lead to production of streamwise vortices that enhance mixing.
- These mechanisms can be considered as protrusions into the main flow, with height just more than the boundary layer thickness. Boundary layers are typically thin and as seen here, a finite protrusion can produce as much as doubling of shear layer growth rate.
- When considering the implciations of these studies to understanding of volcanic jets :
  - At high Mach numbers, entrainment and mixing of jet is reduced.
  - Protrusions as small as about boundary layer thickness, can generate streamwise vortices that significantly increases rate of entrainment and mixing.
- Loss of stagnation pressure an important factor in engineering applications – supersonic ejector.
- We have observed 15% loss of stagnation pressure when using the ESTS lobed nozzle, while the tip ring nozzle gives 50% stagnation pressure loss. Thus, ESTS lobed nozzle is more effective.

Acknowledgements

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Thank You