Understanding Combustion through Images

H S Mukunda

Experiments: Abhishek, Arvind Iyer, Varun Sivakumar,

Video support: Sreenath Y, Indranil Kundu, B S Raju, Narasimha Athani

Composing and editing: Indranil Kundu

….A picture speaks a thousand words….

Authors word.....

The field of combustion that has developed over the last sixty years seems to lack a book of colorful visuals that conveys the essence of the subject. This book and a video have been put together to fill this gap. Hopefully, this will encourage others to produce even more colorful and vivid documentation of combustion aimed at enhancing the understanding of a new initiate 22-Nov-2010

Acknowledgements

It is a pleasure to acknowledge the financial support of the directorate of extramural research and intellectual property rights (ER & IPR) of Government of India under ERIPR/ER/0701102/M/01/1019 dated 04 December 2007 issued on Prof. P. J. Paul, Chief Executive, ABETS as the principal investigator.

Special thanks to Dr. Prahlada, CCR&D, DRDO Hq and Dr. Debasis Chakraborty for facilitating the sanction. Grateful thanks to them for useful technical inputs. Thanks are also due to Dr. V. K. Saraswat, the then CCR&D and the current Scientific Advisor to Raksha Mantri for a review of the early drafts of the video.

Foreword

In some of the most interesting fields in science and technology the basic laws are in a fundamental sense known (i.e. as physics), but the phenomena exhibited are so rich and complex that in many cases they still cannot be deduced from the those laws. The chief reason is that in these cases the mathematical expression of the known laws can be highly nonlinear and therefore very often beyond the reach of known mathematics. Familiar examples are fluid mechanics, combustion science and dynamics of clouds. In these cases laboratory simulations can play a great role in providing insight into the phenomena and have often been very fruitful sources of both understanding and new ideas and models. Furthermore the results of many of those experiments can be presented in striking images, often beautiful, so that they are both attractive and illuminating.

In fluid dynamics the well known album of fluid motion by Milton Van Dyke has now become an essential part of learning the subject and wondering about it, because of its many beautiful surprises for the interested student or scientist. In the present book Prof H S Mukunda has similarly collected a large number of images illustrating the many striking phenomena that occur in combustion systems. I wish to compliment him for putting together so many wonderful photographs. For example those of the flash back phenomenon, the fire whirl, turbulent flame propagation in a spark-ignited reciprocating engine, the combustion source inside a stove, and many others besides, all belong to this class. I hope that all those interested in combustion systems – students, faculty and professionals – will find these wonderful pictures intriguing and illuminating.

Prof. Roddam Narasimha
Jawaharlal Nehru Centre
for Advanced Scientific Research

Images of combustion?

These are the images drawn from several illustrative films on gas, liquid and solid combustion processes, this being produced as a written document accompanying the video. – Flames that arise from an initial premixing of fuel and gas are called premixed flames, flames where mixing occurs at the flame are called diffusion flames, and combustion acoustics is due to coupling between heat release by combustion and acoustic waves generated in the medium.

About 70 % of the videos are from special experimental set-ups constructed for the purpose at the laboratory. Rest is from public domain. The images are from the videos on the following topics.

Gas phase – premixed and diffusion

1) Flame tube, 2) Premixed flame, 3) Flashback, 4) Heat Release, 5) Fire whirl, 6) Spark ignition engine processes, 7) Engine – Schlieren picture. 8) Jet diffusion, 9) Flameless, 10) Gas hydrate, 11) Conducting flame

Liquids

12) Droplet Combustion, 13) Spray Combustion, 14) Hypergolic ignition, 15) Control Rocket

Solids/special

16) Wood sphere, 17) Glass stove, 18) Solid propellant, 19) Strand burner, 20) Atlas V, 21) Model Rocket, 22) Rocketman

Unsteady combustion

23) Rijke tube, 24) Bottle pulse, and 25) Rubens tube

The videos that are drawn from internet sources are as follows:

The first part of Fire whirl

http://www.youtube.com/watch?v=Txq-tHOMxAM&feature=related

There are others of similar kind on youtube.

The high frame rate video is from

http://www.youtube.com/watch?v=Iz31eCym2iQ; Also from

http://paultan.org/2008/04/09/video-inside-a-combustion-chamber/

Gashydrate video is adapted from Dept. Chem engg, Technical University, Denmark

http://www.youtube.com/watch?v=5gpH2-ibjFw

Another adapted from a video created by a student at

http://www.youtube.com/watch?v=s2WmWMMCcB0&feature=related

Hypergolic reaction from www.periodicvideos.com, University of Nottingham

http://www.youtube.com/watch?v=bin_W1xVPfY&feature=fvw

Rocketman drawn from a comprehensive information site at

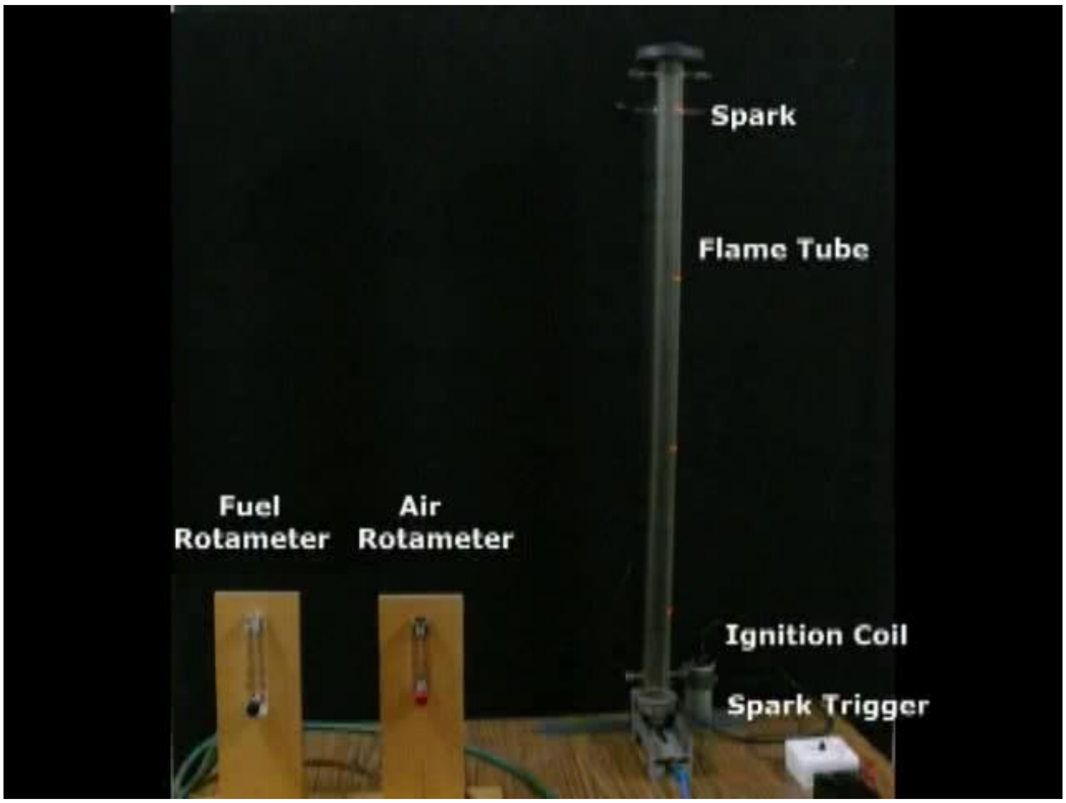
http://www.rocketbelts.americanrocketman.com/martowlis.html

Flashback Phenomenon

http://www.youtube.com/watch?v=7hG7Mbkj2AQ

High pressure strand burner from a lecture by K. Hori, ISAS/JAXA at a conference; a part of flameless combustion and sandwich propellant combustion are from the theses of Drs. K. Narayanan, V. Sudarshan kumar and Dr P A Ramakrishna.

Gaseous flames – Premixed and diffusion



The Premixed flame apparatus

This needs a one-sided open tube with arrangement for filling the tube with a gaseous mixture of known composition and sparking at the top end.

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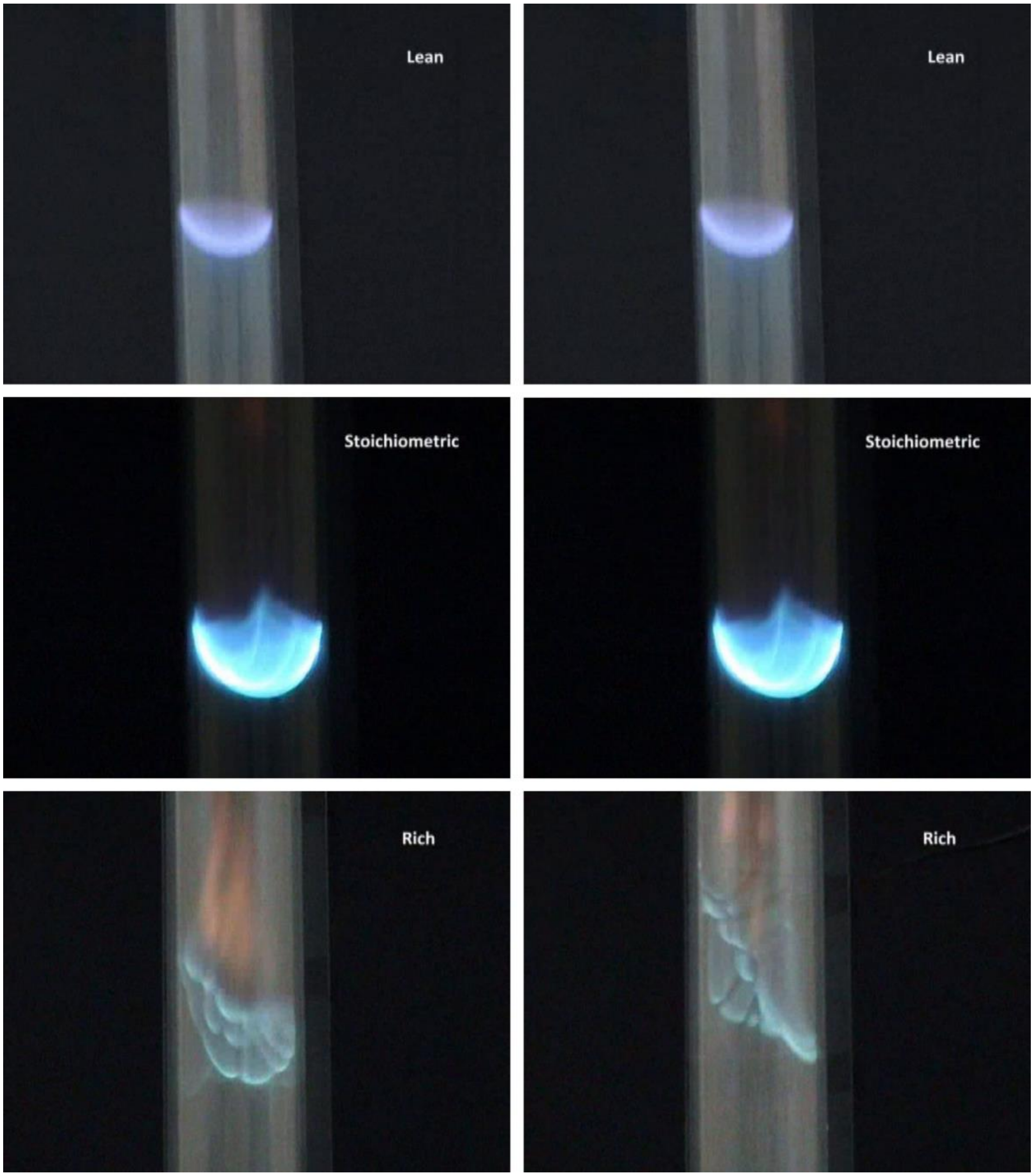

Flame propagation is affected by viscous effects at the tube walls. Rich flames have cellular structure.

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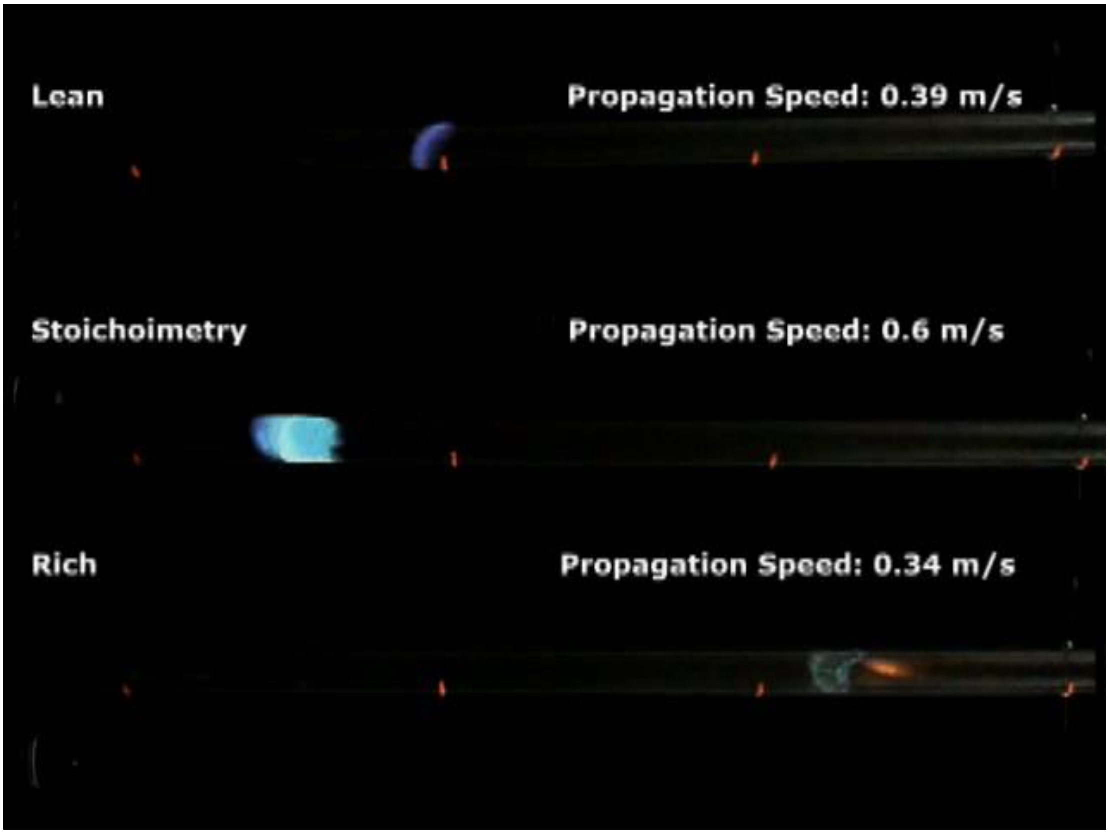
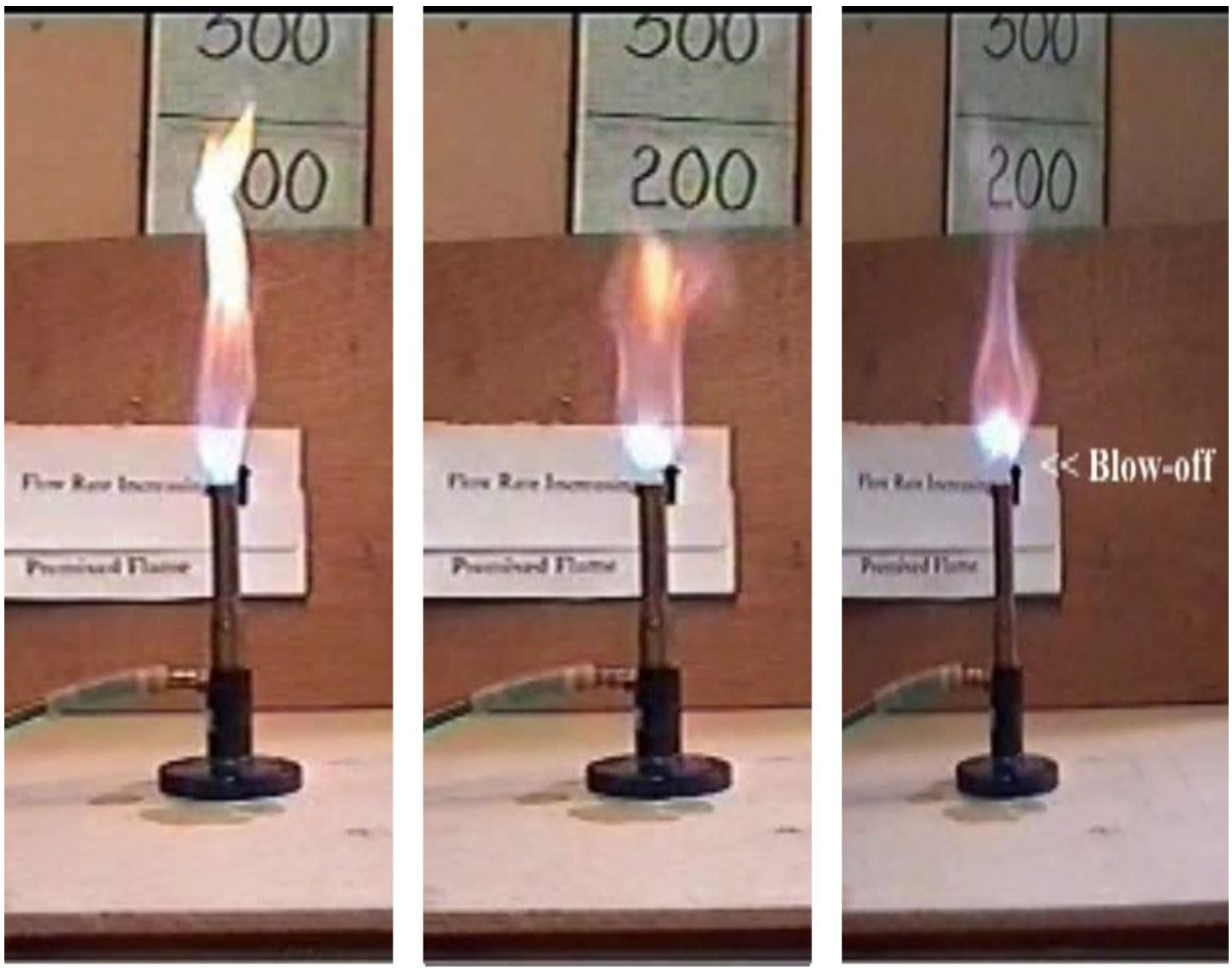
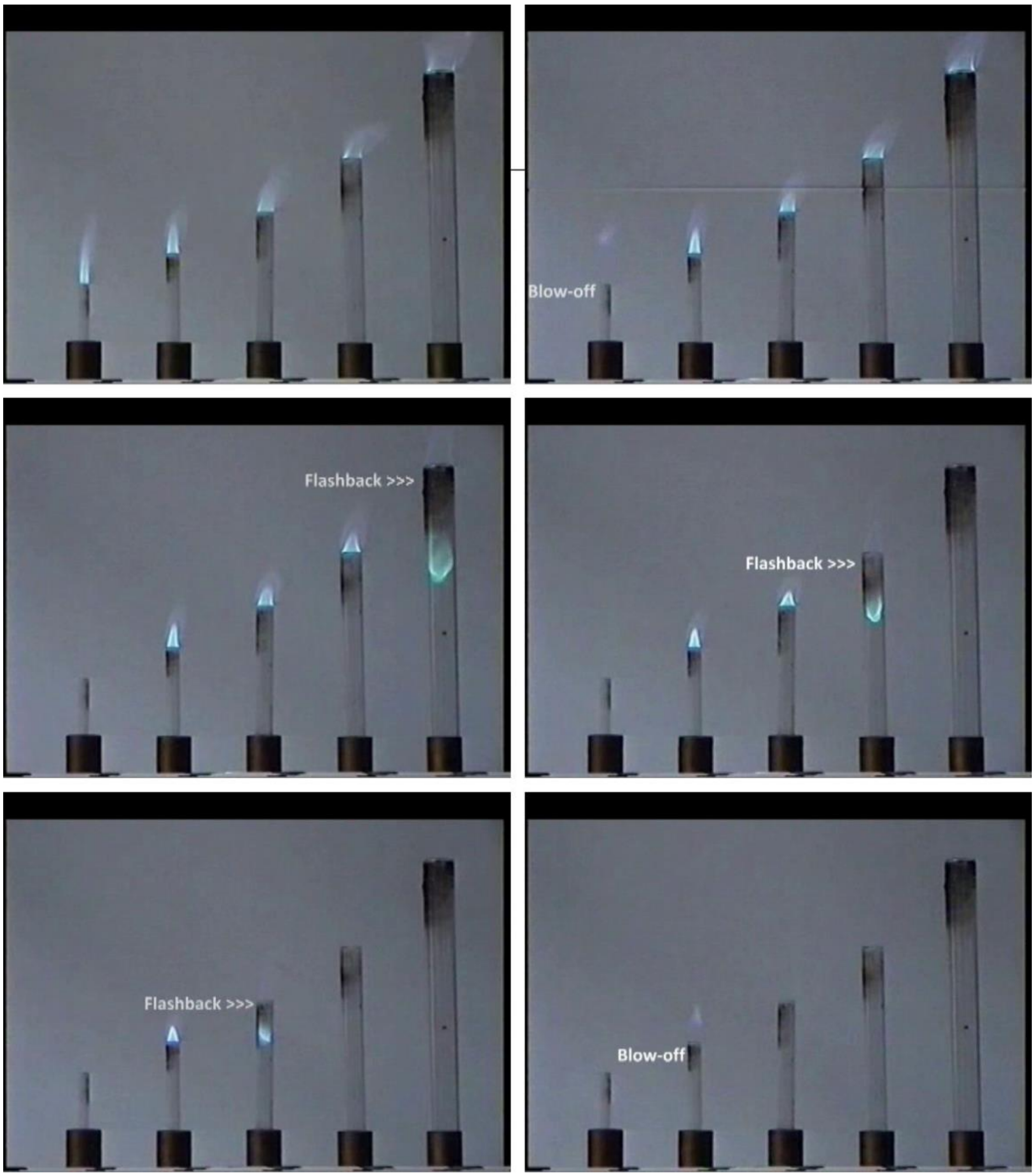


Note that stoichiometric flames are faster than either lean or rich mixtures. The flames are located at different times from start. The thickness on the stoichiometric flame expected to be very thin is a photographic artifact. Flame speed is representative of the reactivity of the mixture.



The steady combustion of the flow of premixed mixture through a Bunsen burner as the flow rate is increased. The flame becomes more intensely turbulent till it cannot sustain. It then blows off.

Flash-back and Blow-off



The flow through a Bunsen burner is slowly decreased through tubes of different diameters. The flame blows off in the smallest diameter tubes since the quench distance of the mixture is comparable to the diameter of the tube. It flashes back in the other three tubes.

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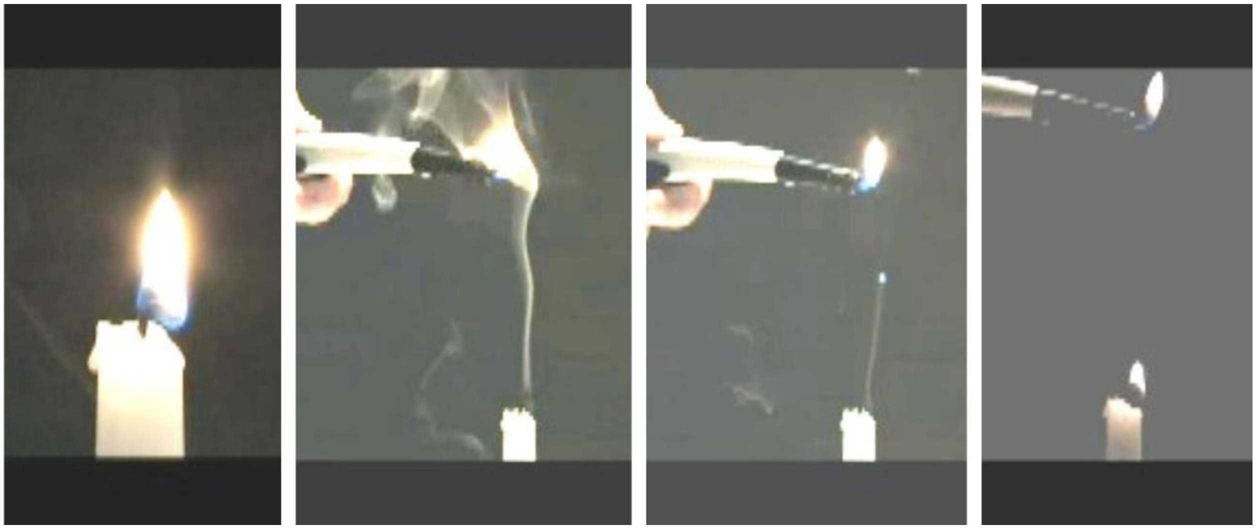


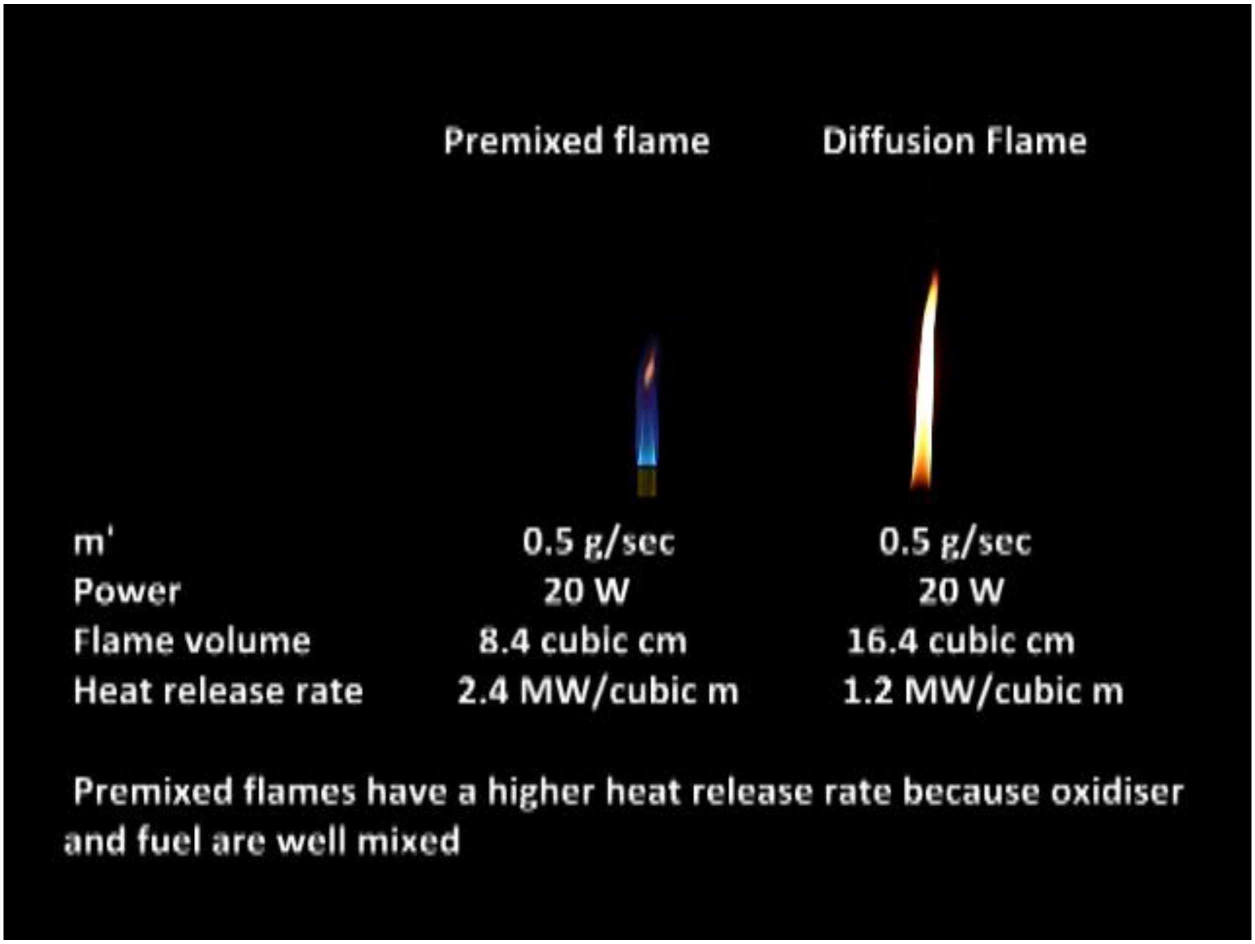
Candle normally burning

The burning candle just blown off and a burning lighter brought close to the emanating fumes- the fuel vapors

The thin strand of the fuel gas is lit and flame Is travelling back – “flashing back”

The flame has finally flashed back and lit the candle. The speed of flash-back is about 10 cm/s

An extraordinarily beautiful capture of the “flash-back” phenomenon



At the same power level, the premixed flame volume is about half of a diffusion flame and hence the volumetric heat release rate of premixed flame is higher correspondingly.

A fire-whirl is a combination of concentrated heat source coupled with an organized source of angular momentum either from wind shear or from the fire's convection column that must help create large swirl velocities as the air is entrained into the fire plume.

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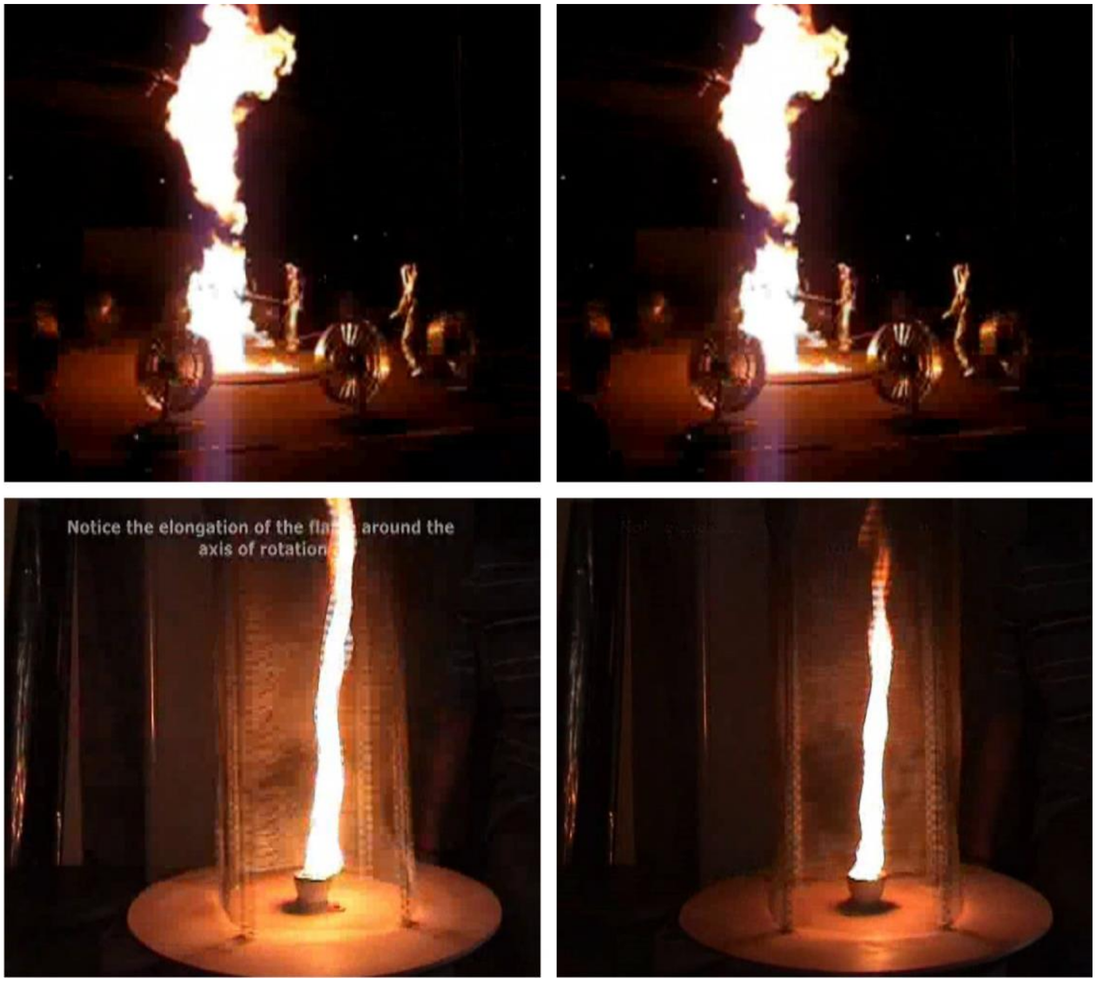
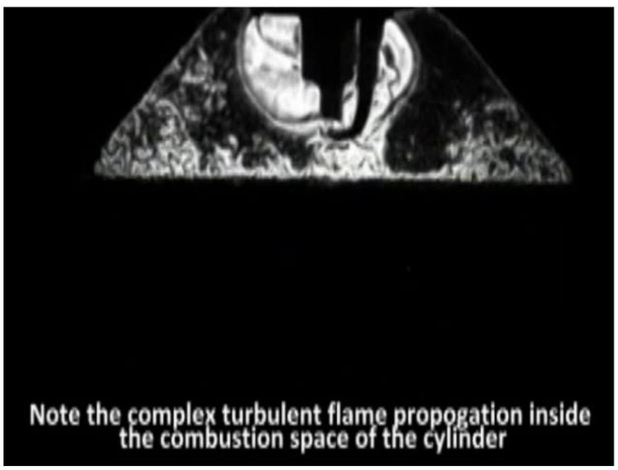
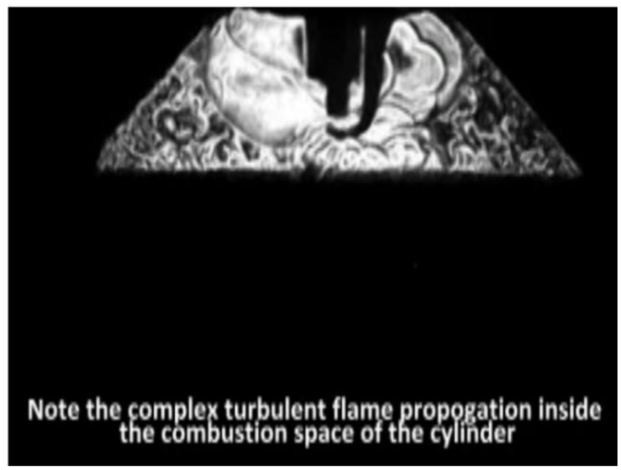


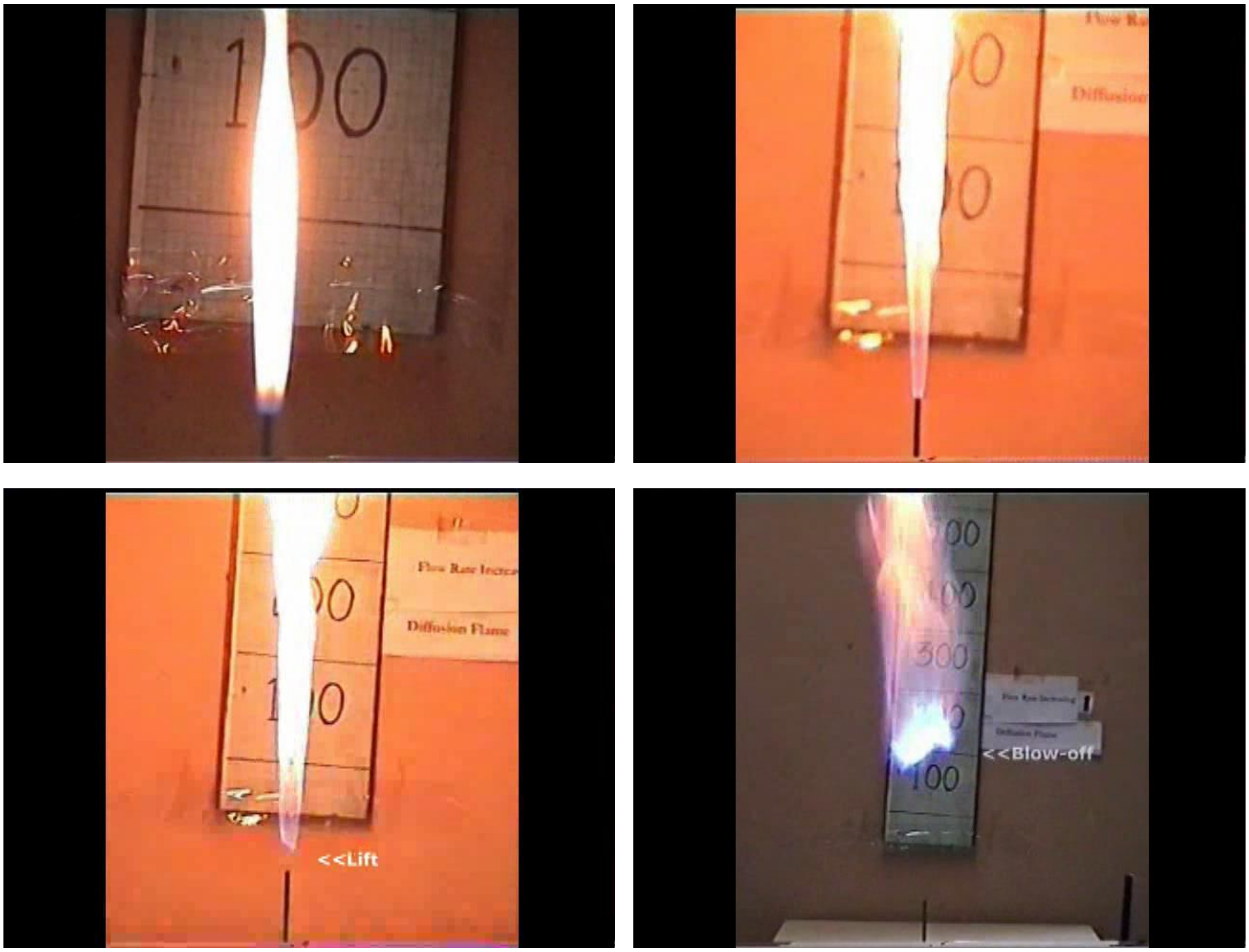
In laboratory experiments one can create the swirl by fans arranged to provide swirling flows (first row) or a rotating table with a meshed cylindrical structure to provide a source of angular momentum (second row).





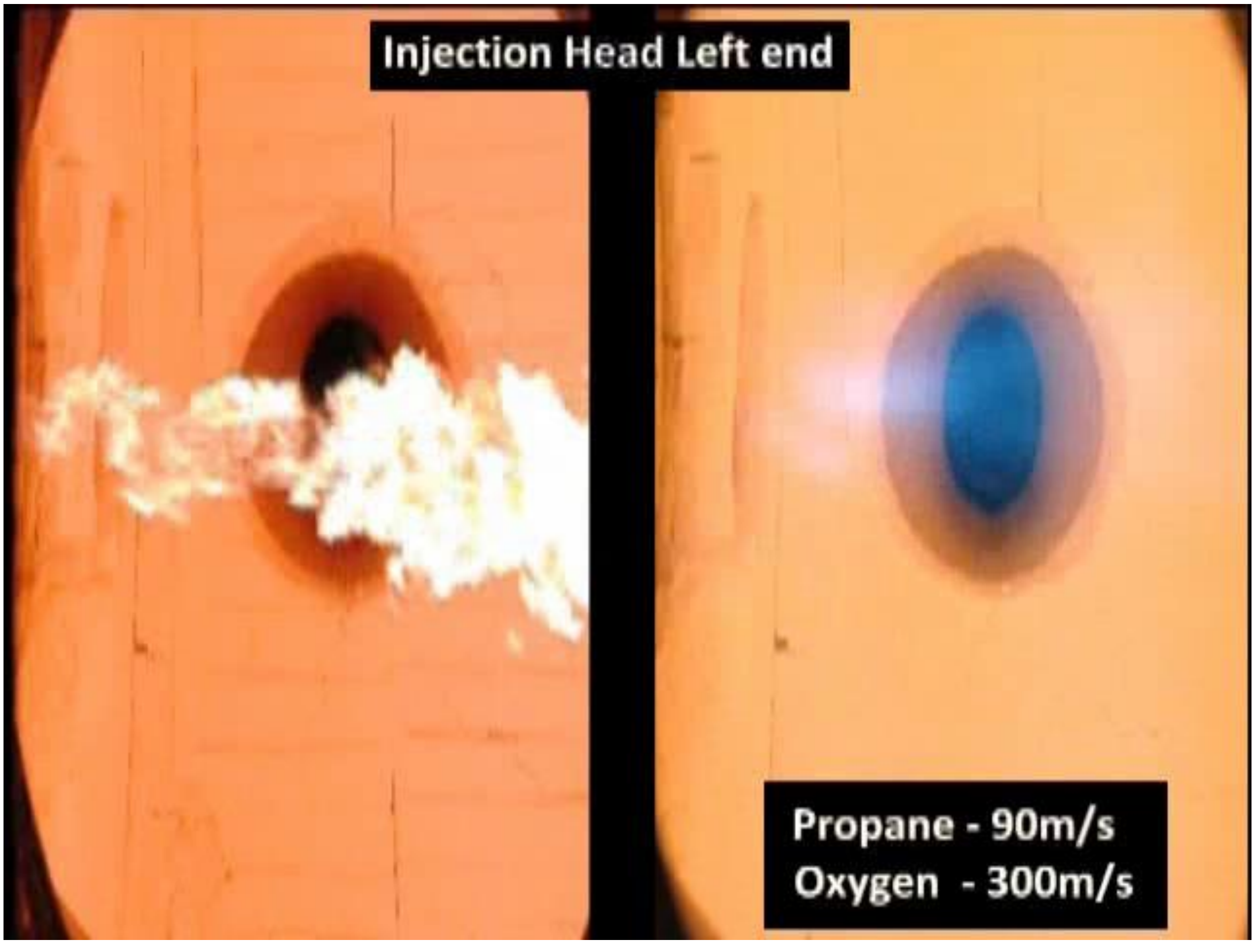
The very ultra-high speed film (10000 fps) shows the flow and combustion behavior in a spark-ignited reciprocating engine. Notice the sparking and the flame inside.

In the bottom row, the combustion structure inside the cylinder is captured as a Schlieren picture that picks out density gradients inside the flow.



Diffusion flame is obtained by causing the flow of a fuel – liquid petroleum gas (LPG) through the Bunsen burner. Air for combustion enters by diffusion. As the flow rate is increased the flame height increases linearly. It also lifts off from the edge of the tube. The height then levels off with the flow becoming turbulent. The jet entrains air from outside causing premixing below the base of the flame. Beyond a flow rate, the flame blows off.

Flameless Combustion



Classical combustion Flame-less mode

Normally fuel jet and air/oxidizer surround each other. This leads to combustion with a visible flame. By arranging the fuel and oxidizer jets at a distance from each other and making the jet speeds high ~ 100 to 300 m/s, the jets entrain the high temperature products of combustion to dilute the fuel and oxidant fractions while increasing temperature of the jets.

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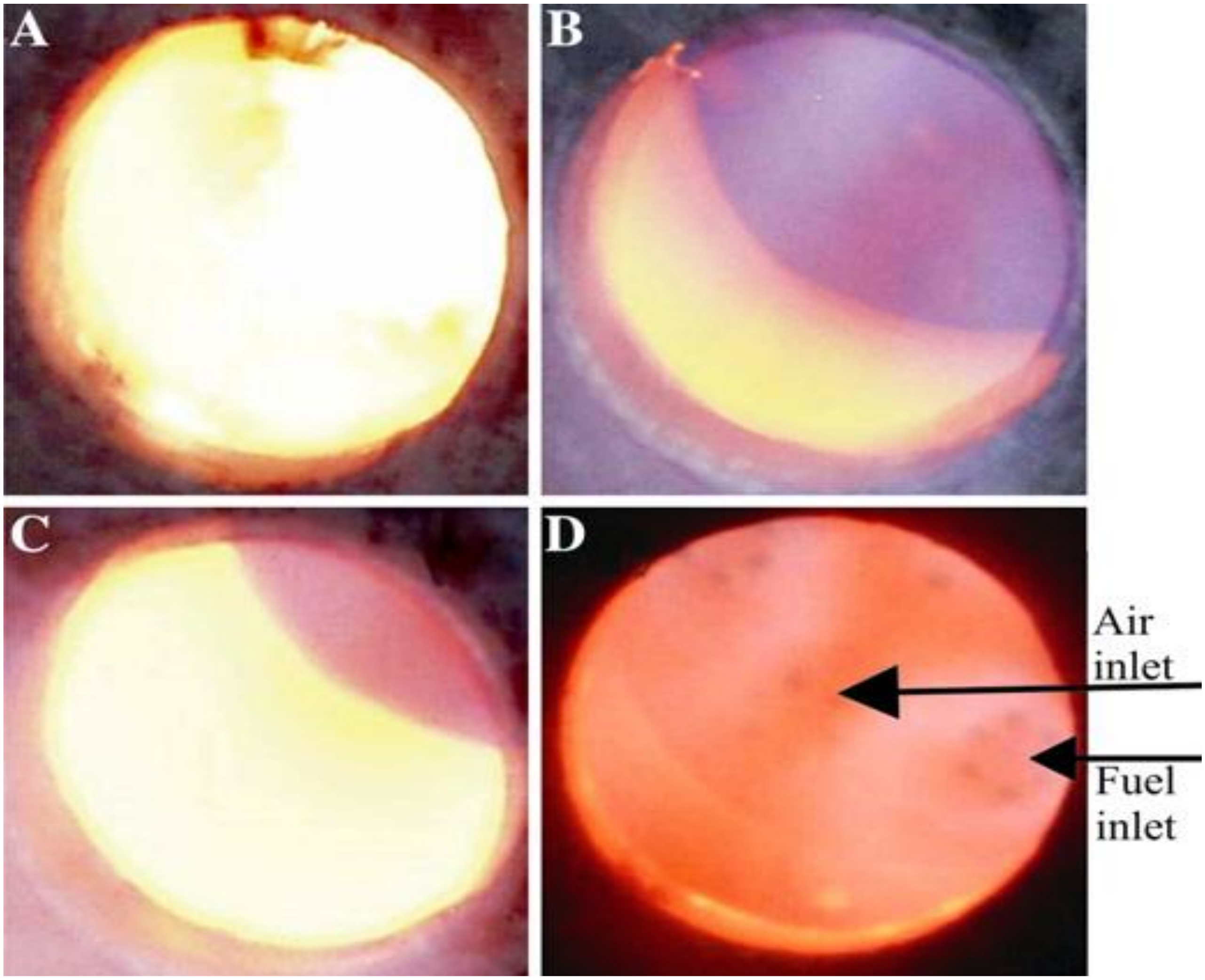
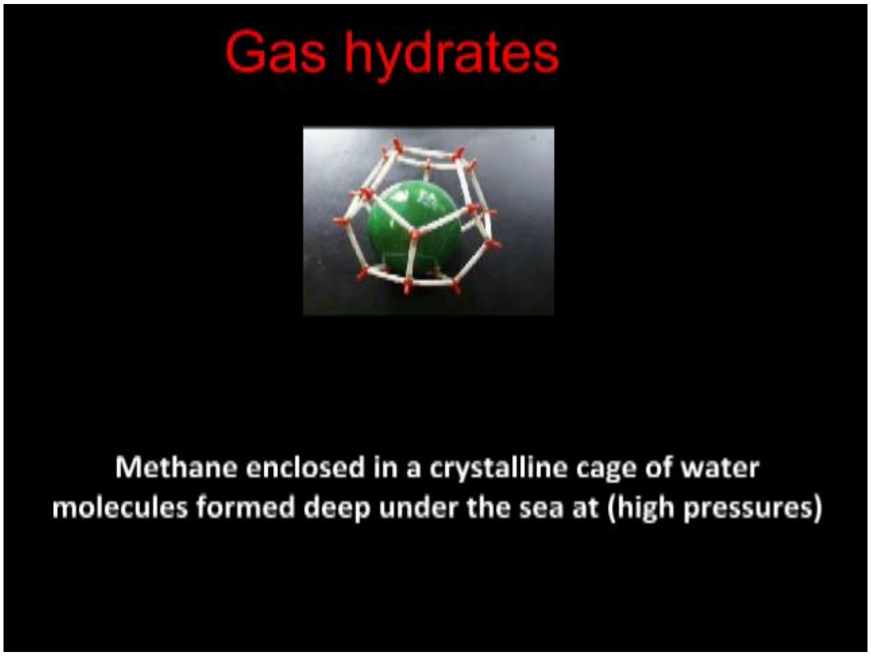


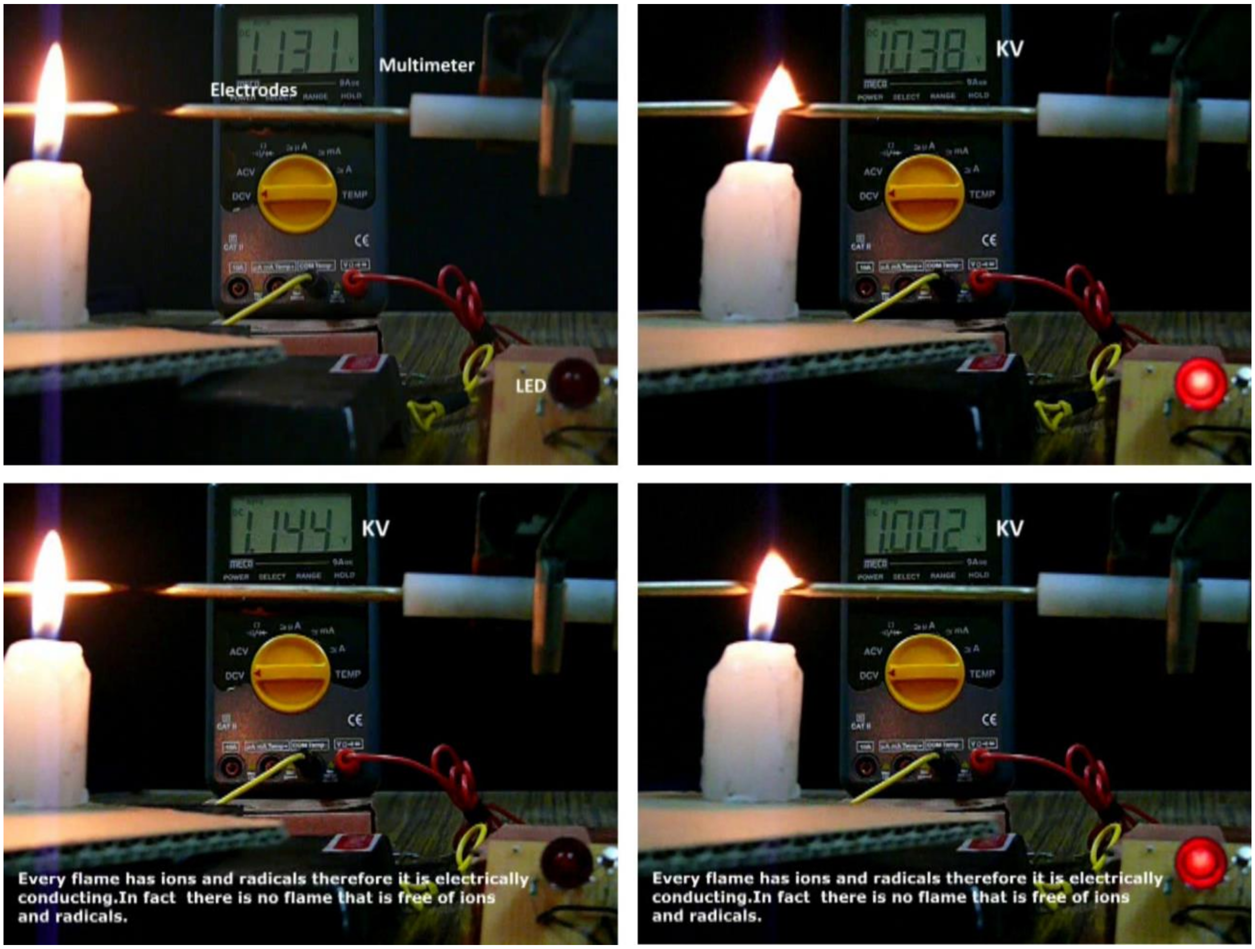
Reaction begins at high temperature, > 1000 C and the combustion process will occur in a mode close to a stirred reactor. Such a combustion process will be non-sooty and the flame will be near transparent; hence the name "flame-less" combustion mode. (A) Conventional turbulent combustion with low recirculation rates. (B,C)

Flame-less combustion mode with LPG fuel. (D) Flame-less combustion mode with producer gas fuel.

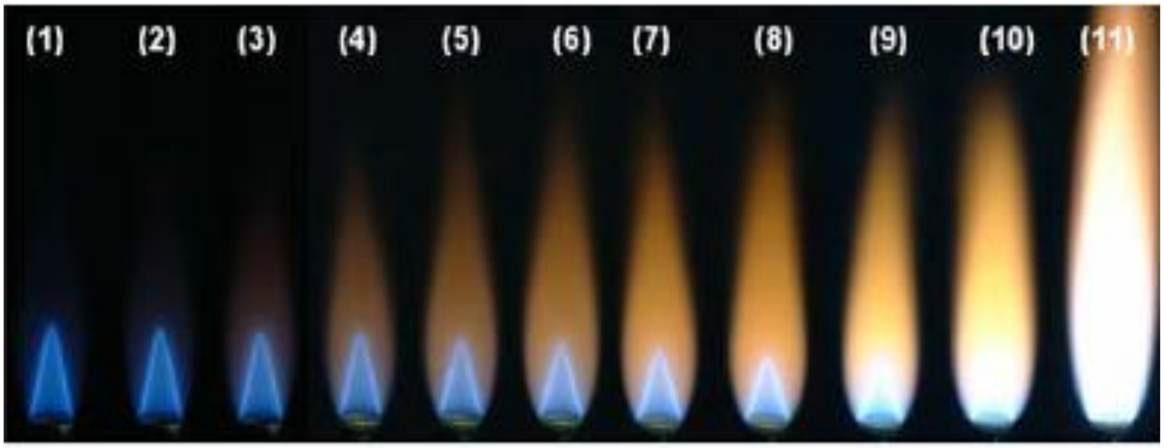
Gas hydrates



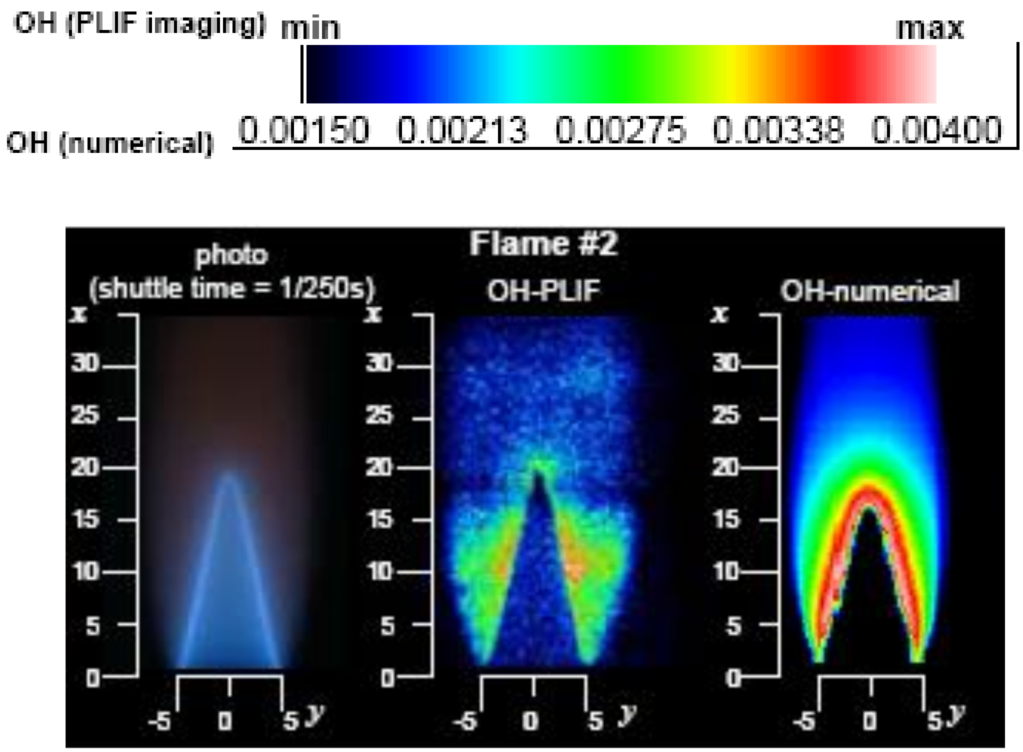
They burn with ice slowly melting away. In the last photograph, it is the cold water present on the palm and the lack of flame here that allows it to be held on the palm.



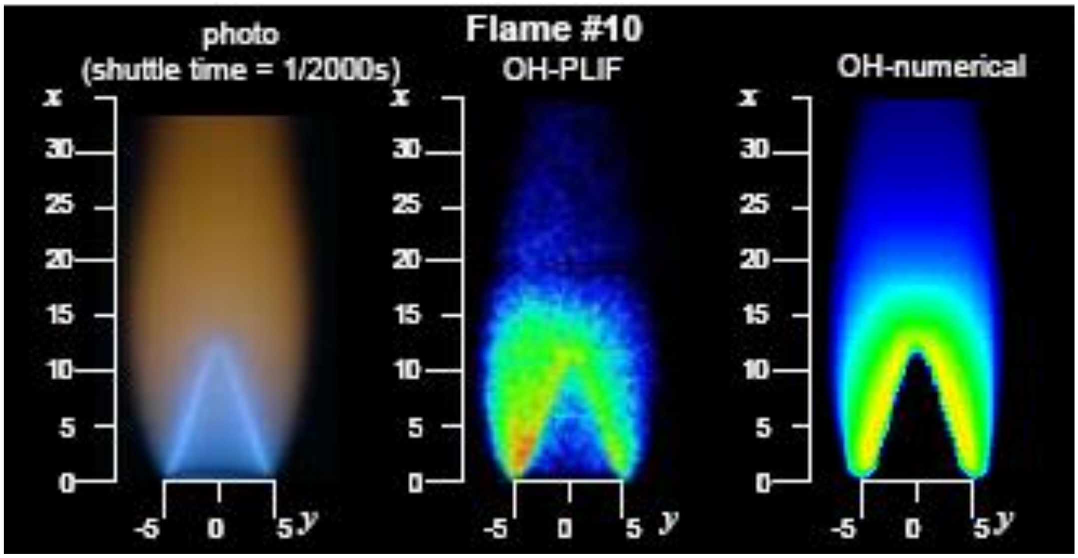
The flame is a conductor of electricity since it is composed of ions. High voltage of 1.1 kV is established between two electrodes with sharp ends. When the flame is brought such that it covers the fine ends of the electrodes, the circuit gets closed, current flows and the bulb glows red. When the flame is drawn away, the circuit is open.



Bunsen flames of stoichiometric mixtures at 2 m/s exit velocity. The first one corresponds to 100% CH_4 and each succeeding picture corresponds to 10% replacement by CO. The last picture is for pure CO. Notice how the brightness changes between CH_4 and CO flames. The conception about blue flame being the best is limited to CH_4 – air flames (hydrocarbon based flames) and see how differently bright CO flames are. (from Investigations of Blended CH_4/CO Premixed Jet Flames– Experimental Measurement and Numerical Validation, C. Y. Wu, Y.C. Chao, C. P. Chen, Y.S. Lien, T. S. Cheng, 21st ICDERS symposium, 2007).



90% CH_4 and 10% CO: direct photograph, and planar laser induced fluorescence (PLIF) that detects OH specially. Computational results of full chemistry showing OH are also presented. The OH distribution shows the reaction zone. The differences between the computations and experiments are due to non-replication of details of the edge region.

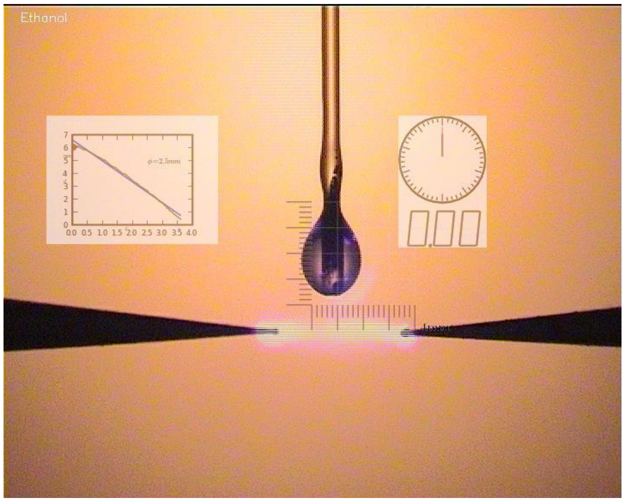


Flame of 100 %, CO with same details as earlier. Notice much less OH in the flame.

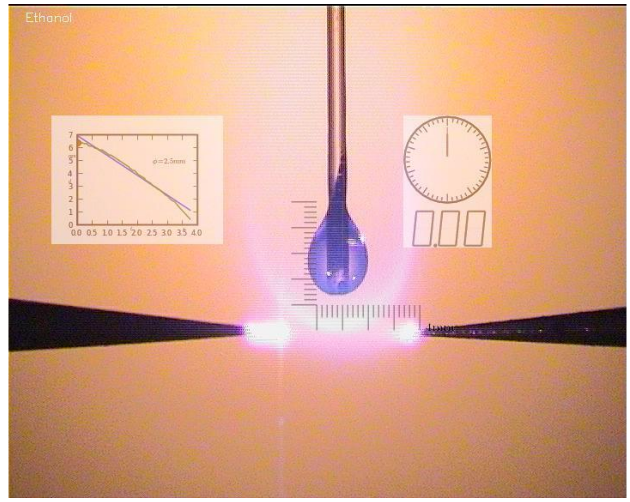
Liquid droplet combustion

Single droplet combustion is a diffusion flame. The heat transferred from the flame vaporizes the fuel. Fuel vapor and air diffuse into the flame from both sides and react exothermically. Diffusion process is rate limiting. The above pictures taken in a laboratory in a normal gravity shows how free convection affects the height of the flame.

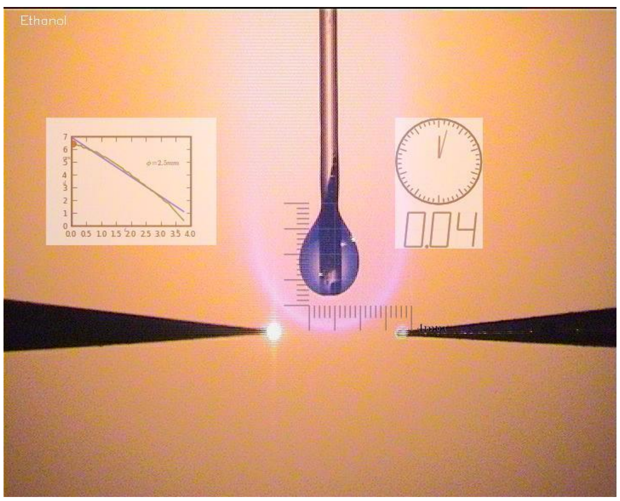
Droplet combustion is an important process that occurs in burners, reciprocating engines and gas turbines. This is captured by burning droplets on a quartz fiber at normal gravity. You will see the following droplets being burnt – Ethanol, gasoline, kerosene and diesel. The ignition is by an electrical spark. The red dot on the plot shows the path of the square of the drop diameter with time.



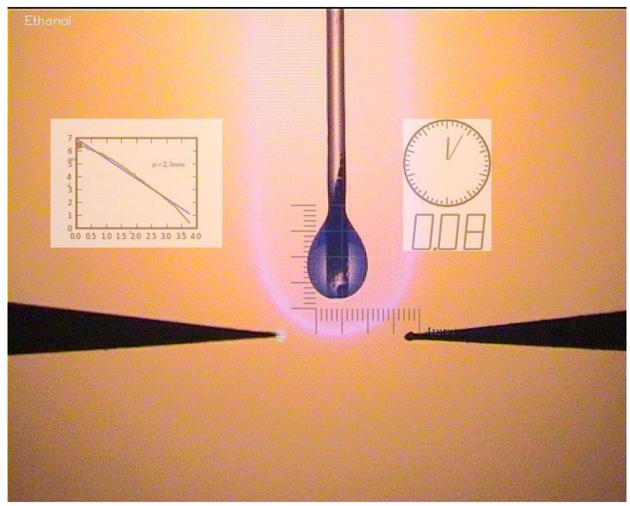
Ethanol: Just when spark is initiated



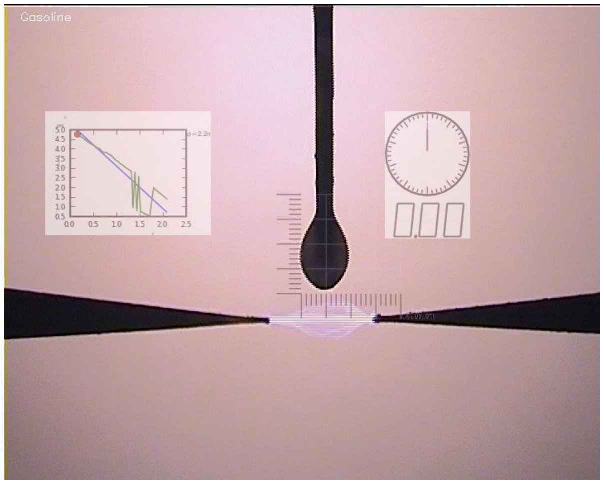
20 ms+, Ignition just complete



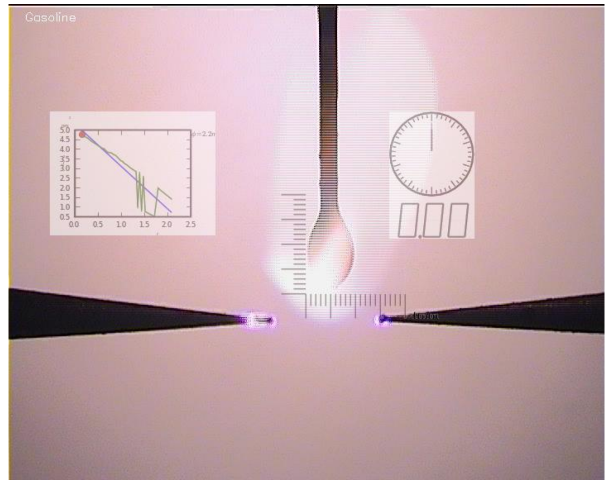
Ethanol: 40 ms later, Spark ending



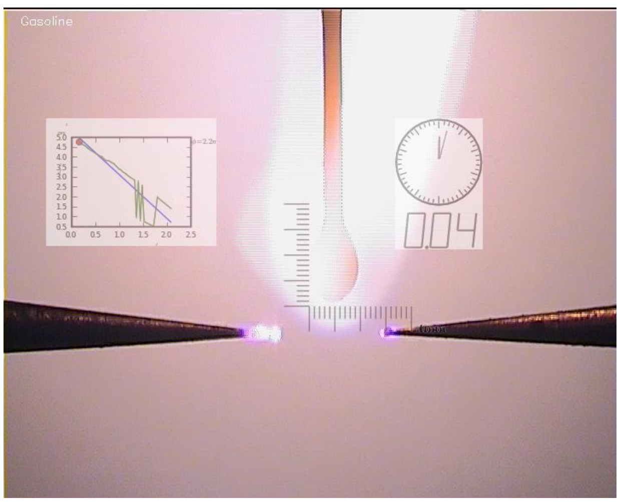
Sparking has ended



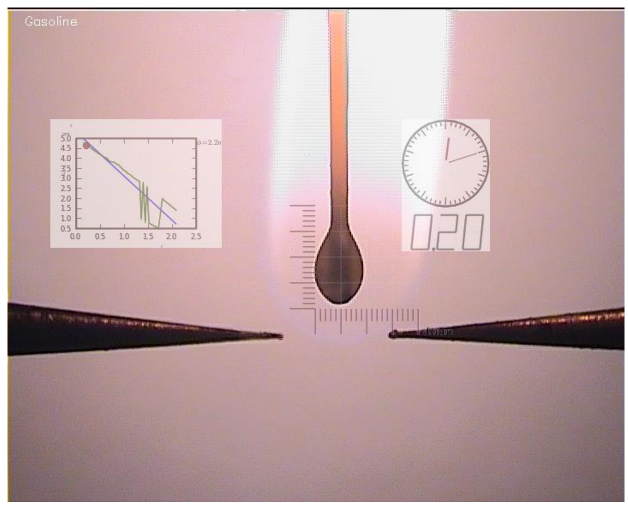
Gasoline: above Spark initiated



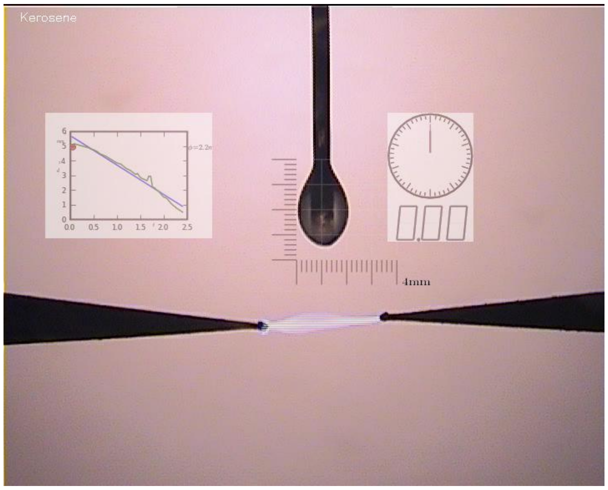
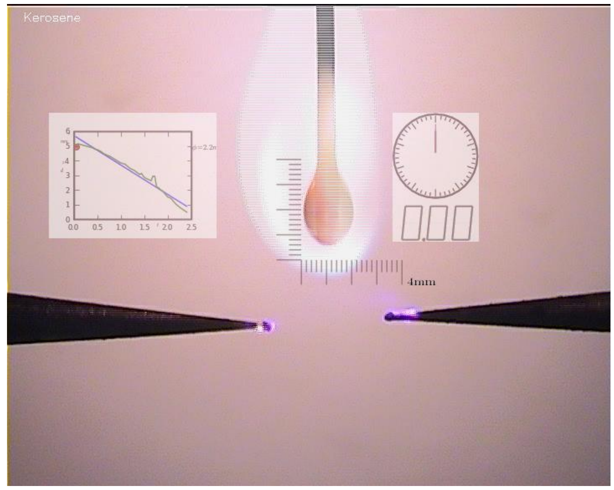
Ignition taking place; 20 ms later



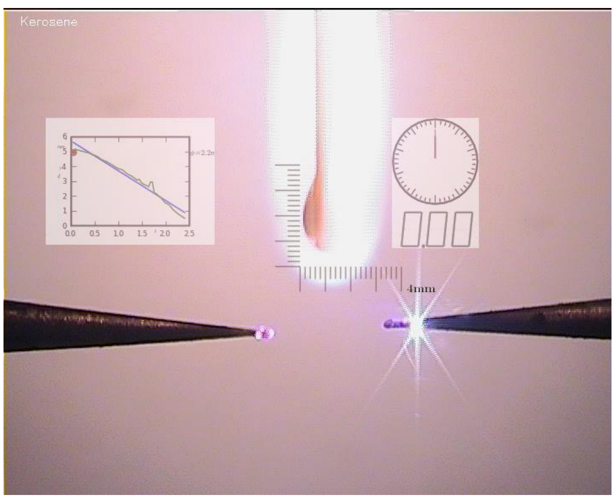
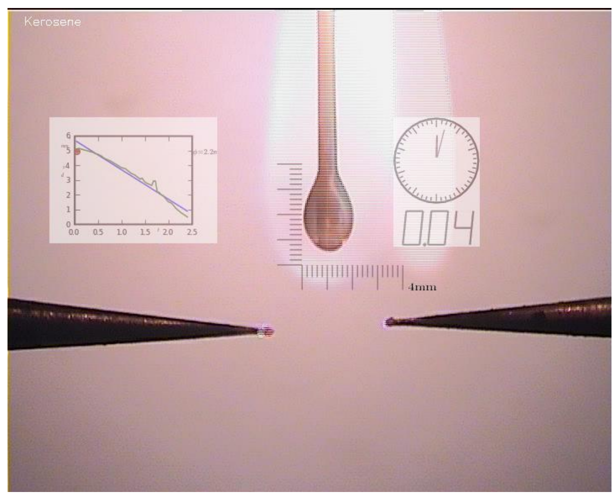
Gasoline: Ignition ending



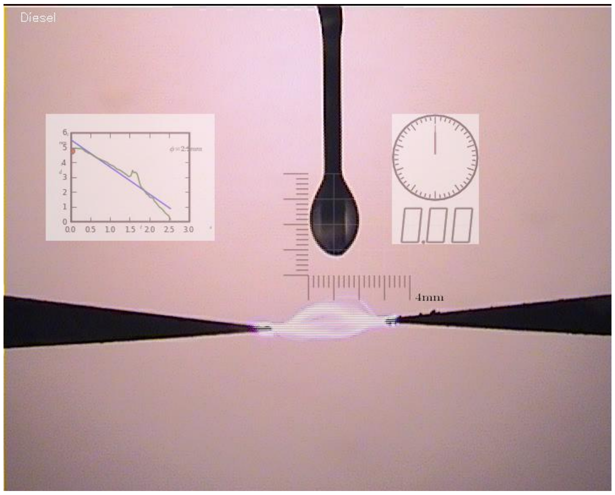
60 ms later; steady combustion

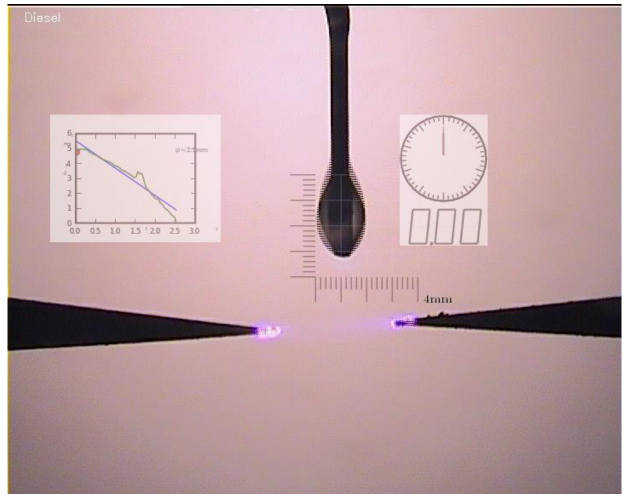



Kerosene: above: just at sparking   Ignited at 20 ms

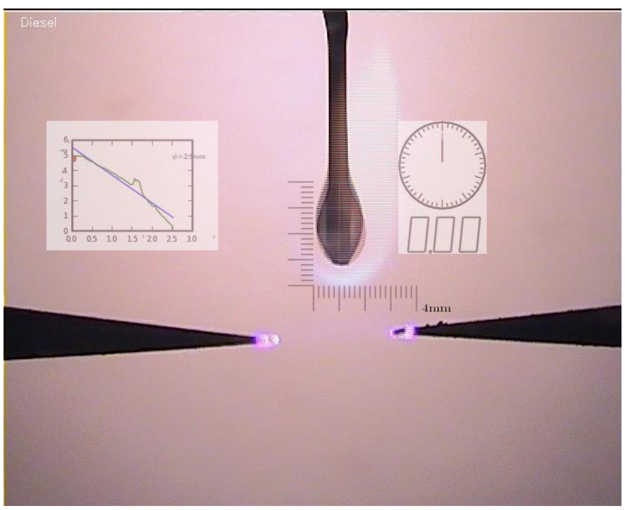



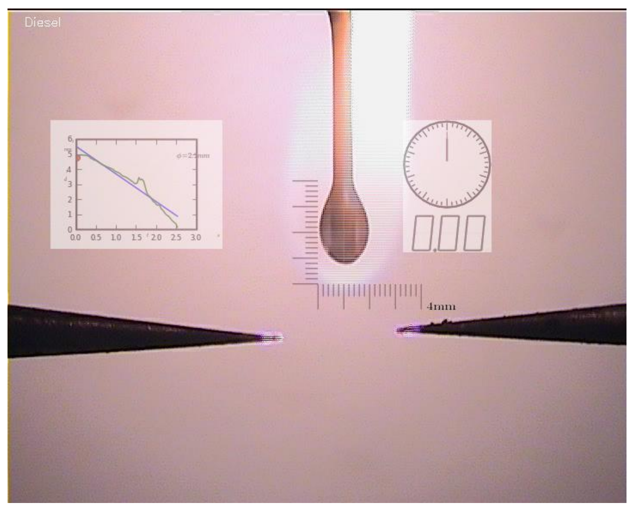
Kerosene: Ignition ending   Steady combustion just started.





Diesel: above top: spark started   Ignition process going on

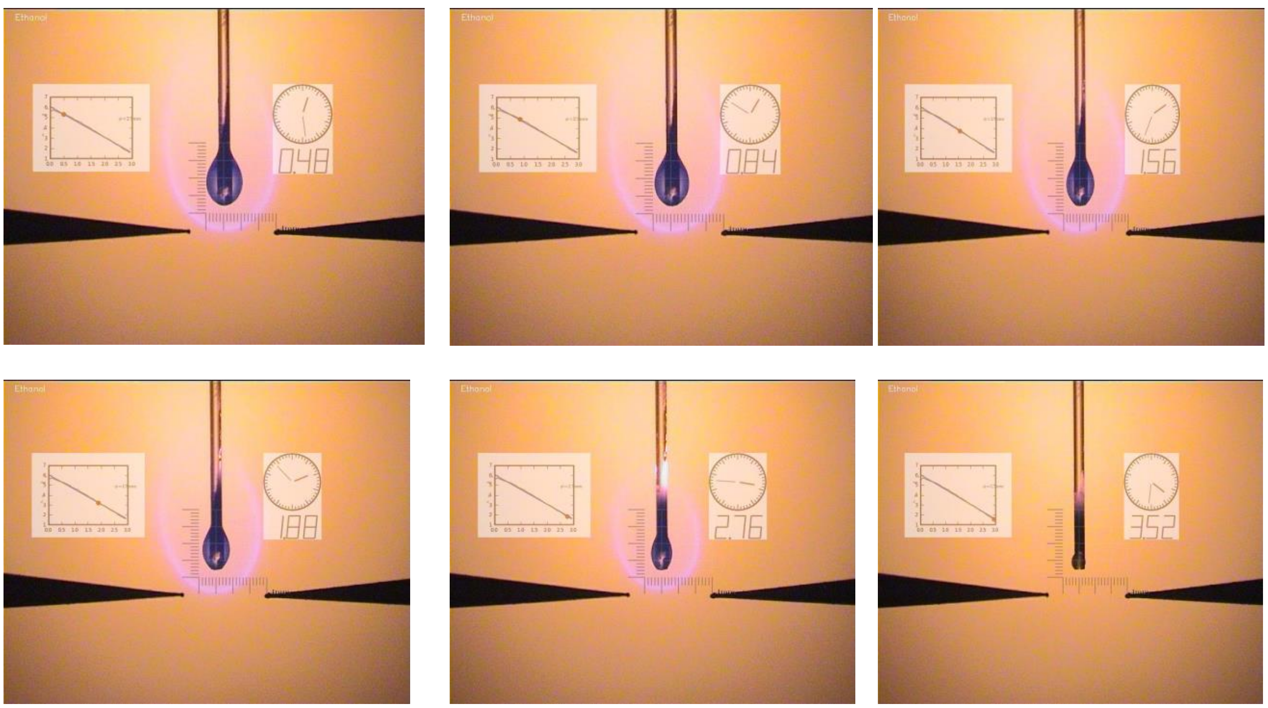


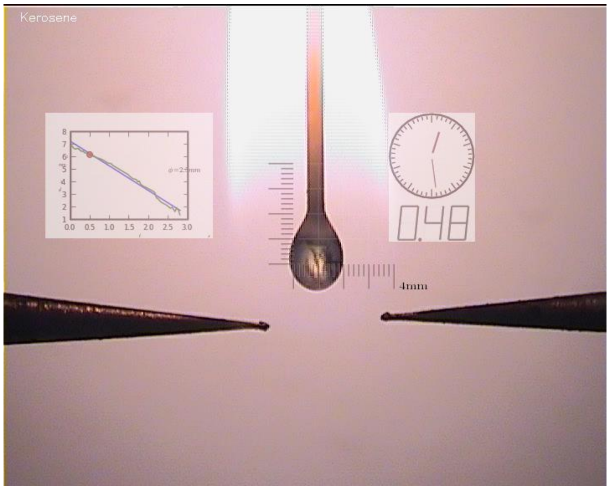


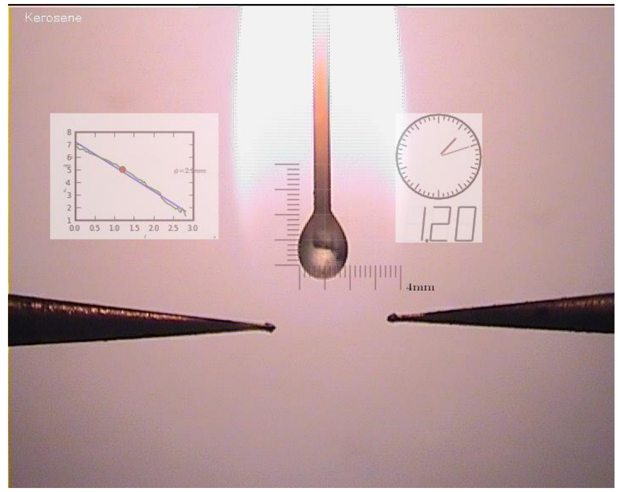
Diesel: 40 ms after; ignition taking place   Steady combustion started

Progress of combustion of ethanol droplet.

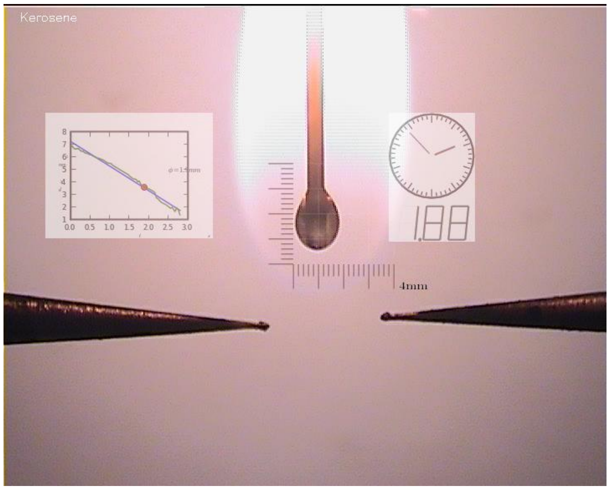
The progress of combustion is marked by the red dot on the near-straight line between the square of the drop diameter with time (in *s*). Note that the flame is transparent and that a tiny mass remains unburnt at the end.

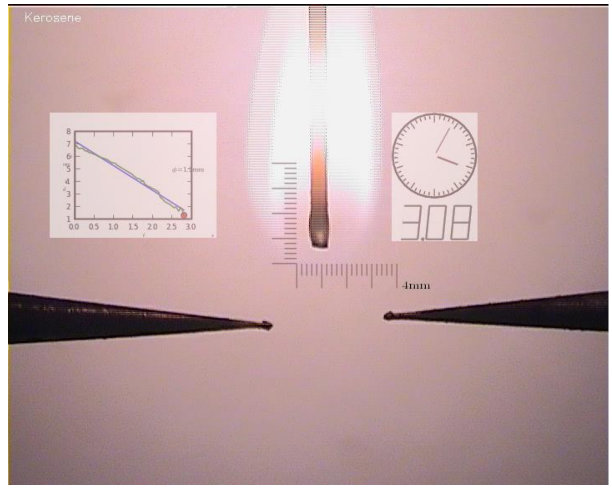






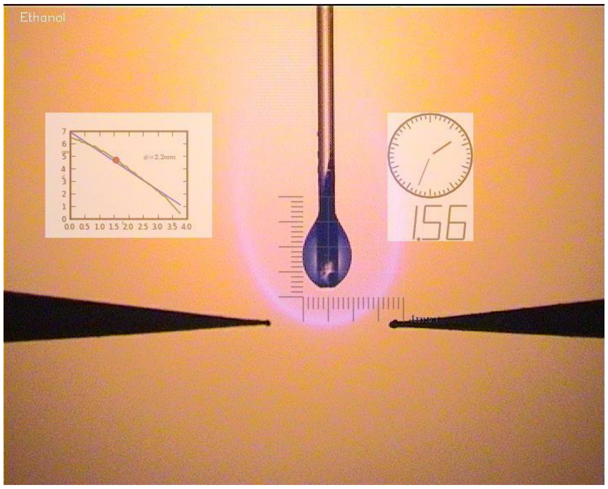
Kerosene drop combustion below shows that the drop burns completely.

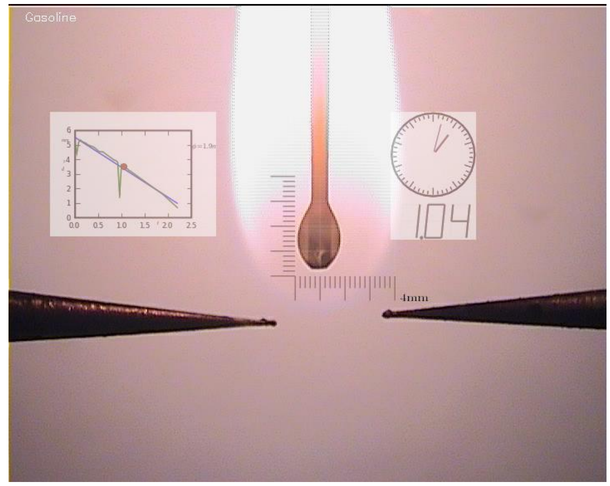


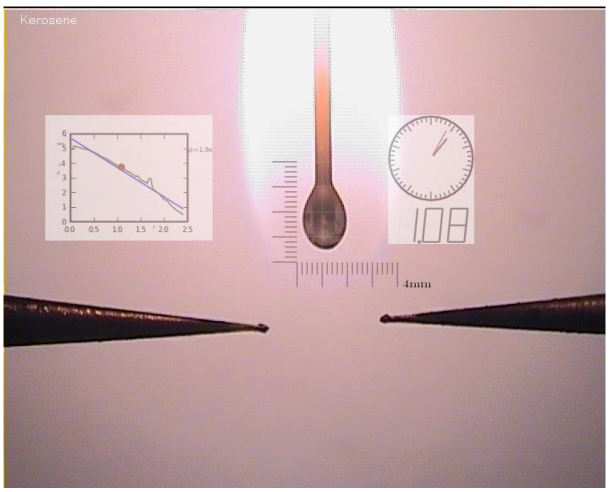


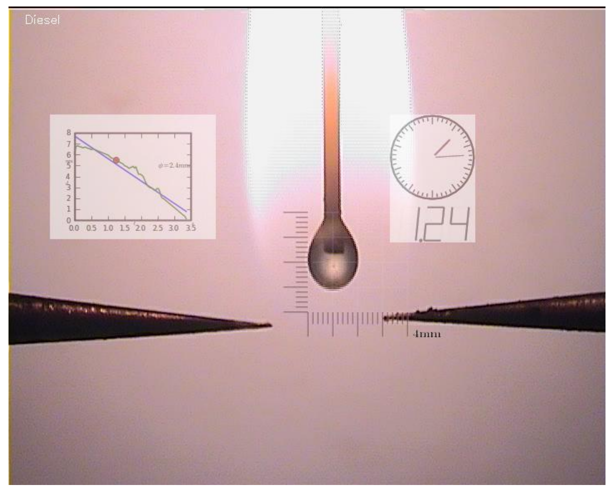
Comparison of combustion of ethanol, gasoline, kerosene and diesel

Notice irregular shape of the actual d^2 vs. t in a few cases. Since the fossil fuels are a mixture of compounds, selective vaporization can lead to bubbling, sudden expulsion in the drop or its expansion

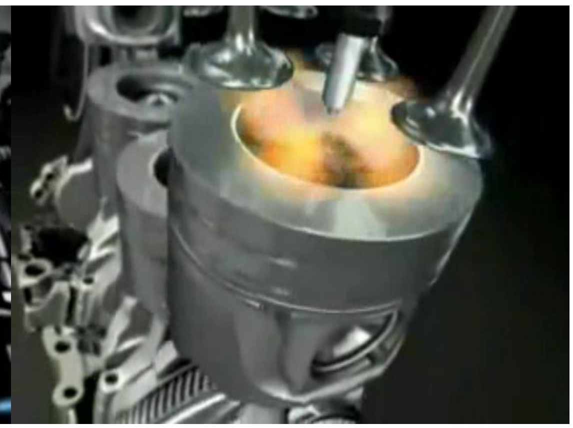


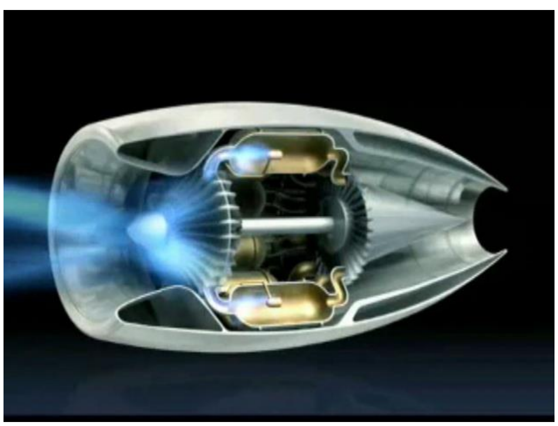


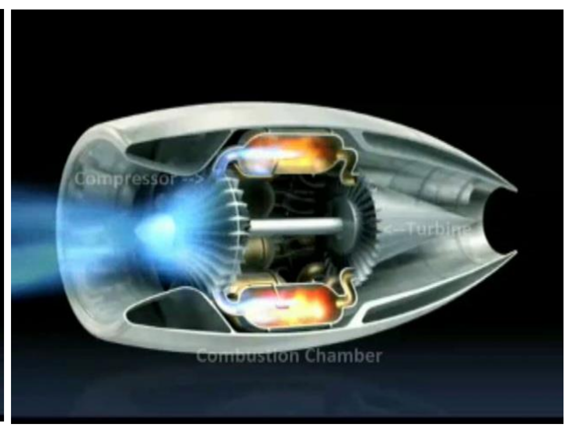




Fuel spray and its combustion



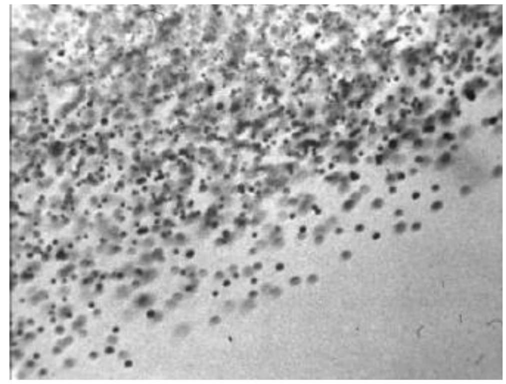


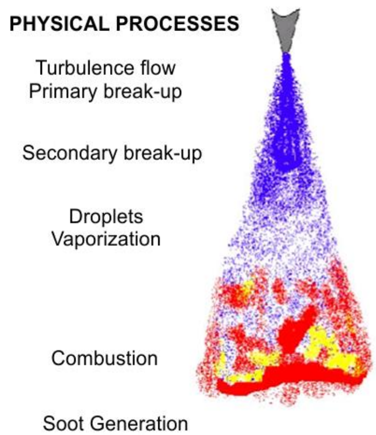


Liquid is always introduced in terms of fine droplets by atomizing the liquid in injectors in all combustion systems – reciprocating engines, gas turbines and rocket engines. The jet diameters are 150 to 200 microns usually. The burn time of the fine drops is in terms of fraction of milliseconds in actual systems.

continued...

Pictures of a diesel fuel spray





The diesel spray inside a diesel engine combustion chamber and the outer zone containing the droplets.
The actual processes inside the combustion chamber

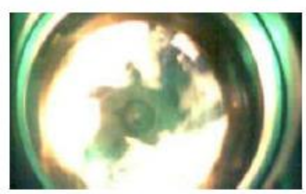

Pilot 27° BTDC


Pilot 26° BTDC


Main 2° BTDC


Main 2° BTDC


Main 1° ATDC


Main 7° ATDC

Note the injection, ignition and combustion processes inside a diesel engine; the jets coming out as six separate radial sprays

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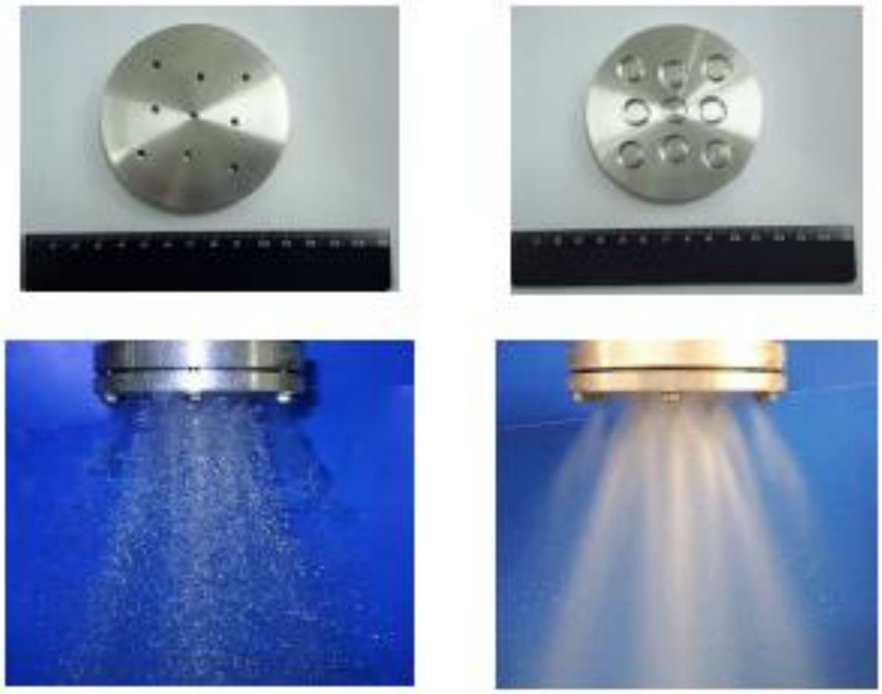


Liquid engine injectors come in varieties – impinging – like (fuel-on-fuel and oxidizer-on-oxidizer) and unlike (fuel-on-oxidizer), number of swirl burners mounted inside the combustion chamber. The sprays from these injectors are seen here.

Hypergolicity

Hypergolicity is a property of specific combination of fuels and oxidizers in which as soon as they come into contact with each other, they react vigorously and lead to a flame in the gas phase.

Here nitrogen tetra-oxide is the oxidizer and Aniline is the fuel. Nitrogen tetra-oxide has a boiling point of 21 °C and is usually stored under pressure. Into the nitrogen tetra-oxide that is placed in the test tube, aniline is dropped from a pipette. Flame appears within 2 to 5 milliseconds. This difference in time between the moment of contact to the appearance of the flame is called " Ignition delay".

Nitrogen tetra-oxide along with other fuels like mono-methyl hydrazine, unsymmetrical methyl hydrazine are used in rocket engines requiring high reliability in ignition, typically as in lunar module departing from the moon.

Liquid rocket engines

The spray from impinging injector head

Two control rockets based on nitrogen tetra-oxide and mono-methyl hydrazine are being fired here on a test bed. Note the shock downstream of the nozzle.

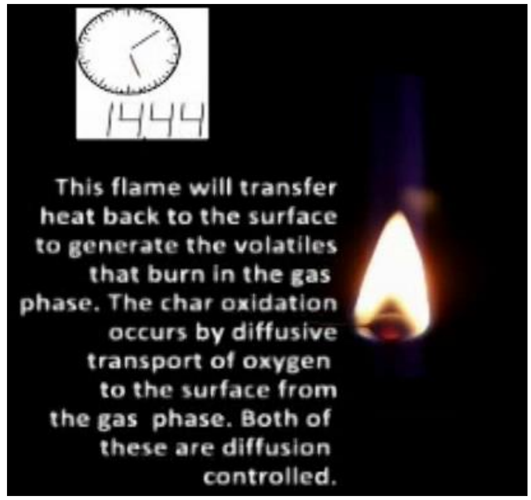
Variety of liquid rocket engines

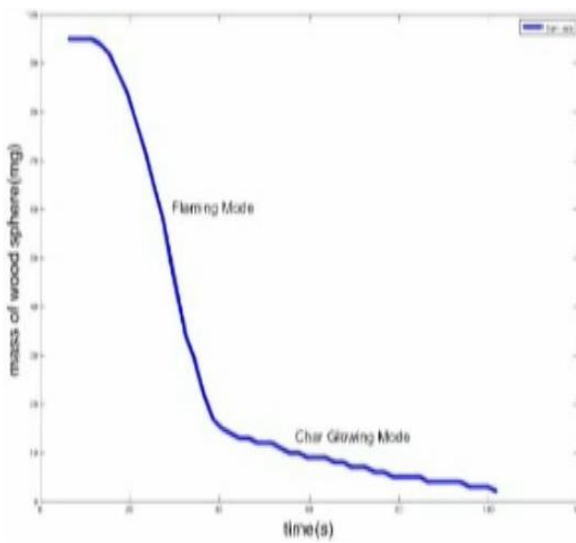
LOX – Kerosene based engine.
Notice the bright exhaust

MMH – N_2O_4 based engine.
Notice exhaust (not-so-bright)

LOX – LH_2 based engine (SSME).
Notice near-transparent exhaust

Solid combustion

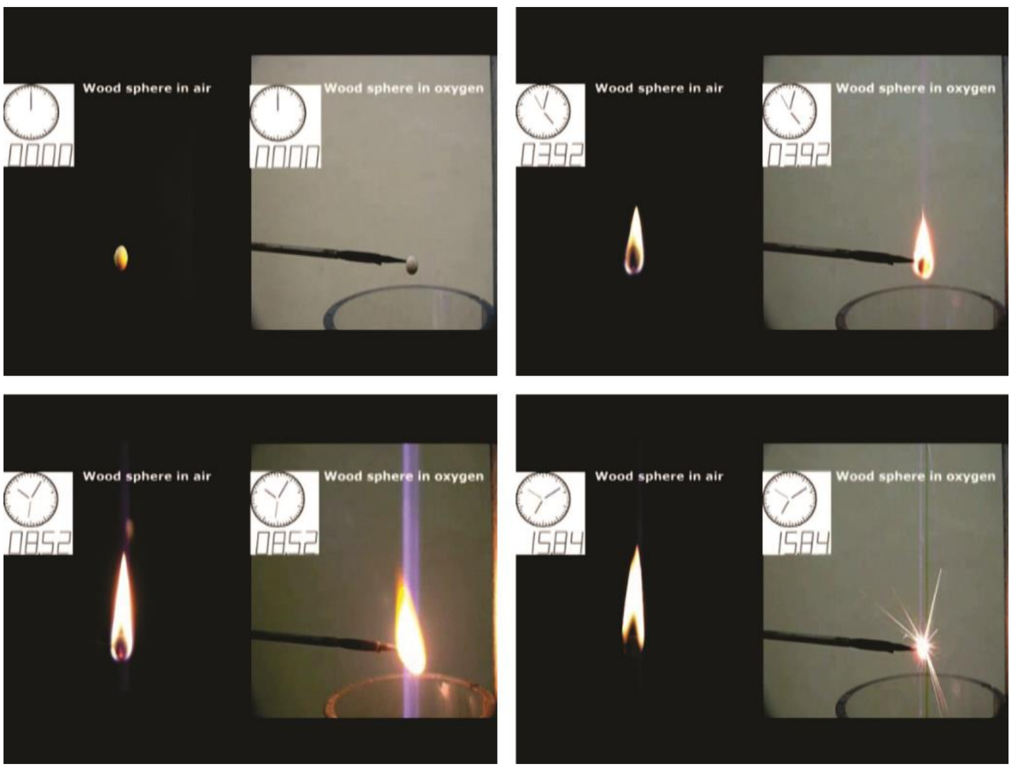




Combustion of wood and any biomass occurs in two steps – flaming combustion and char oxidation. The former occurs in the gas phase and the latter occurs on the surface. Ignition of wood needs a flame to heat up the material till the volatiles are released and a gaseous flame is initiated.

continued...

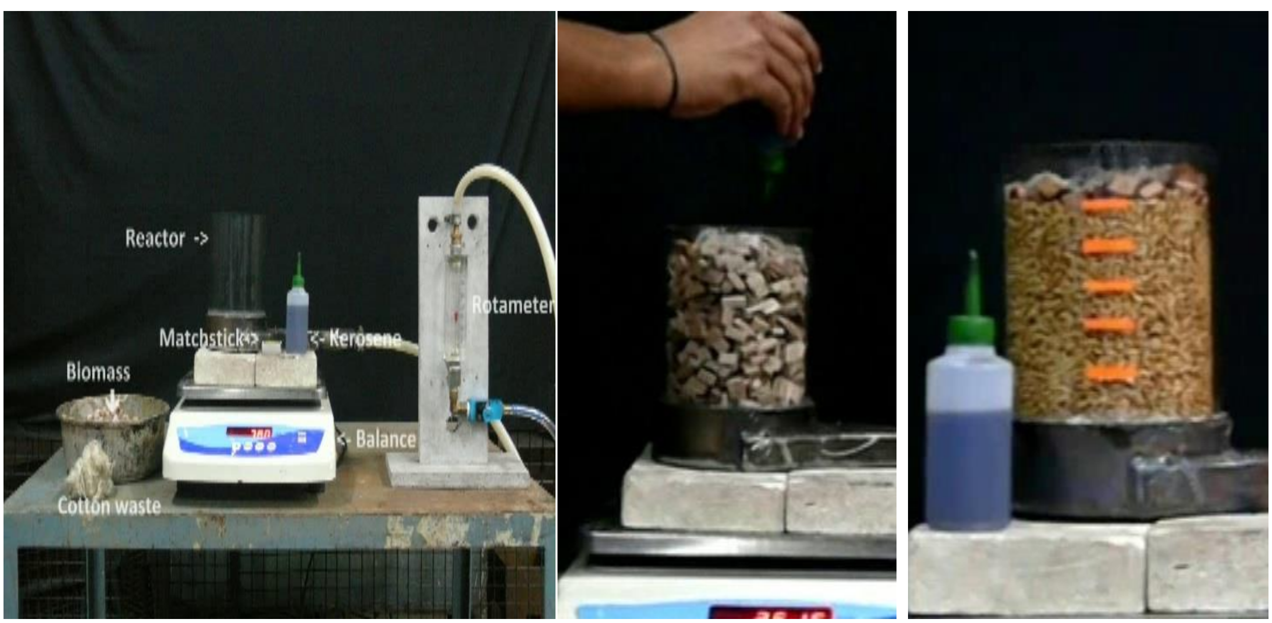
Combustion of a wood sphere is shown here. After ignition, the sustained combustion occurs because the flame transfers the heat to the surface to generate the volatiles that burn in the gas phase. The char oxidation occurs by diffusive transport of oxygen to the surface from the gas phase. Both these are diffusion controlled. Volatile combustion occurs faster than char oxidation.



A comparison of the combustion of wood sphere in air and oxygen as the oxidants is shown here. The flame is brighter with oxygen and the wood sphere burns faster and fragments as well because of sharp heating of the solid. The sparkling radiation seen on the right is due to fine break-up of the solid char at the final stage.

Modern gasifier based stove combustion

Gasification is a process by which solid or liquid fuel thermally reacting with an oxidizer generates a combustible gas. What you see is a reverse downdraft gasifier with solid fuel pieces packed into a container from the bottom of which is passed air and the gases generated are burnt above the fuel bed with secondary air. Ignition is performed by spraying kerosene on to the top layer and then lighting the kerosene. Note that in the char mode the combustible gases are generated at the bottom region and burnt much above it.



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Pieces of wood being lit; Fine biomass lit with kerosene spray

continued...




Various views of the combustion front inside the stove. Note that the gases burn with air only at the top

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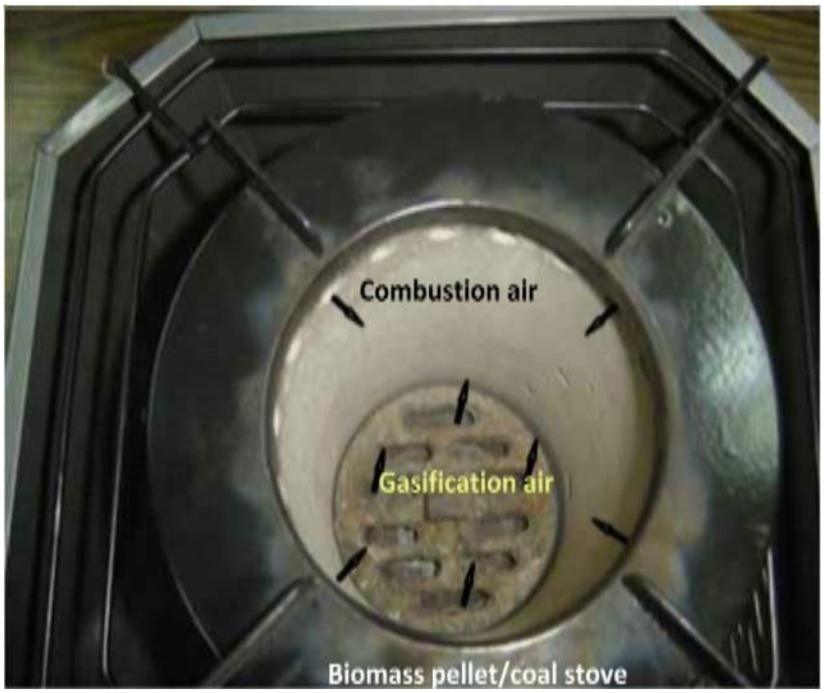
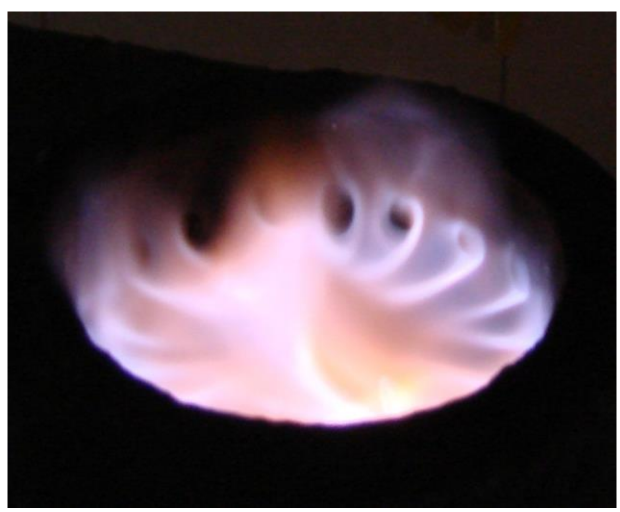


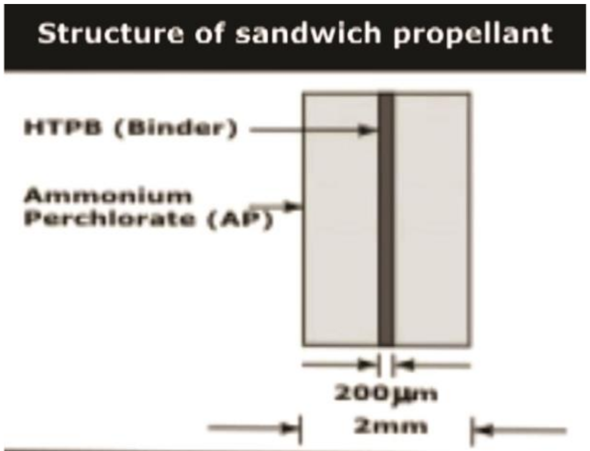


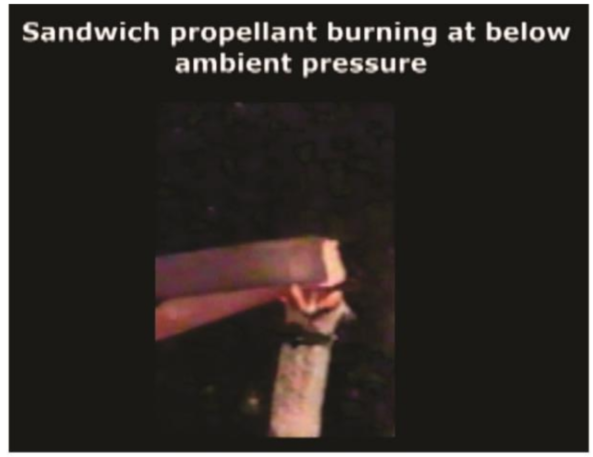
The practical stove using gasifier principles. The fan based air flow from the bottom grate causes gasification and air flow from the periphery towards the top allows combustion of the gases. The bottom left is for biomass pellets and the right is for coal. The air flow from the periphery leads to what appears like holes through the flame.

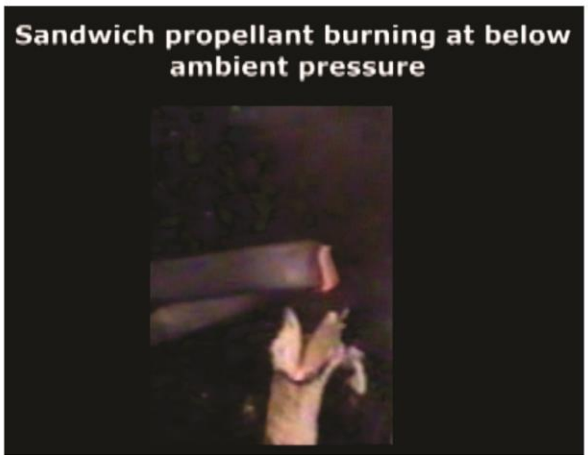
Solid Propellant combustion

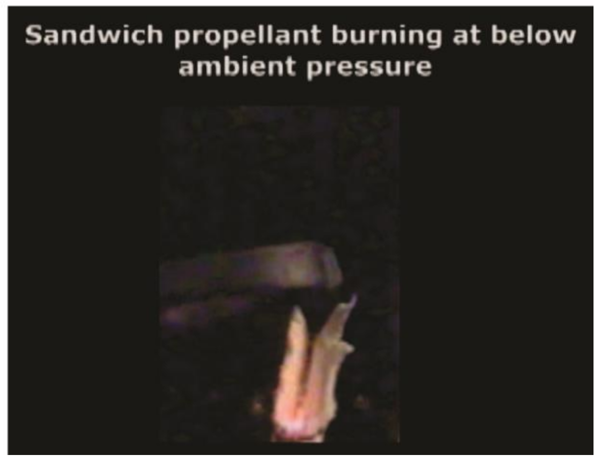
Solid propellants are a mix of solid oxidizer like Ammonium perchlorate and fuel-aluminum powder at high solid loading in a binder matrix of fuel like HTPB or others. A model of solid propellant is a sandwich propellant.

The burn rate of a model sandwich propellant is examined at low pressures. Typical burn rates vary from 1 to 2 mm/s.


Structure of sandwich propellant
HTPB (Binder)
Ammonium Perchlorate (AP)
200µm
2mm

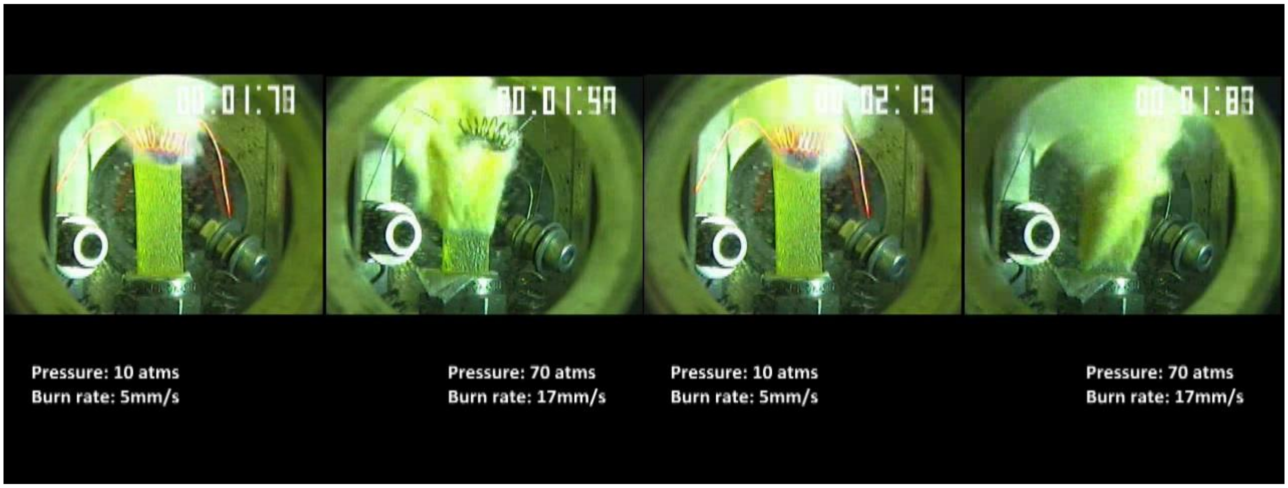

Sandwich propellant burning at below ambient pressure


Sandwich propellant burning at below ambient pressure


Sandwich propellant burning at below ambient pressure

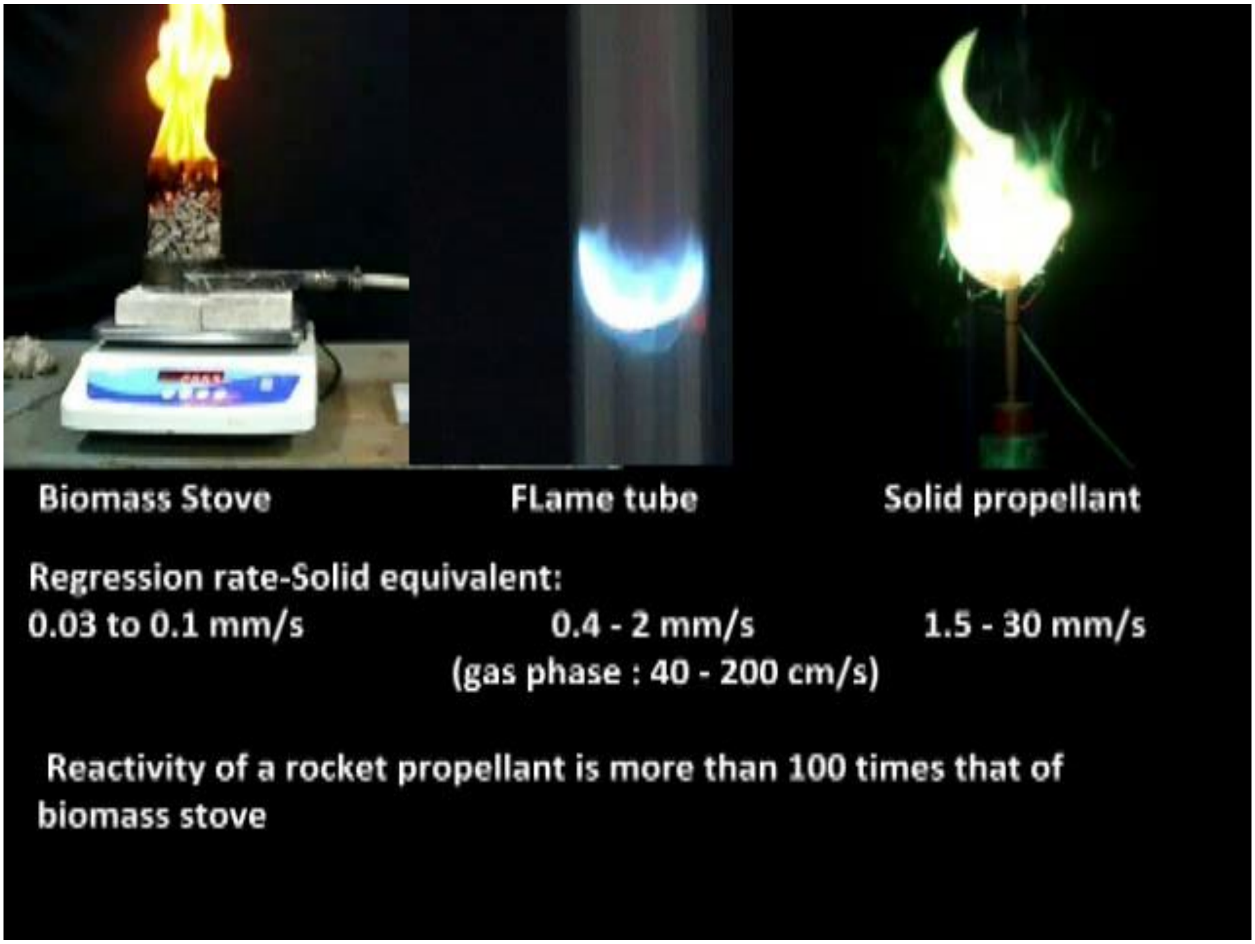
continued....

Solid propellant combustion does not need external oxidizer. A piece of the propellant is placed in a way it is surrounded by nitrogen. A match stick flame is shown to be extinguished in the nitrogen stream. The propellant is electrically ignited here using a nichrome wire and the propellant burns at 2.5 mm/s at ambient pressure. continued....



Solid propellants are designed to burn at very high pressures. They are tested in what are known as Strand burners. You will see the propellant burning at 10 and 70 atms. at 5 and 17 mm/s respectively.

A Comparison of the rates of combustion



Solid rocket motor test

A large solid rocket motor on a test stand. It burns about 500 kg/s of propellant to produce 1100 kN of thrust for about 90 s.

Hybrid rocket

Hybrid rockets are the safest form of rockets. They can use a liquid or gaseous oxidizer and a solid fuel. In the test shown here, it uses gaseous oxygen and a solid polymeric fuel.

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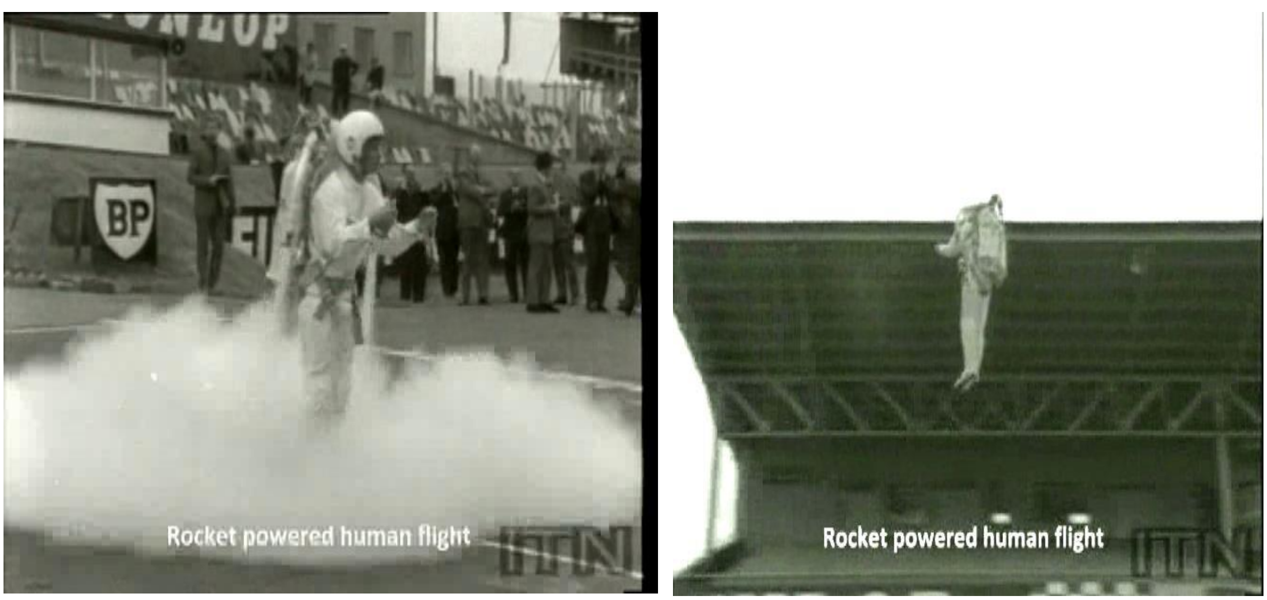
Human flight with rocket-like devices

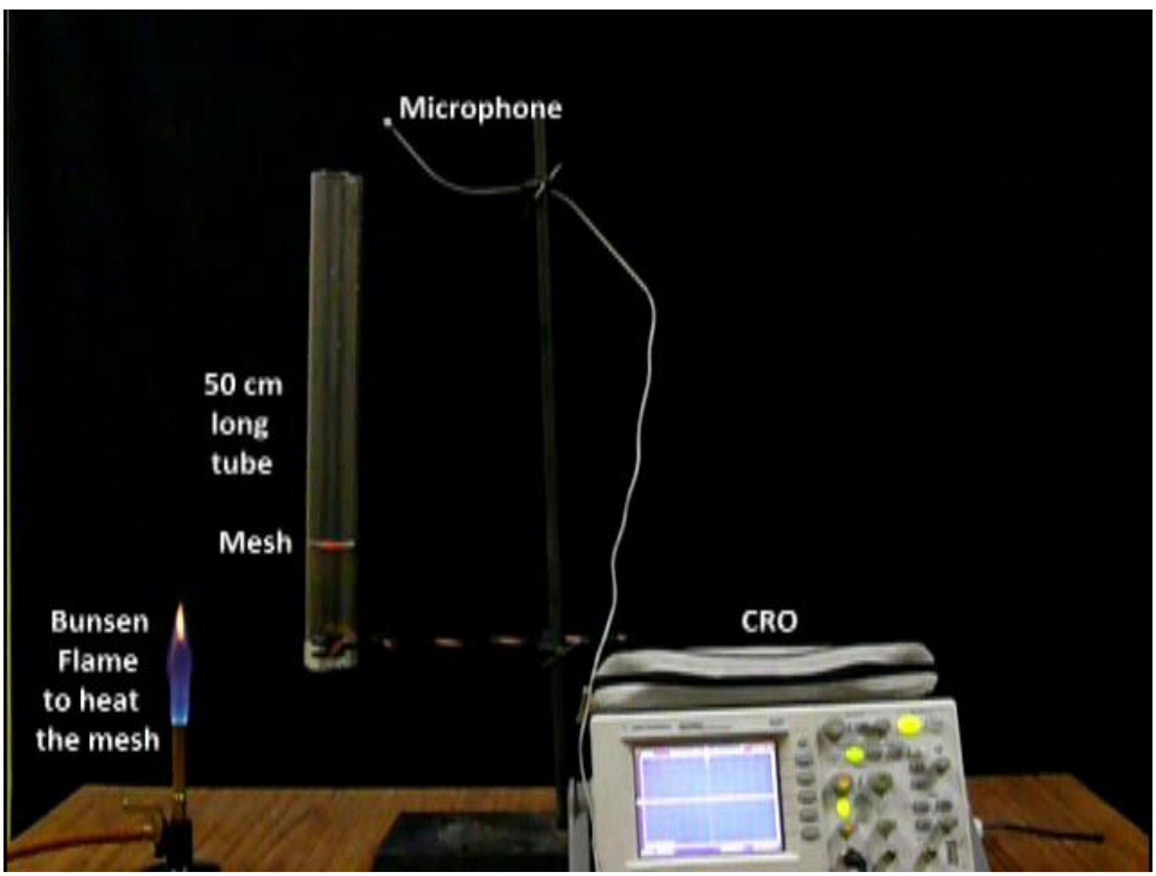


Using jet back-pack and hydrogen peroxide based rocket motor a short duration flight (21 s) is performed.

Unsteady combustion

Rijke tube

Rijke tube is a tube that converts heat applied in specific locations to sound by creating a self-amplified standing wave.



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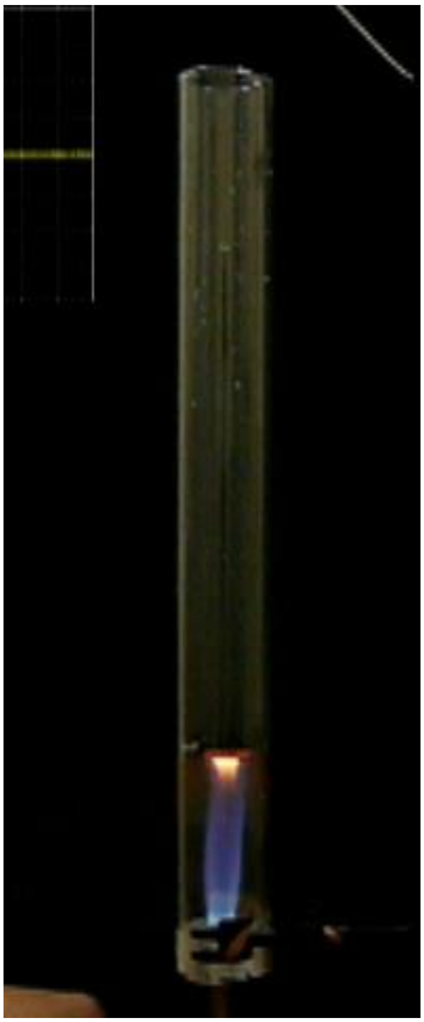
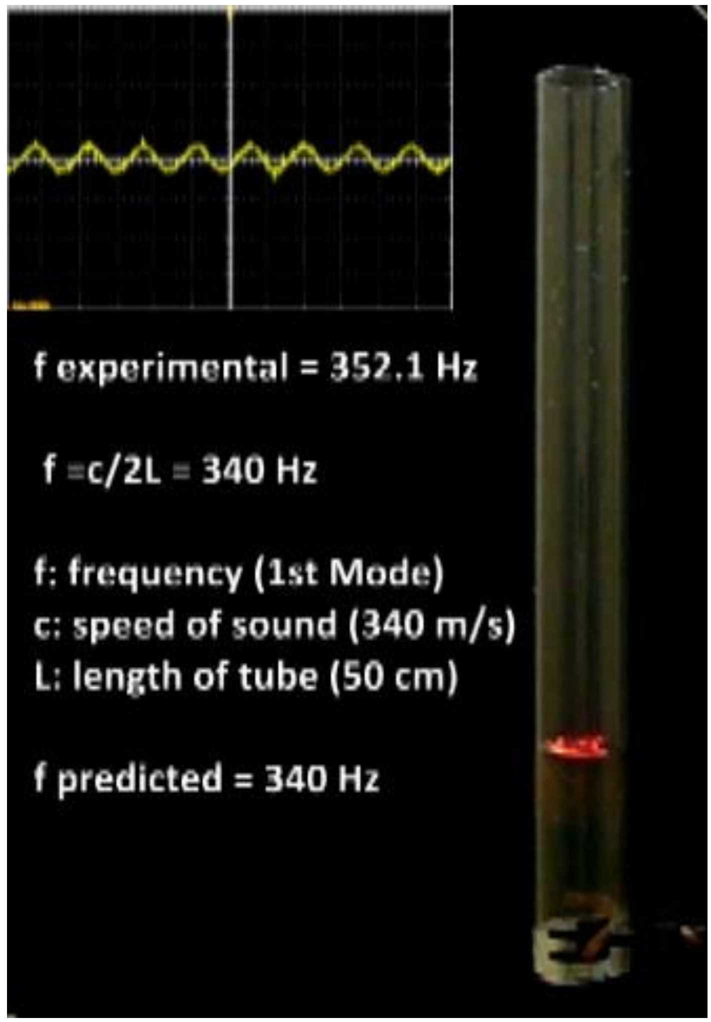




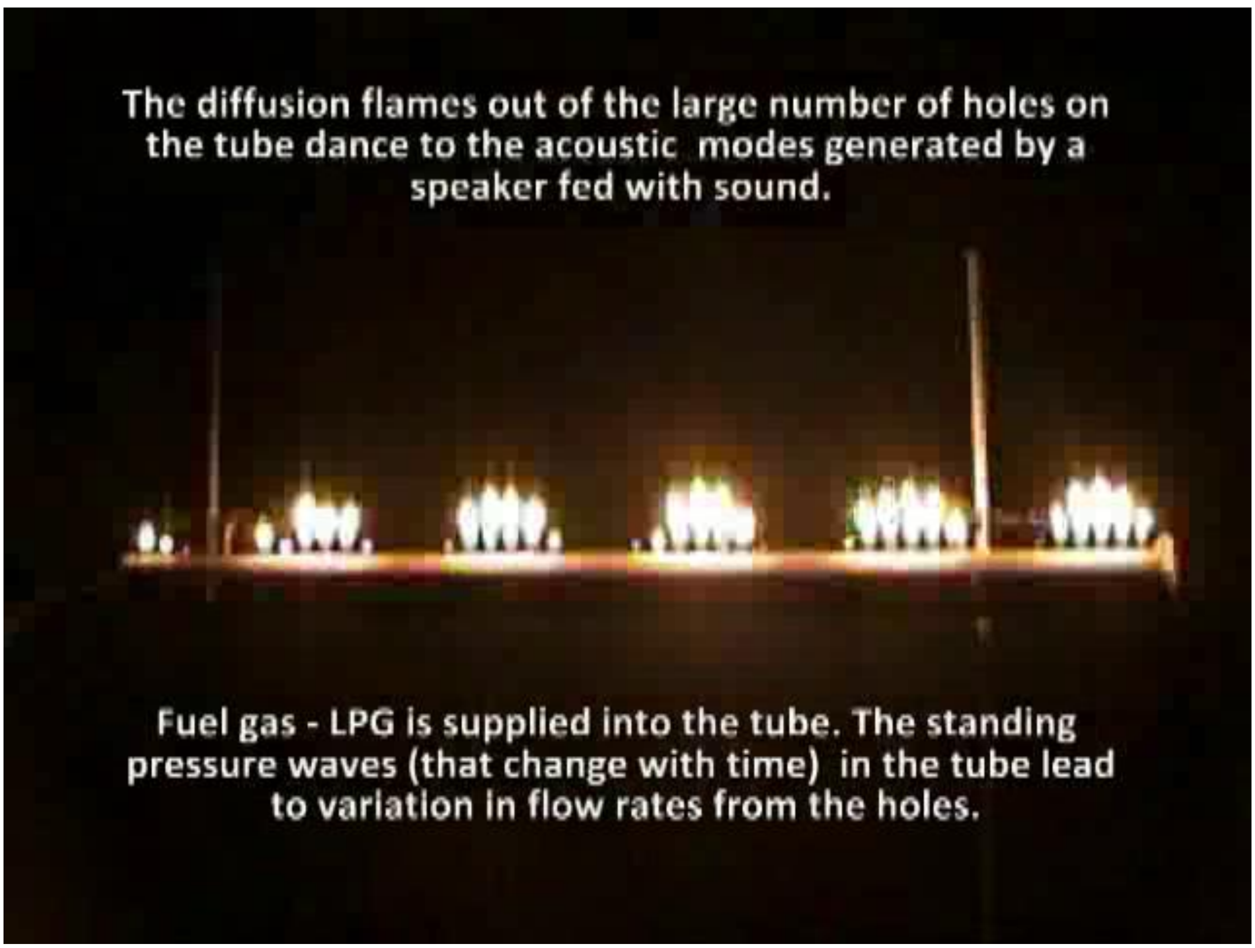
The thermo-acoustic interaction is governed by Rayleigh's criterion which states that the energy introduced into a fluctuating wave must be broadly in phase for the oscillation to amplify.

A few pieces of charcoal set on a wire-gauze at about quarter the height of a glass tube are brought to red hot condition with a Bunsen flame. When this flame is withdrawn, the tube stars singing at a frequency that can be simply calculated for the open tube as the acoustic speed divided by twice the tube length.

Bottle pulse combustion

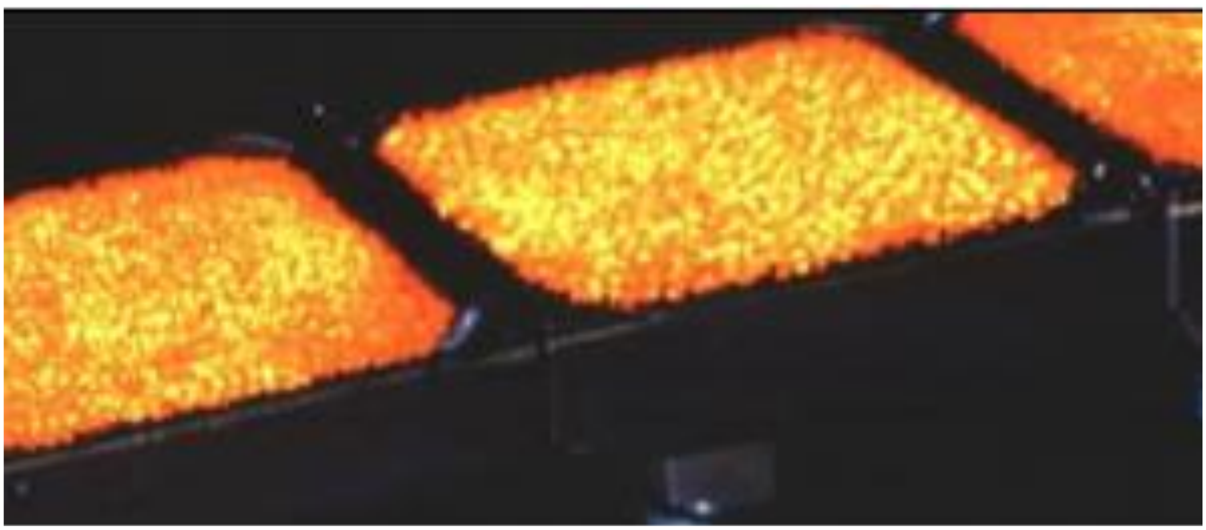
An example of unsteady combustion or pulse combustion can be seen in a bottle with a liquid fuel. When the bottle with the fuel is initially shaken, placed and lit at the top, combustion proceeds in an unsteady mode.

Rubens tube



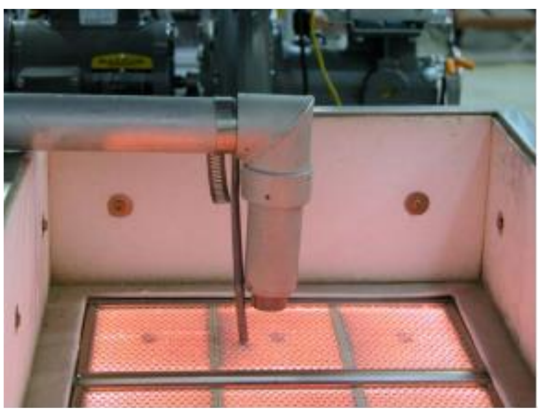
Rubens tube is an example of unsteady combustion. A long tube with a large number of tiny holes over the surface with sound introduced at one end, LPG at the other leads to standing waves that lead to different pressure drops and hence flows. This is what that leads to oscillating flames.

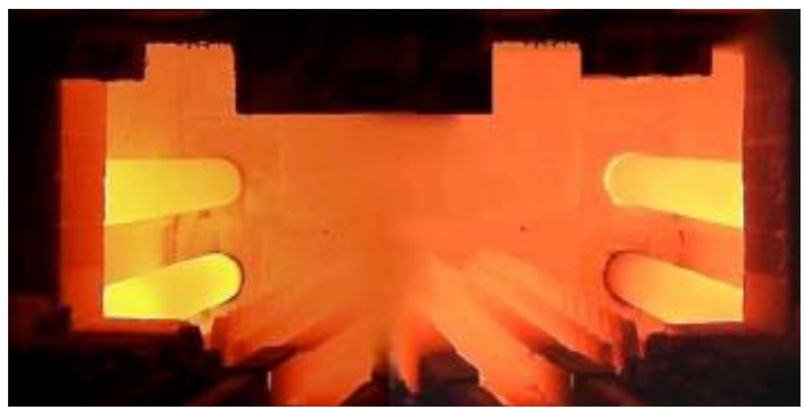
Gas based radiation burners



Gas based Thermal radiation burners used for paper drying, wood drying, paint curing, plastic thermo-forming, and food processing. In these burners, premixed fuel and air are designed to burn just around the surface – below or above. If the mixture flow rate is low, flash back will occur and if the flow rate is too large, flame may blow off. Optimum performance is when the flame is around the surface.

Radiant burners





Radiant burner under test – in operation at 1200 °C and surface at 1000 °C. Radiant tube burner designed to heat system which should not come in contact with combustion products or the flame either due to chemical reaction (steel) or because of finish as with porcelain products. The combustion process occurs with long diffusion flames with staged air injection inside the tubes and the outer part is of high quality alloys or ceramics.