Cool Flames and Autoignition: Thermal-Ignition Theory of Combustion Experimentally Validated in Microgravity

At temperatures as low as 120 °C**,** fuel-air mixtures react chemically and produce very weak flames called cool flames. Unlike conventional flames—which generate large amounts of heat, carbon dioxide, and water—cool flames generate very little heat (e.g., a temperature rise of only 10 °C), carbon dioxide, and water. At low temperatures, the fuel and oxygen molecules have little energy and therefore do not react vigorously. The reaction never proceeds to complete combustion; rather, the molecules break down and recombine to produce a variety of stable chemical compounds including alcohols, acids, peroxides, aldehydes, and carbon monoxide. The weak temperature rise is produced by the breaking and reforming of the chemical bonds.

Cool flames were accidentally discovered in 1817 by Sir Humphry Davy, who noticed that he did not burn his fingers and could not ignite a match in a cool flame. While cool flames were a curiosity at first, they gained widespread attention when Sir Davy noticed that they could spontaneously develop into hot conventional flames. Moreover, an external ignition source such as a spark, hot wire, or hot surface was unnecessary for ignition if the temperature, pressure, and mixture composition were within certain limits.

Understanding cool flames and autoignition is important for engineers and designers to mitigate potential combustion hazards. Cool flames are also responsible for engine knock—the undesirable, erratic, and noisy combustion process that occurs in low-octane fuels. Physically, the crankshaft rotates, the pistons compress the unburned fuel-air mixture, and the gases heat as they are compressed. If the rate at which the heat is liberated by the chemical reactions exceeds the rate at which the heat is lost through heat transport, the temperature of the gas increases and slow reactions ensue. As the temperature continues to increase, cool flames develop and the mixture autoignites. Note that cool flames and autoignitions are not always undesirable. Diesel engines, for example, rely on the compressed fuel-air mixture to autoignite so that the engine can operate without spark plugs.

The objective of this study at the NASA Glenn Research Center at Lewis Field is to hone our understanding of spontaneous chemical reactions and determine the various factors that influence when, where, and how cool flames and autoignitions develop. These factors include the molecular structure of the fuel, the pressure and temperature of the mixture, and the various ways in which heat can be lost—through conduction, convection, or radiation. Generally, radiation heat transfer is weak at low temperatures, and most of the heat is lost through convection or conduction.

Current mathematical models neglect convective heat transport because it introduces nonlinear complexities into the formulation. However, analyses that have been formulated to include conductive heat transport must be tested against experiments to confirm (or refute) their predictions.

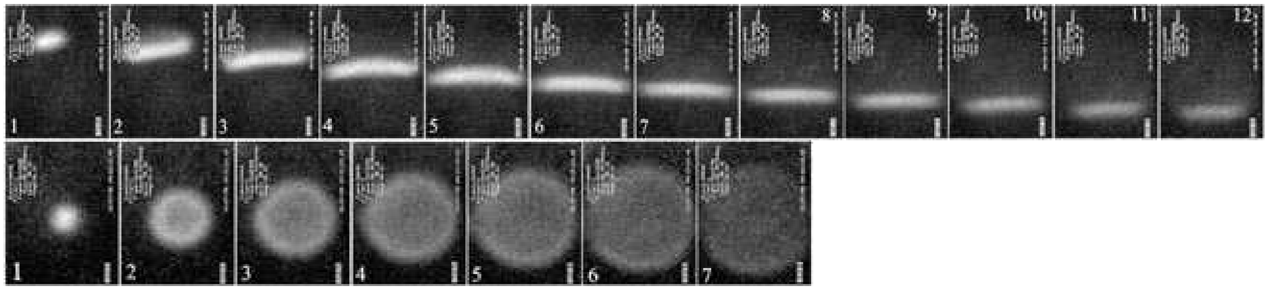
Unfortunately, performing such experiments on Earth is not simple. When the heat liberated by the chemical reactions locally heats the gas, it generates convection, since hot (less dense) gas rises and cold (more dense) gas falls. This self-generated convective flow then alters the transport of heat. In effect, it is a "Catch-22," since the heat liberated by the chemical reactions generates convection, but convection is difficult to incorporate into the mathematical formulation.

The best way to eliminate the effects of convection is to study these reactions at reduced gravity, where hot gas doesn't rise and cold gas doesn't fall. This is precisely why these reactions are currently being studied in NASA's reduced-gravity facilities (drop towers and aircraft) and are planned to be studied on space-based microgravity platforms.

During fiscal year 1999, experiments were conducted using a variety of fuels (hydrocarbons, carbon monoxide, hydrogen, and natural gas) mixed with air at different temperatures and pressures, both in the laboratory and aboard NASA's KC–135 reduced-gravity aircraft. The hardware and crew are shown in the photograph.

Cool flame experiment aboard NASA's KC–135 reduced-gravity aircraft.

It is readily observed that on Earth (1g), the heat generated during the early stages of the chemical reaction rises to the top of the vessel. When the temperature exceeds a critical value, a cool flame develops. This is shown in the top portion of the following figure. At reduced-gravity (10^{-2}g) aboard the KC–135, heat does not rise or fall but accumulates in the center of the flask. A spherically propagating cool flame ensues as shown in the bottom portion of this figure.



Premixture, 50% $n\text{-}C_4H_{10}$*-50%* O_2 *(in volume percent); 4-in. inner diameter spherical vessel; vessel temperature, 300 °C; initial pressure, 3.2 psia; elapsed time between adjacent frames, 1/30 sec. Top: 1g (Earth's gravity). Bottom:* $10^{-2}g$ *(reduced gravity).*

Interestingly, we also learned that cool flames and autoignitions do not occur at the same temperature and pressure at Earth's gravity and reduced gravity. Generally, they occur at lower temperatures and pressures in reduced-gravity environments, since the gas does not readily cool in the absence of buoyant convection. In other words, fuel-air mixtures that do not autoignite on Earth may ignite in reduced gravity, making a space-based atmosphere potentially more susceptible to autoignition.

Ongoing work in this area is actively being conducted at Glenn. Current plans include additional tests with the same fuels as well as with the commercial fuels used in aircraft and spacecraft.

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