

Fundamentals of Fire Suppression in Reduced Gravity Environments

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ABSTRACT

This paper discusses the unique aspects of fire suppression in reduced (micro- and Lunar/martian) gravity environments. It builds on a trade study conducted by the Fire Prevention Detection and Suppression group at the NASA Glenn Research Center that examined the efficacy of fire suppressants in reduced gravity. The first part of the present paper reviews the differences in flame characteristics between terrestrial and extraterrestrial fires and how these characteristics change the action of a fire suppressant. Special emphasis is placed on enriched oxygen ambient environments, a condition that will routinely exist on future spacecraft and extraterrestrial habitats. The most important difference between normal gravity and reduced gravity fires is the increase in the minimum suppressant concentration (for gaseous agents in a total flooding application) required to extinguish a fire in reduced gravity compared to normal gravity. The impact of this observation is that suppressant system design guidelines based on terrestrial standards will either not be adequate or will not offer the same factor of safety in reduced gravity. The paper discussion focusses on inert gas (most suitable for total flooding applications) and water mist systems (suitable for total flooding and streaming applications), with some results for chemically active systems (e.g. Halon 1301) included for reference. Finally, the paper presents recommendations on proposed tests and standards to evaluate candidate suppressant technologies.

INTRODUCTION

The Vision for Space Exploration calls for extending a human presence into space beyond low Earth orbit, returning to the Moon, and then to Mars and beyond. Achieving these goals will require many technological advances in life support, environmental monitoring, space suits for extravehicular activity, power generation and storage, food production, and waste management, to name a few. Because a rapid return to Earth is not an option on long duration missions outside of low-Earth orbit, the crew must have the equipment, systems, and procedures to safely deal with any realistic fire and its after-effects. The

first line of defense in a fire safety strategy is fire prevention through material selection and control. Experience in manned space flight, however, indicates that this control may, but will not necessarily, ensure that fires on spacecraft will not occur. Therefore, fire detection and suppression systems are still required*. Our understanding of the processes involved in microgravity fire suppression, particularly with regard to the practical technology for fire extinguishment, is very limited. In general, fire suppression in microgravity has only been investigated in small-scale experiments using relatively simple geometries.

This paper builds on a previous paper [1] that examined the efficacy of fire suppressants in reduced gravity and discusses the unique aspects of fire suppression in reduced (micro- and Lunar/martian) gravity environments. This paper focuses on the technical aspects of fire suppression, providing a rationale for the ranking presented in the previous paper. Like the previous paper, this paper focusses on the unique suppression environment of the CEV and future spacecraft and habitats; namely operation in reduced gravity and high oxygen.

CURRENT PRACTICES

The Shuttle and International Space Station (ISS) both have portable fire extinguishers for use by the crew. The Shuttle uses Halon 1301 as the suppressant in both fixed and portable fire extinguishing systems. Halon 1301 is a very effective fire suppressant. It is, however, destructive to stratospheric ozone, and its manufacture is banned by the Montreal Protocol of 1987. That fact, coupled with its negative interaction with the Environmental Closed Loop Life Support Systems (ECLSS) on the ISS make it unsuitable for use in the new Crew Exploration Vehicle (CEV).

Carbon dioxide is the current fire suppressant in the U.S. modules of the International Space Station (ISS) and its use is planned for the upcoming Japanese and ESA modules of the

*Russian Soyuz capsules have no dedicated fire suppression capability. This is a programmatic risk that U.S. vehicles have not accepted since the Mercury and Gemini programs.



ISS. The Russian modules on ISS use hand-held water-based foam extinguishers, similar to those used on the *Mir* Orbiting Station. Flight rules dictate that this water-based foam extinguisher, however, not be used on the U.S. modules because of fears of its interaction with the higher operating voltages of the U.S. modules.

The fire suppression techniques currently employed for spacecraft are based almost entirely on testing and practices in normal gravity. For instance the size of the ISS fire extinguisher is based on a National Fire Protection Association (NFPA) guideline that the extinguisher should reduce the oxygen concentration in an International Standard Payload Rack ($\approx 1.6 \text{ m}^3$) by 50 percent within 60 sec [2].

The reduced and microgravity environment aboard spacecraft creates fire scenarios that are dramatically different than those on earth. The fire suppression systems for the CEV and future spacecraft should be based on the unique hazards associated with the microgravity environment. Understanding and providing a rationale framework for the design of a spacecraft suppression system is one of the goals of the Fire Prevention, Detection and Suppression (FPDS) program at the NASA Glenn Research Center.

FUNDAMENTALS OF DIFFUSION FLAMES

There is a fundamental distinction in combustion research between premixed and non-premixed, or diffusion, flames [e.g., 3]. The fuel and oxidizer in a premixed flame form a well-stirred, homogeneous mixture through which the flame propagates. The speed (ν_0) at which the flame propagates through a premixed flame is approximately [3]:

$$\nu_0 \approx \left(\frac{1}{\rho_0} \right) \left(\frac{\lambda}{C_p} \mathcal{W} \right)^{\frac{1}{2}} \quad (1)$$

where ρ_0 is the unburned mixture density, C_p is the specific heat of the mixture and $\mathcal{W}$ is the chemical reaction rate (mass of reactants converted into products per unit volume per unit time). The chemical reaction rate is strongly dependent on, among other things, the ambient oxygen mole fraction (Y_o) [3].

$$\mathcal{W} \approx [Y_o] [Y_f] \exp \left(-\frac{E_a}{R_u T_{fl}} \right) \quad (2)$$

where Y_f is the fuel mole fraction, E_a is the activation energy, R_u the universal gas constant and T_{fl} the flame temperature. In air, flame spread rates are on the order of 100 - 250 cm/s for hydrogen and 30 - 60 cm/s for methane and will be much higher for the higher oxygen concentrations expected on the CEV (up to 0.34 mole fraction).

The presence of gaseous fuels in concentrations that will support flame propagation is extremely unlikely with strict controls and monitors. In the event a premixed flame were to ignite, the expressions and numbers above show that it would propagate across the CEV (diameter 15 ft) in less than 6 s (assuming

$\nu_0 = 80 \text{ cm/s}$). Detecting and extinguishing a fire on this order of time is very challenging, and requires extreme measures in the design of both the suppression system and the vehicle itself.

The other classification of flames, non-premixed or diffusion flames comprises nearly all practical fires. In diffusion flames, the fuel and oxidizer are separate and they mix and meet at the flame. Figure 1 shows a common diffusion flame, the candle. The fuel in this case is solid wax that gets heated by the flame, melts and moves up the wick by capillary action. The heat from the flame then vaporizes the liquid wax from the surface of the wick and it moves towards the flame front. Oxygen from the ambient moves towards the flame and in the flame zone, the fuel and oxidizer mix and react.

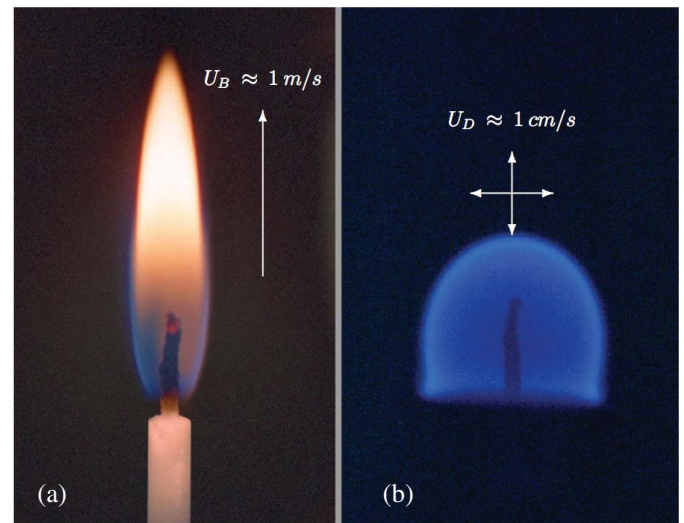


Figure 1: Candle flame images from normal gravity (a) and microgravity (b). The microgravity image is from the *Mir* OS. The candles and scaling are identical on both images. The only difference is the camera settings. The *Mir* candle flame required very long shutter times. The flame was nearly invisible to the naked eye [4].

In a diffusion flame, all of these processes must balance. The flame size, strength and position are determined by the fact that the fuel generation (from the heat feedback from the flame), the oxygen transport and heat loss from the flame balance such that the flame will sustain itself. Changing any one of these and the flame will seek a new equilibrium position.

Figure 2 shows a schematic representation of a flame and the relevant energy and mass transport mechanisms. Equation 2 is valid for the heat release from a diffusion flame. The goal of a suppressant is to drive the chemical reaction rate to zero. This can be done by reducing the oxygen concentration (Y_o), the fuel concentration (Y_f), the flame temperature (T_{fl}) or the activation energy (E_a). This equation also emphasizes the hazard posed by the a high oxygen ambient. Increasing oxygen both directly (through increasing Y_o) and indirectly (by increasing T_{fl}) increases the chemical reaction rate and thus rate of heat release.

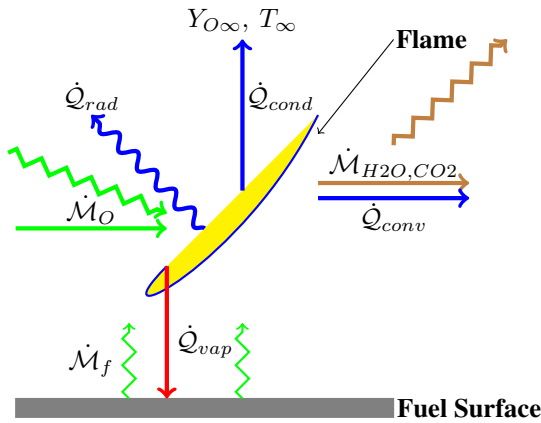


Figure 2: Schematic of flame showing the different energy and mass transport mechanisms. Oxygen is transported to the flame by convection and diffusion ($\dot{M}_O$) and combustion products away from the flame also by convection and diffusion ($\dot{M}_{H_2O,CO_2}$). The flame transfers energy to the fuel surface ($\dot{Q}_{vap}$) causing fuel vapor transport to the flame ($\dot{M}_f$). The flame loses energy by conduction ($\dot{Q}_{cond}$), convection ($\dot{Q}_{conv}$) and radiation ($\dot{Q}_{rad}$).

The heat feedback from the flame determines the melting and vaporization (solid fuel to liquid to gas) or pyrolysis (solid fuel to gas) of the fuel ($\dot{Q}_{vap}$) [5].

$$\dot{Q}_{vap} \sim \lambda_g A \left[\frac{T_{fl} - T_{(fl-fs)}}{L_{(fl-fs)}} \right] \quad (3)$$

where λ_g is the thermal conductivity of the gas between the flame (subscript fl) and the fuel surface (subscript fs), T is the temperature, A is the area of the flame or fuel surface and L a characteristic length. Energy is lost from the flame by conductive energy transport ($\dot{Q}_{cond}$), convective energy transport ($\dot{Q}_{conv}$) and radiant energy transport ($\dot{Q}_{rad}$) [5].

$$\dot{Q}_{cond} \sim \lambda_g A \left[\frac{T_{fl} - T_{\infty}}{L_{(fl-\infty)}} \right] \quad (4)$$

$$\dot{Q}_{conv} \sim hA (T_{fl} - T_{\infty}) \quad (5)$$

$$\dot{Q}_{rad} \sim \sigma A (T_{fl}^4 - T_{\infty}^4) \quad (6)$$

where in Eq. 4 the thermal conductivity is that of the gas between the flame and the ambient and the characteristic length scale is between the flame and the ambient. In Eq. 5, h is the convective heat transfer coefficient which is a strong function of the flow field and the thermophysical properties of the gas. In Eq. 6, σ is the Stefan-Boltzmann constant.

The last important phenomena determining diffusion flame characteristics is the transport of oxygen to the flame (and conversely combustion products away from the flame). This transport can occur via diffusion or convection. Mass diffusion is the mass transport analogy to conductive heat transport. In order to compare the magnitude of the transport mechanisms due to diffusion and convection, it is convenient to estimate a species diffusion velocity of species i ($\bar{V}_i$). This velocity is

$\bar{V}_i \approx [D_{ij} \Delta X_i / (X_i L)]$ where D_{ij} is the binary diffusion coefficient of species i (O_2 for a flame) in species j (N_2 for an air ambient), X_i is the concentration and L is a characteristic length in the flame. For the candle in Fig. 1(b), this expression yields a value on the order of 1 cm/s .

In the absence of gravity or forced convection, the mass transport occurs by diffusion alone, and the energy transport is via both conduction and radiation. The impact of removing this transport mechanism on the flame is significant (e.g. Fig. 1). There are two important features of diffusion-limited flames that merit mentioning. First, there is a common misconception that a flame will self-extinguish in a quiescent environment. The common question is whether a candle flame can exist in a purely quiescent, zero-gravity environment. The assertion that the candle flame will self-extinguish appears in Physics textbooks and the journal *Nature*[†][6]. **It is simply not true.** The experiments in Fig. 1 consisted of a single candle in the glove-box facility on the Mir Orbiting Station. Shortly after ignition, the flame became hemispherical and very dim. The flame changed slowly with time (primarily in response to the gradually decreasing oxygen in the sealed glovebox) and only extinguished when there was no more fuel. For the large diameter candles (with a corresponding large mass of wax), flame lifetimes were in excess of 45 minutes. Further, the experiments showed that after the flame extinguished (due to oxygen or fuel consumption), the wax continued to vaporize and condense creating a potentially flammable wax mist. Therefore, basing any fire suppression strategy on the fact that a microgravity flame will self-extinguish and is somehow inherently safe leads to a false sense of security.

Second, flame characteristics including, but not limited to, heat release rates, luminosity, flammability limits and particulate formation rates are all different for flames in a purely diffusive environment. Flammability limits, or the oxygen concentration below which a steady flame cannot exist, can be significantly lower. For example, [7, 8] showed that the minimum ambient oxygen mole fraction (in nitrogen) supporting steady combustion for a single droplet in a quiescent ambient is approximately 0.15 compared to approximately 0.19 in a normal gravity (buoyant flow) environment. This fact then means that a normal gravity suppression standard, while possibly (or not) sufficient, will not provide the same factor of safety.

INFLUENCE OF CONVECTION

For the microgravity candle flame in Fig. 1(b), the diffusion velocities are on the order of 1 cm/s . The species diffuse in the direction of the concentration gradient and since there is no preferred direction, the species diffuse with a degree of spherical symmetry[‡]. Therefore, any buoyant convective velocity or forced convective velocity on this order will have a

[†]Carleton and Weinberg state that "Indeed, diffusion flames will tend to become spherical and will eventually extinguish as a result of blanketing by their own products." [6]

[‡]The symmetry is violated near the wick. A droplet of fuel, however, will burn with a completely spherical flame in the absence of gravity.