Flame/Vortex Interactions

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Abstract

Microgravity combustion leverages a buoyant-free environment to study turbulent combustion via controlled flame/vortex interactions in a well-defined low-momentum flow. Differences in flow patterns caused by buoyant flow acceleration and entrainment may result in uncontrolled flow interactions and result in instabilities in low-momentum jet flames. This *topical paper* identifies three critical areas to study flame/vortex interactions, the first, on *flame structure and turbulent properties, s*econdly, on *soot formation and oxidation,* and lastly, on *spray flow combustion* characteristics.

Significance of Flame/Vortex Interactions

Vortices are found in many combustion devices, such as, combustors[1], internal combustion engines, and flames traveling in confined ducts [2] and interacting with bluff obstacles[3]. Vortices can be described as naturally or intentionally created, and may develop when a moving fluid encounters an abrupt discontinuity, that takes the form of a physical surface, interacting fluids, or a gradient. Vortices are observed via a change in temperature, velocity, pressure, and density in a fluid. Vortex structures are important because they may appear in propulsion engines, such as rockets or gas turbines [4–6], with the potential for causing instabilities [7,8] while also enhancing mixing and impacting flame stabilization. Besides the impact in engines, scientists also take advantage of vortex structures for process reactors. For example, in the area of advanced Supercritical Water oxidation reactors, where vertical flows are introduced as a control mechanism to stabilize hydrothermal flames and phase regimes[9]. Flame/vortex interactions not only govern turbulent combustion systems, but also assist in the mixing process between fuel and the oxidizer via turbulent transport by influencing the chemical process. There are many technology applications relying on vortical fluid physics as addressed above, however, these are not yet directly transferable to a reduced gravity environment. Therefore, fundamental understanding on vortex-flame interactions on earth, microgravity or partial gravity in Low Earth Orbit (LEO) are of a particular interest to NASA owing to its fascinating, but complex mixing combustion behavior with the stability/instability science that is inherited. Specifically, microgravity experiments can provide an experimental data base for development of sub-grid scale models which will be applicable to practical combustors and extrapolating conditions for modeling purposes. These limit conditions are particularly important for advanced combustion understanding, and therefore, the best numerical method is yet unclear with the absence of the buoyancy force.

Current State-of-the-Art and Knowledge Gaps

Fundamental understanding of flame-vortex interactions is essential as it relates to various aspects of turbulent combustion phenomena occurring in realistic applications. Specifically, the flame and vortex interaction can be seen as the flow transition from laminar to turbulent conditions, with higher power demands which affect flame stability and may lead to unwanted local extinction. Practical combustion and propulsion applications operate at high pressure and Reynolds number, making experiments and simulations challenging (e.g. due to vortical structures of various sizes, shapes, and orientation, limited spatial-temporal data acquisition, and visualization techniques) to adequately represent a system. For these crucial reasons, vortex-flame/interactions have been widely researched on earth experimentally and numerically in both pre-mixed and non-premixed configurations. These studies have focused on vortices centered on flames, jet flames [10], head-on collision between a vortex and a double or single flame [11], and a burning ring [12]. Specific characteristics were observed, such as, differences in ignition, extinction, flickering stability and frequency[13,14], flame roll-up[15], Lewis number effects [16], and detailed chemistry effects [17]. Experimental studies are always incorporated with numerical comparisons (or analytical solutions), for an understanding on the effects from vortex-flame/interaction on strain, stretch, and curvature across various configurations (e.g. jet, premixed, and non-premixed flames) [18,19] . For example, the study by Renard et al. [18] reported that strain rate lengthens the flame front, increases the heat release rate, and could cause local extinction in a flame.

Theoretical simulations involving vortices are restricted to simple geometries, and often they are not representative of the practical application. Simulations are computationally expensive and limit our understanding by simplifying a geometry or the flow behavior. Combustion modeling for turbulent flows commonly use the Navier-Stokes equations and require the use of direct numerical simulations (DNS) for higher precision in predicting all scales of the fluid dynamics phenomenon. Nonetheless, DNS typically requires that the grid spacing be smaller than the smallest turbulent length scale, and so for realistic Reynolds number (Re) conditions this results in oversimplifying three dimensional problems to two-dimensional ones, in order to reduce computational time. DNS studies have shown differences in the production and consumption rates for specific gases and have been reported to vary between the selection of detailed and simple reaction mechanisms[20].

Large-eddy simulations (LES) at high Re are generally carried out for modeling practical combustors where the flow fields are highly turbulent with very high characteristic Re, and are capable of capturing vorticity characteristics (e.g. generation, development, and formation). The large range of turbulent scales present in such flows (the smallest scales ~ $Re^{-3/4}$) makes LES models attractive for solving larger scales, while the smaller sub-grid scales are modeled by various correlations. For LES at high Re, the generally attendant large Froude numbers make buoyancy effects negligible, except for the largest length scales of the flow particularly for near limit (lean) flames where flame speeds become small and buoyant velocities can become important. These correlations ultimately assume some type of relationship with the large-scale behavior. LES neglects the buoyant terms for the smaller scales of vortices on earth, as well as the level of thermal expansion influence directly onto the flame, which might further change the vortices. As experiments for buoyancy effects are negligible at the largest scales for modeling yet the smallest scales are measurable while still maintaining Re >>1 (the condition for turbulent flows) are possible in a microgravity environment. Significantly, microgravity experiments can provide a data base for development of sub-grid scale models which will be applicable to practical combustors.

Need for Microgravity

Current laminar flow flame studies conducted on the International Space Station (ISS) and corresponding theoretical simulations established a baseline knowledge of simple microgravity gaseous combustion phenomena in the past decade. Studies in microgravity involving higher velocities especially between flame and vortices are limited, with some preliminary short period exploration conducted by NASA Glenn Research Center via drop tests focused on 2.2 and 5.2 second drop [21–26] studies involving vortex/flame interactions with a single experiment on turbulent gas-jet diffusion flames on board the Space Shuttle.

Vortex-flame interactions in microgravity remain momentum dominated under laminar as well as moderately turbulent conditions. The latter conditions while still providing the practically meaningful limit of Re >>1 enable experimental resolution of the entire turbulence spectrum without buoyant influence, commonly seen in 1-g laboratory scale flames, which if present may not be feasible. In fluid dynamics, a laminar flow with enhanced velocity is in a transitioning stage toward turbulent flow and then eventually considered fully turbulent flow. Similarly, the current knowledge for combustion is needed to grasp the transition (from laminar flow) in order to further understand the two-way coupling between the flame and flow with vortices in turbulent combustion.

In addition, effects of buoyancy in pulsed laminar and turbulent jet diffusion flames have been studied by performing experiments in both microgravity and normal gravity conditions [13,21,27]. However, these experiments have suffered from limited microgravity duration (which prohibit statistical inferences) and/or limited resolution of time and length scales in diagnostic measurements. With long duration microgravity (e.g., on the ISS) and with currently improved compact packaging of diagnostic hardware the potential for achieving far reaching insights has never been greater. Thus, recommendations will be provided in a later section on recommended diagnostic hardware and facility capabilities for advancing our understanding in flame/vortex interactions. The most critical research areas in the subject of flame/vortex interactions that will have a significant impact following study in microgravity are:

1. *Fundamental Science of Flame/Vortex Interactions at Low and High-Pressure (Experimental and Numerical)*

Fundamental studies of vortices are essential as they relate to various aspects of combustion phenomena, in turbulent flames, flame stability, and local extinction.

- Develop modeling capabilities and apply new experimental methodologies for unit problems that cover practical turbulent applications to validate predictive tools for turbulent properties (such as velocity and temperature) for ranges of characteristic length and time scales under buoyant and non-buoyant conditions
- Observe differences in flame structure (e.g., reaction zone broadening, temperature, species, etc.), flame length, and the flow interaction between the unsteady velocity field and the reaction of a turbulent combustion process.
- Understand when buoyancy effects could be ignored across experimental configurations and establish criteria based on quantifiable threshold levels. Characterize the performance in models and identify the strengths and limitations.

Microgravity studies will provide benchmark data that will enable improvements to turbulent combustion models by isolating gravitational effects, and specifically will:

- Expand existing knowledge on flame/vortex interactions in premixed and non-premixed flame conditions, and in burner configurations from least spatial dependence (e.g. a channel flow propagation) to axisymmetric (e.g. a concentric jet burner).
- Extend the flame/vortex interaction combustion studies to conditions from ambient up to supercritical pressures on existing experimental configurations.
- Examine turbulent flame control with novel concepts in configurations where buoyant flows don’t interfere with interpretation of experimental results.
- Characterizing impact of pressure on vortex-interactions during combustion. For instance, electric field effects on flames correlate with the thermal density, and electric fields can simulate pressure effects, as well as simulating various gravity[28,29] environments and vortex conditions[30] in flame systems.
- Expand the computational capability to simulate turbulent flows for a wide range of time and length scales. Specifically, to translate the knowledge gained from experiments to develop optimized

strategies for smart prediction to simulate a vortex/flame interaction behavior by e.g., machine learning or intelligent adaptive grids.
- Improve simulations to better represent a complex three-dimensional unsteady flow by anchoring on experimental studies.

2. *Soot Formation and Reduction*

Soot formation and reduction via vortex interactions with flames in microgravity will provide insight into the mechanisms of soot, including inception, growth, agglomeration, and oxidation stages. Previous experimental and numerical soot work [31–35] in 0, 0.3, and 1-g environments interacting with vortices have shown differences in soot concentration levels in flame regions of lower strain and along the periphery of a reacting vortex rings, whereas no soot was found inside the reacting vortex ring. Soot formation studies [36,37] in practical applications have widely focused on the negative impact to the environment and health. Generally, the presence of soot in flames results in an increase of radiative heat losses to the surrounding, which can affect the combustion performance, by reducing the effective heat of combustion as some of the carbon that is locked up in particulate matter and since radiation losses significantly reduce local flame temperatures. Gases trapped in vortexes typically experience longer residence times, and if the thermochemical conditions are suitable for soot growth, then production is enhanced. For example, the use of jet-type turbulent flames to study soot formation would be useful to understand basic turbulent-soot chemistry interaction. However, due to slow time scales associated with soot formation, the region where peak production of particles is found is often where turbulence has already decayed or the flow decelerated, such that gravity becomes important. Such effects can be isolated in microgravity environments [38]. Studying soot formation with vortex interactions in microgravity flames will provide qualitative and quantitative information on:

- Understanding the impact of soot on the performance in engine processes, for example, in propulsion and any forthcoming clean combustion technologies (e.g., in rocket, gas-turbine, diesel, or other automobile engines) and across a wide range of operating conditions/turbulent scales (e.g., varying oxidizer and conditions exceeding subcritical to supercritical pressures of fuels).
- Quantification of soot concentrations in turbulent combustion applications to allow investigators to extrapolate existing models [39] (e.g. empirical, semi-empirical, and detailed) to better address complex fuels under turbulent conditions.
- Characterization of new fuel blends, such as, burning characteristics and fuel properties linked to future use in new technologies for defense and industrial applications.

3. *Spray Flame/Vortex Interaction*

Spray characteristics are the most important aspects related to the power sector, such as, gas turbines, internal combustion engines, diesel and rocket engines, most of which are operated by fossil fuels. The utilization of high energy density liquid fuels and interactions with vortices are critical for understanding spray combustion atomization characteristics to assist in the understanding of combustion performance for most earth (transportation) or going into LEO applications, for e.g., design of rocket engine injectors. Spray combustion characteristics are critical for the performance of the abovementioned applications and are highly dependent on the conditions (temperature, pressure, flow velocity, fuel properties). Microgravity research studies involving the interactions between the liquid fuel spray flame and a vortex generated flow from these applications can help identify the mixing behavior as well as limitations. Microgravity research will focus on:

- Spray flow characterization to understand atomization, evaporation, and mixing of liquid and vapor fuel concentrations, and interaction of droplets and turbulent flow.
- Ignition characterization to understand fuel decomposition/radical formation and temperature regimes.
- Understanding of spray combustion characteristics, such as, the structure in the combustion regions and transitions from self-ignition.
- Limited work has been observed experimentally for spray flame combustion in a turbulence gaseous configurations [40], nonetheless in microgravity conditions. Available three-dimensional investigations with DNS for spray flame models have shown a co-existing reaction zone that is premixed and with a diffusive behavior, thus, showing that spray flames have flamelet regimes.

Recommendations

Previous microgravity studies in flame/vortex interactions that were conducted two decades ago suffered from a lack of comprehensive experimental diagnostic capabilities due to instrumentation limitations and challenges (time and volume of space) associated with the drop tower and spacecraft environments. Therefore, new ground (e.g., parabolic flights and drop facilities) and space-based (e.g., ISS) facilities will provide a critical foundation on which future research will improve simulations by reducing the reliance on assumptions, such as the frequent oversimplification of complex geometries or the use of reduced chemistry schemes that currently lead to result uncertainty. The research goals presented in this topical paper could be achieved through use and modernization of existing hardware and ground based facilities, a few recommendations that would allow the study of flame/vortex interaction are:

- High-speed and compact integrated size cameras, sensors, and data acquisition systems to provide quality flame images has the potential to achieve the necessary spatial-temporal resolved data (temperature and major species) for turbulent flame studies. Specific diagnostics may include compact Raman probes, which facilitates temperature and species measurements. In addition, infrared imaging and radiometers permit visualization of extinction behavior, soot formation from flame luminosity, and chemiluminescence measurements from electronically excited species [41,42] to capture specific characteristics, such as extinction and predicting heat release.
- Besides utilizing and upgrading the existing technologies mentioned in previous bullet points, schlieren imaging (previously tested for laminar flames in the 2-second drop test) can bring tremendous benefits for illustrating thermal gradients [43] in the zero-g and further revealing heat release during flame-vortex interaction[44] .
- Other relatively complex techniques to consider for ground studies are planar laser induced fluorescence (PLIF), for species measurement [27], and particle-image velocity (PIV) in order to visualize the vortex flow field to determine the strain field acting on a flame.
- Improvements to facilities such as the Combustion Integrated Rack (CIR) on board of the ISS and potentially the associated Advanced Combustion via Microgravity Experiments (ACME) hardware. Current flexibility in the various burners available, such as the gas-jet burner and co-flow, may facilitate introducing vortices to the flow by performing minor adjustments or provide the guidance to develop a new CIR insert.

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