Abstract: Simulating the Physics and Chemistry of Swirling Flames - from Fire Whirls to the Blue Whirl

The numerical simulations proposed here are to model and study fire whirls, which are large fire tornados that occur naturally and are an integral part of wild fires. Fire whirls, which can also be created in laboratory experiments, have been notoriously difficult to simulate and understand, and are even more difficult to control. Recent laboratory experiments [1] have discovered a new flame, the blue whirl, that evolves naturally from a fire whirl. The blue whirl, which is shown in Figure 1, appears as a stable, quiet, strongly swirling hydrocarbon flame sitting on a water surface. The blue burning state, which implies nearly soot-free combustion, indicates its potential of contributing to highly efficient, low-emission combustion with no harm to humans or to the natural environment. The existence of the blue whirl was first reported in PNAS in August 2016 [1], which described the experiments and how the blue whirl evolves from a fire whirl that evolves from a pool fire created by a small amount of liquid fuel poured onto a water base (Figure 2). Subsequently more experimental work was reported in [2, 3], which showed that this state of burning can evolve from essentially any liquid hydrocarbon fuel and even gaseous fuels with different surface conditions (for example, a water surface, a flat metallic surface, or over a porous ceramic-fiber wick). The discovery of the blue whirl was made under National Science Foundation Early-concept Grants for Exploratory Research (EAGER) funding. Currently there are ongoing experimental research studies at the University of Maryland, University of California, San Diego, Texas A & M University, and the Army Research Laboratory Adelphi. To date, there has been little-to-no successful theory or modeling of the blue whirl flame or the potentially more difficult problem of the blue whirl. The objective of proposed numerical simulations is to determine the flame structure and the dynamics of the blue whirl and to answer the more difficult questions of how the transition (from fire whirl to blue whirl) occurs, how to get to the blue whirl state without going through a very dangerous fire whirl or even a pool fire, and whether the blue whirl can scale to large sizes. These questions are not easily answered in experiments, and probably can be addressed by simulations. Our specific aims are

1. Simulate a fire whirl using a configuration close to the experiment. Ensure that we are reproducing the known features of fire whirls, at least qualitatively.
2. Conduct a parametric study of swirling flames starting with controlling parameters close to the measurements from experiments and then varying parameters to reproduce the blue whirl as closely as possible.
3. Address the issue of how the blue whirl self-regulates the amount of air it entrains. Determine the strength of the fire whirl vortex (measured in terms of tangential velocity or momentum) needed to create a blue whirl.

These simulations will be critical for understanding how the blue whirl can be formed and maintained, and whether it can serve as a new way of burning in combustors or engines for clean and efficient combustion.

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This work will also serve to educate two graduate students in computational methods and combustion applications. The PI's students Joseph Chung and Xiao Zhang are both finishing their PhD's this year. The proposed simulations are central to their theses.