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From fire whirls to blue whirls and combustion with reduced pollution

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Fire whirls are powerful, spinning disasters for people and surroundings when they occur in large urban and wildland fires. Whereas fire whirls have been studied for fire-safety applications, previous research has yet to harness their potential burning efficiency for enhanced combustion. This article presents laboratory studies of fire whirls initiated as pool fires, but where the fuel sits on a water surface, suggesting the idea of exploiting the high efficiency of fire whirls for oil-spill remediation. We show the transition from a pool fire, to a fire whirl, and then to a previously unobserved state, a "blue whirl." A blue whirl is smaller, very stable, and burns completely blue as a hydrocarbon flame, indicating soot-free burning. The combination of fast mixing, intense swirl, and the water–surface boundary creates the conditions leading to nearly soot-free combustion. With the worldwide need to reduce emissions from both wanted and unwanted combustion, discovery of this state points to possible new pathways for reduced-emission combustion and fuel-spill cleanup. Because current methods to generate a stable vortex are difficult, we also propose that the blue whirl may serve as a research platform for fundamental studies of vortices and vortex breakdown in fluid mechanics.

fire whirl | blue whirl | vortex breakdown | combustion | soot free

Fire tornadoes, fire devils, and fire twisters are popular and terrifying common names for fire whirls. These intense swirling fires arise spontaneously with the "right" combination of wind and fire. On the large scale, they appear very similar to atmospheric phenomena such as tornadoes and dust devils (1–4). Fire whirls form in large urban and wildland fires when winds interact with obstacles or natural features in the terrain (2, 4–6) and produce large vortices that intensify as they interact with a local fire. When fire whirls arise naturally in large fires, they present a strong, essentially uncontrollable threat to life, property, and surrounding environments. Due to the strong vertical winds they generate, they can lift and toss burning debris, which can then travel kilometers to spread the fire (5, 7).

A pool fire is a diffusion flame that burns above a horizontal pool of vaporizing hydrocarbon fuel. Pool fires can occur on any flat surface on which fuel is spread, including in situ burning of oil spills (8). Fire whirls can evolve from relatively small fires under proper wind or topographic conditions (1, 2, 5–7, 9). Smaller-scale laboratory experiments have shown that a relatively quiescent pool fire may transform into a fire whirl (2, 7, 10–14), and that the temperature and burning efficiency are higher than those of the initial fire (2, 10, 15). This transition occurs through a pattern of events in which the fire first leans to one side, begins to rotate, and then stretches upward (lengthens) before eventually becoming a fire whirl (7, 10, 14). Flame heights from wildfires, pool fires, and fire whirls range from centimeters to kilometers (1, 12, 14, 16, 17). Smaller-scale experiments may be performed in laboratories so that their properties and behaviors can be studied (2, 4, 6, 7, 13, 18, 19).

Blue Fire Whirl over Water

For the purpose of improving fuel-spill remediation, we began a study of swirling flames ignited and burning on water, as opposed to the usual solid ground. A major, obvious difference between this and prior studies of pool fires and fire whirls on solid surfaces is the physical complexity of the boundary layer between the water, evaporating fuel, and flame. Fig. 1 shows the three states of burning that we observe on water. Fig. 1 *A* and *B* shows the usual pool fire and fire whirl, respectively, created here when winds enter the chamber tangentially. Fig. 1*C* shows the blue whirl, which evolves from the yellow fire whirl and is shown and discussed here.

The experimental setup consists of two half-cylinders and a cylindrical stainless steel pan full of water. A liquid fuel, n-heptane, is poured on the surface of quiescent water at the center of the pan and is then ignited by a small igniter. The two quartz half-cylinders are suspended over the pan. Offsetting the half-cylinders creates two vertical slits that allow air to be entrained tangentially to the flame region, a method often used to create fire whirls for laboratory study (18). To sustain the blue whirl for further observation and study, we introduced a small copper tube under the water to pump heptane to the center region of the water surface at a fixed flow rate. When the fuel injection rate was set between 0.8 and 1.2 mL/min, and the size of the vertical gaps was 1.8–3.0 cm, the blue whirl could be sustained as long as fuel was supplied. (The longest time sustained was just under 8 min, the time when the pump was stopped.) When the fuel supply was cut off, the blue whirl died out quietly as a blue whirl with ever-decreasing size, all of which indicates that it could, in theory, be sustained for longer times if fuel were made available.

Significance

The growing worldwide demand to reduce emissions from combustion calls for development of alternative technologies for high-efficiency and low-emission combustion. Whereas fire whirls are known for their intense and disastrous threat to life and surrounding environments, their swirl properties and thus higher combustion efficiency imply an unexploited potential for highly efficient, low-emission combustion. In studying fire whirls over water for oil-spill cleanup, we discovered a beautiful, swirling flame phenomenon, the "blue whirl," which evolves from a fire whirl and burns with nearly soot-free combustion. Understanding and control of the blue whirl and its predecessor, the fire whirl, will suggest new ways for fuel-spill remediation, reduced-pollution combustion, and fluid mechanics research.
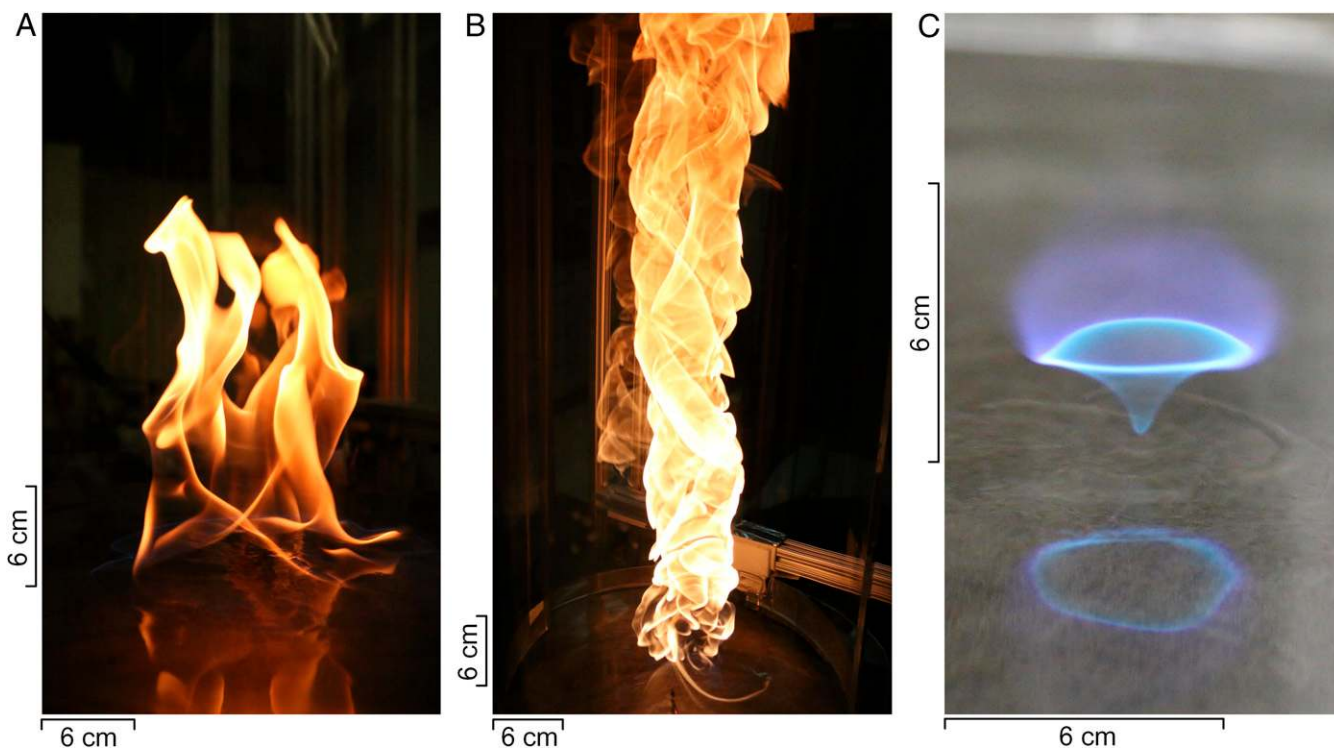
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Fig. 1. Evolution from a pool fire to a blue whirl over water in a swirl generator. (*A*) Pool fire forms following ignition. (*B*) Canonical fire whirl develops subsequent to the pool fire. (*C*) Previously unobserved laminar blue whirl evolves from the yellow fire whirl. The vertical scale marked on the side of each image starts at the water surface.

After ignition, a small, chaotic pool fire forms (Fig. 1*A*). As cold entrained air is drawn into the chamber, the fire creates a strong vertical flow. Initially, the pool fire tilts and meanders (Movie S1), as reported previously (7, 10, 14), but then a canonical fire whirl, over 60 cm high, forms at the center of the apparatus (Fig. 1*B*). As with fire whirls on solid surfaces, this fire whirl on water burns much more vigorously than the initial pool fire. The vortex motions are strong, the fire whirl is taller, and the temperature is higher than in a pool fire. Then, unexpectedly, the fire whirl continues to evolve to a different, unexpected fire structure (Fig. 1*C*): a small, intensely whirling blue flame (Movies S1 and S2).

Whereas the pool fire and the fire whirl are turbulent, the blue whirl shows no visible or aural signs of turbulence. A stable blue whirl is very quiet. The rotation was generally clockwise, consistent with the direction of air inflow from the gaps in the apparatus. Throughout its lifetime, the blue whirl generally revolves clockwise in the center region of the container at an angular speed within 6.3 rad/s.

Structure of the Blue Whirl

Fig. 2 shows a front view of the structure of a blue whirl. This structure consists of two main regions: the bright-blue spinning flame at the base and a faint conical violet flame sitting above and (possibly) partly in the central cup. The lower blue region appears more stable and ~2 cm high. The height of the visible violet region varies from 2 to 6 cm. Thus, the total height of the blue whirl was 4–8 cm, much shorter than the yellow fire whirl (over 60 cm) or pool fire (typically around 25 cm for this system). Near the fuel surface, the blue whirl tapers to a small rounded bottom. Above the bottom point, the blue whirl spreads out as it moves upward and resembles a spinning top. There is often a gap between the water and the bottom of the blue whirl. The top of the blue whirl ends sharply, although there is a hazy violet flame above it. At the end of burning, the blue whirl decreases in height and diameter and dies out calmly and smoothly (Movie S1). Attempts

to relight residual fuel that might be on the water surface do not produce any flames.

Transitions Between Yellow and Blue Whirls

Once the yellow fire whirl has formed and burned for a time, it evolves into a transitional state with a diameter and height that fluctuate, but generally decrease (Movie S1). Eventually it forms a smaller "transitional whirl," which appears unstable and "dances around" on the surface. There is a blue section at the base and a yellow flame that seems to grow out of this base, so that the blue whirl looks like a cup holding a yellow flame. A photograph of this transition state is shown in Fig. 3. After this, the yellow flame dies out, leaving only a blue whirl.

During the lifetime of the blue whirl, it transitions several times from the short-lived transitional whirl and then back to the more stable blue whirl (Fig. 4 and Movies S1 and S2). In the transition process, the upper region is replaced by a yellow flame, as shown in Fig. 4 *C–O*. Then, a blue cup forms again and holds the yellow flame in its center (Fig. 4 *P* and *Q*). Subsequently, the yellow flame spirally shrinks in the blue cup and disappears in the center region of the blue whirl (Fig. 4 *R–Y*), leaving a fully recovered blue whirl. As this is happening, a yellow spiral flame is enclosed in an envelope composed of a blue whirl and a secondary violet, conical flame (Fig. 4 *R–V*).

Understanding the Physics of the Blue Whirl

Vortex-breakdown phenomena, which have been studied extensively in fluid dynamics [see, e.g., reviews in refs. 20–22 and underpinning studies, such as by Taylor (23)], can be defined as a collection of properties and dynamics of a column of fluid (gas or liquid) subjected to various swirl intensities. These studies focus especially on metastable states that evolve as a result of the formation of stagnation points and recirculation regions. These phenomena are often studied confined in tubes in the laboratory, as well as by theory and simulations (e.g., refs. 20–22); however,
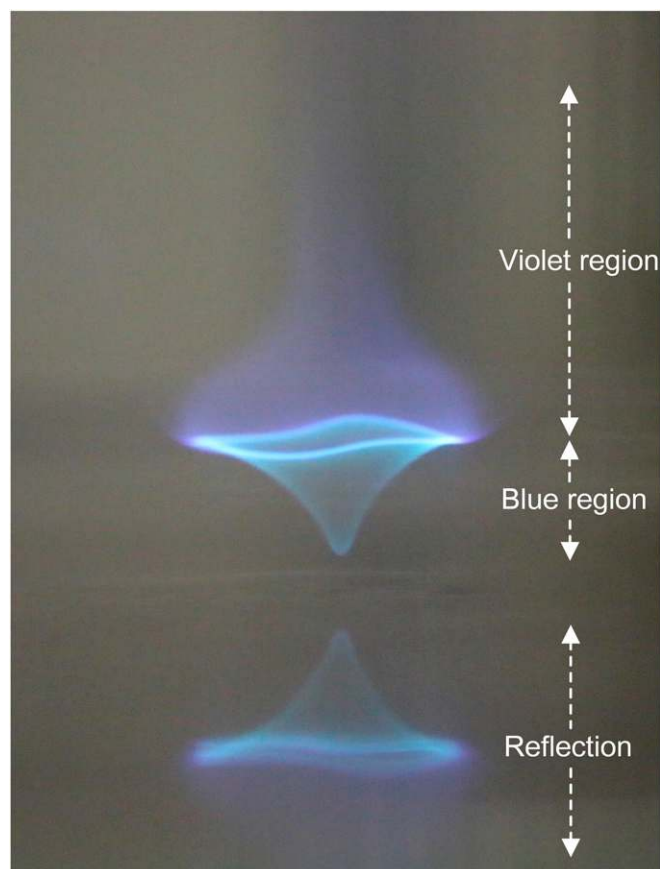
Fig. 2. Front view of structure of a blue whirl generated over water. The structure mainly consists of a blue region and a violet region. A reflection of the blue whirl in the water can be seen in the lower part of the image.

enough oxygen present for complete combustion, and therefore suggests a premixed flame. Previous work has shown that fast mixing, which occurs in certain coflowing or opposed-jet diffusion flames, can create soot-free, blue flames (30–32). The explanation was that the fluid dynamics around the flame helped limit soot precursors and soot in fuel-rich regions, so that complete oxidation occurred in fuel-lean regions (31–33). Similar processes occurring in recirculation zones inside the blue whirl could limit the soot formation here.

Furthermore, we speculate that the boundary conditions, that is, the existence of an air–water–fuel boundary layer instead of a fuel–air boundary on a solid surface, plays an important role for the transition to a blue whirl. For a fire whirl on a solid surface, there is a flame vortex tube that ends on the solid surface. On water, the flame appears to sit above the surface and even generates vortical motions in and on the water. There is likely to be a layer of evaporated fuel between the bottom of the blue whirl and the water, possibly creating a premixed region at the base. On the other hand, flow rotation intensifies air entrainment and causes strong inflow of air near the boundary layer in vortex phenomena (2, 3, 7, 10), which could allow reactants to

they have also appeared naturally in unconfined scenarios, such as tornadoes (24). Two of the most important states of vortex breakdown are the spiral and the bubble modes. As the swirl strength in the spiral mode increases, there may be a transition to a bubble mode, and there may also be transitions back and forth occurring among modes. Vortex breakdown is fundamental to swirl combustion, a spiral mode that operates so efficiently because of turbulent mixing and the recirculation zones that result in the increased residence times required for favorable combustion properties (25–27).

The fluid-dynamic starting point for understanding the blue whirl is to make a visually based, as yet qualitative analogy. Fire whirls appear to be versions of a spiral mode. The lower blue region of the blue whirl appears to be the lower portion of a bubble mode, with the upper portion of the bubble completed by the blue whirl's purple cap. Such a configuration occurring naturally with combustion, to the best knowledge of the authors, has not been observed before. The blue whirl also has a shape similar to that seen in tornadoes (24), and so it may correspond to a reactive bubble mode. We therefore postulate that the blue-whirl bubble evolves when the traditional yellow fire whirl, existing in a spiral-like mode, intensifies naturally. This is a starting point for explaining some of the transition process observed (Fig. 4).

The yellow color of hydrocarbon diffusion flames, such as pool fires or fire whirls, is due to blackbody emissions by radiating soot particles. Soot forms when there is not enough oxygen present to burn the fuel completely. The blue and violet colors are due to chemiluminescence of excited species such as C_2, CH, and OH radicals (28, 29). Blue in the whirl indicates that there is

Fig. 3. Transitioning whirl during the evolution process from a yellow fire whirl to a blue whirl. The height of this structure is about 15 cm. A cup-like blue whirling flame on water holds a yellow whirling flame.
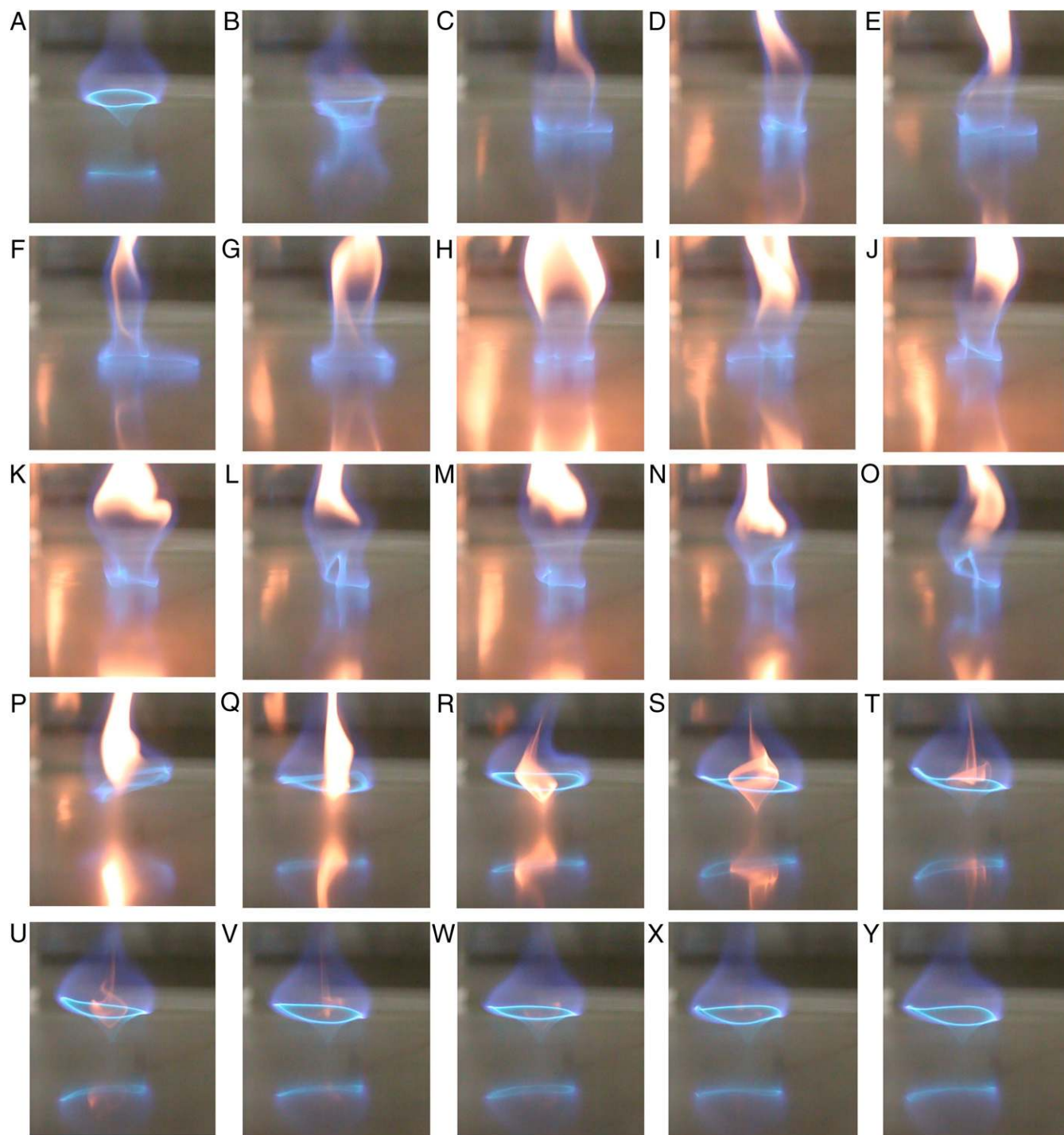
Fig. 4. Successive frames showing transition between a laminar blue whirl and a yellow whirl taken from a high-speed video. (*A*) Blue whirl. (*B*) Collapse of the blue whirl just before it transitions to a yellow fire. (*C–O*) Transitional yellow fire with a blue base. (*P–X*) Transitional blue whirl holding a yellow whirl in its center. (*Y*) Fully recovered blue whirl. The entire transition (blue whirl → yellow whirl → blue whirl) takes approximately 2 s. Inside the yellow center of the blue whirl, there appears to be a rotational core that fades as the whirl becomes stabilized over the fuel and a steady regime commences (*R–U*).

mix quickly above the fuel surface. This would have the general form of a triple flame (34), a small premixed flame connected to a diffusion flame. This may also result in higher temperatures and thus increased burning efficiencies.

Fuel rotation induced by the spinning helps the blue whirl stay centered in the tank. The strong rotation lowers the pressure in the center of the vortex, thus keeping the fuel slick from spreading as it does in pool fires. This helps the blue whirl to burn for extended periods, sometimes removing any visible residual fuel slick. This may be useful for in situ burning, because an oil slick must be maintained with a critical thickness or the fire will burn out (35).

In conclusion, experiments have discovered a flame phenomenon, the blue whirl, which shows a distinct flame structure and reduced soot emissions compared with both traditional pool fires and fire whirls. These changes are thought to occur through a combination of a vortex breakdown transition, in which the flow
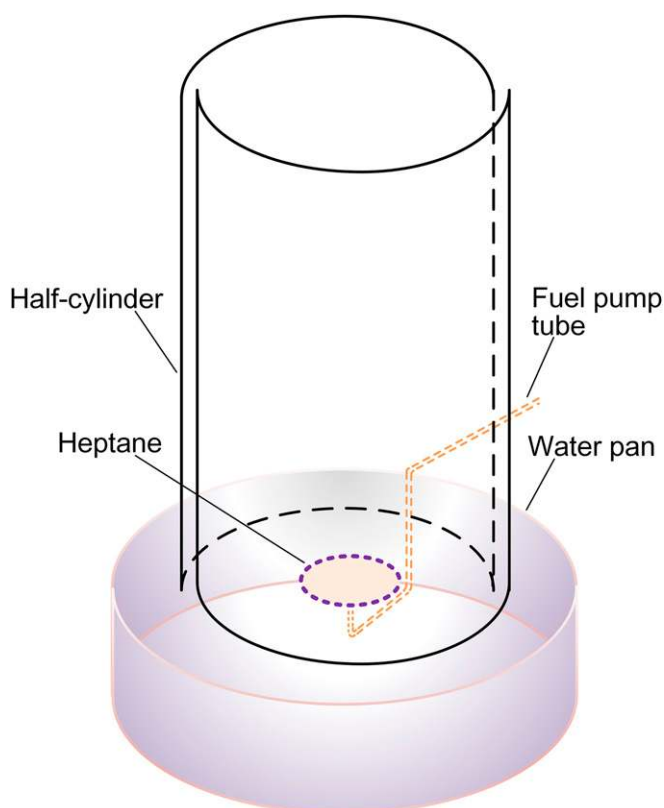
Fig. 5. Experimental design of the fire whirl generator over water. The copper fuel pump tube, which is connected to a syringe pump, is removable.

transitions from a spiral to a bubble mode, and by fast mixing, which limits soot formation in the vortex and creates regions of premixed fuel and oxidizer. Many questions still remain, such as why has this blue whirl not been seen before, what really are the physical and chemical processes controlling the formation of the blue whirl, can this configuration be used for energy production, and can we generate blue whirls at larger scales? Further understanding of the complex, multiphase physics occurring during blue-whirl combustion offers exciting possibilities for the future, and may therefore lead to the development of novel methods for fuel-spill remediation and high-efficiency combustion.

Materials and Methods

The experimental setup is shown in Fig. 5. The experiment was performed on top of a round steel pan filled with water, with a 40-cm inner diameter and 3.2 cm in height. The water surface was flush with the edge of the water pan. Two quartz half-cylinders (30 cm in diameter and 60 cm in height) were suspended about 2 mm over the water surface (Note that the blue whirl can form when the bottoms of the half-cylinders fully or partly touch the water surface.) The ambient pressure and temperature in the experiments were 1 atm and 298 K, respectively. The liquid fuel used was 99.4% pure liquid n-heptane. Initially, the water was quiescent and 2.5 mL heptane was squirted from a syringe onto the center region of the water surface. Shortly thereafter, the heptane was ignited by a small igniter filled with butane (Olympian GM-3X) which was removed immediately after ignition. The gap size between the half-cylinders and the initial amount of liquid n-heptane poured on the water was initially varied, but the observations reported here were all taken at 1.8 cm and 2.5 mL, respectively.

To sustain the blue whirl for extended observation, a syringe (BD 60-mL syringe) was first filled with heptane and then injected slowly to the center region of the water surface through a copper tube (external and internal diameters 0.3 and 0.1 cm, respectively). The copper tube was extended along the bottom of the water pan to the center and bent vertically upward until its opening was about 3 mm below the water surface. A small needle was projected out of the tube opening with its tip just under the water surface to prevent bubble formation when feeding heptane. The copper tube was connected to the syringe using a rubber tube outside the water pan. Injection of fuel was controlled by a syringe pump (Harvard Apparatus Pump 11 Elite) that continually supplied heptane at a constant rate (1.1 mL/min in this study).

Changing the exterior shape of the confining apparatus does not seem to affect whether or not fire whirls or blue whirls can form. Experiments in a four-sided square polymethyl methacrylate apparatus produced a fire whirl evolving into a blue whirl. The gap size of the slits between the two half-cylinders, however, does affect the formation and stability of both the blue and traditional fire whirls. Ultimately, a two-gap configuration with a cylindrical shape was chosen for the study in the belief that the cylindrical shape would allow the blue whirl to form and remain stable in the center region of the apparatus. An important point to make is that the blue whirl formed not only when n-heptane was the fuel, but also formed with heavier hydrocarbons, such as crude oil.

The evolution of the fire and fire whirls was recorded using a Canon EOS 70D digital single-lens reflex camera. The images in Fig. 1 *A* and *B* were taken using a Tv mode with manual focusing and automatic ISO sensitivity. The images in Figs. 1*C*, 2, and 3 were taken using Scene mode with manual focusing. The images taken by the camera in Figs. 1–3 were acquired with a pixel resolution of 3,648 × 3,432 and bit depth of 24. The movie from which Fig. 4 was extracted, and Movies S1 and S2 were taken at a frame rate of 50 frames per second with a pixel resolution of 1,280 × 720.

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