

Fractal flaming hydrogen wiggles through tiny gaps

Enlarge / Lab technician setting fire to a ball with hydrogen blowtorch.

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Hydrogen is not your friend. This was the first lesson I learned when I sent a PhD student off to study hydrogen reactions on a surface. Hydrogen is explosive over a huge range of concentrations, making even the tiniest leak an invitation to study the joys of high-velocity stainless steel, with an added bonus of third-degree burns. I've now learned that the situation is actually worse than I thought, because hydrogen is also able to burn in very confined spaces as well.

Fire needs three things: fuel, oxygen, and heat. If you have a well-mixed fuel-oxygen combination, the first two aren't going to be a problem, so you just need to add heat. When ignition is sparked off, the fuel and oxygen are quickly exhausted locally, so a front of combustion will expand outward from the ignition point, consuming the fuel and oxygen as it goes. For that expansion to take place, the heat generated from combustion must be transferred outward with the flame front, otherwise the gas will not be hot enough to ignite.

In a large space, this is not a problem, because gases don't take much energy to heat up. In a confined space, though, the

walls start to play a role. Energy will go into heating the walls, but the wall temperature may never get above the ignition temperature of the gas. So, if the walls are close enough, a spark will not result in a propagating flame front; instead, the flame dies locally. For hydrogen, though, the story turns out to be a bit more complicated.

Flame trains

To explore this, a team of researchers set up a burning sandwich. Two large plates of glass that could be held at a distance between one and six millimeters apart were used to confine a hydrogen-air mixture. Once the mixture concentrations were chosen, the researcher would either ignite the top or the bottom of the sandwich. The team then tracked the invisible flame by observing the water droplets that formed as a result of hydrogen-oxygen combustion.

[embedded content]

Fractal branching flame traveling upward. Courtesy of Fernando Veiga-López and colleagues.

For wide separations (3mm or more) and high hydrogen concentrations (just over 10 percent), a normal flame front would appear and spread outward from the ignition point as shown above.

But, when the gap was reduced to 2mm, the flame would break up into a branching network of smaller flame channels. The branching followed a pattern similar to that found in bacteria growing in a medium without sufficient food (the branches also resembled the airways in your lungs). The researchers analyzed the branching pattern and showed that it had a fractal nature.

[embedded content]

Double-track flame traveling downward. Courtesy of Fernando Veiga-López and colleagues.

However, that is not the end of the story. A tiny reduction in hydrogen concentration stops the formation in a fractal flame

front. Instead, a single or a pair of narrow flame tracks form. The tracks do not expand or branch. Instead, they simply follow a smooth (but not straight) trajectory until they exhaust themselves against the edge of the plate. Gravity also plays a role: the same behavior is observed for downward- and upward-traveling flames, but for different hydrogen concentrations.

Similar experiments with heavier flammable molecules do not result in the same behavior. Heavier molecules (like methane) either have a continuous flame front or die at the ignition source.

[embedded content]

Multiple single flame tracks traveling upwards. Courtesy of Fernando Veiga-López and colleagues.

Flaming model

To understand why this was the case, the researchers modeled their flaming gas. They found that hydrogen can withstand the heat losses due to the walls because it moves around a lot more (hydrogen can diffuse further compared to heavier molecules). This allows it to form a narrow flame track, which the researchers also observed in their models. Those models, however, do not seem to reproduce the fractal flame front, which I find a bit surprising.

The researchers also claim that these fractal and track-like flame fronts have not been observed before, which indicates that there is an entirely new set of flame dynamics to be studied. I look forward to a followup that explains the observed fractal. In terms of safety and handling of gases, nothing really changes as a result of this research, since our rules are generally abundantly cautious (and with good reason). There is no reason why anyone operating safely would be able to create the right conditions for a fractal flame to form.

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