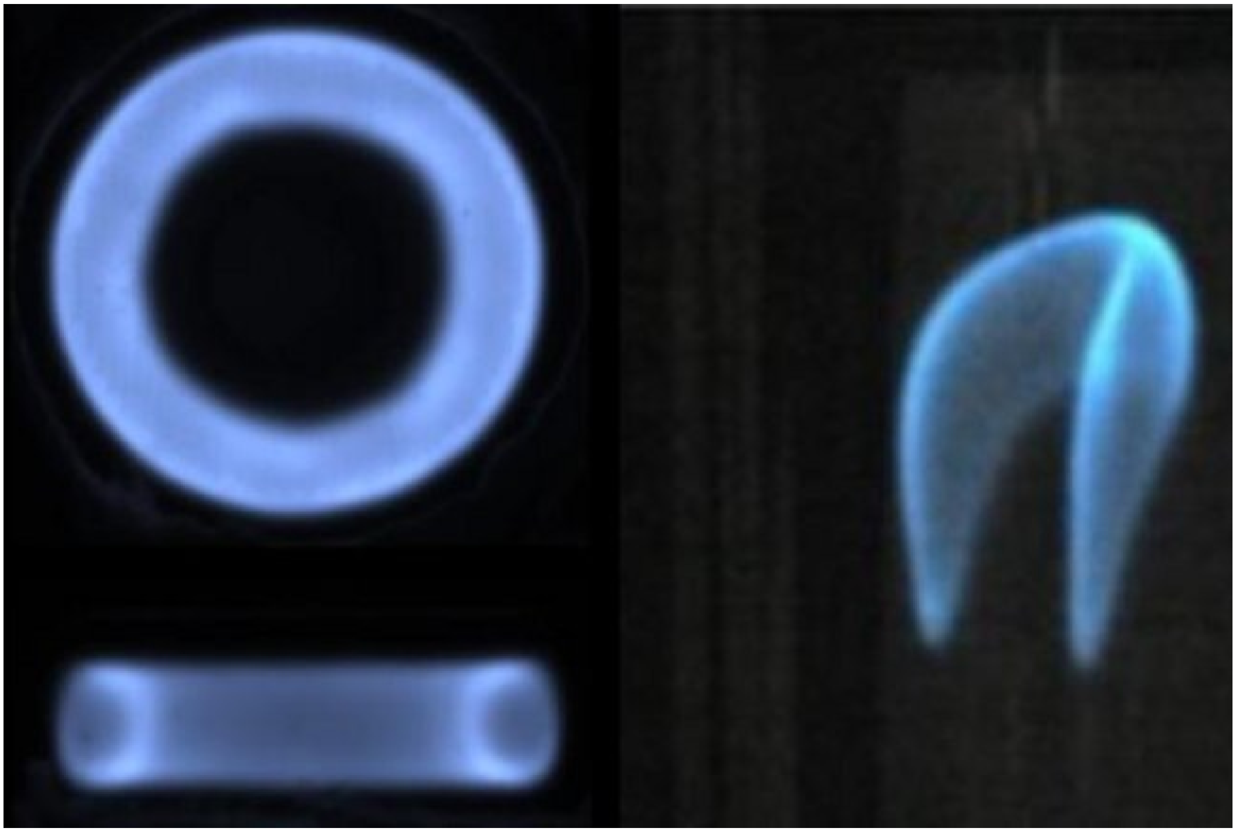
The amazing world of flame balls, doughnuts and horseshoes

June 16 2021, by Henk Van Appeven



On the Left a donut-shaped flame ball. On the right a flameball that has the shape of a horseshoe. Credit: Eindhoven University of Technology

Flame balls are gentle and fragile spherical flames that up till recently could only exist in conditions of near-zero gravity. Researchers at TU/e have managed to observe flameballs at normal earth-bound conditions, and thus, discovered new insights in the working of lean fuel mixtures. Lean hydrogen mixtures are believed to be the fuel of the future as they emit no CO_2 and only low concentrations of nitrogen oxides. Join our researchers in their exciting journey to understand the enigmatic flame ball.

One does not have to be a combustion scientist to understand that, when a fuel-air mixture is ignited, flames start to propagate. Oxygen reacts with fuel in the flame, heat is released and ignites the mixture next to the flame, and this process continues. This happens in the gas stove in your kitchen, in a cylinder of your car engine, or in a gas turbine in a power station.

But even combustion scientists get puzzled when they see a flame ball for the first time. "A flame ball is a tiny luminous spherical flame, which maintains the same size and shape for virtually unlimited time," explains Philip de Goey, head of the Combustion Technology group at TU/e. "It looks as something impossible. It does not expand, while there is a plenty of fresh mixture around, and it does not extinguish, even though there is no fuel inside it."

The secret of the flame ball is that it is a so-called diffusion flame. Its combustion is supported by a continuous feed of oxygen and fuel that diffuses toward this spherical flame from the surrounding mixture. The heat released is given out to the surrounding mixture by diffusion as well, and a fraction of it is carried away by radiation. Because of this heat loss the flame ball is unable to ignite the neighboring mixture and expand. This makes it stable.

Gentle and fragile

Predicted by Drozdov and Zeldovich in 1943, flame balls were long thought as a theoretical curiosity as no one ever observed them for almost half a century after that prediction. The reason is that most combustion labs are built on Earth, and, thus, like everything on Earth, are subject to gravity.

In theory, a combustible mixture has to be motionless for a flame ball to exist. However, flames at Earth gravity tend to generate upward convection flows due to buoyancy forces acting on the hot combustion product, like for instance in candles. While this natural convection helps candles to burn, a flame ball is too gentle and too fragile to survive it.

It wasn't until 1990, when flame balls were first experimentally discovered by Paul Ronney, when gravity-free combustion experiments became possible. Such experiments were carried out inside free falling chambers, dropped from tall towers, or onboard of planes flying in parabolic trajectories—a kind of flying roller coaster, where one can also feel weightless, though for a shorter time.

When experimenting with so-called lean limit mixtures, which contain very small amounts of fuel and can barely support combustion, Paul Ronny observed that multiple flame balls of 5-10 mm size were formed and burned in a mixture of hydrogen and air.

Why flame balls matter

Soon after the discovery, researchers recognized the potential significance of studying flame balls. First, such flames have temperatures much lower than ones found in other flames. They are also extremely sensitive to small changes in the conditions at which they burn. This makes a flame ball an excellent object to validate theoretical combustion models. Such a validation becomes especially important as modern combustion technologies move toward mixtures with low concentrations of fuel. These so-called lean mixtures tend to generate cooler flames that produce fewer nitrogen oxides (NO_x). And flame balls are the leanest flames possible

Second, flame balls may exist in the leanest mixtures that can still burn—if less fuel is present in air, no combustion is possible. The ultimate limits at which flames can exist are important for the development of safety standards and for the design of combustion devices.

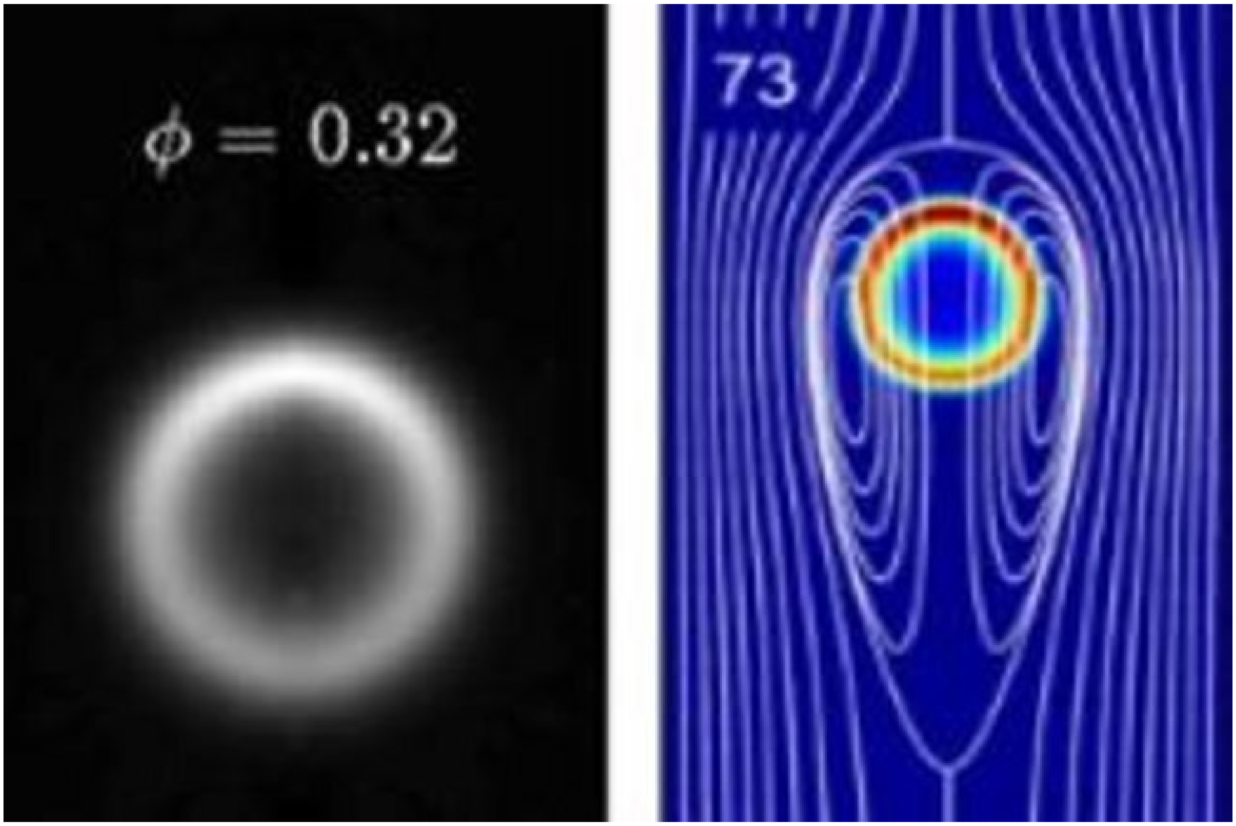
Finally, studying flame ball phenomena may help us to better understand combustion mechanisms of lean hydrogen mixtures. Hydrogen is one of main pretenders to become a 'green' fuel of the future, and lean combustion is considered as the future of the combustion technologies.

Bringing the flame balls to Earth

No wonder then that the discovery of flame balls sparked further intensive theoretical and experimental investigations. Experiments were even carried out at the International Space Station, where the conditions of 'micro-gravity' are optimal and permanent. Extensive measurements in such conditions, however, are not possible due to the very high cost and the limited possibilities for experimental diagnostics.

That changed, however, when flame balls were brought to the ground by TU/e researcher Yuriy Shoshin, working within Philip de Goey's Combustion Technology group. As happened in the case of micro-gravity flame balls, Shoshin discovered 'normal' gravity flame balls by accident.

"When we filled a vertical glass tube with a mixture containing hydrogen and ignited from the bottom end, we observed nearly perfect luminous balls that slowly raised to the tube top end," says Shoshin. It turned out that buoyancy forces induced by the flame create a small vortex in which the flame ball resides. So instead of destroying the flame ball, as was the case in earlier experiments, the gravity-induced convection at proper conditions helps to preserve it.



Left, cross-section of a flame ball in a mixture of hydrogen, methane and air at elevated pressure; right: Simulation of a flame ball residing inside a vortex. Credit: Eindhoven University of Technology

Living cells

Further intensive experimental and numerical studies led to many new insights into the workings of lean hydrogen flames, says Shoshin "Among other things, we found that when a fuel mixture flows downward through a porous plate inside a wide tube, multiple flame balls are being formed that surprisingly behave like living cells, dramatically 'fighting for life.'"

"The balls compete for fuel like food, constantly changing direction every time new fuel becomes available. If a flame ball is lucky to find a location with a plenty of fuel, it divides into two, just like a living cell. Cells that are surrounded by more successful competitors are less lucky, and decay. They can no longer resist the downward gas flow by self-induced buoyancy. These unfortunate balls are removed from the fuel source by gas flow and eventually 'die' from starvation."

Doughnuts and horseshoes

The fact that flame balls exist within a vortex gave rise to the idea that flames with similar combustion mechanisms could possibly be formed at other conditions, where vortices are present. "And, indeed, in further experiments we have found other kinds of flames that burn in a similar way, shaped like donuts and horseshoes."

Such flames form around so-called vortex filaments, lines around which gas rotates. In practical devices, combustion almost always occur in turbulent mixtures, and it is known that such kind filaments are present in turbulent gas. "This gives us hope that studying such flames may help to understand lean hydrogen turbulent flames," says Shoshin.

Flame ball combustion mechanisms may also be relevant for flame stabilization. "Flames need to be stable to be usable in household boilers or gas power plants, and the most common way to stabilize flames is creating a vortex behind some obstacle placed in a combustible mixture flow."

Beyond theory

De Goey stresses the importance of researching flame balls at non-microgravity conditions. "While flame balls at zero gravity remain the most fundamental and most simple example of a flame ball, the flame balls and their relatives studied in our group can exist at various different conditions. This makes their physics much more interesting, and also much more relevant for other fields of combustion science."

"Interestingly, even though our studies were to a large extent inspired by micro-gravity experiments of Paul Ronney, for some of the members of the 'flame ball family' discovered in our labs, the gravity effects turned out to be not important at all."

The next step in the research by De Goey and his team is incorporating the flame ball phenomenon into earlier theories on normal flames. However, their interest in the enigmatic flame ball goes far beyond mere scientific curiosity. "In the end, a full understanding of how they work will help us develop lean fuels that will pave the way for a sustainable energy future," he says.

Provided by Eindhoven University of Technology

Citation: The amazing world of flame balls, doughnuts and horseshoes (2021, June 16) retrieved 19 April 2024 from https://phys.org/news/2021-06-amazing-world-flame-balls-doughnuts.html