The mechanism of tulip flame formation on the early stages of flame propagation in tubes

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Flame propagation in tubes is important for understanding combustion processes under confined conditions, such as explosions and safety issues, as well as for industrial and technological applications. It provides a fundamental physical-chemical platform for the analysis of more complex engineering problems and for the development of appropriate analytical methods and numerical models. Therefore, understanding the structure and acceleration of premixed flames is of primary interest to the combustion community. It has long been known that when a flame is ignited near the closed end of a tube and propagates to the opposite closed or open end, it initially accelerates and then suddenly slows down, and the shape of the flame front rapidly changes from convex with the tip pointing forward to concave with the tip pointing backward. This phenomenon was first photographed in experiments by Ellis in 1928 and later named "Tulip Flame". Subsequent experimental studies have shown that tulip flame formation is remarkably robust across combustible mixtures, highly or slowly reactive mixtures, and downstream conditions: such as open or closed tube ends and tube shapes, tube wall roughness, and obstructed tubes. It has also been shown that the geometry of the ignition source is not critical for tulip flame formation. The transition to a tulip flame always occurs in tubes with a sufficiently large aspect ratio $L/D > 4$ for both laminar and turbulent flames. Only with a relatively strong breaking of the initial symmetry, e.g. with sufficiently strong perturbations of the initial flame front, tulip flame formation does not occur. There are a large number of publications that have attempted to explain the physical mechanism of tulip flame formation. However, despite numerous experimental, theoretical and numerical studies, the mechanism of tulip flame formation, including the role of pressure waves, and until recently this problem remained one of the fundamental unsolved problems in combustion science.

In this presentation I show that the mechanism of tulip flame formation is the rarefaction wave generated by the flame during the deceleration stage. The mechanism of flame front inversion and tulip flame formation is very simple and clear understood if we consider the theoretical model of thin flames, where the flame is considered as a discontinuous surface between unburned and burned gases. The results of the thin flame model are in surprisingly good agreement with 2D and 3D simulations of the fully compressible reactive Navier-Stokes equations with a detailed transport and chemical model of tulip flame formation in highly reactive hydrogen-air and low reactive methane mixtures. I also show that formation of tulip flames is a purely gas-dynamic phenomenon in the sense that it occurs much faster than the time required for the development of flame front instabilities in agreement with experimental observations.