The Hydrodynamic Structure of a Methane-Air Tulip Flame

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Abstract

Flame propagation and structure of a stoichiometric methane-air mixture in a closed vessel is investigated. For the parameter range examined a tulip flame is formed. A qualitative agreement with experiments is obtained for different length to width ratio of the vessel. The results indicate an enhanced tulip effect with increasing vessel length.

Key words: closed vessel, tulip flame, vorticity generation, flame shape.

Numerical simulations of a methane-air flame in closed vessels with a square cross-section (20 mm x 20 mm) and various lengths (30-120 mm) are presented solving the Navier-Stokes equations in the low Mach number limit given by Majda [1] for reactive systems. A single step, irreversible reaction of Arrhenius type [2] is used, $\frac{\partial}{\partial t}[CH_4] = -C_f[CH_4][O_2]\,exp(-\frac{T_a}{T})$, where $C_f = 2.4 \cdot 10^{10} m^3/(mol \cdot s)$ and $T_a = 24370\,K$.

The numerical algorithm is the following: In the first step of the computation the temperature and mass fraction of the fuel are calculated from the conservation equations. and solved by a Crank-Nicolson scheme. The thermodynamic pressure is also calculated from the conservation equation, and density is obtained from the equation of state. In the closing step, velocities and the dynamic pressure field are found using a projection method [3]. The Poisson equation for pressure is solved by an SOR-method.

A first series of computations for a Reynolds number of 250 shows the effect of the combustion chamber length on tulip flame formation (see Figs. 1 and 2). A line igniter with circular cross section, placed at the centerline of the left side wall, initiates the combustion in a stoichiometric mixture of methane and air. The figures show an increasing tulip effect with increasing chamber length and for the shortest chamber (not shown) the tulip is not formed at all in agreement with the experiment described in [4].

Vorticity is generated by the propagating flame due to its baroclinic behavior. Before the flame reaches the side wall, the shape of flame is convex and vorticity is being formed into sheets arranged ahead and behind of the flame with opposite signs. After reaching the side wall the flame becomes flat and vorticity sheets brake into few vortex pairs with alternating signs (Fig. 3). Those vortices deform the flame surface making it wrinkled and larger, indicating that superposition of this voritcal flow on the dominant expansion flow results in a rather complex behavior of tulip flame.

This numerical technique was also applied to cases where the combustion initiates inside and/or at a few positions inside the vessel simultaneously. The generation a vortical flow by several flames as well as interactions of those flows, the deformation of one by others, and also the flame shape as well are investigated.

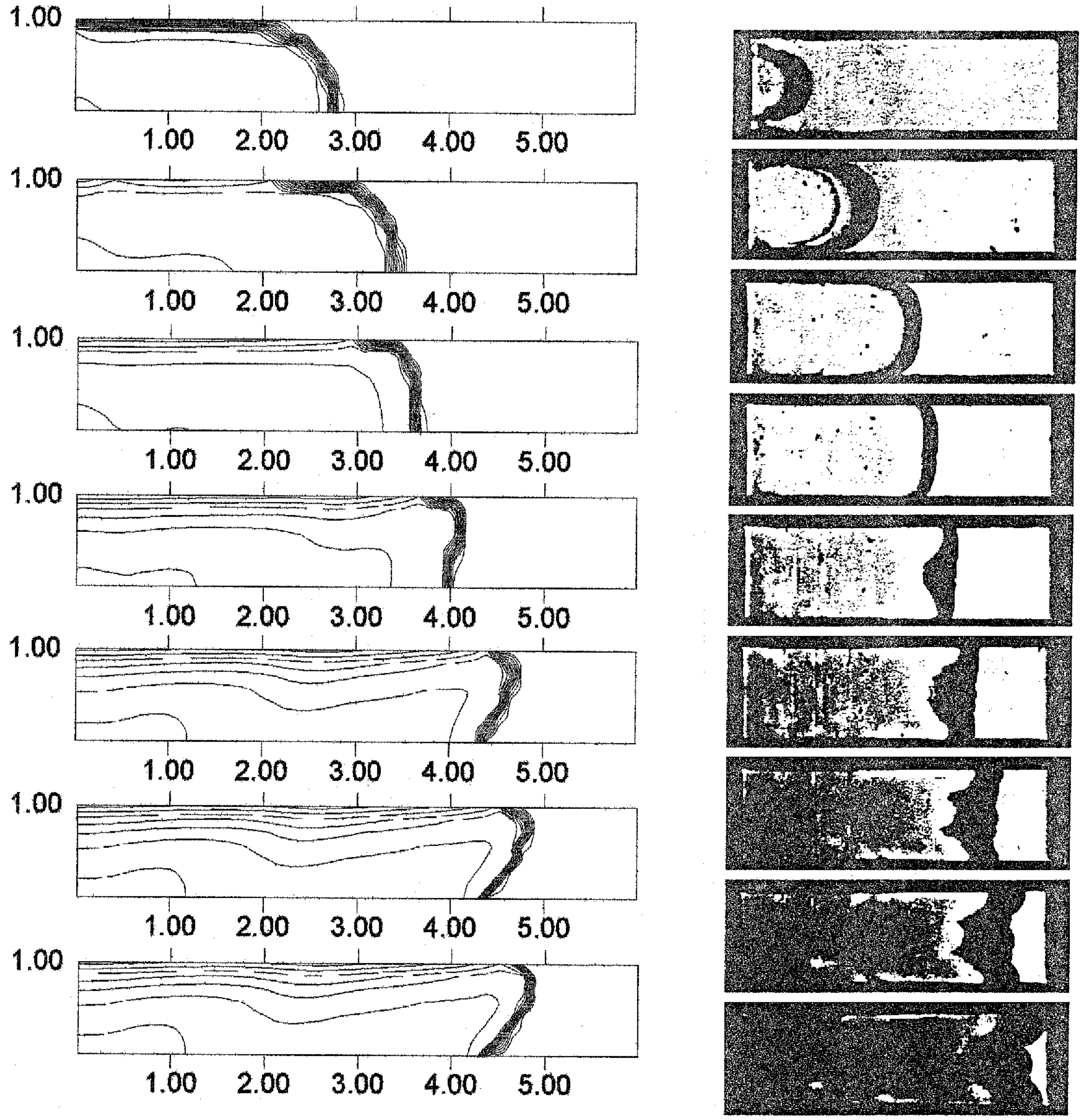

Figure 1: Flame propagation as a function of time, isolines of temperature for $L/h = 6$ (left: computation, right: experiment).

References

[1] A. Majda and J. Sethian, Combustion Science and Technology, 42 (1985).
[2] C. K. Westbrook and F. L. Dryer, Combustion Science and Technology 27, 31 (1981).
[3] R. Peyret and T. Taylor, Computational Methods for Fluid Flow, 1983.
[4] D. Dunn-Rankin , R. F. Sawyer, Experiments in Fluids, 24, 130-140 (1998).

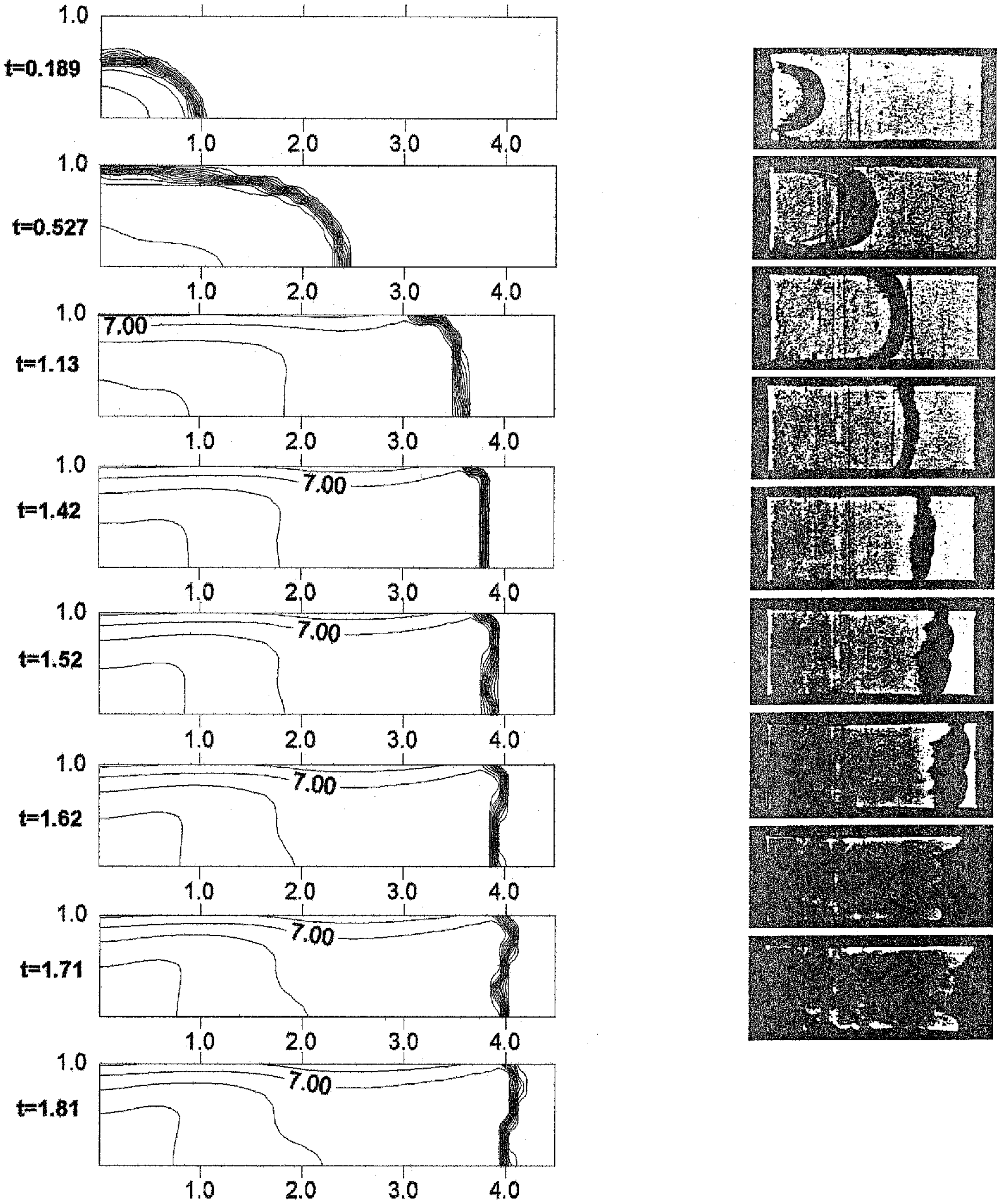

Figure 2: Flame propagation as a function of time, isolines of temperature for $L/h = 4.5$ (left: computation, right: experiment).

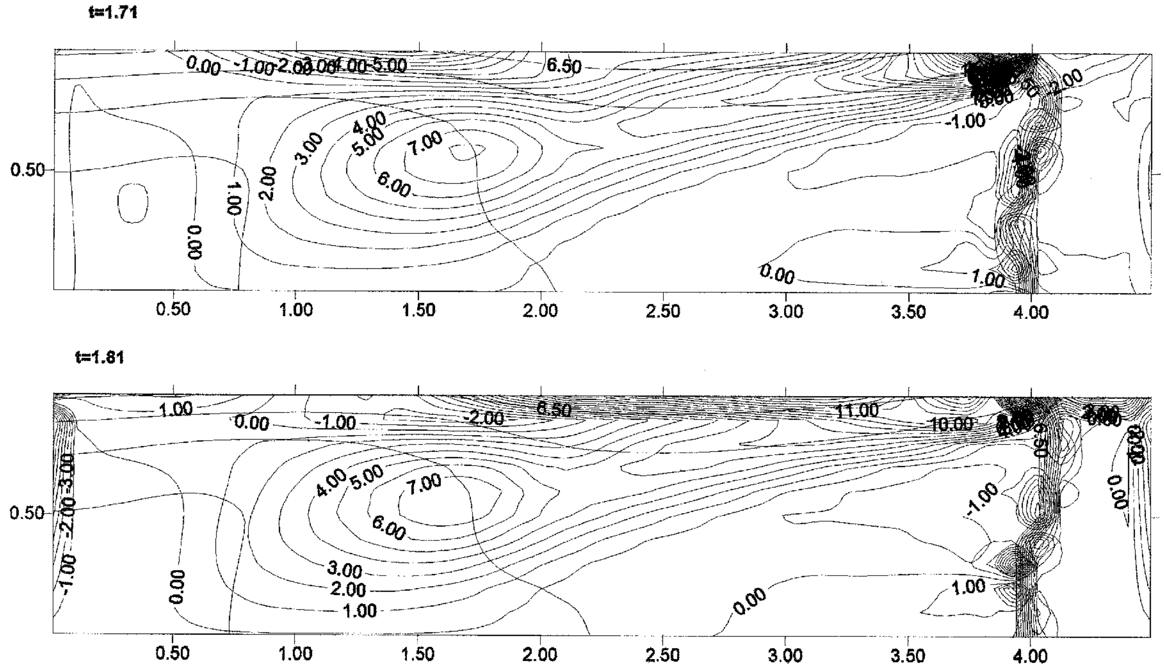

Figure 3: Superposition of temperature isolines and vorticity isolines before (upper part) and after (lower part) reflection at the sidewall.