Numerical Investigation of the Gravitational Influence on Laminar Diffusion Flames

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Abstract

Using a Shvab-Zeldovich like model for laminar diffusion driven combustion the influence of the gravitational acceleration on the transport processes within the flame has been studied. Therefore numerical simulation was carried out with the CFD-program PHOENICS. Both steady state and transient behaviour under earth and microgravity conditions were calculated. The results are compared with experimental data from drop tower experiments. Further predictions are made for different gravity levels.

Within the last decades several efforts have been spent on understanding of the behaviour of non-premixed laminar diffusion flames. Experiments have been carried out on ground as well as under microgravity conditions. The microgravity environment in drop tower experiments or during parabolic flights reduces the buoyancy effects, so that diffusion as the major process for mixing fuel and oxydizer becomes dominant.

The first theoretical model of a laminar co-flow diffusion flame was presented in 1928 by Burke and Schumann [1]. They presented a solution of a single diffusion equation. Later Shvab and Zeldovich assumed an infiniteley thin reaction layer. As soon as the fuel and the oxydizer are mixed they are burnt. If further the diffusivities of the chemical species and of heat have the same value (Lewis number is unity) then only one coupling function, the mixture fraction, i. e. the mass fraction of the amount of gas originating from fuel, is needed in oder to describe the chemical reaction [4].

Until the 1970s the aim of studies were analytical solutions of Burke-Schumann-like models with simple burner geometries. In a publication by Roper [2] a formula was derived to calculate the flame length of a stationary diffusion flame including the buoyant acceleration of the hot gases due to gravity.

The rapid development of information technology enabled the application of numerical simulation in order to solve the governing hydrodynamic equations. Today commercially available Computational Fluid Dynamics (CFD) program packages provide useful algorithms to solve multistep chemical reaction flows. Many details can be simulated sufficiently. Such complex setups are on the other hand not suitable for understanding the underlying basic combustion processes. Therefore the authors applied a Shvab-Zeldovich formulation of a laminar diffusion flame for numerical investigation. The effect of gravitational acceleration on the shape of hydrogen and hydrocarbon diffusion flames has been studied and compared with experimental data [3].

The numerical simulation was carried out using the commercial CFD-program package PHOENICS. The geometrical setup was chosen to represent a cylindrical chamber of 20 cm of diameter and 40 cm height. The fuel nozzle is situated in the center of the chamber bottom, concentric around which air is injected. The cylinder symmetry has been considered throughout the whole simulation. The volume is divided into 30 by 40 non-aequidistant cells in radial and axial directions, respectively. The conservation equations for mass, radial and axial momentum, enthalpy and the mixture fraction are solved. The thermodynamic properties are modelled using the ideal gas law. The temperature dependence of the diffusion coefficients are approximated by a potential expression with the exponent 1.75. The Prandtl and Lewis numbers are unity.

It turned out that even such a comparatively simple model of a diffusion flame was capable to make predictions that agree with experiment. The linear dependence of the flame length on the fuel flow rate

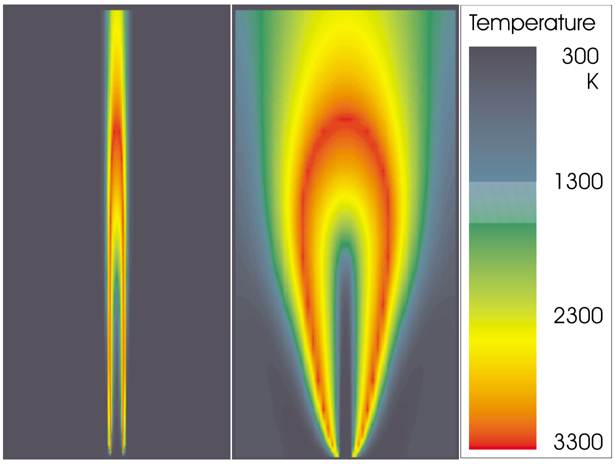

Figure 1: Temperature profiles of the stationary hydrogen flame with and without gravity

was verified. While the length of the flame does not significantly vary between 1 g and microgravity conditions, the diameter changes considerably (Fig. 1). Only under higher gravitational accelerations the flame length appears to decrease exponentially. The radius is more senstive to a change in the low-gravity level (Fig. 2).

Through a transient simulation from the stationary flame under ground conditions to microgravity the development of the shape has been investigated. Like in experiment a shortening of the flame occured within the first 0.1 seconds after exposure to microgravity, which was observed as a tear off of the flame tip. After that the shape grows slowly, mainly into the radial direction.

The numerical results help to explain the transportation processes in diffusion flames. In the case of normal gravity the hot combustion gases are accelerated due to buoyancy. This causes a suction that provides air to burn the fuel. The flow of air prevents the flame from widening. In contrast to this, under microgravity diffusion is the major transport process. Since diffusion is much slower the reaction zone is spreading out.

It is obvious that this simple model cannot explain phenomena due to incomplete combustion. It has been observed that flames under microgravity tend to develop an open tip. The higher the molecular weight of the fuel becomes the more significant this effect appears. The formulation with only one coupling function implies flame contures that are always closed. Also the tear off of the flame tip, which accounts for the flickering under gravity, cannot be deduced.

In a next step the model shall be improved by minimum assumptions that are necessary to explain the open tip phenomenoma.

Acknowledgements

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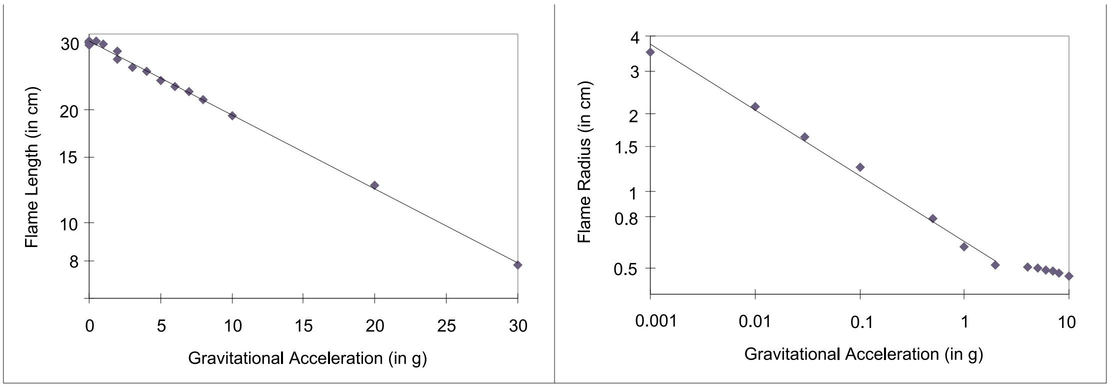

Figure 2: Dependence of the flame length and radius on the gravitational acceleration

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