Concentration and Temperature Profiles of Diffusion Flames in Droptower Experiments

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Introduction

THE investigation of combustion processes under microgravity has become more and more important over the past few years because of the possibility of separating the coupled influence of diffusion and buoyancy in burning behavior. The most recognized theoretical work in the field of diffusion flames is the Burke–Schumann model[1] published in 1928. Technical calculations are often based on this model. An extensive experimental work, recently published in Refs. 2 and 3, investigated diffusion flames from laminar flow conditions to transitional flow conditions with different gaseous hydrocarbon fuels injected into air under microgravity with photography, high-speed movie cameras, or video camera and observed that the flames were generally rounder and thicker than under normal gravity. For a deeper understanding of this different behavior of flames under weightless conditions, however, it is necessary to get more quantitative information about the flames. In this work we present measured profiles of the temperature and the oxygen concentration of a hydrogen diffusion flame and the estimation of the flame contour under gravity and microgravity.

Experimental Setup

The experimental arrangement is designed to fit the geometry of the classical Burke–Schumann model as closely as possible. Therefore, a coaxial coflow condition with an airflow rate of 600 l/h, an air velocity of 2.2 cm/s, fuel flow rates from 80 to 220 l/h, and fuel velocities from 28 to 78 cm/s in a cylindrical combustion chamber are used. The chamber is an aluminum cylinder with a 200-mm diameter and 400-mm height. There are three rectangular ports (300 × 100 mm) positioned around the chamber. These ports can be used for camera monitoring, as well as for access of measuring systems. The flame is ignited by sparks prior to the drop. The pressure inside the chamber is actively controlled at 1 bar with an accuracy of 50 mbar. Three measuring systems were used. An ordinary video camera for visual investigation provides a first evaluation of the experiment and a qualitative analysis of the flame behavior. An array of 18 microthermocouples was used to determine the thermal characteristics of the flame. The oxygen-concentration profile was aquired by means of a special application of solid electrolyte O_2 sensors.[4,5]

Experimental Results

One of the most important characteristics of a diffusion flame is its contour, especially the length or height. The contour is the boundary of the stoichiometric relation between oxygen and fuel with degree of burnout $\alpha = 1$. A qualitative way to determine the flame contour is to analyze the emitted radiation in the visible range. Quantitative methods to obtain the flame contour include the determination of the temperature profile or the determination of the oxygen concentration profiles to estimate the thermal or chemical contours. The flame used for the current investigation is flickering under gravity. This phenomenon correlates with the assumption that flickering occurs due to a gravity-caused vortex structure.[6–8] Because of this flickering, the gravity flames can be characterized with a minimum and a maximum contour. The described flame characteristics are changing drastically under weightless conditions. First, the flame collapses, and afterward, the size increases continuously. A linear relation between the size and flow rate is valid. Figures 1 and 2 show the temperature profile and the concentration profile of a hydrogen air coflow flame with an airflow rate of 600 l/h and a fuel flow rate of 220 l/h under gravity and 4.5 s after transition to microgravity. The temperature profile represents more than 70 data sets measured in six drops. The typical temperature profile under gravity is characterized by a thin reaction zone above 1500 K. The temperature gradient can reach 100 K/mm in the radial direction. With the start of microgravity, the reaction zone moves away from the burner, and the temperature level decreases. The temperature gradients are lower than under gravity. Furthermore, the dark regions in the flame can be identified as low-temperature zones. The error of a single temperature measurement due to data acquisition and to the thermocouple itself is below 5%. The uncertainty of the temperature profile results from the response time and from the interpolation of the temperature profile from various experiments. Neither effect can be quantified with the measured data at present. The temperature peak at the flame border near the burner mouth of the microgravity temperature profile results from disturbance effects due to the ignition electrode.

In Fig. 2, the under-gravity minimum and maximum contours due to flickering are plotted in comparison to contours under microgravity after the 4.5-s drop time. As already mentioned, the chemical stoichiometric contour was determined by solid electrolyte sensors. Three sensors, each with three electrodes, were used in 16 drops. The time-dependent oxygen concentration profile was calculated with the resulting 144 data sets. The signals under gravity show a flame with typical flickering of about 10 Hz in the axial direction and 1 Hz in the radial direction. The microgravity signals represent the collapse and the growth of the flame. The fast Fourier transform analysis of the data does not show any significant frequency. It is easy to see that the flame under microgravity is much bigger than its counterpart under gravity. The wrinkled structure of the microgravity contour results from the interpolation of data sets from a number of experiments with different sensor positions in the

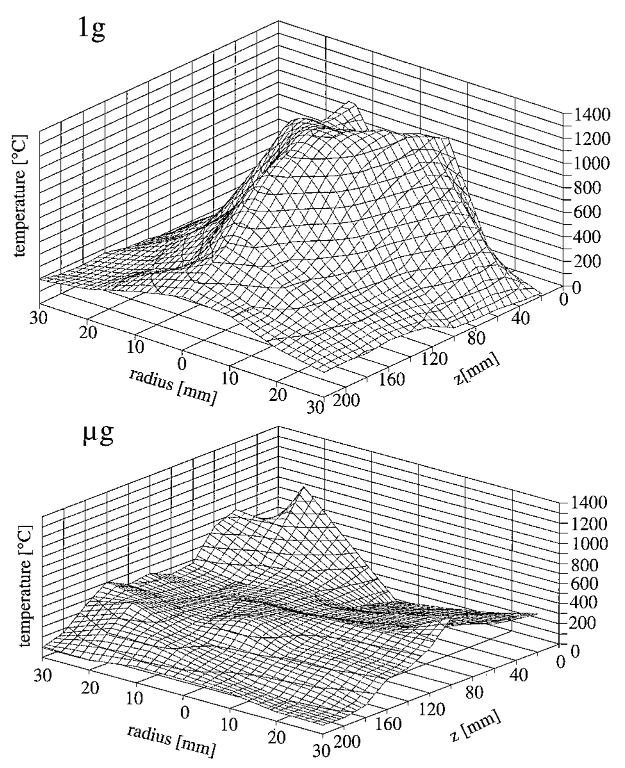

Fig. 1 Temperature profile under gravity and microgravity.

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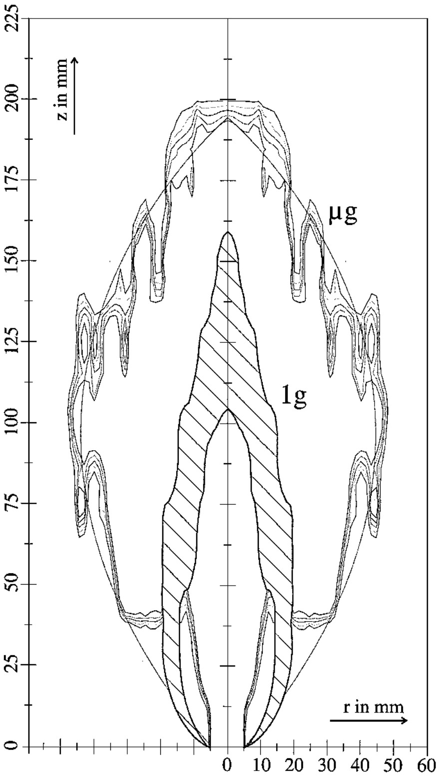

Fig. 2 Stoichiometric minimum and maximum flame contours under gravity and flame contour under microgravity.

combustion chamber. These contours are only a small region in the concentration profile, and the measured data include much more information, such as the burnout and the thickness of the flames. As expected, the calculated thermal and stoichiometric contours differ from the visual ones. These have to be considered for the verification of the numerical models by experimentally determined contours.

Summary

The investigated hydrogen air flames are strongly influenced by buoyancy. Gravity flames show a characteristic flickering, which disappears under microgravity. This fact confirms the correlation with the buoyancy. It may be concluded from visual investigations that the flames under microgravity are bigger and less bright than flames under gravity. The microthermocouples employed are well suited for the measurement of the two-dimensional temperature profile inside the combustion chamber. This method is relatively inexpensive in comparison to the different laser techniques inasmuch as the application of lasers under microgravity is just beginning. Nevertheless, the measured temperature profile describes the evolution of the flame contour quantitatively. The oxygen concentration profile of a hydrogen diffusion flame was determined by means of solid electrolyte sensors and, hence, the contour of the flame. The sensor signals show the quantitative differences between the gravity and microgravity cases. The data show that there is flickering under gravity and continuous growth under microgravity. In the gravity case, it is possible to calculate a minimum and a maximum contour. The microgravity contour at the end of the drop is larger than that under normal gravity conditions. This shows that gaspotentiometry with solid electrolyte sensors is very useful, especially because the sensors are easier to handle and more cost effective than laser-based methods. This method has great potential; however, it is not a nonintrusive method, and the influences on the investigated processes should be evaluated. The described techniques allow a quantitative analysis of the flame behavior under gravity and microgravity and add information about the flame to the usual video techniques. The collected data can be used for evaluation of numerical simulations and flame length calculations. The data show significant differences between visual observations and thermal and stoichiometrical contours. This must be taken into account for the comparison with numerical simulations.

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Explicit Equation for Flow Through American Society of Mechanical Engineers Nozzle Meters

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Nomenclature

A_D = area of pipe containing American Society of Mechanical Engineers (ASME) nozzle meter, m^2
A_d = area of ASME nozzle meter throat, m^2
C = ASME nozzle meter discharge coefficient
D = diameter of pipe containing ASME nozzle meter, m
d = throat diameter of ASME nozzle meter, m
q_m = mass flow rate of fluid in pipe, kg/s
Re_1 = Reynolds number based on pipe diameter, $V_1 D/\upsilon_1$
V_1 = actual upstream fluid velocity in pipe, m/s
Δp = differential pressure, Pa
β = d/D
ε_1 = expansion factor based on upstream pressure
ρ_1 = density of flowing fluid upstream of ASME nozzle meter, kg/m^3

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