NO_X MEASUREMENTS IN THE COMBUSTION OF AN N-DECANE DROPLET ARRAY UNDER MICROGRAVITY CONDITIONS ON TEXUS #46

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ABSTRACT

Emissions of nitrogen oxides (NO_X) in sprays are a complex and crucial topic. The knowledge about NO_X formation in sprays is based on research of droplet combustion. This paper presents the experiment setup for the combustion of an n-decane droplet array under microgravity conditions. Its focus is to investigate the array's undisturbed burning characteristics and the related NO_X formation mechanisms. Since the pre-vaporization time of the fuel droplets is the main experiment parameter, the extended duration of microgravity in a sounding rocket flight is needed for a comprehensive study. Four different combustion regimes will be investigated on the TEXUS #46 campaign. After flame extinction, exhaust gas samples will be withdrawn from the combustion chamber and stored in gas sampling cylinders for a successive analysis on ground. Precursor experiments were conducted on parabolic flights and in a drop tower to thoroughly investigate the reference case for TEXUS as well as to gain additional knowledge about the various technical aspects of the experiment.

1. INTRODUCTION

The ongoing discussion on environmental problems caused by the combustion of fossil fuels is mainly focused on the production of carbon dioxide (CO_2). Accordingly, there are a large number of research activities in the field of CO_2 reduction and separation. This includes working on increased efficiency of the combustion related processes since the amount of CO_2 is linearly dependent on the amount of fuel burned. Increasing the efficiency of heat engine processes is often related to an increase of the combustion temperature. This is due to the fact that the achievable efficiency of a thermodynamic process rises with an increase of the temperature differences in the process. Moreover, a higher temperature level has the advantage of lowering the production of carbon monoxide (CO) as a higher fuel burnout can be achieved. However, the negative effect of this increase in combustion temperature is a higher production rate of thermal NO_X (i.e. nitrogen oxides – mainly NO and NO_2) in the exhaust gas. Thermal NO_X is generated in combustion processes with temperatures > *1800 K*, and its generated amount increases exponentially with even higher temperatures [1 - 3]. Its formation rate is primarily a function of temperature and of the residence time of nitrogen at those high temperatures. NO_X is directly harmful to humans as it affects the respiratory system, is responsible for acid rain, and causes smog in cities. Public debates about these problems led to political decisions for stricter regulations on NO_X emissions in the last decade. Thus, two goals have to be considered in the development of new combustion applications: the increase of their efficiency and the decrease of NO_X emissions. Regarding the described correlation between combustion temperatures and the resulting NO_X, a conflict between these two goals becomes inevitable.

In order to get a better understanding of the fundamental processes in technical relevant spray combustion, and to derive design recommendations for liquid-fueled gas turbines, the degree of fuel vaporization is investigated. This is done systematically by utilizing an experiment with a linear array of 5 n-decane ($C_{10}H_{22}$) droplets. The research project is realized as cooperation between the Japan Aerospace Exploration Agency (JAXA) and ESA's research team, working on the combustion properties of partially premixed sprays, with their focus on flame propagation and NO_X production, respectively [4 - 9]. Based on a sole JAXA concept for drop shaft, the setup was retrofit with an exhaust gas sampling (EGS) system and customized for the TEXUS environment. TEXUS #46 will have the experiment module, called the "Japanese Combustion Module" (JCM), onboard. Originally, the related sounding rocket campaign was scheduled for April 2009 but is currently postponed to November 2009. This set back stems from a delay in the qualification process of a new pyrotechnic chain, which is needed for the ignition of the system's rocket motors.

The particularly investigated experiment parameters are: the degree of fuel vaporization Ψ, the local equivalence ratio Φ along the droplet array, and the dimensionless droplet spacing S/d_0 with d_0 being the initial droplet diameter. Fig. 1 shows a schematic on the approach for droplet pre-vaporization in the utilized configuration. The concept is based on a variable exposure time (t_w) of the low volatile n-decane droplets to the elevated temperature level of *500 K*. The microgravity environment enables experiment conduction without the effect of natural convection which causes difficulties apart from the complexity

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inherent to combustion itself. Since it is important to provide well-defined and idealized conditions for the interpretation of the experiment results and for the validation of related numerical methods, a sounding rocket flight was chosen for the experiment execution. Its extended microgravity duration offers the experiment larger degrees of vaporization compared to the drop shaft or drop tower.

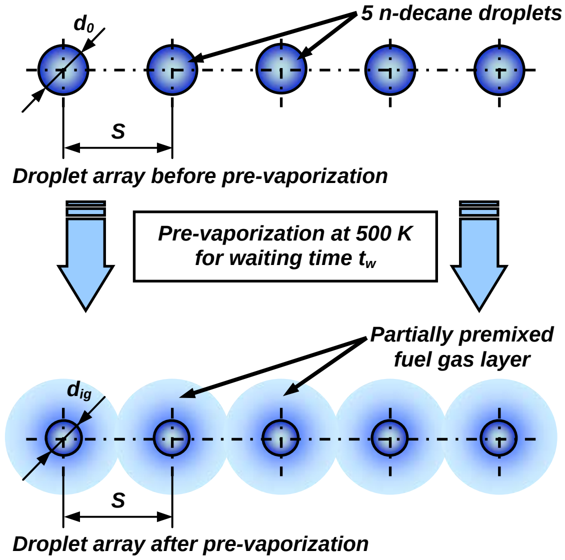

Figure 1. Schematic on fuel pre-vaporization of a linear droplet array.

2. OVERVIEW OF TEXUS EXPERIMENT

In relation to the study's focus on NO_X production, this paper gives a general experiment overview and presents the necessary preparations for the exhaust gas sampling and analysis in particular. JAXA had the main responsibility in developing and integrating the JCM, with the "Droplet Array Combustion Experiment Unit" (DCU) being the experiment core section (cf. to Fig. 2).

The DCU itself was manufactured as engineering model (EM) and flight model (FM). On TEXUS it is mounted on the experiment deck and fastened to the outer structure. A vacuum dome covers the experiment deck to keep the DCU pressurized during all stages of the sounding rocket flight. Controlling devices and batteries are mounted outside of the pressurized dome, at the bottom of the experiment deck. There are a number of interfaces for evacuation, cooling, and remote access. As shown in Fig. 2, the DCU is built of six platforms. Its complete height is *810 mm* and its baseplate has a diameter of *403 mm* with the experiment platforms measuring *372 mm*. The utilized platform technique has the advantage that the experiment can be modified and extended very easily if needed, as in the case of the EGS system.

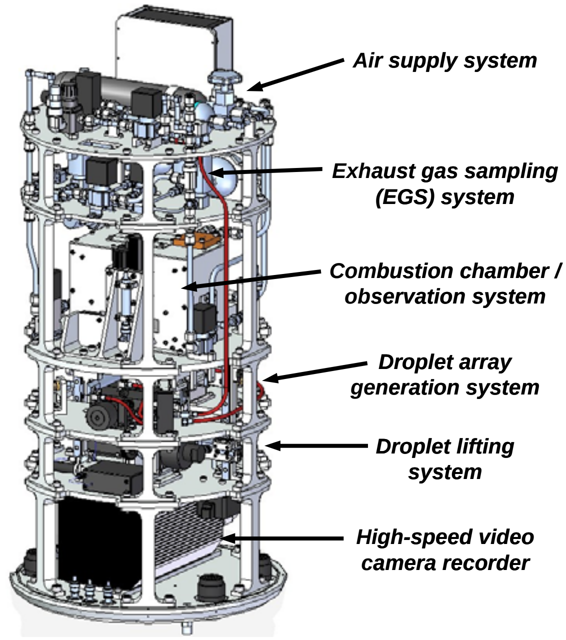

Figure 2. "Droplet Array Combustion Experiment Unit" (DCU), core section of the TEXUS experiment.

In order to perform an experiment run, a droplet array is generated by the droplet array generation system at room temperature of *300 – 315 K*. n-Decane is used as fuel. The droplets are supplied with a fuel pump through glass tubes onto the droplet holder. Each droplet is suspended at the intersection of a pair of X-shaped *14 µm* SiC fibers, which imparts lowest residual motion and highest sphericity [4]. The shutter on the bottom side of the combustion chamber is opened and the droplet holder with the droplet array is moved into the preheated combustion chamber by the droplet lifting system. Depending on the predefined degree of vaporization an ignition wire (iron-chrome alloy) ignites one end of the droplet array to initiate combustion (cf. to Fig. 3). Flame spread occurs over the droplet array. Due to pre-vaporization, the combustion process will initially be characterized by a partially premixed flame and followed by a diffusion flame around the droplets until flame extinction. After flame extinction, the exhaust gas sampling will be performed by the EGS system using one evacuated gas sampling cylinder.

To fully develop a model of NO_X generation in droplet and spray combustion, a wide range of different combustion regimes needs to be investigated. While keeping the pressure at *1.0 bar* (*+/-20 mbar*), the combustion chamber temperature at *500 K* (*+/-1 K*), and the total amount of fuel constant for the four independent combustion runs, the fuel vaporization time t_w is varied in the range of *5 – 18 s*. According to the degree of vaporization Ψ and using the analytic D^2 law, the burnout time t_b for one droplet can be calculated to *8.8 s* and *4.0 s* for the minimum of $t_w = 5\ s$ and the maximum of $t_w = 18\ s$, respectively.

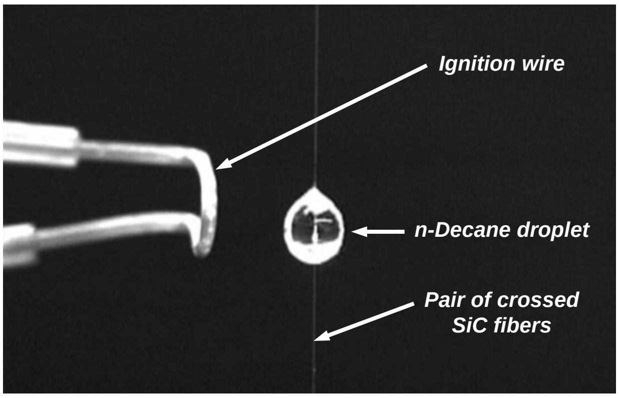

Figure 3. Ignition wire (left) and n-decane droplet, suspended on SiC fibers (middle).

3. EXHAUST GAS SAMPLING SYSTEM

An in-situ measurement of the combustion gases is not feasible since it would require too many resources. Therefore, a concept combining exhaust gas sampling during flight and successive gas analysis on ground is pursued here. The related EGS system is installed on the 5th platform of the DCU, in close proximity to the combustion chamber (cp. Fig. 2), and is shown more in detail in Fig. 4. Four gas sampling cylinders are required to separately sample the emissions of each of the four combustion runs, one by one. The gas sampling cylinders, integrated electro-pneumatic valves, and all piping/fittings are coated with amorphous silicon to prevent negative surface effects and a distorting gas adsorption [9, 12]. The evacuation of the gas sampling cylinders is realized through a late access port for a turbomolecular pump. The specified vacuum level before launch is $10^{-5} – 10^{-6}$ *mbar* with an associated leakage rate of < 10^{-5} *(mbar l)/s*.

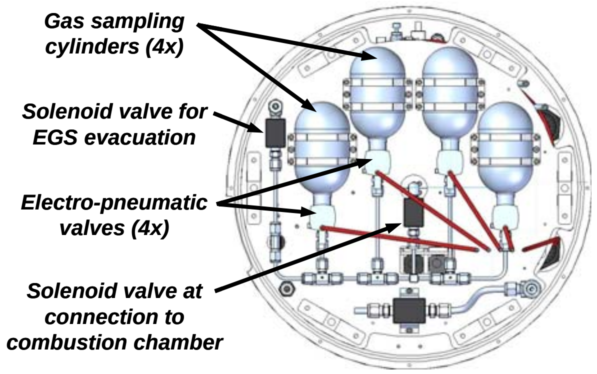

Figure 4. Exhaust gas sampling (EGS) platform with coated gas sampling cylinders and supply units.

The primary problem, which had to be solved with the pursued concept, is to obtain a representative gas sample from every single combustion run. Based on this general goal, and on the constraints of the TEXUS environment, the specifications of the EGS system can be outlined as follows [9, 10]:

- High level of automation (by control routines)
- Compact design (for weight and space reasons)
- Shock resistance (for launch and touch-down)
- Simple operability (e.g. short evacuation times)
- Reproducibility of scientific results
- Small dead volume (by using small cross sections)
- High surface quality (by surface coating)
- High temperature resistance (by special sealing)
- High vacuum level and low leakage rate

Empirical tests in parabolic flight and drop tower were used to derive a correlation between flame extinction and the temperature readings of the combustion chamber. Having developed this correlation, a simple "if – then" algorithm can be used in TEXUS to trigger the start of the exhaust gas sampling. The sampling process itself aims to avoid contamination effects and to keep the direct sampling time short to a minimum of *5 s*. Fig. 5 illustrates the front and the side view of the combustion chamber during the gas sampling with a simplified model of the gas flow. Due to the generated pressure drop, "fresh air" is entrained into the open combustion chamber. For a more detailed description of the related processes the reader may refer to Moesl et al. [9].

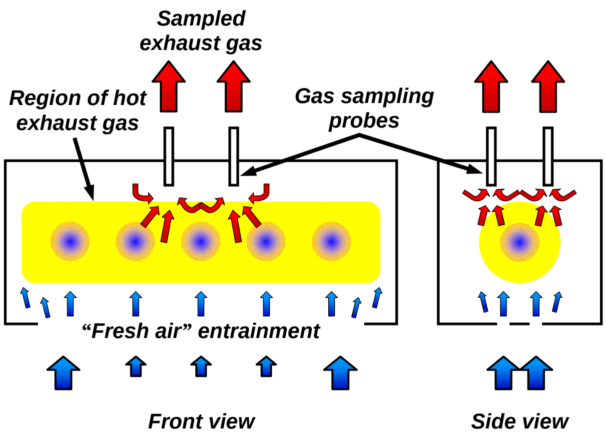

Figure 5. Sectional views of the combustion chamber during the exhaust gas sampling.

The gas analysis itself is ground-based and carried out by FT-IR (Fourier Transform Infrared) spectroscopy as well as by using a NO/NO_X chemiluminescence analyzer. Preliminary results from the precursor experiments in parabolic flight and drop tower are included in Sect. 4 as they will be used as a reference for the results from TEXUS.

4. PRECURSORY EXPERIMENTS IN DROP TOWER

An essential condition of the investigated combustion process is an equal and reproducible degree of fuel vaporization for all five droplets, which is perceivable by the vapor distribution formed around each droplet (cp. schematic of Fig. 5). Producing equally sized droplets of the uniform diameter d_0 is most important in achieving this constraint. In addition, given that there is a spatially uniform temperature in the combustion chamber, the droplet size at ignition d_{ig} yields to be a function of only the vaporization time t_w. Chin and Lefebvre correspondingly study the role of the heat-up period in droplet evaporation in an analytical way [13].

The flame propagation in the linear droplet arrangement has an averaging effect on combustion temperatures and exhaust gas production. The averaged production of thermal NO_X can therefore be considered as representing the NO_X quantities of what a single droplet produces as a single link in an infinite droplet array. Nevertheless, the density decrease of the gas inside of the combustion chamber, pursuant to the temperature increase during the combustion process, is one of the most critical issues of the experiment. It causes a volume expansion of a factor of approximately two. This effect, as well as the fresh air entrainment during exhaust gas sampling (cf. to Fig. 5), needs to be considered within the analysis process and the scientific interpretation of the results. Since the sounding rocket flight itself foresees only four combustion cycles, a statistical evaluation of the gas sampling/analysis procedures and a diversification of the experiment parameters became indispensable. Parabolic flight and drop tower experiments were consequently conducted to thoroughly investigate the reference case as well as to gain additional knowledge about the various technical aspects of the experiment.

4.1. Parabolic Flight Experiments

Utilizing the EM, a parabolic flight campaign (PFC) was conducted with Diamond Air Service (DAS) in Nagoya, Japan, in October 2007. The campaign consisted of two flight days with ten parabolas each. The microgravity duration was in the order of *20 – 25 s*. The main novelty for this campaign was the integration of the EGS system into the former DCU (cf. to Sect. 3). Therefore, the EGS' critical parameters were of major interest. The initial droplet diameter d_0, the inter-droplet distance S, and the number of droplets N were defined reflecting the following aspects:

- Total amount of fuel constant to that used on TEXUS.
- Length of droplet array identical to flight conditions on TEXUS (i.e. *72 mm*).
- Pre-vaporization of droplets promoted as much as possible with the available microgravity duration.

Tab. 1 gives an overview of the experiment parameters characterizing the droplet array of the main TEXUS experiment, the PFC setup flown by DAS, and the drop tower reference setup used at ZARM, which will be described further in Sect. 4.2.

Table 1. Experiment parameters for droplet arrays.

Campaign setup	d_0	S	N
TEXUS (Astrium)	*1.5 mm*	*18.0 mm*	*5*
PFC (DAS)	*1.2 mm*	*8.0 mm*	*10*
TEXNOX (ZARM)	*1.0 mm*	*4.5 mm*	*17*

The PFC was satisfying in terms of the qualitative and quantitative results. All subsystems were operable and produced useful results. Single measurement ranges could be adjusted in regard to their absolute limits and resolution. Four representative exhaust gas samples were collected, apart from tests on the data acquisition system's operability, the droplet lifting system's lifting speed, the optimum distance "first droplet – ignition wire", and the reheating capacity of the combustion chamber after a venting/evacuation process. All four gas samples showed a good consistency of the analyzed exhaust gas species CO_2, CO, NO, NO_2, N_2O, and H_2O (cp. Tab. 2). In comparison with equilibrium assumptions, the absolute values indicate a fresh air content of approx. 50%, which is due to mixing with unburned air and fresh air entrainment during the sampling process [9].

Table 2. Overview of averaged exhaust gas concentrations from precursor PFC.

Species	$t_w = 0.1\ s$	$t_w = 3.0\ s$
CO_2	*19 300 ppm*	*23 000 ppm*
CO	*2 120 ppm*	*2 030 ppm*
NO	*6.0 ppm*	*5.1 ppm*
NO_2	*1.2 ppm*	*0.0 ppm*
N_2O	*1.8 ppm*	*0.7 ppm*
H_2O	*14 900 ppm*	*29 800 ppm*

In addition, the effect of the surface coating with amorphous silicon was evaluated. This was done by collecting gas samples with a coated and an uncoated sampling cylinder for pre-vaporization with $t_w = 0.1\ s$ and *3.0 s* each. The coating reduces gas adsorption and prevents water wet-up, corrosion, coking, and catalytic as well as memory effects. For instance the measured water content from the two uncoated sampling cylinders was 18 – 39% lower than from the coated sampling cylinders. On the other hand, NO_2 and N_2O showed increased values for all uncoated sampling cylinders. The variation of the fuel pre-vaporization Ψ remained without any observable effect as the two values of $t_w = 0.1\ s$ and *3.0 s* are still too low to facilitate a significant change in the flame regime.

4.2. Drop Tower Experiments

The combustion experiments of the TEXNOX drop tower campaign included precursor experiments with droplet arrays consisting of nine to 17 droplets ("TEXNOX" being derived from TEXUS and NO_X). The campaign was conducted at the drop tower of ZARM (Zentrum für angewandte Raumfahrttechnologie und Mikrogravitation) and the EM was used again. Fig. 6 shows the DCU being integrated into the drop capsule structure of ZARM. Electronic controls and data acquisition devices are installed in its lower part. The original high-speed camera of the TEXUS-DCU is replaced by a unit of ZARM (*500 fps* for *5.2 s*).

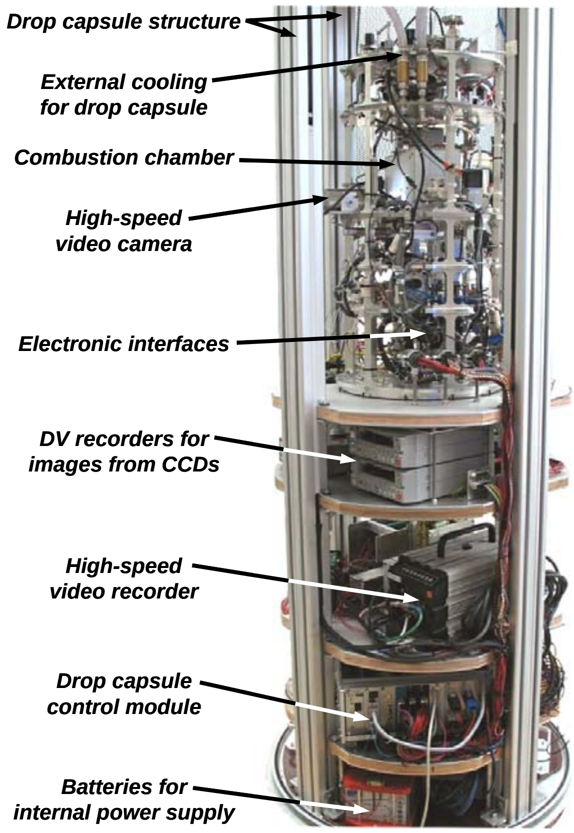

Figure 6. Drop tower setup with the DCU being integrated in the upper half of the drop capsule.

Different to TEXUS and the previously described PFC (cf. to Sect. 4.1), the combustion chamber was preheated to values in the range of *300 – 500 K*. The nominal droplet size was *1.0 mm*, but variations were run in the range of *0.84 – 1.07 mm*. The duration of the overall combustion process was determined by the total fuel mass, the number of droplets N, the inter-droplet distance S, the time of fuel pre-vaporization t_w, and the preheating temperature. Furthermore, it was limited by the available microgravity time of *4.74 s*, which in turn caused a limitation of t_w to $t_{w|max} = 1.0\ s$. In ideal runs, flame extinction occurred before the deceleration of the drop capsule. Exhaust gas sampling was started by timer-control according to the calculated time of deceleration (plus a predefined Δt). The data acquisition was implemented with a frequency of *1 kHz*. The recording of the CCD camera images was performed permanently by three DV recorders (droplet generation, normal view of the combustion chamber, and backlit information in order to determine d_0). The recording of the high-speed images was limited to the drop phase.

Fig. 7 displays NO measurements for different preheating levels and droplet sizes retrieved from the TEXNOX campaign. All data points are based on a droplet array consisting of 17 droplets. An increase of the preheating temperature generally results in an increase of the absolute NO values, which is due to the strong temperature dependency of the NO formed in the postflame gases. Moreover, the NO values of the series $d_0 = 0.9\ mm$ are 20 – 30% below the reference of $d_0 = 1.0\ mm$, which is mainly caused by the correspondingly lower fuel quantity. However, if these values are scaled to the reference of $d_0 = 1.0\ mm$, both series come to a complete match with each other at *300* as well as at *500 K*.

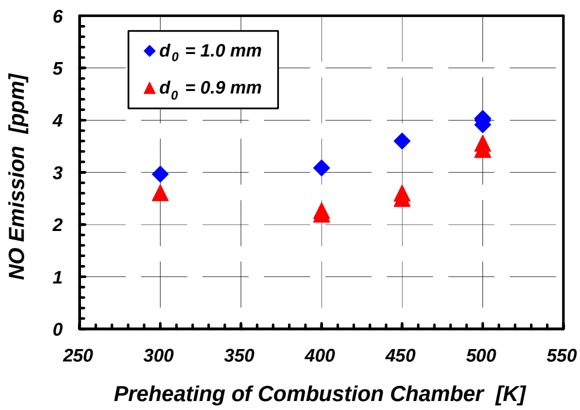

Figure 7. Precursor drop tower experiments with different droplet sizes and preheating levels.

Additionally, backlit images were taken on ground before each combustion run in order to determine the actual performance and the required operation time of the fuel pump iteratively. This helped to stay within a very narrow range of a predefined d_0. Air-bleeding approaches were tested along with this fuel pump optimization on the entire droplet array generation system, and recommended with regard to the operations during the TEXUS campaign.

5. FURTHER PROCEEDING

The JCM – the utilized experimental apparatus – is scheduled to fly on TEXUS #46. As the launch campaign could not be kept in line with the initial planning, a new launch window was defined for November 2009. Apart from this delay all reviews and tests up until the Module Acceptance Review (MAR) were completed successfully. The pending System Integration & Test will be performed within four to six weeks before the actual mission launch.

A further utilization of the EM in drop tower has been discussed between the involved parties but is currently not feasible before completion of the TEXUS campaign. Nomura et al. and Mikami et al. are in the meantime putting efforts towards the combustion of movable droplets and droplet clusters, which is the next step towards the systematic investigation on complex sprays [14, 15].

In order to further study the effect of premixing and pre-vaporization in droplet arrays, numerical studies are being performed as well. They will help to achieve a more complete understanding of the combustion and the NO_X forming processes. Further parameters to study (apart from the degree of vaporization Ψ) are the preheating temperature, the pressure, the inter-droplet distance S, the initial diameter of the droplets d_0, the total droplet number N, the fuel itself, and the superposition of a convective flow around the droplets.

6. CONCLUSIONS

Microgravity research can make a substantial contribution towards the development of novel combustion concepts that offer a high potential for improvement in environmentally neutral combustion engines. It allows the detailed observation of the most essential combustion phenomena without the disturbance of natural convection. This study addresses the question how partial vaporization influences the NO_X emissions of droplet and spray flames under such idealized conditions.

A linear array of five n-decane droplets is burned in microgravity without relative velocity to the ambient gas. The droplet array is suspended on SiC fibers and inserted into a preheated combustion chamber. One end of the array is ignited to initiate combustion. After flame extinction, exhaust gas is collected from the combustion chamber for all four, independent combustion runs. A sophisticated design and optimized control procedures are used to guarantee representative gas samples. The exhaust gas analysis is ground-based and performed by FT-IR spectroscopy and a NO/NO_X chemiluminescence analyzer.

The main experiment is performed on a sounding rocket flight by using the TEXUS environment. Its launch is currently scheduled for November 2009. Precursor experiments were conducted in a parabolic flight and a drop tower campaign with different focuses, but based on each other. The scientific quality of these precursory combustion runs was satisfying and the results showed good consistency. However, since the available microgravity duration was short, the feasible degrees of fuel vaporization Ψ remained low. As expected, no major effects of Ψ on the NO_X production could be observed. TEXUS will allow experiment cycles in the range of $40 – 120\,s$, and thus facilitate a thorough investigation of fuel pre-vaporization Ψ.

7. ACKNOWLEDGEMENTS

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