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Velocities of Reacting Boron Particles within a Solid Fuel Ramjet Combustion Chamber

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ABSTRACT

A 2D-laser doppler velocimeter was used to measure velocities of reacting boron (*B*) particles during the combustion of a metallised solid fuel slab inside a 2D-combustion chamber. The solid fuel hydroxyl-terminated polybutadiene (HTPB) was enriched with *B* particles to increase its specific heat. To obtain information on the combustion process and on the movement of *B* particles, their velocities were measured. The experiments were performed at ambient pressure. The behaviour of the *B* particles concerning the exit velocities from the fuel slab has been discussed on the basis of the experimental results.

1. INTRODUCTION

Addition of boron (*B*) to the commonly used hydrocarbon binders with the application of air breathing propulsion systems like solid fuel ramjets is of special interest due to its high volumetric and gravimetric heat capacity (Table 1). However, full usage of that heat capacity is limited due to the ignition and combustion of *B*, which may lead to incomplete combustion[1]. Several reasons can be attributed for this behaviour:

(a) The combustion is inhibited by a molten layer of B_2O_3 immediately after ignition, whose boiling temperature is about 2580 K.

(b) The boiling temperature of solid *B* is very high (about 2900 K), which results in relatively slow combustion rates if the oxide layer is removed.

(c) Agglomeration increases the size of *B* particles, slowing down their heating and combustion.

(d) Possible kinetic trapping of parts of the combustion products in gaseous form, particularly in the presence of hydrogen, resulting in appreciable loss of heat of condensation.

Natan and Gany[2] showed that for *B* particles, depending on their size, a minimum residency period of some milliseconds within the flame zone are required before they ignite. Experimental investigations by Clauss[3] using single *B* particles within a hot gas flow showed the particles to be strongly affected by the combustion products after ignition. Their flight path tends to form some kind of swirl curves. A recent study by Meinkohn[4] on the behaviour of thin films on reacting surfaces showed that the fluidised B_2O_3 layer may break up locally. Scanning electron microscope (SEM) pictures taken by Ciezki and Schwein[5] seem to confirm these results. At these free surface regions, the combustion process may restart, leading to local production of gas and acceleration of the particle movement.

The objectives of this investigation were to ascertain as to what extent this effect influences the

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combustion, to measure the velocities of exit of *B* particles from the solid fuel slab and to examine the influence, if any, on the velocity of the particles when ignited. For making the measurements, a laser Doppler velocimeter (LDV) was used.

Table 1. Heating values of fuels, assuming H_2O (gas), CO_2 (gas) and metal oxides (fl) as products

Fuel	Gravimetric heating (kJ/g)	Volumetric heating (kJ/m^3)
JP5	425	344
SHELLDYN-H	413	418
Coal	328	741
Al	310	837
$(CH_2)_n$	435	402
B	578	1349
Mg	247	431

2. EXPERIMENTAL SETUP

2.1 Combustion Chamber

A 2D-combustion chamber with a backward facing step and a rectangular cross-section of 150 mm width and 45 mm height, was used to perform the experiments (Fig. 1). The flame holding step height H was 20 mm. Air, vitiated by a hydrogen/oxygen burner, was heated up to 500 °C and fed via rectifiers and meshes into the combustion chamber. Behind the step, the solid was inserted into the lower wall of the test section. The fuel slab was 100 mm in width and 198 mm in length, i.e., a border of 25 mm on each side wall existed without any fuel to prevent the windows from getting covered with soot. Hydroxyl-terminated polybutadiene (HTPB) was used as fuel with the addition of 30 per cent particles by weight. The particle size of *B* was 1.75 µm (sauter size $D_{2,3}$ = 0.96 µm). A second hydrogen/oxygen burner whose flame passed for a short time through a slit at the lower edge of the step was used to ignite the fuel slab. Optical access for the LDV at arbitrary positions downstream the step was provided by movable window elements on each side wall. To prevent deposition of particles and soot on the windows, a special design was used. Each element was built from a converging tube of 100 mm length. The window on the side wall was of 17 mm width and 45 mm height. The outer side of the tube of size 45 mm x 45 mm was closed by a quartz glass window. A slight nitrogen flow was used to purge the windows. The influence of purge flow on combustion flow is negligible, as can be seen from the velocity data. Table 2 shows the overall dimensions of the combustion chamber.

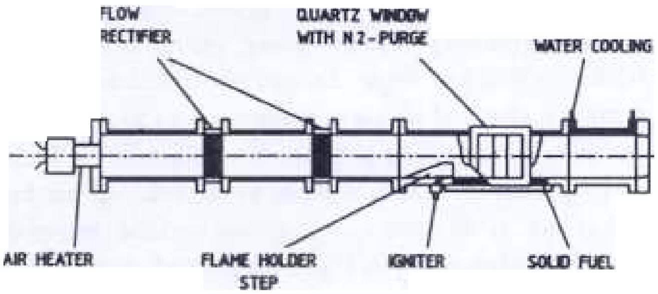

Figure 1. Cross-section of 2D-dump combustor

Table 2. Characteristic dimensions of the 2D-dump combustor of test section M11.2

Character	Dimensions (mm)
Width	150
Length	220
Height	45
Step height	20
Inner window width	17
Length of the fuel slab	198
Width of the fuel slab	100

No nozzle was attached to the exit of the combustion chamber. Thus, nearly ambient pressure was maintained inside. The velocity of the incoming vitiated air above the step was about 90 m/s with a mass flux of 150 g/s at 500 °C. Two inlets attached to the side of the air heater supplied TiO_2 seeding particles with a low air mass flux to facilitate LDV measurements. The average particle size of the seeding was 1µm. To avoid

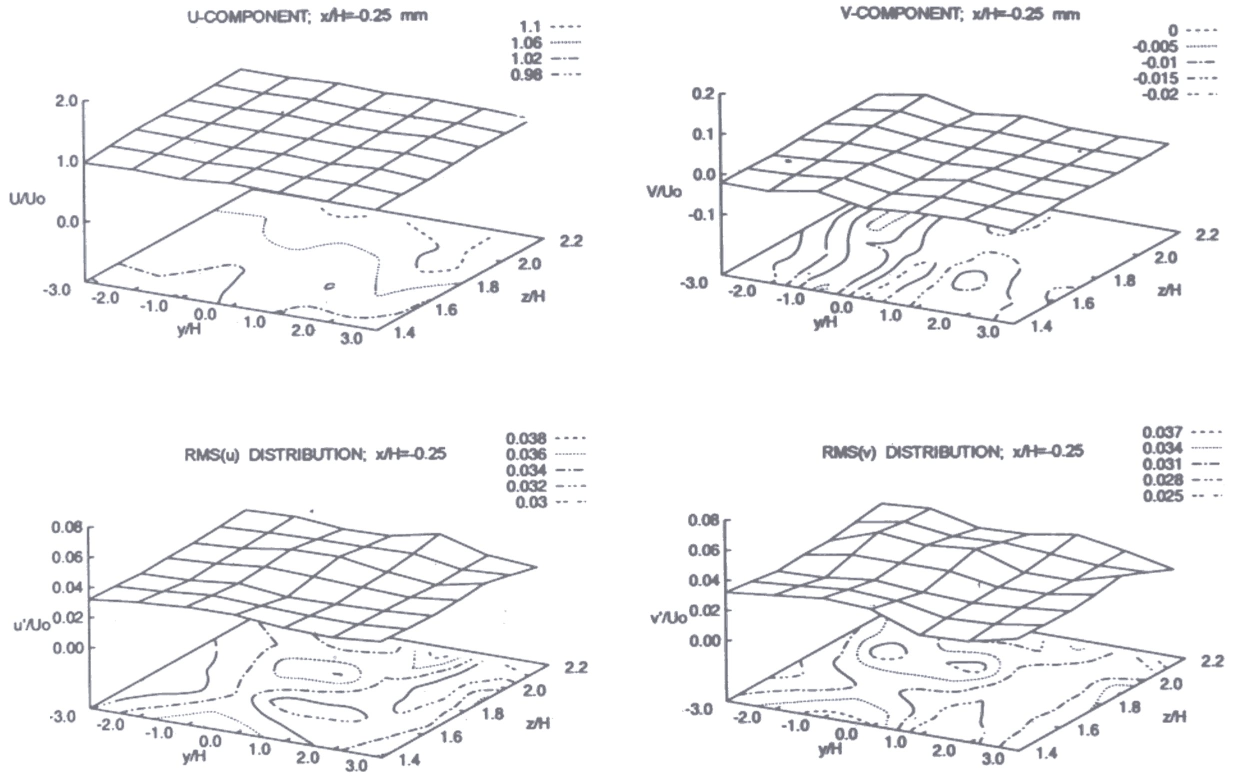

Figure 2. Entrance velocity profile at $x/H = -0.25$; $U_o = 94$ m/s

agglomeration, the particles were dried before use. The seeding was performed using a swirl generator.

Figure 2 shows the normalised velocity distribution directly above the flame holding step at $x/H=-0.25$ corresponding to a Reynolds number (Re_H) of 22800.

2.2 Instrumentation

A 2D-laser Doppler velocimeter from Dantec, equipped with a 5W argon ion laser (Innova 90, Coherent) and two burst spectrum analysers (BSA, Dantec) was used to measure the velocities using forward scatter sampling. The focal length of the transmitting lens was 300 mm. The conversion factor for this configuration was 8.67 ms^{-1}/MHz for 514 nm and 8.23 ms^{-1}/MHz for 488 nm. The beam pairs were rotated at 45° along the z-axis to improve resolution for both x and y velocity components. A total of 6100 samples were taken at each measurement point, scanning the incoming LDV signal at 5k Hz. The LDV was mounted on a 3D-traversing unit controlled by a PC. Data reduction was done using standard software.

2.3 Experimental Procedure

Four configurations (a,b,c,d) with different mass fractions of both TiO_2 and B particles were selected to clarify the visibility of burning B particles with LDV measurements (Table 3). For each configuration, velocities for one cross-section (at x/H=4.75) were measured.

The coordinate system used was located at the lower edge of the step in the centreline of the combustion chamber at ignition time. During run time, the surface of the fuel slab was lowered due to combustion. The regression rate was about 0.06 mm/s, i.e. the overall difference before and after the experiment which took 2 min was about 7 mm. Two runs were necessary to complete one cross-section velocity profile. The reproducibility of flow conditions and thus velocities from run-to-run was excellent. The velocity profiles were taken vertically starting at the ground in each case,

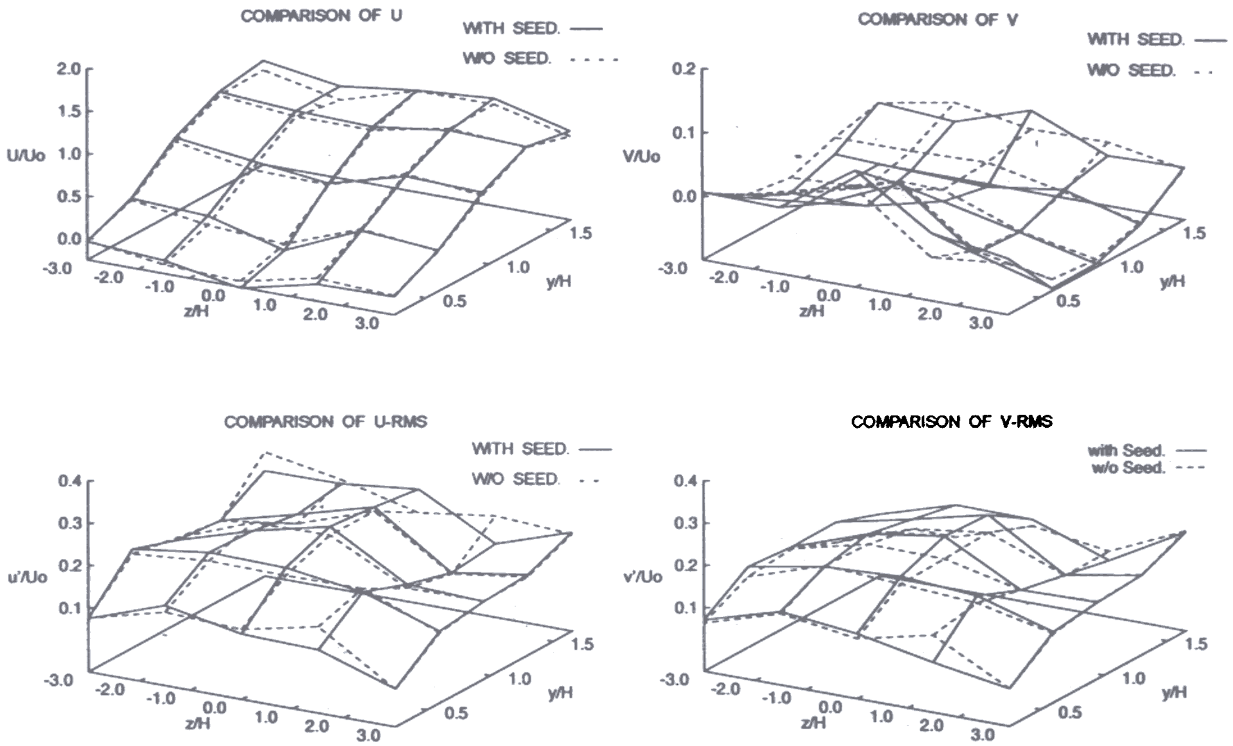

Figure 3. Comparison of velocity and RMS values with and without seeding of the plug flow at x/H = 4.75; U_o =91 m/s; fuel: 30% *B*/HTPB.

to reduce the influence of regression on the coordinate origin during one vertical profile measurement. Thus, the change in geometry was not considered for the data reduction.

Table 3. Configuration of experiments (giving mass fractions of particle additives by weight)

	Main flow (Solid fuel with)	2	
		Without TiO_2 seeding	With TiO_2 seeding
a	No additive		x
b	*B* (30 %)		x
c	TiO_2 (30 %)		x
d	TiO_2(5 %) and *B* (25 %)	x	x

For *Case* 1, cross-section velocity profiles were measured at

x/H= -0.25, 0.75, 2.75, 4.75, 6.75 and 8.55.

The measurement grid for each cross-section

y/H = 0.25, 0.6, 0.95, .3, and 1.65

z/H = -3.0, -1.5, 0.0, 1.5, and 3.0

3. RESULTS

3.1 Boron Particles used as Seeding

Figure 3 shows two-velocity and RMS profiles at x/H=4.75 measured for configurations 1 (d) and 2 (d), i.e. solid fuel with *B* particles without seeding of the plug flow i.e 1 (d) and the plug flow seeded in 2 (d). Both cases show an increase in mean velocities with increase in distance from the fuel slab. The agreement for the profiles within all four diagrams is good, i.e. there is no significant difference whether the outer flow is seeded or not. The RMS values show the typical shape of a step flow. Comparing the horizontal and vertical velocity components, it can be seen that the ability of the *B* particles to follow the flow is comparable to that of TiO_2 particles. On comparison of the RMS profiles, it appears that there is no additional velocity component due to ignition and combustion of the particles, as was observed earlier by Clauss[3] with a laboratory setup. This means that it is correct

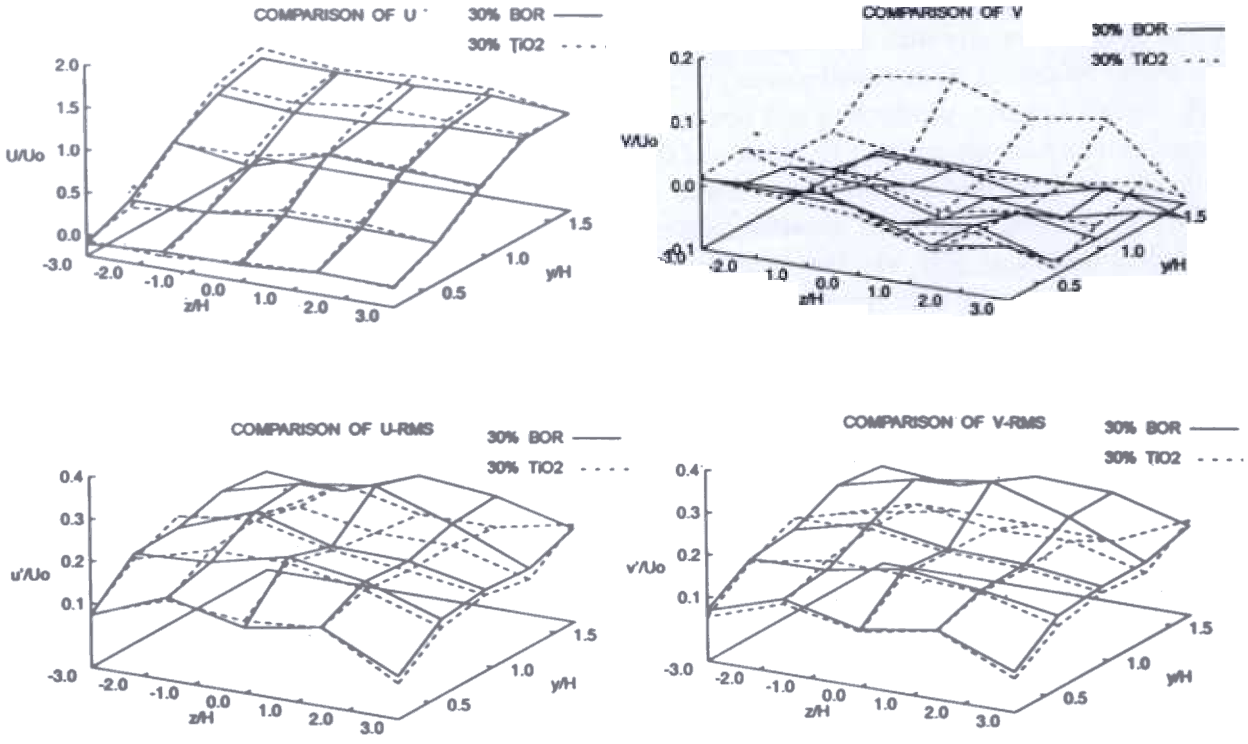

Figure 4. Comparison of velocities and RMS for 30% *B*/HTPB and 30% TiO_2 /HTPB; $x/H = 4.75$; $U_o = 93$ m/s

to measure velocities by means of LDV using *B* particles while additionally seeding the air flow under the conditions adopted in the present study.

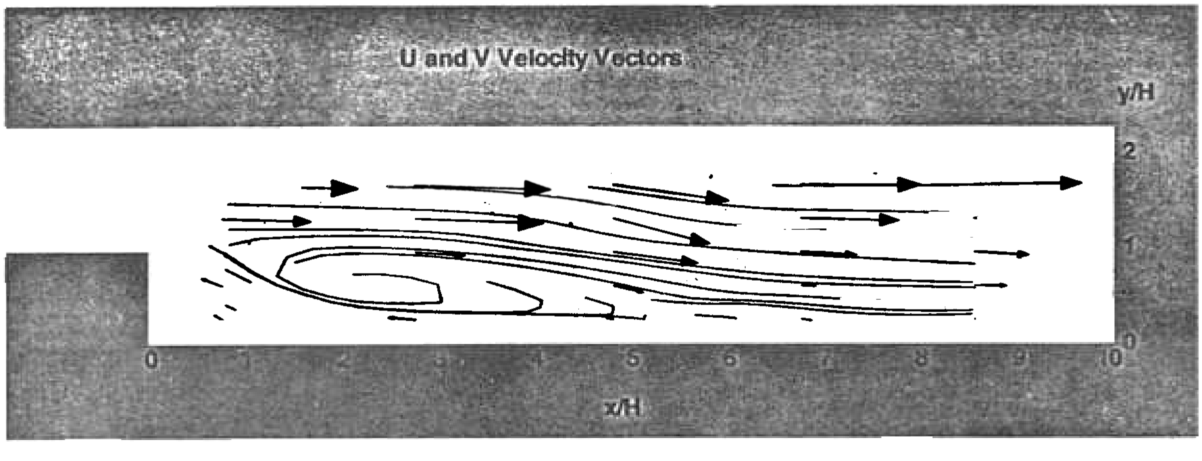

Figure 5. Vector plot with streamlines at $z/H = 0$; $U_o = 91$ m/s; fuel: 30% *B*/HTPB

3.2 Comparison of Reacting and Non-Reacting Boron Particle Phases

Figure 4 shows the mean velocities and RMS values of the *U* and *V* components for combustion of solid fuel with 30 per cent *B* (*Case* 2 (b)) and 30 per cent TiO_2 (*Case* 2 (c) and Table 3) at the position $x/H = 4.75$. No significant differences for the *U* component between the two cases can be seen. Close to the fuel surface, the *U* is negative, indicating the re-circulation zone behind the step. With increasing distance from the lower wall, *U* values increase reaching finally the value of the main flow. The RMS values for both cases show similarity close to the wall. Above y/H=1, the RMS for *Case* 2(b) shows significantly higher values. This seems to be caused by the combustion process and the increased energy production and not by an additional velocity component due to motion of the *B* particles, as mentioned above. The *V*-mean is constantly decreasing and is in good agreement close to the wall. For $y/H > 1$, the velocity for *Case* 2 (b) (*B* additive) is still decreasing, whereas for *Case* 2 (c) (inert additive), the trend changes and the values become positive for $y/H > 1.6$.

Figure 5 depicts the velocity vectors in the $z/H = 0$ plane (centre of the channel from $x/H = 0$ to x/H=10 measured for *Case* · 2 (b) (*B*-additive). Additionally, calculated streamlines were plotted. The re-circulation zone behind the step can be recognised clearly. The region after that zone shows the velocity vectors being oriented horizontal or slightly slanted towards the lower wall. This indicates that *B* particles that leave the fuel slab do not intrude into the far-region of the flow, but remain close to the wall from where they are transported downstream. This is in agreement with the results of Gany and Netzer[6], who identified particle trajectories by means of a high speed camera. It was shown for similar flow conditions that particles of size 100 µm reached a maximum distance of 3 mm from the wall within the region scanned. However, the possibility to measure velocities in the outer flow for *Case* 1 (b) (*B*-additives without seeding outer flow) and the results of Ciezki and Schwein[5] indicate that there are *B* particles in that region and that these particles must have originated from the re-circulation zone.

4. SUMMARY

The velocity field in a 2D-dump combustor using solid fuel with *B*-additives was measured with LDV. The added *B* particles were used successfully as tracer particles. Additional seeding of the incoming air flow did not reveal differences in comparison to measurement without seeding of the incoming air. Under the flow conditions adopted, the *B* particles followed the flow without slip. No significant proper motion due to ignition and local combustion on the particle surface could be seen. Orientation of the velocity vectors behind the re-circulation zone was horizontal or slightly downward indicating that *B* particles in the outer flow originate from the re-circulation zone directly behind the step. No vertical outlet velocity from the fuel slab in the region $0.2 < y/H < 1.65$ was noted.

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