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BURSTING BUBBLES FROM COMBUSTION OF THERMOPLASTIC MATERIALS IN MICROGRAVITY

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INTRODUCTION

Many thermoplastic materials in common use for a wide range of applications, including spacecraft, develop bubbles internally as they burn due to chemical reactions taking place within the bulk. These bubbles grow and migrate until they burst at the surface, forceably ejecting volatile gases and, occasionally, molten fuel. In experiments in normal gravity, Kashiwagi and Ohlemiller[1] observed vapor jets extending a few centimeters from the surface of a radiatively heated polymethylmethacrylate (PMMA) sample, with some molten material ejected into the gas phase. These physical phenomena complicated the combustion process considerably. In addition to the non-steady release of volatiles, the depth of the surface layer affected by oxygen was increased, attributed to the roughening of the surface by bursting events. The ejection of burning droplets in random directions presents a potential fire hazard unique to microgravity. In microgravity combustion experiments on nylon Velcro fasteners[1][2] and on polyethylene wire insulation[3], the presence of bursting fuel vapor bubbles was associated with the ejection of small particles of molten fuel as well as pulsations of the flame. For the nylon fasteners, particle velocities were higher than 30 cm/sec. The droplets burned robustly until all fuel was consumed, demonstrating the potential for the spread of fire in random directions over an extended distance.

The sequence of events for a bursting bubble has been photographed by Newitt et al.[4]. As the bubble reaches the fluid surface, the outer surface forms a dome while the internal bubble pressure maintains a depression at the inner interface. Liquid drains from the dome until it breaks into a cloud of droplets on the order of a few microns in size. The bubble gases are released rapidly, generating vortices in the quiescent surroundings and transporting the tiny droplets. The depression left by the escaping gases collapses into a central jet, which rises with a high velocity and may break up, releasing one or more relatively large drops (on the order of a millimeter in these experiments).

A better understanding of bubble development and bursting processes, the effects of bursting behavior on burning rate of the bulk material, and the circumstances under which large droplets are expelled, as well as their trajectories, sizes, and burning rates, is sought through computer modeling compared with experiment.

EXPERIMENTAL EVIDENCE

The combustion behavior of three types of thermoplastic spheres in microgravity, PMMA, polypropylene (PP), and polystyrene (PS), have been recently studied by Yang and Hamins[5] in a set of experiments flown on the NASA Lewis DC-9 Reduced-Gravity Aircraft. Figure 1 shows sequences from two events recorded during these experiments. In each case there is a sudden disturbance to the flame front, not noticeable in the previous frame. This disturbance decays slowly over the next few timeframes and is advected in the direction of a spherically

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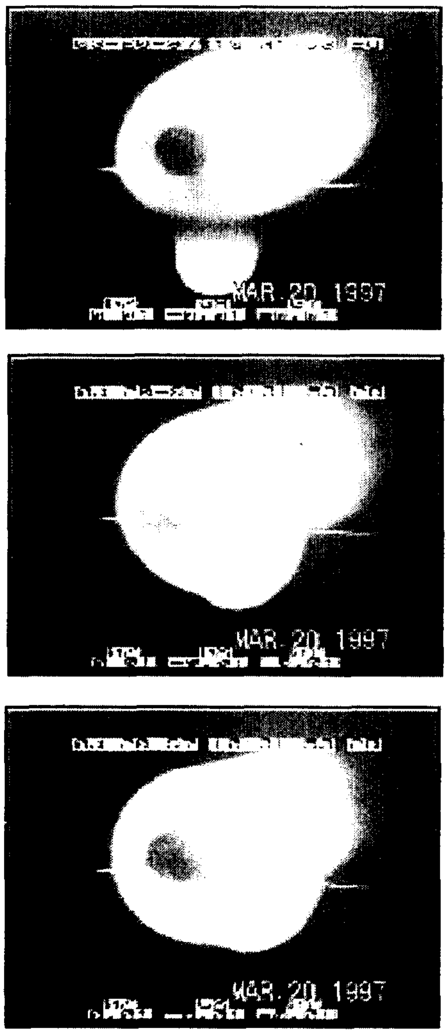
[1] Certain trade names and company products are mentioned in the text in order specify adequately the equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.



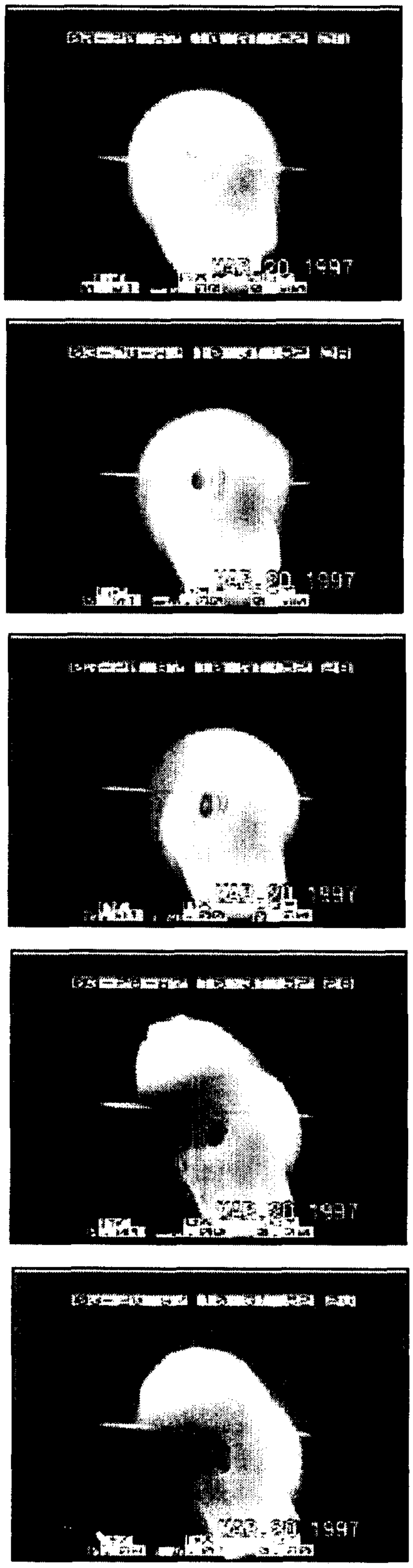


Figure 1: Images from combustion of a PMMA sphere in microgravity. On the left is a sequence of frames showing a developing flamelet in side view. In the previous frame, the lower surface of the flame front was undisturbed. On the right is a sequence showing a developing flamelet emitted toward the camera.

Figure 2: Trajectory of a particle emitted from a PP sphere.

asymmetric flow due to g-jitter. The structures displayed in these two sequences are similar to those of vortex-flame front interactions such as those reported by Roberts and Driscoll[6]. Events of this nature take place frequently during combustion for all three types of thermoplastics.

The ejection of a particle is displayed in Figure 2. Unlike the gaseous events shown in Figure 1, these events do not significantly distort the flame front, and the burning droplet travels in a straight line away from the sphere. Regrettably, the flame front surrounding the droplet is highly luminous, and droplet size could not be measured. Ejected particles were observed for PP but not for PMMA or PS, suggesting a dependence of droplet release on material properties.

MODELING

The bubble bursting process involves large interface deformations and topological changes. A model of this phenomenon must track the distortion of the fluid surface as the bubble approaches, the evolving distribution of the volatile gases released by the burst, the formation of a central jet of melted material, the potential breakup of the jet into one or more droplets, and the trajectory of these droplets away from the melt surface. In addition, the combusting thermoplastic problem must include heat transport and degradation chemistry.

In order to satisfy these requirements, the bubble bursting model applies a diffuse-interface approach based on extended irreversible thermodynamics[7]. This approach adds density gradients to the set of thermodynamic variables, allowing continuous variation of density between phases and providing the ability to follow complex motions of an interface without the need to explicitly track its location. The fluids treated by this model may be compressible, multiphase, and multicomponent. Balance equations of mass, momentum, and energy are rigorously satisfied, and the entropy of a material element of fluid increases or stays the same, as required by the second law of thermodynamics.

The model consists of three separate fluid components representing the polymer melt, a gas that is generated by chemical degradation of the polymer, and an unrelated gas outside of the melt. The effects of the growing bubble on the temperature and flow of its surroundings are included. Using this model, one or more bubbles are studied as they grow, travel toward a heated surface, and burst through the interface into the gaseous component. The formation of a jet is observed, and the conditions under which the jet breaks up and melted material is released into the surroundings are determined. For those cases in which droplets are ejected, their size and velocity are determined.

FUTURE WORK

A three-dimensional model of a combusting thermoplastic sphere in microgravity, including heat transport and the nucleation, growth, and migration of multiple bubbles is under development[8]. Data obtained from the bursting bubble model on the release of gases and molten material for various types of thermoplastics will be added to this model.

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