Estimating Bubble Plume Dynamics in Breaking Waves using the Thermal Signature of the Residual Foam

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Abstract

This study is motivated by the observation that after a wave breaking event in the ocean, the residual surface foam left in the wake of the breaker rapidly cools down. The relationship between the cooling foam and the characteristics of the breaking wave such as bubble plume dynamics, visible surface foam, and energy dissipation is investigated experimentally. Previous studies have suggested that the decay time of the visible foam can be used to determine the dynamics of the subsurface bubble plume, and to estimate the energy dissipation by the breaking process. But the foam decay process can be greatly affected by the surfactant concentration in the ocean and this effect need to be accounted for independently. We present a new approach that utilizes the thermal signature of the cooling foam to infer the breaking characteristics and is less sensitive to surfactant concentration. The experiments are conducted in a wave flume that is equipped with a piston-type wavemaker and is filled with salt water. In order to study the effects of surfactants on the cooling of the residual foam, two sets of experiments are carried out; In the first set clean salt water is used and in the second set, Triton X-100 at a concentration of approximately 200 mg/L is added to the water. Breaking waves are generated using the focusing wavepacket technique and are designed to cover a wide range of slopes and breaking intensities. The bubble plume and the surface foam are imaged using visible cameras and the surface temperature is captured using an IR camera with an overlapping field of view with the visible foam camera. It is observed that the average temperature of the foam initially increases after the passage of a breaking wave due to the disruption of the cool skin layer, but the foam starts to cool down soon after the bubble plume has subsided, and the foam regeneration is not sustained by the bubbles anymore. It is found that the time from the start of the breaking process to the onset of cooling of the foam (τcool) scales with the decay time of the bubble plume (τplume), energy dissipation, and the wavepacket slope of the breakers. It is also observed that the foam decay time is prolonged greatly by the presence of additional surfactants (consistent with the literature), but the bubble plume decay time and the onset of cooling of the foam are not significantly affected.

ON THE THERMAL SIGNATURE OF THE RESIDUAL FOAM IN BREAKING WAVES

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Introduction

- Remote sensing application: inferring subsurface bubble plume dynamics from the residual foam signal in breaking waves
- Previous studies have suggested that the decay time of the visible foam can be used to determine the dynamics of the subsurface bubble plume, and to estimate the energy dissipation by the breaking process [1, 2].
- The foam decay process can be greatly affected by the surfactant concentration in the ocean and this effect need to be accounted for independently.
- This study is motivated by the observation that after a wave breaking event in the ocean, the residual surface foam left in the wake of the breaker rapidly cools down.
- We present a new approach to characterizing the subsurface plume dynamics that utilizes the thermal signature of the cooling foam to infer the breaking characteristics and is less sensitive to surfactant concentration.

Setup

- The experiments are conducted in a wave plume that is equipped with a piston-type wavemaker and is filled with salt water.
- Surfactants: Two sets of experiments are carried out; In the first set clean salt water is used and in the second set, Triton X-100 at a concentration of approximately 200 μg/L is added to the water.
- Breaking waves are generated using the focusing wavepacket technique and are designed to cover a wide range of slopes and breaking intensities.
- The bubble plume and the surface foam are imaged using visible cameras and the surface temperature is captured using an IR camera with an overlapping field of view with the visible foam camera.

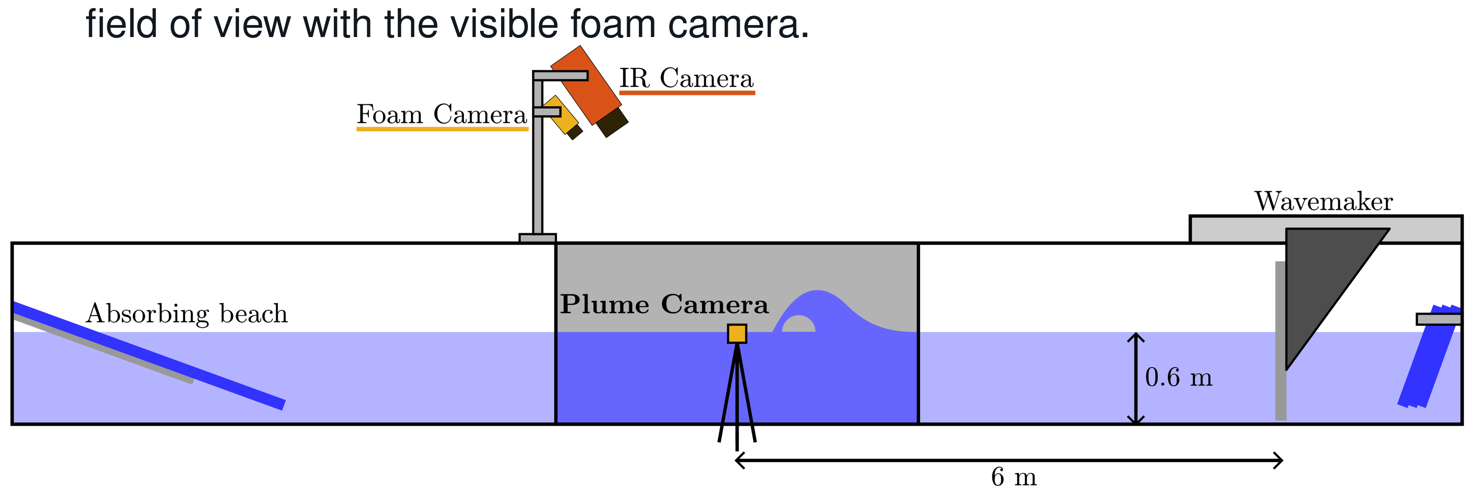

Fig. 1: Schematic of the experiment setup

Experimental Condition

- For the experiments presented here, four breakers with global slope values of $S =$ 0.34, 0.35, 0.36, and 0.37 were used.
- The global slope of the packets scale with the total energy dissipation. This range of slopes corresponds to a range of 74-105 J/m in energy dissipation.
- The air temperature varied during the experiments due to the diurnal cycle, but the temperature difference ($\Delta T = T_{water} - T_{air}$) was in the range of zero to 2 degrees Celsius for all the experimental runs.
- For each wave slope and for a condition with or without additional surfactants, between 50 to 60 runs were recorded and analyzed (462 breakers in total).

Observations

- Visible bubble plume and foam images are converted to B/W images to obtain the plume and foam coverage timeseries. The bubble plume decay time and foam decay time are calculated from the timeseries.
- There is little difference between clean water and surfactant-added cases, both in the amount, and the persistence of the bubbles.
- The longevity of the foam is increased for the cases with additional surfactants and there is more variation among individual runs in the presence of surfactants, especially at later times.

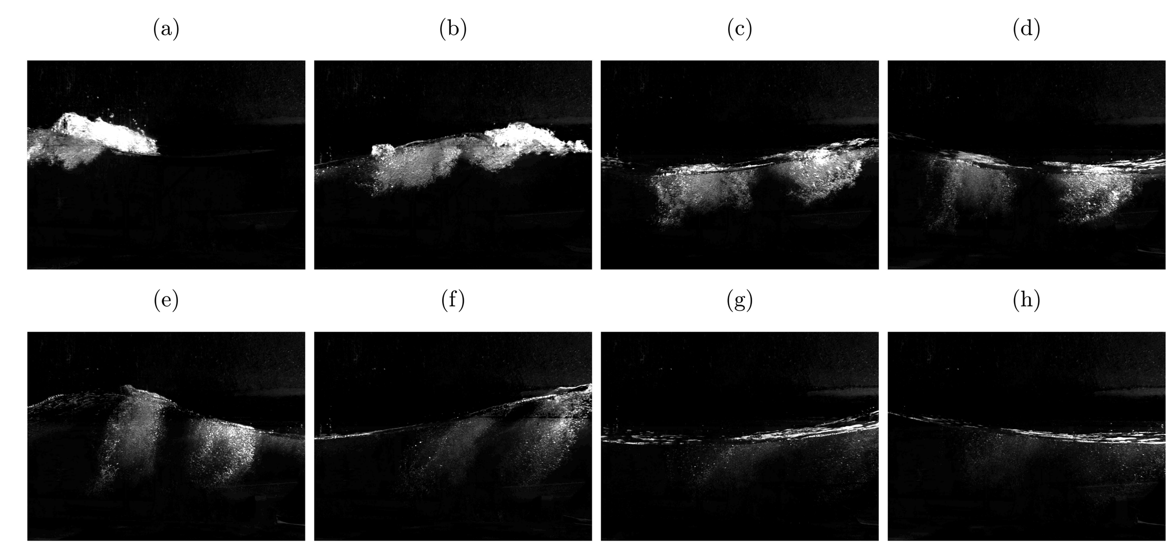

Fig. 2: A sequence of bubble plume images for S = 0.37

- A foam mask is extracted from the visible foam images and is then applied to the corresponding frames of the IR images to isolate the regions covered by foam from the rest of the image.
- The mean temperature of the foam, T_{foam}, is plotted versus time in Figure 4 for all the experimental conditions.
- The foam temperature initially increases because of the disruption of the cool skin layer, then plateaus for a short time and then starts to decrease. The duration of the plateau increases with the slope of the wave packet and the onset of the cooling of the foam is delayed for the larger breakers.

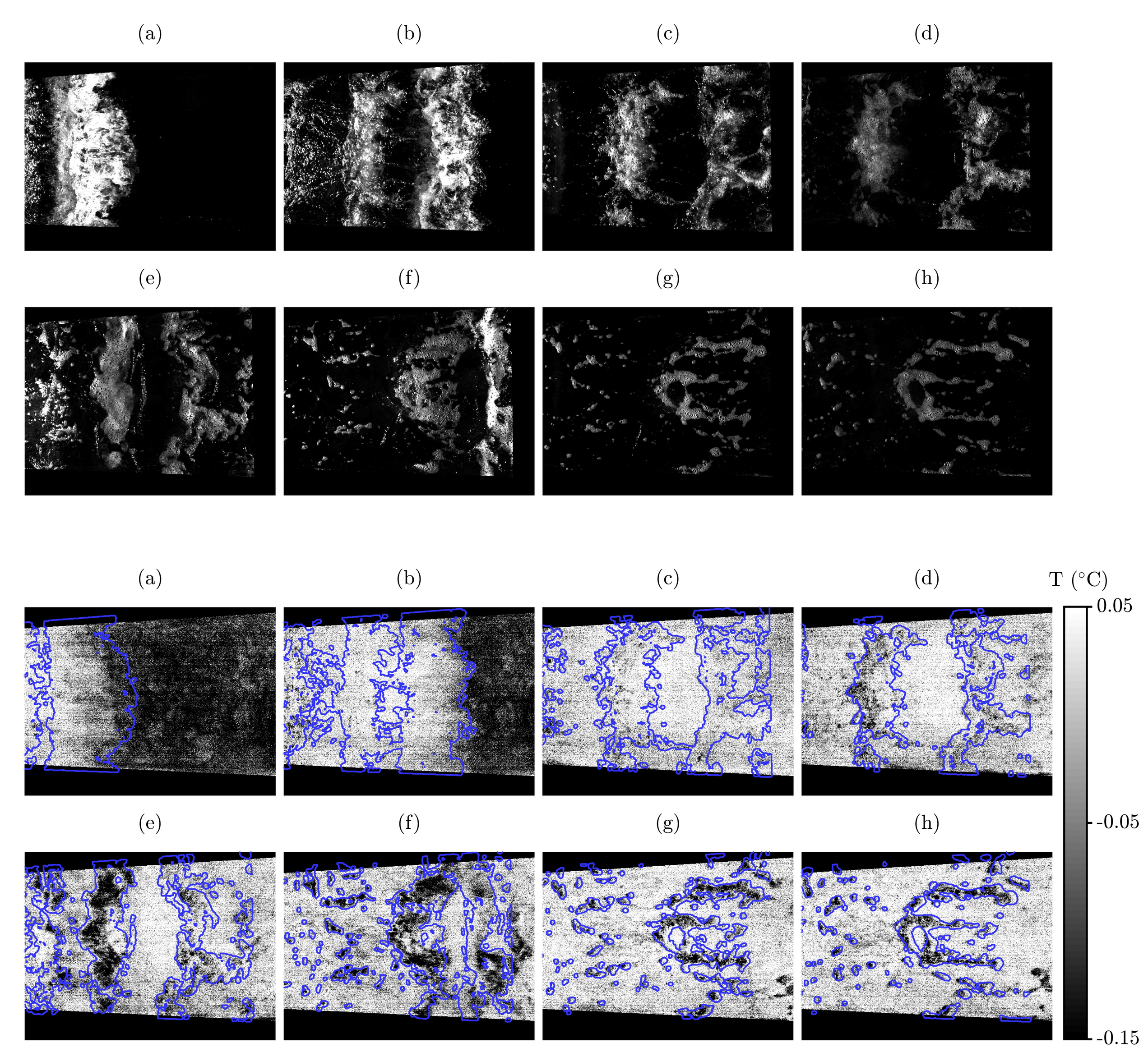

Fig. 3: A sequence of visible foam (top) and surface temperature (bottom) for S = 0.37

Results

- The onset of cooling, τ_{cool}, is defined as the time when the mean foam temperature, T_{foam} falls below a certain threshold from the maximum.

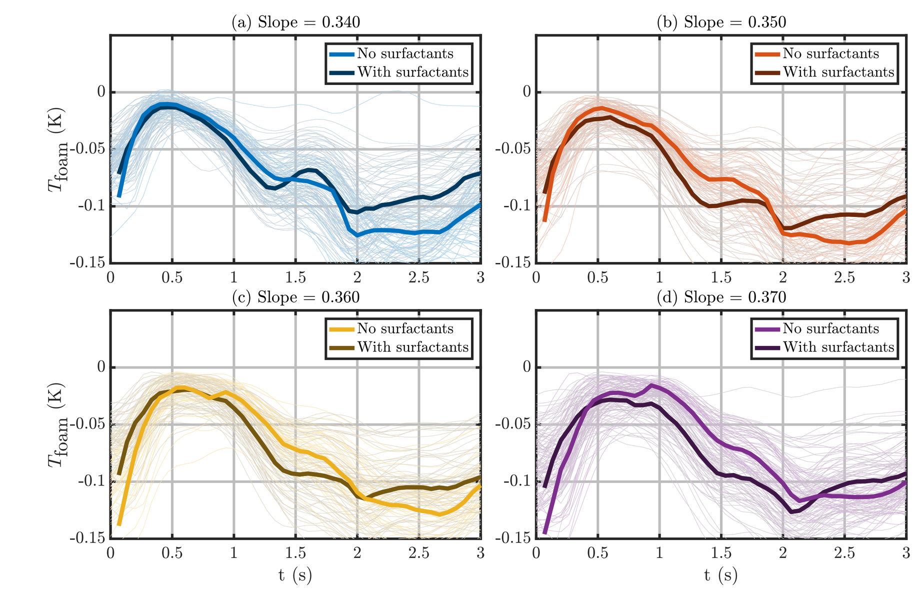

Fig. 4: Mean foam temperature versus time.

- τ_{cool} varies almost linearly with τ_{plume} in both cases and there is negligible difference between the surfactant-free and surfactant-added cases.
- The water-air temperature difference, $\Delta T = T_{water} - T_{air}$, does not seem to have a meaningful effect on τ_{cool} for the explored range.

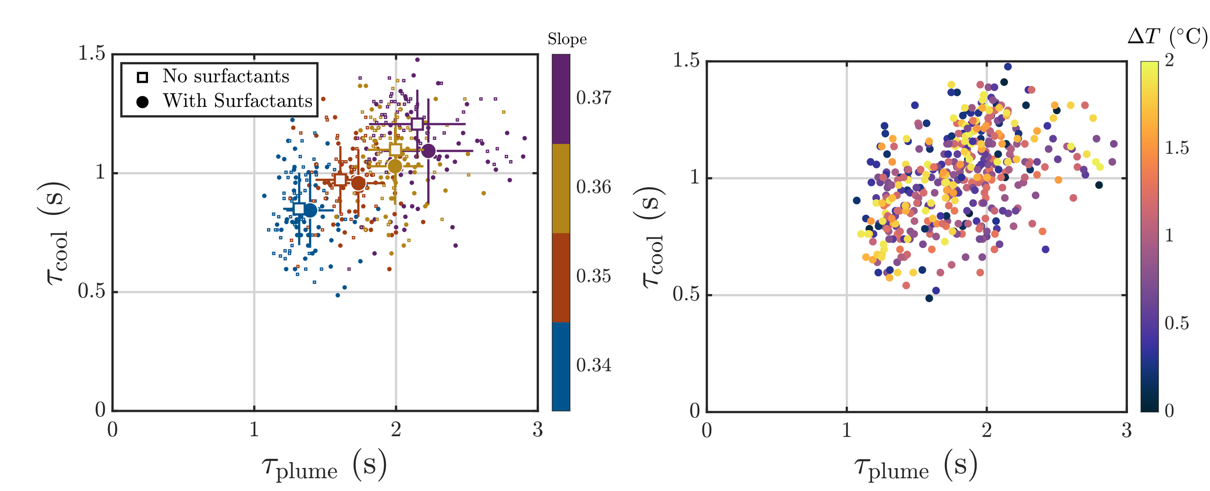

Fig. 5: The cooling time, τ_{cool}, versus the plume decay time, τ_{plume}.

Acknowledgements

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References

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[2] Adrian H. Callaghan, Grant B. Deane, and M. Dale Stokes. "Two Regimes of Laboratory Whitecap Foam Decay: Bubble-Plume Controlled and Surfactant Stabilized". In: *Journal of Physical Oceanography* 43.6 (2013), pp. 1114–1126.

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