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Investigation of Simulated Melting Instability Waves Near Stagnation Region in Hypersonic Flow

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Melting waves in hypersonic flow were simulated at room temperature with parabolic frozen oil models for gas Reynolds number, N_{Re_g}, 15,000 to 37,000, liquid Peclet number, β, 1 to 10^{-3}, for inverse Froude number, G, 1 to 7, and for gas Prandtl number of order one. Results show that Kelvin-Helmholtz instability waves were generated at $N_{Re_g} < 25{,}000$ and $\beta < 0.005$, shear instability waves at $N_{Re_g} < 25{,}000$ but at $\beta > 0.005$. Three-dimensional waves were observed at an approximate increase of 5000 in gas Reynolds number. Inclusion of high temperature data of quartz and Tektite agreed with the simulated wave pattern.

Nomenclature

A	= acceleration in ft/sec^2
C	= $\omega\lambda/U_\infty$ nondimensional wave velocity
ω	= the number of waves generated per second
U_∞	= wind velocity, fps
L	= R, radius of model, in ft
ρ_g	= density of air, slugs/ft^3
ρ_l	= density of liquid, slugs/ft^3
C_{pg}	= specific heat, Btu/slug °R
μ_g	= viscosity of gas, slugs/ft sec
K_g	= thermal conductivity Btu/ft sec °R
P_{rl}	= $C_{pl}\,\mu_l/K_l$ liquid Prandtl number
C_{pl}	= specific heat for liquid, Btu/slug °R
μ_l	= viscosity of liquid, slugs/ft sec
K_l	= thermal conductivity of liquid, Btu/ft sec °R
Λ	= λ/R nondimensional wavelength
λ	= wavelength, ft

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Introduction

ONE of the aerodynamic features of re-entry and entry vehicles through any atmosphere may be the melting ablation in the stagnation region of hypersonic flow. The melting waves generated at the gas-liquid interface play an important role in flight dynamics as well as the heat transfer characteristics. High-temperature tests of such hypersonic flow is a costly task and it is rather difficult to make detailed observations of the type of melting waves present. Conversely an approximated low-temperature simulation can be achieved at a lower cost and provides a longer experimental duration and observation of actual motion of melting waves.

Chen and Ostrach[1] showed a close similarity between simulated melting ablation experiments in a deceleration field using frozen oil model and the actual Tektites described and shown by Chapman.[2,3] In fact when right similarity parameters are simulated the forward portion of the perimeter wave was very similar in appearance of wave spacing and wave amplitude. They also suggested that melting pattern near the stagnation region in the hypersonic flow may resemble that of water waves generated on a thin film as investigated by Craik.[4] Craik showed the existence of slow waves that correspond to Kelvin-Helmholtz instability waves and the existence of fast waves that correspond to the shear instability waves. The slow (fast) wave is defined

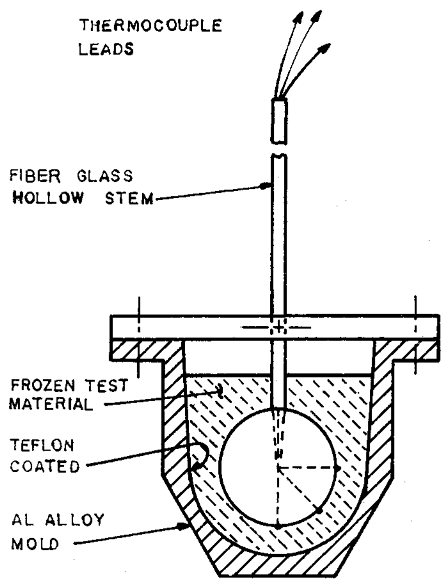


Fig. 1 Test model configuration.

as the wave whose wave speed is slower (faster) than the gas-liquid interfacial speed. Slow waves are generated when the joint influence of the component of normal stress in phase with the wave elevation and the component of tangential stress in phase with the wave slope is sufficient to overcome the stiffness of the liquid surface due to surface tension. Craik[4] also found three dimensional (3-D) waves behind the two dimensional (2-D) fast waves when wind speed is increased. Craik's experimental data plotted with liquid film Reynolds number versus the wind velocity shows that instability may occur whatever the wind velocity provided that the water film is made sufficiently thin. In case of melting phenomenon the thickness of the melting layer corresponds to that of water film. However, the melting layer depends on the heat transfer across the gas-liquid interface and on the melting or softening point of the material. Chen and Ostrach[1] thus suggested that when the Craik's liquid film Reynolds number is replaced by liquid Peclet number a similar instability pattern between water waves on thin films and melting waves in hypersonic flow near stagnation region may exist. They did not however, verify this conjecture.

The present paper verifies this postulation and gives experimental data identifying the slow 2-D waves and the gast 2-D

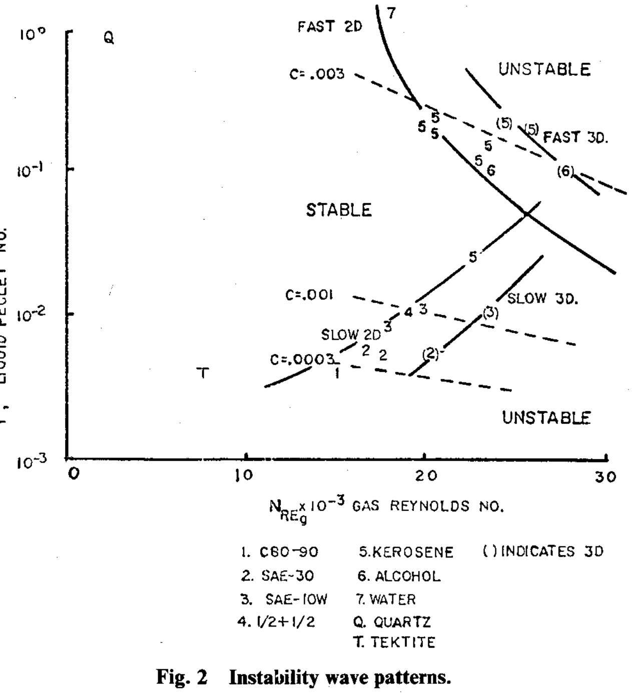


Fig. 2 Instability wave patterns.

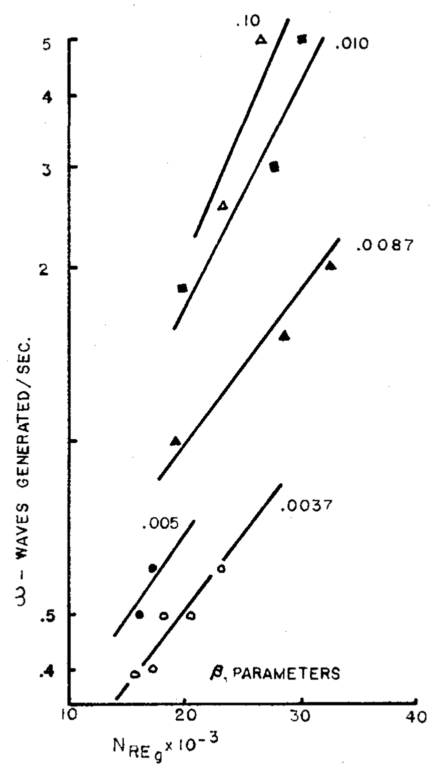


Fig. 3 Wave velocity.

waves, the fast 3-D wave, and the heretofore unannounced slow 3-D waves. The investigation conducted herein covers wide range of liquid Peclet number, β, and gas Reynolds number N_{Reg}, and encompass the unstable slow ring waves of Tektites as well as the stable (without waves) ablation of quartz experimented by Adams, Powers, and Georgiev.[5]

Simulation Analysis

Details of simulation analysis was given by Chen.[6] The basic simulation parameters determined for atmospheric entry and re-entry are: a) the gas Reynolds number, $N_{Reg} = U_\infty L\rho_g/\mu_g$; b) the gas Prandtl number $P_{rg} = C_{pg}\mu_g/K_g$; c) the inverse Froude number, $G = AL\rho_l/U_\infty^2\rho_g$; d) the liquid Peclet number, $\beta = P_{rl}N_{Rel}$; where $N_{Rel} = \mu_g^2\rho_l/\mu_r^2\rho_g$ which is the ratio of the conventional liquid Reynolds number to the conventional gas Reynolds number when the reference liquid velocity is taken as $\mu_g U_\infty/\mu_r$; and e) the heating parameter $N_\gamma = K_l\beta^{1/2}/K_gP_{rg} = (T_\infty - T_r)/(T_r - T_{-\infty})$; where the subscript r refers to the gas-liquid interfacial condition, the subscript g refers to the gas and the subscript l refers to the liquid with its properties evaluated at, T_r, the reference temperature that is determined by the heating parameter.

The first and second parameters are obtained from gas momentum and energy equations while the third and fourth are from liquid momentum and energy equations. The fifth parameter was derived from the thermal boundary condition at the gas-liquid interface. To simulate the high-temperature melting phenomenon at a low-temperature environment, T_∞ for example at room temperature, we choose a melting material (liquid phase at T_∞) to be frozen at $T_{-\infty}$ thus, at the reference interface temperature, T_r, determined from the heating parameter, gives the same value of the parameters N_{Reg}, $P_{rg}G$, and β for the chosen materials at high temperature. Some sample values for melting of Tektite, quartz, and frozen oil models were given by Chen and Ostrach.[1]

From the preceding, we see that for any combination of atmospheric condition and ablation material a melting flow can approximately be simulated at low temperature conditions provided that the radiation and evaporation effects are negligible. For a blunt body in the hypersonic flow because of bow shock,

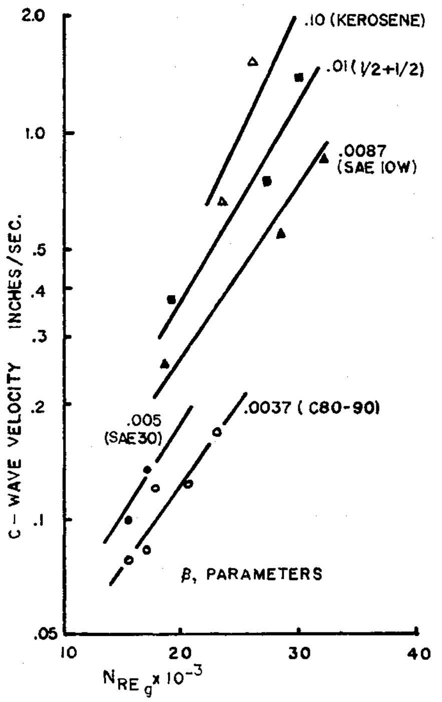


Fig. 4 Waves generated/sec.

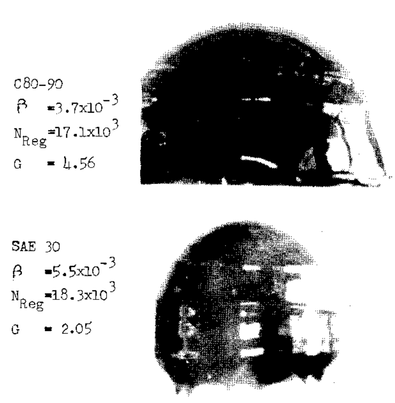


Fig. 6 Slow 2-D waves.

the gas flow is subsonic near the stagnation region, the simulation can be achieved in a subsonic tunnel. Similarily for the flow away from the stagnation region where gas flow is supersonic the simulation can still be achieved in a low temperature supersonic tunnel.

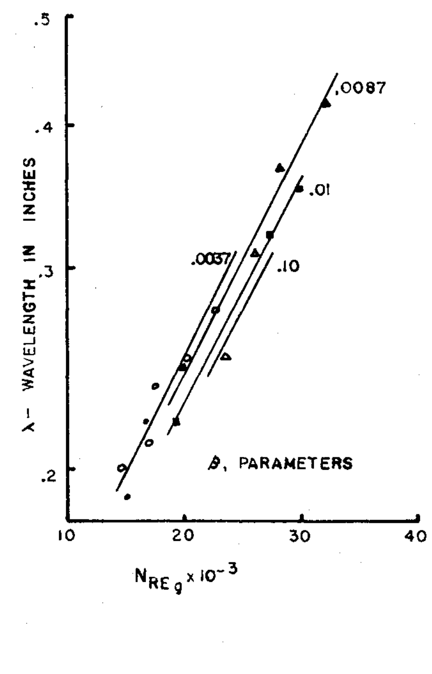
Experiment

The test model as shown in Fig. 1 was constructed from a 2-in.-diam hardwood sphere mounted on a hollow fiber glass rod 18 in. long. Copper-constantan thermocouples wire was embedded in the surface of the sphere for measurements of inner temperature, $T_{-\infty}$. A parabolic model was constructed from aluminum alloy and its interior was coated with teflon. In preparation of the test model with simulation ablative materials the 2-in.-diam sphere was inserted in the model and positioned such that a $\frac{1}{2}$-in. layer of test material was frozen in place in a low temperature liquid nitrogen bath. The mold was subsequently released in warm water where the aluminum mold dropped away. The test model was then quickly dipped into the liquid test material, removed, and momentarily permitted to melt prior to refreezing in liquid nitrogen. The model was then lowered into the cold nitrogen gas and soaked for about 10 min to attain a uniform temperature in the model. The ablative materials used were water, alcohol, and Mobil Oil Corporation kerosene, SAE-10W, SAE-30, and C80-90. In addition equal volumes of kerosene and SAE-10W were mixed and used as a test material. These materials allow three order of magnitude of liquid Peclet number (10^{-3} to 1) when they are evaluated at reference temperature, T_r.

The melting ablation experiments were conducted in a low speed vertical down draft wind tunnel with a 12 × 15-in. working section and 10–90 fps velocity range. The working section was constructed from transparent plexiglass to permit viewing of the ablation phenomena and recording via a 16 mm Kodak movie camera at a frame rate of 24 frames/sec. The wind velocity was measured with a pitot-static probe located midway between the test model and wind-tunnel wall. The temperature of the frozen model, $T_{-\infty}$, was recorded on a Beckman type RS Dynograph direct writing recorder. The ambient air temperature was measured with a calibrated mercury thermometer. This test set up produced a gas Reynolds number range of 7000 to 67,000 and an inverse Froude number range of 1.2 to 7.1.

The frozen blunt nose oil model was affixed to a cross member in the 12 × 15-in. working section of the wind tunnel. The wind tunnel was turned on and the wind velocity was gradually increased until the inception of instability waves was observed (a ring wave surrounding the stagnation point). With the wind velocity stabilized the 16 mm camera was turned on, the inner temperature of the model noted on the strip chart, the ambient air temperature and wind velocity were recorded. In order to obtain wave length, wave velocity, and wave frequency in the amplified region as well as three dimensional waves, the wind velocity was increased in several increments and all test data recorded as above. The preceding tests were repeated using the simulated ablation materials previously noted. The data was recorded and is shown in Figs. 2–5. Detailed data was given by Kuzyk.[7]

Fig. 5 Wavelength.



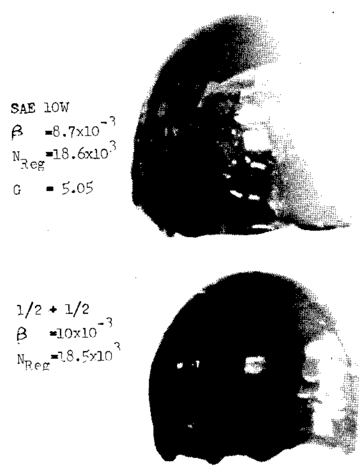


Fig. 7 Fast 2-D waves.

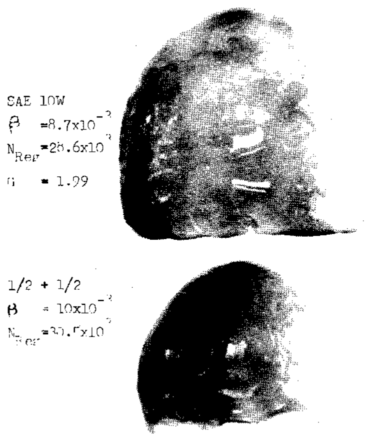


Fig. 8 Fast 3-D waves.

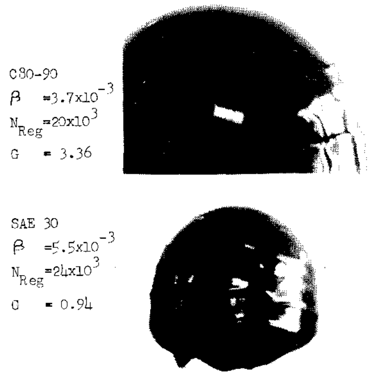


Fig. 9 Slow 3-D waves.

Results and Discussion

The inception of instability wave data is shown in Fig. 2. It is observed that the patterns derived experimentally are strikingly similar to the patterns obtained by Craik[4] with our liquid Peclet number β and gas Reynolds number $N_{\mathrm{Re}g}$, corresponding, respectively, to Craik's liquid film Reynolds number and air velocity. In our simulated ablation the inverse Froude number G varied from 1 to 7, and the gas Prandtl number remains constant. Therefore for small inverse Froude number the body force will not significantly alter the melting phenomena particularly near the stagnation region. Thus, instability patterns given in Fig. 2 is also valid for fixed inverse Froude and gas Prandtl number and no additional parameter need be shown. Two additional test points representing actual high temperature ablation data are shown in Fig. 2 for a) Tektite $\beta = 0.0035$, $N_{\mathrm{Re}g} = 17{,}000$ (Ref. 2) (unstable), b) quartz $\beta = 0.8$, $N_{\mathrm{Re}g} = 11{,}500$ (Ref. 5) (stable). These two data points fall in their respective regions. This is a further verification that low temperature melting simulation is a valid procedure.

In greater detail the results show the inception of the slow 2-D waves (those nearest to the stagnation point, i.e., the first instability wave formation, Fig. 6 occur at liquid Peclet number less than 0.05 and gas Reynolds number, $N_{\mathrm{Re}g}$, less than 25,000. These waves resemble the slow wave as defined by Craik[3] with wave velocity ranged from 0.0003 to 0.001 (normalized by freestream gas velocity, U_∞); as shown in Figs. 4 and 5. The ablative materials used for this region were frozen C80-90, SAE-30, SAE-10W, 1/2 SAE10W + Kerosene, and Kerosene. The inception of the fast 2-D waves (Fig. 7) occurred at liquid Peclet number greater than 0.05 and gas Reynolds number less than 25,000. These waves are characterized by a much faster wave velocity of 0.002 to 0.003. These waves were of increased frequency, and more sinusoidal in appearance than the steep fronted and long shallow through of the slow waves. The sinusoidal appearance was especially predominant in the ice model. The ablative materials used for these models were kerosene, alcohol, and water. Admitting the analogy of melting waves and water film waves, the works of Cohen and Hanratty[8] and Craik[9] may be extended to explain that the fast melting waves are generated, owing to the irreversible transfer of energy from the gas mean flow, to small surface disturbances.

At approximately a 5000 increase in gas Reynolds number beyond the fast 2-D waves we observed the formation of 3-D instability waves as shown in Figs. 2 and 8. The notable difference being that the 3-D melting waves appeared as wavy ring waves in lieu of circular ring waves as for the fast 2-D waves. The longitudinal wave length of the 3-D waves is slightly longer than that of the 2-D waves as shown in Fig. 5. This qualitatively agrees with the prediction of the shear instability that in the amplified region near the upper branch of stability curve the wave length is larger than that of the neutral value. It is observed that the transverse wave length of the 3-D waves is approximately of the same order as that of the longitudinal wave length. On the other hand the slow 3-D waves which was not mentioned by Craik[4] were observed in the present experiment as shown in Figs. 2 and 9. These slow 3-D waves are characterized by a sharp ridge and flat trough with a decrease in film thickness. It seems that the melted liquid is carried down stream mainly by the ridge portion of the wave. Craik[4] mentioned that when the water film is very thin, dry patches may form on the plate. This, perhaps, is the reason that the slow 3-D waves did not appear in his experiment.

The dimensional wave velocity, wave frequency, and wave length are shown in Figs. 3, 4, and 5. Figure 5 shows that the wave length λ increases as liquid Peclet number β decreases for a given gas Reynolds number. On the other hand the wave length λ increases with gas Reynolds number for a given liquid Peclet number. An increase in liquid Peclet number physically means an increase in convective heat transfer and hence increase in liquid thickness. Figures 3 and 4 show that the wave velocity C and wave frequency ω increase with liquid Peclet number β at constant gas Reynolds number, and increases with gas Reynolds number for a given liquid Peclet number.

Conclusion

The mechanism of simulating melting instability waves near stagnation region in hypersonic flow has been experimentally demonstrated. The melting wave patterns are plotted quantitatively and verify Chen and Ostrach's[1] postulated analogy between thin water wave patterns of Craik[4] and melting waves. In addition two actual high-temperature test points representing Tektites and quartz are shown to agree with the simulated patterns.

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