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"The Stability of Particulate Ladden Laminar Boundary-Layer Flows"

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The Stability of Particulate Ladden Laminar Boundary-Layer Flows

During the course of this investigation, the following two topics were studied theoretically:

I. Forced convection and sedimentation past a flat plate

Consider the steady, laminar flow of a suspension of sedimenting solid particles past a horizontal flat plate. Far from the plate, the free stream velocity $\vec{U}_{\infty}$ and the particle concentration ϕ_s are both uniform. We also suppose that the particle Reynolds number is vanishingly small.

The prototype for this situation is that of air flowing past the wing section of an aircraft under heavy rain and high windshear. Aircraft behavior under such conditions has been studied with increasing interest in past ten years due to a number of accidents which occurred in a heavy rain environment under cirucmstances where windshear could have been a contributing factor (Dunham, 1987). Most of these accidents took palce at low altitudes, while the aircraft was either landing or taking off. Extensive experimental investigations on commercial airfoils conducted at NASA (Campbell & Bezos, 1989; Bezos et al., 1992) seem to indicate a pattern of decreasing lift capability and increasing drag coefficient with increasing intensity of rain, especially when the airfoils are in the high lift configuration, as is the case during landing or take-off. In addition, flow-patterns captured via the use of ultraviolet strobe light reveal that, at low angles of attack, a liquid film is formed that covers the wing surface. The flow remains attached and, at some point downstream, the thin film breaks up into rivulets that run towards the trailing edge. As the angle of attack increases, the rivulets begin to form closer and closer to the leading edge of the airfoil until, at very large angles of attack, corresponding to stall conditions, the film disappears and the flow separates with significant performance loss. It is believed that the interaction between the thin liquid film and the surrounding boundary layer is responsible for the above pattern (Campbell et al. 1989).

The long-range objective of this project was to identify the various factors determining the dynamics of the flow and then to develop a theoretical framework for modeling such systems. To this end we note that the flow within the film is a shear flow induced by the airstream above it. When the time scale needed for liquid droplets to coalesce with the film is comparable with the time required for the droplets to reach the gas-liquid interface, one would expect the concentration of the droplets suspended in the gas stream to increase smoothly from its value in the free stream as the suspension-liquid film interface is approached from above. This takes place within a thin layer, where shear-induced particle diffusion (Leighton and Acrivos, 1986) counteracts sedimentation and thereby could, in principle, establish a steady state drop concentration profile. With increasing drop concentration, the suspension viscosity also increases, and hence the tangential velocity at the interface will decrease. As a result, the shear rate will decrease within the film, thereby significantly affecting its stability characteristics.

Early attempts to model the effect of rain on airfoils accounted for the loss of momentum due to the impact of a concentrated rain-cloud on a fast moving aircraft (Rhode, 1941; Haines and Lueres, 1982). In addition, Haines and Luers (1982) calculated the influence of the film formation on the lift and drag by equating the waviness of this layer to an equivalent sand grain roughness and then used empirical data for the effect of roughness on airfoil performance.

During its early phase, this project focused on a more fundamental investigation of the interaction between the thin liquid film and the gas boundary layer above it, while avoiding the use of empircial correlations.

We began with a very simplified model by taking the flow to be laminar, and treating the raindrops as solid spheres due to the action of surface impurities (Levich, 1962). We also ignored the effect of the raindrops splashing on the airfoil surface and limited ourselves to the case of zero angle of attack in order to eliminate the influence of free convection, thus simpliyfying the analysis. Since a significant amount of research has been performed on the stability of surface waves on water film surfaces under wind stress (Kapitza, 1964, Saric and Nayfeh, 1975 and Renardy and Renardy, 1993 among others) we focused on the effect of a non-uniform drop concentration profile on the flow of the airstream past the airfoil. To this end, we neglected the film and airfoil thicknesses and lumped these two regions into a single flat stationary plate. We therefore supposed that the rain drops are convected past this flat surface onto which they sediment, without first coalescing, thereby forming a concentration boundary-layer the thickness of which is limited by shear-induced particle diffusion. Above this region a Blasius-type momentum boundary layer exists, as in the case of dry laminar air flow at large Reynolds number. To be sure, in reality, raindrops escape the concentration layer and coalesce with the film region. Moreover, when we replaced the suspension-film interface by a solid flat plate we ignored the rate of coalescence when formulating the boundary conditions and this is bound to reflect on the results of the analysis. Consequently, and in view of the above-mentioned assumptions, the results emanating from such a study are not directly applicable to the problem of determining the effects of rain falling on an aircraft and should be viewed merely as a first attempt towards constructing a more comprehensive model.

From a mathematical point of view, the problem described above is similar to that considered by Nir and Acrivos (1990) in their study of sedimentation onto an inclined plate, in which a concentrated sediment flows along the inclined plate due to gravity. In that case, the shear created within the flowing sediment gives rise to shear-induced particle diffusion which opposes the sedimentation flux and prevents the particles from accumulating onto the upper surface of the plate. This occurs within a thin region close to the wall, termed the viscous layer, where viscous forces are balanced by buoyancy. In fact, the structure of that solution has several points in common with that of free convection heat transfer from a vertical plate at high Grashof and Prandtl numbers with the notable difference that the particle concentration profile is discontinuous across the interface separating the suspension from the flowing concentrated sediment. The effective medium model developed by Nir and Acrivos (1990) was recently extended by Kapoor and Acrivos (1995) who also tested experimentally a number of theoretical predictions pertaining to the thickness of the sediment layer and the corresponding particle velocity profiles, and confirmed the theoretical results which were arrived at through *ab initio* calculations that did not entail the use of adjustable parameters. Hence, in view of the reliability of this effective medium model, we performed such calculations for the problem at hand in order to determine the degree to which the particle concentration profile is affected by the presence of forced convection.

We began by representing the flow system in terms of an effective medium model and then reduced the basic equations to their boundary layer form. We showed that the stucture of the resulting mathematical system is similar to that which describes laminar heat transfer from a flat plate to a fluid stream moving past it at high Reynolds and Prandtl numbers. We also showed that, given the expressions relating the effective properties of the two-phase mixture to the particle concentration, the system of equations can be recast into one involving only the single parameter, ϕ_s i.e. the particle concentration in the free stream. We next constructed a similarity solution valid near the leading edge of the plate, according to which the particle concentration within the diffusion layer approaches smoothly its constant value, ϕ_s, in the adjacent momentum layer without experiencing the discontinuity found by Nir and Acrivos (1990) in the absence of forced convection. Finally, we solved the boundary layer equations numerically, and thereby obtained a solution valid over the entire length of the plate. We found that the particle concentraiton along the top side of the plate increases monotonically from its value at the tip, ϕ_s, and then, if the plate is long enough, reaches its maximum possible value, ϕ_m, at which point a stagnant layer is formed the thickness of which is predicted to increase continuously in time. In contrast, along the underside of the plate, the particle concentration was found to decrease monotonically until a particle-free region is attained.

The complete solution of the problem outlined above was presented in a recent publication by Pelekasis and Acrivos (1995).

II. The effect of rain on airfoil performance

As was said earlier in the introduction to Part I, it is believed that the interaction betwen the thin liquid film and the surrounding boundary layer is one of the factors responsible for aircraft stall under conditions of heavy rain (Campbell et al, 1989).

We decided to investigate the plausibility of this mechanism from a more fundamental standpoint. The basic idea is that the presence of the gas-liquid interface accelerates flow separation and thus induces performance losses. This is not quite obvious because studies on the effect of roughness on the behavior of airfoils do not predict such significant effect as that observed under flight conditions, and the volume fraction of rain particles, even for very intense rainfall (r=50 in/hr), is very small, $\phi_s = 4\times10^{-5}$. This places serious doubts as to the extent of the importance of the intensity of rain, and consequently, of the flow inside the liquid film. In addition, it is well documented that transition to turbulence is beneficial, as far as airfoil performance is concerned, because it delays separation. Therefore the instability that would cause performance deterioration cannot be of the type usually observed in boundary layer flows. At this point, it should be noted that the strobe light photos mentioned earlier in Part I were obtained for a certain intensity of rain. For the purposes of identifying a mechanism, a series of photos showing the pattern of flow separation for incrasing intensity of rain at a given large angle of attack, would be desirable. Unfortunately, such a comparison is not provided so far, by the available reports. Such an experimental study would also provide estimates of the length scales invovled; liquid film thickness, wavelength of the instability that distorts the interface and gives rise to rivulets and finally the distance from the leading edge where separation occurs, all as a function of the intensity of rain. However, there are a number of studies that report performance losses with increasing intensity of rain, without any mention of the specifics of the flow pattern.

We decided to try and obtain a rough estimate of the thickness of the liquid film for conditions as similar as possible to the ones present in the experimental investigations, and in the context of a simple base flow, and then to perform a stability analysis on this base flow. The idea is the following. Due to the curvature of the airfoil there will be a pressure gradient in the main gas-stream. By design, this will be such that it will postpone separation as much as possible. The secondary flow that arises as a result of the instability will distort the interface and produce a pressure gradient whose magnitude will be determined by the ratio between the amplitude of the disturbance and its wavelength A/l. Clearly, a linear analysis would not be of much help since we need pressure gradients large enough to overturn the effect of the main flow. For this reason the amplitude of the disturbance A will be assumed to be of the same order as the thickness of the film, H_f, as prescribed by the base flow. Thus the secondary flow can be described via a perturbation in the small parameter, H_f/l, with $l << L$, L being the length of the airfoil chord. Another important large dimensionless number involved in the analysis is the Reynolds number in the gas stream defined as, $\mathrm{Re} = \frac{UL}{\nu}$, with U being the free stream velocity and ν being the kinematic viscosity of the air. In addition, the ratio r/U is always a very small number. Finally, the gravitational Bond number $Bo = \frac{gL}{U^2}$, is an important parameter, for non-zero angles of attack, along with the angle of attack α and the angle between the vector of gravity and the free stream velocity, β.

As a first step, and in order to simplify the analysis and establish the perturbative method of approach, we took the flow to be steady and laminar and the angles α and β to be zero and $\frac{3\pi}{2}$. We also assumed that the aspect ratio of the airfoil is so small that it can be treated as a flat plate throughout the analysis. As a result, gravitational effects are not accounted for and the pressure gradient in the base flow is zero. This is not a very realistic situation but we felt that it was going to help us get a rough estimate of the liquid film thickness and simplify the stability analysis. We also took the spanwise direction to be much larger than L and H_f so that only variations within a plane defined by the cross-section of the airfoil had to be considered. Finally, we assumed that the raindrops enter the liquid film at a constant rate r and at right angles with respect to the plate. Because of the very small volume fraction of the raindrops in the free stream, ϕ_s, we neglected shear-induced migration, thereby assuming a constant raindrop concentration everywhere in the gas stream.

For very large values of Re and $\frac{H_f}{L} << 1$, the effect of the liquid film on the main irrotational flow is negligible and for the purposes of our analysis we need only consider the interaction between the Blasius type boundary layer that occupies the region in the gas stream attached to the interface with the film, and the liquid film itself.

At first we simply solved the equations describing the flow within the liquid film on the assumption that the latter is imbedded within the Blasius boundary layer. This gave us the first term of what we thought was the first term of the leading edge expansion of the solution as well as the corresponding expression for the liquid film thickness H_f. The latter was found to be proportional to the product of $r^{1/2}$ and $x^{3/4}$, where, as above, r is the rainfall velocity and x is the distance along the plate from the leading edge.

Unfortunately, in spite of several attempts, we were unable to continue this expansion to higher orders in x and thereby concluded that a steady-state solution to our problem as posed, does not exist. In other words, we came to realize that the shear exerted on the liquid film by the Blasius velocity profile is not of sufficient magnitude to permit the film to flow. Consequently, it would seem that, according to this scenario, the film thickness would be expected to grow steadily in time.

At this point, our project had to be terminated because our grant was not renewed.

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