Air Flow and Turbulence in Boundary Layers

Shortly after arriving at NBS in 1929 as an employee in the Electrical Division, Galen B. Schubauer enrolled in a graduate study program at Johns Hopkins University in Baltimore, as did about two dozen of his newly hired colleagues. These studies required a commute to Baltimore several times per week. The difficult trip was made more efficient by cramming six to eight students into a 1930s sedan, which made the trip much more arduous. During his graduate studies, Schubauer's interest began to focus on aerodynamics, and on boundary layer phenomena in particular. Consequently, he transferred to the Aerodynamics Section of NBS, then headed by Hugh L. Dryden, where he began an illustrious career of research on this topic.

His 1935 paper, *Air Flow in a Separating Boundary Layer* [1], provided great insight into separation (or stall) of a laminar boundary layer developing over an airfoil with the cross-section of an elliptic cylinder. The purpose of the work was to test an approximate solution to the applicable flow equations advanced by K. Pohlhausen. Schubauer's experimental results showed that Pohlhausen's solution produced good agreement in the forward portion of the surface, but it began to fail near the separation point on the surface and could therefore not be used to predict the location of the separation point. The next paper, *The Effect of Turbulence on the Drag of Flat Plates* [2], concerned the effects of free-stream turbulence on four objects: a flat plate, a thin circular disk, a vane anemometer, and a Pitot static tube. The results indicated that there is no appreciable effect of turbulence on the vane anemometer and the Pitot static tube, but there is a small effect on the drag of a flat plate and on the pressure difference between the front and rear of a disk. Furthermore, the effect of turbulence was found to be independent of the air speed or Reynolds Number.

The hot-wire anemometer had emerged as the fundamental instrument for measuring boundary layer turbulence as well as boundary layer velocity distributions. This instrument was known to be sensitive to other parameters which could cause errors in the turbulence and velocity measurements if proper corrections were not made. Water vapor (humidity) in the air stream was recognized to be such a possible extraneous parameter. In his next paper [3], Schubauer quantified this effect by verifying recent results published by W. Paeschke which showed that the effect was to increase the hot-wire heat loss at higher humidities, giving a fractional change of about 2 % for an increase in relative humidity from 25 % to 70 %. It was concluded that the phenomenon could be explained by the effect of humidity on the thermal conductivity of air.

During the next decade, Schubauer continued to focus his attention on the stability of the laminar boundary layer. He was particularly interested in an instability theory which had been under development over a 40-year period and which was published in the mid-1930s by two German investigators, W. Tollmien and H. Schlichting, who were working independently. This theory postulated that a small disturbance introduced into a laminar boundary layer would lead to transition of the laminar layer to a turbulent boundary layer, depending primarily upon the frequency of the disturbance and the longitudinal (in the flow direction) Reynolds Number. For certain values of the governing parameters the disturbance would be amplified and transition would occur, but for other parameter values the disturbance would be attenuated (or damped) and would not cause transition. The regions where disturbances are amplified or damped are separated by a curve of "neutral stability" as shown in Fig. 1. This curve is sometimes referred to as a "Tollmien-Schlichting noodle curve" because of its peculiar shape.

Working during the mid-1930s on his own time and with available equipment, Schubauer began to investigate the T-S theory experimentally. His jury-rigged experimental setup was substantially less than ideal, but he was able to acquire enough data to convince himself that the T-S theory was basically valid. However, Dryden argued that the relatively crude experimental setup employed by Schubauer could not possibly allow measurement of the T-S phenomenon. There were too many extraneous sources of disturbances in the flow, and the signal-to-noise ratio of the available hot-wire instrumentation was insufficient. Substantial improvement of the experimental equipment would be required to provide necessary control of all the parameters and make high quality measurements. Because of higher priorities, Dryden would neither allow any of the Aerodynamic Section's current financial resources to be used for this work nor assist in soliciting additional funds for the research.

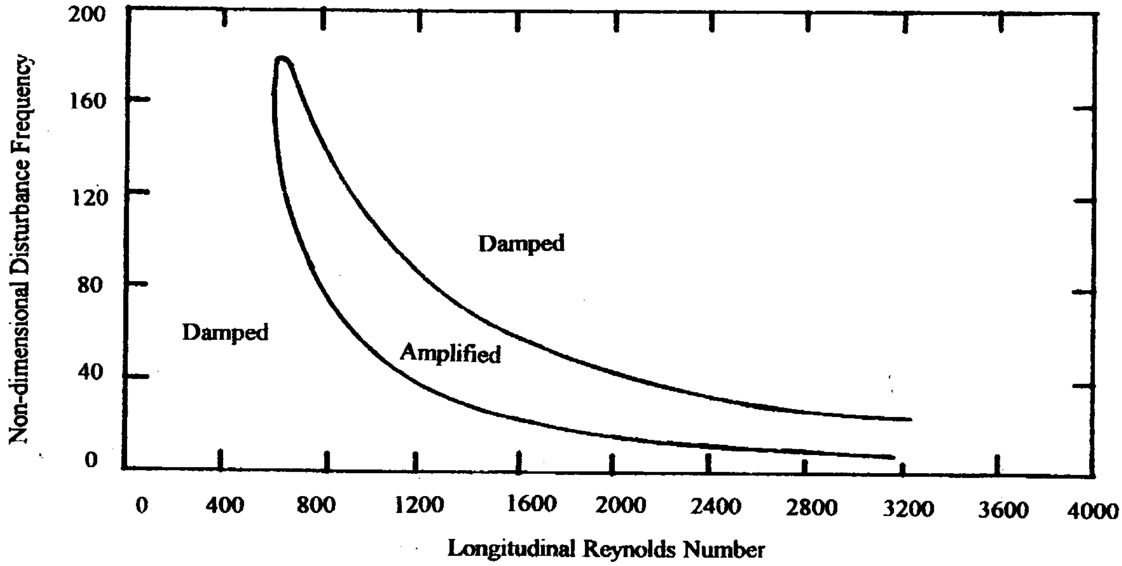

Fig. 1. Zone of Amplification Enclosed by Neutral Curve, According to Schlichting. (Adapted from Figure 13 of [4])

As time passed, Schubauer persisted and continued to work nights and weekends with available equipment to refine his experimental setup. Finally, in the late 1930s, he was able to accumulate enough data to convince Dryden that he was, in fact, able to measure and verify the results of disturbances of known frequencies injected into a laminar boundary layer and that the results consistently fell very close to the T-S theory's predictions.

In the late 1930s, Dryden actively helped Schubauer in securing funding to pursue this work. As World War II approached, its value to the war effort was recognized and it was given a Confidential classification. Now the problem was no longer funding, but securing the materials and equipment necessary to conduct a well-controlled experiment in a war-time economy. However, as the war progressed, advances in the field of electronics were of great help in producing components with which hot-wire instrumentation of higher signal-to-noise ratio could be built, and ways were found to reduce the wind tunnel free-stream turbulence levels below the required level of about 0.1 % of flow rate.

As a result of the Confidential classification placed on the work, Schubauer and his colleagues were prevented from publishing anything about it until after World War II, except as an advance National Advisory Committee for Aeronautics (NACA) Confidential Report in 1943. By 1947, after Dryden had become the head of NACA and Schubauer had become chief of the NBS Aerodynamics Section, the work was published in the open literature in the *Journal of Research of the National Bureau of Standards* [4]. The paper was co-authored by H. K. Skramstad, who was now chief of the NBS Guided Missiles Section and who contributed improvements to the hot-wire instrumentation and other electronic components of the test apparatus. The results were also published in other media, and additional publications by Schubauer and his colleagues about this same time described associated research work.

The T-S theory and its experimental verification by Schubauer and Skramstad contributed greatly to the fundamental understanding of the transition of fluid boundary layers from laminar to turbulent flow. This has led to extensive work in boundary layer control resulting in a myriad of designs for controlling transition to make lifting surfaces, internal flows, and submerged vehicles more efficient. The value of the work has been recognized to the extent that it was nominated for the Nobel Prize in Physics.

Galen Brandt Schubauer was born in Mechanicsburg, PA. He graduated from Pennsylvania State University and received a master's degree in physics from the California Institute of Technology and a doctorate in physics from Johns Hopkins University. His honors included the Fluid Dynamics Prize of the American Physical Society, which he received in 1988 for seminal research findings that concerned the design of wind tunnels and other aspects of research. In 1944 he was the recipient of the Washington Academy of Sciences award for achievement in engineering sciences, and in 1947 he shared the Sylvanus Albert Reed Award of the Institute of Aeronautical Sciences. He was a fellow of the American Physical Society, the Washington Academy of Sciences, and the American Institute of

Fig. 2. Galen B. Schubauer.

Aeronautics and Astronautics. He was a member of the National Academy of Engineering and of the Philosophical Society of Washington.

Upon his retirement from NBS in 1968, Allen V. Astin, then Director of NBS, wrote "Few men have served longer at the National Bureau of Standards than Galen B. Schubauer, and probably none with more dedication. His reputation as an international authority in fluid mechanics, particularly in aerodynamics, reflected credit on the man and, secondarily, on NBS itself. Certainly the papers of Dr. Schubauer are of interest to his friends, to this institution, and to the scientific community. They cover a period of time in which science, technology, and the world itself were completely transformed; yet his last papers are as relevant as his earliest. . . . "

A bound volume [5] containing all of Schubauer's scientific publications that could be found (totaling 25) was prepared by colleagues and given to the NBS library. In the preface to this volume, P. S. Klebanoff wrote "On April 30, 1968, Dr. Galen Brandt Schubauer retired from the National Bureau of Standards. His association with the Bureau was a most fruitful and illustrious one, spanning a period of almost 38 years. . . . His research on boundary layers, flow instability and turbulence not only provided new insight into these important problems, but also provided for new avenues of approach both theoretical and experimental. His work contributed to the prestige of the National Bureau of Standards and in large measure was responsible for the stature of the Aerodynamics Section in the scientific community. Many of his publications are widely cited and are regarded as classical references in the field. . . "

Klebanoff continued, "It is perhaps a comment on man's nature that the occasion of one's retirement is one of the few times that it is considered appropriate to express respect and affection. . . . "

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