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This Week's Citation Classic

Kline S J, Reynolds W C, Schraub F A & Runstadler P W. The structure of turbulent boundary layers. *J. Fluid Mech,* **30**:741-73, 1967. [Department of Mechanical Engineering, Stanford University, Stanford, CA]

Flow visualization of turbulent boundary layers revealed quasi-coherent, intermittent 'structures' in the layers closest to the wall. These structures are inherent in the processes that maintain turbulence, and knowledge of their existence increases understanding of such phenomena as friction, heat transfer, and separation. [The *SCI*® indicates that this paper has been cited over 175 times since 1967.]

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"During 1956, C.A. Moore and I began to employ visualization in low-speed water flows to map systematically the flow regimes in subsonic diffusers as a function of geometric parameters. We employed several visual techniques. In one technique we 'traced' a line of dye on the wall, but normal to the flow —using a long needle on a hypodermic syringe and then observing the motion after the needle was removed. This 'trace' technique revealed unreported phenomena in the inner layers of the turbulent boundary layer. We knew that these inner layers were important with regard to heat and mass transfer, friction, and separation, and that these phenomena had an almost uncountable number of significant applications. We also suspected that the phenomena we were observing were important in production of turbulent fluctuations, and we knew that the 'nature of turbulence' had often been called the most important unsolved problem in fluid mechanics. For these reasons, we began as soon as feasible to augment the diffuser studies with separate studies of the new phenomena. We also published two preliminary reports of the findings —a note concerning turbulent separation in 1957[1] and a full-length paper on turbulence production in 1959.[2]

"The additional studies were undertaken by P.W. Runstadler for the flat-plate and augmented shortly thereafter by F.A. Schraub for flows with streamwise pressure gradients. These more extensive studies on turbulence production were ultimately combined in the 1967 paper.

"These studies showed that the layer closest to the wall, the viscous sublayer, which had been previously described as a very thin, laminar-like sheet of fluid, was in fact composed of alternating spanwise streaks of lower-and-higher-speed fluid. The excursions of these streaks from the mean speed are not small, amounting to ±50% in zero-pressure gradients and more in adverse-pressure gradients.

"Moreover, the 'low-speed streaks' do not stay at the wall, but migrate slowly outward as they move downstream and then turn suddenly outward and become involved in rapid oscillations that quickly 'burst' into intense, small-scale fluctuations. In later work, H.T. Kim, W.C. Reynolds, and I were able to show that a very high fraction of the total turbulence production in the boundary layer does occur during these relatively short 'bursting' times.[3]

"The phenomena have now been studied by a number of workers, and many physical characteristics have been mapped. An excellent summary was published by W.W. Willmarth in 1975.[4] However, significant controversy remains regarding the causal factors underlying 'bursts.' The problem of capturing the essence of this complex production process in sufficiently simple mathematical models for predictive applications also remains unsolved in 1979."

1. **Kline S J.** Some new conceptions of the mechanism of stall in turbulent boundary layers. *J. Aero. Sci.* **24**:6, 1957.
2. **Kline S J & Runstadler P W.** Some preliminary results of visual studies of the flow model of the wall layers of the turbulent boundary layers. *Amer. Soc. Mech Eng. Trans.* **1959**:166-70.
3. **Kim H T, Kline S J & Reynolds W C.** The production of turbulence near a smooth wall in a turbulent boundary layer. *J. Fluid Mech*- **50**:133-60, 1971.
4. **Willmarth W W.** Structure of turbulence in boundary layers. *Adv. Appl. Mech.* **15**:159-254, 1975.