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Ludwig Prandtl and the growth of fluid mechanics in Germany

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ABSTRACT

Ludwig Prandtl (1875–1953) has been called the father of modern aerodynamics. His name is associated most famously with the boundary layer concept, but also with several other topics in 20th-century fluid mechanics, particularly turbulence (Prandtl's mixing length). Among his disciples are pioneers of modern fluid mechanics like Heinrich Blasius, Theodore von Kármán, and Walter Tollmien. Furthermore, Prandtl founded the Aerodynamische Versuchsanstalt (AVA) and the Kaiser-Wilhelm-Institut für Strömungsforschung in Göttingen, nuclei for the growth of fluid mechanics in Germany. In this article I trace this development on the basis of my recent biography of Prandtl.

1. Introduction

At the turn of the 19th century, 'fluid mechanics' in Germany (and elsewhere) was a discipline with a dual identity. Under the label 'hydrodynamics', it belonged to the realm of theoretical physics and was considered first of all as a mathematical challenge. The equations of motion, both in the form of Euler's equations for ideal fluids and the Navier–Stokes equations for viscous fluids, had been studied for decades—without arriving at solutions for most practical applications. Hydrodynamics suggested concepts such as "vortex atoms" and offered one or another argument for an electrodynamic ether, but actual flow phenomena usually eluded this sort of fluid mechanics. As the author of a textbook on hydrodynamics observed in 1900, practical applications were to such an extent beyond its reach "that technology has adopted its own procedure to deal with hydrodynamical problems, which is usually called hydraulics" [1, p. III]. Hydraulics, in contrast to hydrodynamics, was an engineering discipline in the realm of technical mechanics. It was taught at technical colleges (*technische Hochschulen*) rather than universities and disposed of its own corpus of textbooks (e.g., [2]). The renowned *Enzyklopädie der mathematischen Wissenschaften* assigned hydrodynamics and hydraulics to different authors [3,4]. From the perspective of a hydrodynamic textbook writer, hydraulics lacked "so much of a strict method, in its foundations as well as in its conclusions, that most of its results do not deserve a higher value than that of empirical formulae with a very limited range of validity" [1, p. III].

This situation changed in the early decades of the 20th century. "The solution to the dilemma, of course, lay in Ludwig Prandtl's 1904 proposal that flow around immersed bodies be approximated by a boundary zone of viscous influence and a surrounding zone of irrotational motion, and in his insistence that theory and experiment go hand in hand." Thus the renowned hydraulician Hunter Rouse pointed to the boundary layer concept as the crucial step which bridged the gap between hydraulics and hydrodynamics, and to the man who initiated this change towards modern fluid mechanics. And he added "the fact that nearly all who became the charter fluid machinicists were originally mechanical engineers" [5, p. 2].

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In this paper, I analyze this change in more details. Section 2 is dedicated to Prandtl's early career and the origins of the boundary layer concept. Section 3 sheds light on the environment in which practical concerns were addressed by academics, with particular emphasis of a seminar organized by the Göttingen mathematician Felix Klein. The next step to bring theory and practice in closer contact happened with the advent of aeronautics, first with wind tunnel investigations of airship models (section 4) then with a theory of airfoils (section 5). Prandtl's role for the growth of modern fluid mechanics was not limited to theories and experiments. By the end of the First World War, he was head of a huge aerodynamic testing facility, and a few years later he founded the Kaiser-Wilhelm-Institut für Strömungsforschung—an establishment in which fluid dynamics was pursued with a focus on basic research (section 6). But Prandtl's "basic research" in fluid mechanics was close to applications. This becomes apparent in the quest for a theory of turbulence (section 7), a specialty in which Prandtl and his school left a particular mark. Prandtl also served as a science advisor in the political arena—from the German Empire through the Weimar Republic to the "Third Reich". In World War II he served Göring's Air Ministry as chairman of a four-men board (*Forschungsführung*) charged with the direction of aeronautical research; abroad he assumed the role of a goodwill ambassador for Nazi Germany (section 8). His performance calls for a critical discussion of a scientist in the political arena. I conclude (section 9) with some remarks on Prandtl's legacy. For a more detailed account of Prandtl's life, I refer to [6].

2. The practical origins of the boundary layer concept

The idea of a boundary layer may already be found in the 19th century, when "surfaces of discontinuity" were introduced in an attempt to explain some failures of hydrodynamic theory—most clearly in discussions between George Gabriel Stokes and William Thomson (Lord Kelvin) on the stability of plane flows [7, pp. 204–206]. Prandtl's approach to the boundary layer concept, however, was motivated rather by practical concerns. He had studied mechanical engineering at the Technische Hochschule in Munich before he was employed in 1901 as an engineer in a machine factory. Charged with the inspection of an exhaust system for removing shavings and dust from workbenches, he discerned a pressure loss in the exhaust tubes as the cause of undue expenditure of power. The pressure resulted from diverging connections between tubes of different diameters where the flow separated from the wall. "The question why a flow, instead of flowing along the wall becomes detached from it, did not go out of my mind until three years later the boundary layer theory brought the solution," Prandtl recalled this episode from the year 1901 many years later [8, p. 90]. At the time, Prandtl solved the problem by a more appropriate design for joining exhaust tubes. His firm patented this design and Prandtl obtained for many years a share of the firm's profit [6, chapter 2.1].

There were other engineering problems that amounted to the same question why a flow becomes detached from a solid surface. In 1902, by now Prandtl was professor of technical mechanics at the Technische Hochschule in Hanover, steam flow was a major theme at the annual meeting of the Association of German Engineers (*Verein Deutscher Ingenieure*, VDI). Prandtl paid tribute to this subject with several papers. In a "Contribution to the Theory of Steam Flow through Nozzles',' he remarked that an unexplained behavior of steam flow could be due to flow detachment from the nozzle wall as a result of pressure rise in the flow direction. He referred to an "heretofore unpublished hydrodynamic investigation" in which he had analyzed this behavior more closely [9, p. 349].

Prandtl left some notes which shed light on this investigation [6, chapter 2.3]. They reveal a primary interest in a qualitative understanding of the gradual process of flow separation. Prandtl built a special water channel for observing the detachment of vortices from curved bodies. When he finally presented the boundary layer concept at the Third International Congress of Mathematicians in August 1904 in Heidelberg, he illustrated it with photographs from this channel [10]. For a modern reader of this landmark paper, it appears strange that there is little mathematical elaboration. Prandtl derived the boundary layer equations for the flow along a flat plate by canceling terms from the Navier–Stokes equations and presented without proof the velocity profile in the boundary layer and an approximate formula for the resistance of this flow. He left it to Heinrich Blasius, one of his first doctoral students, to elaborate in 1907 the mathematical details [11]. When Prandtl was asked later why he had kept the Heidelberg paper so short—after all this was a congress of mathematicians—Prandtl excused this with the lack of time [12, p. 11]. But, from the perspective of his practical approach, it is more likely that by 1904 he was not yet aware of the mathematical challenges lurking behind the boundary layer concept.

3. Felix Kein's seminar on hydrodynamics in 1907

In 1904, the Göttingen mathematician Felix Klein lured Prandtl away from Hanover to Göttingen University as professor of "technical physics" and director (together with Carl Runge) of a new Institute for Applied Mathematics and Mechanics. Klein's initiative was part of a long-term effort to open the door of Göttingen University to applied sciences—traditionally the domain of technical colleges [13]. In the same vein Klein organized seminars that demonstrated the uses of mathematics in other sciences. He involved Prandtl and Runge already during their first Göttingen semester in the winter 1904/1905 as co-organizers in a seminar "On selected topics of elasticity theory." In summer 1905 another seminar was held "On Electrical Technology," co-organized by Klein, Prandtl, Runge and Theodor Simon, who was appointed in 1901 as director of a new Institute for Applied Electricity. Prandtl's move from Hanover to Göttingen, therefore, did not alienate him from the engineering topics with which he had been concerned before. Prandtl's students, too, would be confronted with techno-

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