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COMPRESSIBLE FLOW IN THE THIRTIES

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1. INTRODUCTION

When the Wright brothers demonstrated on December 17, 1903, that human flight is possible, their range, height, and speed were just enough to prove this fact. From that date on, however, competition to increase these three parameters was a major challenge for both pilots and airplane manufacturers. All three of these parameters are somewhat limited on earth by the finite height of a useful atmosphere, by the limited distance between points on the earth's surface, and by the fact that incompressible flow experience helps a long way, but loses its validity somewhere after reaching half the speed of sound. Charles Lindbergh's flight across the Atlantic Ocean in 1927 brought the flying range into the proper order of magnitude; Anderson and Stevens reached an altitude of 72,400 feet or about three scale heights of the atmosphere in 1935; and the speed races in the famous Schneider Cup competitions from 1913 until 1931 approached half the speed of sound. All these accomplishments within the first thirty years of the birth of flight with heavier-than-air machines are still worth our admiration, even now when we are rather spoiled by the progress in space flight of the last decade going far beyond the limited atmosphere, the limited earth distances, and the speed of sound. The airplane wings did not quite come into the transonic range during the Schneider Cup races, but the propeller tips certainly did, and they brought home to the participants the change of flow behavior due to compressibility. This experience was a rather negative one for those propellers without variable pitch because of the need to compromise within a large range of tip speeds during the acceleration period.

The possibility of supersonic movement through the air was, of course, demonstrated by the ballistics of projectiles, and plenty of compressible-flow problems remained for the internal ballistics. To find, however, a more optimum shape for a spin-stabilized projectile, the nose of which already imitated the ship's bow, was not an urgent problem, while the larger part of the body had to serve as a piston in the barrel of the cannon and had to receive the spinning motion on the way out. Another field of progressing technology in compressible flow was that of turbines, starting with steam turbines late last century, and extending to gas turbines early this century by A. Stodola, of Zurich, who was a very prominent figure in this field. At first the experiments on simple efflux nozzles induced the misconception that a kind of sonic barrier exists in this type of flow, though it was broken by the convergent-divergent shape of the de Laval nozzle in 1889. A rather low efficiency of supersonic deflections as they were used in a few rotor and stator stages to overcome quickly the very high steam temperatures before the subsonic stages could do a better job was accepted with the excuse that energy losses at high temperatures have a high rate of recovery in a Carnot cycle within the later stages of the turbine, with admirable subsonic efficiency and less extreme temperatures for the blades permitting a permanent exposure.

At this state of technology the research in compressible flow was more a frontier attraction in science than an obvious practical necessity or even an investment promising high return. Many scientists like L. Prandtl got interested in this field by writing corrections whenever a new publication about the flow pattern in the minimum cross section of the Laval nozzle, or about the shape of the plumes in the jet behind such nozzles, contained unjustifiable assumptions or conclusions. During the very years when Prandtl introduced the boundary-layer theory and applied it to the streamlining of bodies, which brought us much closer to the d'Alembert paradox of zero pressure drag on properly designed airships for incompressible flow, he also published a Bessel-function treatment of small-disturbance plumes on axially symmetric jets of supersonic speeds surrounded by air of constant pressure. He pictured also in this paper larger disturbances of two-dimensional supersonic jets, which exit through a slit or have side plates. These early pictures were so correct that Prandtl could repeat them two years later in a paper where his famous "flow around a corner" was actually singled out as a self-similar supersonic flow phenomenon.

When Prandtl experimented with water to investigate vortices on the incompressible boundary layers, he had a photographic camera to study the details later at leisure and he made the velocity distribution visible by putting powder of minerals (glimmering iron at first) into the water. Thus Prandtl could obtain pictures of flow in the easy and modern way as the famous Leonardo da Vinci—four centuries earlier—had to do the hard way. Likewise in his study of compressible and especially supersonic flows the photographic camera, in connection with the Toepler-Schlieren Method, served as the tool to make permanent images of his experimental flows of rather short duration. The trick to make the Mach-wave pattern visible was to roughen up the walls of the flow by grooves perpendicular to the flow direction. A similar utilization of modern optical and photographical methods, including interferometers, helped the progress of understanding the compressible flow around projectiles by the physicist E. Mach in Vienna and the ballistician C. Crantz in Berlin. Mathematical treatments of supersonic flow and its mapping into the hodograph plane were independent accomplishments by B. Riemann in 1860, P. Molenbroek in 1890, and S. A. Chaplygin in 1902; but since they were made before the boundary-layer theory established the practical value of ideal mathematical flow theory, they did not attract the immediate interest of large groups of scientists and engineers.

2. After World War I

Priorities in aviation changed quite a lot when, during World War I, airplanes proved their value and even surpassed the airships. In times of war the airship with its large lifting gas volume is, of course, an easy target for anti-aircraft guns; but even its peacetime application for long-distance travel lost the popular belief that the only reasonable mode of transportation is by airship, while airplane flights are like risky circus stunts. The airplanes proved their safety while the dirigibles of rigid construction had to be filled with hydrogen—not yet helium—and were plagued by too many fires caused by the highly explosive mixtures of hydrogen and air.

Enthusiastic youth and war-time pilots made aviation a new field of practical interest, and in the new research centers hastily created during the war they continued their serious investigations. They approached their puzzling problems under a new perspective, regarding them in combination with results of other countries. In Germany, where under the Treaty of Versailles the engine in an airplane was limited to 50 horsepower, the new theory of lifting wings developed during the war, and its major result in M. Munk's doctoral thesis of 1918, which established the elliptical lift distribution on a single wing of given span as the optimum, supported progress toward larger lift-over-drag ratios on monoplane gliders of large span.

After the German runaway inflation was stopped in 1924, the prewar idea of surrounding Ludwig Prandtl with a Max Planck Institute (at that time still called Kaiser Wilhelm Institute), which had to be postponed during the war, became a reality in 1925.

The Max Planck Institute for Flow Research, side by side with the large wind tunnel built during the war, was the place where all those flow problems in Prandtl's past could be revived that had to step aside during the time when the Prandtl-type wind tunnel for the growing interest in aviation was designed, constructed, and improved. Among those overshadowed problems were compressible flow, cavitation in water, turbulent flow in pipes or in the atmosphere by unstable stratification, and other effects in the atmosphere influenced by the rotation of the earth. While Prandtl was very well supplied locally with mathematicians and physicists among his own students at the University of Goettingen, engineers for his wind tunnels and his institute were brought to him by his friends and relatives. Munich, his alma mater, furnished the lion's share (Max Munk, Albert Betz, Carl Wieselsberger); Aurel Stodola in Zurich recommended Jakob Ackeret; and Prandtl's brother-in-law, Otto Foeppl in Braunschweig, passed me on to Prandtl after my doctoral thesis in elastomechanics was finished. My original task was to complete the design and to supervise the construction of the rotating chamber for atmospheric studies according to Prandtl's sketches. This project proceeded rather well until the day arrived when the walls were installed all around. The afternoon before that day it was a great pleasure to try out the rotating platform at all speeds provided by the driving motor. As soon as the walls were closed and the internal lights turned on, the situation was quite different. It was nauseating in the true meaning of the word. The chamber was not the expected tool to study meteorology in an easy chair. You had to learn to keep your head still and to flick only your eyeballs. Instead of reproducing our known environment at higher rotational speed it became an introduction to bio-engineering or the art of living with our biological systems in a strange environment. Although before that time I was one of the first to become seasick in rough seas, after understanding the conflicting mechanics I am now one of the last ones to become seasick. Foreseeing speeds at which the centrifugal forces in the rotating chamber would not be comfortable for the observer inside, Prandtl had already prepared a large cylindrical opening in the upper bearing, to place an inversion prism with half the rotational speed into it for an equivalent observation from the outside.

In the Goettingen atmosphere around Prandtl I had learned plenty of fluid mechanics to be prepared for taking an active part in flow research. As an engineer it would have been appropriate for me to turn to the practical problems of aviation when my first project was finished. But it seemed that I entered our world too late; the earlier research assistants had pretty well divided up among them the urgent problems on the existing airplanes. Contrary to that situation, research work on compressible flow problems was wide open and I was very welcome to join Jakob Ackeret in this field of Prandtl's early loves. In line with my practice of not pretending that I can help where the stars of our profession, Th. von Kármán, J. Burgers, L. Prandtl, and others are already doing their very best, as in turbulence, I joined Ackeret in this frontier area of mechanics in measuring the lift and drag of profiles near and above the speed of sound. The new high-speed wind tunnel for this purpose had a cross section of 2 by 2 inches, which was much larger than the earlier equipment of 1904 to 1908 at which Prandtl worked with Th. Meyer, E. Magin, and A. Steichen.

3. Awakening of Interest in Compressible Flow

In spite of many far-reaching speculations about rocket flights, the general climate was not quite ready for such propositions to be taken seriously. Even when I was ready to present my first experimental results on lift and drag near sonic speeds, Prandtl himself suggested adding in parentheses "with regard to propellers" for the meeting in Danzig, 1928, to indicate some practical value of them. The meeting, however, proceeded in a quite unexpected manner, when Hermann Oberth had to defend his theory against Prof. Hans Lorentz, the host of the event at the Technical University of Danzig, who tried to prove that leaving the earth with a rocket-driven vehicle is impossible. His error was that he confused the "staging" of rockets with the "clustering" of smaller rockets for simultaneous combustion. It was not too hard for Oberth to straighten out this essential difference, at least for objective listeners. After that the younger generation, enthused by this discussion, was quite a pleasant audience for my paper, whether it was with or without regard to propellers.

The scientific world in general showed at least some interest in compressible flow as a special item. The two competing German handbooks of that time, the *Handbook of Physics* first and the *Handbook of Experimental Physics* soon after, included compressible flow under the title "Gasdynamics" to follow the many aspects of modern "Hydrodynamics" in a special chapter. The obvious choice to write this chapter was, of course, Ludwig Prandtl.

But Prandtl suggested J. Ackeret for the *Handbook of Physics*. Consequently he got another invitation from the *Handbook of Experimental Physics* and this time he passed it on to me. Undoubtedly it is a great honor to be selected to write such an article on a frontier science, but nevertheless, to write the same chapter as another young man from that same school—and after such a short interval—was not without danger. Since the most interested readers like Th. von Kârmân, G. I. Taylor, and A. Stodola could be counted almost on the fingers of one hand, and they would certainly remember every word that Ackeret had said, the danger of ruining one's future by plagiarism was quite evident. So I had to sit down and try to stretch the natural difference between "physics" and "experimental physics" as a starting point. For an engineer of the steam-engine area, this was not too difficult a problem: If Ackeret uses simplified equations for perfect gases, experiments are made with real gases as we find them in the Mollier diagram for steam. Since the only visible progress in Goettingen since Ackeret was in making graphical constructions of perfect wind tunnel nozzles by applying the characteristics diagram, the shift to graphical representations for Ackeret's analytical equations may not only save the day but it may add another dimension for the perspective picture of some basic features in such a novel territory (deviation from local equilibrium was, of course, not considered). Otherwise the writing of that article was not too difficult for me after I had been used by Ackeret for trying out first reactions of the reader. (When he wrote his article I was sharing his office!) The only trouble was that the requested 60 pages of print were already doubled before nonsteady compressible flow, the oldest part of gas dynamics, was entered. The editor was willing to print those 120 pages, but told me not to go any further. This itself was quite a concession on his part, for this was at the time of the American bank crash when publishing in journals was next to impossible because of the flood of manuscripts by every young man who needed a break in his career.

I remember, when I gave in Prague in 1929 a short introduction in a ten-minute talk to the graphical integration of the supersonic flow around a conical tip with the intention of presenting the whole series of integrated "Apple Curves" at the International Congress of Applied Mechanics in Stockholm in 1930, that the German committee had to impose a strict rule on all speakers not to repeat any subject already discussed before. Under this rule I had to find a new subject. Conical flow was mentioned again at the Volta Meeting in 1935, but the complete result was published no sooner than in the C. Wieselsberger memorial issue of *Luftfahrtforschung* in 1942. At the German national meetings for applied mechanics there were some lonesome specialists like G. Weinblum for ship waves and Busemann for supersonic flow; at the international congresses of that time there was already quite a group of scientists interested in compressible flow who were collecting around G. I. Taylor in England, around von Kârmân in the USA, around Ackeret and myself from the school of Prandtl, and around some French and Italian specialists. But none of us could really predict how soon our specialty would be introduced to the general society of aerodynamicists with more practical ambitions.

4. The Fifth Volta Congress in Rome, 1935

No matter how optimistic a scientist could have been to defend the immediate value of his flow research, the invitations to the Fifth Volta Congress in Rome in 1935 under the title "High Velocities in Aviation" were still a surprise and a great challenge for every single one of the invited speakers. Words like lift and drag at supersonic speed were now the subtitles for special sessions to be discussed by internationally known theorists complementing the review of practical experiences during the Schneider Cup races and the progress since the final victory by the British participants. Annual Volta Congresses arranged by the Royal Academy of Science in Rome and supported by the Alessandro Volta Foundation began in 1931 with the subject "Nuclear Physics" and were of international interest combined with some special relevance for the Italian people. The Third Congress in 1933, for instance, was devoted to "Immunology" to discuss progress in fighting diseases in swamp areas that are uninhabitable, especially in warmer climates. But only the odd numbers were from the class of mathematics, physics, and natural sciences of the Academy, while the even numbers concerned humanities. The Second Volta Congress had the title "Europe" and the Fourth was about "The Dramatic Theater." This was quite a large variety of subjects, and the translators at these Congresses, who were extremely clever at comprising a whole paragraph of the speech into a few sentences in popular terms, had to change to a sentence-by-sentence translation for us, after Prandtl felt the need to correct them "it is not force but energy . . . etc." in our scientific expressions.

All invited scientists appreciated this unique opportunity to apply their collected experience fully to the progress in aviation, and each worked very hard on his specific subject between the invitation, in early January, and the delivery of the manuscript, the first of July, and even beyond toward the actual Congress from September 30 to October 6, 1935. Even von Kármán told me that he usually gave new publications to one of his assistants to report about in a seminar; but for this Congress he went over all the relevant papers himself and discovered a lot of ideas not revealed in those seminars.

Though most of the participants were known to each other, like members of one scientific family, two major political events of 1935 caused some difficulties. Hitler, after the murder of Ernst Roehm and the death of President Hindenburg in 1934, reestablished in a show of power the German Air Force, contrary to the Treaty of Versailles. Mussolini announced on October 3, at the time when my talk was originally scheduled, his intentions in Abyssinia, which were in strong contrast to the British policies. My troubles were not great in Germany. The fact that I was invited, together with the famous Prandtl, opened all of a sudden many doors for me. In the middle of March I was invited to see W. Dornberger and W. von Braun on their rocket research place near Berlin. One week later all three of us went to Munich to discuss the proposal of Paul Schmidt with regard to his buzzing thrust machine. In May I got my contract as division head for "Gasdynamics" in a new research center to be established near Braunschweig. On the trip to Rome I was asked to stop at Vienna and take a good look at Eugen Saenger, who worked on rocket flights with wings, and to decide whether I would like to have him as part of my Institute for Gasdynamics.

There was, however, a difficulty about my subject in Rome. It was originally "Supersonic Windtunnels" for the man who cleans up the tunnel flow according to the characteristics method, and it was "Supersonic Lift" for J. Ackeret, the man of the linearized lift theory. Because I had been four years away from Goettingen and working more theoretically in Dresden, while Ackeret was constructing wind tunnels even for the Italians at Guidonia near Rome, it was not too hard to arrange a switch of our subjects. Lift at supersonic speeds was obviously not connected to any sensitive development for the German Air Force, being too far out in speed. The swept wing design, however, derived originally to reactivate the high response of the air that tends toward zero at hypersonic speeds, could also be used to diminish the supersensitivity of the air approaching the speed of sound. This almost inverse application became a classified matter in 1936.

The British participants being invited as final winners of the Schneider Cup solved their political difficulties about Mussolini's actions by strictly avoiding any public appearances outside the Congress during the remaining three days. Except for these minor difficulties, the international relations at the Congress were as warm as one could hope. Only the Russian rocket expert, N. S. Rinin, did not appear in person after he mailed his paper on time, and it had to be read by the President of the Congress in the final session. The treatment of the foreign guests, who could even bring their wives with full payment of all expenses inside Italy, was almost like that of royalty. Only during lunch on Thursday, when many waiters of the Embassadore Hotel had to appear in their black uniforms in front of the Palazzo Venezia at Mussolini's balcony, they were in a great hurry serving us before their other duties started; but we could understand that this event had a higher priority for them. The President for the Fifth Volta Congress was General Arturo Crocco (the father of Luigi Crocco who worked in Princeton later), a very able chairman and aeronautical scientist in Italy, in both research and teaching. His comments after the delivery of the manuscripts and finally at the actual Congress added much to the spirit and vitality of the discussions. His career brought him in close contact since 1903 with the lighter-than-air and heavier-than-air aviation in Italy, and his latest field of interest was ramjets as an arrangement of negative drag, published in 1931.

5. Practical Experience in High-Speed Aerodynamics

Two British and three Italian experts discussed at the Congress experience accumulated during the Schneider Cup races and beyond. Their listing of areas of importance for future developments has not lost its validity in retrospect. I quote here from G. H. Stainforth of London: "More power, less weight, less frontal area, cleaner design with enclosed cockpit and smoother surfaces, lift- and drag-increasing devices, variable and reversible-pitch propellers, retractable undercarriage, retractable wings; to achieve the best results requires a compromise in altitude between the following four components: (1) power obtainable by supercharging, (2) lower drag due to lower density, (3) distance of journey and time for climbing, (4) comfort of the passengers with respect to pressure, oxygen, and temperature." Except for the missing jet propulsion and the heat created by friction at higher Mach numbers all these items are still up-to-date and some of them became standard equipment very soon after the conference.

6. Theory of High-Speed Aerodynamics

The theoretical aerodynamics of the Congress was divided by the President into two separate fields, general methods to master the involved mathematical and physical relations, as opposed to the treatment of particular questions; both fields were further subdivided into both subsonic and supersonic speed ranges.

(*a*) The general introduction to compressible flow was given by L. Prandtl, who illustrated his survey by many Schlieren pictures, especially of the transonic regime, which still was one of the greatest problem areas of interest to him. Geoffrey Ingram Taylor followed him in discussing "Well established problems in high speed flow," and his main concern was also with the understanding of transonic flow behavior to which he contributed the stepwise approximation of two-dimensional solutions by carving step by step new wax bottoms, according to the gas-density variations in an electrolytic tank of large extent with a shallow fluid layer. The lines of constant voltage may be used to represent either potential lines of the flow (in which case no lift is possible) or streamlines of the flow in this analogy. The simple method of carving the bottom after each test, fitting everywhere to the observed electric field, does not converge as soon as the flow field contains supersonic enclosures. A more sophisticated procedure of improving the bottom shape, which makes at least some distinction between the upstream and downstream directions within the supersonic portions, can be conjectured to imitate the nonsteady build-up in nature, but nothing like that has yet been found. The converging purely subsonic flows compare very well with the theoretical solutions including the increasing sensitivity when approaching the speed of sound locally; they also confirm wind-tunnel results. In supersonic flow fields G. I. Taylor was mostly interested in the conical flow field around a circular conical nose without angle of attack in which potential flow is preserved by equal shock losses on all streamlines. He compared exactly integrated results with the small-disturbance theory of von Kármán, which has quite an extent of validity for practical, though small, angles of cones.

(*b*) Treatments of particular questions encountered in aviation started with the paper of Th. von Kármán on "The problem of resistance in compressible fluids" in general, and wave drag in supersonic flow in particular. Drag in boundary layers exists at all speeds and is, of course, not independent of Mach number, especially when the friction paired with heat transfer causes density changes even for the simple constant-pressure case, because of temperature differences. While the boundary-layer friction itself may not vary too many orders of magnitude with Mach number, the boundary-layer separation is affected extremely by the supersensitive regime of Mach numbers near one and because of shock waves throughout the supersonic regime. At supersonic speeds the wave drag is added, and in the combination of both, a boundary-layer separation can sometimes be the lesser evil. Taking wave drag alone, Th. von Kármán and N. Moore started in 1932 the axially symmetric and small-disturbance theory for the body drag by assuming sources and sinks along the axis. The whole audience enjoyed it when von Kármán demonstrated how he now succeeded in finding the optimum shape for a body of revolution with given caliber and nose length. The fact appreciated most of all was the result that there is a simple analogy between the optimum nose and the optimum lift distribution for a wing of given span. The determination of forces on a source or sink in the field of an upstream arrangement of such singularities simplifies the function, valid off the axis, to an inverse second-power relation of distances along the axis, which can in turn be compared with the field energy of two-dimensional vortex-pair distributions along one axis. After this relation is established, the lift distribution integrated from one wing tip corresponds along the span to the cross-sectional area of the supersonic nose along its distance from the nose tip, while the total lift corresponds to the final cross section of the afterbody at the end of the nose length. Compared with the popular ogival nose of projectiles, the von Kármán nose, which is the integrated ellipse, has not constant curvature of the meridian line, but is somewhat blunt at the tip and curves into the afterbody rather sharply. Anybody who does not like this new shape may argue that the given length is not the most practical constraint for the actual problem; but, just as in the optimal lift distributions, other constraints can be used and the analogy between the two physically different problems very often reduces the new wave-drag problem to an already known lift-distribution result.

"Lift at subsonic speeds" was the title of a paper by Enrico Pistolesi of Pisa. The linearized Prandtl-Glauert relation prescribing how to reduce the thickness and the angle of attack for keeping the incompressible flow experience alive (by preserving its complete pressure field around the profile) may serve as a first impression of the changes due to compressibility; but higher-order calculations by Rayleigh and Poggi are also available and the G. I. Taylor electric tank values, as long as the flow stays completely subsonic, can be used to find the perfect flow field in two-dimensions. The final stall for any profile of finite thickness and angle of attack by boundary-layer separation was supplied from experimental data in wind tunnels.

Now the afternoon came on which I had to present my paper, though somewhat delayed because of Mussolini's declaration of war on Abyssinia. The title "Lift at supersonic speeds" meant the basic question: is there hope that supersonic flight is possible when already approaching the speed of sound the lift seems to vanish and the drag to increase vastly? My idea, to use a "razor-blade"-thin and straight wing to give even the most uncooperative flow no chance to find a pressure distribution to produce simultaneously low lift and high drag at small angles of attack was already mentioned by our president Crocco in his introductory survey. Finding a very high response, measured in dynamic pressure, just above the speed of sound but a diminishing response for high Mach numbers made me try for a lower "apparent" Mach number by turning the wing backward closer to the Mach cone. Such a swept wing configuration would keep the lifting force upward, would even turn the wave-drag force somewhat away from the flight direction, and might recover more flow response than is demanded by the increased friction drag, because of that useless velocity component along the span. President Crocco, after receiving my original manuscript, also suggested an appendix—which is therefore missing in the version of my talk given to the German authorities for publication in the October issue of *Luftfahrtforschung*. It was a more detailed explanation of my sentences: "One cannot find a single two-dimensional body of finite thickness and finite length without supersonic wave drag. For two such bodies one can construct solutions of perfect flow without drag." Whether such ideas far beyond the state of the art at that time did establish real hope for supersonic flight in the listeners is hard to say; but a supersonic airplane with swept wings and a propeller with swept blades in front of it was drawn as a cartoon on the head table during the banquet of the Congress.

7. Wind-Tunnel Research at High Speeds

Following the theoretical papers of the Congress came wind-tunnel designs and wind-tunnel results from research laboratories. E. N. Jacobs presented the latest tests from NACA in Langley Field from the earlier 11-inch-diameter induction jet wind tunnel followed later by a larger one of 24-inch diameter. The results documented mainly the troubles with profiles when approaching the speed of sound and were shown in slides and movies of Schlieren pictures. M. Panetti from Torino reported on tests with moving bodies on rotating supports and he discussed also free-flight interferometer pictures on flying projectiles. Further tests also made on moving objects were from propeller blades described by G. P. Douglas at the National Physical Laboratory in Teddington; they required a correction from the S. Goldstein propeller theory for shed vortices in the case of lift. All these tests in the transonic flow regime were in reasonable agreement with each other and with the Prandtl–Glauert theory up to those forward speeds when stall sets in by supersensitivity of the near-sonic flow.

Wind-tunnel designs for all kinds of subsonic and supersonic speeds were presented by Jakob Ackeret of Zurich, some of them with a short time duration and others with permanent flow, the latter with multi-stage compressors and cooling equipment. Besides seeing these wind tunnels in sketches and photographs, we also had the opportunity during the Congress to inspect the new Italian aerodynamical research center in Guidonia near Rome, equipped with a variety of such high-velocity wind tunnels of Ackeret's design.

8. Thermodynamics and Combustion

Like early flight, high-speed flight depends also on propulsion. Therefore, another chapter of the Congress was devoted to high-speed and high-altitude propulsion devices under the heading of thermodynamics and combustion. Not all of the engineering problems related to such engines may concern compressible flow, and in the discussion some participants of the Congress even said that they missed the evaluation of weight for a larger engine that works for shorter time with increased power. Nevertheless, there is much relation to compressible flow, just as I mentioned before. A. Stodola's steam and gas turbines run with good efficiency at the smallest number of stages both in the compressors as in the turbines and under endurable temperatures.

The first paper of G. C. Costanzi, of Rome, was an investigation of all altitude-related problems: "Stratospheric aviation." The next two speakers, H. R. Ricardo of London and A. Anastasi of Rome, subdivided the more specific problems of "High altitude engines: (*a*) thermodynamics and carburetion, (*b*) mechanics and cooling." Their concern was about superchargers, cooling, poppet valves that may be replaced by sleeve valves, and even the fact that the actual power generation from combustion may be surrendered to a vapor engine with any kind of a fluid between the combustion chamber and the condenser.

Less conventional problems were presented in the last two papers "Propulsion by jets with utilization of outside air," like ramjets, by Maurice Roy of Paris, and "Rocket propulsion with air admixing," prepared by N. A. Rinin of Leningrad. "Ramjets on the outer tips of helicopter blades" was one of the items presented by M. Roy. A survey of the work by many other rocket scientists besides his own—that of H. Oberth, F. Zander, E. Saenger, and K. Ziolkowski—was included in Rinin's contribution, and it was combined with ramjets and other means to involve the outside air in early stages of rocket flight.

These five papers are interesting historical documents with respect to the question of how we hit or miss the actual development of jet propulsion. H. E. Wimperis, London, finished a discussion remark with these words: " . . . Hence for such altitudes we must await the coming of the jet-propulsion engine. That, however, we have not nearly got. Some day, thanks no doubt in large part to the labours of this Volta Congress, we shall discover how to do it. And then our remaining task will merely be the discovery of the passengers who wish to fly at such altitudes!" That this "some day" was just five to ten years away, and that the jet age for passenger service was twenty years off, with so many passengers wishing to fly with them that air travel causes severe problems for trains and ocean liners was, of course, hard to foresee.

9. Conclusion

The Fifth Volta Congress in Rome was a great success in international cooperation and exchange of experience between the former Schneider Cup rivals. For high-speed flight and the compressible-flow sciences, it was the turning point from work in a grey area of our knowledge to an advancement in practical aviation. Whether such a success was accidental or could be duplicated in other parts of science may be hard to generalize. At any rate, the participants in the Congress went home with an enlarged view, and they found a better reception for their further research in their countries. Some immediate additions of high-speed research facilities were built not only in