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THE ORIGIN OF WIND TUNNELS IN RUSSIA

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Abstract

The general overview of the earliest Russian wind tunnels built before the World War I is given. The original photos, schemes, formulas and results taken from papers published by the wind tunnel designers at the turn of 19th and 20th centuries are presented.

1 Introduction

Abroad, the first wind tunnels were constructed by Francis H. Wenham, Horatio F. Phillips and Hiram S. Maxim in the United Kingdom, Ludwig Mach in Austria, Charles Renard and Etienne Marey in France, H.C. Vogt and Paul LaCour in Denmark, Alfred J. Wells in the USA [1]. Ref. 1 cites the Russian wind tunnel been built by N.E. Zhukovsky at the Moscow Imperial University in 1891 as well as the wind tunnel built in Aerodynamic Institute in Kuchino.

In accordance with Russian historical documents, the first wind tunnels in Russia were built by V.A. Pashkevich at the Mikhailov Artillery Academy in St. Petersburg, Tsiolkovsky in Kaluga (it was a home-made apparatus), N.E. Zhukovsky at the Moscow Imperial University and the Imperial Technical School, D.P. Ryabushinsky under the guidance of N.E. Zhukovsky at the Aerodynamic Institute in Kuchino.

2 Wind Tunnel constructed by V. Pashkevich

The first Russian wind tunnel was built by V.A. Pashkevich, professor of the Mikhailov Artillery Academy in 1871 just in the same year as Francis H. Wenham. V.A. Pashkevich (born in 1844) graduated from the 1st Junker class of the Combatant Department of the Artillery School senior class with the rank of officer in 1863. In 1865 he enrolled at the Academy of the same school. He graduated from the Academy in 1868 and stayed with the rank of staff captain as a tutor at the Artillery School and the Academy [2]. In 1873 by imperial order he was sent to Belgium and England to get acquainted with the chronograph developed by the captain of the English service Nobel. Later he became an associate professor at the Academy in the rank of colonel and a major specialist in the field of ballistics. His best known work in this area is the "Course of artillery. Structure and use of artillery and hand-held weapons" ([3]).

He set as a goal to determine the total force that acts on a projectile at various angles of attack as well as the location of the point of application [4]. To solve this problem, he designed a wind tunnel and a three-component aerodynamic balance which were constructed at public expense by the request of the conference at the Mikhailov Artillery Academy.

The wind tunnel had open circuit and was featured by a rectangular closed test section (Fig.1). An inlet tube about 1.4 m long and approximately 40 cm in diameter was connected to the entry into the test section (right part of Fig. 1); the other tube at the outlet was of 1.8 m long. The test section crosscut was a rectangle with 41 x 17 cm sides (the test section dimensions were not given in the original paper and were evaluated based on author's schemes). The blockage ratio was about 10% based on projectile cross section area, according to the author. The wind tunnel was housed in an ordnance workshop. The air was provided by a fan about 25 cm in diameter with a rotational speed of about 800 rpm.

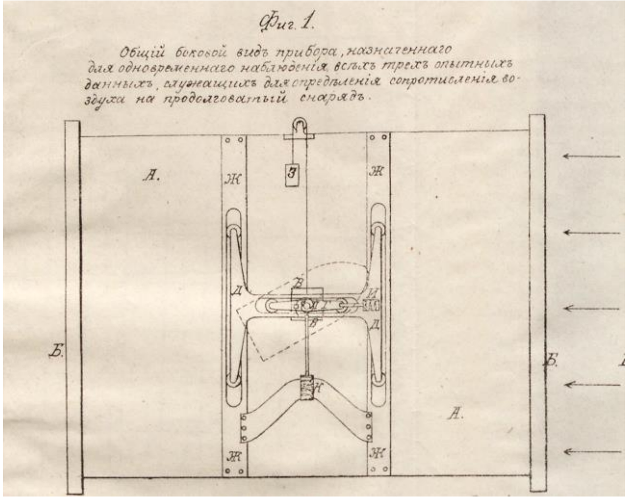

Fig.1. The test section of Pashkevich's wind tunnel and his mechanical balance

Due to the insufficient funding granted to create the apparatus V. Pashkevich was not able to procure an anemometer to measure the flow velocity in the test section. The two pounds model of 17 cm length that simulated the four-pound grenade was used as a test object. The model was supported by a thin horizontal axle.

V. Pashkevich determined the value of the total aerodynamic force ρ, the angle ψ between the total force direction and the model axis of symmetry and the distance D between the total force application point and the model center of mass. The calculated results for the parameters D, ψ, and ρ as a function of the angle of attack are shown in Figure 2.

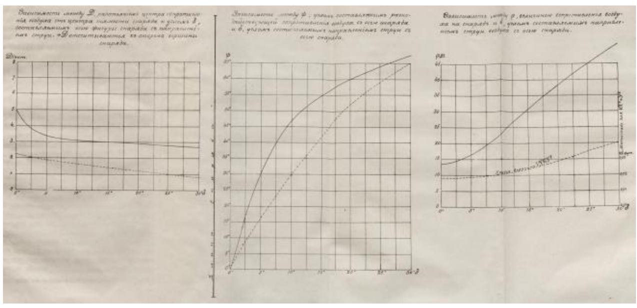

Fig.2. The pressure center, the direction and the value of resultant force as a function of the angle of attack

The dashed lines are the theoretical curves available at that time. The results obtained by V. Pashkevich qualitatively agreed with the theoretical ones. One did not succeed in comparing directly, as no measuring the flow velocity in the test section was performed. Figure 2 shows a line segment that corresponds to the model length. The segment is beside the left plot that indicates the position of the resultant force application point.

In his paper, V. Pashkevich had drawn the following conclusions:

• *The apparatus I have designed, by virtue of its construction, is quite enough suitable for handy determination of air drag of nonrotating bodies. To ensure the measurement of the air drag on rotating objects, it is necessary to insignificantly modify the apparatus.*

• *The cross section of the intake tube must be larger than that used in the existing apparatus; the fan diameter must also be increased.*

• *As far as it could be judged by the obtained results, the experiments support the character of the theoretical dependence of the air drag of nonrotating elongated object as a function of the angle between its axis of symmetry and its forward velocity.*

Moreover, V. Pashkevich developed a technique of determining and making allowance for support devices drag and flow field nonuniformity.

3 Facility constructed by K. Tsiolkovsky

3.1 Wind tunnel

In the mid -1890's, K.E. Tsiolkovsky became engaged in designing a large airship of metallic design with a capacity of 200 passengers. First of all it was necessary to know the suitable bodies configurations drag. The idea came into his head to use the artificial airflow to study the bodies drag.

To implement this idea Tsiolkovsky designed and built in 1896 an apparatus [5] with appearance reminiscent of winnower (Fig. 3). The wind tunnel layout is somehow similar to that used by Francis H. Wenham [1]. The apparatus was about 1.5 m high and 0.45 m wide. It had a blade wheel with a diameter of 1 m with 12 blades *Л*. The wheel *B* was powered by a weight *Г* in the range from 0.5 to 16 pounds.

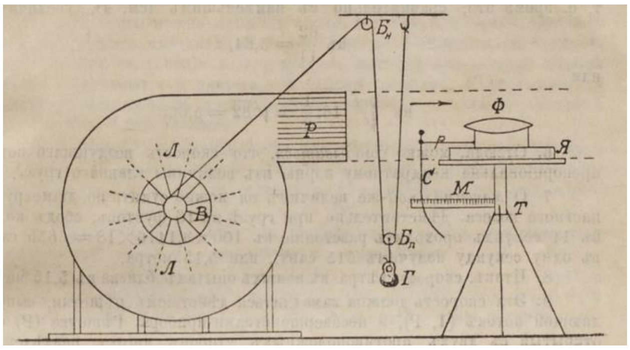

Fig.3. The first wind tunnel with a one-component balance designed by K.E. Tsiolkovsky

The weight operated as follows: the fine string was wound round the *B* shaft by the lever (not showed in the figure) and then it was thrown over the *Бп* fixed hoisting tackle that was screwed into the ceiling and at last, the string was fastened to the hook hammered into the ceiling near the fixed tackle. Different weights were suspended to the movable *Бп* tackle with two hooks. There was an additional small weight up to ¼ pound, which compensated the friction in tackles and this was of great importance when the basic weights were of light load. Another fine string more was suspended to the *Г* weight. This string contacted constantly with the floor in order to compensate the main fine string weight. All these arrangements provided a constant airflow speed. The air outlet had a flow homogenizer *P* screen with 11 horizontal and *3* vertical partition plates. In modern wind tunnels such devices are called honeycombs. As a matter of fact, the Tsiolkovsky's apparatus represented an open-circuit wind tunnel with an open jet test section and a nozzle with a honeycomb inside. The airflow speed was proportional to the square root of the weight mass. At a maximum weight mass of 16 pounds, the maximum observation time was at least 11 sec. The maximum airflow speed at a 16-pound weight equaled (according to Tsiolkovsky's calculations) to 4.3 m/s.
The air blower was composed of a wooden screwed frame with lateral walls covered inside with cardboard and the convex surface was made of tin-plate. The shaft and the impeller spokes were made of metal and the blades were made of thin cardboard. According to the author's estimation, the facility weighted up to 50 pounds.

3.2 Wind tunnel models

K.E. Tsiolkovsky constructed his models of paper. The wind tunnel models production technology is of interest. The researcher drew an envelope line for the bodies of rotation. Based on this line he turned two wooden half-bodies, which were then attached along the maximal cross section. These halves were covered with the pieces of wet paper and then this structure was bandaged. After desiccation the paper took the model shape and these two paper halves were glued together. The major part of models to measure their drag he made of thick drawing paper. The original photo of his models is shown in Figure 4.

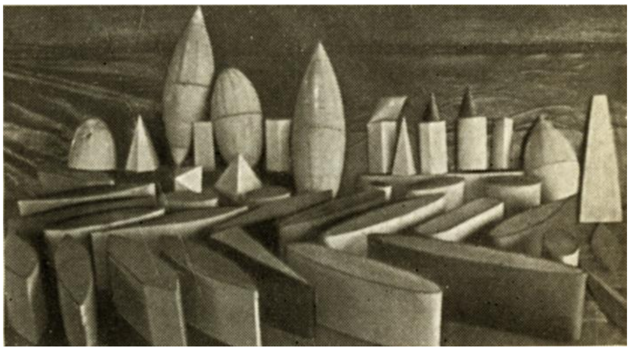

Fig.4. Photo of test models made of paper

This photo was made in 1900. K.E. Tsiolkovsky sent it to N.E. Zhukovsky on May 1, 1910.

3.3 Experimental investigations

The drag of balance components (*C* pointer and tin bands) and supporting means (struts, crossbeams) that were streamlined was monitored constantly. In the course of testing the drag of balance components and the suspension was deducted from the measurements results.
After the tests of plates with area of 80 and 100 cm^2 were performed K. Tsiolkovky made a conclusion that the flow cross section *is perfectly sufficient (as if flow was infinite) for shapes whose cross section area did not surpass*

80cm^2. This was the first Russian research of one of the most important issues in methodology for experimental researches in wind tunnels: the flow boundary influence and the estimation of the test section maximum blockage ratio.
Using his wind tunnel K.E. Tsiolkovsky measured the drag coefficients of objects of different forms as a function of airflow speed. He investigated various regular prisms, cylinders of round, oval and streamlined forms as well as regular polyhedrons and the sphere. K.E. Tsiolkovsky derived that the drag coefficient for streamlined bodies decreased as the airflow speed increased. In particular, he found in his experiments the drag coefficient for a sphere to be equal to 0.5, that had a good agreement with the current measurement results of different researchers.

4 Wind tunnels constructed by N. Zhukovsky

4.1 The first wind tunnel of the Moscow Imperial University

In 1902 N.E. Zhukovsky designed and built a wind tunnel (a *gallery with artificial airflow*, Fig. 5) for the aerodynamic laboratory associated with the Cabinet of applied mechanics at the Moscow Imperial University.

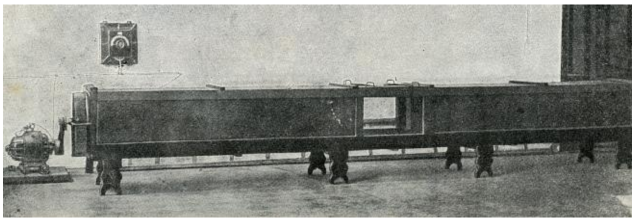

Fig.5. Photograph of Zhukovsky's first wind tunnel

The tunnel with a 0.75 x 0.75 m test section cross section (0.63 x 0.54 m flow core) was one of the first European wind tunnels operating via the airflow suction into the test section [6, 7]. This laboratory was involved in investigations of objects drag in airflow. In 1904 the wind tunnel was equipped with a new 2 hp motor and the airflow speed was increased to 11 m/s. A vane blower was mounted on one of its ends and driven by a motor. The rheostat that was hung on the wall provided the airflow speed regulation in range of 1.5-11m/s. The air motion speed was measured by either Caselli anemometers or a micromanometer.
The models under consideration were mounted in the middle part of the wind tunnel. The lateral windows and the removable upper glass cover were used to observe these models.
The rectangular shape of the test section turned out to be convenient to study the lattices and the infinite length surfaces. The insertion that provided the test section cross section taper was manufactured in order to achieve higher speeds. The airflow speed inside the insertion reached 20 m/s.
The experiments that had been performed in this wind tunnel demonstrated that in order to provide a higher homogeneity and to prevent the airflow swirling the airflow was to be sucked from the duct but not to be blown.
This wind tunnel was used in multiple tests including studies of airflow action on the airfoils arranged in cascade, center of pressure determination, objects drag measurements as a function of airflow speed (stated in modern scientific terms, this is the determination of the drag coefficient as a function of Reynolds number).
In the aerodynamic laboratory the researches were also performed that were devoted to *clarification of the key issue of aerodynamics, namely, friction in mixing layers.* The rectangular cowl was attached to the middle of the small wind tunnel (Fig. 6).

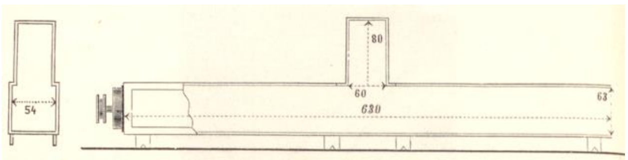

Fig.6. Wind tunnel superstructure to investigate the mixing layers

The lateral cross section of the cowl separately is shown in the right part of Figure 6. The air stream inside the wind tunnel forced to move the mass that was contained in the cowl along the closed trajectories as one can see from the photo of small tufts that are located on the cowl wall directed downstream (Fig. 7).

Fig.7. Photograph of superstructure lateral wall flow around spectrum

This photo enables drawing the streamlines that will allow finding out all speeds of the flow based on the speeds that were found at the cowl middle vertical line. The evaluation of the pressures at the cowl front wall and the rear one will allow estimating the total force of the slip flows. Afterwards this method of visualization was called a tuft method.

4.2 The large wind tunnel of the Moscow Imperial University

The insufficient cross section of the small wind tunnel and the insufficient speeds stimulated the Cabinet to set about to the construction of a large cylindrical wind tunnel (Fig. 8) that was erected late 1909 under sponsorship of the Ledentsov Society.

Fig.8. Photograph of the large wind tunnel at the Moscow Imperial University

To make the airflow uniform as much as possible a Sirocco type centrifugal fan that sucked out the air from the wind tunnel was installed. The wind tunnel was 10 m long and had a diameter of 1.6 m. The electromotor had a 160A current under a 120V voltage that corresponded to a maximum power of 38 hp. The wind tunnel as a whole was made of pasteboard except the wooden middle part. The bottom paper sections that were adjacent the wooden middle part were removable for the sake of usability. The upper parts and the rear walls were made of glass.
Models in the test section were supported either by Eiffel method or by string one of Prandtl. The large and long models were suspended via the parallelograms.
The flow field inside the wind tunnel was investigated in detail. The measurements were performed simultaneously with an anemometer and a micromanometer that were moving along the wind tunnel diameter. Figure 9 shows the diagrams of speeds inside the wind tunnel in various points of vertical diameter of the middle cross section with a speed variation range of 6-14m/s.

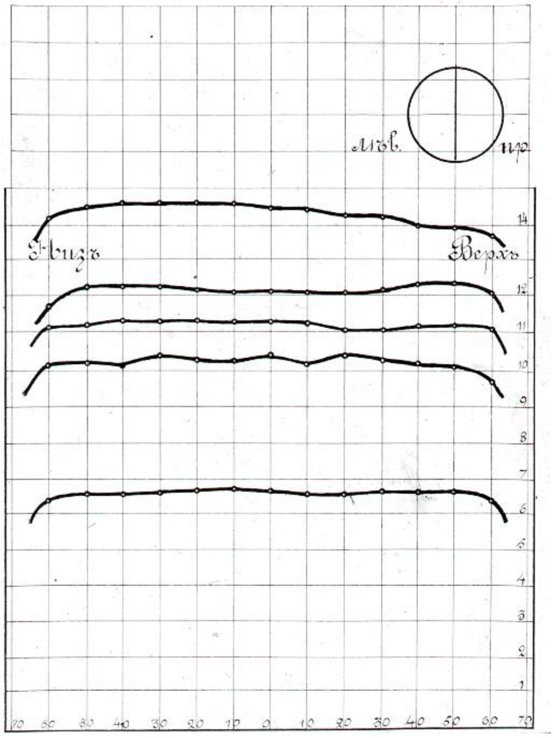

Fig.9. Distribution of flow speed in the test section of the large wind tunnel at the Moscow University

The distance to one of the walls is indicated on the abscissa axis and the speed is indicated on the ordinate axis. The diagram demonstrated that the flow nonuniformity in the 1.2 m diameter cross section did not exceed 4.5% that was a good result for that time.

4.3 The aerodynamic laboratory at the Imperial Technical School

In 1909, N.E. Zhukovsky founded the aerodynamic laboratory attached to the Imperial Technical School [7]. Two wind tunnels were built (Fig. 10).

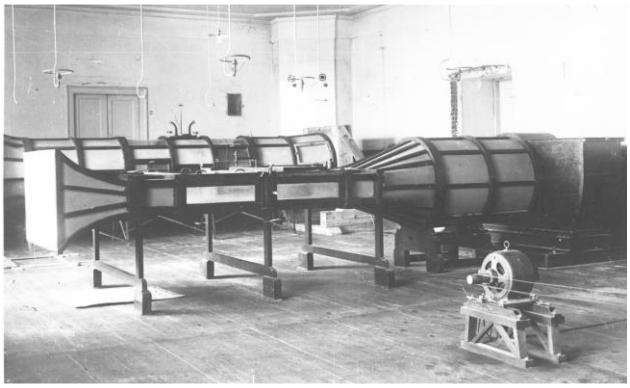

Fig.10. Photograph of two wind tunnels of the Imperial Technical School

As one can see in the photo, the wind tunnels of the Imperial Technical School as compared with that one of the University of Moscow were equipped with new elements: a nozzle and a diffusor. They operated from a single 23 hp DC motor.

Figure 11 shows a photo of N.E. Zhukovsky with his team in the big hall of the laboratory [8].

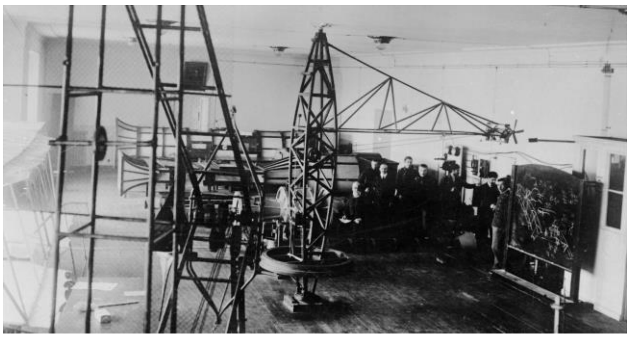

Fig.11. N.E. Zhukovsky with his team in the aerodynamic laboratory of the Imperial Technical School

In the center of the room a whirling arm was installed which was driven by a 2 h.p. electric motor. The same motor rotated a helical fan in a small Eiffel-type wind tunnel with a nozzle 0.3 m in diameter. The maximum flow speed equaled 43.5 m/s. This facility is located on the photo behind the rotary machine. The "flat" and round wind tunnels are located farther.

The cross section of the test section of the "flat" wind tunnel (in the foreground on Fig.10) was 150 cm x 30 cm.

The air was sucked in through the intake by a Sirocco fan through the intake. The airflow speed in the test section was up to 20 m/s. The tunnel was intended to study objects of infinite span (i.e. in two-dimensional, planar, flows). The built wind tunnel produced a highly regular field. Fig. 12 shows an airflow speed distribution in the wind tunnel middle cross section.

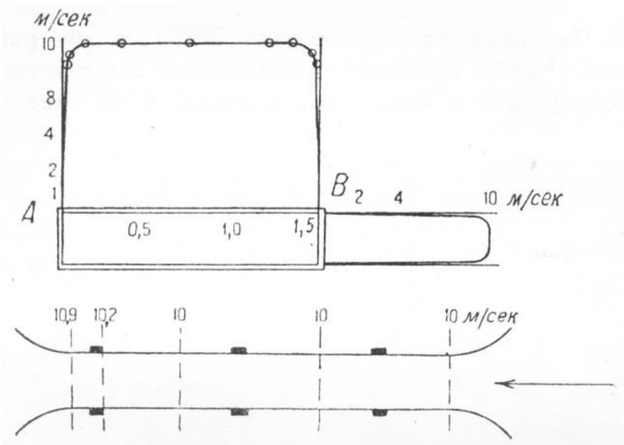

Fig.12. Distribution of velocities in the "flat" wind tunnel at the Imperial Technical School

The upper diagram corresponds to the speed distribution in the horizontal cross section and the lower diagram corresponds to the distribution in the vertical one. This wind tunnel has remained intact to the present day and now is on display at the N.E. Zhukovsky Scientific and Memorial Museum in Moscow (Fig. 13).

The diameter of the large wind tunnel equaled 1.2 m, the airflow speed was up to 30 m/s. This wind tunnel was driven by the same motor as the flat one. The air was sucked into it by the vane blower.

Fig.13. Photograph of the "flat" wind tunnel on display at the N.E. Zhukovsky Scientific and Memorial Museum

Mounted on the upper wall of the test section was an apparatus (Fig. 10) analogous to that designed by D.P. Ryabushinsky to measure the aerodynamic force acting on a plate, as well as the force application point [8]. The apparatus, representing a single-component balance, was installed on two legs with pivots allowing it to swing. The legs could be arranged in parallel with the airflow direction, or normally to it. In the first case the balance measured the lift and the drag in the other case.

In 1915 the construction of a large closed circuit wind tunnel with a cross-section of 2.5 x 2.5 m was completed. A photo of N.E. Zhukovsky in the test section is given in Figure 14. The wind tunnel was intended for testing propellers and windmills. A four-blade suction-type fan installed in the depth of the channel was rotated by an electric motor with a capacity of 47 h.p. (shown in the foreground of the photo). Behind the electric motor there was mounted a model of a helicopter rotor developed by Yuriev and Sabinin, members of N.E. Zhukovsky's team. At the top of the photo the return leg of the wind tunnel is seen.

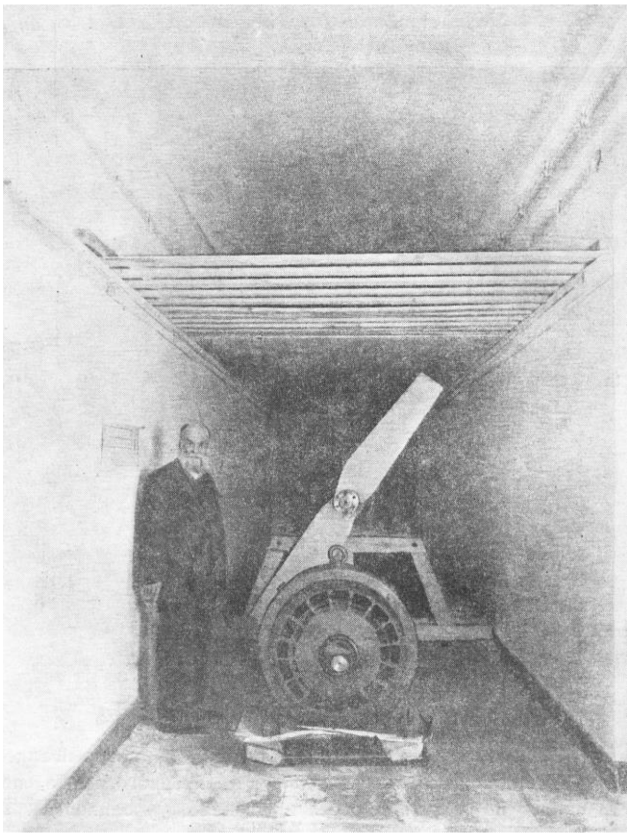

Fig.14. Photo of N.E. Zhukovsky near the electric motor of the large closed circuit wind tunnel of the Imperial Technical School

5 Wind Tunnel in Kuchino Aerodynamic Institute

The Kuchino Aerodynamic Institute was established upon an the initiative of D.P. Ryabushinsky [9, 10] and on his expenses. In 1904 D.P. Ryabushinsky invited the prominent Russian scientists N.E. Zhukovsky, V.V. Kouznetsov and S.S. Nezhdanovsky to become members of the Institute Organizing Committee. N.E. Zhukovsky was responsible for the general scientific guidance and D.P. Ryabushinsky was the director and he was engaged in experiments implementation. By the end of 1904 the Aerodynamic Institute was built in Ryabushinskys' estate (in Kuchino, not far from Moscow). The Institute that was provided with high-performance equipment included the main building (view in plan as 13 x 70m and in height 8.5m, Fig. 15), a tower (6.5 x 6.5 x 20m), workshops, an engine house, a residential house and a house for workpeople.

Since 1906 N.E. Zhukovsky and S.S. Nezhdanovsky had not participated in the activities of this Institute.

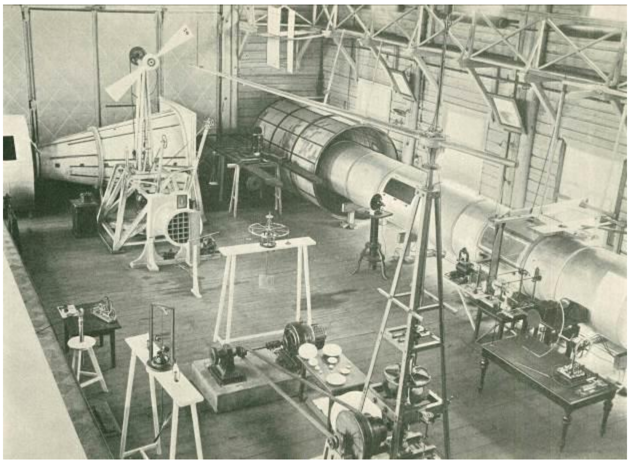

Fig.15. Photograph of the main hall of the Kuchino Institute

The results of researches performed at the Institute during 10 years were published (in French) in six issues of “Bulletin de l’Institut Aérodynamique de Koutchino” [11].

For wind-on studies at the Aerodynamic Institute, at the suggestion of Professor N.E. Zhukovsky, there was installed a horizontal wind tunnel (Fig. 16) 14.5 m long and 1.2 m in diameter.

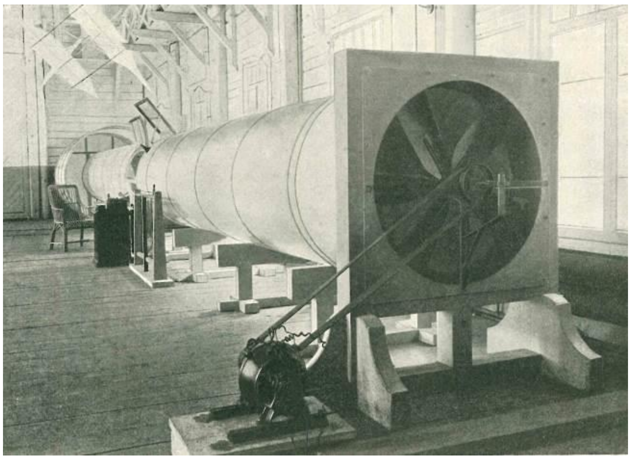

Fig.16. Wind tunnel of Kuchino Aerodynamic Institute

The suction fan (front view) that was mounted in the wind tunnel exit section and driven by the electric motor, speeded up the airflow up to 6 m/s. The suction principle was chosen based on the results of experiments carried out by P.P. Sokolov under the guidance of N.E. Zhukovsky in the Moscow University mechanics office and showed that when being sucked the air flow in the tunnel was more uniform than when being injected into it.

Before starting the tests studies were performed on the flow field in one of the sections. For this purpose one stretched steel threads vertically or horizontally along which Caselli small anemometers moved.

The first experiments discovered the effect of the floor and the lateral walls on the non-uniform core flow speed which amounted to 15% of the average speed (dash-dotted inclined line in the upper graph of Figure 17).

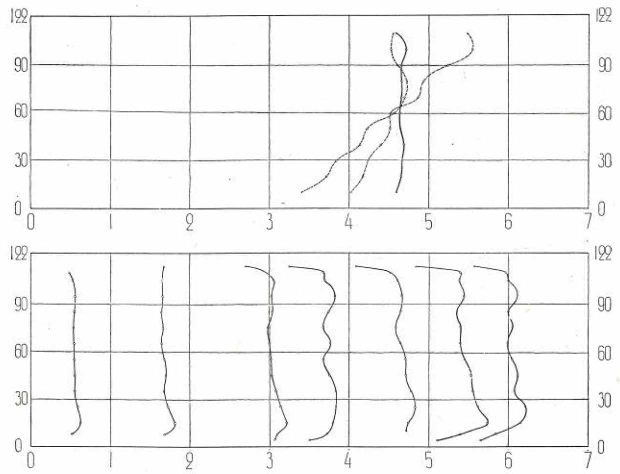

Fig.17. Dependence of the longitudinal velocity in m/s (abscissa) on the distance from the tunnel wall facing the room in cm (ordinate axis).

To reduce the nonuniformity an attempt was made to establish a thin copper grid at the tunnel inlet. The grid influenced only the average speed reduction at the same fan speed (dashed curve in the upper graph of Fig. 17). After several attempts to establish various types of screens near the inlet the developers chose a coaxial cylindrical cover (at the left end of the tunnel in Figs. 15, 16) 2.2 m in diameter and 3.5 m long, half the length of which was dressed on the tunnel. This led to a significant improvement in flow uniformity to 0.8% (solid curve in the upper graph of Fig. 17). The lower graph in Fig. 17 shows curves for different flow rates when the wind tunnel inlet was covered with a cylindrical cover. Later on N.E. Zhukovsky installed a similar headpiece on the large wind tunnel of the University of Moscow (Fig.8).

The subject of one of the first studies was determination of the effect of the ratio of its area *S′* to the tunnel cross-section area *S* on the disk drag coefficient. The scheme of the test unit and scales designed to measure the drag of the disc *A* is shown in Figure 18. The drag of a part *B* of the rod *a* long measured without the disk and subtracted from the test results. The studies were conducted at various flow rates with simultaneous measurement of electric current and voltage of the electric motor for calculating the tunnel power consumption.

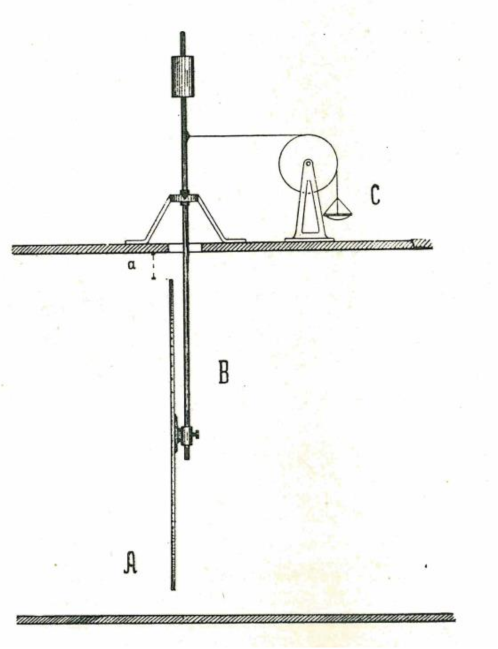

Fig.18. Experimental setup scheme for determining disk drag

D.P. Ryabushinsky concludes that the disk drag and electric motor power spent on putting the fan in motion increase as the *S′/S* ratio increases.

Figure 19 shows the dependence of the disc drag coefficient $P/V^2S\Delta$ (*P* is the drag, *V* is the flow velocity, Δ is the density of air) on the disc and tube diameters ratio *D′/D*.

The results were approximated by a cubic parabola:

$$\frac{P}{V^2 S' \Delta} = \left\{ 0.0798 + 0.785 \left(\frac{D'}{D} \right)^3 \right\}$$

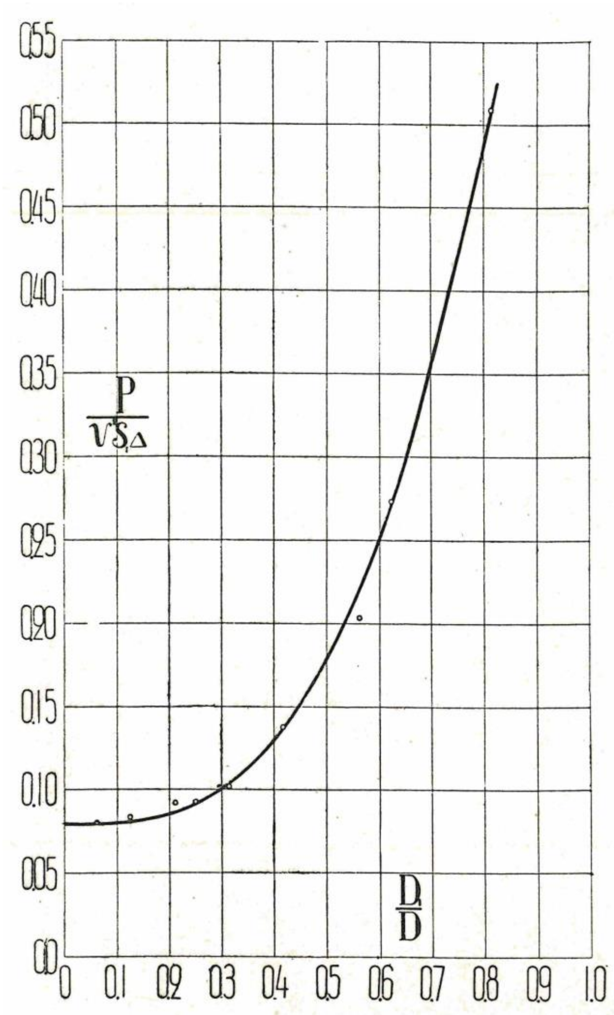

Fig.19. Dependence of the disc drag coefficient *P/V²S′* on the disc and tube diameters ratio

This allows determining the systematic error due to the interaction of the disc with the tunnel walls, depending on the tunnel degree of engagement. It should be noted that this is one of the first studies on the crucial issue of the experimental procedure – the influence of flow boundaries on the aerodynamic characteristics of the studied models.

D.P. Ryabushinsky developed a model flow visualization method using the light Lycopodium powder (Lycopodium spores) placed on a piece of metal together with a two-dimensional model (Fig. 20). He noted that the flow spectra, even though they do not reproduce the streamlines around the models with high accuracy due to the presence of the boundary layer on the metal, in general give a true idea of the flow.

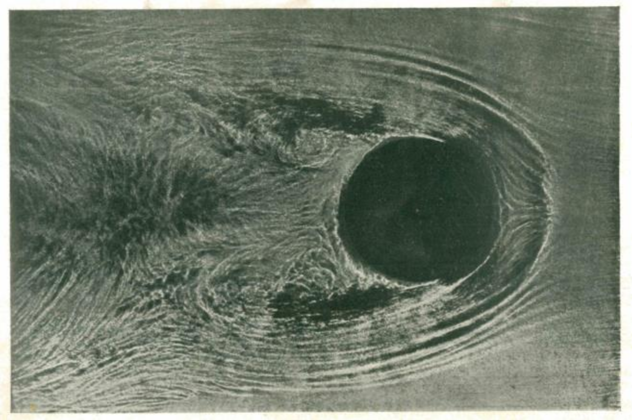

Fig.20. Visualization of cylinder flow field

D.P. Ryabushinsky built small models of all major types of wind tunnels that existed at the time. The reason for this was the discrepancy between the experimental data obtained by different researchers. The Eiffel wind tunnel model was the first to be constructed which can be seen in the upper left corner in Figure 15. Then L. Prandtl's wind tunnel model was built.

D.P. Ryabushinsky may be considered as the first researcher thoroughly engaged in one of the most important issues of wind tunnel testing methodology – the influence of the flow boundaries on the models' aerodynamic characteristics.

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