sheet metal and protected from over-heating. Two doors sliding perpendicularly to the axis of the flue will isolate the working section while the model is being handled. The measuring devices will be placed in an airtight cabin on the wall of the working section, so that the rods of the model supports can traverse the wall of the flue by joints which should not be airtight. The measurements will be registered automatically by apparatus installed either in the cabin and visible from outside, or actually installed outside the cabin. In the latter case the apparatus will consist of manometers connected with dynamometric capsules placed in the cabin. The propeller-fan will have adjustable blades so that it can be adapted to the density of the fluid used in the tunnel.

[. . .]

Document 2-18(g), Max M. Munk, "On a New Type of Wind Tunnel," NACA Technical Note No. 60, 1921.

Introduction.

The difficulties involved in conducting tests on airplanes and airships in actual flight, difficulties greater in the early years of aviation than now, and the matter of expense also, induced investigators to seek information through tests upon models. The first of such tests was made by moving the model through stationary air either by means of a whirling arm or in a straight line. Later the method adopted was to suspend the model in a current of air flowing in a large tube. Wind tunnels of this type have become of increasingly great importance. At first the tunnels were only small pieces of physical apparatus in a laboratory, but at last they require an entire building. The latest wind tunnel of the Zeppelin Company in Germany provides a current of air ten feet in diameter, which has a velocity of 110 mi/hr. and absorbs 500 H.P.

The results obtained with this type of wind tunnel are of very great value and at the present time they are the chief source of information for the aircraft designer. However, there are certain critics who declare that the results of wind tunnel tests are valueless for purposes of design. Indeed, justification for such opinions is not wholly lacking. There is, in fact, no necessary and exact connection between the motion of air around a small airplane model and that around the full-sized airplane. Sometimes the results of the tests on models agree well with those observed with the airplane itself, but important cases are known where the two do not agree. Further, there are questions the answers to which it is most important for the designer to have, and yet the answer deduced from tests of models in wind tunnels would be absolutely wrong. There is always an uncertainty connected with such tests, because one is never quite sure whether or not the results thus obtained may be applied to full-sized bodies.

In spite of this uncertainty, wind tunnels have been of the greatest use in the development of aeronautics. Tests upon models led to the construction of streamlined bodies having small resistance, and of aerofoils of good section. Experiments in wind tunnels led to the discovery of the theorems referring to the lift of aerofoils and to the effect of combining several aerofoils. A wind tunnel is still the most important means available for scientific tests. It can not be denied, however, that it is becoming more and more difficult to find a problem suitable for study by a wind tunnel, which can be immediately applied in aeronautics. Many tests of a theoretical character can be suggested, but it is difficult to interpret them. There are many important and urgent tests with respect to the design of aircraft which should be performed, but the results would be worthless if they were carried out in a wind tunnel of the present type. The theory of non-viscous motion is almost complete, the tests referring to it have been made, and the field of investigation lying between non-viscous motion and actual motion in the air is cultivated so intensely that it is difficult to find a new problem.

For all these reasons, the author believes that his proposition to make use of compressed air in a new type of wind tunnel comes at the right moment. Tests in such a tunnel will give information concerning those questions which could not be investigated with the present tunnels because of the exaggerated effect of viscosity. The new type of tunnel is free of the uncertainty characteristic of the older type, and will indicate clearly what problems may be undertaken with the latter. It will make unnecessary many full-flight tests, and will mark a step in advance in aeronautics.

Let us then consider this new type of wind tunnel; its advantages, the difficulties attendant upon its use, and the special methods required.

I. PRINCIPLE OF THE PROPOSED WIND TUNNEL.

The main difference between the new type of wind tunnel and the ones now in operation is the use of a different fluid. The idea is to diminish the effect of viscosity. It would not be surprising if any other fluid were better than air in this respect. However, there does not seem to be such a fluid. Water, the liquid most easily obtained, has, indeed, a comparatively small viscosity; that is, the ratio of its viscosity to its density is only the 13th part of the similar ratio for air. The density of water, however, is so great that it is hardly possible to afford the horsepower required to force water through a large tunnel. But, even supposing that such a current of water could be obtained, e.g. by using a natural waterfall, it would be quite impossible to make tests in it. A model could not be made sufficiently strong to withstand the enormous forces acting on it, nor would it be possible to hold the model stationary. The same difficulty would be met in using any other liquid. As for gases other than air, carbonic acid is the only one which has a ratio of viscosity to density less than that of air, but the difference is so small that it would not pay to use it. It is less expensive to build a larger wind tunnel than to construct one for using carbonic acid gas, which has to be sealed and requires gasometers and other contrivances for holding the gas; and, further, the difficulties of operation would all be increased.

The fact that there is still another way of changing the fluid did not occur to any one for many years. Air may be used, but, if it is compressed, it becomes a fluid with new properties,—a fluid which is the best suited for reliable and exact tests on models. When air is compressed, its density increases but its viscosity does not. The increased pressure, it is true, requires strong walls for the tunnel to withstand the pressure and to prevent the air from expanding, but the increase of effectiveness secured for the tests is so great that it will pay to make the necessary changes and to replace the light walls of existing tunnels by heavy steel ones.

Before discussing this point we must first convince ourselves that the increase of pressure greatly increases the range and value of wind tunnel tests.

II. THE REYNOLDS NUMBER.

We are inclined naturally to compare small objects with large ones, with the assumption that all the qualities are independent of the size of the object, and that therefore the effects will be correspondingly smaller or larger. Coming at once to our problem, we are disposed to think that useful information for the designer of a flying machine may be obtained by observing the shapes of a butterfly or of various insects. In fact, this is the idea underlying tests on models. The absolute size of bodies is, it must be noted, a concept devoid of exact meaning. There is no absolute length; the length of any object can only be compared with that of another. Imagine all scales to have been destroyed, and let us not be conscious of the dimensions of our own bodies. Then we would not be able to decide whether our physical world should be called a dwarf one or a giant one—we would have no basis of comparison. We may therefore reasonably expect that a world on a different scale than ours would not differ essentially from ours if the same physical laws are valid in both.

This does not mean that all numerical ratios would be the same in both. It is not necessary that the same physical laws produce the same motion of a fluid, i.e. a geometrically similar motion, around two similar bodies. For the streamlines of a fluid around an immersed solid are not related to its shape by geometrical relations but by those derived from the laws of mechanics. It is possible, however, to derive the condition for obtaining such similar motions by extending our general considerations, without using mathematical processes.

We picture two phenomena, independent of each other; in particular we presuppose that no scale is carried from the seat of one phenomenon to that of the other. We consider separately two geometrically similar solids, each immersed in its own fluid, and endeavor, under these conditions, to see if we can detect any difference between them. If we can not, it would be absurd to expect two different motions, for one of the absolute truths, of which everyone is convinced, is that equal causes have equal effects. Further, where we can not find a difference, we believe, there is equality.

The two solids being supposed to be geometrically similar, no difference can be found between them, since we do not have a scale. By selecting any particular length of the body, its dimensions can provide us only with a standard length for the investigation of the relation between the body and the space qualities of the fluid.

For the same reason we can not detect any difference between the densities of the two fluids. Instead of considering density as the second standard unit—length being the first—we will obtain a more useful one and one to which we are more accustomed if we combine the concepts of volume and of density, and consider, for instance, the mass of a cube of unit volume filled by the fluid as our standard unit of mass.

The velocity of the fluid relative to the immersed body and at a great distance from it may be considered as a third standard unit.

It is essential to realize that it is not possible to find any relation between these three quantities. Neither do any two of them mean the same physical thing, nor can any two of them be combined in such a way that the third appears. If, therefore, the qualities mentioned were sufficient to determine all the features of the phenomenon, the flow around similar bodies would always be similar also; we would not be able to detect any difference. This is the actual case if the fluid is non-viscous, and therefore motions around similar bodies immersed in perfect fluids are similar.

The viscosity of a fluid is characterized as follows: consider a unit cube of the fluid, so chosen that in any plane parallel to one of its faces the fluid has a constant velocity; let the velocity of the fluid increase uniformly as one passes from this face across to the opposite one; then, if this change in velocity equals the unit of velocity, the force of friction on the face of the cube is called the coefficient of viscosity of the fluid. This appears to be a complicated concept, so we shall try to combine it with the two standard units of length and of mass, so that we obtain a velocity characteristic of the viscosity of the fluid, in combination with the other two qualities. Let us imagine now a unit cube of the fluid and any difference of velocity on the two opposite sides. There is a force of friction on each such face. If this force were to act on a unit cube of the fluid, i.e., on a unit mass, it would produce an acceleration, and in the course of being moved through a unit distance this cube would have its velocity increased from 0 to a definite value.

We may imagine the conditions of velocity on the two opposite faces of the unit cube varied until the force of friction is such that the resulting velocity of the second cube equals the difference in velocity at the two faces of the first cube. Half this velocity may be called the "Reynolds velocity." It is characteristic of the viscosity of a fluid whose density is known, the dimensions of a solid body immersed in it being known, so as to furnish a unit of length. It can be determined for one of the two phenomena considered without reference to the other.

Therefore the ratio of the velocity of a fluid to this Reynolds velocity can be determined without reference to another phenomenon; it is an absolute number, called the Reynolds number. It may be the same in the case of two phenomena, or it may be different. If it is not the same, here is an essential difference between the phenomena, which may be observed and stated; and it would be most remarkable if, in spite of this difference, the fluids should have the same motions; it would in fact be impossible. But if, on the other hand, the two numbers are equal, we describe the motions of the two fluids as identical, taking viscosity into account, too. We may seek other differences; if there are none, it would be absurd to expect different motions.

Before extending our general considerations, we shall express the Reynolds number in terms of the quantities ordinarily used. Let r be the density of the fluid; m be the coefficient of viscosity; B be the characteristic length of the immersed solid. The mass of a cube of the fluid of length B on each edge is B3r; the force of friction on a face of area B2 is mBV1, when V1 is the difference of velocity at the two opposite faces; the work performed by this force if acting through a distance B is mB2V1, which equals the kinetic energy gained by the (second) cube of mass rB3 —i.e. $\frac{1}{2}\rho B^3 V_1^2$. Hence, if $V_1 = V_2$

$$\mu B^2 V_1 = \frac{1}{2}\rho B^3 V_1^2 \text{ or } V_1 = 2\frac{\mu}{\rho}\frac{1}{B}$$

the Reynolds velocity is one-half of this, i.e.

$$V_R = \frac{\mu}{\rho}\frac{1}{B}.$$

Writing V for the velocity of the fluid at a great distance from the solid, we have, by definition, the Reynolds number

$$= \frac{V}{V_R} = \frac{VB}{\mu/\rho} .$$

If this has the same value in two phenomena of flow, they are alike in all respects. This may be called the Reynolds Law.

III. DEDUCTIONS FROM THE REYNOLDS LAW.

In the preceding section an attempt has been made to derive the expression for the Reynolds Law in as elementary a manner as possible. Only by knowing the basis of the law can one grasp its complete meaning and obtain the absolute confidence in it which is required for one to apply it safely. A mathematical proof was not given although it would have been shorter, for it would at the same time have been poorer of content.

We considered only the viscosity of the air, and did not discuss the other differences which exist between the tests on models and those on full-sized objects. The next stop is to investigate whether these differences do not introduce such errors that it would not be worthwhile simply to get rid of a possible error due to viscosity. Before doing this we must consider the deductions from the Reynolds Law so far as wind tunnel tests are concerned.

Let the span of the wing of a model be 3 ft., and the air velocity be 60 mi/hr. (= 88 ft./sec.). The kinematical viscosity of air at 0°C and normal pressure is 0.001433, i.e., about $^{1\ \text{ft.}^2}\!/_{700\ \text{sec.}}$. Hence the Reynolds number, regarding the span as the characteristic length is

$$\frac{3\text{ft.} \times 88\text{ft/sec.}}{\frac{1\text{ft.}^2}{700\text{sec.}}} = 185{,}000.$$

That is, the velocity of the air in the tunnel would be almost <u>two hundred thousand times</u> the velocity called the Reynolds velocity. The full-sized airplane may have a span ten times as great, and the velocity of flight may be 1 ½ times as great; so that its Reynolds number is

$$10 \times 1.5 \times 185{,}000 = 2{,}775{,}000.$$

The magnitude of these numbers is surprising. The viscosity of the air is so small that in the neighborhood of the wings of an airplane the velocities produced by the forces of friction are only about <u>three millionth</u> of the velocity of flight. Equation (1) shows that the kinetic energy is proportional to the square of the velocity, while the work performed by the frictional force is proportional to the velocity. Hence the work performed by the frictional force is a minute fraction of the kinetic energy, $^{10}\!/_{185{,}000}$ in the model test referred to and $^{10}\!/_{2{,}775{,}000}$ in the case of the airplane. It seems surprising that any effect of friction can be detected, since it increases or decreases the kinetic energy by such a small fraction.

However, in the calculation of the Reynolds number one quantity is chosen arbitrarily. An arbitrary length occurs in the formula, and the magnitude of the number depends upon the choice of this length. Indeed, within a range of a dimension like the span of wings, the viscosity has almost no influence, but the smaller the range considered, the greater is the effect of viscosity, provided there are in this range the same differences of velocities as in the other. It must be noted that great differences of velocity occur within very small ranges. Near the surface of the wing velocities almost zero occur close to velocities of the magnitude of the velocity of flight. The character of the motion depends upon the stability of flow near the surfaces, and therefore, upon phenomena within small ranges. Within these the Reynolds number and the ratio of the acceleration to the viscosity is less than the number commonly used for comparison.

In any case, tests show that there are considerable differences of motion at the Reynolds numbers of the test and the flight. There is even instability, changing the character of the motion near the largest airships, on increasing its velocity, when flying at normal velocities.

These facts are not contradictions of the Reynolds Law, but, on the contrary, are in agreement with it. The surprising fact that, even when the Reynolds number is large, its influence is considerable, does not furnish the least reason-for doubting the correctness of a law based upon such elementary considerations.

Doubts about the Reynolds Law are based upon a different fact. In spite of the convincing proof, it happens that model tests at the same Reynolds number sometimes give quite different results. Now the Reynolds Law does not mean that at the same Reynolds number only one particular motion of the air is possible. It states that there is no difference between two phenomena with the same number. It may be that two or more motions are possible, but then they are possible in any case of the same Reynolds number.

There must be some reason, however, why the one or the other motion occurs. The reasons may be different. Sometimes there is a kind of hysteresis, the fluid remembered, as it were, what happened before this particular motion began; and the motion is different, for instance, if the angle of attack was larger or smaller immediately before. If such a phenomenon occurs with the full-sized body, it can be investigated by a model test at the same Reynolds number. Sometimes there is no such hysteresis, but the motion is very sensitive and is changed by the least change of the shape of the body, or of the smoothness of its surface, or with a change of the turbulence of the air. In such cases the motion around the full-sized body will be sensitive at the same Reynolds number as in the model tests. In this case it will be difficult to obtain the exact shape of the model and the right smoothness of its surface in order to have the same motion. At the same time other differences between the model test and the actual flight will produce differences in the results; but in such cases it is very doubtful whether two airplanes which are apparently identical have the same qualities. There does not exist a definite motion around the body at that particular Reynolds number. The careful investigator will observe this fact. Then the model test has shown all there is to be shown, and the method is not to be blamed for revealing phenomena which are surprising to the designer but true nevertheless.

IV. ERRORS DUE TO OTHER CAUSES.

There are still other differences between the tests on models and in actual flight, which will cause errors. It is necessary to realize that these, other than the one due to viscosity, do not affect seriously the value of the results of the tests. The new type of wind tunnel may, then, be expected to give reliable results.

The best evidence of the insignificance of these errors due to other causes is obtained by comparing tests made in different wind tunnels. It may be stated that there is found a certain agreement, but only with the same value of the Reynolds number. Reynolds himself deduced the law called by his name from experiments upon water flowing through pipes. In the two wind tunnels at Göttingen very careful investigations were made on aerofoils, over a large range of Reynolds numbers, and under very different conditions. Most results at the same Reynolds number agree well; even the results which can not be plotted on a curve against the Reynolds number appear much more regular when so plotted than when plotted in any other way. The results of these tests show that full-sized tests are much better than model ones, and provide the designer with clear, reliable and useful information. It is not sufficient, however, to compare the results of several tests in a perfunctory manner; care must be taken.

The Göttingen tests were not made under conditions geometrically similar; the two tunnels are not equally good. There are many tunnels which have more turbulence than is necessary, the designer having only taken care to obtain a uniform velocity. The older wind tunnel at Göttingen was exceedingly turbulent. The surfaces of the models were different purposely. Only the results obtained in good wind tunnels should be compared, the model having a proper surface, and the test being thoroughly laid out with reference to its influence. Then the differences would be smaller, and the reliability and usefulness of tests at the full-sized Reynolds number would appear more distinctly.

The matter may be considered also from another point of view. The tests show that under particular conditions the results of different tests agree very well; in certain cases only is good agreement lacking. Now it is not evident that the results may be expected to agree. It may be and is very probable that the motions which do not agree with each other are such sensitive motions as were described in the previous section. Of course this sensitiveness appears exaggerated if the differences in the test conditions are.

Theoretical reasons are not wanting, however, as to why the character of the motion depends almost exclusively on the ratio of the velocity of air to the Reynolds velocity, and not upon other ratios, e.g. the ratio of the Reynolds velocity to the velocity of sound in the medium, the latter being characteristic of its compressibility. It is not at all sufficient to state that this ratio is small, the Reynolds number (or its inverse) being small too. But the ratio of velocity to the velocity of sound has only one meaning; there is no arbitrary quantity used in forming it—such as B in the-Reynolds number. It does not matter whether this ratio is calculated for a wide range or for a small one. There is no discontinuity if the range or the compressibility passes to zero. In this case the fluid acts, with respect to its compressibility, like a perfect fluid. If the ratio of the velocity of flight to the velocity of sound is small, there is no physical reason for expecting a large influence. So much the less is the influence of a difference of compressibility in the tests on the model and in flight. Stated mathematically, any coefficient is a function of the two ratios; but, when both are small, the function is continuous with respect to the one and irregular with respect to the Reynolds number.

The same deduction is valid for the other errors; whether the cause be the contrivance used for supporting the model, the turbulence of the air, the variation of pressure or of velocity, or the finite distance of the walls of the tunnel or the boundaries of the current of air, the error is small provided the cause is. Their influence can be made as small as is necessary and customary in any technical test. Not only is the error small, it is regular, it can be compensated for, and it does not impair the comparison of different tests, as would the error due to viscosity.

V. THE DIMENSIONS OF A COMPRESSED AIR WIND TUNNEL.

In a tunnel filled with compressed air it is possible to obtain a Reynolds number much larger than in the tunnels now in use. But the range is limited in several respects, and its features must harmonize with each other in order to secure good results and also a low cost of operation.

The size of the tunnel is limited by the size of the models. It is not possible to make correctly shaped models if they are too small. The velocity of flow, on the other hand, must not be too great, lest the contrivances for supporting the model become so large that they disturb the motion. The stresses in the model must also be considered. This condition is duly respected if the dynamical pressure of the air does not exceed a particular value.

Hence the velocity must be the smaller the greater the density. This is desirable also with respect to the power required, to the increase of temperature produced, and to the dimensions of the fan and its shaft. The designer must also consider the time required to fill the tunnel with a compressor of proper dimensions. The pressure is limited only by questions of construction.

Let D be the diameter of the section where the model is placed, V be the velocity of the air and P be the maximum pressure. Then

Reynolds number	$R \alpha DVP$
Power required	$P \alpha D^2V^3P$
Heat produced per unit of surface	αV^3P
Dynamical pressure	$q \alpha V^2P$
Weight of tunnel walls	αD^3P

Energy required to fill tunnel $\alpha D^3P^{1.25}$
Shaft diameter/diameter of tunnel $\alpha VP^{1/3}$
(velocity of circumference of fan constant)

The designer, in the first place, must choose the dynamical pressure he can permit without the supports of the model introducing too great an error. Then he may calculate the pressure needed for the Reynolds number desired, and the smallest diameter he considers proper. If he selects too high a pressure, the diameter must be made greater. Generally this will increase both the cost of operation and other difficulties. The Reynolds number and the dynamical pressure being given, the diameter and the velocity may be expressed as functions of the pressure.

If $R=aDVP$ and $q=bV^2P$ then $V=AP^{-1/2}$ [and] $D=BP^{-1/2}$ where a, b, A and B are constant coefficients. Substitutions may then be made in the expressions for the different quantities. It appears:

Power absorbed $\alpha\ P^{-3/2}$
Heat produced per unit of surface $\alpha\ P^{-1/2}$
Weight of tunnel walls $\alpha\ P^{-1/2}$
Energy required to fill tunnel $\alpha\ P^{-1/4}$
Shaft diameter/diameter of tunnel $\alpha\ P^{-1/6}$

That is to say, all the quantities mentioned are more favorable the higher the pressure. This advantage must be compared with the difficulty of construction in consequence of high pressure, and the disadvantage of a smaller diameter. A theoretical limit for the pressure is the critical point where the air ceases to be a "perfect gas." In the neighborhood of this point the viscosity increases and therefore it is of no advantage to increase the pressure; but reason of construction would prevent this point being reached. The critical point of carbonic acid gas is, however, much lower, especially if it is cooled.

We can not close this chapter without considering the most interesting question, whether it would be possible to build a wind tunnel for tests of models of airships, having a Reynolds number equal to flight conditions. Let the length of the actual ship be 655 ft., and its velocity be 95 mi/hr. In a tunnel designed for tests of ship models only, the dynamical pressure could be increased to 2000 lbs./ft.^{2} The pressure could be 100 atmospheres (200,000 lb./ft.^{2}). Then the velocity would have to be just 95 mi/hr., and happens to be "full sized." The scale would be 1:100; the diameter could be 2 ft., and the power about 1000 HP. We think this tunnel could be made. It would give the designer information long desired.

The results of tests in a compressed air wind tunnel would be applied in the same way as is the practice with existing tunnels. The tunnel would give the ordinary coefficients, and the right ones. The Reynolds number could be calculated from the observed temperature and pressure.

The results would be, first of all, for the information of the designer of aircraft, giving him the true values of the coefficient required for any problem. The tunnel could also be used with advantage for scientific investigations. The differences in the Reynolds numbers which could be realized in such a tunnel are much greater than can be obtained in existing tunnels. At the same time, the pressures and the forces on the model vary only as the Reynolds number, if the same model is used, whereas in existing tunnels they vary as the square of this number.

Document 2-18(h), F. H. Norton, memorandum to G. W. Lewis, 1921.

October 6, 1921

From: Langley Memorial Aeronautical Laboratory
To: National Advisory Committee for Aeronautics
(Attention Executive Officer)
Subject: Design of compressed air wind tunnel

1. There are at present three Draftsmen spending almost all of their time on this work as it takes most of Mr. Morgan's time to supervise Mr. Pratt and Mr. McAvoy. Mr. Morgan feels that they are working very inefficiently and are getting very few results, as Dr. Munk does not seem to have any clear idea as to what he wishes in the engineering design excepting that he is sure that he does not want anything that Mr. Griffith or myself suggest. At the end of this week I must take Mr. Morgan and Mr. Pratt entirely away from this work and let Mr. McAvoy struggle along as best he can. For this reason it is requested that Mr. McAvoy be ordered to Washington so that he can be directly under Dr. Munk's supervision. I am getting so disgusted with the way the whole thing is being carried out that I would like to keep as much of it in Washington as possible.

[signed] F. H. Norton
F. H. Norton
Chief Physicist.