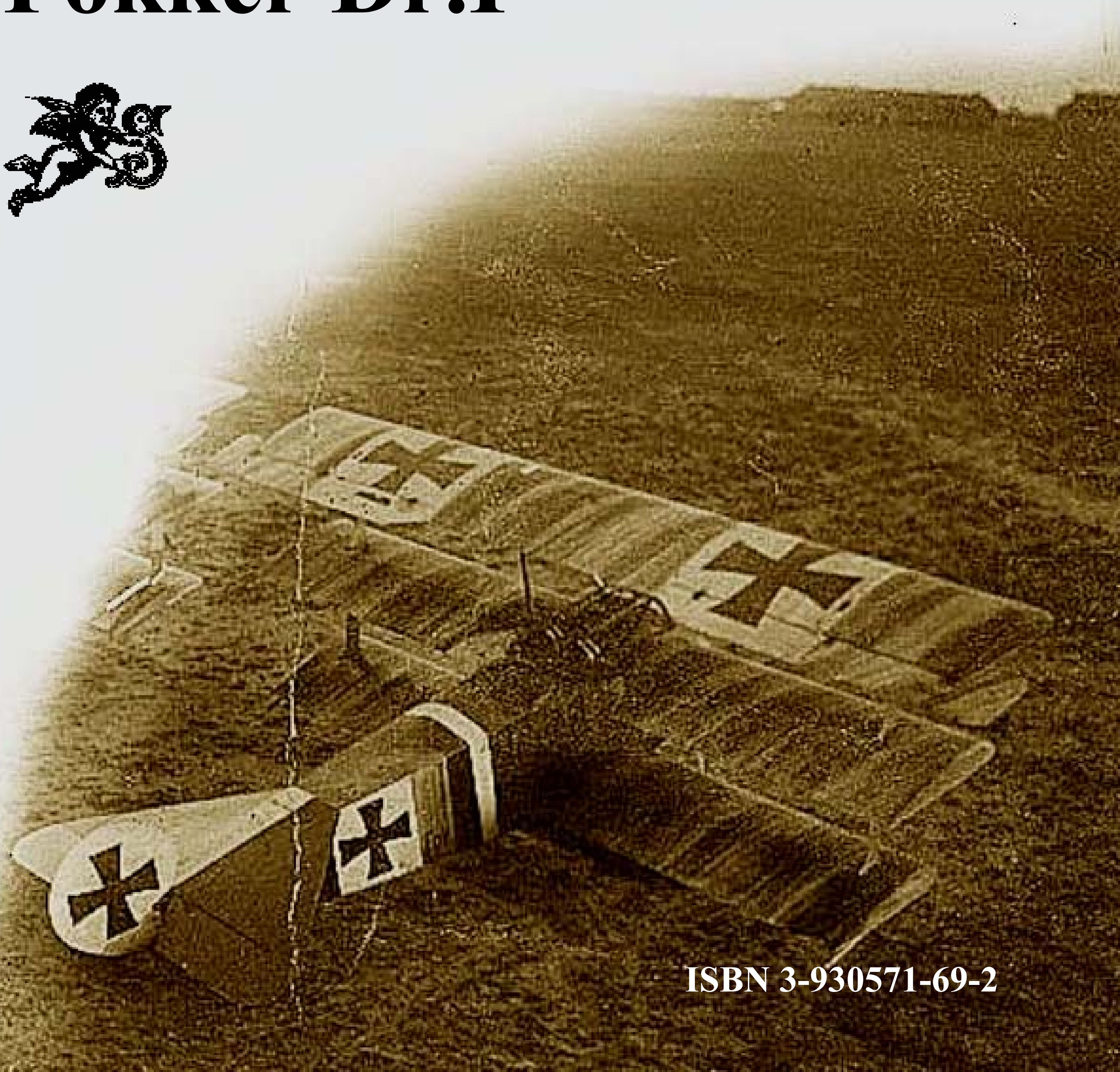
DEUTSCHE FLUGZEUGTECHNIK 1900 – 1920

Achim Sven Engels

Treatise on the aerodynamics of the
Fokker Dr.I



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Treatise on the aerodynamics of the

FOKKER DR.I

of the year of war 1917

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No part of this book lays claim to correctness and completeness. Nones of the calculations given here are provided for the calculation of actual aeroplanes. Any use of these formulae happens on own responsibility.

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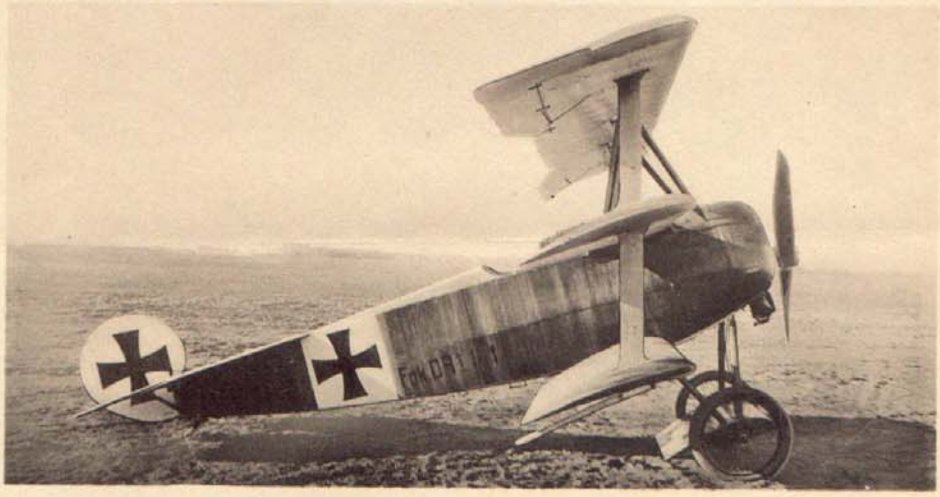

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Introduction to commence

The Fokker-Team-Schorndorf will produce a new series entitled

'GERMAN AIRCRAFT TECHNOLOGY 1900-1920'

intended to make the results of their research available to all interested groups. The primary focus of this series will be technical aspects of German aeronautics.

There will be both books that deal exclusively with technical descriptions of airplane structures and books that deal with other technical aspects of aircraft or aspects that were used in the operation of the aircraft. While the historical development of German aeronautics is not of major interest here, it is not completely ignored.

We very much hope that this series of booklets will be of interest to readers and that it will eventually come to be found in all libraries interested in aeronautical technology. In this meaning we wish these little deeds much success.

To be able to understand the topic which is to be discussed here a certain understanding of basic information is necessary. Since we cannot assume that all of our readers have an understanding of the basics of aerodynamics, we must start with a simple introduction to them. Where needed, our sample calculations will be related to the Fokker Dr.I.

However, many of our readers will already be familiar with the science of fluid mechanics (mechanics of flow) so, in order to retain their interest, we will use a little trick.

Since the Second World War there has been a great deal of development in the understanding of fluid mechanics and, in particular, in the design of the formulæ used in the calculation of different forces acting on bodies under the influence of flow. At the beginning, the designers at the aircraft manufacturing companies as well as the scientists at the evaluation centres in England, France, Germany and other nations did the work themselves and used many different formulae and different literal notations to describe such simple conditions like average air density or the coefficient of drag. However, they have come together more closely after the Second World War and developed more regulated and standardized literal notations to be used by all. For sure the basic calculations did not experience such a great amount of change, however there have been added many more helpful calculations since then.

So that it will not get too boring for those of our readers who are experienced in this field of calculations we will go and strictly use those formulae that has been common in those days during the First World War among German aircraft designers. This way, not only does the layman learn the basic knowledge of aerodynamics, but the expert still learns at the same time some little historical facts about how these calculations had been executed during and after the First World War. As previously stated, sample calculations shall be related to the triplane in particular.

This treatise shall not represent any comprehensive calculation of the triplane aerodynamics, but should enable the interested reader after its study rather to carry out the necessary calculations for most different flight situations in which he is particularly interested and to create the required diagrams himself.

Author´s Acknowledgements

The Author – that's me – wants to keep this one brief. There are only a few people whom I wish to thank for their help with the development of the English edition of this book. First of all, my good friend Bil Hardenberger who is closely working with me on many of the illustrations given here. The other ones are Bill Broussard, Brad Smith, Darryl Hackett, Paul S. Leaman, Lloyd Leichentritt and Rockland F Russo. These have been so kind to provide their service of proof reading that book or parts of it to make it even more enjoyable by you – the reader.

1. The Forces of the Air and the Air Resistance

1.1. The Air Pressure

Castelli Evangelista Torricelles (*15.10.1608 +25.10.1647) befitted on recommendation of his teacher to *Galilei* in 1641 and eventually became his successor as a court mathematician of the grand duke of Tuscany.

During this time *Torricelles* occupied himself with studying the behaviour of different substances and investigated what happened if they were exposed each on one another to mutual pressures. He found that a piston filled with mercury could run dry only to a certain degree, if it is put into a vessel upside down, as long as no air was allowed to flow into the piston, even if he lifted the piston from the bottom of the vessel as long as the piston edge was in the mercury still. He inferred from this that the surrounding air applied a pressure to the mercury remaining in the piston. He also noticed that over time the height of the mercury varied slowly in the piston. Therefore he assumed that the surrounding air pressure must have been changing. All other liquids also exhibited the same behaviour. He called his instrument the barometer.

One therefore understands the pressure by the name air pressure, which the atmospheric air exerts on a certain area. Under normal conditions the air pressure is 1.036 kg/cm² at sea level. You can best explain this to yourself by imagining a hollow body pumped out to reach vacuum. A pressure of 1.036 kg/cm² is exerted on the outer surface under these circumstances. The expression "**at**" became an abbreviation for the measurement unit of kg/cm² or "atmosphere" imported written out. The normal average air pressure therefore amounts to 1.036 at.

The common measure for the measuring of the air pressure is the height of the column of mercury in the barometer. Torricelles made up his mind for the following reason to use the medium mercury. Since the specific weight of the liquid metal mercury is 13.60 kg/l or 13.60 kg/dm^3, consequently the total weight of a column of a cross section 1 cm² and a height of 762mm is exactly $0.01 \cdot 7.62 \cdot 13.60 = 1.036$ kg. This in turn is exactly the air pressure, which acts on 1cm² of an arbitrary area. So the barometer reading lies with 1 at surrounding pressure at 762 mm. If the air pressure relieves, which has an effect on the mercury, the reading changes in the column accordingly.

Since the density of the air is of special significance for flying we do come to mention the three major laws of the air density for calm or evenly busy air here.

1. The density of the air always is of equal value in every layer of air, although this must lie spatially for places far separated from each other.

2. With increasing height of the layers of air the air pressure decreases almost evenly.

3. The decrease of the air density is immediately connected with the respective ground lever temperature and the decrease of the temperature with increasing height.

The amount with which the temperature at increasing height falls is called "gradient of temperature". His quantity is 0.5 degrees Celsius at 100 m each approx., but lies with a considerable certainty between 0 degrees Celsius and 1 degrees Celsius.

It still is remarked here that the decrease of the air density grows with the quantity of the gradient of temperature and is also all the bigger the less the ground level temperature is accepted.

Of course it is not to be assumed that the barometer reading will be 762 mm in the column on the ground. It varies from time to time and from place to place in considerable measure. The influence of the barometer reading at ground level is of rather subordinate significance to the decrease of the air density with increasing height however.

Under the premise that the air is an "ideal gas" having the gas constants $R = 29.24$ (this calculates by the quotient of the pressure by the volume and the absolute temperature) there have been calculated theoretical tables which indicate the air pressure in mm of column of mercury for different ground level temperatures and gradients of temperature. See table No.1.

Using these purely theoretical calculations it is possible to use the decrease of the air pressure for the measuring of the altitude by reading a calibrated barometric scale. Since the air density however – as already mentioned above - depends on several factors and anyway very much fluctuates, the specification of the barometric height scale is based on relatively unsafe assumptions of the gradient of temperature, the ground level temperature etc. Therefore these “measurements” can be considered to merely be sufficiently exact estimations.

The density of the air has an immediate influence on its specific weight. One also talks about the volume of the air. We understand here the weight of a defined unit of the gas "air" by it. As a rule, the unit of the volume, which is used for calculations, is m^3 accompanied by the weight unit of kg. As a common expression for the volume of a substance is the Greek character of “***r***“ (Gamma.)

Table No.1

Air pressure in mm of column of mercury for heights of 0 to 8000 m at different ground level temperatures and gradients of temperature

Altitude in Meters	Temperature at Ground Level 0ºC			Temperature at Ground Level 10ºC			Temperature at Ground Level 20ºC		
	Temperature at every 100m:			Temperature at every 100m:			Temperature at every 100m:		
	0ºC	0,5ºC	1ºC	0ºC	0,5ºC	1ºC	0ºC	0,5ºC	1ºC
0	762	762	762	762	762	762	762	762	762
1000	671	671	671	675	675	674	678	677	677
2000	593	590	587	598	596	593	603	601	598
3000	523	517	512	530	825	519	537	532	527
4000	462	453	443	470	462	452	478	470	461
5000	407	395	381	416	405	392	425	414	402
6000	359	344	326	369	354	387	378	364	348
7000	317	298	277	327	309	288	337	319	300
8000	280	258	233	290	269	245	300	279	256

The specific weight of the air at a surrounding temperature of 10 degrees Celsius and a barometer reading of 762 mm is exactly 1.252 kg/m^3. The volume of the air can be seen in immediate dependence with the temperature and the air pressure.

A.) Change of the Atmospheric Pressure

If the atmospheric pressure changes, then the volume of the air changes itself also proportionally to this. If the volume of the air is 1.252 kg/m^3 under the conditions just mentioned above, then the volume of the air decreases as soon as the pressure falls. So, what is the volume of the air at a temperature of 10 degrees Celsius and an atmospheric pressure of 567 mm of column of mercury? This simply can be calculated. One must multiply merely 1.252 by the ratio 567:762. Therefore 1.252 · 567:762 = 0.932 kg/m3. From this we also can derive the first formula for the calculation of the volume of the air by using the variable "***b***" for barometer reading (column height of mercury). We have the following equation with that:

$$\tau = \tau_1 \cdot (b : 762)$$

Here τ_1 describes the specific weight of the air at 10 degrees Celsius and 762 mm height of column of mercury.

B.) Change of the Temperature

As soon as the temperature changes, the volume of every substance, as the air, also changes itself inevitably. We can explain this as: expansion is caused by the increasing oscillation of the single atoms with increasing temperature and therefore less of the substance will fit into one m^3 as the fixed unit. The so-called expansion coefficient of the air for 0 degrees Celsius lies around 1/273. Any air volume therefore enlarges at the heating of 0 degrees Celsius to 1 degrees Celsius at 1/273 portion of the former volume.

The volume of the air is τ_1 at +10 degrees Celsius.

How does the volume change at the same barometer reading and an increase of temperature on 20 degrees Celsius? An air quantity that has the volume of $1m^3$ at 0 degrees Celsius will change the volume at 10 degrees Celsius to 283/273 m^3 = 1+10/273 and 293/273 m^3 and at 20 degrees Celsius accordingly to 1+20/273. In the same term the volume of the air at different temperatures changes, the weight changes, too. If is assumed that τ_1 is the value at 10°C, then it is for 20 degrees Celsius the following:

$$\tau = \tau_1 \cdot (283 : 273) = 0.966\ \tau_1$$

This would be in general for the temperature:

$$\tau = \tau_1 \cdot (283 : (273+t))$$

The two orders just listed can also without further ado be summarized in a formula:

$$\tau = \tau_1 \cdot (b : 762) \cdot (283 : (273+t))$$

The volume of the air for every arbitrary height and the individual gradients of temperature and ground level temperatures finds its respective volume of the air under consultation of the values given in table No.1 and can be calculated with this formula.

However, one must keep in mind, that the data that were charged to table No.1 merely have been calculated theoretically. These, as said, have therefore not to be inevitably correct at 100 percent. For the gradient of temperature of 0.5 degrees Celsius per 100 m of increasing height the results are represented in table No.2.

One understands the density of the air is the quotient of its volume by the gravity ***g*** = 9.81 m/sec². Under the prerequisite that the temperature is 10 degrees Celsius and the barometer reading amounts to 762 mm the density of the air is τ_0 **: g** = 1.252 : 9.81 = 0.128, that is 1/8. The value 1/8 is the mean average value set for the density of the air on ground level. The density of the air relieves to almost about the half in larger heights. The letter "***m***" will be set for the quotient ***τ : g*** in the following calculations. For the aerodynamics and its calculations the variability of the composition of density of the air always is of outstanding importance.

Table No.2

Volume ***τ*** in kg/m^3 and the density ***m*** = *τ* : g for heights to 8000 m at a ground level pressure of 762 mm of column of mercury and a gradient of temperature of 0.5 degrees Celsius per 100 m

Altitude in Meters	Temperature at Ground Level 0ºC			Temperature at Ground Level 10ºC			Temperature at Ground Level 20ºC		
	Tempe-rature	τ	τ:g=m	Tempe-rature	τ	τ:g=m	Tempe-rature	τ	τ:g=m
0	0°C	1,298	132	10°C	1,252	128	20°C	1,210	123
1000	-5°C	1,165	119	5°C	1,129	115	15°C	1,094	112
2000	-10°C	1,044	106	0°C	1,015	104	10°C	988	101
3000	-15°C	933	95	-5°C	911	93	5°C	890	91
4000	-20°C	833	85	-10°C	816	83	-0°C	800	82
5000	-25°C	741	76	-15°C	730	74	-5°C	719	73
6000	-30°C	658	67	-20°C	651	66	-10°C	644	66
7000	-35°C	583	59	-25°C	579	29	-15°C	575	59
8000	-40°C	515	53	-30°C	514	52	-20°C	513	52

Related to a ground level temperature of 10°C and a gradient of temperature of 0.5° per 100 m of increasing height we are able now to establish the following average values to appear for heights to 8000 m as rough guidelines:

Height in Meters	1000	2000	3000	4000	5000	6000	7000	8000
Density in %	90	81	73	65	58	52	46	41

1.2. The Impact Pressure

The orders listed in section 1 for the variability of the atmospheric pressure in different heights apply to both resting and monotonously busy air. For our work here other than steady motions of the air are not to be considered. It should be mentioned here that there are also nonuniform motions, which of course also have influence on the aerodynamic qualities of an object. One also talks about turbulences. These nonuniform motions of the air appear in the immediate proximity of objects, which are moved through the air. This can be explained by the fact that the particles of the air that waft over the objects surface have to follow the surface at full speed or have to avoid the objects. This subsequent movement disappears with increasing distance from the objects because of the friction between the individual atoms in the air. For this reason there appear turbulences (nonuniform motions) in the air next to the object moved through it.

Hand in hand with this uneven speed distribution between the air particles at increasing distance from the object goes a change of the atmospheric pressure. A constitution of the mechanics forms the connection between these pressure and differences in speed:

Force = Mass · Acceleration.

How this all is linked we will take a look at in the following formula?

If one imagines for example a uniform flow of several air particles succeeding one another at an even acceleration passing the path $AB = l$, one can calculate the force, the mass and the acceleration of the air particles.

The pressure in point A is $\boldsymbol{p_1}$ the pressure in B is $\boldsymbol{p_2}$. The speed of the air particles is $\boldsymbol{v_1}$ in A and $\boldsymbol{v_2}$ in B. We describe the average cross-section of the airflow as an $\boldsymbol{f}$.

The force $\boldsymbol{p_1 \cdot f}$ acts into the direction of motion and the force $\boldsymbol{p_2 \cdot f}$ works contrary to the direction of motion. From this results that the **force** of the air particles looked at has to be calculated from $\boldsymbol{(p1 - p2) \cdot f}$.

The **mass** of the air particles of the airflow can be derived from $\boldsymbol{m \cdot f \cdot l}$, $\boldsymbol{m}$ just because this describes the air density of the unit.

We describe the increase of the speed as an **acceleration** in the time unit. We equate the average speed for $(v_1 + v_2):2$, now results from this the time out of the quotient path/speed = $l:([v_1 + v_2]:2) = 2l:(v_1 + v_2)$ and the acceleration therefore is:

$$\boldsymbol{(v_2 - v_1) : (2l : [v_1 + v_2]) = (v_2^2 - v_1^2) : 2l\ .}$$

We multiply this expression by the mass of the air flow $m \cdot f \cdot l$ then we get the form $m \cdot f \cdot ([v2^2 - v1^2]:2)$. Now, if we equate $(p1-p2) \cdot f$ this product from mass · acceleration of the resulting force, then the cross section f of the air flow falls out of the equation and we have:

$$p_1 - p_2 = m \cdot ([v_2^2 - v_1^2]:2) = m \cdot (v_2^2:2) - m \cdot (v_1^2:2) .$$

From the derivation of this formula we see that the difference in pressure between two points is as large as the difference of the product of density and half speed square. With this order the speed also can be measured relative to the "resting" air by a so-called concentration device. The force of pressure of the incident air is measured compared to the surrounding pressure. By:

$$p2 - p1 = m \cdot (v1^2:2),$$

can be charged the sought-after speed v_1 now. This equation is correct under the condition that before for $v_2 = 0$ was put, assuming that the air rests in point B.

For the product very frequently appearing in the aerodynamics from the air density and half the speed square one has already soon introduced a name of its own. One calls it the impact pressure and abbreviates it into calculations with the letter q. Therefore be always valid:

$$q = m \cdot (v^2:2).$$

Since m is the mass of the unit one also can describe the impact pressure as the "live" force of the "unit" air. As the atmospheric pressure is measured in kg/m^2 the impact pressure is correspondingly measured in weight per area unit, in kg/m^2.

It perhaps still should be said as an additional remark here that the impact pressure q is at a speed of 40 m/Sec. (144 km/h.) and a normal air density of 1/8, (1 : 8) · (1600 : 2) = 100kg/m^2, for example.

The impact pressure can also ascertainably be explained by a graphic consideration. One imagines only an object that is moved by the air. Will there be a point at which the speed of the air particles is 0 and these are divided and orbit the object at his front. This one on this point arising overpressure is the impact pressure being part of the speed of the object, q.

We can now go on and include q into the equation $p_1 - p_2$ for the calculation of the differences in pressure. In this case we will get;

$$p_1 - p_2 = q_1 - q_2$$

or

$$p_1 + q_1 = p_2 + q_2.$$

In turn this means that the sum of atmospheric pressure and impact pressure is the same at any old place of the air flow we imagined before. One can speak of a constants as a sum of impact pressure and atmospheric pressure generally because:

The bigger - at any place - the speed is and with that the impact pressure increases, the lower the atmospheric pressure gets. The same order is valid in the opposite direction.

(This is also the reason for the formation of a negative pressure at the top side of the cambered wing and an overpressure at her underside.)

1.3. The Air Resistance

As soon as an object is moved through the air, everybody can notice easily by himself that a force that is judged contrary to the direction of motion gets noticeable. This phenomenon very simply can be explained.

On the surface of the object that is facing towards the direction of motion, the particles, which are flowing around the object, get "jammed". This jamming results in an increase of drag, which wants to reject the direction of motion. This is an enlargement of the impact pressure, which is one overpressure. A negative pressure forms on the back of the object.

A force results from these two different quantities oppositely to the direction of motion, the so-called "air resistance". The air resistance is marked by the letter *"W"* and also measured in kg/m ^{2}.

For the calculation of the air resistance ***W*** that has an effect on a busy wing the following equation comes to the application:

$$\text{a.)} \quad \boldsymbol{W = z \cdot m \cdot F \cdot v^2}$$

The respective letters stand for the following conditions in this calculation:

W = air resistance in kg/m ^{2},

z = coefficient of drag (so-called abstract number or coefficient),

m = average value of the air density (normally 1/8),

F = front surface of the object,

V^2 = speed in the square.