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The Effective Porosity of Parachute Cloth^{*)}

Übersicht: Stabilität, Widerstand und Entfaltungseigenschaften von Fallschirmen aus Stoffbahnen ändern sich mit der Einsatzhöhe. Ähnliche Veränderungen der aerodynamischen Eigenschaften kann man beobachten, wenn die Luftdurchlässigkeit des Gewebes bei konstanter Höhe oder Luftdichte variiert wird. In der vorliegenden Arbeit wird die effektive Luftdurchlässigkeit oder Porosität in Abhängigkeit von der Luftdichte experimentell untersucht. Die effektive Porosität wird dann in Beziehung zu der Reynolds- und der Machzahl eines charakteristischen Stromfadens gesetzt. Es wird gezeigt, daß die Strömung durch den Stoff im allgemeinen zwar turbulent, unter gewissen Umständen jedoch beinahe laminar ist. Gleichungen, Koeffizienten und Diagramme werden angegeben, welche es ermöglichen, die effektive Porosität bei gegebener Einsatzhöhe und der Anströmgeschwindigkeit des Fallschirmes zu berechnen.

Summary: Stability, drag, and opening characteristics of solid cloth parachutes change with altitude. Similar changes can be obtained at a given altitude by varying the air permeability or porosity of the cloth. In this study it is shown that the porosity of a given cloth changes effectively with the density and the compressibility of the air. The effective porosity is related to Reynolds and Mach numbers and it was found that the flow of the air through the cloth is in general turbulent but may approach under certain circumstances a laminar flow character. Equations, coefficients, and graphs are established which permit the calculation of the effective porosity for various operational conditions of the parachute.

Résumé: La stabilité, la traînée et les caractéristiques de déploiement de parachutes en toile varient avec la hauteur d'opération. Les caractéristiques aérodynamiques varient de façon semblable lorsque la perméabilité du tissu est variée à hauteur ou à densité de l'air constante. La perméabilité ou la porosité effective en dépendance de la densité de l'air est étudiée expérimentalement. La porosité effective est ensuite mise en rapport aux nombres de Reynolds et de Mach d'un filet de fluide caractéristique. L'auteur montre que l'écoulement à travers le tissu est en général turbulent mais peut être presque laminaire sous certaines conditions. Les équations, coefficients et diagrammes de ce rapport permettent d'estimer la valeur effective de la porosité à une hauteur d'opération et une vitesse de soufflage donnée du parachute.

1. Introduction

Wind tunnel experiments have shown that the drag and the static stability of parachutes are strongly influenced by the cloth porosity of the parachute canopy. Furthermore, it has been observed that the opening shock of solid cloth parachutes increases with altitude while the oscillations of statically unstable parachutes become more violent [1, 2].

Attempts have been made to explain the increase of the opening shock as a consequence of the decrease of the apparent mass and the mass of air included in the parachute canopy with the air density [3]. The variation of the stability behavior of a parachute may in part also be attributed to the effect of the apparent and included masses because the motion of a freely descending parachute is a problem of dynamic stability in which the air masses are significant terms [4].

If the parachute cloth is considered to be a screen through which, during the use of the parachute, a certain amount of air passes, one may assume that the air permeability

or porosity of this screen depends on the *Reynolds* and *Mach* number of the flow conditions. Therefore, the observed changes in parachute drag and stability may be caused by *Reynolds* and *Mach* number effects, characteristic for the flow of air through the porous cloth. Furthermore, experiments have shown [5] that the apparent mass of parachutes depends also on the porosity of the canopy material. Therefore, the opening shock and the dynamic stability characteristics of a parachute are probably also affected by the variation of the cloth porosity.

Since the opening shock imposes the maximum stress upon all parts of the parachute, a reliable prediction of the parachute safety factor under various operational conditions also appears to depend on the knowledge of the cloth porosity for the given circumstances.

In view of these circumstances it appears to be possible to predict the opening shock, the stability behavior, the rate of descent, and the strength of parachutes for various speeds and altitudes if the porosity characteristics of the cloth are satisfactorily known. Therefore, the air resi-

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stance or the porosity of the parachute material as a function of *Mach* and *Reynolds* numbers appears to be the most fundamental parameter in performance calculations.

2. The Effective Porosity

The porosity, also called air permeability, is conventionally expressed as the volumetric flow rate of air per unit of area under a specified differential pressure [6]. Fig. 1 shows a typical diagram of this nominal porosity versus differential pressure for three commonly used parachute materials. This is in many respects a very unsatisfactory way of presentation, and I would like to recall that my old teacher, Prof. Dr.-Ing. G. Madelung, suggested about twenty years ago that more meaningful definitions and presentations should be introduced.

Fig. 1. Nominal porosity of parachute material versus differential pressure

Another way of presenting the porosity characteristics is the derivation of a drag coefficient as a function of the differential pressure or *Reynolds* number as, for example, shown in [7].

For the calculation of parachute filling times and opening shocks, one has to solve a mass balance equation in which one compares the volume of air flowing into the canopy with the air which escapes through the porous canopy material [8]. This process has led to the establishment of a dimensionless term which is the ratio of the average velocity, U , through the porous surface to a conveniently defined free stream velocity, V , with a dynamic pressure identical to the pressure differential between the upstream and downstream sides of the cloth. Fig. 2 shows schematically the cloth as a grid, the free stream velocity, V , the pressure differential, Δp , and the average velocity through the cloth, called U . The ratio U/V is identified as effective porosity; the nominal porosities presented in Fig. 1 are converted to effective porosities and shown in Fig. 3.

Looking at the cloth as a porous screen leads to the idea of considering the volumetric flow through the cloth as a function of the openings or orifices and the air resistance of the individual threads, which possibly could be considered as circular cylinders, and a number of attempts have been made to compute the air resistance of a woven sheet in this manner [9, 10, 11, 12]. However, microscopic pictures (Fig. 4) of four frequently used materials indicate that the assumption of a simple cloth

Fig. 2. Derivation of the term "effective porosity"

Effective porosity

$$C = \frac{U}{V} = \frac{U}{\sqrt{2 \Delta p / \rho}}$$

Fig. 3. The effective porosity of parachute materials versus differential pressure

geometry may be an oversimplification and the results of a purely analytical treatment in the indicated fashion would probably neglect several significant characteristics. Therefore, it was decided to measure the actual flow rate through the cloth and the results of these experiments will be reviewed in the following.

Fig. 1 indicates that the flow rate through the cloth increases with the differential pressure. One may assume that this relationship will exist in somewhat monotonic manner, influenced by a *Reynolds* number effect, until the critical pressure differential is reached at which the velocity through the orifice reaches the speed of sound. A further increase of the differential pressure will then not further increase the air velocity, but a so-called choking effect will occur. Therefore, it appears to be advisable to study the flow in both the incompressible and compressible flow regimes and to interpret the results in view of the classical aspects of *Reynolds* and *Mach* numbers.

A further objective of this study is the derivation of a relatively simple relationship between effective porosity and air density, because this may help to explain the increase of opening shock and the change of the stability behavior with altitude.

Considering first incompressible flow, one may assume that the air flows through the fine orifices of a relatively thick cloth somewhat like through a short tube and that the flow is neither completely laminar nor all turbulent. Therefore, an analysis of the two border cases seems to be in order.

For fully developed laminar flow, Hagen-Poiseuille's law provides the following relationship:

$$(1) \quad \Delta p = \frac{128 \mu L Q}{\pi D^4}$$

in which L is the length, D the diameter of the tube.

With $Q = U \pi D^2/4$, the average velocity in the tube is

$$(2) \quad U = \frac{D^2}{32 \mu L} \Delta p$$

$$0 \quad 0.05''$$

Fig. 4. Microscopic photos of four generally used parachute materials (U. S. specifications)

- a) MIL-C-7020, type I, 40 lb/in nylon, $t = 0.0032''$
- b) MIL-C-7350, type I, 100 lb/in nylon, $t = 0.006''$
- c) MIL-C-8020, type I, 200 lb/in nylon, $t = 0.020''$
- d) MIL-C-8020, type II, 300 lb/in nylon, $t = 0.024''$

and the effective porosity may be written

$$(3) \quad C = \frac{U}{V} = \frac{D^2}{32 \mu L} \sqrt{\frac{\rho \Delta p}{2}}$$

and specifically for sea level density

$$(3a) \quad C_0 = \left(\frac{U}{V} \right)_0 = \frac{D^2}{32 \mu_0 L} \sqrt{\frac{\rho_0 \Delta p}{2}}$$

For the first approximation one may set $\mu_0 = \mu$ and with $\rho/\rho_0 = \sigma$, the effective porosity for any altitude but for the same differential pressure is

$$(4) \quad C = C_0 \sigma^{1/2}$$

A similar analysis may be made for the assumption of fully developed turbulent flow. With the Blasius formula [13].

$$(5) \quad \frac{\Delta p}{L} = \frac{\lambda}{D} \frac{\rho}{2} U$$

and

$$(6) \quad \lambda = 0.3164 \left(\frac{U \rho D}{\mu} \right)^{-1/4}$$

the velocity is

$$(7) \quad U = \left(\frac{2 \Delta p D^{5/4}}{0.3164 L} \right)^{4/7} (\mu \rho^3)^{-1/7}$$

Using $V = (2 \Delta p / \rho)^{1/2}$ and the subscript zero for sea level density, the effective porosity C may be written

$$(8) \quad C = C_0 \left(\frac{\Delta p}{\Delta p_0} \right)^{1/14} \left(\frac{\mu_0}{\mu} \right)^{1/7} \left(\frac{\rho}{\rho_0} \right)^{1/14}$$

With $\mu_0 = \mu$, and for the same differential pressure, one obtains for fully developed turbulent flow

$$(9) \quad C = C_0 \sigma^{1/14}$$

The assumption of both laminar and turbulent flow in the region of incompressibility leads to a relationship of the form

$$(10) \quad C = C_0 \sigma^n$$

and it is now one of the objectives of this study to establish experimentally the value of the exponent n for various types of parachute material from which one also may conclude if we have laminar, mixed or turbulent flow.

Once the differential pressure is high enough to establish sonic flow, the effective porosity of the cloth will decline with increasing pressure. Therefore, besides the density ratio, σ , the pressure ratio $\Delta p / \Delta p_{cr}$ shall be introduced as a basic parameter.

In view of the methods used in the performance calculations, the experimental study will contain the velocity U in terms of the volumetric flow on the upstream or high pressure side of the cloth.

3. Measurement and Analysis

In accordance with the preceding analysis, the effective porosity of one wire screen and four textile materials frequently used for parachutes was measured by means of the apparatus shown in Fig. 5. The experiments were made over a density range of σ between 0.1 and 1.0 and a pressure ratio of $\Delta p / \Delta p_{cr}$ between 0.05 and 2.0. The cloth and wire samples were bonded to a ring with two inch internal diameter and then placed in the test section of the apparatus. The permanent bonding was chosen in order to avoid slippage with the associated uncertain effective cloth area. The density ratio, σ , is defined as the ratio of the density on the downstream side of the porous screen to the standard sea level density. The

Fig. 5. Porosity measuring apparatus

wire screen has been incorporated because one may suspect that the textile screens change their geometry with the pressure loading and therefore their observed porosity may reflect not only *Reynolds* and *Mach* number effects, but also consequences of the elasticity of the cloth. The wire screen would not have any elasticity effects.

Figs. 6 through 10 and Tables 1 through 4 show the results of these measurements [17]. It can be seen that

Fig. 6. Effective porosity of nylon cloth, 40 lb/in, MIL-C-7020 B, type I

Fig. 7. Effective porosity of nylon cloth, 90 lb/in, MIL-C-7350 B, type I

Fig. 8. Effective porosity of nylon cloth, 200 lb/in, MIL-C-8021 A, type I

Fig. 9. Effective porosity of nylon cloth, 300 lb/in, MIL-C-8021 A, type II

Fig. 10. Effective porosity versus pressure ratio for 30 x 40 mesh stranded weave wire screen

Table 1. Effective porosity of MIL-C-7020 B, type I, 40 lb/in nylon cloth
All points are average of several experimental values

$\sigma = 1.0$		$\sigma = 0.9$		$\sigma = 0.8$		$\sigma = 0.7$		$\sigma = 0.6$		$\sigma = 0.5$		$\sigma = 0.4$		$\sigma = 0.3$		$\sigma = 0.2$		$\sigma = 0.1$	
$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C
0.03	0.052	0.03	0.050			0.03	0.047	0.03	0.044			0.03	0.039	0.03	0.033				
0.05	0.052	0.05	0.051	0.05	0.050	0.05	0.048	0.05	0.046	0.05	0.043	0.05	0.041	0.05	0.037			0.05	0.031
0.10	0.052	0.10	0.051	0.10	0.050	0.10	0.048	0.10	0.048	0.10	0.045	0.10	0.043	0.10	0.042	0.10	0.023	0.10	0.036
0.20	0.050	0.20	0.049	0.20	0.048	0.20	0.047	0.20	0.047	0.20	0.045	0.20	0.043	0.20	0.042	0.20	0.030	0.20	0.038
0.40	0.045	0.40	0.044	0.40	0.044	0.40	0.042	0.40	0.042	0.40	0.041	0.40	0.039	0.40	0.038	0.40	0.032	0.40	0.037
0.60	0.041	0.60	0.041	0.60	0.040	0.60	0.038	0.60	0.038	0.60	0.037	0.60	0.036	0.60	0.034	0.60	0.032	0.60	0.033
0.80	0.039	0.80	0.038	0.80	0.038	0.80	0.036	0.80	0.035	0.80	0.034	0.80	0.033	0.80	0.032	0.80	0.028	0.80	0.031
1.00	0.036			1.00	0.036	1.00	0.034	1.00	0.033	1.00	0.032	1.00	0.031	1.00	0.030	1.00	0.026	1.00	0.029
												1.50	0.028			1.50	0.022	1.50	0.024
												2.00	0.026			2.00	0.020		

Table 2. Effective porosity of MIL-C-7350 B, type I, 90 lb/in nylon cloth
All points are average of several experimental values

$\sigma = 1.0$		$\sigma = 0.9$		$\sigma = 0.8$		$\sigma = 0.7$		$\sigma = 0.6$		$\sigma = 0.5$		$\sigma = 0.4$		$\sigma = 0.3$		$\sigma = 0.2$		$\sigma = 0.1$	
$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C
0.02	0.054	0.02	0.053	0.02	0.053	0.02	0.053							0.02	0.043				
0.05	0.055	0.05	0.054	0.05	0.054	0.05	0.054	0.05	0.054	0.05	0.053	0.05	0.047	0.05	0.046	0.05	0.035	0.05	0.021
0.10	0.054	0.10	0.054	0.10	0.054	0.10	0.053	0.10	0.053	0.10	0.052	0.10	0.048	0.10	0.046	0.10	0.041	0.10	0.030
0.20	0.051	0.20	0.051	0.20	0.051	0.20	0.050	0.20	0.050	0.20	0.049	0.20	0.047	0.20	0.045	0.20	0.041	0.20	0.034
0.40	0.046	0.40	0.045	0.40	0.045	0.40	0.044	0.40	0.044	0.40	0.043	0.40	0.042	0.40	0.040	0.40	0.038	0.40	0.034
0.60	0.041	0.60	0.041	0.60	0.040	0.60	0.040	0.60	0.039	0.60	0.038	0.60	0.037	0.60	0.036	0.60	0.035	0.60	0.032
0.80	0.038	0.80	0.037	0.80	0.037	0.80	0.036	0.80	0.036	0.80	0.035	0.80	0.034	0.80	0.033	0.80	0.032	0.80	0.030
1.00	0.035	1.00	0.035	1.00	0.034	1.00	0.033	1.00	0.033	1.00	0.032	1.00	0.032	1.00	0.031	1.00	0.029	1.00	0.027
1.50	0.030	1.50	0.030	1.50	0.029	1.50	0.029	1.50	0.028	1.50	0.028	1.50	0.028	1.50	0.026	1.50	0.025	1.50	0.024
												2.00	0.025	2.00	0.024	2.00	0.023	2.00	0.021

Table 3. Effective porosity of MIL-C-8021 A, type I, 200 lb/in nylon cloth
All points are average of several experimental values

$\sigma = 1.0$		$\sigma = 0.9$		$\sigma = 0.8$		$\sigma = 0.7$		$\sigma = 0.6$		$\sigma = 0.5$		$\sigma = 0.4$		$\sigma = 0.3$		$\sigma = 0.2$		$\sigma = 0.1$	
$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C
						0.02	0.016	0.02	0.015										
						0.05	0.019	0.05	0.018	0.05	0.016	0.05	0.015	0.05	0.012				
0.10	0.023	0.10	0.023	0.10	0.021	0.10	0.020	0.10	0.019	0.10	0.018	0.10	0.017	0.10	0.014	0.10	0.012		
0.20	0.023	0.20	0.023	0.20	0.022	0.20	0.021	0.20	0.020	0.20	0.019	0.20	0.018	0.20	0.016	0.20	0.013	0.20	0.010
0.40	0.021	0.40	0.021	0.40	0.021	0.40	0.020	0.40	0.020	0.40	0.019	0.40	0.018	0.40	0.017	0.40	0.014	0.40	0.012
0.60	0.020	0.60	0.020	0.60	0.019	0.60	0.019	0.60	0.019	0.60	0.018	0.60	0.017	0.60	0.016	0.60	0.014	0.60	0.012
0.80	0.019	0.80	0.019	0.80	0.018	0.80	0.018	0.80	0.018	0.80	0.017	0.80	0.016	0.80	0.015	0.80	0.014	0.80	0.012
1.00	0.018	1.00	0.018	1.00	0.017	1.00	0.017	1.00	0.017	1.00	0.016	1.00	0.015	1.00	0.014	1.00	0.013	1.00	0.012
1.50	0.016	1.50	0.016	1.50	0.015	1.50	0.015	1.50	0.014	1.50	0.014	1.50	0.014	1.50	0.013	1.50	0.012	1.50	0.011
2.00	0.014	2.00	0.014	2.00	0.014	2.00	0.013	2.00	0.013	2.00	0.013	2.00	0.013	2.00	0.012	2.00	0.011	2.00	0.010

Table 4. Effective porosity of MIL-C-8021 A, type II, 300 lb/in nylon cloth
All points are average of several experimental values

$\sigma = 1.0$		$\sigma = 0.9$		$\sigma = 0.8$		$\sigma = 0.7$		$\sigma = 0.6$		$\sigma = 0.5$		$\sigma = 0.4$		$\sigma = 0.3$		$\sigma = 0.2$		$\sigma = 0.1$	
$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C	$\frac{\Delta P}{\Delta P_{cr}}$	C
0.10	0.029	0.10	0.028	0.10	0.028	0.10	0.027	0.10	0.026	0.10	0.027	0.10	0.023	0.10	0.022	0.10	0.021	0.10	0.016
0.20	0.028	0.20	0.028	0.20	0.027	0.20	0.027	0.20	0.026	0.20	0.026	0.20	0.023	0.20	0.023	0.20	0.022	0.20	0.018
0.40	0.026	0.40	0.026	0.40	0.025	0.40	0.024	0.40	0.024	0.40	0.022	0.40	0.022	0.40	0.021	0.40	0.021	0.40	0.018
0.60	0.024	0.60	0.024	0.60	0.023	0.60	0.022	0.60	0.022	0.60	0.021	0.60	0.021	0.60	0.020	0.60	0.019	0.60	0.017
0.80	0.022	0.80	0.022	0.80	0.021	0.80	0.021	0.80	0.020	0.80	0.020	0.80	0.019	0.80	0.018	0.80	0.018	0.80	0.016
1.00	0.021	1.00	0.020	1.00	0.020	1.00	0.019	1.00	0.019	1.00	0.019	1.00	0.018	1.00	0.017	1.00	0.017	1.00	0.015
1.50	0.018	1.50	0.018	1.50	0.017	1.50	0.017	1.50	0.017	1.50	0.015	1.50	0.015	1.50	0.015	1.50	0.015	1.50	0.014
2.00	0.015	2.00	0.015	2.00	0.015	2.00	0.015	2.00	0.015	2.00	0.015	2.00	0.013	2.00	0.013	2.00	0.013	2.00	0.012

the porosity characteristics of the cloth and those of the wire screen are principally identical, and it may be concluded that the most significant characteristics of the recorded effective porosities are consequences of aerodynamic phenomena and not caused by structural deformations.

It is evident that the effective porosity of the wire and cloth screens decreases with decreasing air density. Since for a constant pressure ratio the density is the prime variable of the governing *Reynolds* number, it can be concluded that the effective porosity of the screen is a function of the *Reynolds* number.

The slope of the effective porosity curves versus the differential pressure is in all cases positive up to a certain pressure ratio and then becomes negative. This seems to indicate that the air resistance of the cloth decreases as the *Reynolds* number increases until compressibility effects become more influential; choking of the flow occurs when sonic speed in the cloth orifices is reached.

Analyzing the experimental results first in view of *Reynolds* number effects one may remember the postulation that the effective porosity possibly can be presented as an exponential function on the basis of the density ratio. Therefore, the results shown in Figs. 6 through 10 were rearranged in accordance with Eq. (10) and presented in this form in Figs. 11 through 14 [16].

Originally the relationship between effective porosity and density was derived on the basis of identical pressure differential Δp . However, in the following treatment the pressure ratio $\Delta p/\Delta p_{cr}$ was used which is also the parameter in the Figs. 11 through 14. If the postulated rela-

tionships for laminar and turbulent flow are expressed in terms of $\Delta p/\Delta p_{cr}$ and for $\Delta p_{cr} = 0.89 P_2$, and also the equation of state is used, one obtains respectively for laminar and turbulent flow relationships

$$(11) \quad C = C_0 \sigma$$

and

$$(12) \quad C = C_0 \sigma^{1/7}.$$

Reviewing the results shown in Figs. 11 through 14, one observes that the results of many experiments seem to follow Eq. (12) almost perfectly which would indicate fully developed turbulent flow. The minimum pressure at which this occurs varies with the thickness and the type of weave of the cloth.

All screens under investigation indicate an exponent larger than $1/7$ for relatively small density and low pressure ratios. In particular, the lightest and thinnest cloth with a tensile strength of 40 lb per inch approaches for very low density and smaller differential pressures the relationship shown in Eq. (11). This indicates that for this type of cloth and under these flow conditions, the flow through this cloth is nearly laminar.

In general, the experiments confirm the original assumption that the effective porosity of these porous screens is a function of the *Reynolds* number. The practical aspect of these experiments is the fact that for the same differential pressure or for the same pressure ratio, the effective porosity of the woven screen decreases with decreasing density.

The exponent in Eq. (10) signifies the character of the flow through the cloth orifices, and for further analysis it appears to be useful to plot the density exponent n

Fig. 11. Effective porosity versus density ratio for MIL-C-7020 B, type I, 40 lb/in nylon cloth

Fig. 12. Effective porosity versus density ratio for MIL-C-7350 B, type I, 90 lb/in nylon cloth

Fig. 13. Effective porosity versus density ratio for MIL-C-8021, A, type I, 200 lb/in nylon cloth

Fig. 14. Effective porosity versus density ratio for MIL-C-8021, A, type II, 300 lb/in nylon cloth

versus the *Reynolds* number of the related flow condition.

A meaningful *Reynolds* number can be established for a rectangular stream tube which approaches the cloth from the free stream and which then passes through the orifice of the cloth. The width of this stream tube before passing through the orifice is the characteristic length, L , and can be found from the number of threads per unit length of the cloth.

In view of the definition of the effective porosity, the *Reynolds* number of the stream tube is

$$(13) \quad Re = \frac{L C V \varrho_1}{\mu}$$

Since all density references in this study are made in relationship to the downstream conditions, one may introduce

$$\varrho_1 = \varrho_2 \frac{P_1 T_1}{P_2 T_2}.$$

Experimentally it was found that $T_1 \approx T_2$ and with $P_1 = P_2 (1 + 0.89 \Delta p/\Delta p_{cr})$ and $\varrho_2 = \varrho_0 \sigma$, the reference density amounts to

$$(14) \quad \varrho_1 = \varrho_0 \sigma \left(1 + 0.89 \frac{\Delta p}{\Delta p_{cr}} \right).$$

By definition

$$(15) \quad \left\{ \begin{aligned} V &= \left(\frac{2 \Delta p}{\varrho_1} \right)^{1/2} = \left(\frac{2 (P_1 - P_2) R T_2}{P_2} \right)^{1/2} = \\ &= \left(1.78 \frac{\Delta p}{\Delta p_{cr}} R T_2 \right)^{1/2}. \end{aligned} \right.$$

Again, with $T_1 \approx T_2$, and combining Eqs. (13), (14) and (15), the *Reynolds* number of the stream tube amounts to

$$(16) \quad \left\{ \begin{aligned} Re &= \frac{L C \varrho_0 \sigma}{\mu} \left(1 + 0.89 \frac{\Delta p}{\Delta p_{cr}} \right) \times \\ &\times \left(1.78 \frac{\Delta p}{\Delta p_{cr}} R T_1 \right)^{1/2}. \end{aligned} \right.$$

The *Reynolds* numbers of the experiments, derived in accordance with Eq. (16), are now combined with the density exponents of Figs. 11 through 14 as shown in Figs. 15 through 18. It can be seen that all four fabrics apparently have fully developed turbulent flow at *Reynolds* numbers larger than 200. The region of transition is obviously between *Reynolds* numbers of 100 and 200. The lightest and thinnest cloth approaches

Fig. 15. Density exponent versus *Reynolds* number for MIL-C-7020 B, type I, 40 lb/in nylon cloth

Fig. 16. Density exponent versus Reynolds number for MIL-C-7350 B, type I, 90 lb/in nylon cloth

Fig. 17. Density exponent versus Reynolds number for MIL-C-8021 A, type I, 200 lb/in nylon cloth

Fig. 18. Density exponent versus Reynolds number for MIL-C-8021 A, type II, 300 lb/in nylon cloth

laminar flow at a Reynolds number of approximately 10 whereas the heavier materials indicate a mixed flow for the same Reynolds number. The thickest and heaviest cloth, 300 lb per inch tensile strength, has apparently the highest degree of turbulence and the lowest Reynolds number at which transition to full turbulence occurs.

4. Calculation of the Effective Porosity

In view of the surprising regularities between effective porosity and Reynolds and Mach numbers, one is indeed tempted to calculate the flow of air through the cloth by a somewhat conventional method.

Utilizing again the stream tube concept, one orifice in the cloth may be considered to be a nozzle with a particular discharge coefficient. For mechanical nozzles, such discharge coefficients are known, as for example, in [14], from which Fig. 19 is taken.

With the energy equation, continuity condition, and adiabatic expansion one has for the flow velocity in a jet the equation [15].

Fig. 19. Nozzle discharge coefficient (from [14])

$$(17) \quad U = \frac{A_2}{A_1} \left(\frac{P_2}{P_1} \right)^{1/\gamma} \left\{ \frac{2 \frac{\gamma}{\gamma-1} \frac{P_1}{\rho_1} \left[1 - \left(\frac{P_2}{P_1} \right)^{(\gamma-1)/\gamma} \right]^{1/2}}{1 - \frac{A_2}{A_1} \left(\frac{P_2}{P_1} \right)^{2/\gamma}} \right\}^{1/2}$$

in which A_2/A_1 represents the contraction ratio of the stream tube.

Microscopic pictures show that the contraction ratio A_2/A_1 is in the order of 0.07, and since $P_1 > P_2$, Eq. (17) can be simplified to:

$$(17a) \quad \left\{ U = \frac{A_2}{A_1} \left(\frac{P_2}{P_1} \right)^{1/\gamma} \left\{ 2 \frac{\gamma}{\gamma-1} \frac{P_1}{\rho_1} \times \left[1 - \left(\frac{P_2}{P_1} \right)^{(\gamma-1)/\gamma} \right]^{1/2} \right\} \right.$$

Introducing the equation of state and rearranging Eq. (17a) provides:

$$(18) \quad \left\{ U = \frac{A_2}{A_1} \frac{P_2}{P_1} \left\{ 2 R T_1 \frac{\gamma}{\gamma-1} \left(\frac{P_1}{P_2} \right)^{(\gamma-1)/\gamma} \times \left[\left(\frac{P_1}{P_2} \right)^{(\gamma-1)/\gamma} - 1 \right] \right\}^{1/2} \right.$$

If the critical pressure ratio between the two sides of the cloth is reached, $P_2/P_1 = 0.528$, sonic velocity exists in the orifices or in the throat of the assumed nozzle. For this condition one has [15]:

$$(19) \quad \frac{P_{thr}}{P_\infty} = \left(\frac{2}{\gamma+1} \right)^{\gamma/(\gamma-1)}$$

Because of $A_2/A_1 \ll 1$, $P_1 \approx P_\infty$, and when P_2 is replaced by P_{thr} , Eq. (17a) provides

$$(20) \quad U = \frac{A_2}{A_1} \left[\gamma \left(\frac{2}{\gamma+1} \right)^{(\gamma+1)/(\gamma-1)} \frac{P_1}{\rho_1} \right]^{1/2}$$

Eqs. (18) and (20) can now be used in the expression for the effective porosity, which was

$$C = \frac{U}{V}$$

with

$$(21) \quad V = \left[\frac{2 (P_1 - P_2)}{\rho_2} \right]^{1/2}$$

Furthermore, the experiments indicated $T_1 \approx T_2$ and introducing the discharge coefficient, K , the effective porosity for the subcritical case follows from Eqs. (18) and (21) and with the equation of state for

$$(22) \quad \left\{ \begin{aligned} \rho_2 &= \frac{P_2}{R T_2} \\ C &= K \frac{A_2}{A_1} \frac{P_2}{P_1} \left\{ \frac{1}{\frac{P_1}{P_2} - 1} \times \frac{\gamma}{\gamma-1} \left(\frac{P_1}{P_2} \right)^{(\gamma-1)/\gamma} \left[\left(\frac{P_1}{P_2} \right)^{(\gamma-1)/\gamma} - 1 \right] \right\}^{1/2} \end{aligned} \right.$$

For the critical and supercritical case, Eqs. (20) and (21) provide

$$(23) \quad C = K \frac{A_2}{A_1} \left\{ \frac{\gamma}{2} \left[\frac{2}{\gamma+1} \right]^{(\gamma+1)/(\gamma-1)} \frac{1}{\frac{P_1}{P_2} - 1} \right\}^{1/2}$$

These equations can now be written in terms of $\Delta P/\Delta P_{cr}$ and one obtains for

$$\frac{P_1}{P_2} = 0.893 \frac{\Delta P}{\Delta P_{cr}} + 1$$

which allows one to write Eqs. (22) and (23) in the following form:

$$(22a) \quad \left\{ C = \frac{K \frac{A_2}{A_1}}{0.893 \frac{\Delta P}{\Delta P_{cr}} + 1} \left\{ \frac{1}{0.893 \frac{\Delta P}{\Delta P_{cr}}} \left(\frac{\gamma}{\gamma-1} \right) \times \left[0.893 \frac{\Delta P}{\Delta P_{cr}} + 1 \right]^{(\gamma-1)/\gamma} \times \left[\left(0.893 \frac{\Delta P}{\Delta P_{cr}} + 1 \right)^{(\gamma-1)/\gamma} - 1 \right] \right\}^{1/2} \right.$$

$$(23a) \quad C = K \frac{A_2}{A_1} \left[\frac{\gamma}{2} \left(\frac{2}{\gamma+1} \right)^{(\gamma+1)/(\gamma-1)} \frac{1}{0.893 \frac{\Delta P}{\Delta P_{cr}}} \right]^{1/2}$$

The equations above, combined with the Reynolds number from Eq. (16) and the discharge coefficient from Fig. 19 provide now a certain basis to calculate the effective porosity under a number of idealizing assumptions. These assumptions are a certain regularity of the cloth porosity, the knowledge of the actual geometric porosity of the cloth orifices and a mechanical nozzle. Of course, these conditions are not exactly fulfilled and the deviations provide a welcome explanation if the results of the calculations and the measurements do not agree perfectly.

Fig. 20. C computed from the isentropic flow equation and empirical discharge coefficient; experimental values of C for 90 lb/in cloth — — — theoretical, — — — experimental

Fig. 20 is such a comparison and the judgment about the practical usefulness of an analytical derivation of the effective porosity shall be left to the reader. However, the calculation seems to indicate that the presented treatment of cloth porosity comes close to the actual mechanics of the flow phenomena.

5. Conclusion

The investigation has shown that the effective porosity of woven sheets can be calculated in the right order of magnitude, that its characteristics follow the general

aerodynamic principles related to Reynolds and Mach numbers. In particular the investigation has shown that under otherwise similar circumstances, the effective porosity decreases with the air density, which explains the variation of the parachute performance characteristics with altitude.

6. References

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