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ASSESSMENT OF THE THERMAL INSULATION
PROPERTIES OF CLOTHING

V. I. Yankelevich

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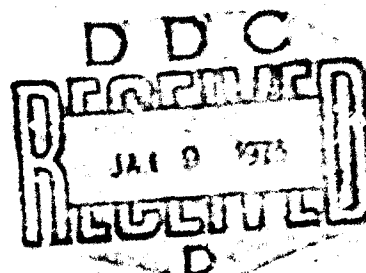
V.I. Yankelevich

Technologiya Legkoy Promyshlennosti
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At the present time there are various methods known for testing the thermal insulation properties of materials. These simulate condition when air-penetrable clothing is worn in wind. A detailed survey of these methods is given, for example in ⁽¹⁾. However, conditions for testing thermal insulation properties of materials in models differ from conditions for testing air-penetrable clothing in wind. To assess the degree of difference and the authenticity of the results achieved it is essential to examine the physical processes which govern the transfer of heat through air-penetrable clothing in wind.

We will look at clothing as if it were a multi-layered cylindrical package containing an air layer (Fig. 1). The thermal insulation properties of clothing are accepted to be the sum thermal resistance, which is (Fig. 1) the sum of the thermal resistance to heat emission from the external surface R_{surface} , of the external package R_{external} , of the air layer R_{air} , and of the internal package R_{internal} . When there is an increase in wind velocity and the outer material of the external package is completely wind proof R_{external} will diminish, but the thermal resistance of the materials and the air layers will not change. Therefore the lessening of R_{sum} of an air proof package in wind is determined by the reduction of R_{surface} only.

Now let us see what happens when air-penetrable clothing is exposed to wind. Because of dynamic interaction between the wind flow and the surface of the obstruction, a definite pressure builds up on the outer surface - a pressure which, generally speaking, distributes itself unevenly (Fig. 2). The pressure in Fig. 2 is shown as a fraction of the dynamic wind pressure p_D .

$$p_D = \rho w^2 / 2 \quad (1)$$

where w - wind velocity, metres/sec.

ρ - air density kg/metres³, which depends on its temperature t , °C, and the barometric pressure H , in column mm of mercury

$$\rho = 1.293 \frac{t}{t + 273} \cdot \frac{H}{760}.$$

The pressure p_D is found at the frontal point A. At points B and C, where the air stream is moving parallel to the surface, there is a rarefaction (vacuum). At the rear end of the body (point D) pressure may be partially restored.

At a certain air penetrability of the external package, air will filter through it in directions from areas of maximum pressure to areas of minimum pressure. If the thickness of the air layer is sufficient for the passage of filtered air, air will move through the material in a transverse direction, but along the surface lengthways it will move along the air layer (along the path of least resistance).

When this is happening a constant pressure p_{air} is established in the layer. In general, the velocity of filtration u will be determined by D'Arcy's Law⁽³⁾

$$u = k \frac{\Delta p}{l} \quad (2)$$

where Δp - the fall in pressure H/m^2 over a length l metres.

$\Delta p/l$ is the finite expression of the pressure gradient. The coefficient k , m⁴/H.hour reflects the texture and porosity of the material and is the velocity of filtration (air-penetrability) of the material (package) in a given direction at a pressure gradient $1 \frac{H}{m^2}/m$.

In areas where the external pressure $p > p_{air}$, air filters in, but in areas where $p < p_{air}$, air filters out from the air layer. The quantity of air which passes through the envelope is proportional to the corresponding shaded area in Fig. 2*.

*The quantity of air entering the layer through the surface, where $p > p_{air}$ equals $\frac{k}{l} \int (p - p_{air}) dS$ (dS - element of area). The magnitude of the integral is proportional to the shaded area between p and p_{air} .

Because in a stable regime the quantity of air entering the layer equals the quantity which leaves, the value p_{air} is determined by the equation of the shaded areas in Fig. 2.

The movement of air through clothing fundamentally affects its thermal insulation properties. Air filtering through the package carries with it a certain amount of heat (enthalpy), which lowers the effective thermal resistance of the external package $R_{external}$. The thermal resistance of the air layer R_{air} is also reduced because of the systematic movement of air in it. Therefore when there is an air layer, air filtering causes a noticeable reduction in R_{sum} in air-penetrable clothing compared to air proof clothing. As all the air going through the external package passes along the external air layer, the heat resistance of the internal package does not change.

When there is no air layer the velocity of filtration is mainly directed lengthways along the material, the filtration path is significantly greater, and the quantity of filtered air according to formula (2) is much less than that in the conditions of diagram 1,a. Therefore additional transfer of heat by the moving air, although it takes place, is relatively small.

The additional transfer of heat by filtered air can depend on the geometrical dimensions of the body. Where there is an air layer the movement of air from an area of high pressure to an area of low pressure takes place along the air layer, which does not offer resistance to air movement no matter what length its path (that is the absolute dimensions of the body). Therefore additional transfer of heat by air in this case does not depend on the dimensions of the insulated body. Where there is no air layer, filtration takes place along the material, and in an envelope of larger dimensions the filtration path will be greater. In accordance with Formula 2, a lesser quantity of air will pass along this path, and the additional heat transfer will be smaller.

On a flat insulated body too, air filtration can take place only because of pressure differences on the flat outer surface, and all the results obtained above are applicable, qualitatively, to a flat body.

On the basis of these physical considerations, it is possible to assess the applicability of various apparatus and methods described in literature for analyzing the thermal insulation properties of air-penetrable clothing in wind.

When flat models are tested in wind which is blowing at an angle to their surface, the dynamic wind pressure can be distributed unevenly, but where there

is no air layer, reduction in the thermal insulation properties of the material is very small⁽⁸⁾. Tests where there is no air layer can be considered as attempts to simulate close fitting clothing (sweaters and so forth). However with close fitting material, results of tests depend on the dimensions of the object. Therefore any value in analyzing the thermal insulating properties of such clothing can only be found in tests in calorimeters⁽⁹⁾ which simulate the form and size of a man.

In⁽¹⁰⁾, the opinion is expressed that in the established work regime for a flat apparatus, a pressure must be set up in the air layer equal to the dynamic pressure at the surface, and therefore the existence of a layer does not cause additional filtering. This can be true only when the wind pressure is constant along the whole surface of the model. These conditions cannot correspond to actual conditions, where the nature of pressure distribution along a surface must be close to that depicted in Fig. 2.

Tests of the thermal insulation properties of materials in wind carried out by many authors^(1,11 and others) have shown that, in full accord with the propositions discussed above, the thermal resistance of materials where there is an air layer is significantly lower than where there is no air layer. However, if on the surface of a material no difference in dynamic pressures is created (for example, when wind blows parallel to a flat surface or to the axis of a cylindrical calorimeter^(6,7)) then, whether or not there is a layer, because filtration is absent thermal resistance is not lowered⁽¹¹⁾.

Tests with flat apparatus where air filtration through the material takes place can only give a qualitative assessment of the thermal insulation properties of air-penetrable materials in wind. This is because for a plane and cylindrical surface the magnitude and character of the dynamic pressure distribution along the surface can vary greatly at the same wind velocity. Therefore the quantity of filtered air through a unit of surface and the corresponding additional transfer of heat for the latter can be noticeably different.

The nearest results for clothing must be given by calorimeters where there is a compact envelope of material (cylindrical), because here the general character of surface pressure distribution is close to that expected on the surface of clothing. However, even in this case it is essential to take account of differences between the trial conditions and actual conditions. Of these differences it is necessary to note first of all the fixed air layer in calorimeters.

In clothing there are significant air layers⁽¹²⁾, but under the action of wind the thickness of these layers can change. In particular at the frontal end (point A in Fig. 1,a) due to action of the pressure differential, the material (package) can be pressed towards the internal package, and at a sufficiently high wind velocity there can be a total tightening at this point. Then the quantity of air filtering inside the package is significantly reduced (due to the increase in the length of the filtration path when it is directed in this instance partially lengthways along the material). This cannot happen in calorimeters, where the air layer is intended to be rigidly fixed and closed contact is not permitted. For this reason clothing can be much warmer in wind than might be expected from the results of tests in calorimeters.

There are other factors besides, which cause differences between the thermal insulation properties of models and clothing (the curvature of the models, the difference between the clothing form and a cylinder and so on). Let us also note that the pressure distribution of wind on the surface of a cylinder in an aerodynamic tunnel and in the atmosphere can be widely different.

CONCLUSIONS

In wind, filtration of air takes place through the material of air-penetrable clothing as a result of the difference in dynamic pressures on the surface of the clothing. When there is an air layer under the material, air filtration through the clothing and the associated transfer of heat is significantly greater than when clothing is tight fitting.

When there is an air layer, the reduction of the thermal resistance of an air-penetrable package compared with a similar airtight package does not depend on the dimensions of the insulated object. When clothing is tight fitting, this lowering of the thermal resistance will be lesser in a larger object.

The most authentic results must be given by testing the thermal insulation properties of air-penetrable materials and packages of outer clothing in cylindrical calorimeters in wind tunnels. However, even in these experiments it is necessary to take account of the fact that air layers can be compressed and therefore clothing can be a good deal warmer than an envelope of the same material in a calorimeter with a fixed air layer.

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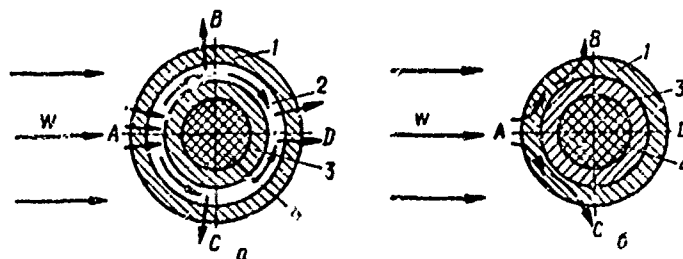


Fig. 1. Cross section of a clothing package.

- 1.- external package; 2.- air layer;
3.- internal package; 4.- insulated body.

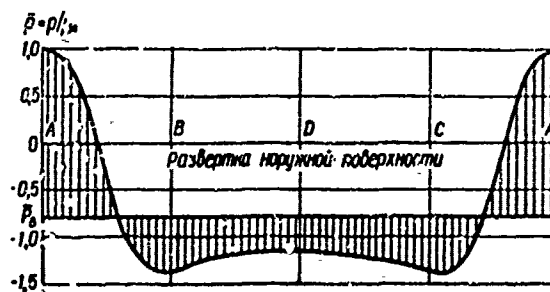


Fig. 2. Distribution of dynamic pressure along the surface of a curved cylinder $\varnothing$ 100 mm in an air stream, with a wind velocity of 15 m/sec⁽⁴⁾.

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