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Theoretical and Experimental Study of Airflow Through Clothing Around Body Parts

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The air flow profile around a cylinder, covered with textile, was analyzed both theoretically and experimentally. A model was deduced, which describes the air flow through and underneath clothing that is covering a body part. In the air profile model presented here, the body part is represented by a cylinder. The model was validated by conducting pressure measurements around the cylinder, both with and without clothing. These pressure profiles were used to calculate the velocity profile around the cylinder, which was then compared to the theoretically predicted velocity profile. There is a good agreement between the measurements and the model. The model was also used to validate an empirical formula, which is used at present, that described the air velocity through the clothing as a function of the wind velocity. A correction factor for this formula is proposed. © 2006 American Institute of Chemical Engineers *AIChE J,* 52: 3688–3695, 2006
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Introduction

A soldier can experience the threat of chemical warfare agents when working in the field. To protect himself against these vapors or liquids, he can wear NBC-clothing. To predict how well he is protected against vapors, not only the material itself must be studied,[1] but also the flow profile through and underneath the clothing. Depending on the flow profile, more vapor can penetrate the clothing and can finally deposit onto the skin of the soldier. This air flow profile determines at which place of the body part the largest amount of deposition will occur. The behavior of the air flow profile is modeled in this article. The modeling of the resulting concentration profile and the deposition profile will be presented later.

To model the air flow profile, a simplification has been made by assuming this to be a two dimensional problem. The body part is represented by a cylinder that is placed in airflow. At the front of the (dressed) cylinder, the wind will penetrate the clothing and at the backside it will flow back to the environment.

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A lot of quality tests are being performed on pieces of NBC-clothing material being exposed to a chemical vapor, which is sucked through the clothing with a defined velocity. The velocity used is often predicted by an empirical formula, which couples the wind velocity with the air velocity through the clothing. By modeling the wind flow, a more fundamental expression can be derived.

Air flow profile

To model the airflow profile underneath clothing of a human, it is necessary to use computational fluid dynamics (CFD) since the human shape is very complicated. The modeling of the air flow profile around cylinders by using CFD was described earlier.[2-4] Since the calculation time is quite high, it would be convenient to have a model that can predict the air flow profile without using CFD, without high loss of accuracy.

If only homogeneous perpendicular flow of the outside wind is assumed and the air flow underneath the clothing is modeled only one dimensionally, the process can be solved without using CFD. A schematic picture of the problem is shown in Figure 1.

The wind is blowing against the clothing around the cylinder with a velocity v_0. At the front of the cylinder, at point C (the stagnation point), the wind will partly flow through the porous clothing and will continue to flow underneath the clothing. At different points around the cylinder (different angles from the stagnation point, for example, point A), the velocity through the clothing will be different, due to the fact that the pressure around the cylinder is not the same at different angles. Up to a certain angle, the wind will flow into the air gap, but at larger angles, the wind will flow out again. This process is dependent on the pressure in the air gap underneath the clothing, which is also a function of the angle around the cylinder.

Theory

The flow profile between the clothing material and the cylinder can be approximated by a flow profile between two infinitely large plates. In Figure 2 two plates are shown with a flow of a fluid between them. The distance between the two plates equals 2ΔR. The length of the plates (in the depth of the figure) equals L.

Poisseulle flow is assumed. The velocity of the air can thus be described by:

$$\nu_r = \frac{1}{2\eta}\left(-\frac{\partial P}{\partial x}\right)((\Delta R)^2 - r^2) \tag{1}$$

Note that the symbols are defined in the Notation section. The flow between the plates can be calculated by:

$$\phi_\nu = 2\int_0^{\Delta R} L\nu_r dr = \frac{2}{3}\frac{L}{\eta}\left(-\frac{dP}{dx}\right)(\Delta R)^3 \tag{2}$$

This equation will give the flow between two parallel plates. This relation can be modified for the flow of air between clothing and a cylinder by assuming that the radius of the cylinder is large in comparison to the size of the air gap. In that case, the next approximation can be used:

$$dx \approx Rd\theta \tag{3}$$

which gives:

$$\phi_\nu(\theta) = \frac{2}{3}\frac{L}{\eta}\left(-\left.\frac{dP_{in}}{d\theta}\right|_\theta\right)\frac{(\Delta R)^3}{R} \tag{4}$$

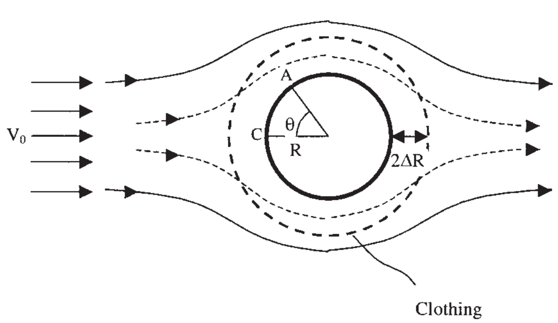

Figure 1. Representation of a body part dressed with clothing, with airflow around and underneath the clothing.

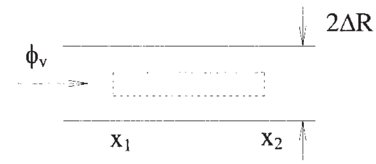

Figure 2. Airflow between two plates.

A volume element is shown.

The average velocity of the air between the clothing material and the cylinder is:

$$\nu_{air}(\theta) = \frac{\phi_\nu(\theta)}{2\Delta RL} = \frac{1}{3\eta}\left(-\left.\frac{dP_i}{d\theta}\right|_\theta\right)\frac{(\Delta R)^2}{R} \tag{5}$$

The maximum velocity (in the center between the plates, at r = 0) is:

$$\nu_{air,\max}(\theta) = \frac{1}{2\eta}\left(-\left.\frac{dP_{in}}{d\theta}\right|_\theta\right)\frac{(\Delta R)^2}{R} \tag{6}$$

The velocity of the air through the clothing is dependent on the pressure difference over the clothing. For high velocities (for instance, through parachutes), the relation is quadratic.[5,6] For lower velocities (which is the case here), this relation becomes linear. Clothing material can be seen as a filter. The law of Darcy describes the velocity through a filter as[7]:

$$\nu_{mat} = K_D\frac{1}{\eta}\Delta P \tag{7}$$

In the case of air, K_D, l, and η can be combined into a new term, Γ, which is called the air permeability. Thus, the velocity through the clothing is calculated by:

$$\nu_{mat} = \Gamma\Delta P \tag{8}$$

Due to this air velocity, the flow underneath the clothing will change[8,9]:

$$d\phi_{\nu,2D} = 2\Delta R\nu_{mat}dx = 2\Delta R\nu_{mat}Rd\theta \tag{9}$$

By inserting Eqs. 5 and 8 into Eq. 9, the next partial differential equation can be deduced:

$$\frac{2}{3\eta}\left(-\left.\frac{d^2P_{in}}{d\theta^2}\right|_\theta\right)\frac{(\Delta R)^3}{R} = \Gamma R\Delta P = \Gamma R(P_{out} - P_{in}) \tag{10}$$

If the pressure outside of the clothing is known, the pressure underneath the clothing can be calculated by this equation. The velocity of the air through and underneath the clothing will follow from Eqs. 5 and 8.

The pressure outside the clothing can be calculated if the airflow is laminar.[10] However, if the airflow is turbulent (which is usually the case), the outside pressure cannot be calculated as a function of the angle. It is, though, possible to use experimental (outside) pressure values to calculate the inside pressure. This will be done in this article.

Mean air velocity through the clothing

At the present moment, a lot of test facilities use an empirical formula to calculate which air velocity through the clothing must be used for a vapor penetration test. This formula was originally proposed by van de Wal.[11]:

$$v_{mat} = K_{emp}\Gamma v_{wind}^2 \tag{11}$$

where K_{exp} is the empirical van der Wal constant. As described in the air flow profile model, the velocity through the clothing is strongly dependent on the orientation around the cylinder. The velocity that is calculated by this formula is a mean velocity of all the inward directed airflow. The air will flow inward at low angles, and at high angles it will flow out again. The angle where change of direction occurs is defined as θ_c (the inflow angle). In laminar cases, this angle can be calculated and equals 45 degrees. In turbulent cases, this value will change and was studied earlier by using CFD.[2,3,12] The mean inward velocity can be calculated by using the inflow angle by:

$$\overline{v_{mat}} = \frac{\int_{-\theta_c}^{\theta_c} v_{mat} d\theta}{\int_{-\theta_c}^{\theta_c} d\theta} = \frac{\int_{-\theta_c}^{\theta_c} \Gamma(P_{out,\theta} - P_{in,\theta}) d\theta}{2\theta_c} \tag{12}$$

The pressure inside the air gap will be a function of the outside pressure and the angle. By proposing the next relationships:

$$P_{in,\theta} = P_{out,\theta} f(\theta) \tag{13}$$

and

$$P_{in,\theta} = P_{out,0} f'(\theta) \tag{14}$$

it can be found that:

$$\overline{v_{mat}} = \frac{P_{out,0}\int_{-\theta_c}^{\theta_c} \Gamma f'(\theta)(1 - f(\theta)) d\theta}{2\theta_c} \tag{15}$$

The pressure at the stagnation point is known[13]:

$$P_{out,0} = \frac{1}{2}\rho_{air} v_{wind}^2 \tag{16}$$

which will lead to:

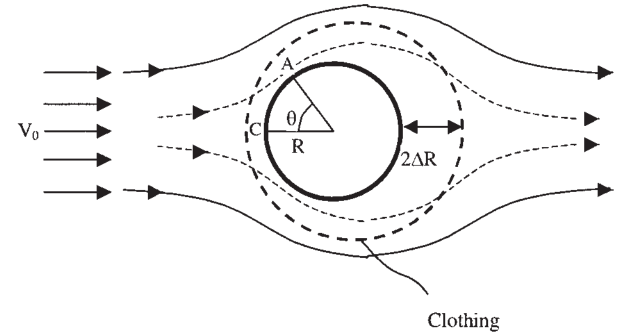

Figure 3. Representation of a body part, dressed with clothing, which is shifted from the center point of the cylinder.

$$\overline{v_{mat}} = \frac{\rho_{air}}{4\theta_c}\Gamma v_{wind}^2 \int_{-\theta_c}^{\theta_c} f'(\theta)(1 - f(\theta)) d\theta \tag{17}$$

or:

$$\overline{v_{mat}} = K_{model}\Gamma v_{wind}^2 \tag{18}$$

with

$$K_{model} = \frac{\rho_{air}}{4\theta_c}\int_{-\theta_c}^{\theta_c} f'(\theta)(1 - f(\theta)) d\theta = \rho_{air} f'(\theta_c) \tag{19}$$

The theoretically derived formula will be equal to the empirical formula if the constants K_{emp} and K_{model} are equal. For specific setups, this can be the case. However, it can be seen that it is expected that the constant will be a function of the inflow angle, which means it is not a real constant. The inflow angle can change, depending on parameters such as the air gap thickness, the radius of the cylinder, and the clothing permeability, which means this constant will change as well with these parameters. A parameter study was conducted to analyze this constant.

Variable air gap size

When a cylinder is covered with clothing and wind is blowing against it, the pressure of the wind can change the size of the air gap. At the front, the size can be decreased, and at the back it is possible that it is increased a bit. This can be modeled by assuming that the center point of the clothing cylinder is shifted backwards compared to the center of the body part cylinder. Furthermore, the radius of the clothing layer can also change somewhat (Figure 3).

Geometrical considerations will show that the shift, S, of the center point of the outer circle (radius R_{cloth}) will change the size of the air gap as a function of the angle as follows:

$$2\Delta R(\theta) = -R - S\cos\theta + \sqrt{-S^2\sin^2\theta + R_{cloth}^2} \tag{20}$$

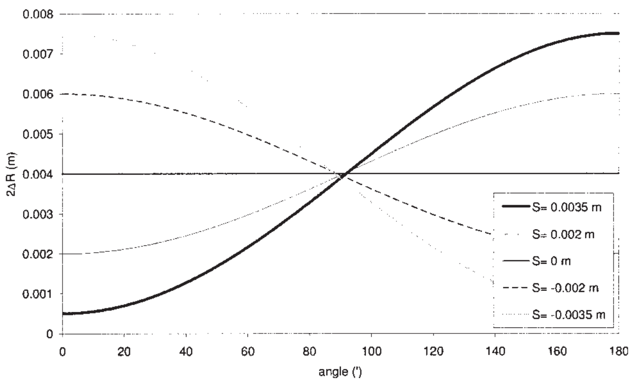

Figure 4. The air gap size as a function of the angle around the cylinder for various shifts of the center point.

If the radius of the body part cylinder and the radius of the clothing cylinder are kept constant, the air gap size will change as a function of the shift and the angle as shown in Figure 4.

The shift and the radius of the clothing can also be expressed in terms of minimal and maximal air gap size:

$$S = \frac{1}{2}(2\Delta R_{\max} - 2\Delta R_{\min}) \tag{21}$$

$$R_{cloth} = R + \frac{1}{2}(2\Delta R_{\max} + 2\Delta R_{\min}) \tag{22}$$

Both the shift and the clothing radius will be used to study their effect on the velocity profile around the cylinder.

Experiments

The experimental setup

A cylinder as a model for a body part is placed in a test chamber. In this test chamber, airflow can be generated with a defined wind velocity. The wind velocity is measured continuously during the experiment with a hot-wire anemometer, which is mounted at a distance of circa 20 cm at the side of the cylinder.

The flow blows against the cylinder, causing pressure differences around the cylinder. These pressure differences are detected by micro tubes, which are mounted inside the cylinder. The pressure tubes are separated from each other by an angle of 10° around the cylinder to measure a pressure profile around the cylinder.[14,15] The micro tubes are connected to a pressure-difference scanning device (NetScanner Model 9016), which measures the pressure difference between the sample tube and a reference tube. This device can monitor 16 micro tubes at a time. The reference tube is placed in the same room (thus has the same temperature), but influences of airflow are minimized by placing it perpendicular to the air flow and by covering it with a thin (flexible) layer of tape. The pressure results are processed in a data application module (NetScanner Model 90DB), which in turn is connected to a PC to analyze the data.

Every measurement consists of the average value of the measured pressure during 1 min, which reduces the variations due to turbulent flow. To account for systematical errors, every measured pressure was subtracted by the measured value at a wind speed of 0 m/s at the same location.

The cylinder is covered by a layer of clothing, which is draped at a defined distance from the cylinder wall. The distance wall to clothing is set by rings around the cylinder, which in turn are used to mount the clothing on. The thickness of the rings determines the distance cylinder wall to clothing (the air gap). Though the air can cause the clothing to be deformed, as described in the variable air gap size section, it is presumed that this does not happen.

The pressure profile around the cylinder was measured for both a bare cylinder and a cylinder that is dressed with clothing. For the theoretical pressure calculations in the air gap, it is assumed that the pressure profile around a bare cylinder resembles the pressure profile at the outside of the clothing of a dressed cylinder.

Values were varied in the experimental set-up as follows:

- A low and a high wind velocity were studied (1.4 ms/ and 7.2 m/s).
- Two types of clothing were used, one with a low and another with a high air permeability ($7.3*10^{-3}$ and $6.2*10^{-4}$ m/(Pa s)).

The air gap size was kept constant at 4 mm during all experiments.

Results

Accuracy of the pressure measurements

To get an indication of the accuracy of the pressure measurements, the measured pressures around the bare cylinder were used to calculate the wind velocity. Theoretically, the pressure at the stagnation point equals:

$$P_{stag} = \frac{1}{2}\rho_l v_0^2 \tag{23}$$

Thus, the wind velocity can be calculated from these measured pressures. In Table 1 these calculated wind velocities are given, together with the values, measured with a hot wire anemometer (which was calibrated at the Dutch Measurement Institute: NMI) and the set point of the test chamber where the experiments took place.

The difference between the values measured with the hot-wire anemometer and the values calculated from stagnation point pressures is 5% at maximum. Thus, the accuracy of the pressure measurements is quite acceptable.

Outside pressure profile

Pressure profiles around a bare cylinder were measured as described. The measured profiles were normalized by dividing them by the measured pressure at the stagnation point. In

Table 1. Wind Velocities Calculated from Stagnation Pressures and Measured with a Hot-Wire Anemometer

Hot-Wire Velocity (m/s)	Stagnation Pressure (Pa)	Calculated Stagnation Air Velocity (m/s)
1.4	1.28	1.47
7.2	32.09	7.37

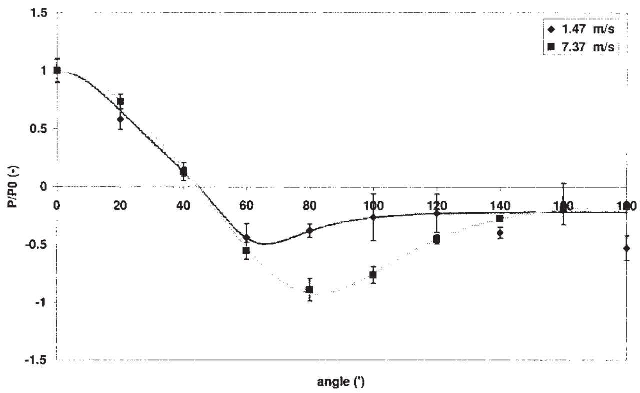

Figure 5. Reduced measured pressure profiles around a bare cylinder.

Trend lines through the data points are added as eye-catchers.

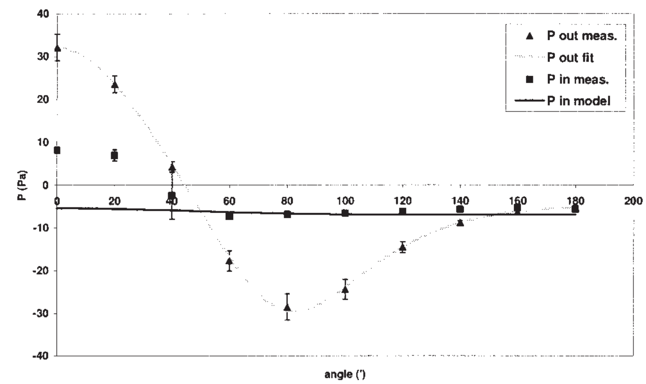

Figure 7. Pressure profile around a bare cylinder and under clothing with low air resistance at a high wind velocity.

Figure 5 these measured profiles are given for the two wind speeds.

The shape of the curve is quite similar to values reported in literature.[7] These outside pressure profiles were taken as input parameters for the model, as mentioned previously.

Pressure profile in the air gap

The pressure profile in the air gap was measured as described. The calculated pressure profiles in the air gap are shown together with the measured values.

In the experiments both the wind velocity and the air permeability of the material were varied. In Figures 6 and 7 the measured effects of these parameters onto the inside pressure are shown.

The air gap pressure (underneath the clothing) does not vary much for the two types of clothing (high and low air permeability). A change in the velocity has much more effect on both the inside and the outside pressure.

The calculated pressure underneath the clothing shows good agreement with the measured values. In the case of highly air-permeable clothing at high air velocity, in the front of the cylinder the measured pressures are somewhat higher than the calculated values. A possible explanation for this observation can be that the size of the air gap at the front of the cylinder is not exactly the same as the value that is used in the calculations, because the pressure of the wind will decrease this size somewhat (see variable air gap size results).

Air velocity through the clothing

The air velocity through the clothing can be calculated from the measured outside pressure and the pressure in the air gap. The velocity profiles predicted by the model are also shown (Figures 8 and 9).

The model predicts a somewhat higher value for the air velocity through the clothing. This is presumably the result of the effect, which is discussed previously, regarding a variable air gap size.

The velocity through the clothing scales linearly with the air permeability. Thus, air permeability has a large effect onto the velocity through the clothing.

As can be seen (compare Figures 8 and 9), the air velocity through the clothing changes largely with the wind velocity.

A parameter study was conducted to analyze the constant, which determines the mean air velocity through the clothing as a function of the wind velocity. It was found that there is a relation between the reciproque of this constant and a combination of setup constants:

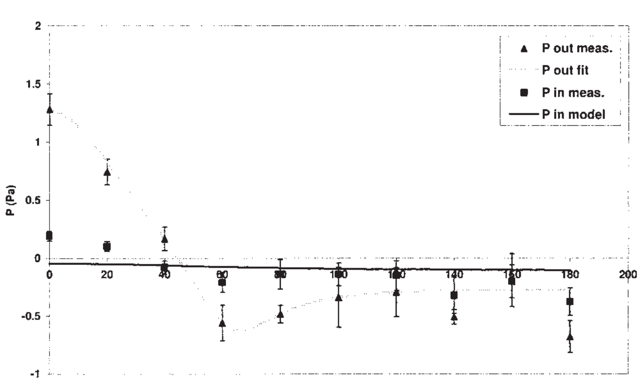

Figure 6. Pressure profile around a bare cylinder and under clothing with high air resistance at a low wind velocity.

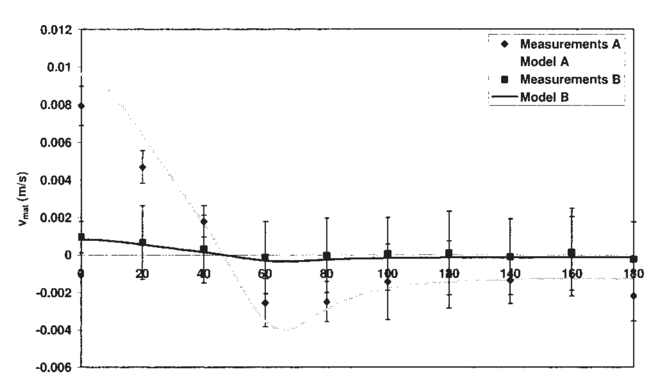

Figure 8. Measured and calculated velocity profile through clothing with high (A) and low (B) air permeability at a low wind velocity.

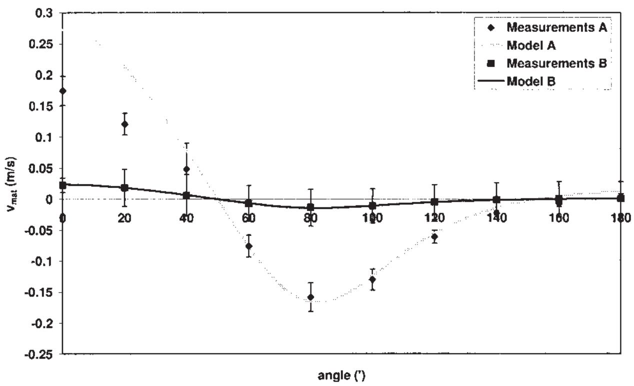

Figure 9. Measured and calculated velocity profile through clothing with high (A) and low (B) air permeability at a high wind velocity.

$$1/K_{model} = f\left(\frac{R^2\Gamma}{(2\Delta R)^3}\right) \quad (24)$$

In Figure 10 this is shown for the observed turbulent case and the calculated laminar case.

As can be seen from Figure 10, the airflow constant is not constant according to the theory. Only for a specific combination of set-up values is the empirical value equal to the theoretical value. The empirical value was found by performing measurements at one setup. Therefore, it is recommended here to perform measurements at various set-up conditions. The next fit gives an r^2 of 0.991:

$$1/K_{model} = 1.13*10^{-10}\frac{R^2\Gamma}{(2\Delta R)^3} + 1.76 \quad (25)$$

The intercept of this equation almost equals the empirical value (this can also be seen from Figure 10, since the lines cross very near to the 0-axis). By using this equality, the next equation can be found:

$$K_{model} \approx \frac{K_{emp}}{1 + 6.42*10^{-11}\frac{R^2\Gamma}{(2\Delta R)^3}} \quad (26)$$

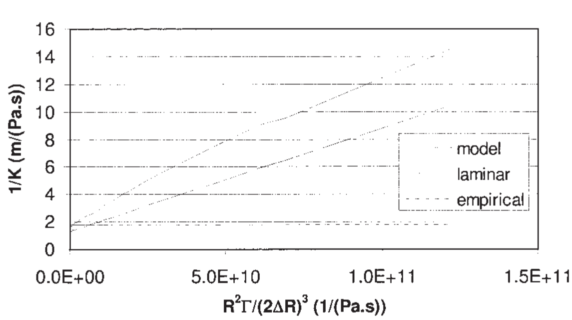

Figure 10. The reciproque of the airflow constant as a function of setup parameters.

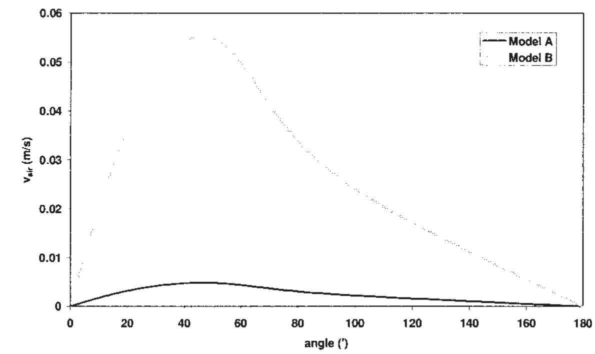

Figure 11. Calculated velocity profile underneath clothing at a high (A) and a low (B) air permeability at low wind velocity.

This equation describes the deviation of the calculated K_{model} from the empirical value.

Air velocity in the air gap

The air velocity in the air gap between the cylinder and the clothing is related to the pressure difference in this air gap over the angle (Eq. 4). Since the variation in the pressure measurements is larger than the difference between the values of two angles, it is not realistic to calculate the air velocity underneath the clothing from these measurements. Theoretically expected values can, however, be calculated (Figure 11).

The air velocity underneath the clothing is a lot higher than the air velocity through the clothing (compare Figures 8 and 10). At a high wind flow combined with high air permeability, the air velocity almost equals the wind velocity at a certain angle.

Variable air gap size

Due to the pressure of the wind, a positive shift can be expected. However, to analyze the effect of changing the shift, negative shifts were also taken into account.

In a previous paragraph, the effect of the air gap size was investigated. However, the air gap size was assumed constant over the angle. In this paragraph a shift in center point of the radius of the clothing is investigated, resulting in a variable air gap size over the angle.

If the shift approaches the mean air gap size, the front air gap size will approach zero. Consequently, the flow through the clothing will decrease to zero.

The inside pressure is related to this flow. Since the flow through the clothing decreases, the inside pressure will approach the outside pressure, and thus the inside pressure will increase with increasing shift (Figure 12).

The inside pressure increases with a positive shift both at the front and at the back of the cylinder. At the front this increase is larger, since at this side the change in the air gap size is the largest. This observation is in accordance with the assumption that was made earlier from the difference in measurements and calculations of the inside pressure. The pressure at the front of the cylinder can almost become equal to the outside pressure. Furthermore, it can be seen that the clothing has an equalizing effect onto the pressure underneath the clothing (the pressure at the back is not much different from the pressure at the front of

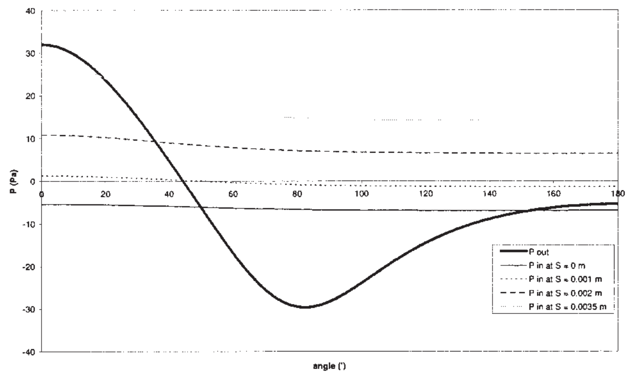

Figure 12. The pressure underneath the clothing as a function of the angle around the cylinder at varying shifts of the center point.

The outside pressure is also shown.

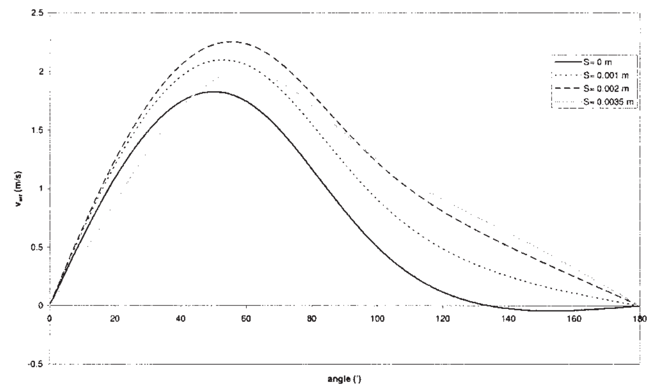

Figure 14. The velocity underneath the clothing as a function of the angle around the cylinder at varying shifts of the center point.

the cylinder). The resulting velocity through the clothing as a function of the angle is shown in Figure 13, and the velocity underneath the clothing in Figure 14.

The main effect of the shift onto the velocity through the clothing is the change in the angle at which the velocity changes direction. The larger the shift, the smaller the angle of change. Furthermore, the absolute value of the velocity decreases with increasing shift. This is logical, since when the air gap approaches zero the velocity must also approach zero.

The absolute value of the velocity under the clothing does not seem to change much. The main effect is the increase in velocity at the back, which is caused by the increase of the size of the air gap. Even back flow can be observed at certain shifts of the clothing. Though back-flow does seem unlikely at first, it has been shown by means of CFD, that this can really be the case for certain air gap sizes in combination with wind velocities. It is important to notice that the proposed one dimensional model is also capable of predicting this back-flow.

Discussion

Both the model calculations and the measurements show that the pressure in the air gap pressure underneath the clothing is almost independent of the air permeability of clothing. The calculated pressure underneath the clothing shows good agreement with the measured values. In the case of highly air-permeable clothing at high air velocity, in the front of the cylinder the measured pressures are somewhat higher than the calculated values. A possible explanation for this observation can be that the size of the air gap at the front of the cylinder is not exactly the same as the value that is used in the calculations, because the pressure of the wind will decrease this size somewhat (see variable air gap size results).

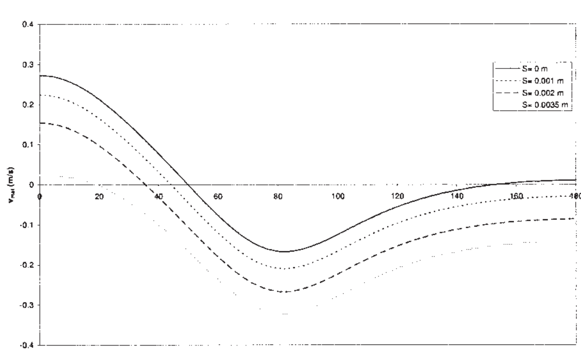

Figure 13. The velocity through the clothing as a function of the angle around the cylinder at varying shifts of the center point.

A change in the wind velocity has a much larger effect on both the inside and the outside pressure. Since this pressure difference, combined with the air permeability, defines the air velocity through the clothing, this air velocity varies also to a larger extent. However, the velocity through the clothing is always considerably lower than the wind velocity (this can be up to two orders of magnitude different). On the other hand, the air velocity underneath the clothing can be of the same order of magnitude as the wind velocity.

The protective behaviour of the NBC-clothing material itself usually is analyzed at an air velocity through the clothing, which is calculated with an empirical formula. An additional mathematical study was carried out to reconfirm this formula. The mean inward velocity through the clothing was calculated as a function of the air permeability of the clothing, the air gap thickness, the radius of the cylinder, and the wind velocity. At a certain specific combination of these parameters, the empirical formula can be found. However, the formula will change if other values for these parameters are used. Therefore, a correction factor was proposed, to make the empirical formula also applicable for other conditions.

Theoretically, a low air gap size will give a low air flow through the textile. Increasing the air gap size will increase the inflow. However, the flow underneath the clothing will decrease with increasing air gap size. If the pressure of the wind reduces the air gap size at the front of the cylinder (and maybe increases the air gap size at the back), a similar effect can be found.

Conclusions

A model that describes the pressure profile and the air velocity profile through and underneath clothing around a cylinder has been deduced. The model was validated by experiments. The model and the experiments show good agreement.

Both the increase in wind velocity and air permeability will result in a higher air flow underneath the clothing. Lowering the air gap size will result in a lower flow through the clothing.

If the air gap size at the front decreases due to the pressure of the wind, the flow through the clothing will also decrease. The flow underneath the clothing will increase at the back side of the body part because of the increasing air gap size at the back.

The protective performance of NBC-clothing is usually analyzed at an air velocity that is calculated with an empirical formula. The correctness of this formula was analyzed with the model. Only at a specific combination of parameters was this formula found. A correction factor for this formula was proposed.

Acknowledgments

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Notation

Roman letters

K = constant (Pa s^2/m^2)
K_D = Darcy constant (-)
K_{emp} = constant (Pa s/m)
$K_{laminar}$ = constant (Pa s/m)
K_{model} = constant (Pa s/m)
l = thickness of clothing (m)
L = length of cylinder (m)
P = local pressure (Pa)
P_{in} = local pressure in air gap (Pa)
P_{out} = local pressure outside clothing (Pa)
P_{stag} = pressure at stagnation point (Pa)
r = distance from the center of the air gap (m)
R = radius of cylinder (m)
ΔR = half size of air gap (m)
R_{cloth} = radius of clothing cylinder (m)
R_{max} = maximum air gap size (m)
R_{min} = minimum air gap size (m)
S = shift of center point clothing (m)
v_0 = wind velocity (m/s)
v_{air} = air velocity in air gap (m/s)
v_{mat} = air velocity through clothing (m/s)
v_r = local velocity at r (m/s)
x = distance along surface of cylinder (m)

Greek letters

η = dynamic viscosity of air, Pa s
ϕ_v = flow in air gap (m^3/s)
Γ = air permeability of clothing (m/(Pa s))
ρ = density of air (kg/m^3)
θ = angle around cylinder (°)
θ_c = inflow angle (°)

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