Permeability Simulations in Textiles

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***Abstract*—** The paper deals with numerical flow simulation in permeable textile structures and their combinations. Permeability parameters are evaluated from permeability measuring on such real structures and combinations. The flow inside of the permeable volume is explained by numerical flow simulation. The received images of flowfields give a good idea about the behavior of the studied structure at the intended purpose. Several examples are presented here – the permeability of thick yarn layer, wound on the bobbin, permeability of combined multi-layer clothing under wind effect and condition for water vapor condensation in such multi-layer clothing.

***Keywords*— Numerical flow simulation, air permeability, multi-layer clothing**

I. Introduction

Numerical flow simulations enable to examine many processes in real permeable layers and to judge about suitability of designed structure for intended purpose.

II. Permeability

A. Permeability Measuring

A simple measuring device [1] was used for measuring the permeability of yarn layer wound at various stiffness, see Fig. 1. The air inlet is set at suitable pressure value measured by pressure gauge (1); the air flow is measured by flow meter (2). The perforated core (3) is closed by two plugs so that the air is flowing out through the yarn layer (4) wound on the core. The measured air volume is proportional to the real stiffness of the winding.

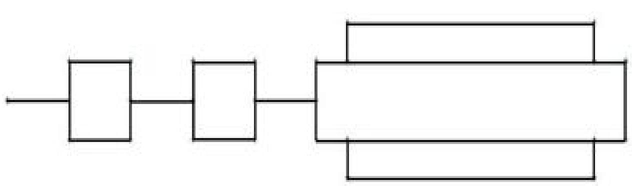

Fig. 1 Scheme of measuring device

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For the defined range of stiffness, the presented method is sufficiently sensitive. The measured characteristics

$$V(m^3/h) = f\,(\Delta p(kPa)) \qquad (1)$$

for various possible stiffness of winding, see Fig. 2. For the soft bobbin (No. 1), there it is characteristic its higher flow, comparing with the hard one (No. 13).

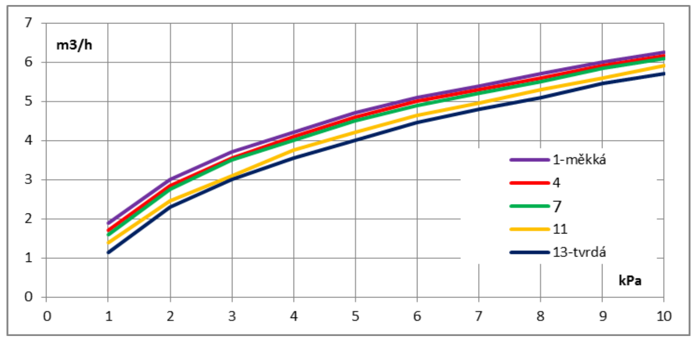

Fig. 2 Permeability of measured bobbin samples (1 = soft, 13 = hard)

B. Permeability Evaluation

The permeability of the observed layer is given by its flow resistance. After [2], [3] etc., this resistance consists from linear term, typical for instance for soaking at small velocities (so-called Darcy's law) and from quadratic term, typical for flows around bodies or through channels (Weissbach's or Moody's law)

$$\Delta p = C_2 \,.\, \rho/2 \,.\, tl \,.\, w^2 + \mu / \alpha \,.\, tl \,.\, w \qquad (2)$$

where

$w = V/S$ (m/s)	flow velocity
V (m^3/s)	volume flow
S (m^2)	flow cross section
tl (m)	layer thickness
ρ (kg/m^3)	medium density
μ (m^2/s)	viscosity (for air 1,375e-5)
α, C_2	permeability parameters [3].

Two unknown permeability parameters α, C_2, depending on the layer structure, are necessary to determine. In a real permeable structure, there usually exists some combination of both such limiting cases (linear term, only or quadratic term, only).

From the measured characteristics $V = f\,(\Delta p)$ in Fig. 2 it is necessary to create an inverse characteristic $\Delta p = f\,(V)$ to get the equation formally corresponding with the above mentioned formula $\Delta p = f\,(w, w^2)$ (2).

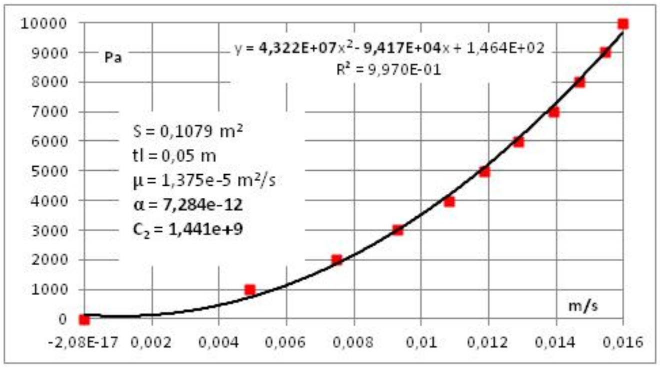

Fig. 3 Evaluated permeability (as an example)

In Fig. 3, there is presented the resulting function (as an example), together with simple substitution by quadratic function [5]. The achieved correlation coefficient is very high (R^2 = 0.997).

Comparing the coefficients of linear and quadratic terms from Fig. 3 with the above mentioned formula (2) for pressure resistance it is possible to determine two unknown permeability parameters α and C_2 of the measured winding. The mentioned absolute term (here 146.6) represents the absolute error of measuring and of the used substitution. But for the used working pressure difference of 10 kPa it is negligible.

III. Permeability of Wound Yarn Layer

One of the standard methods for colouring of textile yarns consists in plunging a wound bobbin in dyeing bath and repeated reciprocal pushing-through of the bath from the bobbin axis direction through the perforated bobbin core, further through the wounded layer of yarns to the bobbin outer surface and vice versa. Of course, the flow resistance of such permeable layer of wound yarns depends on the layer density (stiffness) and on the layer thickness, too, which is different in the middle and at the faces of the bobbin shape. The result of such uneven flow could be an uneven intensity of coloration and further an uneven colouring of final product, for instance woven fabric, knitwork, etc.

A. Used Methods - Overview

Known methods of winding stiffness evaluation use the measuring of resistance force, for instance against the needle penetration into the wound yarn layer or against the rotation of flat needle, pushed in the wound yarn layer. Another method measures the resilience characteristics of falling testing body by the wound surface. The general disadvantage of results from such methods is the punctual measuring, only, containing the objective error of used measuring device (for instance mechanism friction, clearances) and subjective error of operator, too. For the determination of the average values of measured results it is necessary to make more measuring for each bobbin, together with statistical evaluation. It is known that such method needs many time and the variability of such results is considerable.

The principle of the proposed method exactly corresponds to the real procedure of said dyeing – the pushing the dyeing bath through the volume of wound yarn layer. The fluid flow through the permeable yarn volume is measured – in the stiffer wound layer the flow resistance is higher and the flow passage is lower. Using the same shape and dimensions of the wound bobbins, it remains the only one parameter – its permeability, depending on the winding stiffness. In the case when the outer dimensions of the winding (diameter, length) are not standard, the winding permeability is changing, too.
For practical reasons, the air is used instead water solution. The aim of the method is the relative comparison of permeability / stiffness of individual wound bobbins, not any absolute value. It is clear that the permeability of water is absolutely other than that for air.

B. Model Description – one bobbin

For understanding of processes into the wound permeable volume during the flowing through it should be to use any suitable flow simulation.

For rotational geometry of the bobbin with central cavity it is appropriate to use an axis-symmetrical model and to use the transverse plane of symmetry as well. The two determined permeability parameters above should be used as a local “pressure jump” [3], while the flow resistance of the wound bobbin is uniformly distributed along and across the thick layer of the winding. So it is necessary to divide the volume of the permeable layer of wound yarns into more elementary layers in both radial and axial directions. In such a way, the volume is divided into many elementary volumes of elementary permeability.

The model geometry is designed after the real shape of the bobbin. In order to be able to use the suitable axis-symmetrical model, the core body should be designed with narrow radial gaps of equal cross-section, instead of rows of individual holes.

Meshing of such simple geometry is without problems, with smaller elements in narrow radial gaps. Defined boundary conditions are logical from previous description – pressure inlet/outlet at axial inlet/outer outlines or reverse, pressure jumps and axis. The solution is running without problems with good convergence.

Remark: In the real operation, there is used a dyeing liquid, but for this modelling it is used air. The principle of both solutions remains the same.

C. Results of the Simulation

The following serial of Figures shows the typical parameters of the flow field – velocity, pressure and streamlines. Using the planes of symmetry, there is displayed the upper half of the modelled area, only, the rotation axis is situated at the bottom of each Figure. Absolute values of observed flow parameters are not important here, in general the maximum value is red, the minimum is blue – the same as in the light spectrum.

The rotational axis is situated always horizontally down, due to save extent of the article, the only one (upper) symmetrical half of the model is outlined here. And more, one typical result is presented here, only, other solved cases give similar results.

The first set (Fig. 4 to Fig. 6) presents the result for the flow direction from the perforated core axis to the periphery; the second set (Fig. 7 to Fig. 9) is for the reverse flow direction, from the periphery to the axis. While the pressure field is really reversed, the field of the absolute value of the velocity and the streamlines field, too, seem to be the same.

In general, on both velocity and streamlines fields, it is visible the "short-circuit" flow between the axial inlet through the core axis and axial outlet through the side front of the winding, in both flow directions (from the axis to the periphery and on the contrary, too). In the middle part of the winding the flow is radial, unaffected by boundary conditions. At both faces of the wound body it is visible an expressive flow bend into the reverse direction. This result is very important for correction of designed measuring method after the Par. II-A. Firstly, the streamlines images (Fig. 6 and Fig. 9) show an important influence of faces boundary condition – in the middle part the flow is exactly radial, but at faces the flow is deformed. So the global measuring of the bobbin permeability should be replaced by measuring in the middle part, only.

Remark: The velocity scale is suppressed here, to get a more detailed velocity field in the volume of the winding. The flow in the core is not interesting here; the empty area means the higher velocity value in the axial tube (out of the used scale).
It is clear that a model with higher number of smaller volumes of elementary permeability gives better results, but the time of solution is increasing.

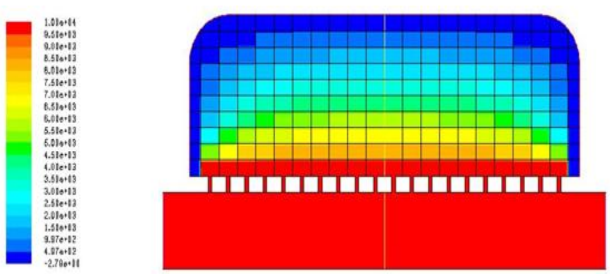

Fig. 4 Pressure field - flow from the axis (max.) to the periphery (min.)

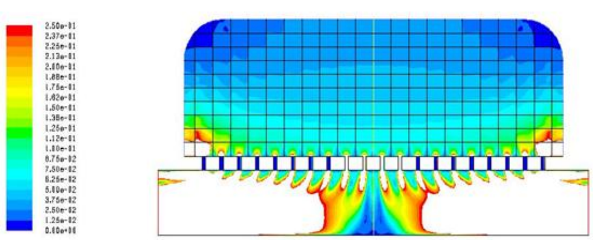

Fig. 5 Velocity field (suppressed scale) – flow from the axis to the periphery

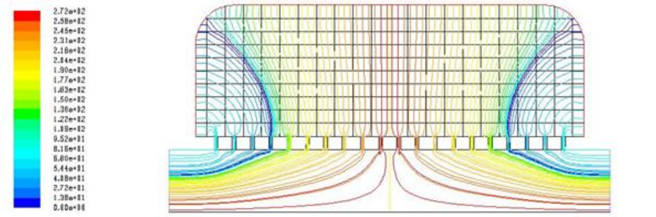

Fig. 6 Streamlines - flow from the axis to the periphery, „short-circuit" flow at faces

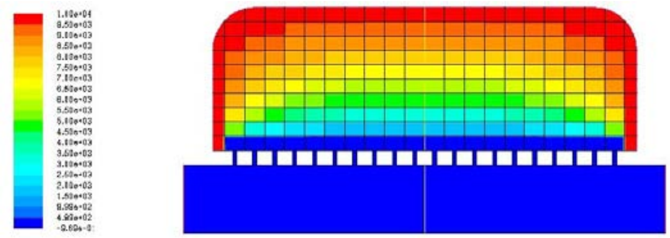

Fig. 7 Pressure field - flow from the periphery (max.) to the axis (min.)

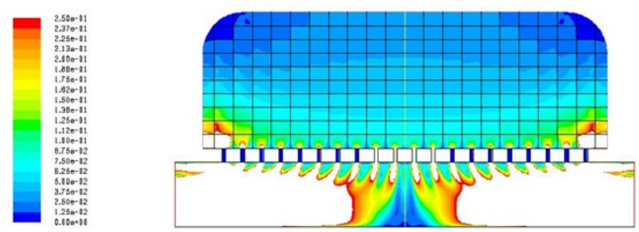

Fig. 8 Velocity field - flow from the periphery to the axis (suppressed scale)

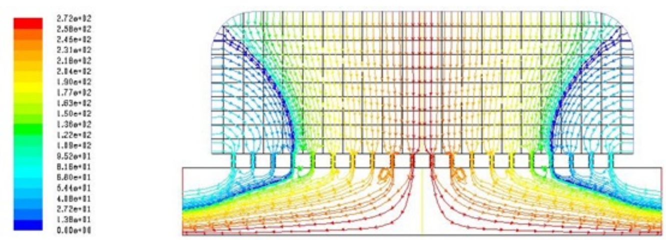

Fig. 9 Streamlines - flow from the periphery to the axis, „short-circuit" flow at faces

The relative simple meshing together with standard procedure of standard commercial code make no problems as to the stability of convergence.

E. Suppression of short-circuits

The next set, Fig. 10 to Fig. 12, presents the simulation of the real situation in the dyeing tank, i.e. the flow in the relatively narrow gap between two adjoining bobbins, situated side by side as in real equipment. The rotation axis remains the same at the bottom of each Figure, left and right edge of each Figure is situated in the middle plane of symmetry. Without next investigation it is possible to say that such configuration could suppress partially the flow through front (side) faces of adjacent bobbins. Only one case is presented here – axial inlets are defined at the ends of cores, i.e. in the central part of the Figures, see the streamlines.

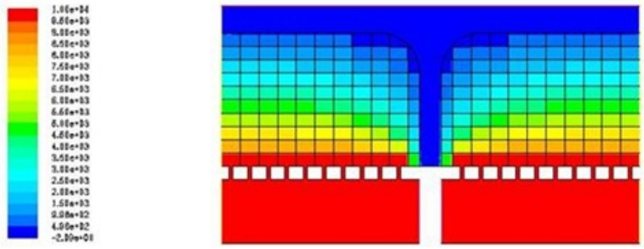

Figure 10. Pressure field in the gap between two adjacent bobbins

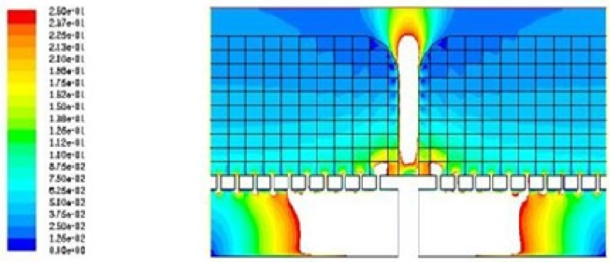

Figure 11. Velocity field between two adjacent bobbins (suppressed scale) – maximum outflow in the free gap (from side faces of both bobbins), not in the wound volume

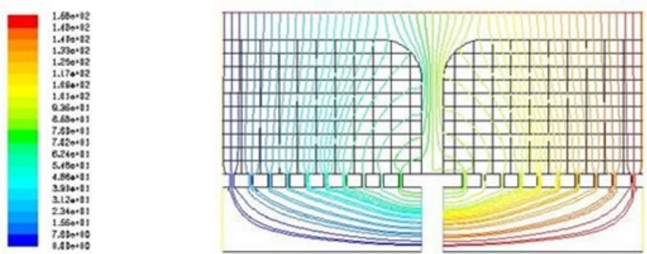

Fig. 12 Streamlines between two adjacent bobbins (flow from axis to the periphery, as in Fig. 6)

Comparing Fig. 12 (view on the gap between two halves of adjoining bobbins) with Fig. 6 (view on the one whole bobbin) we can state that the effect of the "short-circuit" flow is here suppressed a little.

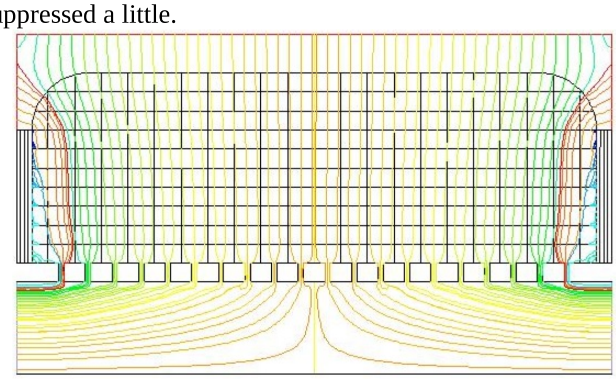

Fig. 13 Frontal partition suppressing the short-circuit flow

Similar suppression could be made by any rigid radial partition between both bobbins, see for instance Fig. 13. In both cases the most streamlines remain radial, the axial deformations due to the short-circuit through frontal faces are suppressed, so we can state that conditions for uniform dying are kept in the major part of the winding volume.

Another suppression could be made by blinding of several end orifices in the core body – see Fig. 14, where 0-1-2 orifices are shut and the flow velocity (m/s) along the radius (m) of the front face is more uniform, the effect of the short-circuit is suppressed.

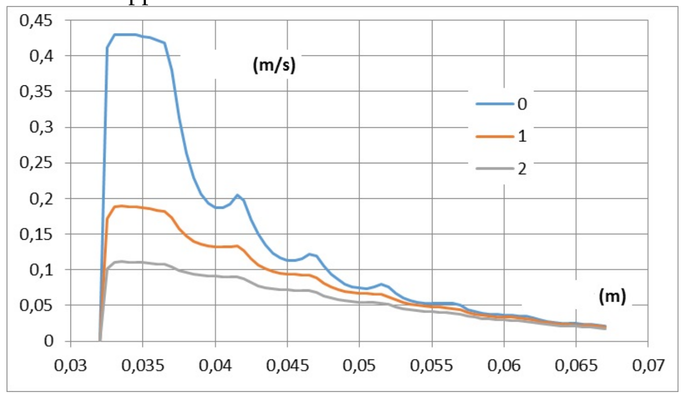

Fig. 14 Velocity suppressing at the frontal side of the bobbin by blinding of 0-1-2 rows of orifices in the perforated core

F. Situation in a real dyeing machine

The last model presents the situation in a real dyeing tank, where sets of four bobbins are situated in sequence. So we can state that such configuration makes some suppression of short-circuit flows, as mentioned on the Fig. 10 to Fig. 12 above. This set of Fig. 15 to Fig. 17 presents fields of velocity, pressure and streamlines of such configuration (the left side of symmetrical case, only) – the flow direction from axis to the contour, only, as on the Fig. 4 to Fig. 6.

At first we can state that the cross-section of the common inlet is sufficient, it allows the uniform flow distribution in all four bobbins.

At seconds, small gaps, only, between front faces of adjacent bobbins achieve some suppression of short-circuit of the flow through front faces. It is important for more uniform flow through the winding volume.

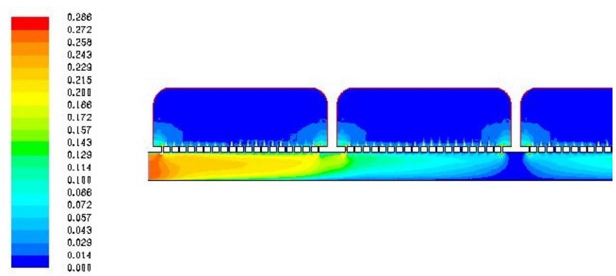

Fig. 15 Velocity field in configuration of four bobbins

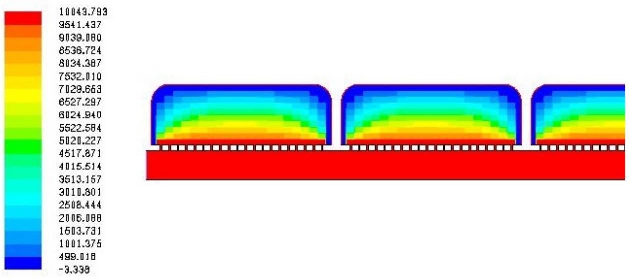

Fig. 16 Pressure field in configuration of four bobbins

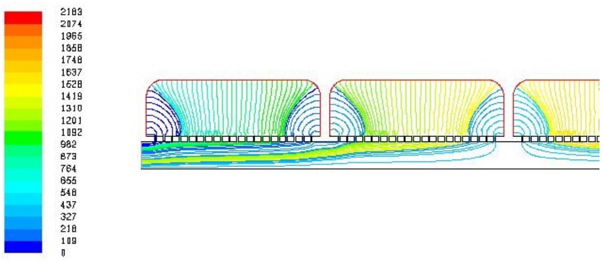

Fig. 17 Streamlines in configuration of four bobbins

Evaluating the received results of numerical flow simulation we can state that the common inlet is well dimensioned, in each of four bobbins just one quarter of the whole flow is flowing, small deviations are due to numerical error of the simulation.

But the flow distribution in each bobbin volume is very non-uniform – the volume flow through the front faces is very high, 230% approx. of the average flow and the flow through the radial periphery is 43%, only of the average flow. So the dyeing time must be longer, corresponding to this lower flow, to get uniform coloration of the whole bobbin volume. Some "overdyeing" is not possible, the textile material can be saturated, only, by coloring agents, not "oversaturated".

G. *Uneven stiffness of wound layer*

On the really wound yarn layer the uneven stiffness (permeability) can be observed. Even if the yarn brake effect remains the same, the inner layer on the small radius receives higher density (stiffness) comparing with the outer layer on the bobbin contour. The effect of such phenomenon is simulated, too, results are as follows:

Fig. 18 presents different flow resistances for hard – medium – soft bobbin.

Using such different parameters on three radial layers, we can state that differences of the flow are not important, see Tab. 1.

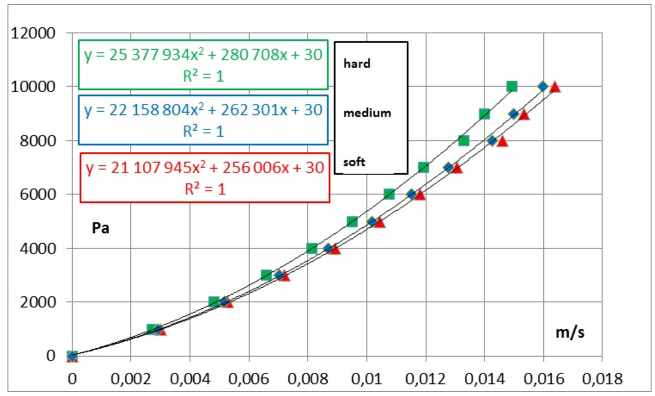

Fig. 18 Different flow resistance for hard – soft bobbin

Tab. 1 Relative flows at various winding stiffness

	inlet	outlet		
winding	core	front	arc	periphery
	%			
const soft	100,0	47,0	7,2	45,7
const med	97,6	45,9	7,1	44,6
const hard	91,2	42,9	6,5	41,7
stepped	98,9	47,2	7,1	44,5

As an illustration, only, the Fig. 19 presents the velocity field for comparison with previous results - here at different scale, but very similar character. Other flow field parameters are very similar to previous, too, so they are not presented here.

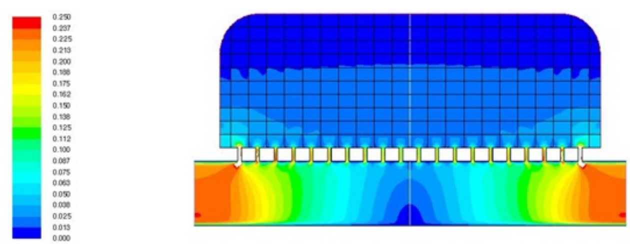

Fig. 19 Velocity field in the winding of three layers of different permeability in radial direction

IV. WIND TUNNEL EXPERIMENTS

Wind tunnel is an experimental device for testing of a real clothing combination under the conditions of strong wind. But data evaluation from the experimental wind tunnel is very complicated and time-consuming, but not reliable. There is a problem of temperature stability of both temperatures (inner and outer) in time.

A numerical experiment can solve the problem – the results are reliable, exact, many parameters can be set, tested and evaluated.

The flowfield around a rigid cylinder in cross flow is well known, see this velocity field in Fig. 20, the main flow from the left side. For the recapitulation: the area of minimum velocity is situated in the stagnation point on the left side, the areas of maximum velocity are situated on both sides (here up and down) and behind the cylinder, there arises an area of backflow. Corresponding streamlines are visualized in Fig. 21.

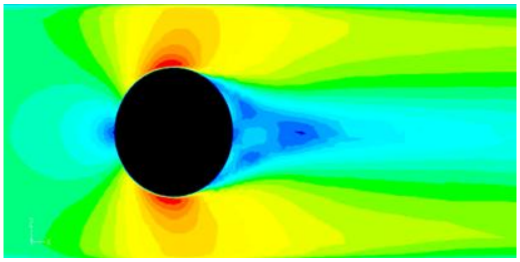

Fig. 20 Velocity field in the crossflow around a rigid cylinder

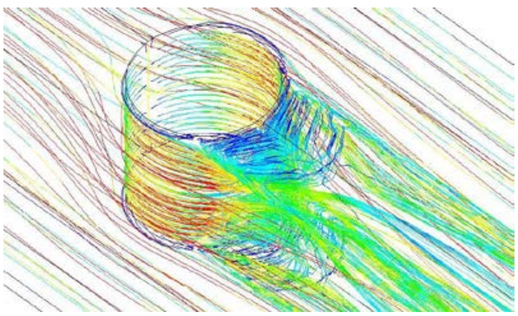

Fig. 21 Streamlines in the crossflow around a rigid cylinder

The experimental setup of wind tunnel is very similar. It contains a wire cylinder „dressed“ by real clothing or by a real combination of clothing layers. The inner air is heated on a body temperature of 30°C approx., the outer air is cold.
The evaluation of experimental data - interactions of cold and warm air through the porous layer - is not exact for several reasons, first of all for an unstable temperature field in time. Using the numerical flow simulation of relevant flowfield (temperatures, pressures, and velocities), the results in and around the permeable (porous) clothing layer are very simple and reliable.

The pressure field can be directly defined from the velocity field in Fig. 20, using Bernoulli’s equations. Fig. 22 presents the symmetric half of the pressure field in the model.

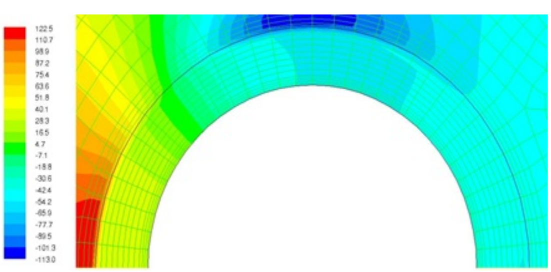

Fig. 22 Pressure field around a permeable cylinder

The area of maximum pressure is situated in the area of the stagnation point (left), where the velocity is minimum. The cold outer air can here penetrate inside through the permeable structure.

The area of minimum pressure is situated at both sides (here up/down), where the velocity is maximum. In this area, the warm inner air can penetrate outside.

The next Fig. 23 presents a corresponding temperature field.

Cold outer air from the left side penetrates through the permeable layer of clothing up to the heated inner volume – the surface of „arm“.

Warm inner air is escaping out on the sides.

On the back side (wake), the cold air from the surroundings is penetrating to the arm surface again („there is a draught“).

Such simple results can predict the behavior of the used multi-layer structure of clothing, where parameters of permeability should be defined in advance, see the Par. II above. It should be to remark that any exact calculation of real fabric or knitwork is not possible due to the very complicated structure.

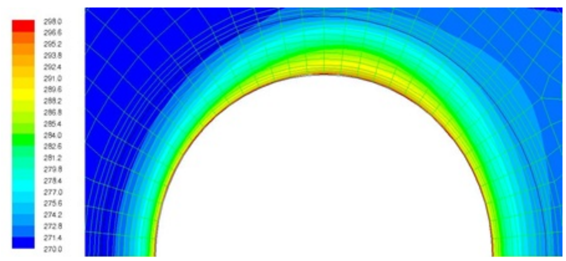

Fig. 23 Temperature field around a permeable cylinder

V. Water vapor condensation

Advertising of the so-called outdoor clothing presents the admirable values of vapor permeability of such clothing structures. The reality is a little different – laboratory tests are made for tropical climate (outdoor temperature of +35°C), but temperatures in the Central Europe are lower. What happens under the real conditions in the studied clothing structure is possible to simulate as follows.

The recommended clothing composition consists of three standard layers: the inner very absorbent layer, followed by a standard thermal insulation and an outer windproof and waterproof layer. In this simulation surrounded by cold air (-3°C) from outside (right). The measuring during the real tests of physical effort in laboratory conditions [6] gives the real values of temperature and its relative humidity on the body surface – typically +30°C, 90%. So the dew point is situated very close, the air cooling of about 2° only means the water condensation from such wet air.

The next Fig. 24 shows the relevant typical temperature field, including the area of outer air. A relevant temperature profile is presented in Fig. 25. The inner body surface of +27°C (300 K) is slowly decreasing in the layer of thermal insulation. Outer thin layer is impermeable for wind and water (rain), its thermal insulation can be neglected.

The temperature profile along such clothing combination is presented in Fig. 25. The temperature is slowly decreasing in the thermal insulating layer, on the outer surface the temperature is quickly decreasing due to the heat transfer by convection into the surroundings (dotted line, heat flow 305.1 W/m^2 for dry material).

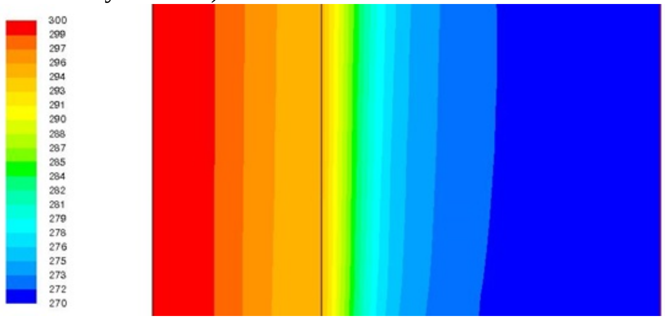

Fig. 24 Temperature field in three-component clothing

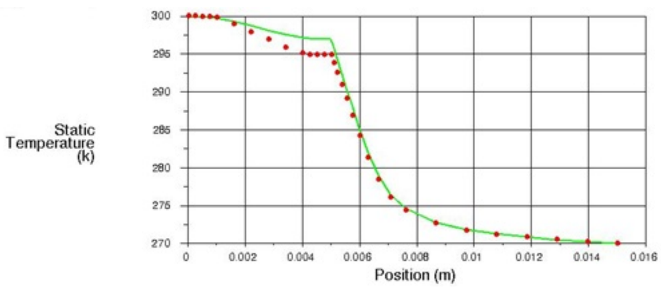

Fig. 25 Temperature profile in three-component clothing

If some water vapor condensation is arising due to the temperature decreasing under the dew point, the thermal insulation becomes wet and its coefficient of heat conductivity is increasing after the Fig. 29 (full line, heat flow 335.2 W/m^2 for wet material).

Really, between the thermal insulation and the outer membrane it is always situated some air layer. Therefore, it should be taken into account the convection on the inner surface, too. In such a case, the temperature decreasing arises on both sides of the membrane and the risk of water condensation is higher. The following Fig. 26 shows the temperature field and Fig. 27 shows the temperature profile of such a case.

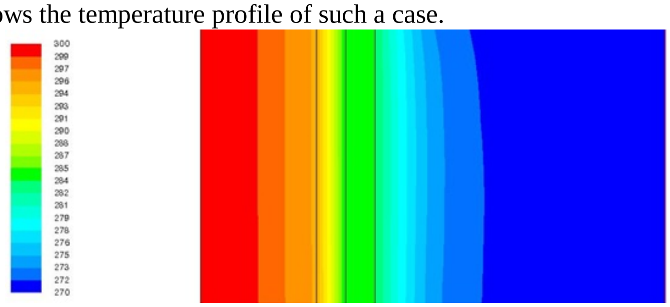

Fig. 26 Temperature field in three-component clothing with added inner air layer

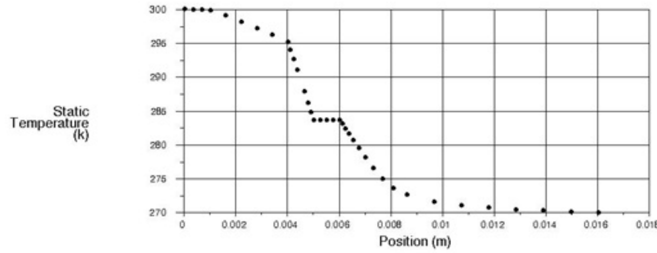

Fig. 27 Temperature profile in three-component clothing with added inner air layer

Using a simple formula for the humidity rate

$$\omega = mv / (mv + ms),$$

we can evaluate the decreasing of the coefficient of heat conductivity by such a moisture rate

$$ms \,.\, \lambda s + mv \,.\, \lambda v = (ms + mv) \,.\, \lambda,$$

where v – water mass, s – dry mass.

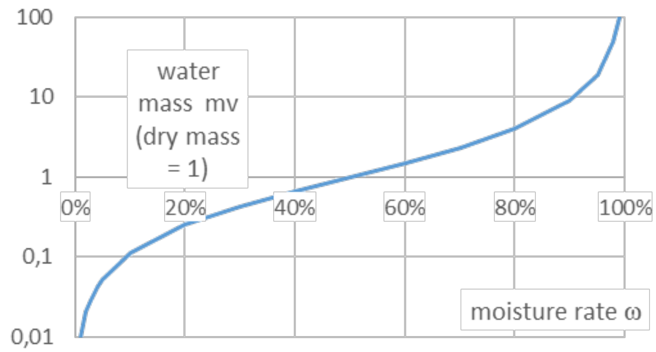

Fig. 28 Moisture rate in wet material

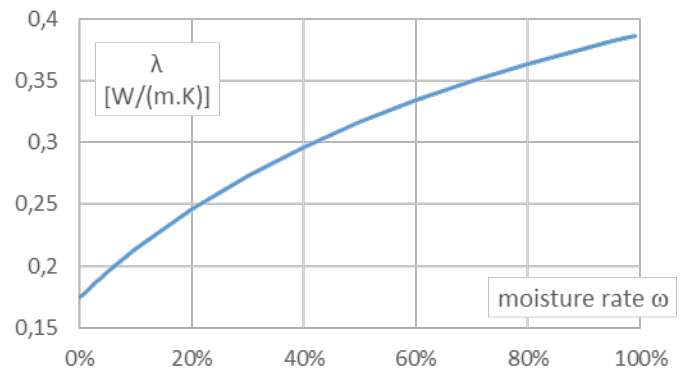

Fig. 29 Heat conductivity material as a function of moisture rate

VI. Conclusion

The proposed method [1] of air permeability measuring for testing the stiffness of the yarn layer wound on the perforated core is simple and reliable, suitable for serial operation with automated manipulation and data storage. And more, using any simple marking of individual bobbins, it is possible to determine retroactively the reason of found defective stiffness of wound bobbin (working unit, yarn brake, etc.).

The presented method of the numerical flow simulation, for instance [4], gives a good overview about the flow through the yarn layer wound on the perforated core and about the uniform dyeing of yarn material, too. Finally, for the real operation, in such a way, there could be tested the optimal results of such simulations, only. In this way, the costs of development are reduced and the results can be directly used in a real plant.

The used numerical flow simulation can predict the influence of any inserted obstacle /partition at the bobbin front face on the more uniform flow through the winding, without necessary experiments. It remains to judge the positive effect of the uniform flow and the uniform dyeing of wound yarn layer, too, contrary to the higher manipulation requirements when preparing a system of bobbins for dyeing.

The density (permeability) of the wound layer can be non-uniform in the radial direction, so the flow penetration can be affected. This influence can be simply simulated, but the real values of permeability must be defined by measuring. Flow ratio for soft/hard bobbin is 1.1 approx., and it is well detected by the designed method of permeability measuring.

The method of flow simulation through and around the porous textile layer (or a combination of layers) gives very good view on the real behavior of such a structure. The results are more reliable than temperature measuring in real wind tunnel – it is visible that temperature values are changing in short distances and together with the oscillations of main air stream they are not constant in time. And more, in a real laboratory, the circulating main stream of air is warming during the period of experiment and so the temperatures are not steady here.

As to possible water condensation in clothing combination under the conditions of physical effort, it should be stated that it is possible under the conditions of real weather. And more, such condensed water cannot pass through the outer impermeable clothing layer and can influence the thermal insulation coefficient of inner layer and the user's comfort, too.

In general, there are three possibilities where the applications of numerical flow simulation are very useful. Firstly, for a hypothesis verification of fully new technical solutions, before manufacturing a functional model for the first verification and measuring. From several theoretical models, there is evident the effect of individual parameters, changed during such numerical experiments.

Secondly, for simulations of existing devices whose functionality (reliability, efficiency, etc.) is poor or unsuitable. It is usually possible to find the reason of such an unsuitable operation and more, the simulation can verify the effect of the designed new solution, the better usable features.

And thirdly, numerical flow simulation can give the imagination about the flow field in the areas where it is not possible to use any standard measuring gauges.

Some examples of the received results from the branch of textile technologies and from other branch, too, were solved, realized and published under [6] to [16].

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