WICKING AND WETTING IN TEXTILES

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Abstract

The proposed model is based on the simplified description of the thread structure, and it works with the textile description of thread structure. The following textile parameters are used in the model: fineness of fibres, and number of fibres at the cross-section in the bundle and the filling. The formation of the liquid in the longitudinal textile is described in detail, and particular phenomena are discussed. Important parameters are used in the model of wicking. The parameters with very small influence in usual threads are disregarded. The proposed wicking model allows a functional dependence of suction height on the parameters of the fibre bundle to be expressed in analytical form.

Keywords

wetting, wicking, liquid amount fibres, liquid surface

Wicking

The behaviour of a given textile during its contact with water (or with the liquid generally) is one of the important properties of textiles. This work focuses on spontaneous liquid wicking, which especially influences the consumer properties of textiles. If the liquid rises (by absorption) in fabric, it can be used as a liquid perspiration outlet from the skin, for the production of hand towels and dishcloths, textiles for cleaning works, and many other such applications. Wicking makes it possible to use textiles for a series of other special applications: wicks for candles and lamps with oil, or some modern flameproof finishings for housing textiles.[1] Spontaneous liquid wicking into fabrics has not been sufficiently theoretically examined till to this time. Wicking can be formally divided into the course and the wicking result; in this work, the equilibrium was analysed as a result of this process.

The equilibrium of the wicking process has not been sufficiently elaborated, but at the same time a series of phenomena can be found on the equilibrium which from the practical standpoint influence the more interesting dynamics of the process. Most authors understand the equilibrium of process only as a physical state without considering the peculiarities related to such a state. Important factors such as acknowledging wicking peculiarities in textile structures (or from passive assumption of theories from other porous systems) are also frequently neglected, and then the results are weighted by useless error. [1,2] The relationships accepted for capillaries are commonly used for analysing the wicking equilibrium . The essential difference between the classical capillary and fabric is that the capillary is a 'closed' and the textile fabric an 'open' capillary system. The liquid does not flow out in all directions from the capillary; solid walls oppose it. There are no firm walls in the textile fabric; the liquid in the system is held by its surface tension.

Proposed model of liquid wicking into the fibre bundle

This model has already been partially published [3]

In this work the thread is defined as a formation of sufficient length, with a circular cross-section, having a constant filling, and without any variation in linear mass of the thread. This formation can be a monofilament yarn, a continuous filament yarn, tow, and so on. Synthetic filament yarn is the most experimentally suitable. With the wicking through the fibre bundle, the liquid generally assumes the shape drawn in Figure 1:

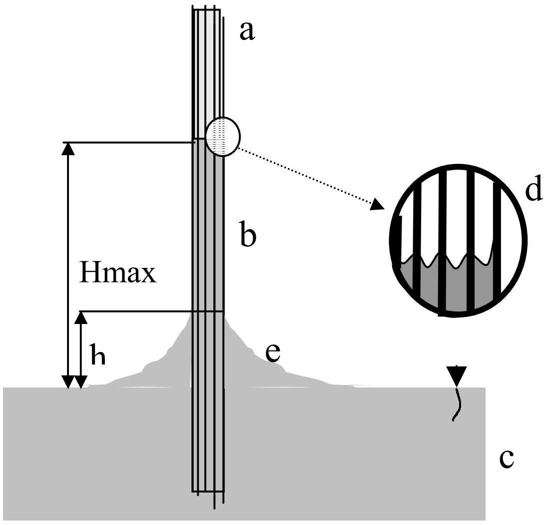


Figure 1. General case of the liquid wicking into the vertical fibre bundle.

a) fibre bundle; the segment without liquid
b) fibre bundle; the segment with liquid; at the equilibrium the liquid will rise to the maximum height H_{max}. This is a main part of wicked liquid
c) liquid
d) the detail of the liquid's shape in contact with fibres at the height H_{max} (planar formation section), upper region
e) transient region (with maximum height h) among wetted fibres and the surface of the 'distant' liquid

The result of the wicking depends on a series of factors, for example those which influence interfacial tensions (temperature, pressure, impurities, polarity…), the other properties of liquid (viscosity, liquid evaporation…), and fibre properties (surface articulation, fibre fineness…).

According to the number of fibres, filling, interfacial properties etc., the separate segments of wicking formation (see Figure 1) share a wicking equilibrium to a different degree. For the usual textile threads (yarns, filament), the 'main part' of the formation of the wicked liquid , in principle influences the suction height.

Main part

The liquid completes inter-fibre spaces and creates a formation with minimum energy. These conditions correspond to a cylinder, which contains all wetted fibres. This cylinder has a surface created by the liquid and the partially un-wetted fibres. The specific situation depends on hydrostatic pressure, cylinder radius, filling, fineness of fibres, interfacial tensions and so on.

The foundation is a calculation of liquid surface curvature at the specific height above its free level. The previous Laplace equation (2) can be simplified because the curvature in the direction of fibre axis is zero, which means that the curvature radius is infinite:

$$P = \sigma_{LG} \times \left(\frac{1}{R_K} \right) \tag{1}$$

where:

P - relative pressure in Pa,
σ_{LG} - surface tension between liquid and gas in $N.m^{-1}$,
R_K - curvature radius of liquid surface in m.

The hydrostatic pressure in liquid is compensated by pressure, which is provoked by curvature of the free liquid surface. On the basis of the Laplace equation, the radius of curvature can be expressed for the surface of the main part:

$$R_K = \frac{\sigma_{LG}}{H \times g \times \rho} \tag{2}$$

where:

g - gravity acceleration at 9,81 $m.s^{-2}$,
ρ - liquid density in $kg.m^{-3}$,
H - height above free level in m,
σ_{LG} - surface tension between liquid and gas in $N.m^{-1}$.

So if we know a surface tension of the liquid and its density, it can be calculated what curvature the liquid surface will have at various heights above its non-curved surface. The graph presented in Figure 2 was calculated for water.

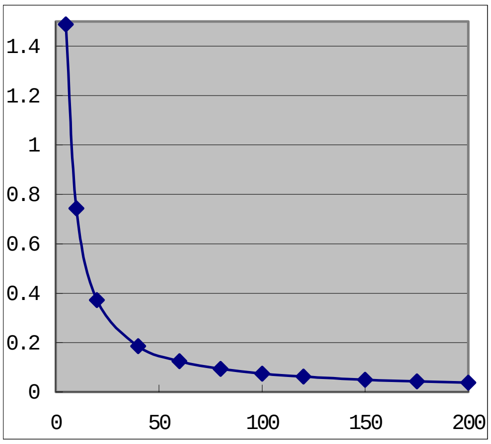


Figure 2. Dependence of the radius of level surface curvature on the height above its non-curved level for water (surface tension 0.073 $N.m^{-1}$; density 1000 $kg.m^{-3}$, g = 9,81 $m.s^{-2}$)
axis x - height above non-curved liquid level in mm
axis y - radius of liquid level curvature in mm

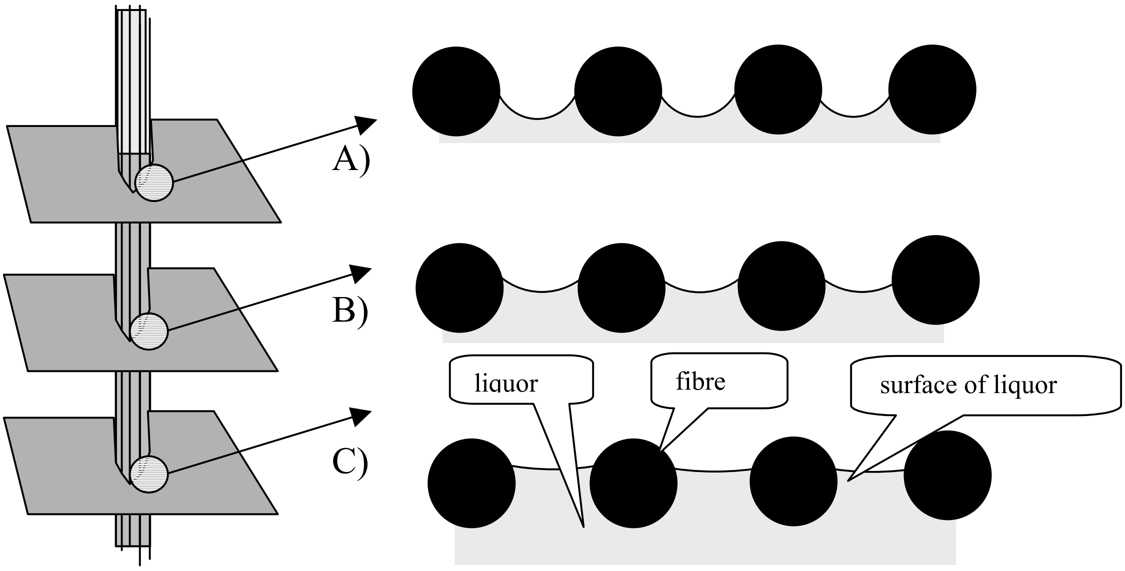


Figure 3. Influence of hydrostatic negative pressure (or height) to the liquid surface curvature on the surface of the fibre bundle

A) the situation almost at the height H_{max} above free liquid surface – the hydrostatic negative pressure is extremely high, and that is why the curvature of surface is high. The small radius of curvature makes it possible to connect only adjacent fibres (high filling)

B) intermediate stage between A) and C)

C) the situation in small height above free liquid surface – the hydrostatic negative pressure is low; that is why the curvature of free surface of liquid is also low (large radius)

Under the presumption of constant filling, the relationship for the average distance of fibre axes in the bundle can be deduced:

$$a = k \times \sqrt{\frac{\pi \times R_V{}^2}{\mu}} \qquad (3)$$

where:

μ - filling of the fibre bundle [-]
R_V - radius of fibre in m,
l - distance of axes of two neighbouring fibres in m,
a - distance of axes of two neighbouring fibres in m.

For various fibre arrangements the coefficient k is different (in the previous equation):
Layer fibre arrangement: k = 1.075, square fibre arrangement: 1

Figure 4 shows the liquid surface between two fibres at the surface of the cylindrical part (see Figure 1 and Figure 3).

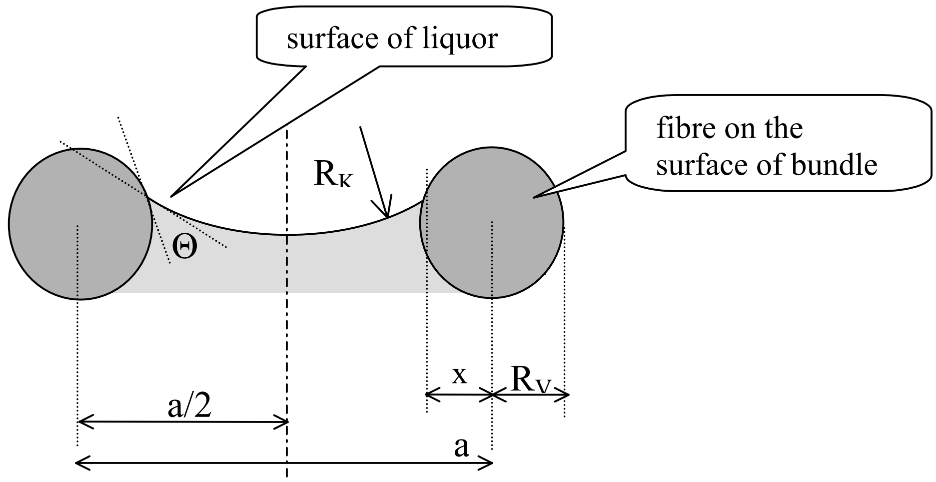
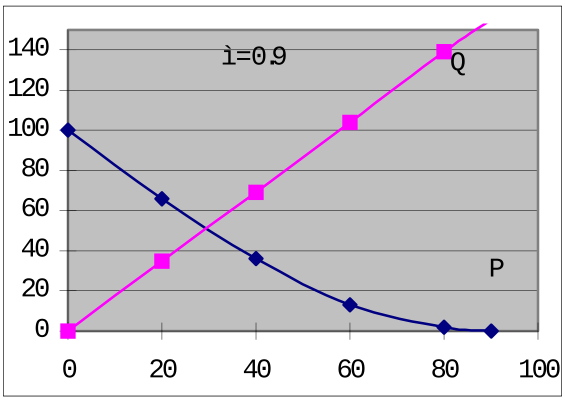
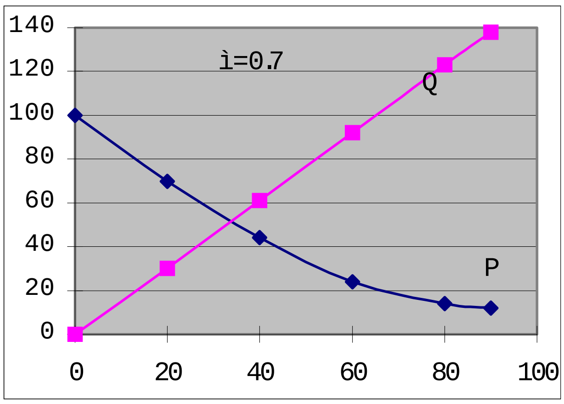


Figure 4. The detail featuring the geometry of the liquid and fibre contact at the surface of fabric
R_V - radius of fibre,
R_K - curvature radius of the liquid level,
X - point of contact of fibre with liquid level,
Θ - contact angle,
a - distance of axes of two neighbouring fibres.





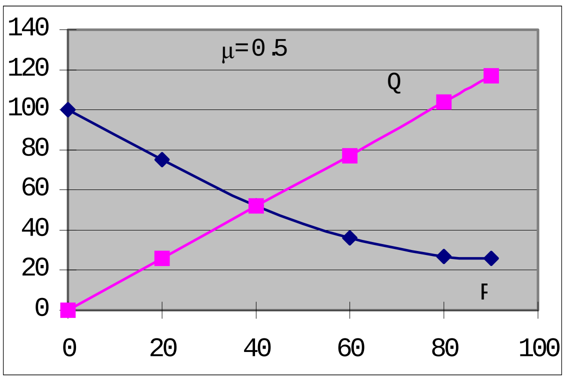


Figure 5. Calculated dependence of percentage part of liquid surface (P) and percentage part of non-wetted fibres (Q) from fibre bundle circumference for various fillings (μ) under the following input parameters: k = 1.075, R_V = 0.00001 m, R_K = 0.005 m. The diagrams are useful even for the other parameters of fibres and threads – their influence does not vary in the normal systems, so that the error was larger than +/- 10 %.
axis x - contact angle Θ in degrees
axis y - P (or Q) in percentages

Under the presumption that the surface of liquid and fibre has the shape of a circle, this case can be easily solved if we know the fibre radius and the curvature radius of the liquid level. However the problem is to determine the point of contact X (see Figure 4), which will accomplish requirements on the contact angle. This exercise does not make for a analytical solution, but it can be numerically solved.

On the basis of the calculations based on geometric considerations and the calculated liquid surface curvature, it can be stated that the surface of the fibre bundle with the liquid is created both from dry fibres and a liquid.

From the practical standpoint, it is important to note what percentage of the bundle surface creates un-wetted surface of fibres (Q) and what percentage creates a liquid (P). The ideal circle is considered as the bundle surface from which these percentages are calculated. The surface of the bundle which is made partially by fibres and partially by liquid surface is larger; that is why the sum P and Q is greater than one hundred percent.

The values of P and Q influence the process and wicking equilibrium, and they can be either calculated according to previous considerations or they can be experimentally determined, by analysis of the wicking equilibrium for fibre bundles with different number of fibres, that is, even a different surface. The courses of values P and Q which influence the contact angle are plotted in the following diagrams.

The radius of curvature of the liquid surface does not influence the values P or Q while the radius of curvature does not decrease to the same value of order as the fibre surface has. This case would occur at the height of some metres (!) above free liquid level – it cannot amount to this height in real systems, and that is why the values P and Q can be considered as a constant for one 'bundle of fibres-liquid' system.

Calculation of suction height at the vertical bundle of the parallel fibres

It is true of the bundle of parallel fibres that the transient part and the upper part only have a very small influence on the process and wicking equilibrium. Calculation of the wicking equilibrium can be based on the equilibrium of forces at the section of the main part. At the point of maximum (equilibrium) suction height, the interfacial force will be just compensated by gravity force.

Then at the section, the interfacial tensions assert themselves at these interfacials:

- between fibre and air (non-wetted segments of fibres)
- between fibre and liquid (wetted segments of fibres)
- between liquid and air (free liquid surface)

The phenomena described below decide which part of the fibres is wetted.

The illustration of the yarn cross-section of the wetted fibre bundle is presented in Figure 6:

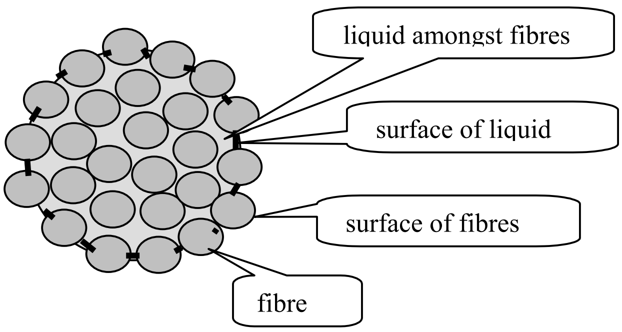


Figure 6. Cross-section of yarn with the liquid

The system will remain in equilibrium until the gravity force is compensated by the resultant interfacial force. On the basis of this consideration, the maximum suction height H_{max} can be directly expressed:

$$H\max = \frac{\sigma_{LG} \times \cos(\Theta) \times 2 \times \mu - \left(\frac{2}{100} \times \sigma_{LG} \times \sqrt{\frac{\mu}{N}}\right) \times (Q \times \cos(\Theta) + P)}{R_V \times (1-\mu) \times g \times \rho} \qquad (4)$$

where:

H_{max} - equilibrium suction height, m
N - number of fibres in bundle
R_V - radius of fibre, m
P - part in percent of liquid from surface of bundle, %

Q - part in percent of non-wetted fibres from surface of bundle, %
μ - filling
ρ - density of liquid, kg.m^{-3}
σ_{LG} - interfacial tension liquid-air, N.m^{-1}
Θ - contact angle

Note: In a hypothetical situation when the number of fibres in bundle is infinite and the surface of bundle does not exist, all the fibres in section of fibres bundle would be wetted. The suction height for this case proceeds as follows:

$$H\max(n=\infty)=\frac{\sigma_{LG}\times 2\times\cos(\Theta)\times\mu}{R_V\times g\times\rho\times(1-\mu)} \qquad (5)$$

where:

H_{max} - equilibrium suction height in a bundle with infinite number of fibres, m
N - number of fibres in bundle
R_V - radius of fibre, m
μ - filling
ρ - density of liquid, kg.m^{-3}
σ_{LG} - interfacial tension liquid-air, N.m^{-1}
Θ - contact angle

If we want to use this simplified formula, a certain minimum number of fibres must be in the bundle. With the presumption that the deviation of 10% between H_{max} and $H_{max}(n = \infty)$ will be accepted, the maximum number of fibres in bundle is given by this formula:

$$N=\frac{1}{100\times\mu}\times\left(Q+\frac{P}{\cos(\Theta)}\right)^2 \qquad (6)$$

in the case that μ = 0,5, Θ=80º, (P=25 a Q=120) proceeds N = 50
in the case that μ = 0,9, Θ=80º, (P=0 a Q=140) proceeds N = 200
in the case that μ = 0,9, Θ=20º, (P=65 a Q=35) proceeds N = 200

Fibre in experiments

linear density of fibre bundles:	144 tex
Fibres:	infinite
fibre cross-section:	noncircular-trilobal
linear density of single fibre	2,27 tex
quantity of fibres in the bundle:	63
twist intensity	without twist
shape factor:	0.5

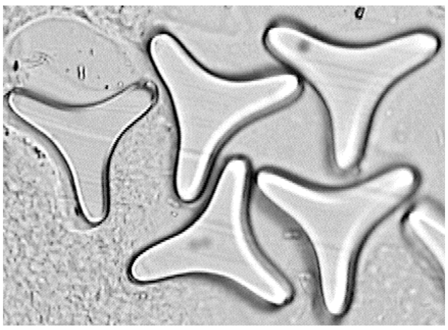


Figure 7. Cross-section of polyamide fibres used - magnification 400x

Experiment

For the testing of wicking, the Czech national standard ČSN 80 08 28 is usually used, which can quantify suction into the fabric. In this standard water is used as a wicked liquor, but for our experiments we used a mixture of water and isoprolyalcohol (in weight ratio 90:10). This liquor has a lower surface tension for all wetted fibres hydrophilic and hydrophilic fibres as well.

As a dyestuff for visualisation of suction Astrazon Rotviolett FRR was used in a concentration of 0.5 g/l. This solution is not prejudicial to health, and it is very easy to see the surface of the liquid in the fibre structure.

Evaporation occurs from the fibre bundles, and this process influences the suction height. This phenomenon was minimised; all our experiments were carried out in the closed systems with a relative humidity near 100%. The textile material was conditioned for 2 hours before the measurement.

Sample of experiments - Influence of the number of fibres in the bundle on the suction height

The number of the fibres at their cross-section is one of the important thread parameters; the suction height changes with the changing number of the fibres. If we proceed from the presumption that all other parameters of the system are constant, the following formula can be obtained:

$$H\max = k1 - k2 \times \sqrt{\frac{1}{N}} \qquad (7)$$

This relation can be used to verify the value of some parts of this model by linearisation.
Theoretical solution based on the tested model is presented in Figure 8.

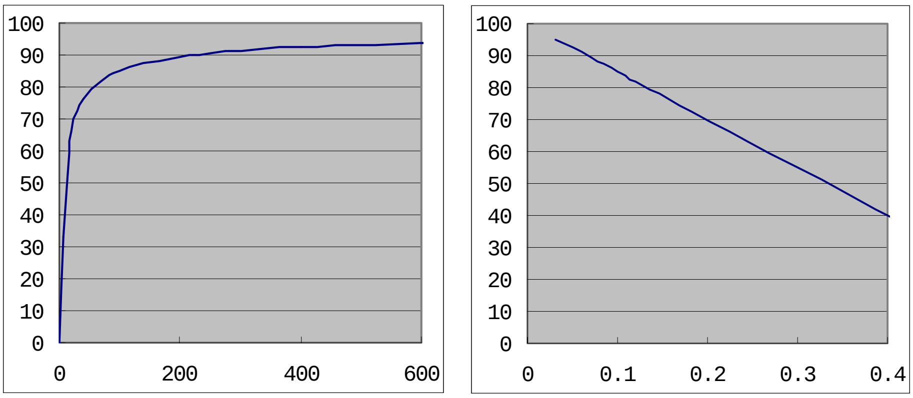


Figure 8. Influence of suction height (at infinity) on the number of fibres in the bundle (all other parameters of experiment are constant). Theoretical results
Left: axis x – number of fibres in the bundle /-/, axis y – suction height /mm/
Right: linearisation of data from the left side: axis x – 1/(square root of number of fibres in the bundle)/-/, axis y – suction height /mm/

The experimental results shown in Figure 9 are similar:

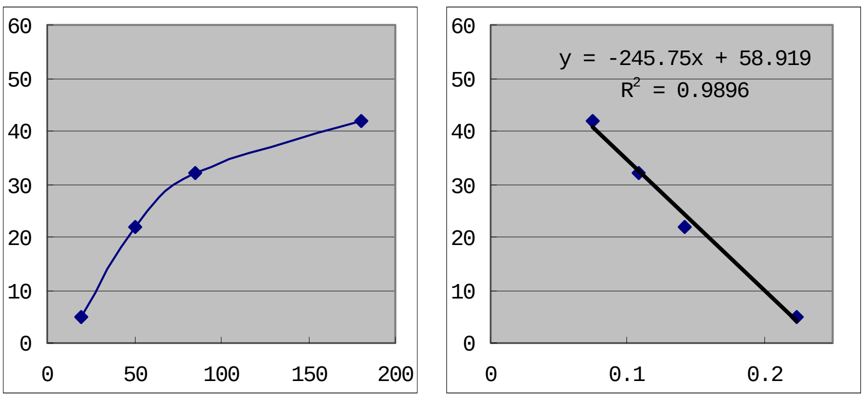


Figure 9. Influence of suction height (at infinity) on the number of fibres in the bundle (all other parameters of experiment are constant) – polyamide filament yarn, fibril fineness 2,27 tex, non-circular cross section-experimental results
Left: axis x – number of fibres in the bundle /-/, axis y – suction height /mm/
Right: linearisation of data from the left side: axis x – 1/(square root of number of fibres in the bundle)/-/, axis y – suction height /mm/

Conclusion

On the basis of the background research carried out, an equilibrium model for spontaneous liquid wicking into the longitudinal textile from an infinite liquid reservoir was proposed. This problem had not been comprehensively solved up to this time.

The proposed model is based on the simplified description of the thread structure, and works with the textile description of its structure. The following textile parameters are included in the model: fibre fineness, number of fibres at the cross-section of thread, fibre shape factor and the filling.

The formation originated by wicking the liquid into the longitudinal textile was described in detail; the separate phenomena have been discussed. Important parameters are used in the wicking model. Parameters with very small influence on normal threads are neglected.

The proposed model of wicking allows the functional dependence of suction height on the thread parameters to be expressed in an analytical form.

The influence of the number of fibres in the cross-section of the bundle was tested experimentally. The influence of the tested parameter was analysed by well-arranged linearisations.

This work could form a basic study for a future system, which would allow prediction of the wetting of multidimensional textile formations under real conditions.

Acknowledgements

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